Title

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Author
Delucchi, Mark

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by

Mark A. Delucchi

Institute of Transportation Studies
One Shields Avenue
University of California, Davis
Davis, California 95616
Tel.530/752-6548 Fax 530/752-6572
http://www.engr.ucdavis.edu/~its/events/index.html
email: itspublications@ucdavis.edu

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ABSTRACT

Hydrogen is an especially attractive transportation fuel. It is the least polluting fuel available, and can be produced anywhere there is water and a clean source of electricity. A fuel cycle in which hydrogen is produced by solar-electrolysis of water, or by gasification of renewably grown biomass, and then used in a fuel-cell powered electric-motor vehicle (FCEV), would produce little or no local, regional, or global pollution.

Hydrogen FCEVs would combine the best features of battery-powered electric vehicles (BPEVs) -- zero emissions, high efficiency, quiet operation and long life -- with the long range and fast refueling time of internal-combustion-engine vehicles (ICEVs). If fuel-cell technology develops as hoped, then hydrogen FCEVs will be a significant advance over both hydrogen ICEVs and solar BPEVs: they will be cleaner and more efficient than hydrogen ICEVs, have a much shorter refueling time than BPEVs, and have a lower lifecycle cost than both. Solar-hydrogen fuel-cell vehicles would be general-purpose zero-emission vehicles, and could be an important component of a strategy for reducing dependence on imported oil, mitigating global warming, and improving urban air quality, at an acceptable cost.

1. INTRODUCTION

Despite significant reductions in emissions over the past two decades, motor vehicles still account for 30 to 70% of emissions of all urban air pollutants (EPA, 1991), and up to 30% of emissions of carbon dioxide from the use of energy (DeLuchi, 1991). In most countries of the world, ground transportation uses petroleum fuels exclusively, and hence is vulnerable to supply and price volatility in the world oil market. These concerns have motivated researchers and policy makers to seek alternatives to gasoline and diesel fuel.

Hydrogen is an especially attractive alternative transportation fuel. It is the least polluting fuel that can be used in an internal combustion engine (ICE), and it is potentially available anywhere there is water and a clean source of power. The prospect of a clean, widely available transportation fuel has spurred much of the research on hydrogen fuels.

Hydrogen has been successfully demonstrated in experimental cars, buses, trucks and airplanes (Buchner and Povel, 1982; Stewart, 1984; Buchner, 1984; Brewer, 1986; Feucht et al., 1988; Furuhama, 1988; Protosenko, 1988; DeLuchi, 1989; Grunenfelder and Schucan, 1989; Ogden and Williams, 1989). If hydrogen is used in an internal-combustion engine (ICE), the only pollutant of concern is oxides of nitrogen (NOx), which probably can be controlled to low levels over most parts of a driving cycle. (Small amounts of hydrocarbons [HCs] and carbon monoxide [CO] can be emitted from combustion of the lubricating oil in a hydrogen ICE). But if hydrogen is used in a fuel cell -- an electrochemical device that converts the chemical-bond energy of hydrogen into electricity -- even NOx emissions (and any HCs and CO) are eliminated. A fuel cycle in which hydrogen is produced by solar electrolysis of water, or by gasification of renewably grown biomass, and then used in a fuel-cell powered electric-motor vehicle (FCEV), would produce little or no local, regional, or global pollution.

Virtually all experimental hydrogen vehicles to date have used internal combustion engines (ICEs), and most general analyses of hydrogen transportation have focused on ICEVs (DeLuchi, 1989; Petkov et al., 1989; Plass and Barbir, 1991; Sperling and DeLuchi, 1992) . Recent progress in fuel-cell technology has motivated me to expand the analysis of hydrogen transportation to include hydrogen FCEVs. Hydrogen FCEVs would combine the best features of battery-powered electric vehicles (BPEVs) -- zero emissions, high efficiency, quiet operation and long life -- with the long range and fast refueling time of ICEVs. In this report I show that if fuel-cell technology develops as hoped, then hydrogen FCEVs will be a significant advance over both hydrogen ICEVs and solar BPEVs: they will be cleaner and more efficient than hydrogen ICEVs, have a much shorter refueling time than BPEVs, and have a lower lifecycle cost than both. Solar-hydrogen fuel-cell vehicles would be general-purpose zero-emission vehicles, and could be an important component of a strategy for reducing dependence on imported oil, mitigating global warming, and improving urban air quality, at an acceptable cost.

This report examines the technology, performance, environmental impacts, safety, and economics of solar-hydrogen FCEVs. I compare hydrogen FCEVs with several other kinds of vehicles: with advanced gasoline ICEVs; with hydrogen ICEVs, in order to determine whether hydrogen is best used in ICEVs or in FCEVs; and with BPEVs, to see which (the BPEV or the FCEV) is the most attractive nonpolluting transportation alternative.

1.1. A brief history of hydrogen in transportation.

Serious work on hydrogen ICEVs began in the 1930s, when Rudolph Erren converted over 1000 ICEVs to hydrogen and hydrogen/gasoline operation in England and Germany (Hoffman, 1981). However, interest in the fuel waned after World War II. A resurgence of research and experimental activity came in the late 1960s and early 1970s as Japan, West Germany, and the United States began funding hydrogen programs. There are now important hydrogen development programs in Europe, North America, the Soviet Union, and Japan (Stewart, 1986). The strongest hydrogen ICEV development efforts are in Japan and Germany.

Work on hydrogen FCEVs has developed more recently, in part because until recently fuel cells have been much too heavy, bulky, and expensive to use in motor vehicles. In the past few years, however, advances in fuel cells (especially the proton-exchange-membrane fuel cell), have spurred interest in fuel-cell vehicles. There are several projects in North America. Energy Partners of Florida is designing and building a hydrogen-powered FCEV with a 20-kW PEM fuel cell, a 20-kW peaking battery, and compressed-hydrogen storage (Ewan, 1991). Ballard Technologies of Canada is working on a program to demonstrate a 30-foot transit bus powered by compressed hydrogen and a PEM fuel cell (Prater, 1991a). H-Power of New Jersey and Rolls Royce have teamed to develop a hydrogen PEM fuel-cell vehicle. The U. S. Department of Energy is supporting two fuel cell-vehicle projects: the Georgetown Bus Project, which is using reformed methanol and a phosphoric acid fuel cell (Kevala, 1990; Romano, 1990), and a project with General Motors, which is slated to deliver a methanol-fueled, PEM-powered fuel cell automobile by 1996 (Creveling and Sutton, 1990; USDOE, 1991b). There also are fuel-cell vehicle projects in Japan and Europe.

2. THE FUEL-CELL POWERED ELECTRIC VEHICLE (FCEV)

A fuel cell converts chemical energy in hydrogen and oxygen directly into electrical energy. It differs from both a rechargeable (or secondary) storage battery, such as is used in a battery-powered EV (BPEV), and a heat engine, although it is much more similar to the secondary battery than to the heat engine. Fuel cells and batteries are electrochemical devices; the main difference between them is that in a battery, the electricity-producing reactants are regenerated in the battery by the recharging process, whereas in a fuel cell, the electricity-producing reactants are continually supplied from an external source (e.g., air and a hydrogen storage tank).[1]

2.1. The Operation of a Fuel Cell.

Several kinds of fuel cells are being developed: proton-exchange membrane (PEM), phosphoric acid, alkaline, molten carbonate, and solid oxide. (Fuel cells generally are named after their electrolyte; hence the name PEM.) I will describe the operation of the PEM (also called the

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[1]At a fundamental level, all energy-producing chemical reactions that can power an automobile -- that is, all heat-producing combustion reactions (e.g., burning gasoline or hydrogen), and all electricity-producing electrochemical reactions (e.g. producing electricity from a lead/acid battery, or from a hydrogen/oxygen fuel cell), -- are the same: they involve the transfer of electrons, and are called electron-transfer, or oxidation-reduction reactions. Energy is made available as a result of electron transfer.

Although electrochemical cells and heat engines both produce energy via electron-transfer reactions, there is, beyond this fundamental similarity, an important difference between them. In a heat engine, the reactants (say, hydrogen and oxygen) come together and transfer electrons directly: for example, hydrogen transfers an electron to oxygen, and with it forms water. In an electrochemical cell, however, the reactants do not come together immediately, and do not not transfer electrons directly; rather, the reducing agent (hydrogen) gives up its electron while it is still physically separated from the oxidizer (oxygen), and the freed electron then travels through an external electrical circuit before reaching the oxidizer. The essential fact is thus that in an electrochemical cell, the electron travels through an external electrical circuit, and performs useful work, before it combines with the other reactant. For this to occur, the reactants must be physically separated; if they were not, the electron transfer would be direct, and there would be no possiblity of having an external electrical circuit. (By this account, a combustion reaction can be viewed as a short-circuited electrochemical-cell reaction.)

Electrochemical reactions can be run forwards to produce electricity, or backwards, with electricity input, to produce starting reactants such as hydrogen and oxygen. A rechargeable battery is an electrochemical device inside of which the reverse reaction (the charging or electricity-input reaction) as well the forward reaction (the discharging or electricity-producing reaction) take place. When a battery is discharged, the chemical reactants combine to produce electricity and new chemical compounds; when it is charged, electricity is applied to the new compounds to regenerate the original chemical reactants. A fuel cell also is an electrochemical device, but one in which the products of the electricity-producing reaction are removed from the system rather than used to regenerate reactants, and in which fresh reactants (hydrogen and oxygen) are supplied continually, rather than regenerated immediately from the products of electricity generation. The reactants are made at a location outside of the fuel cell system, and transported to the system.

solid-polymer-electrolyte, or SPE, fuel cell), which appears to be the most promising fuel cell for automobiles in the near-to-mid term. In a PEM, hydrogen, either stored as such on board the vehicle, or produced by reforming methanol into hydrogen and carbon monoxide (CO), is delivered to an electrode (the anode), where it separates, with the help of a platinum catalyst, into hydrogen ions and electrons. The electrons are collected into an external circuit and sent to perform useful work by turning an electric motor. The hydrogen ions -- protons -- are transported by an ion-conducting membrane (the proton-exchange membrane) to the opposite electrode, where they combine with oxygen from the atmosphere and the electrons returning from the motor to form water. The water is removed from the fuel cell. The reactions at each electrode are simply:[2]

$$\text{anode: } H_2 \xrightarrow[\text{catalyst}]{} 2H^+ + 2e^-$$

$$\text{cathode: } 2H^+ + (1/2)O_2 + 2e^- \xrightarrow[\text{catalyst}]{} H_2O$$

2.2. The FCEV System

A fuel-cell vehicle is an electric-drive vehicle that uses a fuel cell system in place of, or perhaps in parallel with, a rechargeable storage battery. The fuel-cell system, like the battery, provides electricity to an electric drivetrain. An electric drivetrain has three major parts: a) an electric traction motor; b) an electronics package, including a motor controller, dc-to-ac inverter, and dc-to-dc converter; and c) a transmission, which transmits power from the motor to the wheels. The FCEV vehicle would have all the desirable features of the BPEV -- no emissions, long life, low maintenance, and quiet operation -- plus an important additional advantage: it could be refueled for a 400-km driving range in a few minutes, whereas a battery holding enough energy for a 400-km range would take at least 30 minutes to recharge with extremely high-power recharging (which would require very high voltage and current), and several hours under typical recharging regimes.

A complete hydrogen fuel-cell system consists of several components: the fuel cell stack itself, which produces the electricity; a container to store the hydrogen or hydrogen-containing compound; an air compressor, to provide pressurized oxygen to the fuel cell (the power density of the fuel-cell system increases with the partial pressure of oxygen); a cooling system, to maintain the proper operating temperature; and a water management system, to keep the fuel-cell membrane saturated but at the same time prevent product water from accumulating at the cathode. If the vehicle stores the hydrogen in the form of methanol, it also will have a reformer, to convert the methanol into hydrogen and CO. Finally, as discussed below, it may be cost effective to have a small battery or an ultracapacitor (or perhaps even a flywheel) as a supplemental power source.

In a hydrogen-powered FCEV, the largest, heaviest, and most expensive components are the fuel-cell stack, the supplemental peak-power source, and the hydrogen-storage system. For each of these major components, several different technologies are available. In the following sections I discuss the major options, and my choices for the base-case analysis. Note, though, that I am not predicting that the technologies that I have selected for the base case will prove to the best in the long run; nor am I recommending that research and development be concentrated on these technologies. There is so much development work to be done on all the major components of fuel-cell vehicles that virtually any of the technologies identified here -- or others not identified here -- could prove to be the most attractive in the long run. As explained below, I have chosen technologies that on present evidence appear to be attractive for the near-to-middle term.

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[2]The operation of a PEM or SPE fuel cell is the reverse of the operation of an SPE elelctrolyzer.

2.2.1. The Fuel Cell.

Table 1 shows some of the major characteristics of four kinds of fuel cells that could be used in highway vehicles: phosphoric-acid, alkaline, PEM, and solid-oxide. Today, many researchers believe that PEM fuel cells, which will be commercially available within a few years (Prater, 1990), are best suited for use in highway vehicles in the near term. Phosphoric-acid fuel cells are too large and heavy to be used in light-duty motor vehicles, although they may be satisfactory in heavy-duty vehicles. Alkaline fuel cells perform very well, and have been projected to have a low materials cost (Appleby, 1990, 1991), but the electrolyte is so intolerant of CO_2 that the system must be supplied with either bottled oxygen or air scrubbed of CO_2. Most researchers have assumed that the extra cost and space requirement of storing pure oxygen or removing CO_2 from air make alkaline fuel cells unattractive for light-duty vehicles. However, if CO_2-tolerant alkaline electrolytes or low-cost air-separation or CO_2-removal methods are found, alkaline fuel cells could prove to be superior to PEM fuel cells for transportation. Solid-oxide fuel cells are projected to have excellent performance (Table 1), but are far from commercialization, and if started cold will require a relatively long warm-up period to reach their operating temperature (although a battery could provide the energy required at start up) (Table 1). (Also, Hsu and Tai [1992, 1990], indicate that solid-oxide fuel cells will be costly -- about \$350 kW_e manufacturing cost -- although, Miller [1991] believes that they will be less expensive than PEM fuel cells.)

For these and other reasons, most vehicle research, development, and demonstration programs are using, or planning to use, PEM fuel cells. I have specified a PEM fuel cell here, sized to provide the driving range and cruising power -- but not the peak power -- for a light-duty vehicle.

2.2.2. The Peak-Power Device.

Although technically a fuel cell could be sized to provide the peak power for a vehicle, several systems analyses have indicated that it would be more cost-effective to use a small, high-power battery to provide the peak power instead (Patil and Huff, 1987; Swan, 1989; Kevala, 1990; Romano, 1990; Adcock et al., 1992). The cost of a battery scales roughly with the amount of energy it can store, whereas the cost of a fuel cell scales with its power, and as a result a battery with a relatively large power capacity but modest energy storage capacity would be relatively inexpensive, compared to a fuel cell sized to meet the maximum power demand of a vehicle. Thus, in most designs for FCEVs, the fuel cell provides the cruising power, and the battery provides the peak power.

The peak-power device in a fuel cell vehicle need not be an electrochemical battery; it could be an ultracapacitor (a charge storage device) or a flywheel (an electromechanical battery). Ultracapacitors have extremely high power density (Table 2), but, at present, very low energy densities. However, if energy performance goals are achieved then ultracapacitors will be quite attractive as peak-power devices for fuel cell vehicles. Composite flywheels, as shown in Table 2, are projected to have high power density and reasonable energy density, but also are likely to be very expensive, and may lose up to 10% of their stored energy per day (Comfort et al., 1992).

Because the battery in the FCEV will provide peak power, rather than driving range, it should have a very high power density (in W/kg and W/l). In a BPEV, however, the battery must supply the full driving range of the vehicle, as well as the peak power, and so should have high energy density (in Wh/kg and Wh/l) as well. Table 2 shows the characteristics of several near-term and long-term batteries, and ultracapacitors and composite flywheels. For the base-case analysis, I have chosen the bipolar, high-temperature lithium/disulfide (Li/S) battery, for two reasons. First, the battery offers both high power density and high energy density. It could be configured to provide very high power density in an FCEV, or high energy density in a BPEV (Table 2). The recently formed U. S. Advanced Battery Coalition appears to have chosen the high-temperature Li/S battery "as the back-up for sodium-sulfur as a 'mid-term' battery and [for] lithium polymer electrolyte batteries for the 'far term'" (Halpert, 1991). Miller et al. (1987), in a study aimed specifically at finding peak-power batteries most suitable for hybrid vehicles, found that Na/S and

Li/Fe-S were the most promising of the systems currently under development, and that in the longer run Li/FeS_2 and bipolar Li/FeS batteries were extremely promising. And even though the bipolar Li/S battery is still in the laboratory stage of development, its developers feel that it could be commercially available by the year 2000. Second, some cost and performance data are available for this battery. Consequently, I have assumed in the base-case analysis that the bipolar Li/S battery would be used in both BPEVs and FCEVs, configured for high power density in the FCEV, and high energy density in the BPEV.

However, even if it is successfully commercialized, the high-temperature Li/S battery will have at least one serious drawback: if it is not used for long periods of time, it will consume a substantial amount of energy -- perhaps its own -- to maintain itself at its operating temperature of over 400^{o} C (see notes to Table 2; I account for heating energy in this analysis). Because of this, I discuss the performance and cost implications of using other batteries or peak-power devices.

2.2.3. Hydrogen Storage.

The hydrogen fuel needed by the fuel cell can be provided by reforming methanol into hydrogen and CO, or by storing hydrogen on board the vehicle. I do not consider methanol in detail in this analysis, although I do show summary cost results and vehicle attributes (Tables 4 and 7). (For an analysis of fuel cell vehicles using methanol and hydrogen made from biomass, see DeLuchi et al., 1991.) Hydrogen can be stored on board a vehicle as a compressed gas, a metal hydride, a cryogenic liquid, a liquid hydride, a cryoadsorbed gas, or a cooled and compressed gas (Table 3; DeLuchi, 1989). Recently, Werth (1992) has applied for a patent on a iron oxidation/reduction system in which hydrogen is generated onboard the vehicle from water and sponge iron. (This is discussed more below.) There are, of course, proponents of each of these methods, which makes it difficult to select a system for analytical purposes without appearing to be an advocate. As I explain next, I have chosen high-pressure gas storage because it is simple, reasonably light and compact, commercially available, and safe (I discuss safety later), and in principle should allow for fast refueling.

Because hydrogen is the lightest element, it is difficult to store compactly, and no hydrogen storage system can begin to approach the volumetric energy density (in mJ/l) of gasoline storage (Table 3). In the past, analysts have ruled out storing hydrogen as a compressed gas because at the pressures typically considered -- 3000 psi or so -- the system would be unacceptably bulky. However, if the storage pressure were increased to 8000 psi, compressed gas storage in carbon-wrapped aluminum-lined vessels would be attractive compared to most other hydrogen-storage options. In fact, as shown in Table 3, only liquid-hydrogen storage, and perhaps the iron oxidation/reduction system proposed by Werth (1992), would be substantially more compact than would compressed-gas storage at 8000 psi. Ultra-high-pressure storage would be more compact than cryoadsorption and most metal hydrides. It also would be lighter than any other option except liquid-hydrogen storage. And thanks to recent drops in the price of carbon fiber, carbon-wrapped aluminum-lined cylinders would be economically competitive with many other forms of hydrogen storage.[3]

In addition to being much lighter, compressed-gas storage would have two other important advantages over metal-hydride storage (which many analysts favor): it would be much simpler, and in principle would allow for much faster refueling. (I say "in principle" because so far as I know nobody has built a public-use system for fast delivery of ultra-high-pressure hydrogen, but

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[3] Most analysts have known that the bulk of a compressed-gas storage system could be reduced by increasing the storage pressure (by increasing the thickness of the liner and the fiber overwrap). The difficulty with ultra-high pressure storage has been that, on the one hand, the less expensive fiber wraps, such as kevlar and fiberglass, have a relatively low tensile strength per pound of wrap, and that, on the other hand, the high-strength carbon fibers have until recently been very expensive. Only a few years ago, carbon fiber cost at least $50 per pound, about 10 times as much as fiberglass. According to several industry sources, however, the price is now down to around $12/lb -- less than the price of kevlar, and close to the price of fiberglass (Takagashi, 1991; Richelieu, 1991; Price, 1991). This remarkable drop in price makes carbon-wrapped aluminum-lined ultra-high pressure vessels much more economical.

a supplier of natural-gas refueling equipment I spoke to sees no insurmountable technical obstacles to building one.) Metal hydride systems have relatively complex heat and water management systems, which add to the maintenance requirements of the system and reduce its reliability. Compressed-gas storage systems would have no thermal or water management systems, and no complicated piping or insulation. More importantly, it probably would take 5 times longer to refuel a metal hydride than a high-pressure tank (Table 3). This refueling problem by itself makes metal hydrides unattractive as potential replacements for gasoline vehicles.[4] And FeTi metal hydrides would not have any compensating cost advantages over compressed gas storage (Table 3).

Although liquid-hydrogen storage would have several advantages over compressed-gas storage -- it would be lighter and more compact, and the dewars themselves would be less expensive than high-pressure vessels (Table 3) -- I have ruled out liquid-hydrogen storage for four reasons: first, the liquid hydrogen itself and the liquid-hydrogen refueling stations would be quite expensive; second, the refueling operation would be relatively time-consuming if the refueling lines and the tank were warm and had to be precooled; third, the storage system would be relatively complex, because of the rigorous insulation and heat-management required; and fourth (and most importantly but probably least objectively), the public might be leery of a system that operated at only a few degrees above absolute zero and would start to vent fuel if the vehicle sat idle for a few days (or less).[5]

The key advantage of ultra-high pressure storage, and one which I think generally is not full appreciated, is its simplicity and ease of use. The motoring public is accustomed to a fuel storage system that is simple, extremely reliable, and easy and fast to refuel. Of all forms of hydrogen storage, high-pressure storage (in principle) most closely replicates gasoline storage in these respects. The basic components of a high-pressure system would be analogous to the components of a gasoline system: a tank, a fuel-flow control device (a pressure regulator or a fuel pump), and fuel lines.[6] The refueling operation should prove to be as fast and easy as with gasoline: one would connect the high-pressure line to the tank port, press a start button, wait a few

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[4] The hydrides used in the Mercedes Benz hydrogen-vehicle program had half the hydrogen storage capacity of the compressed-gas cylinders assumed in this analysis, but still took 10 minutes to refill to 90% capacity (*Alternative Energy Sources for Road Transport*, 1990). It probably would take at least 15 minutes to deliver to a hydride the amount of hydrogen needed for the full 400-km driving range assumed here. To motorists who are accustomed to not having to allot time for the 2 to 3 minutes it takes to refuel a gasoline vehicle, a factor of 5 or more increase in the refueling time would transform the refueling operation from a minor nuisance into a chore that had to be scheduled into the daily driving routine. The owner of a hydride vehicle could not simply squeeze in a stop at the service station on the way to work; he or she would have to make a point of getting up earlier in order to have time enough to refuel. Refueling no longer would be an incidental task; it would be psychologically significant, and people would have to worry about it. I believe that people would not like to have to worry about refueling and plan it into their day, and would tend to avoid buying hydride vehicles because of it.

[5]An additional minor and perhaps temporary advantage of compressed-hydrogen storage over liquid-hydrogen storage is that the regulations currently governing the storage of compressed hydrogen at installations like refueling stations are less strict than those governing the storage of liquid hydrogen. The National Fire Protection Association specifies that LH_2 tanks must be at least 50 feet from public places and property lines, 75 feet from openable windows, 50 feet from walls that are constructed of combustible materials and that have sprinler systems, and 5 feet from walls constructed of noncombustible materials (Air Products and Chemicals, 1989; the requirements apply to a storage capacity of between 3501 and 15,000 gallons). For compressed-hydrogen tanks, the distances are: 25 feet from windows, 15 feet from sidewalks, 5 feet from property lines, 50 feet from walls constructed on noncombustible materials, and 5 feet from walls constructed of combustible materials (Air Products and Chemicals, 1987).

[6] One could take advantage of the great simplicity, reliability, long life, and strength of high-pressure tanks by integrating them permanently into the frame of the vehicle, as a part of the structure. This would reduce the intrusivenes of the system.

minutes for the fuel to be delivered, press a stop button, and then disconnect the line. The potential speed, simplicity, and safety of this operation is quite appealing.

Still, key advances in either liquid hydrogen or metal hydride storage[7], or the successful development of H-Power's iron oxidation/reduction system (Werth, 1992), could make any of these systems more attractive than ultra-high-pressure storage. H-Power's system has one major advantage over compressed-gas storage: it is likely to be much less costly. It also is likely to be less bulky. On the other hand, it probably will be slightly heavier and somewhat more complex. (See the notes to Table 3 for a brief description, and Werth, 1992, for details.) I did not choose this system for the base-case analysis because it is still being developed, and hence cannot be characterized confidently in detail. However, it is interesting enough that I have considered it in the cost scenario analyses (discussed below).

The hydrogen gas could be stored at any pressure from atmospheric up to 690 bar (about 10,000 psi) or even higher. The higher the pressure, the smaller the storage volume, but the higher the cost of the pressure vessel and the cost of the compressor. Because a complete fuel cell system would be very bulky, it probably would be worthwhile to buy compactness by increasing the storage pressure -- up to a point. At pressures above about 550 bar (about 8000 psi), the overall cost of reducing the storage volume (by increasing the pressure) begins to increase substantially, because of non-ideal gas behavior. I therefore have assumed storage at 550 bar (8000 psi). For the cost analysis, summarized below, I obtained estimates from manufacturers and consultants of the cost of every major part a storage and refueling system designed specifically for high-pressure hydrogen storage and refueling (see Appendix A).

2.3. Summary of Technical Development Challenges Facing Fuel Cell Vehicles.

Although the successful development and eventual commercialization of fuel cell vehicles does not depend on technical "breakthroughs," in the way that battery development has been supposed to, it does require the resolution of many design and engineering challenges, and success is by no means guaranteed. Important issues are summarized below.

• The fuel cell, peak-power device, motor, electronics, and fuel -storage system must be designed and arranged to fit into as small a space as possible, without creating safety hazards. (For example, high-voltage components must be completely isolated.) The modularity of the components and the electronic (as opposed to mechanical) connections between them will afford designers and systems engineers some flexibility in separating and arranging the parts.

• Because BPEVs so far have been targeted for comparatively low-power, short-range applications, there is little experience with electric drive systems in long-range, high-power, and rapid-transient applications. Furthermore, most EVs have been developed for commercial or institutional users, who presumably take better care of their vehicles and use them more predictably than the general public does. However, because FCEVs in principle could be used in virtually in any application, by virtually any type of user, it is important to design and test electric drives for the types of uses (and abuses) that hitherto have been assumed to be irrelevant to EVs.

Similarly, it will be important to test advanced FCEVs and BPEVs under a wide range of weather conditions. In recent tests a PEM fuel-cell system was able to start instantly at 3^{o} C, but

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[7] Magnesium hydrides, which would have a high mass-energy density yet be relatively inexpensive, appear especially promising (Collier et al., 1991). To date, the difficulty with using magnesium hydrides in ICEVs has been that the temperature required to liberate the hydrogen from the hydride is higher than the temperature of the available heat source (the exhaust from the engine). This problem would be aggravated by the use of PEM fuel cell in place of an ICE, because the temperature of the waste heat from a PEM is much lower than the temperature of the exhaust gas from an ICE. The use of solid-oxide fuel cells, which produce very high-temperature waste heat, could solve this problem.

took 15 minutes to achieve full power (Prater, 1992a). The developers feel that this time "certainly" can be reduced.[8]

• Advanced electronics systems capable of controlling two power sources (the fuel cell and the peak-power device) and three battery-recharging paths (from the fuel cell, from regenerative braking, and from external outlets) have been developed only recently. The ultimate cost, performance, and reliability of these systems is not yet known.[9]

• At least four challenges face the developers of PEM fuel cells:[10] a) improve the performance and reduce the cost of the membrane, without compromising its mechanical properties

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[8]Ballard Power Systems has frozen, thawed, and toasted several membrane/electrode assemblies, and has found that after several thousand hours of freezing and about a hundred freeze-thaw cycles, there is no change in fuel cell performance (Prater, 1992b). They have not frozen a complete fuel cell system, because in the present design the flow fields and manifolds would be damaged by the freezing-expansion of residual water. However, they do believe that it will be possible to design a system able to withstand "low temperature storage" (Prater, 1992b). They have not attempted to start a fuel cell below zero centigrade, but think that it might be possible if the high ionic content of the interior of the membrane prevents the water within the membrane from freezing, and if the heat of reaction at the catalyst surface is sufficient to prevent the initial product water from freezing (Prater, 1992b). It is clear, though, that once the fuel cell is operating, it generates more than enough heat to prevent water and moisture from freezing in the system.

Cisar (1991) found that voltage increased with increasing temperature (as long as there was some current flow), primarily due to decreasing resistance. Cisar states that as the temperature rises, each proton has more energy available for "hopping" from one anionic site to another in the membrane, and the anion sites oscillate more as well.

[9] Patil and Huff (1987) discuss some of the design and engineering issues involved in integrating a fuel cell and a peak-power device. They analyzed a hybrid battery/fuel cell system, with a PEM fuel cell, a methanol reformer, and a Ni/Z or Pb/acid battery, and found the following:

a). "The strategy of not using the batteries during nominal power conditions was found to be the best approach to parallel operation. The study results indicate that battery disconnect during nominal cruise optimizes the tradeoff between fuel-cell efficiency, fuel-cell transient demands, and battery energy range" (p.995).

b). When the impedances of the battery and the fuel cell are closely matched, so that each can deliver maximum current during peak power operation, there is so little voltage difference between the battery and the fuel cell that there is relatively little current flow from the fuel cell to the battery during idle. Hence, the requirement to use both the battery and the fuel cell during peak operation limits the amount of energy that the fuel cell can deliver to the battery during idle.

c). Regenerative braking returns a significant amount of energy to the battery over the urban driving cycle, and should be used by the hybrid system.

d). In the optimum system, the nominal fuel cell system power is equal to the average duty-cycle power.

e). The battery cannot be so small that its voltage falls below the range that the controller can accept. If the battery is so small that its voltage is less than that of the fuel cell (but within the range of the controller), than one must have an "impedance matching device" that makes the impedance of the fuel cell and the battery equal, so that both can deliver maximum current during peak power demands. The feasibility and cost of an impedance matching device is not known, according to the authors.

[10] Until recently, this list would have included "reducing the amount of platinum catalyst used in the PEM fuel cell". However, recent reductions in catalyst loading (to 0.1 mg/cm^2 [Wilson et al., 1991], combined with modestly optimistic assumptions about the maximum power density of future PEM fuel cells (1250 mA/cm^2-active area, at 0.55 volts), result in only 3.6 mg of platinum per vehicle with a 25-kW fuel cell -- about twice as much as is used in the catalytic converters of gasoline ICEVs (see Appendix A). Allowing for a 50% increase in the price of platinum due to the increased demand per vehicle (FCEVs vs. ICEVs), the total cost of platinum in the FCEV still would be less than $100 at the manufacturing level. At these quantities and costs, platinum use in PEM-FCEVs is not much of a concern. I estimate that if in the future *all* vehicles in the world used PEM fuel cells, the *extra* yearly *mine* production (compared to the all-ICEV case) probably would be 2 to 3 orders of magnitude less than 1989 platinum reserves (56 million kg), and *total* annual world mine production of platinum probably still would be 2 orders of magnitude less than 1989 reserves (allowing for some recycling of platinum; based on Loebenstein, 1990).

or making it susceptible to impurities in the gas stream;[11] b) find a simple and effective way to keep the membrane moist, but at the same time not allow product water to build up at the cathode (Springer et al., 1991); c) reduce the size and energy consumption of the air-compression system (Swan et al. [1991] suggest that it might be best to have a variable-speed "smart" air compressor, programmed to operate at the optimal efficiency point depending on the load; such a compressor might not even operate at low loads); and d) reduce the weight, bulk, and manufacturing cost of the stack plates and assembly.

For alkaline fuel cells, the major challenge is to find a CO_2-tolerant electrolyte, or an inexpensive way to remove CO_2 from the air. Success in either area will make alkaline fuel cells very attractive. Solid-oxide fuel cells are still in the early-development stage.

• Although there are many candidate peak-power devices for fuel cell vehicles (several types of high-power batteries; ultracapacitors; flywheels; or simply very large fuel cells; see Table 2), none are yet completely satisfactory. Commercially available batteries are relatively heavy, bulky, expensive, or short-lived. Advanced high-power batteries, and ultra-capacitors, have not yet been commercialized and their ultimate cost, life, and performance is not known. High-temperature batteries may consume a substantial amount of their own energy just to maintain their operating temperature when the vehicle is idle (Bentley and Teagan, 1992). The ultimate choice of the peak-power device, and of its capacity and operating profile compared to the capacity and operating profile of the fuel cell, will be based on several factors: an analysis of the cost and performance of the peak-power device and the fuel cell; the characteristics of the driving cycle; and the amount, availability, and cost of the energy sources (regenerative braking, the fuel cell, or the outlet) used to recharge the battery.

• As discussed above, there are many ways to store hydrogen onboard a vehicle, but all that have been developed thus far are expensive and bulky. The development of an inexpensive, compact, safe, and easy-to-refuel hydrogen storage system will greatly improve the economics and marketability of fuel cell vehicles.

• The methanol reformers that are available today take a relatively long time to warm up, and cannot follow rapid changes in power demand. (Note that it is only the reformer, and not the PEM fuel cell itself, that cannot load follow; PEM fuel cells can load follow virtually instantaneously [Strasser, 1992; Amphlett et al., 1991b; Ballard, 1990].) The U. S. DOE is sponsoring research addressing these problems (U. S. DOE, 1991c). Present external reformers also are bulky and relatively complicated and moderately expensive. These latter problems would be solved by the successful development of internal-reforming solid-oxide fuel cells.

• Electric-drive technology is evolving and being refined, and engineers and designers are addressing several issues: the optimal system voltage, the choice of motor, (e.g., ac induction vs. dc brushless permanent-magnet vs. switched-reluctance), the choice of power-switching device (e.g., insulated-gate bipolar transistors [IGTBs] or metal-oxides semi-conductor field-effect transistors [MOSFETs]), and whether to use a single-speed (fixed-ratio) transmission or a two-speed transmission (Appleyard, 1992; Braess and Regar, 1991). These issues cannot be considered separately from one-another, or from the choice of battery or peak-power device. Note, though, that electric drivetrains already are satisfactory technically (Wallace, 1992); the remaining tasks are to further improve performance and reduce cost, rather than solve fundamental technical problems.

• Present air-conditioning systems can consume a substantial fraction of the energy in an EV storage battery. Work is underway to develop to more efficient heating and cooling systems, and to reduce the heat load (Dieckmann and Mallory, 1991). The GM Impact has special glass that reduces the heat load from solar infrared radiation by about 30%, compared to standarad tinted glass (Wyczalek, 1991).

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[11] The thickness of the membrane is a key design parameter for PEM fuel cells: thinner membranes cost less and have lower protonic resistance (and therefore higher power density), and might even simplify water management (Springer et al., 1991), but they also might deteriorate more quickly or be damaged more easily.

• A fully satisfactory state-of-charge indicator for batteries has not yet been developed (Burke, 1991b). This probably will prove to be a relatively minor problem.

3. CHARACTERISTICS OF THE VEHICLES ANALYZED IN THIS REPORT

In the following sections I will compare the efficiency, environmental impacts, and life-cycle cost of gasoline ICEVs, hydrogen-powered FCEVs, BPEVs, and hydrogen-powered ICEVs. The first step in this comparison is to specify the attributes of the vehicles (Table 4). In this analysis the baseline gasoline vehicle, from which all the alternative vehicles are hypothetically derived, is an advanced year-2000 version of the 1990 Ford Taurus, a popular mid-size car whose price, power, and fuel economy were close to the U. S. fleetwide averages for 1990. The hypothetical year-2000 Taurus features new designs and components that raise the fuel economy substantially above the level in 1990, make the vehicle safer, reduce emissions to the levels required in Tier I of the 1990 Clean Air Act Amendments, and increase the power-to-weight ratio. The resultant baseline vehicle has even better fuel economy than the "maximally efficient" year-2001 Taurus described by the U. S. Office of Technology Assessment (U. S. Congress, 1991). It also has relatively high horsepower, and a very high power-to-weight ratio . In short, this gasoline ICEV baseline, against which the FCEV and the BPEV are compared, is an efficient, powerful, relatively clean ICEV.

I assume that the EVs would have a shorter driving range and lower *peak* performance (in terms of the maximum instantaneous power delivered to the wheels at 60 mph, accounting for any differences in vehicle weight, rolling resistance, and aerodynamic drag) than the baseline ICEV, but, as discussed below, not necessarily a worse *overall* performance. My selection of range and peak performance for the EVs is based on a qualitative balancing of several factors: longer range and higher peak performance would make the EV more attractive to consumers, and more comparable to the baseline gasoline vehicle, but also would be relatively costly, because fuel cells, batteries and to a lesser extent hydrogen storage systems are more expensive per unit of energy or power provided than are gasoline tanks and gasoline ICEs.

The main text here discusses the important input variables, methods, and results of the cost analysis. Details of the cost analysis are given in the appendices.

3.1. Driving Range.

The lifecycle cost of a gasoline ICEV is virtually independent of its driving range, because gasoline storage is virtually free. However, batteries and hydrogen storage systems are bulky and expensive and often heavy, and as a consequence the lifecycle cost and performance of BPEVs and hydrogen FCEVs and ICEVs definitely will be related to the amount of energy stored on board. In theory, there would be an "optimal" range for these vehicles: the point at which the cost of providing the last increment of additional driving range (energy storage) equaled the benefit of the additional driving range. Although I do not know what this optimal driving range for BPEVs would be, I are fairly sure that it would be less, and perhaps substantially less, than the range of a gasoline ICEV, because range will be more expensive to provide in a BPEV than in ICEV (because a battery is so much more expensive than a gasoline tank). For the base-case cost analysis, I assume what I consider to be a "minimally acceptable" driving range for all-purpose vehicles, and a minimally acceptable range for urban vehicles. According to unpublished survey data from researchers at the University of California at Davis, the minimum acceptable range for "all-purpose" vehicles appears to be around 400 km. For special-purpose urban vehicles, 250 km might be the lowest acceptable range. Although the FCEV likely would have a longer range than the BPEV, because the fuel-storage system (especially for methanol) would not be as expensive or heavy as even the most advanced batteries would be, I estimate costs for the FCEV at the same driving ranges (400 km and 250 km) as for the BPEV, in order to compare the results for the FCEV with the results for the BPEV. Summary performance and cost statistics are given for both the 400-km and the 250-km cases (Details are in the appendices.) In the scenario analysis presented below I estimate costs for BPEVs and FCEVs at other driving ranges. I also assume a 400-km range for the hydrogen ICEVs, even though hydride and perhaps compressed-hydrogen ICEVs probably would not have such a long range, in order to be able to compare the ICEV cost results with the results for BPEVs and FCEVs.

3.2. Peak Performance and Overall Performance.

The assumed maximum power output of the motor, like the assumed driving range, affects the lifecycle cost of the vehicles. In the base cases I assume that the BPEV and FCEV would have 80% of the maximum acceleration capability of the ICEV at 60 mph (Table 4). I chose a lower peak performance for the EVs because of the high cost of providing power in an electric vehicle, but the particular figure chosen (80%) is arbitrary. The cost scenario analyses (discussed later), examine the effect of different assumptions about the peak performance. Note, though, that even though the EVs are assumed to have lower *maximum* performance than the ICEVs, they would not necessarily have a worse *overall* performance. In fact, they actually would perform better than the ICEV in the lower load regimes that characterize most driving. There are two reasons for this. First, an electric motor can deliver high torque at low rpm, whereas an ICE cannot. Since power is the product of torque and rpm, the high-torque electric drive can attain higher power at lower rpm than can the ICE. Second, with an electric drive, there need not be any appreciable lag between the application of the pedal and the response of the motor, because the power flow is electrical. In an ICE, the response lags somewhat because of lags in the mechanical linkages and friction in the flow of air and fuel. For both these reasons, high power can be made available more rapidly -- and to *feel* as if it is available more rapidly -- with an electric drive than with an internal-combustion-engine drive. Experience with properly designed EVs has borne this out.

I assume that the BPEV and the FCEV would have the same peak performance, in order to compare the cost results. (Note that because the BPEV would weigh more than the FCEV, it must have a higher peak power in order to have the same peak performance as the FCEV.) (The relative performance of the hydrogen ICEVs is not estimated here, because the model used to calculate the life-cycle cost of the hydrogen ICEVs is different from the model used to calculate the lifecycle cost of the EVs, and does not include vehicle performance as a parameter.)

3.3. Vehicle Life and Other Factors.

The assumed vehicle life is an important cost parameter, because it affects the amortized initial cost-per-km of the vehicle. It is well known that electric motors last many times longer than heat engines in the same application. What is not well known, however, is how the life of the drivetrain affects the life of the vehicle. I expect that lifetime advantage of the EV over the ICEV would be less than the advantage of the electric drive over the ICE drive, because vehicles are scrapped for reasons other than failure of the drivetrain. Still, experience in England does indicate that electric fleet vehicles can last much longer -- in some cases, several times longer -- than their ICEV fleet counterparts (Steele, 1984; Hamilton, 1988; see Appendix A for further discussion). On the other hand, this experience with fleet vehicles might not be entirely applicable to future household EVs, which would have different drivetrains and would be used differently. I assume, perhaps conservatively, that the EVs would have a 33% longer life than ICEVs. In scenario analyses I examine the effect of different assumptions about vehicle life.

DeLuchi (1989) suggests that in the best case hydrogen ICEVs might have a slightly longer life than gasoline ICEVs; I assume so here (Table 4), to give hydrogen ICEVs every advantage in the comparison with hydrogen FCEVs.

I also assume that the BPEV and FCEV would have lower aerodynamic drag and a lighter body than would the gasoline ICEV, because higher energy efficiency pays off in increased performance and longer driving range (or lower fuel storage costs), as well as in lower fuel costs, and these benefits are more important in EVs than in ICEVs. This assumption is consistent with the design of several recent advanced BPEVs and FCEVs, which are lightweight and aerodynamic and very energy efficient (General Motors, 1990; Ewan, 1991; Tange and Fukuyama, 1992; Sato et al., 1990). I assume that the hydrogen ICEVs also would have a lighter body than would the gasoline ICEV, but implicitly assume that they would have the same aerodynamic drag as the gasoline ICEV, because aerodynamic drag is not a parameter in the hydrogen ICEV cost model.

However, I do assume that the hydrogen engines would run ultra lean, in order to improve fuel economy (Table 4).

To recap, I compare FCEVs, BPEVs, and ICEVs in the year 2000. The year-2000 baseline gasoline ICEV is a very efficient, powerful, and clean mid-size car. The year-2000 BPEV and the FCEV are assumed to have a somewhat shorter range and lower peak performance than the year-2000 gasoline vehicle, but better low-end performance and longer life. In scenario analyses discussed later, I examine the lifecycle-cost implications of making the FCEV and the BPEV have the same peak power and nearly the same range as the gasoline ICEV.

4. CALCULATED VEHICLE CHARACTERISTICS: WEIGHT, BULK, AND ENERGY EFFICIENCY

4.1. System Weight.

Table 6 shows the calculated weights of the individual components of the FCEVs and BPEVs, and the total extra weight, compared to the gasoline ICEV, for the baseline vehicles of Table 4. The analysis indicates that hydrogen FCEVs could weigh less than gasoline ICEVs (Table 4). With an FCEV, the extra weight of the hydrogen storage system, fuel cell, and battery, compared to a gasoline tank, would be more than offset by the weight savings resulting from replacing the ICE powertrain with an electric powertrain. Thus, vehicle weight *per se* will not be especially important in the design of the FCEV. (Requiring the FCEV to have the same performance as the gasoline vehicle would not change this conclusion qualitatively.) Of course, it still will be important to keep the vehicle as light as possible in order to reduce fuel consumption and improve performance.

If advanced batteries (e.g., bipolar lithium/iron-disulfide, bipolar lithium/polymer, or Electro-fuel's zinc/air) are developed successfully, weight per se will be a constraint in the design of BPEVs only if the driving range is very long (and the battery relatively large). Tables 4 and 6 show that a 400-km BPEV with a very advanced battery (Li/S) might weigh only 100 kg more than a comparable gasoline ICEV, even with a 400-kg battery, because of the lighter weight of the electric drivetrain compared to the ICE drivetrain, and the weight-reduction measures I assume will be applied to EVs. If the BPEV has only a 250-km range, it might even weigh less than the ICEV, as indicated here (Table 4). However, the use of batteries with a lower energy density than the Li/S (see Table 2), or the failure to reduce the weight of the rest of the vehicle as much as possible (as assumed here), would increase the weight considerably. The BPEV then would weigh several hundred kg more than the comparable gasoline vehicle, and would need a much more powerful motor than would the FCEV to provide the same performance as the FCEV. In fact, if the Li/S battery were not available, and a battery with lower specific energy, such as sodium/sulfur, were used instead, it no longer would be practical to provide a 400-km range, because the battery and the vehicle would be too heavy.

The LH_2 ICEV in the analysis weighs less than the gasoline ICEV, because the minor extra weight of the LH_2 tank compared to the gasoline tank is more than offset by the assumed extra weight-reduction measures applied to the hydrogen vehicle. (Also, LH_2 fuel weighs less than the amount of gasoline providing the same range.) However, the hydride ICEV is several hundred kg heavier than the gasoline ICEV, because of the very low mass energy density of hydride storage. The compressed-hydrogen (CH_2) ICEV weighs only slightly more than the gasoline ICEV, because the weight of the storage tank is nearly canceled by the weight-reduction measures assumed to be applied to the rest of the vehicle, but it is nearly 200 kg more than the CH_2 FCEV, because ICE drivetrain is much heavier than the electric drivetrain.

4.2. Bulk and Range.

Fitting the energy-storage and power systems into the vehicle will be a challenge in the design of FCEVs and BPEVs with more than a 300-km range. As shown in Tables 4 and 6, the battery in the 400-km BPEV, and the complete fuel cell/hydrogen/battery system in the 400-km FCEV displace about 250 liters. The battery in the BPEV is slightly less bulky than the whole hydrogen fuel-cell system. The compactness of the electric drivetrain compared to the replaced ICE system (engine, fuel system, cooling system, electrical system, exhaust system, pollution control system, etc.) would mitigate but not obviate the space problem, even in an FCEV or BPEV designed from the ground up. For example, the battery tunnel in General Motor's 2-seat "Impact" BPEV is less than 200 liters (General Motors, 1990), which is not nearly enough space to house the components of the 400-km FCEV or the battery of the 400-km BPEV analyzed here. And the Impact was designed from the ground up, partly with the intention of maximizing the space available for the battery.

If the vehicle range were 250 km instead of 400 km, the bulk of the components in the FCEV and the BPEV (especially in the BPEV) would be much more manageable -- for example, they could fit into the battery tunnel of the GM Impact. However, if the bipolar Li/S battery, or other advanced batteries (such as the bipolar lithium/polymer, or Electrofuel's zinc/air) do not develop as expected, other batteries, with a lower volumetric power density and volumetric energy density (see Table 2), might have to be used in both the FCEV and the BPEV. In this case, the volume of the battery or fuel-cell system would increase considerably. For example, a sodium/sulfur battery in a BPEV would be nearly 50% larger than the base-case battery assumed here (see the battery performance characteristics of Table 2). A bipolar lead/acid peak-power battery in a FCEV would be more than 3 times larger than the Li/S battery, and as a result the whole fuel-cell system would be more than 60% bulkier than the base-case fuel-cell system. In an FCEV an ultra-capacitor would be about twice as large as the Li/S battery providing the same range, and the resulting fuel-cell-plus-battery system about 20% larger than the base-case system. (One could take advantage of the ultracapacitor's extremely high power/energy ratio and design it to handle very high power but not store much energy, in which case the bulk of the ultracapacitor would be reduced, but the driving range at maximum power also would be reduced.)

The challenge in designing an FCEV or BPEV with a long driving range will be to accommodate the energy and power systems without seriously sacrificing the space available for passengers and luggage. In the case of the FCEV, the bulk of the hydrogen storage container could be reduced by increasing the pressure, but this would be costly, and beyond a certain point would not even be very effective, because of non-ideal gas behavior. A better idea would be to integrate the storage tanks into the frame of the vehicle. This would require a rescission of the regulation that now requires that pressure vessels periodically be removed from the vehicle to be tested.

4.3. FCEVs vs. BPEVs: System Efficiency.

Energy for BPEVs or FCEVs can be produced from solar power or from biomass. The efficiency with which this energy is used, expressed here as gJ of useful energy provided to the wheels of the vehicle per gJ of primary energy input, is important in three ways. First, the efficiency of hydrogen or electricity use affects the fuel cost per kilometer. This effect of efficiency is accounted for in the lifecycle cost analysis described later in this report. Second, the efficiency of energy use often determines total emissions of greenhouse gases (which also is discussed later). Third, the overall efficiency of converting solar energy into energy at the wheels determines total land requirements for solar- or biomass-hydrogen energy production.

Figure 1 shows the overall and stage-by-stage efficiency of four energy-production-and-use pathways: 1) solar electricity used by battery-powered electric vehicles; 2) solar-electrolytic hydrogen used in fuel cell vehicles; 3) biomass-derived hydrogen used in fuel cell vehicles; and 4) biomass-derived methanol used in fuel cell vehicles.

Several points are noteworthy. First, the FCEV pathway using solar electricity would use solar energy about 50 times more efficiently than the FCEV pathways using biomass, because of the inefficiency of photosynthesis compared to photovoltaic (PV) solar-energy conversion, and the relatively high loss of energy in converting biomass to fuels. As discussed later, this means that biomass/FCEV systems would require much, much more land than would the PV/FCEV system. Second, because the production of bioenergy would require so much land, it would be especially important to produce and use biofuels efficiently. In this regard, biomass-hydrogen FCEVs would be slightly superior to biomass-methanol FCEVs, because of the extra energy loss in converting biomass to methanol (compared to converting it to hydrogen) and the extra energy consumption of the methanol reformer would exceed slightly the energy requirement of compressing hydrogen. (If hydrogen were stored as a hydride, or in some other form that required less energy than compression to high pressures, then the overall efficiency advantage of hydrogen FCEVs would be greater.) Third, the solar-power BPEV system would be about twice as efficient as the solar-hydrogen FCEV system, because of the loss of energy in converting electricity to hydrogen and the hydrogen back to electricity, and about 100 times more efficient than the biomass/FCEV systems, because of the low efficiency of photosynthesis. Direct use of solar power in BPEVs would be the most efficient use of solar energy.

5. ENVIRONMENTAL IMPACTS OF FUEL-CELL AND BATTERY-POWERED ELECTRIC VEHICLES

5.1. Urban Air Quality.

The great attraction of hydrogen fuel-cell vehicles is pollution-free operation. While a host of undesirable compounds are emitted from gasoline and diesel fuel vehicles, or are formed from the emitted compounds, a hydrogen FCEV would emit only water. Hydrogen FCEVs would not produce carbon monoxide (CO), nonmethane organic compounds (NMOCs; involved in the production of ozone [also refered to simply as hydrocarbons, or HCs), nitrogen oxides (NO_x; also involved in ozone production), particulates, sulfur oxides (SO_x), oxidants (such as ozone), carcinogenic aromatic compounds (such as benzene), toxic metals (such as lead), aldehydes, or greenhouse gases. They would be environmentally superior even to hydrogen ICEVs, which produce some NO_x as a result of the relatively high temperature of the internal-combustion engine, and small amounts of CO and NMOCs from combustion of the lubricating oil (Table 8). (PEM fuel cells operate far below the temperature required to produce NO_x, and do not consume oil.) Only battery-powered EVs can match the zero-emission performance of hydrogen-powered FCEVs (Table 8).

Solar FCEVs and BPEVs are the cleanest personal-transportation options available. The extent to which they would improve urban air quality depends, of course, on the extent to which they would penetrate the vehicle fleet. Because FCEVs could be refueled much more quickly than could BPEVs, and likely would have a lower lifecycle cost (see section 7.3), they probably could attain a greater market share, and hence ultimately could provide greater total air-quality benefits.

5.2. Greenhouse Gases.

The use of solar electricity to recharge BPEVs, or to make and compress hydrogen for FCEVs, would eliminate not only emissions of urban air pollutants, but all fuelcycle emissions of greenhouse gases as well (Table 8).[12] In fact, solar-powered BPEVs or FCEVs are the lowest-greenhouse-gas emitting personal-transportation options available. If solar power were used to make but not compress the hydrogen, and instead the U. S. average power mix were used for compression (to 550 bar for vehicle storage tanks), the reduction in greenhouse-gas emissions (relative to the gasoline fuel cycle) would be between 85 to 90%, versus 100% in the case where solar power is used for compression (Table 8).

The use in FCEVs of fuels derived from biomass also would provide a very large reduction in emissions of greenhouse gases, relative to gasoline, although not as large the reduction provided by the all-solar/FCEV cycle (Table 8). For example, the use of biomass-derived methanol in FCEVs would produce roughly the same amount of greenhouse-gases as the use of solar-electrolytic hydrogen compressed using the U. S. power mix projected for the year 2000. There are two reasons why the use of biomass-derived fuels in FCEVs would provide large reductions in

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[12] There still would be greenhouse-gas emissions from making and assembling materials for vehicles and solar energy facilities. However, DeLuchi (1991) has estimated that the emissons from the manufacture and assembly of materials for energy facilities probably would be insigificant. This means that vehicle manufacture and assembly would be the only significant source of emissions from an all-solar BPEV or hydrogen-FCEV fuel cycle.

emissions, relative to gasoline: first, any CO_2 released from the production and use of a biofuel would not count as a net emission to the atmosphere, because the carbon in the CO_2 would have come originally from CO_2 in the atmosphere, via photosynthesis. Second, the vehicles themselves would emit very little (in the case of methanol FCEVs) or zero (in the case of hydrogen FCEVs) non-CO_2 greenhouse gases. However, the use of biomass would not reduce greenhouse-gas emissions as much as would the all-solar cycles because of emissions from planting, fertilizing, harvesting, transporting, and gasifying biomass (DeLuchi, 1991).

In the very near term, hydrogen will continue to be made from natural gas. The use of natural-gas derived hydrogen in an FCEV would provide a large reduction in emissions of greenhouse gases, compared to the use of gasoline, because of the high efficiency of the FCEV, the elimination of emissions of greenhouse-gases other than CO_2, and the low carbon-to-hydrogen ratio of natural gas. However, some greenhouse-gas emissions would result from the production and transmission of natural gas, the reforming of natural gas to hydrogen, and the use of electricity to compress hydrogen.

5.3. Land and Water Use Issues.

Most renewable energy systems require more land than do fossil-fuel energy systems providing the same amount of end-use energy. Land use appears to be an especially serious issue in the case of biomass-energy systems, because much more land is required to produce a unit of bio-energy than is required to produce a unit of solar photovoltaic energy or even wind energy (Table 9), and because the potential demand for biofuels is so large. For example, DeLuchi et al. (1991) compared the amount of bio-energy (45 eJ) that could be produced from energy crops and trees, urban and agricultural residues, and better management of existing commercial forests, to the amount of primary biomass energy that would be required to fuel the highway vehicle fleet in the year 2030, considering different vehicle technologies and fuels. They found that if highway vehicles used ICEs fueled by methanol derived from biomass, virtually all of the 45 eJ maximum supply would be needed. If the vehicle fleet used fuel cells fueled by methanol derived from biomass, 2/3 of the total biomass primary energy supply would be required; and if the fleet used fuel cells fueled by hydrogen derived from biomass, half of the potential biomass supply would be required.

Considering that biomass would be demanded by other energy sectors, such as electricity generation, and perhaps by non-energy sectors, as well as by transportation, it is clear that the use of biomass-derived fuels in transportation, even with fuel cell vehicles, would, *at the level of fleet-average vehicle efficiency assumed by DeLuchi et al. (1991)*, place great pressure on potential biomass supplies. This could lead to the development of large biomass energy farms, with their attendant environmental risks: soil erosion, the adverse consequences of the use of herbicides and fertilizer, the potential loss of biological diversity (Miles and Miles, 1992; Cook et al., 1991; Hall et al., 1991), and high water consumption. For example, in the DeLuchi et al. (1991) scenario, if the entire 45 eJ of potential biomass supply were demanded by energy end users, then some 78 million hectares of additional land would have to be devoted to producing energy crops alone (not counting land already in commercial forests). This is about the size of California, Oregon, and Washington combined -- 10% of the land area of the lower 48 states.

To avoid such an outcome, there would have to be environmental constraints on the development of biomass supplies, and less demand for biofuels. Demand could be reduced by greatly improving the efficiency of energy use. For example, if fleet-average fuel consumption were half the level assumed by DeLuchi et al. (1991), then the total amount of biomass demanded by a hydrogen-powered fuel-cell highway fleet could be met by biomass residues and better management of existing forests -- i.e., without energy crops -- with more than 5 eJ of potential supply left over for other energy-using sectors.

In any event, both solar-power and wind energy systems would use significantly less land than would biomass or hydro-power systems. They also would use much less water. In turn, solar- thermal and solar-PV systems would require less land than would wind systems. Solar-PV systems would require the least amount of land of any energy system considered here: about 1/3 of that needed for solar thermal, 1/3 to 1/20 that for wind, and 1/25 that for biomass (Table 9) -- and unlike solar thermal systems, could be used in cloudy areas. A biomass energy-crop system that required all the land in California, Oregon, and Washington could be replaced by a solar -PV energy system that required only part of the California desert.

5.3.1. Ecological issues.

Not only would PV systems require much less land and water than would biomass energy-crop systems, per unit of end-use energy made available, they would use the land in a less damaging and exclusive way. The environmental concerns mentioned above -- erosion, the adverse consequences of the use of herbicides and fertilizer, and the potential loss of biological diversity -- will eliminate particularly sensitive or unique lands from consideration as potential biomass resources, and govern the development and managemement of the lands that are suitable. Careful and creative development and management techniques will be needed to satisfy espespecially stringent environmental constraints (Hall et al., 1991).

But even "ecologically diverse" biomass plantations would have access roads (which in forests often cause a great deal of erosion) and would have to be kept relatively free of undergrowth. At least some plantations, and perhaps many of them, would use fertilizers and irrigation. Clearing, planting, managing, cutting, or hauling would go on continously, and would rout many kinds of wildlife. It is difficult to imagine that such heavily disturbed and managed land could support other human uses simultaneously, or would be ecologically as healthy as would an indigenous, unmanaged system.

PV systems, on the other hand, would require relatively little attention after they were built. There would be no large-scale inputs of chemicals or water on-site, and at any given time there would be no human activity throughout most of the site. PV systems of course would require access roads, but generally it is easier to build roads with minimal environmental disturbance in flat deserts than in hilly forests. PV systems also could be built on top of other things, such as roofs or storage areas; in such instances, PVs would have effectively no land requirement.

For these reasons, energy-crop systems are less desirable environmentally than solar energy systems. However, better management of exisiting forests and crop systems, and use of agricultural, forest, and urban residues, is much less objectionable, and, with improvements in the efficiency of end use, could provide a substantial portion of transportation energy demand.

6. SAFETY: A MISUNDERSTOOD ISSUE?

In spite of its considerable environmental benefits, hydrogen will not be used widely until policy makers and the public are convinced that it is no more dangerous than the petroleum fuels they are accustomed to. Although hydrogen has a reputation as a particularly dangerous fuel, the limited experience with hydrogen, and analyses of its physical and chemical properties, indicate that hydrogen is in some ways more dangerous than gasoline, but in other ways is safer.

Hydrogen is more hazardous than gasoline in several ways. First, it is invisible and odorless, and therefore requires odorants and colorants to enable detection. Second, because hydrogen flames are very hot, yet radiate very little heat and are invisible, they are harder to locate, and thus harder to extinguish or to avoid. Third, hydrogen can ignite within a rather large range of hydrogen/air densities, from 4 to 74% by volume. Compared to methanol or gasoline, it needs very little energy to ignite. (However, all three fuels have such low ignition energies that similar precautions must be taken when handling them.)

But hydrogen also has several safety advantages over gasoline. First, hydrogen must reach a concentration of 18% to 59% in air before it will detonate (as exposed to merely ignite), whereas gasoline can detonate at concentrations as low as 1% to 3% in air. Second, because of its very low molecular weight, hydrogen, if leaked, disperses exceedingly fast -- unlike gasoline, which puddles and remains a fire hazard for much, much longer. Third, hydrogen fires burn quite rapidly and are relatively short-lived, compared to gasoline fires involving the same amount of energy.

Researchers have judged hydrogen storage systems to be relatively safe (Strickland, 1978; Bockris, 1980; Huston, 1984; Peshcka, 1986). Carbon-wrapped aluminum containers, which in the base case I have assumed would be used in hydrogen FCEVs, would have to undergo extensive safety testing before they could be certified.[13] Presently, the USDOT requires that commercial cylinders withstand gunfire without fragmenting, a bonfire without exploding, and several pressure cycling and thermal cycling tests. One manufacturer has done additional testing, and has found that dragging a CNG (compressed natural gas) cylinder from the back of a car, dropping it repeatedly onto a steel plate from 10 to 16 feet, partially cutting its fiber wrap, or leaving it pressurized outdoors for up to 11 years does not lower the burst pressure (Morris, 1986). The exterior of a composite high-pressure cylinder must resist water, cleaning solvents, and salt air (Structural Composite Industries, 1986).

Furthermore, composite pressure vessels actually fail more safely than do gasoline tanks or all-steel pressure vessels. According to Young (1990, p. 967):

> "Steel pressure vessels or gasoline tanks tend to fail in a catastrophic seam or line rupture from over-pressure or ballistic damages. [However,] composites tanks will generally relieve the pressure through a small local site. The fibers act as "rip-stop" cross-yarns as the failure site tries to propagate. The rapid relieve of the pressure also rapidly reduces the stress on the adjacent fibers."

For the reasons cited above, the U.S. National Bureau of Standards (Hord, 1978), the Stanford Research Institute (in Hoffman, 1981), and the German "Alternative Fuels for Road Transport" program (Quadflieg, 1986), have concluded that the hazards of hydrogen are different from, but not necessarily greater than, those presented by current petroleum fuels.

This conclusion, shared by many in the hydrogen technical community, must be accepted by policy makers and the public. In this regard, a recent University of California study of public reaction to high-pressure storage of natural gas is encouraging. The study suggested that the use of high-pressure CNG tanks, integrated into the frame of a vehicle, probably would not be of serious concern to the motorists (Sperling, 1991). As Appleby (1992) points out, "if the public and vehicle manufacturers can be persuaded that natural gas is acceptable, then hydrogen should also be acceptable using identical pressurized storage equipment" (p. 229). Nevertheless, to extend this favorable outlook to hydrogen, a wide range of demonstrations would be desirable, to show the safety of hydrogen in routine public refueling, storage, and use.

Finally, it is worth noting that in the iron oxidation-reduction system developed by H-power (Werth, 1992), hydrogen is not even stored as such on board the vehicle. Instead, hydrogen is formed as needed, by the reaction of steam and reduced iron. Only the reduced iron is carried on board the vehicle. This storage system obviates concerns about the safety of *storing* hydrogen on board vehicles, although hydrogen still has to be handled, between the time it is generated by the oxidation reaction, and the time it is consumed in the fuel cell.

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[13] Today, there are barriers to the use of very-high pressure storage of hydrogen on a vehicle. For example, the U. S. Department of Transportation (USDOT) presently limits gas storage on board vehicles to no more than 3000 psia. This rule, however, is not based on technical assessments of the safety of advanced-technology, ultra-high-pressure systems; rather, it is due to USDOT wishing to be conservative as it gains experience with a new technology, and, I presume, to the lack of interest in ultra-high pressure storage.

Nor do I see any reason to believe that the public would be more leary of high-pressure hydrogen storage than of any other form of hydrogen storage. There is no evidence that the use of high pressure storage has seriously inhibited the marketing of natural gas vehicles. In fact, the little work that has been done in this area suggests that people would quickly forget about the storage system if it were out of sight. Given that the difference between 8000 psi and 3000 psi would be meaningless to most people, it is likely that most people could get used to ultra-high pressure storage per se.

7. A LIFECYCLE COST ANALYSIS

Hydrogen fuel and hydrogen vehicles will be costly. Even assuming substantial cost reductions over the next 10 to 20 years, renewable hydrogen is likely to cost considerably more than gasoline per gJ (Ogden and Nitsch, 1992; Ogden and DeLuchi, 1992), and hydrogen storage systems are likely to cost orders of magnitude more than gasoline tanks (Table 6). In the case of hydrogen *ICEVs*, the higher fuel price and vehicle price probably will result in a *lifecycle* cost substantially higher than that of gasoline vehicles (DeLuchi, 1989; Table 7 here). But I will show that this conclusion might not apply to hydrogen-powered *fuel-cell vehicles*, which would be much more efficient than ICEVs (and hence have a lower fuel cost per km), and would use a relatively long-lived and low-maintenance electric powertrain. In this section, I examine the economics of FCEVs, by making a detailed and comprehensive lifecycle cost comparison between gasoline ICEVs, hydrogen FCEVs, and BPEVs.

7.1. Methods.

I compare these vehicles using two summary cost parameters: the total cents-per-km lifecycle cost, and the breakeven price of gasoline. The total lifecycle cost, expressed here in U. S. cents (1990$) per km of travel, is the sum of all yearly operating costs and all annualized initial costs, divided by the average distance traveled per year. Initial costs include the vehicle shell and chassis and interior, the drivetrain, the fuel storage system, and in the case of FCEVs and BPEVs, the traction battery, the fuel cell, and the peak-power device. Operating costs include fuel and/or electricity, insurance, maintenance, registration, inspection and maintenance fees, accessories, replacement tires, and parking and tolls. In this analysis, most of these initial and operating costs are a function of many other parameters. Details of the analysis are given in the appendices.

The other summary cost statistic used in this analysis is the break-even gasoline price. The break-even price of gasoline is that retail price of gasoline, in $/gallon, including current total average fuel taxes in the U. S. ($0.31/gallon), which equates the total cost-per-km of the gasoline vehicle (insurance cost, maintenance cost, tire cost, amortized initial cost, fuel cost... everything) with the total cost-per-km of the hydrogen vehicle. The breakeven gasoline price is shown in Tables 8, 10, and 11.

I assume that all vehicles and their major components, such as fuel cells, hydrogen storage tanks, and batteries, are mass-produced at high enough volumes (typically, at least 10,000 units per year) to capture most economies of scale. The estimate of the cost of producing solar hydrogen is based on the detailed analyses presented in Ogden and Nitsch (1992) and Ogden and DeLuchi (1992), and is summarized in Table 5. Although hydrogen produced electrolytically from wind or solar power would at present cost much more than most other transportation fuels, costs are projected to drop considerably over the next ten to twenty years, to perhaps $18/gJ (delivered to the refueling station) by the early part of the next century. Hydrogen produced from biomass would be even cheaper -- as little as $6/gJ at the plant gate.(Larson and Katofsky, 1992; Table 5 here). In scenario analyses I consider biomass-derived hydrogen.

Generally, my cost assumptions for FCEVs and BPEVs are optimistic but plausible. They assume continued improvement in all the key technologies, but no *major* technological innovations. For most of the important cost parameters for BPEVs and FCEVs, I can cite at least one estimate that is more favorable to BPEVs or FCEVs than is mine (see the appendices). The cost assumptions for hydrogen ICEVs are perhaps even more optimistic than the estimates for FCEVs: in virtually every case, they are at the low end of an estimated cost range. I chose relatively optimistic base cases because pessimistic cases would not be very interesting: obviously, if fuel cell vehicle technology does not develop, and costs do not decline, then fuel cell vehicles will not be economical. (This is demonstrated clearly in the scenario analyses of Table 11.) I think it is more useful to show the conditions under which a technology might succeed, than to say that if technologies do not develop as hoped then they will fail.

7.2. Interpreting the Results of the Cost of the Analysis.

The cost results presented here are scenarios, not predictions or projections. There is far too much uncertainty to be making projections: although I have documented or explained all the important assumptions (see the appendices), and believe that the analytical method is detailed and sound, I cannot avoid speculating about some of the cost parameters. Therefore, the reader should not view the base-case cost analysis as an attempt at a definitive cost projection, but rather as a scenario analysis -- an "if-then" statement" -- or as a parametric analysis. For example, as shown below, the base-case assumptions for FCEVs result in life-cycle cost comparable to the life-cycle cost of gasoline ICEVs at the projected price of oil in the year 2000. But this does not mean that I are confidently predicting the economic success of fuel cell vehicles. Rather, it means either: a) that if my assumptions are correct, then solar-hydrogen FCEVs will be economically competitive with gasoline ICEVs; or b) that *one way* to make fuel cell vehicles economically competitive is to realize the set of cost specifications used here. (Of course, as discussed below, there are many other combinations of assumptions that produce a lifecycle cost equal to or lower than the base-case lifecycle cost, as well as many sets of assumptions that produce a higher lifecycle cost.)

7.3. Results of the Base-Case Analysis.

The base-case cost analyses are summarized in Tables 7 and 10. There are four noteworthy results. First, hydrogen FCEVs probably will have a lower lifecycle cost per km than hydrogen ICEVs. Second, hydrogen FCEVs probably will have a lower lifecycle cost than BPEVs, except perhaps if BPEVs have a very short range. Third, with the base-case cost parameters used here, hydrogen FCEVs will be competitive with gasoline vehicles at gasoline prices of less than $1.50/gallon (including taxes). Fourth, life-cycle competitiveness with gasoline ICEVs does *not* depend on large reductions in the cost of the fuel cell itself. Each of these results is discussed in more detail next.

1). The lower lifecycle cost of hydrogen FCEVs, compared to hydrogen ICEVs (even with very optimistic cost assumptions for the hydrogen ICEVs), is due to several factors: the much higher net efficiency of the fuel-cell electric-drive system (about 46% for the fuel cell, including auxiliaries, and 88% for the drivetrain, for a total of 40%; see Figure 1) compared to the IC engine and transmission (about 14% in combined city and highway driving, in use); the lower average-annual maintenance costs (Table 7); and, most importantly, the longer life of the electric drivetrain. The higher efficiency of the fuel cell not only reduces fuel costs, but also reduces the amount of fuel that must be carried to provide a given range, which reduces the cost of the fuel storage system. This reduction in the cost of fuel storage is significant in the case of hydrogen, because hydrogen storage is expensive per unit of fuel carried. The longer life of the drivetrain is important because it substantially reduces the amortized cost-per-km of buying a vehicle. These advantages, plus the significantly lower cost of the electric drivetrain, more than compensate for the extra cost of the fuel-cell-plus-battery system in the FCEV. Therefore, if these cost results prove accurate, then it clearly will be more economical to use hydrogen in FCEVs then in ICEVs.

2). The lower projected lifecycle cost of hydrogen FCEVs, compared to BPEVs, is due entirely to the great cost of the battery required for a 400-km or even a 250-km range. Although the BPEV would have slightly lower maintenance costs and fuel (electricity) costs than would the FCEV, and would not have a fuel-cell or hydrogen-storage system, these savings would be swamped by the cost of a 400-km battery -- well over $10,000 at the retail level.[14] Moreover, the

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[14] One might ask why the battery in this analysis is so costly. It is not because I have made unfavorable assumptions about battery performance and cost; in fact, I have assumed that recent low-end *manufacturing* cost estimates for sodium/sulfur would apply to the bipolar Li/S, which is projected to perform much better than the sodium/sulfur battery. Rather, it is because a very large battery (over 60 kWh) is needed to provide a 400-km range, and because Table 6 shows the retail-level price of the battery, not the manufacturing cost. Most estimates of battery costs in the literature are estimates of manufacturing cost. However, the final selling price (including retail taxes) typically is almost twice the manufacturing cost (Appendix A). In the scenario analyses I consider different ratios of selling price to manufacturing cost.

great weight and cost of the battery would increase the cost of insurance, tires, and registration, and would necessitate a larger, more expensive powertrain to match the performance of the FCEV (Tables 6 and 10).

Of course, if the battery were much smaller, and the range of the BPEV much less, the lifecycle cost would be less. This analysis indicates that a BPEV with a 160-km (100-mile) range would have approximately the same lifecycle cost as an FCEV with a 400-km (250-mile) range. Based on this, I believe that BPEVs with a long driving range probably would never compete economically with FCEVs with the same driving range, but that BPEVs with small, low-cost batteries could compete with FCEVs with a short range. This suggests that battery researchers should concentrate at least as much on reducing the cost of batteries as on improving performance.

3). The prospect that hydrogen-FCEVs could be economically competitive with gasoline-fired ICEVs, despite the high initial cost of the FCEVs, and the higher cost of solar-electrolytic hydrogen (Tables 5 and 7), is due to three factors. First, the electric powertrain (excluding the battery and fuel cell) would cost much less than the ICE system it replaced (Appendix A). Second, the FCEV would be nearly three times as efficient as the ICEV (Table 4). This would lower the cost of fuel, so much so that the cost-per-km of hydrogen in an FCEV actually would be lower than the cost-per-km of gasoline in an ICEV (Table 10), given the base-case fuel prices (Table 7) of this analysis. Third, the electric drivetrain probably would have lower maintenance costs and last much longer than the ICE drivetrain. If the longer life of the electric drivetrain translated into a longer vehicle life, the amortized cost per km of vehicle ownership would be dramatically reduced. The longer life and lower cost of the electric drivetrain would compensate for many of the cost disadvantages of the FCEV (Table 10). However, even though the assumption of a longer vehicle life is supported by experience in England, where electric fleet vehicles last longer -- in some cases, several times longer -- than their ICEV fleet counterparts, it still is unproven as regards all household and commercial vehicles. I therefore test different assumptions about vehicle life in the scenario analyses.

4). In order to get a rough idea of the economics of FCEVs, analysts often compare the cost of hydrogen or methanol fuel with the cost of gasoline, and the initial cost of a fuel-cell system with the cost of an engine (e.g., Appleby, 1992). These comparisons can be interesting, but because they omit several important variables, they usually do not tell the whole story. As demonstrated here, the advantages of FCEVs -- longer life, lower maintenance costs, and higher efficiency than with ICEVs -- can compensate for the higher $/gJ-cost of hydrogen and the higher $/kW cost of the complete fuel-cell, hydrogen-storage, and electric-drive system (compared to the ICE system). In fact, this analysis indicates that achieving a very low cost for hydrogen fuel and the fuel-cell system is by itself neither necessary nor sufficient to make the life-cycle cost of an FCEV competitive with that of a gasoline ICEV. For example, in the base-case analysis, the fuel cell and auxiliaries *alone* (excluding the electric drivetrain) cost over $150/kW at the vehicle-retail level, whereas the retail-level cost of the *entire* ICE powertrain (*all* the parts removed from the ICEV) is about $55/kW -- yet on a lifecycle-cost basis the hydrogen FCEV can compete economically with the gasoline ICEV. This is partly because of the lifecycle-cost advantages discussed above, and partly because the peak power of th EV in this analysis is less than the peak power of the ICEV, and the fuel cell itself suplies only part of the peak power -- a battery, with a lower power cost than the fuel cell, supplies the rest. Thus, I believe it is unnecessarily stringent, and perhaps misleading, to set cost targets for fuel cells or fuel-cell components based only on a comparison with the cost of an engine. The economics of FCEVs should be evaluated on a systems life-cycle basis.

I do recognize that the cost disadvantages of FCEVs (the high initial cost, and the high fuel cost) might be more prominent in the eyes of consumers than the cost advantages (long life, high efficiency, and low maintenance costs), at least initially. Thus, FCEVs might have a reasonable lifecycle cost, but seem relatively expensive to many consumers. I believe that this gap between perception and reality can and to some extent will be closed in two ways.

First, education and experience will make consumers understand, believe in, and ultimately value the longer life and lower maintenance costs of FCEVs (assuming, of course, that these benefits are real). Experience with diesel vehicles supports this hypothesis (Kurani and Sperling, 1989; see also Turrentine et al., 1991, on perceptions of the maintenance costs of EVs). If buyers do not now think much about vehicle life and maintenance, it probably is because the differences in these attributes among vehicles are minor and unreliable. However, even now, most consumers do not think solely in terms of initial cost, because most take out a loan to buy a vehicle, and hence face a monthly payment rather than an initial cost.[15] It is not difficult to imagine that prospective car buyers already used to considering monthly vehicle payments would begin to weigh more explicitly the operating costs and resale value of the vehicle, if there were significant and certain differences in these attributes between EVs and ICEVs.

Second, government can subsidize or even mandate FCEVs, or penalize ICEVs, in recognition of the environmental benefits of FCEVs, and to help overcome initial consumer wariness. Individuals, acting as *citizens* in favor of the public good, might support such policies, even though as *consumers* they might not buy FCEVs in the absence of the policy (Kempton, 1991).

7.4. Scenario Analyses.

7.4.1. EVs versus gasoline ICEVs.

Many of the important cost parameters are very uncertain. Although as mentioned above I do not assume any major technological breakthroughs, and generally have *not* used the lowest cost estimates available for major components, I do assume that the key battery, fuel cell, and hydrogen storage technologies will be developed successfully, and that mass production will greatly reduce costs to levels that are being targeted or estimated by industry analysts and others. As shown in Table 11, if I have been too favorable in the estimation of any one of several important cost parameters -- the cost of the fuel cell, the cost of the battery, the cost of the electric drivetrain, the lifetime of the battery, the lifetime of the BPEV or FCEV, the ratio of the retail price to manufacturing cost, the production cost of hydrogen, the efficiency of the electric powertrain relative to the ICE powertrain, the cost and characteristics of the hydrogen storage system (scenarios 3, 4, 10-15, and 18), -- then the break-even gasoline price for the FCEV and BPEV would increase substantially, in many cases by over $0.30/gallon. The assumed driving distance, maximum performance, and driving cycle of the FCEV and BPEV also are quite important: a high-power, long-range FCEV or BPEV used mainly in highway driving would have a much higher lifecycle cost than the vehicle assumed for the base-case analysis (scenarios 1, 2, 6, and 19). Assumptions about financial parameters -- e.g., the interest rate, and the percent of people taking out a loan to buy the vehicle -- (scenarios 8 and 9) are less important but not trivial. But most importantly, any combination of two to four of the high-end scenarios of Table 11 would result in a much higher vehicle lifecycle cost than in the base case, and would make the FCEV economically unattractive (e.g., scenarios 20 through 22). (The BPEV already is somewhat unattractive in the 400-km case.)

On the other hand, the base-case scenario is not the *only* one in which FCEVs are competitive with gasoline ICEVs. In fact, as shown in the low-end scenarios of Table 11, there are many others favorable scenarios. For example, if hydrogen were produced from biomass instead of from solar power, the production cost would be much lower (Table 5), and the breakeven gasoline price would be significantly lower (Table 11). Or, the lifetime of the BPEV or FCEV might exceed the lifetime of the ICEV by more than 33%; in this case the breakeven gasoline price would be reduced considerably for both the BPEV and the FCEV. If ratio of the retail price to the manufacturing cost was 1.5:1 instead of 1.77:1, then the breakeven price for both FCEVs and BPEVs would be much lower than in the base case, and hydrogen FCEVs would be competitive with gasoline ICEVs at well under $1/gallon of gasoline. If the fuel cell, battery, or electric drivetrain cost less than I have estimated or assumed, or if the vehicle had less power and a shorter

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[15] This cost analysis assumes both that more people would take out loans to buy cars in the FCEV world than in the ICEV world, and that the interest rate on loans in the FCEV world would be higher than in the ICEV [no-FCEVs] world, due to the increased demand for credit. In both worlds, the interest rate on loans is substantially higher than the interest rate consumers effectively face when paying cash for a vehicle. See Appendix A for details.

range, or if the EV drivetrain was more efficient, then the breakeven gasoline price for both the BPEV and the FCEV again would be much lower than in the base case.The successful development of H-Power's iron oxidation/reduction system could lower the cost of hydrogen storage by nearly an order of magnitude, and reduce the breakeven gasoline price for FCEVs to about $1/gallon. And if several of the favorable cases were combined, the hydrogen FCEV would have a lower lifecycle cost than the gasoline ICEV at any conceivable future gasoline price, and the BPEV with a long driving range would be attractive at gasoline prices of around $1.40/gallon -- less, in some cases.[16] (The lifecycle cost of the BPEV is particularly sensitive to changes in parameters that affect the lifecycle cost of the battery. These parameters include the OEM battery cost, the driving range, the ratio of the retail-level price to the OEM cost, and the battery life.)

7.4.2 Hydrogen FCEVs versus hydrogen ICEVs.

In order for hydrogen ICEVs to have a lower lifecycle cost than hydrogen FCEVs, one must combine very optimistic assumptions for ICEVs (the base case here), with pessimistic assumptions about FCEVs (for example, scenarios 20 and 22 of Table 11 combined). In the vast majority of scenarios, hydrogen FCEVs have a lower lifecycle cost than hydrogen ICEVs.[17]

7.4.3. Summary.

Clearly, there is a good deal of uncertainty in this cost analysis. Nevertheless, two conclusions are fairly robust. First, there are *many* scenarios in which hydrogen FCEVs have a lower lifecycle cost than gasoline ICEVs. Second, in *most* scenarios hydrogen FCEVs have a

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[16] Of course, this economic analysis does not account for the environmental and "energy security" benefits of FCEVs and BPEVs. If these benefits were monetized, hydrogen-powered FCEVs probably would be socially cost-effective under a relatively wide range of conditions. In general, there are several differences between EVs and ICEVs -- including some that are unfavorable to EVs -- that I have not monetized. These are summarized below.

Unmonetized attributes of hydrogen FCEVs

Attributes undesirable to consumers
1) Power is more expensive than in an ICEV.
2) Probably somewhat shorter range than current gasoline vehicles.
3) Possibly less storage space (or larger vehicles).
Attributes desirable to consumers
1) Less time spent taking car to repair shop, and less aggravation from dealing with repairs.
2) No time spent getting pollution control inspection.
3) Instant start-up under any conditions.
4) Instantaneous acceleration response.
5) No idling.
Benefits for society
1) Near-zero emissions of greenhouse gases (if solar hydrogen is used).
2) No emissions of CO, NMHC, NO_x, SO_x, PM, or toxic pollutants.
3) No use of imported petroleum.

[17] I want to emphasize, again, that I have made very favorable assumptions about the values of the key cost parameters for hydrogen ICEVs. For example, my estimate of the cost to manufacture an LH_2 vehicle appears to be considerably less than BMW's recent estimate (Reister and Strobl, 1992). As mentioned above, I have assumed that hydrogen ICEVs would last longer than gasoline ICEVs (see Table 4), even though there is no evidence to support this. Finally, note that Reister and Strobl (1992) estimate that the lifecycle cost of a mass-produced dual-fuel LH_2/gasoline ICEV would be 60% higher than the lifecycle cost of a conventional gasoline vehicle, whereas I estimate that an LH_2 ICEV would have about a 25% higher lifecycle cost (Table 7).

lower lifecycle cost than BPEVs and hydrogen ICEVs. (The second conclusion is robust because there is less uncertainty in comparing hydrogen FCEVs with BPEVs or hydrogen ICEVs than with gasoline ICEVs, because hydrogen FCEVs will be more like BPEVs and hydrogen ICEVs.)

8. SUMMARY AND CONCLUSIONS

If fuel-cell and electric-drive technology develops as I have assumed, then hydrogen FCEVs will have roughly the same lifecycle cost as gasoline ICEVs when gasoline retails for around $1.50/gallon (including taxes). However, hydrogen FCEVs probably would be attractive from society's point of view at lower gasoline prices, because of their significant local and global environmental benefits (compared even to relatively clean year-2000 gasoline ICEVs). Solar-powered BPEVs would be equally as attractive environmentally, but likely would have a higher lifecycle cost than solar-hydrogen FCEVs (unless the BPEVs had a relatively short range), and would take much longer to refuel [recharge]. Solar-hydrogen FCEVs thus could satisfy a much larger market than could BPEVs (Nesbitt et al., 1992), and hence could do more to improve urban air quality and mitigate global warming. Solar-hydrogen FCEVs could be the all-purpose "zero-emission vehicles" of the future.

Hydrogen FCEVs also would have a lower lifecycle cost than hydrogen ICEVs, and slightly lower emissions of criteria pollutants and greenhouse gases (assuming the same fuel feedstock). Thus, I believe that if hydrogen is to be used at all in transportation, it should be used in FCEVs rather than ICEVs. Future hydrogen research programs should be directed with this in mind.

Of course, these conclusions assume the successful development of fuel-cell vehicles. The critical technology in the FCEV is the fuel cell itself. Because the development of the fuel cell has lagged the development of the other components of FCEVs (batteries, electric drivetrains, and even hydrogen storage systems), its cost and performance cannot yet be characterized as well. I have assumed that high specific power and high net energy efficiency can be achieved at relatively low total cost. Fuel-cell technology must progress steadily over the next decade in order to realize these assumptions. The peak-power device and the hydrogen storage system in the FCEV also must be developed further to reach the cost and performance levels assumed here.

Although none of these R & D tasks are trivial, there are so many technology and design routes for each task -- at least three different kinds of fuel cells potentially suitable for highway vehicles (PEM, alkaline, and solid oxide), at least four different ways to supply peak power (several types of batteries, ultracapacitors, flywheels, or the fuel cell itself), and many ways to store hydrogen (see Table 3) -- that I am optimistic that eventually all the components of FCEVs will be developed successfully.

Ultimately, marketability will be the yardstick of success. To begin to understand how consumers will use and react to hydrogen FCEVs, a large number of experimental vehicles should be built and tested. The purpose of these projects should not be to display a purportedly finished technology, but rather to experiment -- to provide information from users that can feed back to basic research and development. Hydrogen FCEV technology already is far enough along that this experiment and feed-back strategy could begin today. Within a decade this strategy could provide a reasonably clear picture of the ultimate technical and economic potential of the fuel cell in transportation. With success, hydrogen FCEVs could be an economical clean transport option by the early part of the next century.

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Table 1. Characteristics of fuel cells.

Type of fuel cell	Status[a] (1991)	Power Density[b] (kW/kg)	(kW/liter)	Temperature[c] (°C)	Contaminated by:
Phosporic acid	CA	0.12[d]	0.16[d]	150-250	CO
Alkaline	CA	0.1-1.5[e]	0.1-1.5[e]	65-220	CO_2[f], CO
Proton exchange membrane	D/L	0.1-1.5[g]	0.1-1.5[g]	25-120	CO[h]
Solid oxide	L	1-8[i]	1-4[i]	700-1000[j]	

[a]CA = commercially available; D = development of prototypes; L = laboratory cells.

[b]These figures are for the fuel cell stack only; they do not include fuel processing or auxiliary systems, unless otherwise specified. The ranges shown are my estimates based on data in the literature, summarized below. For several reasons, a point estimate cannot be given.The power density is a function of the air pressure, which is a design variable, and of the technology of the fuel cell and electrolyte, which is evolving. Also, there are not enough details in the original sources for me to be certain that the same parts are being counted (or not counted) in the weight and volume estimates that go into the calculation of power density.

[c]From Lemons (1990), unless indicated otherwise.

[d]This is the power density of the 36-kW brassboard PAFC fuel cell stack being developed for the U. S. Department of Energy bus project (Chi et al., 1990). The reformer and the 52-kg cooling system are not included in these power-density estimate. The fuel cell uses reformed methanol.

[e]Siemens AG of Germany has developed a 6-kW alkaline fuel cell system that is roughly 0.13 kW/kg and 0.17 kW/liter (excluding the auxiliaries and the container) on hydrogen and oxygen (not air) pressurized to 2.1 bar (Strasser, 1990; I have assumed that the weight of the auxiliaries is equal to the weight of the stack). Including the auxiliaries and container, the system is about 0.03 kW/kg and 0.05 kW/liter. Appleby (1990) states that International Fuel Cells projects 7 kW/kg (including cooling system, auxiliaries, and pressure vessel) for an alkaline fuel cell designed for space use and operating on pure hydrogen and oxygen pressurized to 13.6 atm. A system operating on air rather than oxygen, and at much lower pressure, would produce much less power, and hence have a much lower power density: Appleby says that a "terrestrialized" version of the space fuel cell, operating on CO_2-scrubbed air, might achieve 1.5 kW/kg and 1.5 kW/liter (presumably including auxiliaries and cooling).

[f]The ambient concentration of CO_2 is sufficient to degrade an alkaline fuel cell. Commercially available alkaline fuel cells must run on pure hydrogen and pure oxygen. However, Appleby (1991) suggests that "quaternary amine anion exchange membranes with fluorinated backbones" may be tolerant of CO_2."

[g]In 1990, Ballard (1990) reported that its fuel cell stack with a Dow membrane provided 0.23 kW/kg and 0.34 kW/liter (based on the "peak" fuel-cell output of 10 kW) using hydrogen and air pressurized to 3.4 atm (Ballard, 1990; the figures were 0.26 kW/kg and 0.39kW/liter based on "maximum" ouput of 11.2 kW). However, Prater (1992) has said more recently that the Ballard fuel-cell stack using the latest Dow membrane and air achieves only 0.17 kW/liter. At least part of the difference is due to the lower performance of the newer membrane. All the Ballard figures

are for the fuel cell stack only. Appleby (1990) believes that it should be possible to achieve 1.2 kW/liters and 1.3 kW/kg for a PEM fuel cell stack operating at atmospheric pressure. At higher air pressures, the current and power density of the stack would be higher.

[h]At 80°C, the allowable concentration of CO in the fuel is only a few ppm (USDOE, 1991b).

[i]Myles and McPheeters (1990) expect that monolithic SOFCs can achieve 8 kW/kg and 4 kW/liter. Dees and Kumar (1990) show a design for a monolithic SOFC stack with an energy density of 1.4 kW/kg and 2.32 kW/liter. Hsu and Tai (1992, 1990) specify 1.0 kW/kg and 0.9 kW/liter for a near-term planar solid oxide fuel cell stack, and 6.6 kW/kg in the medium term.

[j]Myles and McPheeters (1990).

Table 2. Characteristics of batteries and peak-power devices for EVs.

Battery type (developers)	Status[a] (1991)	Energy density (3-hour rate)[b] (Wh/kg)	Energy density (3-hour rate)[b] (Wh/l)	Power density (at 80% Dod)[c] (W/kg)	Power density (at 80% Dod)[c] (W/l)	Energy effic.[d] (%)	Battery life[e] (cycles)
Bipolar sealed lead/acid (GNB)[f]	CA	32*	52*	250*	400*	n.s	short
Nickel/cadmium (Saft)[g]	CA	57*	115*	160*	322*	n.s	2,000
Nickel/iron (Eagle-Picher)[h]	PC	50*	113*	80*	181*	58*	1,100
Sodium/sulfur (Powerplex & CSPL)[h]	PC	105	120	150	171	91*	600
Bipolar lithium/disulfide, BPEV (ANL)[i]	L	142	257	319	577	high	1,000+
Bipolar lithium/disulfide, FCEV (ANL)[i]	L	110	188	657	1130	high	1,000+
Lithium/polymer electrolyte (IREQ)[j]	L	128	129	201	202	77	?
Bipolar lithium/polymer[k]	L	170	221	380	494	n.s.	n.s.
Zinc-air battery (Electric Fuel)[l]	PC	260*	341*	113*	148*	n.s.	n.s.
Nickel metal-hydride (Ovonic)[m]	PC	56*	n .s.	200+*	n.s.	high	1,000+
Ultra-capacitor (Japan; Pinnacle Research)[n]	L	29	97	$25\cdot10^6$	$80\cdot10^6$	78*	120,000*
Composite flywheel (LLNL)[o]	L	37	33	307-819	269-718	96	long?

*Measured performance of a module or battery. All other estimates are projections or modeling results.

[a]CA = commercially-available batteries; PC = pre-commercial battery prototypes; L = laboratory cells.

[b]The discharge rate was not specified for the lithium/disulfide battery, the nickel/metal-hydride battery, the ultracapacitor, or the flywheel. The discharge rate for the zinc/air battery was 5 hours at a constant current.

[c]DoD= depth of dishcarge. Typically, the power density is based on a peak-power pulse of 15 to 30 seconds at 80% depth of discharge. Exceptions are noted below.

[d]Efficiency is defined as the amount of electrical energy output from the battery terminals divided by the amount of electrical energy input to the battery from the charger. The total amount of electrical energy (expresed in joules) input to the battery is equal to the number of

electrons (expressed in coulombs) input multiplied by the electrical potential energy per electron (expressed in volts). Given this simple representation, one can see that there are two ways in which electrical energy might be "lost" within the battery, and not end up at the battery terminals as electrical energy: electrons might be "lost" from the electricity-producing electrochemical pathways, or energy per electron might be reduced. The successful transfer of charge is represented by a measure called the "coulombic efficiency;" the loss of energy per electron is related to the internal resistance of the battery. One also can count in the efficiency expression any use of energy necessary to maintain the operating temperature of the battery. However, I do not count this energy here (except in the case of the low-temperature lithium/polymer battery, because so little is required; see note j). However, I do account for battery heating in the cost analysis. Note too that batteries are less efficient when discharged in an actual driving cycle than when dishcarged during a contsant-current discharge test. I make rough estimates of this effect.

[e]The number of cycles to 80% depth of discharge, until the battery performance falls to a certain level, unless noted otherwise. The lifetime in actual use is likely to be less than the lifetime measured in the laboratory. Burke (1991b) notes that "field experience with lead-acid batteries in vehicles and the limited laboratory data available show that battery life on the FUDS or SFUDS is much shorter than that found from constant-current discharge testing" (p. 19). I account for this in the cost analysis.

[f]From Burke and Dowgiallo (1990). The USDOE (1991a) shows 30 wh/kg and 48 wh/l. Burke and Dowgiallo (1990) state that the 12-volt side-by-side bipolar GNB battery tested at Idaho National Engineering Lab is "commercially available," but I presume that it is not commercially available in electric-vehicle pack sizes. The peak-power figures shown are for a 10-second pulse at a 80% DoD.The power density was very strongly dependent on the DoD: for a 10-second pulse at 50% DoD, the power density was 400 W/kg. However, the USDOE (1991a) reported only 67 W/kg for a 15-second pulse at 50% DoD, for the same kind of battery, from the same manufacturer, tested at the same facility (Idaho National Engineering Laboratory). Thus, either the power density is extraordinarily sensitive to the length of the pulse, or the battery does not perform consistently.The efficiency of the battery was not specified (n.s.); the battery has relatively high coulombic efficiency (USOE, 1991a), but also a very high internal resistance (Burke and Dowgiallo, 1990).

[g]From EPRI (1990). The life-cycle numbers are projections. DeLuca et al. (1991) report test results of 55 Wh/kg (3-hr rate), 104 Wh/l (3-hr rate), and 191 W/kg (@50% DoD) for Ni/Cd batteries. (Note that the DeLuca et al. W/kg results are at 50% DoD, whereas the EPRI results are at 80% DoD.) See also Cornu (1990).

[h]From EPRI (1990), except for the estimates of battery efficiency, which are from DeLuca et al. (1991), and the indication of pre-commercial status for sodium/sulfur, which is based on CSPL's (1991) statements that the commercialization of sodium/sulfur batteries already is being planned. DeLuca et al. (1991) report test results of 51 Wh/kg, 118 Wh/l, and 112 W/kg for Ni/Fe batteries, and 81 Wh/kg (3-hr rate), 83 Wh/l (3-hr rate), and 152 W/kg (@50% DoD) for the ABB Na/S battery. (Note that the DeLuca et al. W/kg results are at 50% DoD, whereas the EPRI results are at 80% DoD.) The life-cycle numbers for both batteries are projections. See also Dustmann (1990). CSPL =- Chloride Silent Power Limited.

The efficiency estimate shown for sodium/sulfur does not account for the potentially substantial amount of energy required to maintain the operating temperature of the battery. If this heating energy were deducted, the battery efficiency probably would be 75% or less. (See note i for a sample calculation of the amount of energy required to maintain a lithium/iron-sulfide battery.) Also, the indicated efficiency apparently was measured at constant-current charge and discharge. The efficiency over a standard-driving cycle discharge would be lower. Thus, the overall in-use efficiency of the battery might be between 60% and 75%. (The efficiency of the nickel/iron also probably would be lower in-use than shown here.)

[i]The estimates of energy density and power density are mid-range values from battery-modeling exercise reported by Nelson and Kaun (1991). The BPEV case refers to a battery designed to supply the full driving range and power in a BPEV; the FCEV case refers to a battery designed to supply only the peak power in an FCEV. The battery probably would be very efficient, because the coulombic efficiency of the cells thus far exceeds 98%, and the internal resistance is very low (Kaun et al., 1991).

However, the battery also may require a substantial amount of energy to maintain its operating temperature of at least 400o C. Although the battery would generate more than enough heat to maintain its temperature when the vehicle was being used, it would lose at least 150 Watts when the vehicle was idle. It might be possible to design the battery to tolerate a temperature drop of 50^0 C or so, but if the battery remained idle after reaching this lowest tolerable temperature, the temperature would have to be maintained by a heating system. The developers of the battery hope to limit the heat loss to 150 Watts, presumably for a relatively large battery. If the battery typically remained idle for no more than two days in a complete charge/dishcarge cycle, and could cool for 12 hours before heating was required, then 36 hrs x 150 Watts = 5.4 kWh of energy -- about 10% of the total stored energy of a large battery -- would be required to offset the heat loss (assuming 100%-efficient resistive heating). However, a greater percentage of the stored energy would be required to maintain the temperature of a smaller battery, because of the higher surface-to-volume ratio. Moreover, if the heat loss was greater than 150 Watts (a sodium/sulfur battery tested at Argonne National Lab used a 176-Watt heater to maintain a temperature below that of Li/S batteries), or if the battery remained idle for longer than two days, or if the allowable cool-down period was less than 12 hours, then still more energy would be required for heating. It is not difficult to imagine that a small battery, such as might be used to provide peak -power in an FCEV, might consume 50% of its energy to maintain its temperature over several days.

The estimate of cycle life is based on EPRI (1990; 1000+); Kaun et al. (1990; 1000-2000); and Kaun et al. (1991; 1000). ANL = Argonne National Laboratory.

[j]From Belanger et al. (1990). All the estimates are based on a "conceptual batttery design," for the DOE's IDSEP urban-fleet van. A graph in the source projects that about 52 kWh hours will be available at a 3-hour discharge rate. At 80% depth of discharge, the battery will provide an 82-kW pulse for 20 seconds. The concept battery weighs 407 kg and displaces 404 liters. These figures apparently are based on 1990 cell performances. See also EPRI (1990). The authors also project that the battery can be manufactured for $100 to $150/kWh.

The efficiency estimate is the projected round-trip energy efficiency, *including* energy lost to maintain the 80^0 C operating temperature. (Because the operating temperature of this battery is much less than the temperature of the high-temperature batteries, Na/S and Li/S, much less energy is required to maintain its temperature.) The authors actually project 1000 to 2000 cycles over 5 to 6 years, based on 1990 cell performances. However, they have defined "end of life" differently, and more leniently, than have other researchers. The battery they describe actually loses 6% of its capacity per year, which is a relatively high loss rate. IREQ = Research Institute of Hydro-Quebec in Canada.

[k]Projections for a 90-kW, 40-kWh advanced battery, in 1998 (Neslon, 1992).

[l]From Harats et al. (1992). The energy densities shown here are equal to the total energy (based on consumption of 100% of the zinc fuel; 5-hour constant-current discharge) in a 12-cell module divided by the mass or volume of the complete system, including all auxiliaries (such as CO_2-scrubbing equipment). The power densities are based on 30-second high-current discharges down to 71% fuel consumption (i.e., they are for up to 71% "depth of discharge"); at greater than 71% fuel consumption, the peak-power declines. In this battery design the zinc slurry is static, so there are no circulation pumps or storage tanks. The battery has a higher power density than other zinc/air batteries (Appleyard, 1992; Cheiky et al., 1991; *Modern Battery Technology,* 1991) because it does not have a bifunctional air electrode. That the air electrode is not bifunctional means that the battery is mechanically rechargeable only (not electrically rechargeable). The battery would be "recharged" by replacing cassettes of spent zinc fuel with cassettes of electrochemically regenerated fuel; the electrochemical regeneration would occur off-board the vehicle, perhaps at a central facility. Although the life of the battery was not specified, the elimination of the bifunctional air electrode, and the constant replenishment of the spent zinc with fresh zinc, suggests the possibility of a long life.

[m]Estimates are from Venkatesan et al. (1991). The authors state that they already have achieved 65-70 Wh/kg in prototype cells, and believe 80 Wh/kg can be achieved. The conditions of the test measuring energy and power density were not given. They state that energy efficiency is "exceptional". Because the battery operates between -20^{o} C and 60^{o} C, it will not require extra energy for heating. The battery cycle life was achieved at a two hour discarge to 100% DoD. They also state that the batteries are sealed and maintenance-free, and can be charged as quickly as one hour.

[n]The energy and power densities are performances projected by Pinnacle Research, for 1994 (Burke and Dowgiallo, 1990). Presently available devices have an energy density of 1-2 Wh/kg and 2-3 Wh/liter (Burke, 1991a). The efficiency and life-cycle estimates are from Burke (1991a). Burke (1991a) reports that the electrical efficiency of devices made by Pinnacle Research and by Japanese manufacturers ranges between 77% and 80%. The Japanese ultracapacitor showed only 20% degradation in capacity after 120,000 charge/discharge cycles (15- to 30-second cycles between 100% and 50% of initial voltage). The Pinnacle Research ultracapacitor failed after 120,000 cycles (Burke, 1991a). Capacitors are commercially available for many applications, but ultra-capacitors for electric vehicles are not yet commercially available (Burke, 1991a). See also Trippe and Blank (1992).

[o]The performance values are from conceptual designs of an electromechanical battery: a flywheel (or rotor) consisting of six shells of carbon-fiber composite material, wrapped around a permanent-magnent motor/generator (Comfort et al., 1992). The power densities are based on the ability to accelerate or decelerate at 0.34g between 0 and 60 mph. The high end of the range assumes that the rotor is operating at maximum speed; the low end assumes 3/8 of maximum speed. The flywheel (rotor) has a design lifetime of 10 years or 120,000 miles. LLNL = Lawrence Livermore National Laboratory.

Table 3. Characteristics of hydrogen storage systems.

Storage system	Installed fuel-system energy density[a]		Container cost[b]	Refuel time[c]	Station cost[d]
	(mJ/liter)	*(mJ/kg)*	*($-OEM/gJ)*	*(minutes)*	*($/gJ)*
Gasoline tank[e]	32.4	34.0	20	2-3	0.6
H-Power iron oxidation/reduction[f]	5.8?	5.0?	500?	?	3?
Carbon-wrapped aluminum cylinder, 8,000 psi[g]	3.4	7.0	4000	3-5	4-6
Liquid hydrogen[h]	5.0	15.0	1000-2000	5+	3.5-5-(11)
Cryoadsportion[i]	2.1	6.3	2000-4000	5	4-5
Thermocooled pressure vessel[j]	2.5	8.2	4000+?	5+	5+ (8+)
FeTi metal hydride[k]	2-4	1-2	3300-5500	20-30	3-4
Organic liquid hydride[l]	0.5	1.0	?	6-10	?

[a]Weight and volume of container, fuel, and auxiliaries.

[b]Cost to the original equipment manufacturer (OEM), per gJ of storage capacity.

[c]Time to deliver fuel; does not include time to pull in, pull out, or pay.

[d]The full owning and operating cost of the station. The cost of hydrogen is not included here.

[e]Energy density was calculated assuming that an empty gasoline tank weighs 12-kg, and that the ratio of the outside displacemen of a tank to its inner capacity is 1.075:1. The estimate of the cost of the tank is based on data in the American Council for an Energy-Efficient Economy (ACEEE,1990). The station cost is based on data in Appendix A.

[f]H-Power, a company located in New Jersey, is seeking a patent on a reduced-iron/oxidized-iron (oxidation/reduction) hydrogen-generation system (Werth, 1992). The process begins with iron oxide (Fe_3O_4) and a reducing gas (H_2 or CO), offboard the vehicle. The reducing gas and the iron oxide are reacted at high temperature (about 800 to 1,100° C if hydrogen is used) to produce reduced iron and steam: $Fe_3O_4 + 4H_2 \rightarrow 3Fe + 4H_2O_{(g)}$. If pure hydrogen is used as the reducing gas, the reaction requires an external source of heat; if enough CO is added, no external heat source is needed, because the reaction becomes exothermic. The reduced iron is transferred to the vehicle, and stored onboard, as a powder, in metal tubes.

To produce hydrogen fuel onboard the vehicle, the iron-reduction reaction is reversed: steam or hot water (over 50° C) is reacted with the reduced iron to produce hydrogen and iron-oxide. This hydrogen-generation (iron-oxidation) reaction takes place between 25° C and 900° C. However, below about 500° C, a catalyst, probably a noble metal, is required. Generally, the necessary reaction energy can be supplied by some combination of a catalyst and external heat. At 25° C, one would need a very good and effective (and presumably costly) catalyst, but no external heat; above 500° C, no catalyst would be needed. The balance between the use of a catalyst and the use of external heat will be determined by overall cost, complexity, and performance. The catalyst may be alloyed with the metal, mixed with the water, or introduced in other ways. The fuel cycle is completed when the oxidized iron is removed from the vehicle to undergo the initial reduction (regeneration) reaction. (Details are in Werth, 1992).

Madeda (1991) of H-Power gives the following performance specifications for this system: 22.66 Wh-electricity per in_3 of storage, and 366 wh-electricity per lb of storage, assuming 50% hydrogen-to-power efficiency on a LHV basis (42% HHV basis). This translates into 11.7 MJ/L and 6.8 MJ/kg. These values refer to the actual iron (Fe) storage media only, and do not include metal tubes, steam and water lines, fuel lines, pumps (if any), separators, preheaters (if any), insulation, or the overall enclosure. I assume that the overall system volumetic energy density is half of the energy density of the iron "storage media" alone, and that the overall weight energy density is 3/4 of the energy density of the iron alone.

The iron-material cost of the system is only 15 cents/kWh, but the entire selling cost of the system (tubes, steam lines, catalyst, enclosure, etc.. probably will be several times higher than this. I assume that it would cost $200 to $300 to manufacture the system (recall that a noble-metal catalyst might be used), or about $500 at the retail level.

The refueling time depends on details which have not yet been worked out. The developers believe that refueling can be done very quickly. Because the station would not have compressors or coolers, the station mark-up should be less than the mark-up for CH_2, LH_2, or cyroadsorbed hydrogen. I assume a cost slightly lower than that for hydride refueling.

[g]I commissioned a consultant to the pressure-vessel industry to estimate the weight, size, and cost of ultra-high-pressure carbon-wrapped containers for vehicular use (Price, 1991). Based on his results, I calculated the energy density and cost of the containers alone (no auxiliaries), and then assumed that the auxiliaries reduce the energy density values by 5%. The energy density values for 9000 psi are 7.0 MJ/kg and 3.6 MJ/L, and the values for 6000 psi are 6.8 MJ/kg 32.8 MJ/L. The estimate of refueling time is mine; no ultra-high-pressure fast refueling systems have been built.

[h]DeLuchi (1989) reports a range of 3 to 5 MJ/liter for LH_2 systems, including the pump, but not including the other auxiliaries. Collier et al. (1991) report 9 to 25 MJ/kg and 2-5 MJ/l for LH_2 systems (it is not clear if this includes the pump, plumbing, preheater, and so on). Peschka (1987) reports a goal of 37 MJ/kg, probably for the tank alone.

According to Iwatani (n.d.), the 100-liter tank in the Musashi-8 weighs 60 kg when full (16.7 MJ/kg). However, the tank also has a pump, motor, heat exchanger, and gas storage bottles, which are not included in the energy-density figures just cited. A diagram in Furuhama et al. (1990) indicates that their small 80-liter tank has a 191-liter outer displacement including the pump (but no other auxiliaries), resulting in 3.7 MJ/L.

I assume that including all auxiliaries would reduce these energy density values by 10%.

BMW has developed two LH_2 versions of its model 745i, one using external mixture formation, and the othe using direct injection. The tank in the external-mixture vehicle operates at 2.5 bar, has a boil off rate of 2.0%/day, has a capacity of 130 liters and weighs 80 kg full (16.3 MJ/kg). The tank in the direct-injection vehicle operates at 2.0 bar and has a capacity of 45-liters and weighs 45 kg full (10.0 MJ/kg) (Strobl, 1987).

Takiguchi et al. (1987) give the following data for the tank in the Musashi-7 vehicle: 155-l capacity, 90-kg when full (17.1 MJ/kg), and 280-liter outer displacement (5.56 MJ/liter). The tank is double-walled stainless steel, and operates at 2.5 bar. It also has an 8-L pressurized-H_2 storage tank, a motor for the injection pump, an oil tank for the lubricating oil for the motor, and a heat exchanger to vaporize the fuel. Assuming that these total 30 liters and 20 kg, the total storage system specifications, including all auxiliaries, would be 14 MJ/kg and 5.0 MJ/liter.

The estimates of the tank cost and the station cost are based on data in DeLuchi (1989). (Reister and Strobl (1992) have stated that a dual-fuel LH_2/gasoline vehicle would cost aroud 30-40% more to manufacture than a conventional gasoline vehicle, under mass production.) The estimate of the station mark-up in parantheses includes the cost of liquefying hydrogen (about $6/GJ); the other estimate does not.

According to Strobl (1987), the BMW LH_2 tanks can be refilled in 5 minutes when they are cold (Strobl, 1987). If the tanks and the refueling lines are warm, they have to be cooled first with liquid nitrogen, and this is a very time consuming process. However, Reister and Strobl (1992) state that "once suitable components and the process technology have been developed, the entire refueling process will probably take less than 10 minutes (compared with the previous 1 hour) with virtually negligible eergy losses" (p. 6). It is not clear if the "entire refueling process" in this case includes precooling.

[i]Young (1990) estimates 1.92 MJ/l and 6.83 MJ/kg (including fuel) for a carbon adsoprtion system storing hydrogen at 55 atm and 150° K. In another paper from the same research group, Amankwah et al. (1989) estimate 7.2 MJ/kg and 2.4 MJ/l (they assume kevlar-wrapped tanks). However, the system needs active cooling system to maintain the low temperature. I assume that including such auxiliaries would reduce these energy-density values by 15%.

The refueling station would require a compressor, refrigerator, and vacuum pump. I used Amankwah et al.'s (1989) estimate of the station cost, except that I assumed $0.07/kWh for electricity. I estimated the cost of the container based on statements in Amankwah et al. (1989) that indicate that the vessel would cost a bit more than an LH_2 vessel, but less than half as much as a hydride system. The refueling time is my estimate.

[j]Krepec et al. (1990) estimate that a combination of low-temperature and high-pressure storage, with no carbon adsorption, would provide 9.45 MJ/kg and 2.84 MJ/l at 300 bar and 100° K, and 5.67 MJ/kg and 1.61 MJ/L at 300 bar and 200° K. The system also would require a pressure regulator, pre-heater, and a gas accumulator, which I assume would reduce the tank-only figures above by 15%.

The refueling station would be complex and probably expensive, because it would store and deliver both LH_2 and high-pressure gas. Refueling would be a two-step process: first deliver LH_2, then deliver high-pressure gaseous hydrogen. This suggests that the refueling time and the refueling mark-up would be at least as high as for LH_2 sytems. The station mark-up estimate in parantheses accounts for the extra cost of liquefying half of the hydrogen delivered to the vehicle.

[k]DeLuchi (1989) reports 2-5 MJ/liter and 1-2 MJ/kg for various hydrides, excluding auxiliaries. Collier et al. (1991) estimate that conventional hydrides contain 1-3 MJ/kg and 0.5-5 MJ/L. They have a research goal of 7 MJ/kg and 5 MJ/l. I assume that the auxiliaries (heat exchanger, piping, pressure regulators, etc.) reduce these values by 15%.

Hama et al. (1988) describe a lanthium-nickel-aluminum ($LaNi_{0.5}Al_{0.1}$) hydride that weighs 663 kg, displaces 201 liters, and contains 7.1 kg of hydrogen. In addition, it has an 18-liter exhaust heat exchanger, a voluminous pressure reduction device, and associated electronic controls. If the size and weight of the auxiliaries could be reduced somewhat, the total system would contain 4.2 MJ/l and about 1.4 MJ/kg.

Lanyin et al. (1990) described an advanced TiFe hydride that contains about 2.1% hydrogen by weight. The total system energy density probably is about 2.3 MJ/kg.

The estimate of the cost of the hydride is based on data in DeLuchi (1989). (Magnesium hydrides would be several times less expensive than FeTi hydrides, but they are not yet suitable for vehicular applications, because of their high dissociation temperature.) The service-station mark up was calculated using the refueling station model described in Appendix A, with input parameters set for hydrogen at 50 bar.

[l]In this system methylcyclohexane (MCH), a liquid, would be carried on board the vehicle and dehydrogenated by an onboard reformer to produce hydrogen and toluene. The system would be

very bulky and heavy for several reasons: 1) the effective volumetric and mass density of hydrogen in MCH is low; 2) two large tanks would be needed -- one for the MCH, and one for the toluene; and 3) the reformer itself would be large and heavy, even assuming major improvements over the current models. Based on data in Grunenfelder and Schucan (1989) and Taube et al. (1985), I estimate that an advanced system storing 0.66 GJ of hydrogen and providing 55-kW of would weigh 675 kg and displace 1230 liters installed. The system would have to be further improved by an order of magnitude to be attractive in light-duty applications. (Note, though, that it may be attractive in heavy-duty vehicles, which can accomodate much more weight and bulk.)

I estimated the refueling time by assuming that MCH would be delivered and toluene removed simultaneously, and that the gal/min delivery rate would the same as with gasoline.

Table 4a. Characteristics of ICEVs in the analysis.[a]

	Gasoline (baseline) *(640-km range)*	Hydride *(400-km range)*	Liquid hydrogen *(400-km range)*	Compressed hydrogen *(400-km range)*
Energy storage system	metal tank	iron/titanium hydride	cryogenic dewar	carbon-wrapped aluminum vessel (550 bar)[b]
Maximum power at wheels (kW)	101	n.e.	n.e.	n.e.
Vehicle life (km)[c]	193,000	212,400	212,400	212,400
Volume of energy system (liters)[d]	63	n.e.	n.e.	n.e.
Weight of complete vehicle (kg)[e]	1,371	1,831	1,326	1,425
Coefficient of drag	0.28	n.e.	n.e.	n.e.
Fuel economy (mpg-equivalent)[f]	25.9	27.4	31.3	32.2
(liters/100 km)	9.1	8.6	7.6	7.3

[a]The gasoline vehicle is a year-2000 version of the 1990 Ford Taurus. The other vehicles are "built" hypothetically from this. n.e. = not estimated. Fe/Ti = iron/titanium hydride. The vehicle life and the coefficient of drag are input directly into the model; the other parameters are calculated by the model. See the appendices for details not given here.

[b]As one increases the storage pressure the bulk of the storage system decreases but the cost increases. I chose 550 bar because a tradeoff analysis indicated that it represents a good balancing of these two opposing tendencies (see Appendix A).

[c]I assume that hydrogen ICEVs would have a slightly longer life than gasoline ICEVs. This assumption is quite optimistic, but ensures that hydrogen ICEVs are not slighted in the comparison with hydrogen FCEVs.

[d]The sum of the volume of the energy storage system (the battery, the methanol tank, the gasoline tank, or the hydrogen containers), the fuel cell, and the methanol reformer (from Table 5).

[e]Inlcuding one passenger and fuel to 40% of tank capacity.

[f]Gasoline-equivalent fuel economy in miles/gallon is calculated as the mile/million-Btu fuel economy of the alternative vehicle in combined city and highway driving in the year 2000, divided by 125,000 Btu/gallon-gasoline (34,830 kj/liter). I use the higher heating value of hydrogen (286 kJ/mole). The mpg fuel economy of the baseline gasoline ICEV is calculated from a detailed set of input parameters, including vehicle weight, powertrain efficiency, aerodynamic drag, the amount of city vs. highway driving, and other factors (see Appendix A).

The mi/million-Btu fuel economy of the hydrogen ICEVs is calculated from the assumed thermal efficiency of the hydrogen engine and the calculated weight of the vehicle relative to the gasoline ICEV, using an updated version of the model described in DeLuchi (1989). I assume that the hydride/hydrogen engine would have a higher compression ratio than would the gasoline engine, and would operate at a very high air-to-fuel ratio (but still meet the 0.25 g/km NO_x standard), and that as a result of these two factors would be 27% more thermally efficient than the gasoline engine. However, the considerable extra weight of the hydride storage system would reduce the overall fuel-efficiency advantage. The LH_2 vehicle would have two efficiency advantages over the hydride vehicle: the low temperature of the liquid hydrogen would reduce heat loss and improve thermal efficiency (I assume a 30% advantage over the gasoline ICEV), and the LH_2 storage system would weigh only slightly more than the gasoline storage tank. Note, though, that these assumptions of very high efficiency and very low NO_x emissions are quite optimistic.

The fuel economy estimate shown in the table is given in terms of hydrogen delivered to the motorist, and does not account for boil-off losses of hydrogen upstream. Assuming that 3% of the hydrogen would be lost at each of three transfer points in the hydrogen distribution system, then the gasoline-equivalent mpg, expressed in terms of hydrogen produced at the LH_2 facility, would be 8.7% lower than shown here ($1-0.97^3$).

Table 4b. Characteristics of FCEVs and BPEVs in the analysis.[a]

	FCEV Hydrogen *(400-km range)*	FCEV Hydrogen *(240-km range)*	FCEV Methanol *(560-km range)*	BPEV *(400-km range)*	BPEV *(240-km range)*	BPEV *(160-km range)*
Energy storage sytem	carbon/aluminum tank (550 bar)	carbon/aluminum tank (550 bar)	metal tank	bipolar Li/S	bipolar Li/S	bipolar Li/S
Battery type	bipolar Li/S	bipolar Li/S	bipolar Li/S	see above	see above	see above
Maximum power at wheels[b]	73	69	76	85	75	70
Maximum fuel-cell power (kW)[c]	25	25	25	n.a.	n.a.	n.a.
Vehicle life (km)[d]	256,800	256,800	256,800	256,800	256,800	256,800
Volume of energy system (liters)[e]	268	201	288	237	155	114
Weight of complete vehicle (kg)	1,238	1,167	1,275	1,462	1,275	1,184
Coefficient of drag	0.23	0.23	0.23	0.23	0.23	0.23
Fuel economy (mpg-equivalent)[f]	74.0	76.3	62.4	120.0	129.2	134.1
(liters/100 km)	3.2	3.1	3.8	2.0	1.8	1.8

[a]The FCEVs and BPEVs are based on the year-2000 Ford Taurus of Table 4a. The vehicle life and the coefficient of drag are input directly into the model; the other parameters are calculated by the model. See Appendix A for details. Li/S = lithium/sulfide. See also notes to Table 4a.

[b]I calculate the peak power of the EV and FCEV motor given the peak power of the ICE, the desired high-end acceleration of the EV relative to the high-end acceleration of the ICEV, and the mass, drag, and rolling resistance of the EV and ICEV. In the base case, I assume that the ratio of the maximum acceleration of the EV at 60 mph to the maximum acceleration of the ICEV at 60 mph is 0.80:1.00. Note, though, that the EVs would perform better than the ICEVs at low speeds.

[c]This is the gross maximum power output of the fuel cell; the power requirement of the auxiliaries is deducted from this to determine the net power available to the drivetrain from the fuel cell. By trial-and-error runs of the cost model I find the combination of gross maximum fuel-cell power and maximum battery power that result in the lowest life cycle cost per km, subject to constraints on battery size and performance.

[d] As discussed in the text, I assume that EVs will have a longer life than ICEVs. See Appendix A for further documentation and discussion.

[e] The sum of the volume of the energy storage system (the battery, the methanol tank, the gasoline tank, or the hydrogen containers), the fuel cell, and the methanol reformer (from Table 5).

If the volumetric power density of the fuel cell could be reduced to 0.04 ft^3/kW, as specified by Lemons (1990) and projected by Appleby (1990) and Meyer (1989), and if the hydrogen-storage pressure was increased to 10,000 psi, the total system volume would be reduced by about 20%. However, the breakeven gasoline price would increase by roughly $0.10/gallon.

[f] Gasoline-equivalent fuel economy in miles/gallon is calculated as the mile/million-Btu fuel economy of the alternative vehicle in combined city and highway driving in the year 2000, divided by 125,000 Btu/gallon-gasoline (34,830 kj/liter). I use the higher heating value of hydrogen (286 kJ/mole), and count electricity consumption from the outlet at 3413 Btu/kWh. The mpg fuel economy of the baseline gasoline ICEV, and the mi/million-Btu fuel economy of the FCEVs and BPEVs are calculated from a detailed set of input parameters, including vehicle weight, powertrain efficiency, aerodynamic drag, the amount of city vs. highway driving, and other factors (Appendix A).

An electric powertrain, consisting of the motor, controller, and transmission, is at least 6 times more efficient than an ICE powertrain, in combined city/highway driving (after accounting for regenerative braking; see documentation in Appendix A). PEM fuel cells are about 45% efficient (after accounting for the energy consumption of auxiliaries); hence, the fuel cell/electric motor system would be almost 3 times as efficient as the ICE, before accounting for differences in vehicle weight and aerodynamic drag. The explanation of the calculation of the efficiency of the BPEV would follow the explanation for the FCEV, except that the efficiency of the battery and recharging system (up to 80%, not counting the energy required to heat a high-temperature battery) would be substitituted for the efficiency of the fuel cell. However, the BPEV also would be much heavier than the fuel cell vehicle.

Table 5. Calculated weight, volume, and cost of components of BPEVs and hydrogen FCEVs (400-km

	Retail prices[b] ($)		Weights (kg)		Volumes[c] (liters)	
	BPEV	FCEV	BPEV	FCEV	BPEV	FCEV
Traction battery, storage tray and auxiliaries	13,625	4,205	430	126	237	75
Fuel storage system[d]	0	2,692	0	66	0	108
Fuel cell stack and associated auxiliaries	0	4,496	0	50	0	85
Extra support structure in the EV	34	(14)	9	(4)	n.e.	n.e.
Difference between the EV & the ICEV powertrain[e]	(2,839)	(3,298)	(281)	(305)	n.e.	n.e.
Extra weight and drag-reduction measures on EV[f]	107	107	(147)	(147)	n.a.	n.a.

[a]The results shown here are from the model and input data described in the text and in the appendices, and apply to the vehicles of Table 4. n.e. = not estimated. () = negative value.

[b]The retail price includes the vehicle licencing fee, shipping cost, and taxes.

[c]These are estimates of the water volumes of the components themselves, and do not account for unuseable void spaces created by packing and arranging the components.

[d]The estimate of the weight of the fuel-storage system of the FCEV includes the weight of valves, fuel lines, and regulators, and fuel (added to 40% of capacity.) However, the estimate of the volume of the fuel-storage system does not include the volume of fuel lines, valves, or regulators.

[e]The EV powertrain consists of all parts in an EV and not in an ICEV, except the fuel cell system, fuel storage system, and battery, which here are treated separately. The ICEV powertrain includes all parts that are in an ICEV but not in an EV: the engine, transmission, driveline, fuel system, cooling system, pollution control equipment, and so on.

The difference in volumes between the two powetrains could not be estimated because of the difficulty of determining the water displacement volume of the engine, transmission, fuel system, exhaust system, pollution control, electronics, etc., in a modern vehicle. Note, though that an electric powertrain requires much less space than does an ICE powertrain.

[f] I assume that the EV would have a lower aerodynamic drag and lower body weight than the ICEV, because there would be a greater benefit to improving the efficiency of an EV than of an ICEV. See the text and Appendix A for further discussion.

Table 6. Percentage change in gm/km emissions from alternative-fuel light-duty vehicles, relative to gasoline vehicles, year-2000.[a]

	Criteria Pollutants[b]					Green-house Gases[c]
Feedstock/Fuel/Vehicle	NMOC	CO	NO_x	SO_x	PM	
NG/methanol/ICEV	-50	0[d]	0	-100[e]	lower	-2
U.S. power mix/BPEV	-95	-99	-56	+321	+153	-11
NG/hydrogen/FCEV	-100	-100	100	-100[e]	-100	-43[f]
Biomass/hydrogen/FCEV	-100	-100	-100	-100[e]	-100	-67[g]
Biomass/methanol/FCEV	-90[h]	-99[i]	-99[i]	-100[e]	-100	-86
Solar/hydrogen/FCEV	-100	-100	-100	-100[e]	-100	-87[j]
Solar/hydride/ICEV	-95	-99	-?[k]	-100[e]	lower	-88[l]
Solar power/BPEV	-100	-100	100	-100	-100	-100
All solar/hydrogen/FCEV	-100	-100	-100	-100[e]	-100	-100[m]
Baseline emissions on gasoline, g/km[n]	0.48	3.81	0.28	0.035[o]	0.01	305.3

[a]The percentage changes shown are with respect to the baseline g/km emissions shown at the bottom of this table, except in the case of BPEVs (see note b).

[b]The estimates of relative emissions of criteria pollutants from all vehicles except the methanol/fuel cell vehicle and the BPEV using the national power mix are based on data summarized in Sperling and DeLuchi (1992). The estimates for the methanol/fuel cell vehicle are based on sources cited in note i to this table. The estimates for the BPEV using the national power mix are the "Year-2010 minimum-impact" (minimum-emissions-reduction) scenario of Wang et al. (1990), which compares emissions from power plants with emissions from ICEVs (exhaust and evaporative) plus emissions from petroleum refineries. All of the estimates here are only approximations, meant to be indicative of relative emissions potential. Actual emissions from any vehicle will depend on the particular characteristics of the engine and emission control systems and on the composition of the fuel, and could differ substantially from these estimates.

I assume that all vehicles would use advanced engines and drivetrains, would be optimized to run on the particular fuel shown, and would meet the in-use emissions standards mandated by the 1990 amendments to the U. S. Clean Air Act.

NMOCs = nonmethane organic compounds (total emissions of organic compounds less emissions of methane, which is almost nonreactive and hence usually does not contribute significantly to ozone formation). CO = carbon monoxide. NO_x = nitrogen oxides. SO_x = sulfur oxides. PM = particulate matter.

[c]The percentage changes refer to the sum of emissions of CO_2, CH_4, N_2O, CO, NO_x, and NMOCs from the entire fuel-production and use cycle (excluding the manufacture of vehicles and equipment), per km of travel. Emissions of gases other than CO_2 have been converted to an "equivalent" amount of CO_2, using the global-warming-potential factors of the

Intergovernmental Panel on Climate Change (1990). The CO_2 equivalents of these gases have been added to actual CO_2 emissions, to produce an aggregate measure of greenhouse-gas emissions. The result for natural-gas derived methanol and the result for BPEVs using the U. S. national power mix (in the year 2000) are from DeLuchi (1991); all the other results are from unpublished runs of the model documented in DeLuchi (1991).

[d]CO emissions depend very strongly on the ratio of air to fuel. Generally, the higher, or "leaner," this ratio -- that is, the greater the amount of oxygen -- the lower the CO emissions. Although, methanol engines can burn leaner mixtures than gasoline engines can, I assume that the new 0.25 g/km NO_x standard in the U. S. will preclude the use of lean burn, except in hydrogen vehicles (see note below). The National Academy of Sciences (1992) has concluded that a NO_x standard of 0.12 g/km would preclude the use of lean-burn for all except the lightest gasoline-powered cars and trucks.

[e]SO_x emissions areproportional to the sulfur content of the fuel. I assume that methanol and hydrogen would contain virtually no sulfur.

[f]I assume that hydrogen would be made at the refueling site from natural gas delivered by pipeline, and then compressed to 550 bar for delivery to vehicles. I assume that the compressor would use electricity generated from the projected national mix of power sources in the U.S. in the year 2000 (EIA, 1991).

[g]I assume that hydrogen would be made in centralized biomass-gasification plants (Larson and Katofsky, 1992; DeLuchi et al., 1991), compressed for pipeline transport using bio-electricity generated at the biomass plant, and compressed for delivery to vehicles at the refueling station using the projected national mix of power sources in the year 2000 (EIA, 1991)

[h]A methanol\fuel cell vehicle would have no tailpipe emissions of NMOCs, but the storage, distribution, and transfer of methanol would produce a small amount of evaporative emissions of methanol (DeLuchi, 1991; DeLuchi et al., 1992).

[i]The methanol reformer, which would convert methanol into hydrogen and CO, would emit negligible amounts of CO and NO_x. Data and statements in Patil (1992), Zegers (1990), Patil et al. (1990), Kevala (1990), and Werbos (1987) indicate that these emissions would be on the order of 1% or less of the emissions from a gasoline ICEV. For example, Patil (1992) reports 0.002 g/mi HC, less than 2 ppm CO, and 0.001 g/mi NO_x. The PEM fuel cell itself would not produce any NO_x, because of its extremely low operating temperature.

[j]I assume that hydrogen would be produced from water using solar power, but that the hydrogen compressor at the refueling station would run off electricity generated from the projected national mix of power sources in the U. S. in the year 2000 (EIA, 1991).

[k]Hydrogen vehicles built and tested to date have shown a wide range of NO_x emissions (Sperling and DeLuchi, 1992). A hydrogen engine can be designed to operate at a very high air-to-fuel ratio (i.e, very "lean"), and as long as such an engine actually operates very lean, it has very low NO_x emissions, because of the reduced temperature due to the excess air. But if the air/fuel mixture is enriched to stoichiometric, so that the engine operates at full power, then engine-out NO_x emissions increase substantially. Overall, such a scheme (lean-burn at part load, stoichiometric at full load and no NO_x reduction catalyst) probably would result in NO_x emissions comparable to

those from a gasoline vehicle equipped with a 3-way catalytic converter. (For example, see the FTP test results in Withalm and Gelse, 1986). To achieve a considerable reduction in NO_x emissions relative to emissions from a well-controlled gasoline vehicle, the hydrogen vehicle either would have to be restricted to very lean operation (meaning that the full power of the engine would never be exploited), or else equipped with a NO_x reduction catalyst for full-load operation.

[l]I assume that solar hydrogen would be delivered by pipeline to refueling stations, and then compressed to 50 bar for delivery to hydride vehicles. I assume that the compressor would run off electricity generated from the projected national mix of power sources in the U. S. in the year 2000 (EIA, 1991).

[m]As in the solar/hydrogen/FCEV case, except that I assume that the hydrogen compressor at the station would run on solar power.

[n]These are projected emissions of criteria pollutants and greenhouse gases from a light-duty vehicle operating on reformulated gasoline in the year 2000 (DeLuchi, 1991).

[o]This is calculated from the following assumptions: that gasoline is 0.03% sulfur by weight, that the vehicle gets 7.84 l/100 km (30 mpg), and that all sulfur oxidizes to form SO_2. Reformulated gasoline might contain less sulfur than this, because recent tests by the automobile and oil industries indicate that reducing the sulfur content to 0.005% can reduce emissions (Auto/Oil Air Quality Improvement Research Program, 1992).

Table 7. Land and water requirements for hydrogen production.[a]

	Land		Water
	hectares/mW$_e$-peak	*m^2/gJ/yr)*	*liters/gJ (HHV)*
Electrolytic hydrogen from:			
Photovoltaics[b]	1.3	1.89	63
Solar Thermal Electric[b]	4.0	5.71	63
Wind[c]	4.7-16	6.3-33	63
Hydroelectric[d]	16-900	11-500	>>63
Biomass Hydrogen[e]	n.e.	50	37,000-74,000

[a]From Ogden and DeLuchi (1992). n.e. = not estimated. HHV = higher heating value.

[b]Annual energy production is given for a Southwestern US location with average annual insolation of 271 Watts/m^2. Water requirements are for electrolyzer feedwater.

[c]The high-energy-output/low-land-use end of the range is for areas with a unidirectional or bidirectional wind resource (as in some mountain passes); the low-energy-output/high-land-use end is for areas with more variable wind direction, such as the Great Plains. Water requirements are for electrolyzer feedwater.

[d]Land use for hydroelectric power varies greatly depending on the location. The range shown is for large projects in various countries (Moreira, 1991). Water requirements are for electrolyzer feedwater only. At some sites evaporative losses at the reservoir could be much greater than feedwater consumption.

[e]This estimate is based on a biomass productivity of 15 dry tonnes/hectare/year. Water use is based on a rainfall of 75-150 cm per year needed to achieve a biomass productivity of 15 dry tonnes/hectare.

Table 8a. Summary of cost results, hydrogen ICEVs.[a]

	Gasoline (baseline) *640-km range*	Hydride *400-km range*	Liquid hydrogen *400-km range*	Compressed hydrogen *400-km range*
Fuel retail price ($/gallon-equivalent)[b]	1.18	2.86	4.22	2.97
Full retail price of vehicle ($)[c]	17,302	26,118	18,719	24,467
Maintenance cost ($/year)	516	464	464	464
Life-cycle cost (cents/km)	21.45	28.67	25.96	26.67
Breakeven gasoline price ($/gallon)[d]	n.a.	4.28	3.36	3.61

[a]The results for the hydrogen ICEVs are from an updated but unpublished version of the analysis described in DeLuchi (1989). n.a. = not applicable.

[b]Dollars per gasoline-equivalent gallon is calculated as the $/million-Btu (HHV) price of the fuel to the motorist, *excluding* Federal, state, and local taxes ($0.31/gallon in the U. S.), multiplied by 0.125 million Btu/gallon-gasoline. Note that this gasoline equivalence is defined in terms of energy delivered to the vehicle, and hence does not account for the efficiency with which the vehicle uses that energy. The estimate of the cost of gasoline assumes the EIA's (1992) reference-case estimate of the world oil price in the year 2000 ($26.40/bbl), and reformulated gasoline (15 cents/gallon more than conventional gasoline). For hydrogen ICEVs, the gasoline-equivalent fuel price is based on the cost of producing, distributing, and retailing hydrogen fuel. The hydrogen production and distribution costs are from Table 5; in the base case I assume $18 per gJ of hydrogen delivered to the refueling station.To this is added the cost of the refueling station: $4.50/gJ for compressed hydrogen for ICEVs, $3.70/gJ for hydride ICEVs, $3.79/gJ for LH_2 ICEVs, and $4.74/gJ for compressed-hydrogen ICEVs. The gasoline-equivalent price for LH_2 accounts for boil-off losses (3% at each of three transfer points).

[c]Including sales tax, dealer costs, and shipping costs.

[d]The retail price of gasoline (including Federal, state, and local taxes in the U. S., which at present amount to $0.31/gallon) at which the life-cycle consumer cost-per-km of the alternative-fuel vehicle would equal that of the gasoline vehicle. To compare these figures with gasoline costs in other countries, subract the $0.31/gallon U. S. total tax assumed here, and divide by 3.7854, to obtain $/liter pre-tax breakeven gasoline cost.

Table 8b. Summary of cost results, BPEVs.[a]

	Gasoline (baseline) *640-km range*	BPEV *400-km range*	BPEV *250-km range*	BPEV *160-km range*
Fuel retail price ($/gallon-equivalent)[b]	1.18	2.57	2.57	2.57
Full retail price of vehicle ($)	17,302	28,247	22,656	20,114
Maintenance cost ($/year)	516	388	388	388
Life-cycle cost (cents/km)	21.45	22.96	21.65	21.44
Breakeven gasoline price ($/gallon)	n.a.	2.11	1.57	1.48

[a]The results for the battery-powered electric vehicles and the gasoline ICEV are based on the analysis outlined in this paper and detailed in the appendices. n.a.= not applicable. See also notes to Table 8a.

[b]For the BPEV, the gasoline-equivalent fuel price is based on the assumed price of off-peak electricity in the year 2000 (7 cents/kWh) and 3412 Btu/kWh.

Table 8c. Summary of cost results, FCEVs.[a]

	Gasoline (baseline) *640-km range*	FCEV hydrogen *400-km range*	FCEV hydrogen *250-km range*	FCEV methanol *560-km range*
Fuel retail price ($/gallon-equivalent)[b]	1.18	2.97	3.04	1.71
Full retail price of vehicle ($)	17,302	25,446	23,183	24,810
Maintenance cost ($/year)	516	434	434	450
Life-cycle cost (cents/km)	21.45	21.33	20.94	20.29
Breakeven gasoline price ($/gallon)	n.a.	1.43	1.27	1.00

[a]The results for the fuel cell vehicles and the gasoline ICEV are based on the analysis outlined in this paper and detailed in the appendices. n.a.= not applicable. See also notes to Table 8a.

[b]The gasoline-equivalent fuel price is based on the cost of producing, distributing, and retailing hydrogen or methanol fuel. The hydrogen production and distribution costs are from Table 9; in the base case I assume $18 per gJ of hydrogen delivered to the refueling station. To this is added the cost of the refueling station, $4.50/gJ for compressed hydrogen for FCEVs. The methanol case assumes that methanol is made from biomass (Larson and Katofsky, 1992).

The fuel retail price of hydrogen is estimated to be higher in the 240-km case than in the 400-km case because in the 240-km case there would be slightly less hydrogen throughput at refueling stations than in the 400-km case, but the same total operating and initial cost for the station. There would be less hydrogen throughput in the 240-km case because the ratio of time spent delivering hydrogen to fixed time spent paying and getting in and out of the station would decrease, because of the smaller hydrogen containers.

Table 9. Current and projected production costs of hydrogen ($/GJ).[a]

	1991	Near Term	Post 2000
Renewable sources of hydrogen			
Electrolysis of water by:[b]	54-121	29-57	12-19
Solar-PV (Southwest U.S.)	37	25	17
Wind power (630 W/m^2)	53	38	21
Wind power (350 W/m^2)			
Solar thermal (Southwest U.S.)	45-60	37-63	22-30
Off-peak hydroelectricity[c]	10-20	10-20	10-20
Biomass gasification[d]			6-9
Fossil sources of hydrogen			
Steam reforming of natural gas[e]	6-8	6-8	8-10
Coal gasification[f]	8-13	8-13	8-13

[a]Levelized production costs, estimated assuming a real discount rate of 6%, and annual insurance + property taxes equal to 2.0% of the installed capital cost. The values shown do not include compression (for storage), underground storage, pipeline transmission, and local distribution, which would add $2-$3/gJ to the price of solar- and wind-electrolytic hydrogen, and about $0.50/gJ to the price of biomass-derived hydrogen (which would not have to be stored, and which would be distributed locally only). Filling station costs would add another $3-6/gJ depending on the type of storage system used on the vehicle. The total hydrogen cost to the motorist would be $4-9/gJ higher than the production cost. See Ogden and DeLuchi (1992) and Ogden and Nitsch (1992) for details.

[b]From plants producing 0.5 million standard-cubic feet per day (SCFD), or 180 gJ/day. Such a plant would provide enough energy to fuel 1000 to 2000 fleet fuel-cell vehicles, each traveling 20,000 to 40,000 miles/year.

[c]Assuming that off-peak hydroelectricity at existing sites costs 1 to 4 cents/kWh.

[d]Assuming that the plant has a capacity of 50 million SCF/day, and that the biomass feedstock costs $2-4/GJ.

[e]Assuming that natural gas costs $2-4/gJ in the 1990s and $4-6/gJ in the year 2000 and beyond. (The Energy Information Administration [EIA], 1992, projects $4/gJ for industrial consumers and $6/gJ for commercial consumers in the year 2000.) The plant is assumed to produce 100 million SCF/day. Costs would be about $5-6/gJ higher for a plant producing only 0. 5 million SCF/day.

[f]Costs for coal gasification are based on the steam-iron process, assuming coal costs $1.80/gJ in the year 2000 (EIA, 1992). The low end of the range is the cost for a plant producing 100 million SCFD; the high end is for a plant producing 25 million SCFD.

Table 10. Lifecycle cost of gasoline ICEVs, BPEVs, FCEVs (cents/km).[a]

ICEV (gasoline)	BPEV (400-km range)	BPEV (100-km range)	FCEV (solar hydrogen)	FCEV (biomass methanol)	Cost item
	1.48	1.24	0.20	0.22	Purchased electricity[b]
11.17	7.59	6.89	7.18	7.22	Vehicle, excl. battery, f.c., H_2 system[c]
	7.08	7.01	2.15	2.03	Battery, incl. tray and auxiliaries
2.82	0.00	0.00	1.96	1.34	Fuel, excluding retail taxes
	0.00	0.00	0.81	0.02	Fuel storage system
	0.00	0.00	2.23	2.62	Fuel cell system, including reformer
	0.04	0.04	0.00	0.00	Home recharging station
2.53	3.23	2.82	3.09	3.05	Insurance[d]
2.89	1.69	1.69	1.89	1.96	Maintenance and repairs[e]
0.07	0.00	0.00	0.00	0.00	Oil
0.25	0.29	0.19	0.28	0.28	Replacement tires[f]
0.50	0.50	0.50	0.50	0.50	Parking and tolls[g]
0.14	0.12	0.09	0.10	0.10	Registration fees[h]
0.22	0.09	0.09	0.09	0.09	Vehicle inspection fee[i]
0.74	0.74	0.74	0.74	0.74	Fuel taxes[j]
0.11	0.11	0.11	0.11	0.11	Accessories[g]
21.45	22.96	21.44	21.33	20.29	**Total cost per km**
	2.11	1.48	1.43	1.00	**Breakeven gasoline price ($/gal)[k]**

[a]Calculated from the input data and formulae shown in the appendices. n. a. = not applicable. Vehicle characteristics and cost parameters as in Tables 4 and 8. FCEVs have a 400-km range.

[b]In the base case, this includes electricity bought to heat the battery when the vehicle is idle, as well as electricity bought to recharge the battery. (In the base case, the peak-power battery in the FCEV is recharged from the outlet). In the scenario analyses, I consider a case in which hydrogen (via the fuel cell) is used to heat and recharge the battery in the FCEV (to the extent that regenerative braking does not). It is costly to use hydrogen for these purposes, but it does liberate the vehicle from plug-in recharging.

[c]The amortized initial cost of cost of the EVs (excluding the battery, the fuel cell, and the fuel storage system, which are treated separately), is less than the amortized initial cost of the ICEV, because the EVs have both a lower initial cost (excluding the components listed above) and a longer life.

[d]The insurance cost per km is calculated as a function of the km driven per year, the value of the vehicle, the amount of the deductible, and the number of years that insurance against collision damage is carried. Because the complete EVs (i.e., with the battery, fuel cell, and fuel storage

system) of this analysis are more expensive than the ICEV, and are assumed to be driven more km per year, they have a higher insurance cost per km.

[e]EVs are expected to have lower maintenance costs than ICEVs (Appendix B).

[f]The cost program estimates the present value of all tire replacement costs, and then amortizes this present value on a monthly basis. Since the present value of replacement costs is a function of the number of replacements and the time of occurrence, it is necessary to estimate differences in tire replacement intervals for EVs and ICEVs. Although tire wear is a function of vehicle weight, road conditions, and driving patterns, I assume that the only difference in the rate of tire wear between EVs and ICEVs would be due to vehicle weight. In the cost program, tire life for the EV is estimated relative to tire life for the reference gasoline vehicle in proportion to the relative weight of the EV. I have assumed that tires are not replaced if the last replacement interval falls within 7500 miles of the end of life of the vehicle. In the base case, it turns out that the lifecycle tire cost is higher for the FCEV than for the ICEV, even though the FCEV weighs less, because the last tire purchase for the FCEV falls much closer to the end of the FCEV's life than the does the last tire purchase for the ICE relative to the ICEV's life (recall that the FCEV has a longer life). Hence, there are fewer miles over which to amortize the last purchase, and so the cost per km is higher.

[g]I assume that the cost per km would be the same for all vehicle types.

[h]I assume that the vehicle registration fee is a function of vehicle weight, as it is now in most states.

[i]I assume that the inspection of an ICEV covers safety and emissions. Since EVs do not have emission controls, the part of the inspection concerned with emissions could be eliminated, and the inspection fee be reduced accordingly.

[j]Assumed to be the same for all vehicles, and based on the current national-average state-plus-Federal gasoline tax of $0.31/gallon.

[k]The retail price of gasoline, including Federal, state, and local taxes ($0.31/gallon in the U.S.) at which the life-cycle consumer cost of the gasoline vehicle equals that of the fuel cell vehicle.

Table 11. Scenario analyses: sensitivity of the breakeven gasoline price to important cost parameters.

Scenario examined (low end -- high end) [base case][a]	Breakeven gasoline price[b] (1990$/gallon)	
	BPEVs	FCEVs
0) Base case results (400-km range)	2.11	1.43
1) Miles of city driving div. by total driving miles (1.00 - 0.00) [0.68]	1.91 - 2.81	1.24 - 2.12
2) Km of driving range per tank or battery charge (160 - 560) [400][c]	1.48 - 2.98	1.50 - 1.67
3) In-use once-through electric-drivetrain efficiency (0.76 - 0.62 [0.69][d]	1.61 - 2.77	1.04 - 1.87
4) Life VMT of EV divided by life VMT of ICEV (1.66 - 1.00) [1.33][e]	1.67 - 3.18	0.82 - 2.72
5) Life miles to scrappage, gasoline ICEV (100k - 140k) [120k][f]	1.76 - 2.46	1.17 - 1.65
6) Ratio of EV to gasoline ICEV max. acceleration (0.60 - 1.00) [0.80]	1.60 - 2.69	1.05 - 1.84
7) Horsepower of baseline gasoline-vehicle engine (120 - 170) [145][g]	1.72 - 2.55	1.14 - 1.72
8) How the vehicle is payed for (0% of buyers take out loan - 80% take out loan, no downypayment) [70% take out loan, 11% downpayment]	1.67 - 2.24	1.18 - 1.53
9) Foregone real before-tax interest rate on cash (2.5% - 15%) [3.6%]	2.08 - 2.39	1.41 - 1.68
10) Ratio of retail price (excl. taxes) to OEM cost (1.50 - 2.30) [1.77][h]	1.40 - 3.58	0.88 - 2.56
11) OEM $/kW cost of electric drivetrain, excl. battery (($400 + $16/kW) - ($625 + $25/kW)) [$500 + $20/kW]	1.88 - 2.41	1.23 - 1.69
12) Fuel-cell cost, retail level, w/tax ($100/kW - $250/kW) [$180/kW][i]	n.a.	0.92 - 1.89
13 Battery manufacturing cost (($400 + $72/kWh + $5.20/Kw) - ($600 + $108/kWh + $7.80/kW)) [$500 + $90/kWh + $6.50/kW][j]	1.41 - 2.84	1.22 - 1.65
14) Delivered cost of electricity and hydrogen ($0.04/kWh - $0.13/kWh and $7/gJ - $33/gJ) [$0.07/kWh and $18/gJ][k]	1.85 - 2.64	1.00 - 2.05
15) Hydrogen storage (Iron redox - FeTi hydride) [Compressed gas][l]	n.a.	1.02 - 1.98
16) Battery heat loss (no heat loss - heating energy comes from battery or fuel cell) [loss of 4.0 W/kWh made up by electricity from outlet][m]	2.05 - 4.72	1.42 - 1.90
17) Battery heating & recharging in FCEV (from fuel cell) [wall outlet]	n.a.	1.77
18) Battery cycle life, to 80% depth of discharge (1100 - 500) [800][n]	1.43 - 3.62	1.23 - 1.89
19) Scenarios 2 and 6 combined	1.05 - 3.72	1.06 - 2.12
20) Scenarios 2, 4, and 6 combined	0.66 - 4.99	0.55 - 3.51
21) Scenarios 3 and 14 combined	1.38 - 3.38	0.69 - 2.56
22) Scenarios 10, 11, 12, and 13 combined	0.63 - 4.66	0.21 - 3.34

[a]In each scenario, only the parameters named change from their base-case values, except that the sizing tradeoff between the battery and the fuel cell is reoptimized where necessary (these instances are noted below), and any variables linked to the parameter of interest (e.g., vehicle weight),

change automatically. Each scenario shows the effect of substituting low and high values (shown in parantheses) for the parameter of interest. The "low-end" value is the value that results in the low-end breakeven gasoline price, not necessarily the numerically lower value. The "high-end" value is the value that results in the high-end breakeven gasoline price. The base-case values of the parameters are shown in brackets, and are documented in the appendices.

"EV" refers to both the BPEV and the FCEV. n.a. = not applicable. OEM = original equipment manufacturer.

[b]The breakeven price of gasoline is the retail price of gasoline, including U. S. Federal, state, and local taxes ($0.31/gallon in the U. S.), at which the full lifecycle cost-per-km of the gasoline vehicle equals the full lifecycle cost of the FCEV or BPEV.

[c]The fuel cell and the battery are resized in these scenarios. Note that the 160-km range FCEV has a higher lifecycle cost than the 250- and the 400-km range FCEVs. This is because the peak-power battery in the 160-km FCEV has a very high lifecycle cost, primarily because it must be replaced more frequently than the batteries in the longer-range FCEVs. It must be replaced more frequently because it has the same cycle life as the larger batteries, but provides fewer miles per cycle, and hence is cycled more rapidly.

[d]The electric drive inlcudes the motor, electronics package (controller and inverter), and transmission. "Once-through" means that regenerative braking is not included in this metric (it is accounted for in the final cost results, however). "In-use" means that an adjustment is made for the difference between the efficiency measured over a test cycle and the efficiency achieved in the real world. The fuel-cell and battery are resized in this scenario.

[e]The life of the fuel cell is assumed to be equal to the life of the FCEV, but the life of the battery is assumed to be 800 cycles regardless of the life of the vehicle.

[f]The *relative* lifetime of the BPEV and the FCEV remain the same (1.33 times that of the ICEV).

[g]Only the horspepower of the baseline gasoline vehicle changes in this scenario. The weight and cost of the baseline vehicle, and the *relative* high-end acceleration of the BPEV and FCEV (80% of that of the ICEV) remain the same.

[h]I define the OEM (original equipment manufacturer) or manufacturing cost of the vehicle as the direct variable cost, which is equal to the cost of materials and parts plus the cost of assembly labor (including benefits) plus the operating cost of the assembly plant. This manufacturing cost does not include the cost of research and development, design engineering, major equipment and facilities, advertising, testing and certification, executives, shipping, retailing, and so on. The retail price is equal to the manfucturing cost plus all these other costs (here excluding sales taxes).

[i]In the low-end scenario (in which the fuel cell is relatively inexpensive), if the maximum gross power of the fuel cell were increased from 25 kW to 33 kW, and the peak power of the battery were reduced by 8 kW, *and* if the battery held only enough energy to drive the vehicle when the power demand exceeded 33 kW, then the breakeven price would decline to $0.80/gallon. However, in this case, the power density of the battery would be around 1150 W/kg, which probably would exceed the maximum design capacity of a bipolar Li/S battery (I have assumed a limit of 800 w/kg). The development of batteries or peak-power devices with the same cost as but better performance than the Li/S would allow one to obtain this cost benefit ($0.80/gallon).

[j]Applies to the battery in the FCEV as well as the battery in the BPEV.

[k]Hydrogen produced by gasification of biomass could be delivered to the refueling station for as little as $7/gJ (Table 9). On the other hand, solar-electrolytic hydrogen could cost over $30/gJ delivered (Table 9). Utilities might charge customers as little as $0.04/kWh for off-peak battery recharging, but as much as $0.13/kWh or more for the use of peak power.

[l]Table 3 describes and shows estimates of the cost of hydrogen-storage and refueling systems. I have changed the weight parameters as well as the cost parameters for the storage scenarios presented here; these weight changes affect the efficiency of the vehicle which in turn affects fuel consumption and the size of the fuel storage system needed to achieve a given range. "Iron redox" is the iron oxidation/reduction system proposed by Werth (1992).

[m]If the battery were to provide the energy needed to maintain its own heat (the high-cost end of this scenario), then it would have to contain enough energy to heat itself *and* provide the original driving range (400-km in the case of the BPEV). This would require a very large and costly battery.

[n]In the high-end scenario (in which the battery would have a short cycle life and hence a high lifecycle cost), if the gross maximum power of the fuel cell were increased from 25 kW to 33 kW, and the power of the battery decreased by 8 kW, then the breakeven gasoline price would be reduced to $1.74/gallon. However, in this case the power density of the battery would be 1200 W/kg, which would exceed the 800 W/kg limit I have assumed for bipolar Li/S. (See note i for further explanation.)

Figure 1. Energy efficiency of renewable-fuel pathways (primary energy to wheels).[a]

Solar electricity used by BPEVs:

Efficiency of stage: 0.15 0.85[b] 0.92[c] 0.81[d] 0.88[d]
Sunlight --> PV (dc) --> power conditioning --> ac transmission --> recharger and battery --> powertrain --> wheels
Energy into stage: 1.00 0.15 0.128 0.117 0.095 0.084

Solar electricity used by hydrogen FCEVs:

Efficiency of stage: 0.15 0.85[b] 0.85[b] 0.92[e] 0.91[f] 0.46[g] 0.88[d]
Sunlight --> PV (dc) --> power cond. --> H_2 prod. --> H_2 trans. --> compression -->fuel cell --> powertrain --> wheels
Energy into stage: 1.00 0.15 0.128 0.109 0.100 0.092 0.042 0.037

Biomass-derived hydrogen used in FCEVs

Efficiency of stage: 0.003[b] 0.70[h] 0.92[e] 0.91[f] 0.46[g] 0.88[d]
Sunlight --> green biomass --> H_2 production --> H_2 trans. --> compression --> fuel cell --> powertrain --> wheels
Energy into stage 1.00 0.003 0.0021 0.0019 0.0018 0.0008 0.00071

Biomass-derived methanol used in FCEVs:

Efficiency of stage: 0.003[b] 0.66[h] 0.98[i] 0.39[j] 0.88[d]
Sunlighy --> green biomass --> MeOH production --> methanol distribution --> fuel cell --> powertrain --> wheels
Energy into stage: 1.00 0.003 0.0020 0.0019 0.0008 0.00067

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[a]All paths start with one GJ of biomass energy or electricity. The paths consist of only those stages that consume either the primary energy source (electricity or bio-energy) or the end-use fuel (methanol, electricity, or hydrogen). The energy efficiency of stage S_i is defined as: net GJ of product out of S_i and into S_{i+1} divided by total GJ (feedstock plus process energy) into S_i. PV = photovoltaics. (Note that it is more meaningful to compare the two electricity pathways with each other and the two biomass pathways with each other than to compare the electricity with the biomass pathways.)

Ideally, the energy-efficiency chain would end with a unit of service provided by all the fuel/vehicle pathways. This unit of service might be the energy used to accelerate the vehicle over one km during a typical driving cycle. The amount of energy required to accelerate a vehicle is a function of the vehicle's weight, aerodynamic drag, rolling resistance, and braking system. (The characteristics of the braking system are relevant because some of the energy used to accelerate the vehicle can be recovered by regenerative braking; i.

e., by having the wheels run the motor backwards to recharge the battery.) I have stopped the efficiency calculation at energy delivered to the wheels, and have not considered weight, aerodynamic drag, and rolling resistance (regenerative braking is included, though). The reader should be aware, however, that at the very least, differences in vehicle weight among the alternatives would make the overall efficiency of providing a unit of service different than the efficiencies of delivering energy to the wheels.

[b]Based on data in Ogden and DeLuchi (1992).

[c]Average efficiency of power transmission in the United States (EIA, 1990).

[d]Based on the estimates documented in Appendix A. The estimate of the efficiency of the powertrain accounts energy recovered from regenerative braking over the entire drive cycle. The recharging and battery efficiency does *not* include the use of any energy to heat a high-temperature battery.

[e]Calcuated assuming compression from atmospheric pressure to 1000 psi by hydrogen-fueled turbine-driven compressors; I assume that the hydrogen turbines are 45% efficient.

[f]Compression from 50 psi to 8000 psi.

[g]This is calcualted as the product of the efficiency of the PEM fuel cell and the efficiency of the fuel-cell auxiliaries (Appendix A).

[h]From Larson and Katofsky (1992).

[i]This estimate is based on the assumption that methanol would be distributed by trucks that themselves would use biomass-derived methanol (DeL

[j]This is calculated as the product of the efficiency of the fuel-cell system (45%) and the efficiency of the reformer (86%; Kumar et al., 1988, 1989

HYDROGEN FUEL-CELL VEHICLES: TECHNICAL APPENDICES

INTRODUCTION TO THE APPENDICES

These appendices tabulate and document most of the input data used to calculate lifecycle costs. In Appendix A the input parameters and calculated results are grouped in seven tables: financial parameters, characteristics of ICEVs, characteristics of EVs, batteries and battery recharging, hydrogen production and storage, hydrogen refueling stations, and fuel cells. The notes following each table explain most of the important data assumptions and some of the calculated results. Each input assumption of each table is recapitulated in bold italic print in the notes after each table, for ease of following along, even though for some of the input assumptions there is at present no explanation or documentation. In a later version of this report, all assumptions will be explained. Calculated results are recapitulated in bold italic in the notes only if there is some discussion of the result.

In Tables A.3, A.4, and A.5 there are two columns of input data and calculated results. The first or left-hand column refers to the FCEV; the second or right-hand column refers to the BPEV. In some places in Table A.1 there 3 columns; these refer to the ICEV, FCEV, and BPEV, respectively. *In all tables, the calculated results refer to the 400-km range case for the FCEV and BPEV.*

Appendix B discusses the estimation of maintenance and repair costs.

APPENDIX A

Table A.1. Financial parameters used in the analysis.

Investment in electricity and hydrogen production, transmission, and distribution: input data

0.061	Real rate of return on investment
0.005	Yearly insurance cost, fraction of initial capital cost
0.015	Yearly property taxes, fraction of initial capital cost

Investment in hydrogen refueling stations: input data

0.020	Yearly insurance and property tax (fraction of total initial investment)
0.06	Real return to investment, after taxes
0.075	Real rate of interest on loan, before taxes (assume period of loan = life of equipment)
0.40	Corporate income tax rate
0.50	Loan taken out to finance project (fraction of initial investment)
20	Life of building and all equipment at the station (yrs)

Ratio of retail-level price to manufacturing cost: input data

1.50	Ratio of factory cost to manufacturing (labor plus materials) cost
1.18	Ratio of dealer cost, exc. shipping and taxes, to factory cost
1.07	Sales tax factor

Gasoline	EV	Buying a new car: input data
0.11	0.11	Downpayment on the car (fraction of full vehicle selling price)
58	calculated	Length of financing period for cars bought on loan (months)
0.70	calculated	Fraction of new car buyers who take out a loan to buy a new vehicle
0.080	calculated	Real annual interest rate on loans for buying a new car, before taxes
0.036	0.036	Real annual interest rate that would have been earned on the money used for transportation expenditures, before taxes
0.20	0.20	Effective (average) income tax on interest, after deductions
2000	2000	Target year for cost analysis
1990	1990	Base year of analysis
No	No	Can interest payments be deducted from taxable income?

Gasoline	FCEV	BPEV	Economic parameters: calculated results
input	68	71	Length of financing period for cars bought on loan (months)
input	0.82	0.85	Fraction of new car buyers who take out a loan for a new car
input	0.092	0.095	Real annual interest rate charged on new-car loans, before taxes
0.029	0.029	0.029	Real annual interest rate that would have been earned on cash used for transportation expenditures, after taxes
1.89	1.89	1.89	Ratio of retail-level price (inc. sales tax) to manufacturing cost
NA	0.0966	0.0966	Capital charge rate, exc. property tax and insurance, and salvage value

Documentation to Table A.1.

0.061 Real rate of return on investment
0.005 Yearly insurance cost, fraction of initial capital cost
0.015 Yearly property taxes, fraction of initial capital cost

These values are suggested by the Electric Power Research Institute for utility-owned electricity- production systems (EPRI, 1986).

0.020 Yearly insurance and property tax (fraction of total initial investment)

Based on the EPRI recommendations shown above.

0.06 Real return to investment, after taxes

From 1984 to 1988 the return on equity in the transportation industry was 7.5%, and in the oil industry 6.6% (*Statistical Abstract of the United States*, 1990). However, the all-industry median was 13.9%. In 1988, the return to investors in the largest industrial corporations in the U. S. was 14.1%. I assume a nominal return on investment in hydrogen refueling stations of 10-11%, which, assuming an average inflation rate of 4.2%, yields a real return on investment of about 6%. This is consistent with the EPRI-recommended rate mentioned above.

0.075 Real rate of interest on loan, before taxes (assume period of loan = life of equipment)

From 1980 through 1990 the prime rate charged by banks for short-term business loans was 11.7% (*Federal Reserve Bulletin*, 1991; *Statistical Abstract of the United States*,1990). Over the past three years, the rate has been around 10%. I assume that in the long run the prime rate will be about 11%, but that investment in hydrogen refueling stations would be viewed as somewhat risky and would be charged slightly more than the prime rate. I assume a 12% nominal rate on loans for hydrogen refueling stations in the year 2000. With an inflation rate of 4.2%, the real rate becomes 7.5%.

0.40 Corporate income tax rate

To calculate the required selling price of hydrogen, one must take into the account the corporate taxes that the station owner will have to pay. The formula that I use here to calculate the capital charge rate has as variable for the corporate-income-tax rate. As with any tax, there is a difference between the marginal tax rate, which is the rate applied to the next unit of income, and the effective average tax rate, which is based on actual total tax liability and total income. Which rate is appropriate depends on whether or not the investment and the station are a new taxable entity, or merely an expansion of a larger entity already subject to tax. In the first case, the effective average corporate rate is applicable; in the second case, the investment is marginal, and so therefore is the tax rate. I assume that for tax purposes refueling stations would be independently owned, and therefore a new taxable entity. Total corporate tax liability, before tax credits, has ranged from 40 to 48% of pre-tax income or profits (*Statistical Abstract of the Unites States*, 1990). Most but not all of the tax credits available appear to be foreign tax credits. I assume an effective average tax liability of 40%.

0.50 Loan taken out to finance project (fraction of initial investment)

In most industries, debt is about 50% of equity (*Statistical Abstract of the United States*, 1990). However, I assume that investment in refueling stations would be undercapitalized for many years and that debt would be 100% of equity. This means that 50% of the total investment would be financed by loans.

20 Life of building and all equipment at the station (yrs)

My assumption. Dresser Rand states that compressors will last at least 20 years (Tothe, 1991)

1.50 Ratio of factory cost to manufacturing (labor plus materials) cost
1.18 Ratio of dealer cost, exc. sales tax and shipping cost, to factory cost

In this analysis, I calculate the selling price of the FCEV or BPEV as: the selling price of the base-case ICEV, less the retail-level price (the manufacturer's suggested retail price, or MSRP) of the equipment removed from the ICEV, plus the retail-level price of the motor, controller, transaxle, fuel-cell system, battery, and hydrogen-storage equipment. I calculate the retail-level price by multiplying the manufacturing cost, or the cost to the original equipment manufacturer (OEM), by a factor equal to the ratio of the retail cost to the manufacturing or OEM cost. This factor accounts for all the costs incurred from the time an automaker acquires or manufacturers an item (e.g., a battery or fuel cell) to the time a dealer sells the vehicle. These costs include the labor required to assemble the item into the vehicle, and a portion of: the cost of the factory and the equipment in the factory; the cost of vehicle design and testing; the cost of research and development; the cost of administrators, managers, accountants, and lawyers; the cost of advertising and marketing; the cost of money; the cost of shipping the vehicle, the dealers' cost, and more.

It is difficult to estimate the ratio of the retail-level price (MSRP) to the manufacturing or OEM cost. In the first place, automobile manufacturers generally do not explicitly calculate this ratio for each part of an automobile, and so one must estimate an "implicit" or general ratio, based on expert opinion, or costs for complete car lines. Moreover, this ratio, however estimated, undoubtedly is different for different components, because different components entail different amounts of post-manufacturing costs. Furthermore, the ratio of the MSRP to the cost of buying a component is different from the ratio of the MSRP to the cost of manufacturing that component, if the manufacturing cost is only a variable cost, and the OEM cost includes fixed costs and overhead.

For this analysis, I have estimated the ratio of the MSRP to the manufacturing cost for a complete automobile, and have applied this ratio to the OEM or manufacturing costs for batteries, fuel cells, electric drivetrains, and hydrogen-storage systems. (This probably overestimates the ratio for parts bought by the automaker [batteries probably will be bought] compared to the ratio for parts manufactured by the automaker [drivetrains probably will be manufactured]). To estimate this ratio, I interviewed three analysts, including cost analysts at two major automotive companies, and reviewed the available literature. Their estimates are shown below. Some of the estimates comprised two parts: the ratio of factory cost to manufacturing cost, and the ratio of MSRP to factory cost. These cost categories are defined as follows:

The *manufacturing cost* includes: materials for the vehicle; vehicle assembly; salary, benefits, and fringe benefits for plant workers; maintenance and utility costs of the production plant; supervisor salaries; janitorial services; and perishable tools. These also could be called the "direct variable costs" associated with building an automobile.

The *factory cost* is equal to the manufacturing (or variable) cost plus all other costs (which perhaps could be called "fixed costs") incurred by the automobile manufacturer: large equipment, the factory and all buildings, vehicle design and safety testing, the cost of money, profit, executives, engineers, managers, accounts, designers, advertisers, research and development, and so on.

The *Manufacturer's Suggested Retail Price* (MSRP) is equal to the factory cost plus all costs -- mostly dealer costs -- incurred after the factory gate. Dealer costs include advertising, license, dealer preparation, and warranty work.

Summary of estimates of the ratio of the MSRP and the factory cost to the manufacturing cost.

Source	Vehicle	Factory cost/ manuf. cost	MSRP/ factory cost	MSRP/ manuf.
Gladstone et al. (1982)	GM Citation	1.33	1.14	1.51
Gladstone et al. (1982)	Plymouth Reliant	1.33	1.14	1.51
Lindgren (ACEEE, 1990)	Ford Escort	2.24	1.20	2.69
Lindgren (ACEEE, 1990)	Ford Taurus	1.92	1.22	2.34
Lindgren (ACEEE, 1990)	GM Caprice	1.71	1.22	2.10
Humphreys and Brown (1990)	electric cars	---	---	1.50
U. S. DOE (1990b)	EV batteries	---	---	1.50
Auto industry 1 (1992)[a]	(generic)	---	---	1.40-1.67
Auto industry 2 (1992)	(generic)	---	---	1.8
F. Fields (1992)	(generic)	1.5-2.0	1.15-1.20	1.73-2.40
Woomack et al. (1991)[b]	(generic)	---	1.15	---

[a]The first auto industry source said that 79% of the MSRP of a car was variable (materials plus direct and indirect labor, but also including engineers, designers, and some higher level costs), and 21% was profit (plant amortization, cost of money, corporate and division costs, and dealer costs and profit). When asked to estimate the breakdown using the definitions of manufacturing cost and factory cost used here, the source estimated that it would be about 69%/31%, but said that there was some uncertainty in the estimate, and indicated that a range of 60% to 72% would be reasonable.

[b]Woomack et al. (1990) write that "most analysts estimate that 15% of the buyers' total cost is incurred after the factory gate, when the new car is turned over to the assembler's selling division before being sent on to the dealer" (p. 174). The costs include manufacturer and dealer advertising, warranty work, staff, overhead, and shipping. If shipping is 2% of the total cost, then dealer mark-up, as defined here, is 0.98/0.85 = 1.15.

These estimates indicate that the ratio of the MSRP to the manufacturing cost ranges from 1.5 to 2.5. If the outlying estimates by Lindgren are excluded, the ratio is between 1.5 and 2.0. (Note that the estimates summarized above include the cost of shipping the vehicle from the factory to the dealer. My estimate of the ratio of the MSRP to the manufacturing cost excludes the shipping cost, which is about 2% of the MSRP, and which I treat separately.

One also should include the labor cost of assembling the new part (hydrogen storage system, battery, or fuel cell) into the vehicle. However, this cost is trivial compared both to the purchase cost of the item (typically several thousand dollars) and to the portion of division, factory, and dealer costs that should be assigned to the item (also several thousand dollars). Assuming that it would take no more than 2 man-hours to assemble the parts into the vehicle (a complete car takes about 30 man-hours of assembly), and that direct plus indirect labor (or "burdened" labor) costs $30/hour (based on conversations with auto industry sources and experts), the assembly cost would be around $60. Therefore, I do not explicitly consider the assembly cost as a separate item (except in the case of the fuel cell, discussed below), but rather fold it into the ratios discussed above.

1.07 Sales tax factor

In most states the general state sales tax is between 3% and 6% (*The Book of States*, 1990). However, in many or most states there are additional local taxes, which in some places are substantial. Moreover, it is more likely that sales taxes will increase than decrease by the year 2000. I assume a national-average population-weighted state-plus-local sales tax of 7% in the year 2000.

0.11 Downpayment on the car (fraction of full vehicle selling price)

From 1980 through 1990 the loan-to-value ratio for new cars ranged between 0.85 and 0.94, and averaged 0.89 (*Annual Statistical Digest*, 1983, 1986, 1989; *Federal Reserve Bulletin*, 1991). One would expect this ratio to be a function of the interest rate on the loan, the interest rate available on saved money, the availability of money, the cost of new cars, the length of time of the loan, and probably other factors. I simply assume the 10-year average of 0.89, which means that 0.11 of the value of the car must be a downpayment.

58 calculated length of financing period for cars bought on loan (months)

The loan period for new cars rose fairly steadily from 45.0 months in 1980 to 56.2 months in 1988. In 1989 it dropped to 54.2 months, but rose again, slightly, in 1990 (*Annual Statistical Digest*, 1983, 1986, 1989; *Federal Reserve Bulletin*, 1991). Based on this trend, and without any further analysis, I assume that the average loan period for new gasoline ICEVs will be 58 months in the year 2000. (Below, I calculate a separate period for EVs.)

0.70 calculated fraction of new car buyers who take out a loan to buy a new vehicle

In 1988, 70% of car buyers financed their purchase (*MVMA Facts and Figures '90*, 1990). I assume that the same fraction of buyers of gasoline ICEVS will finance their purchase in the year 2000. (Below, I calculate a separate fraction for EVs.)

0.080 calculated real annual interest rate on loans for buying a new car, before taxes

From 1980 through 1990 automobile finance companies charged an average nominal interest rate of 13.1% for loans for new cars, and 17.4% for loans for used cars (*Annual Statistical Digest*, 1983, 1986, 1989; *Federal Reserve Bulletin*, 1991). Commercial banks charged an average of 13.2% for new-car loans over the same 11-year period. From 1988 to 1990, automobile finance companies charged 12.6% for new-car loans, and commercial banks charged 11.6%. According to the Motor Vehicle Manufacturer's Association (1990), commercial banks provided financing to 45% of buyers, and credit unions and automobile companies provided financing to most of the rest. Given these figures, it thus seems reasonable to assume a nominal rate of 12.5% for the gasoline base-case in the year 2000.

To derive a real interest rate from this, the effect of inflation must be netted out. From 1980 through 1990, inflation, as reflected in the GNP implicit price deflators, averaged 4.8% per year (*Survey of Current Business*, 1991; *Statistical Abstract of the United States*, 1990). There has been a similar change in the Consumer Price Index. (While this average does reflect the unusually high inflation of the early 1980s, so does the average of the nominal-interest-rate series over the same period.) In the past few years, the rate has been around 4% per year. I assume 4.2% inflation. This means that the real rate of interest on loans for new gasoline ICEVs will be: 1.125/1.042 = 1.080 = 8.0%. (Below, I calculate a separate rate for EVs.)

0.036 Real annual interest rate that would have been earned on the money used for transportation expenditures, before taxes

I assume that the interest opportunity cost of money spent on a new car is the rate the money would have earned in a reasonably liquid but also reasonably high-yielding investment, were it not spent on a new car. Over the past three years, the nominal interest rates on various kinds of money-market funds and deposits have ranged between 7% and 9% (*Federal Reserve Bulletin*, 1991). The nominal rates on U. S. Treasury bonds of various maturities have been between 8% and 9%; the nominal rates on state and local bonds have been between 7% and 8%, and the nominal rates on corporate bonds have been between 9 and 10%. The rates on ordinary savings accounts typically are lower, and sometimes considerably lower than rates on bonds. Considering this data, I assume that the nominal opportunity interest cost of money spent on transportation is 8%. Given an inflation rate of 4.2% (see the preceding footnote), the real before-tax opportunity interest rate becomes 1.08/1.042 = 1.036 = 3.6%. The after-tax rate, of course, will be even lower.

0.20 Effective (average) income tax on interest, after deductions

This is the marginal state and Federal interest-income tax, used here to calculate the after-tax real rate of interest. The marginal Federal tax rate for a married couple with 2 children and income up to about $35,000/year is 15%; at higher incomes, the rate is 28%. State income taxes are between 2 and 10% (*The Book of the States*, 1990). I assume a combined marginal rate of 20%. Interest income is not charged the FICA tax. I ignore the fact that some forms of interest are tax-free.

One perhaps could argue (although I think not convincingly) that the effective average tax rate, equal to tax liability divided by stated personal income, and not the marginal tax rate, should be used. In 1989, the effective average Federal income tax rate was 7.1% for a 4-person household with a total income of $25,000/year, 9.3% for a 4-person household earning $35,000/year, and 12.6% for a $50,000/year household (*Statistical Abstract of the United States*, 1990). In 1986, state taxes paid were 27.5% of Federal taxes paid (which is consistent with the marginal tax-rate data cited above). This indicates a total effective average tax rate of 11.9% for a $35,000/year household.

No Can interest payments be deducted from taxable income?

Interest payments no longer can be deducted from taxable income

Gasoline	FCEV	BPEV	
input	*68*	*71*	***Length of financing period for cars bought on loan (months)***

I expect that over time, the average loan period is a function of the average cost of motor vehicles, personal income, demand for motor vehicles, the money supply, and other factors. I therefore assume that the loan period for EVs, relative to the period for ICEVs, would be a function of the cost of EVs relative to the cost of ICEVs. However, because the loan period undoubtedly is a function of other factors besides the cost of the car, it cannot be strictly proportional to the cost of a car. Given a loan period for the baseline gasoline vehicle, I calculate the loan period for the FCEV or BPEV as:

$$Lev = Lg \times (Pev/Pg)^{0.4}$$

where:
Lev = loan period for the FCEV or BPEV (months)
Lg = loan period for the baseline gasoline ICEV (months)
Pev = Selling price of the BPEV or FCEV ($)
Pg = Selling price of the gasoline ICEV ($)

input 0.82 0.85 Fraction of new car buyers who take out a loan to buy a new vehicle

The fraction of buyers who finance must be related to the average price of vehicles (at constant household income). Given an assumption regarding the fraction of buyers who would finance the purchase of a gasoline ICEV, I calculate the fraction who would finance the purchase of an FCEV or BPEV as:

$$Fev = Fg \times (Pev/Pg)^{0.40}$$

where:
Fev = fraction of people who would take out a loan to buy an EV
Fg = fraction of people who would take out a loan to buy a gasoline vehicle
Pev = selling price of a new EV
Pg = selling price of a new gasoline vehicle

If the calculated value of Fev is greater than 1.00, 1.00 is used.

input 0.092 0.095 Real annual interest rate charged on new-car loans, before taxes

It seems reasonable to assume that interest rates for loans are a function of the total amount of money borrowed. If the introduction of electric vehicles increases the total demand for loaned money for automobiles, because of the higher initial cost of EVs, it is likely that interest rates will be higher than they otherwise would be. Given an interest rate on loans for the baseline gasoline vehicle, I calculate the interest rate on loans for the fuel cell vehicle as:

$$Iev = Ig \times ((Fev \times Pev \times (1-Dev))/(Fg \times Pg \times (1-Dg))^{0.25}$$

where:
Iev = real interest rate on loans for new electric vehicles
Ig = real interest rate on loans for new gasoline vehicles
Fev = fraction of people who would take out a loan to buy an EV (calculated above)
Fg = fraction of people who would take out a loan to buy a gasoline vehicle
Pev = selling price of a new EV
Pev = selling price of a new gasoline vehicle
Dev = fraction of selling price that is a downpayment, for EVs
Dg = fraction of selling price that is a downpayment, for gasoline vehicles

Note that because Fev and Fg cannot be greater than 1.00, and Fev is greater than or equal to Fg if Pev > Pg, as soon as Fev reaches 1.00, an increase in Fg results in no change in Fev, and hence in a decrease in Iev.

0.029 0.029 0.029 Real annual interest rate that would have been earned on cash used for transportation expenditures, after taxes

This interest rate is applied to all payments for the automobile -- to the loan payments as well as to the downpayment. -- in order to arrive at a total lifetime levelized monthly cost for the purchase of an automobile. First, the monthly loan payments are calculated using the loan rate, loan period, and amount of the loan. The present value of these payments is calculated, using the real annual interest rate that would have been earned on cash expenditures, and added to the actual downpayment. This total (downpayment plus present value of loan series) is then levelized over the life of the car (not the loan period, but the life of the car), using, again, the foregone real interest rate on cash. Note that the loan payment is simply a monthly bill, which must be handled using the foregone real annual interest rate on cash expenditures. The loan rate does not represent the consumer's opportunity cost of money; the foregone interest rate on cash does.

1.89 1.89 1.89 Ratio of selling price to manufacturing cost

The product of the ratio of the factory cost to the manufacturing cost, the ratio of the selling price to the factory cost, and the sales tax factor. Excludes the cost of shipping the vehicle.

NA 0.0966 0.0966 Capital charge rate, exc. property tax and insurance, and salvage value (levelization factor)

This calculated factor is used to levelize, or amortize, the initial investment in the hydrogen refueling station.

Table A.2. Cost and performance parameters for the reference gasoline ICEV, a year-2000 Ford Taurus.

The initial price of the gasoline vehicle ($): input data	
5,940	Cost of engine, transmission, fuel system (inc. fuel and tank), electrical system, exhaust and emission control, 1990 ($-manufacturer's suggested retail price [MSRP])
7,520	Cost of rest of vehicle, 1990 ($-MSRP)
350	Shipping cost of baseline gasoline vehicle ($)
1,460	Cost of options, new standard equipment, year 2000 ($-MSRP)
250	Cost of emission control equipment added through year 2000 ($-MSRP)
200	Cost of safety features added through year 2000 ($-MSRP)
500	Cost of engine and transmission fuel economy improvements through year 2000 ($-MSRP)
(50)	Cost of all other fuel economy improvements through year 2000 ($-MSRP)
Fuel economy parameters: input data	
22.0	Unadjusted EPA city-cycle fuel economy, 1990 (miles per gallon [mpg])
37.0	Unadjusted EPA highway-cycle fuel economy, 1990 (mpg)
0.145	Unadjusted efficiency of engine, EPA city cycle, 1990 (Btu/mi [engine-out] div. by Btu/mi [fuel- in], higher heating value [HHV])
0.200	Unadjusted efficiency of engine, EPA highway cycle, 1990 (Btu/mi [engine-out] div. by Btu/mi [fuel in], HHV)
0.80	In-use mpg divided by EPA unadjusted mpg, city driving, year 2000
0.77	In-use mpg divided by EPA unadjusted mpg, highway driving, year 2000
0.68	Miles of city driving divided by total miles of driving, year 2000
17.0	Average speed in city driving, year 2000
45.0	Average speed in highway driving, year 2000
0.33	Coefficient of drag (Cd), year 1990
0.28	Coefficient of drag (Cd), year 2000
1.17	Year-2000 unadjusted city-cycle engine efficiency divided by year-1990 efficiency
1.12	Year-2000 unadjusted highway-cycle engine efficiency divided by year-1990 efficiency
1.05	Efficiency improvement due to better transmission, tires, accessories
0.93	Efficiency of transmission, year 2000
0.55	Percent decrease in fuel consumption per 1.0% decrease in vehicle weight
0.12	Percent decrease in unadjusted fuel consumption per 1.0% decrease in Cd, city cycle
0.35	Percent decrease in unadjusted fuel consumption per 1.0% decrease in Cd, highway cycle
Weight and performance parameters: input data	
145	Power of engine, year 2000 (hp)
1,070	Curb weight of engine, transmission, fuel system (inc. fuel and tank), exhaust, emission control, electronics, 1990 (lbs)
2,080	Curb weight of rest of vehicle, 1990 (lbs)
(100)	Weight reduction of engine, transmission, through year 2000 (lbs)
(240)	Weight reduction of rest of vehicle, through year 2000 (lbs)
60	Weight increase due to extra emission controls and safety equipment through year 2000 (lbs)
60	Weight increase due to improved options and other luxury features (lbs)
0.40	Fuel level assumed for weight calculations (fraction of capacity)
0.1250	Higher heating value of gasoline (million Btu/gal)
Other cost parameters (year 2000): input data	
120,000	Life of the vehicle to scrappage or resale (mi)
0.005	Vehicle salvage or resale value (fraction of full selling price of new vehicle)

47.08	Insurance payments, for first n years with coverage for damage to own vehicle ($/month)
5.00	Length of time carrying insurance against damage to own vehicle (yrs, n)
26.50	Insurance payments after collision-damage coverage is dropped ($/month)
100.00	Insurance deductible ($)
45,000	Occurrence of first accident in which deductible must be paid (total miles on car)
7.50	Parking and tolls ($/month)
250.00	Cost of four replacement tires, including taxes ($/set of four)
45,000	Life of tires (mi)
20.00	Cost of accessories ($/yr.)
12.19	Cost of oil ($/yr.)
25.00	Vehicle registration fee ($/yr.)
40.00	Fee for vehicle inspection, including inspection of pollution control equipment ($/yr.)
The price of gasoline (year 2000): input data	
26.40	Price paid by refiners for crude oil ($/bbl)
0.90	Fraction of a gallon of gasoline derived from crude oil
0.25	Refinery cost of making standard gasoline ($/gal)
0.15	Incremental cost of making reformulated gasoline ($/gal)
0.13	Cost of gasoline storage and distribution ($/gal)
0.08	Retail station mark-up, exc. all taxes ($/gal)
0.31	Federal, state, & local gasoline taxes ($/gal)
Cost parameters: calculated results	
13,460	Manufacturer's suggested retail price (MSRP), exc. options, shipping charges, taxes, year 1990 ($)
17,302	The full selling price of the vehicle, inc. taxes and fees, year 2000 ($)
46.14	Cost of engine, transmission, fuel system (inc. fuel and tank), electrical system, exhaust and emission control, 2000 ($-MSRP/hp-engine)
11,086	Distance driven per year, with "mileage" discount rate applied (mi)
10.8	Age of vehicle when it is scrapped or sold (yrs)
515.86	Levelized maintenance costs ($/yr.)
1.49	Selling price of gasoline, inc. all retail taxes ($/gal)
Fuel economy parameters: calculated results	
20.1	Lifetime-average in-use fuel economy, year 1990 (mpg)
28.5	Unadjusted EPA city-cycle fuel economy, year 2000
47.6	Unadjusted EPA highway-cycle fuel economy, year 2000
25.9	In-use combined city and highway fuel economy, year 2000 (mpg)
0.158	Efficiency of engine & transmission, unadjusted EPA city cycle, year 2000 (Btu/mi basis)
0.208	Efficiency of engine & transmission, unadjusted EPA highway, year 2000 (Btu/mi basis)
0.137	Efficiency of engine & transmission, in-use city & highway cycle, year 2000 (But/mi basis)
Weight and performance parameters: calculated results	
100.6	Maximum power delivered to wheels, when not using air conditioning (kW)
0.045	Power-to-weight ratio of gasoline vehicle, year 2000 (engine-hp/lb-loaded-driving-weight)
3,150	Curb weight of vehicle, year 1990 (no payload, full fuel tank) (lbs)
2,930	Curb weight of the vehicle, year 2000 (no payload, full fuel tank) (lbs)
3,023	Actual EPA test weight of vehicle, year 2000 (one passenger, 40% full gasoline tank) (lb)
3,230	Loaded driving weight of vehicle, year 2000 (curb weight plus 300 lbs)
38.0	Weight of gasoline tank (lbs)
95.0	Weight of full amount of gasoline (lbs)
21.2	Average driving speed, over life of vehicle (mph)

Documentation to Table A.2.

5,940 Cost of engine, transmission, fuel system (inc.fuel and tank), electrical system, exhaust and emission control, 1990 ($-manufacturer's suggested retail price [MSRP])

7,520 Cost of rest of vehicle, 1990 ($-MSRP)

Lindgren has provided a detailed cost breakdown of the components in a 1989 Ford Taurus, in 1989 dollars (ACEEE, 1990). According to Lindgren's analysis, the engine, transmission, engine electrical system, fuel injection and emission system, final drive, exhaust system, catalytic converter, fuel system, fluids, and battery contributed $5714 to the MSRP. In 1990$, this would be about $5,940. The rest of the standard vehicle contributed $7,244 in 1989$, or $7520 in 1990$. The total MSRP, which excludes shipping charges, options, and taxes, would be $13,460 for the 1990 Taurus. According to the *1991 Market Data Book* (1991), the 1991 Taurus has a MSRP of $13,934. This is consistent with a 4% inflation rate between 1990 and 1991. The final selling price of the 1990 Taurus, with a $350 shipping fee, $1000 worth of options, and 7% sales tax, would be $15,850. This is very close to the average selling price for new cars in 1990: according to Moran (1990), by the middle of 1990, consumers were paying on average about $16,000 for a new car, including sales taxes, options, premiums, and discounts (Moran, 1990). Thus the Ford Taurus will nicely represent the typical automobile purchase in 1990.

Lindgren's cost breakdown for the Taurus is similar to his breakdown for two other vehicles, a Caprice and an Escort. More importantly, all of Lindgren's estimates are consistent with independent cost breakdowns estimated for different vehicles by Gladstone et al. (1982). The following table summarizes the Lindgren and Gladstone et al. manufacturing cost estimates. Note that there is very good agreement on the most important number, the ratio of the cost of the parts removed from an ICEV (to make an EV) to the cost of the entire vehicle (about 0.40).

Summary of studies of the manufacturing cost of automobiles

	Gladstone et al. (1982)		Lindgren (ACEEE, 1990)		
	Citation	Reliant	Escort	Taurus	Caprice
Cost of removed ICE parts/cost of vehicle	0.384	0.399	0.376	0.441	0.412
Assembly cost/ cost of vehicle	0.278	0.266	0.287	0.210	0.206
MSRP (1989$)	9,300	9700	9,300	12944	15125
Weight (lbs)	2507	2580	2230	3244	3978
Horsepower	n.s.	n.s.	90	140	170

MSRP estimates in Gladstone et al. (1982) updated from 1982$ to 1989$ using GNP price deflators. n.s. = not specified.

350 Shipping cost of baseline gasoline vehicle ($)

From Lindgren (1991).

1,460 Cost of options, new standard equipment, year 2000 ($-MSRP)

I assume that by the year 2000, anti-lock, anti-skid brakes, which are options on the 1991 Taurus, will be standard equipment, and will add $260 to the MSRP (Lindgren, 1991). Note that as options on the 1991 Taurus, anti-lock brakes cost $950 (*1991 Market Data Book*, 1991).

According to the *1991 Market Data Book* (1991), air conditioning on the Taurus costs $800. A driver's side air bag and an automatic transmission are standard equipment on the 1991 Taurus, and as mentioned above, I have assumed that anti-lock, anti-skid brakes will be standard equipment by the year 2000. I assume that the typical buyer would opt for air conditioning and a few other options (e.g., a better stereo system) that all together would cost $1,200. The total cost of options and new standard equipment would be $1460.

250 Cost of emission control equipment added through year 2000 ($-MSRP)

The 1990 amendments to the Clean Air Act require significant reductions in tailpipe emissions from motor vehicles (EPA, 1990). In addition, EPA is likely to tighten the test procedure for evaporative emissions. To meet the new standards, vehicles in the year 2000 will have onboard refueling controls; a larger or additional catalytic converter, with an electric heating to reduce cold-start emissions; and a larger evaporative-emissions canister. A consultant to the automotive industry estimates that these will add about $250 to the MSRP. The EPA, which understandably tends to produce relatively low estimates of the cost of pollution control, estimates that the Clean Air Act Amendments will add $150 (Walsh, 1992) to $200 (Schaefer, 1991) to the price of a new vehicle. To meet even lower emission standards, such as the "ultra-low-emissions-vehicle" (ULEV) standards adopted in California, probably would add at least $500 to the MSRP.

200 Cost of safety features added through year 2000 ($-MSRP)

I assume that future side-impact requirements (U. S. Congress, 1991) and other forthcoming safety requirements will add $200 to the price of the vehicle by the year 2000 (1990$). This figure appears to be in line with the cost of safety requirements during the 1980s (MVMA, 1990).

500 Cost of engine, transmission fuel economy improvements through year 2000 ($-MSRP)

In its assessment of the potential to improve the fuel economy of LDVs, the Office of Technology Assessment (OTA) (U. S. Congress, 1991) has hypothetically redesigned the Ford Taurus for high efficiency in the year 2000. I follow their analysis, and assume that a 2.0 liter, 4-valve, 4-cylinder overhead-cam engine with electronic valve control replaces the current 3.0 liter, 2-valve, 6-cylinder pushrod engine; that the compression ratio is increased from 9.3 to 10:1; that advanced engine friction reduction is used; that the engine is made out of aluminum; and that a 5-speed automatic transmission with electronic control replaces the 4-speed automatic. Note that OTA considers this to represent the "maximum technology" scenario for the Taurus for the year 2001. Cost estimates for these changes are:

Increment to MSRP of fuel-economy improving technologies (1990$)[a]

Technology / Estimate by:[b]	Lindgren	EEA	ACEEE
4-valve, DOHC, RCF, intake valve control replaces 2-valve, pushrod, no valve control	630	440	285
5-speed auto. trans. w/lock-up, elect. control, replaces 4-speed auto. trans. w/lock-up	648	134	219
advanced friction reduction	24+	33	83
compression ratio from 9.3 to 10	n.e.	n.e.	n.e.
aluminum engine	~75[c]	n.e.	n.e.
4 cylinder replaces 6 cylinder	~(400)[c]	n.e.	n.e.

[a]DOHC = direct-overhead-cam engine. RCF = roller-cam followers. n.e. = not estimated. EEA = Energy and Environmental Analysis. ACEEE = American Council for an Energy-Efficient Economy.

[b]Lindgren is ACEEE (1990); OTA is U. S. Congress (1991); ACEEE is Ledbetter and Ross (1990). I have updated Ledbetter and Ross (1990) and Lindgren (ACEEE, 1990) estimates from 1989$, and EEA estimates from 1988$, to 1990$ using the GNP implicit price deflator. Ledbetter and Ross estimates are based on earlier estimates by EEA, and by the estimates provided by Lindgren. Some EEA estimates may be based on Lindgren's work.

[c] = my estimate based on data in Lindgren.

Unfortunately, these estimates are all over the map. The discrepancies are due to different baselines, different cost-estimation methods (e.g. top down vs. bottom up), different technologies included under generic headings (e.g., "friction reduction"), and other factors. I am unable to fully reconcile all the differences. I assume that on balance, including the cost reduction realized by going from a 6-cylinder to a 4-cylinder engine, the net increase in the MSRP would be $500.

(50) Cost of all other fuel economy improvements through year 2000 ($-MSRP)

OTA (U. S. Congress, 1991) assumes that its hypothetical, maximally efficient year-2001 Taurus would use lightweight plastics in place of some of the metal in the 1990 model, have a drag coefficient (Cd) of 0.30 (vs. 0.33 for the 1990 model), and have more efficient tires than the 1990 model. I follow the OTA analysis, except, as explained below, that I assume a CD of 0.28 instead of 0.30.

Vehicle weight: Ledbetter and Ross (1990) note that greater use of aluminum and reinforced plastics could reduce the weight of an ICEV by 10% by the year 2000, at a cost to the consumer of $250. However, this cost increase probably is due to increased use of aluminum, which is expensive, and not to increased use of plastic/composite materials. EEA (1990) also notes that the use of plastic/composite materials in the body, chassis, and bumpers of vehicles could reduce the weight of the vehicle by more than 10%.

The substitution of plastic/composite materials for steels probably would not increase the cost of the vehicle. Lindgren's analysis (ACEEE, 1990) indicates that more extensive use of plastic/composite material in the Ford Taurus actually would *reduce* the retail price of the vehicle by $300, as well as reduce the weight. Similarly, EEA (1990) cites a GM estimate that a plastic/composite bumper would cost less than the standard bumper. However, large-scale use of plastic/composite materials in the automotive industry likely would drive up the price of these materials, so that the cost reduction for the Taurus might be on the order of $100 to $200, instead of $300.

Aerodynamic drag: Ledbetter and Ross (1990) estimate that reducing the Cd from 0.37 to 0.30 would add $83 to the price of the vehicle (1990$). EEA (U. S. Congress, 1991) estimates that going from 0.33 to 0.30 would add only $17 to the price of a vehicle. I assume that reducing the Cd from 0.33 to 0.28 would add about $50 to the price of the vehicle. EEA (U. S. Congress, 1991) and Ledbetter and Ross (1990) estimate that improved tires would add $30 to $40 to the retail price. Lindgren's analysis (ACEEE, 1990) indicates that advanced tires could cost several hundred dollars more than current tires, but I assume that at such high prices the tires would not improve fuel economy cost-effectively and would not be bought. Improvements in the efficiency of accessories would add about $20 to the price of the vehicle (Ledbetter and Ross, 1990; U. S. Congress, 1991; according to Lindgren, some improvements actually would save money).

Total cost: If improved tires, aerodynamics, and accessories would increase the MSRP of the Taurus by about $100, but the use of plastic materials would reduce it by, say, $150, then on balance the cost of these changes would be a savings of $50.

22.0 Unadjusted EPA city-cycle fuel economy, 1990 (miles per gallon [mpg])

37.0 Unadjusted EPA highway-cycle fuel economy, 1990 (mpg)

These are the midrange values reported for the 3.0-liter, 4-speed Taurus sedan in the EPA's test list for new cars, and in the *1991 Market Data Book* (1991).

0.145 Unadjusted efficiency of engine, EPA city cycle, 1990 (Btu/mi [engine-out] div. by Btu/mi [fuel- in], HHV)

0.200 Unadjusted efficiency of engine, EPA highway cycle, 1990 (Btu/mi [engine-out] div. by Btu/mi [fuel in], higher heating values [HHV])

Using the model and model parameters described in An and Ross (1991), I calculate that the four baseline vehicle engines modeled by An and Ross are from 13 to 16% efficient over the urban driving cycle, and 18 to 22% efficient over the highway driving cycle (HHV basis). An and Ross' "average-power" vehicle, which has specifications very similar to those of the Ford Taurus, is 13.4% efficient in the city cycle, and 17.8% efficient in the highway cycle. However, their average-power vehicle is the least efficient of all the vehicles in the analysis -- less efficient even than the high-power vehicle. My calculations using the An and Ross model indicate that their average-power vehicle violates what appears to be a general inverse relationship between power and efficiency. If the efficiency of the average-power vehicle were in line with the general efficiency from the least powerful to the most powerful vehicle, it would be about 14.5% in the city cycle, and 20% in the highway cycle.

These figures are consistent with other estimates in the literature. Brogan and Venkateswaran (1991) project that a "near-term" 4-stroke spark-ignition gasoline engine will be 16.0% efficient over the urban driving cycle, and that a "long-term" 4-stroke spark-ignition gasoline engine will be 17.6% efficient over the urban drive cycle. I assume that these values have been calculated on a lower-heating-value basis, so that on a higher-heating-value basis the figures would be 14.7% for the near-term engine and 16.2% for the long-term engine.

0.80 In-use mpg divided by EPA unadjusted mpg, city driving, year 2000

0.77 In-use mpg divided by EPA unadjusted mpg, highway driving, year 2000

The "unadjusted" city and highway fuel-economy figures reported by EPA are the unadjusted results of specific drive-cycle tests on a dynamometer. These unadjusted test results, of course, do not necessarily represent the actual fuel economy that vehicles would achieve in real use. In the real world, vehicles are driven differently than on the dynamometer, and in ways that tend to reduce fuel economy. To account for this discrepancy, the EPA adjusts the dynamometer results to obtain an estimate of the in-use fuel economy: the unadjusted city-cycle fuel economy is reduced by 10%, and the unadjusted highway fuel economy is reduced by 22%. However, it is now widely believed that the adjustment factors are too small -- that is, that the gap between test-cycle and in-use fuel economy is greater than 10% in the urban cycle, and 22% in the highway cycle (U. S. Congress, 1991; EIA, 1990c; Ross, 1989). OTA (U. S. Congress, 1991) analyzes a recent estimate of the gap between in-use and test fuel economy, and implies that increasing urban congestion will further increase the gap between in-use and test-cycle urban fuel economy by about 10 percentage points (to about 20%), and that increasing highway speeds will further degrade the highway-cycle gap by about a percentage point (to 23%).

0.68 Miles of city driving divided by total miles of driving, year 2000

The EPA estimates fuel economy in *combined* city and highway driving by assuming that 55% of all driving is done on urban roads. However, OTA (U. S. Congress, 1991) reports that in 1987 63% of all miles driven were on urban roads, and estimates that by the year 2010 72% will be done on urban roads. I interpolate between these values for the year 2000.

Note that since the city/highway fraction is expressed in terms of mileage, it must be applied to a Btu/mi or a kWh/mi figure, not to a mi/Btu, mpg, or mi/kWh figure. On the other hand, the test-cycle-to-in-use adjustment factor applies to mpg, or mi/Btu or mi/kWh, not the inverse.

17.0 Average speed in city driving, year 2000
45.0 Average speed in highway driving, year 2000

The average speed in the city-cycle fuel economy test is 19.6 mph; in the highway-cycle test, 48.3 mph. However, as noted above, because of congestion real speeds are lower than in the tests, and are expected to decline further. The numbers shown here are my estimate of the real or in-use average speeds in the year 2000.

0.33 Coefficient of drag (Cd), year 1990
0.28 Coefficient of drag (Cd), year 2000

As noted above, I think that OTA's (1991) assumption of a Cd of 0.30 for the year-2001 Taurus is too conservative. I assume 0.28 instead. EEA's (1990) analysis suggests that it should not be difficult to achieve a Cd of 0.28 in the Taurus; in fact, EEA projects that the fleetwide average Cd will be between 0.20 and 0.24 in the year 2010. An and Ross (1991) state that new cars have a coefficient of drag (Cd) of about 0.35, and believe that in the 1990s many cars will have a Cd below 0.30. Bentley and Teagan (1992) and Bentley et al. (1992) assume a Cd of 0.29 for the Taurus in the year 2001.

1.17 Year-2000 unadjusted city-cycle engine efficiency/year-1990 efficiency
1.12 Year-2000 unadjusted highway-cycle engine efficiency/year-1990 efficiency

In the An and Ross (1991) analysis, the overall efficiency of the engine (e.g., 15% in the urban cycle) is the product of the thermal efficiency and the mechanical efficiency, which are approximately equal. The thermal efficiency of the engine can be increased by increasing the compression ratio, increasing the air/fuel ratio, and recovering energy from the exhaust (An and Ross, 1991). However, in a standard 4-stroke, spark-ignition, gasoline-fueled engine, the compression ratio is limited by the ability of the gasoline to resist preignition, and the air/fuel ratio is limited by the NO_x emission standard. Two-stroke, spark-ignition gasoline engines and compression-ignition diesel-fuel engines are more thermally efficient than four-stroke spark-ignition gasoline engines, but will have a difficult time meeting all future emission standards. Therefore, I follow Energy and Environmental Analysis (1990) and assume only a 2% improvement in thermal efficiency by the year 2000.

Estimating the potential improvement in mechanical efficiency is tougher. An and Ross (1991) estimate that by reducing pumping losses, reducing the displacement of the engine (while maintaining maximum power), reducing the friction of the engine, and using stop-start (idle-off) and aggressive transmission management, the mechanical efficiency could be increased by 42-66% in the urban cycle and 28 to 45% in the highway cycle, depending on the characteristics of the baseline vehicle. The biggest gains would be provided by reducing the displacement of the engine (while maintaining the same maximum power) and using idle-off and aggressive transmission management. However, it seems likely that idle-off will not be used (see Energy and Environmental Analysis, 1990), and that engine displacement will decline only slightly (engine size has not changed much over the last five years [Heavenrich et al., 1991]). Moreover, the base-case 1990 vehicle assumed here already is relatively efficient. I therefore assume a 15% improvement in mechanical efficiency in the urban driving cycle, and a 10% improvement in mechanical efficiency in the highway driving cycle, for the year 2000. Bentley et al. (1992) assume only a 10% improvement in the Taurus' "engine/driveline efficiency" by the year 2001.

Overall, then, I assume that engine efficiency improves by 1.15 x 1.02 = 17% in the city cycle, and by 1.10 x 1.02 =12% in the highway cycle.

1.05 Efficiency improvement due to better transmission, tires, accessories

This is my estimate, based on data in Ledbetter and Ross (1990) and EEA (1990).

0.93 Efficiency of transmission, year 2000

Brogan and Venkateswaran (1991) assume an efficiency of 85%. An and Ross (1991) assume 85 to 95%. The efficiency of front-wheel drive probably is closer to 95%.

0.55 Percent decrease in fuel consumption per 1.0% decrease in vehicle weight

Based on estimates in Energy and Environmental Analysis (1990) and DeLuchi (1991).

0.12 Percent decrease in unadjusted fuel consumption per 1.0% decrease in Cd, city cycle

0.35 Percent decrease in unadjusted fuel consumption per 1.0% decrease in Cd, highway cycle

From EEA (1990). Ledbetter and Ross (1990) estimate that reducing the coefficient of drag from the 1987 value of 0.37 to 0.30 in the year 2000 would improve combined city/highway fuel economy by 4.6%, which implies a sensitivity factor of 0.24.

145 Power of engine, year 2000 (hp)

This is OTA's (1991) estimate for the maximally efficient year-2001 Ford Taurus.

1,070 Curb weight of engine, transmission, fuel system (inc. fuel and tank), exhaust, emission control, electronics, 1990 (lbs)

2,080 Curb weight of rest of vehicle, 1990 (lbs)

These estimates are based on Lindgren's (ACEEE, 1990) detailed component-by-component weight and cost analysis for the 1989 Ford Taurus.

(100) Weight reduction of engine, transmission, through year 2000 (lbs)

(240) Weight reduction of rest of vehicle, through year 2000 (lbs)

60 Weight increase due to extra emission controls and safety equipment through year 2000 (lbs)

60 Weight increase due to improved options and other luxury features (lbs)

These estimates are based primarily on the analysis in OTA (1991).

0.40 Fuel level assumed for weight calculations (fraction of capacity)

This is the level used in the loaded-driving-weight EPA fuel economy and emissions tests.

0.1250 Higher heating value of gasoline (million Btu/gal)

The average heating value of gasoline, as reported by the U. S. Energy Information Administration and others (see DeLuchi, 1991, for references).

120,000 Life of the vehicle to scrappage or resale (mi)

The FHWA (USDOT, 1984) says that "recent data" indicate that automobiles are staying on the road 12 years and 120,000 miles. Oak Ridge National Lab estimates that 50% of automobiles are scrapped when they are 11.8 years old, and that automobiles travel an average of 10,200 miles/year over their lifetime (Davis and Morris, 1992). This results in an average lifetime travel of 120,360 miles. Data from the California Air Resources Board (CARB, 1988) data indicate that vehicles have traveled 116,000 miles when they are 12 years old.

0.005 ***Vehicle salvage or resale value (fraction of full selling price of new vehicle)***

I assume that at the end of its life a vehicle is worth between $50 and $100 for parts. This is about 0.5% of the initial value of the car.

47.08 ***Insurance payments, for first n years with coverage for damage to own vehicle ($/month)***

5.00 ***Length of time carrying insurance against damage to own vehicle (yrs, n)***

26.50 ***Insurance payments after collision-damage coverage is dropped ($/month)***

The FHWA (USDOT, 1990) estimated that in 1984 collision-damage insurance for a mid-size car cost $24.92/month, and for a compact car, $15.16/month. They estimated that insurance against liability, property damage, personal injury, and uninsured motorists cost $36.08 for the mid-size car and $29.58 for the compact. The MVMA (1990) cited estimates by the American Automobile Association (which in turn got its data from Runzheimer International) that in 1990 collision-damage insurance cost $21.58 /month, property-damage and liability insurance cost $26.50/month, and fire and theft insurance cost $9.16/month. The MVMA and FHWA estimates of the cost of collision-damage insurance are very close. The estimates of the cost of the other kind of insurance also are close, when one accounts for the differences in assumed coverage.

It appears, though ,that consumers actually spend less on insurance than estimated by FHWA and MVMA. According to U. S. Department of Labor surveys of actual consumer expenditures (USDL, 1991), households in 1989 had 2.0 vehicles and spent about $290/year to insure them both -- about $24 per month per vehicle. This total is much less than that estimated by FHWA and MVMA, probably because some vehicles are not insured at all and many carry much less coverage than assumed by FHWA and MVMA.

In this analysis I use the MVMA estimates, except that I assume that the motorist does not carry insurance against theft and fire.

The FHWA (USDOT, 1984) assumes that collision-damage insurance is carried for 5 years. I use their assumption.

100.00 ***Insurance deductible ($)***

In its analysis of the cost of owning and operating cars and trucks, FHWA (USDOT, 1984) assumed that the deductible amount from insurance coverage "usually" was $100. However, the MVMA (1990) cites estimates by the American Automobile Association (which in turn got its data from Runzheimer International) that the deductible from collision-damage insurance was $250 from 1978 to 1990.

45,000 ***Occurrence of first accident in which deductible must be paid (total miles on car)***

As mentioned below in Appendix B, the FHWA (USDOT, 1984) apparently assumed that typically a vehicle owner will cause an accident and hence have to pay his or her insurance deductible in the fourth year of life of the vehicle . This seems plausible. In the fourth year of life the vehicle will have accumulated at least 40,000 miles.

7.50 ***Parking and tolls ($/month)***

The FHWA (USDOT, 1984) estimated that in 1984 drivers spent an average of $7.84/month on parking on tolls over the life of the car.

250.00 ***Cost of four replacement tires, including taxes ($/set of four)***

My estimate, based on 1990 tire prices in Sacramento, California.

45,000 ***Life of tires (mi)***

My estimate, based on current tire life.

20.00 ***Cost of accessories ($/yr.)***

The FHWA (USDOT, 1984) estimated that in 1984 owners of mid-size automobiles spent $16.50/year on vehicle accessories. This would be $20/year in 1990$.

12.19 ***Cost of oil ($/yr.)***

I assume that a quart of oil is consumed every 1000 miles (including oil changes), and that oil costs $1.10/quart, including taxes. Given the estimated mileage per year (see Table A.2), the result is $12.19/year.

25.00 ***Vehicle registration fee ($/yr.)***

The average fixed registration fee in the U.S., for the 20 states with fixed fees, is about $22. The average weight-based fee for a 3000 lb. vehicle, in 24 states, is $23. The remaining 6 states have value-based fees, ranging up to 4% of value, with an average of 2.75% (IntelliChoice, 1988). I use a weight-based fee, because it is the most common, it produces results close to the average fixed fee, and has a solid rationale (road damage is proportional to weight). The cost program assumes a $25 dollar yearly fee for the baseline passenger ICEV, and increases the EV registration fee, compared to the ICEV registration fee, in proportion to the extra weight of the EV.

40.00 ***Fee for vehicle inspection, including inspection of pollution control equipment ($/yr.)***

An increasing number of states are requiring I&M of pollution control equipment. The new Clean Air Act Amendments (EPA, 1990) require inspection and maintenance in ozone nonattainment areas; the further from attainment, the more stringent the I&M requirement. In California the inspection is every two years, and costs about $35 if the car passes the first time. If the vehicle fails and has to be fixed, but has not been tampered with, the owner is required to spend several hundred dollars to repair it. If the pollution control equipment has been tampered with, the owner must pay all repair costs. BPEVs and Hydrogen FCEVs will not have any pollution control equipment, and hence will not be subject to I&M.

50.00 ***Price of gasoline tank, excel. sales tax (addition to vehicle retail price, $)***

Based on data provided by Lindgren (ACEEE, 1990).

26.40 ***Price paid by refiners for crude oil ($/bbl)***

Price projected by the EIA (1992) for the year 2000.

0.90 ***Fraction of a gallon of gasoline derived from crude oil***

Based on the analysis in DeLuchi (1991).

0.25 ***Refinery cost of making standard gasoline ($/gal)***

This is the cost indicated by the difference between the refinery wholesale gasoline price and the refinery crude acquisition price (EIA, 1990b).

0.15 ***Incremental cost of making reformulated gasoline ($/gal)***

ARCO (Boekhaus et al, 1990; *Clean Fuels Report*, 1991; Walsh, 1992) estimates that reformulated gasoline will add about $0.15 to the price of gasoline. The Interagency Commission on Alternative Motor Fuels (1991) estimates that reformulation will add 10 to 20 cents to the price of gallon of gasoline in the year 2000.

0.13 ***Cost of gasoline storage and distribution ($/gal)***
0.08 ***Retail station mark-up, excel. all taxes ($/gal)***

Morris and Bollman (1991) estimate that in 1998 the wholesale distribution and storage mark-up will be 12 cents/gallon, and the retail mark-up 5 cents gallon. Dougher and Jones (1990) estimate 13 cents/gallon for the wholesale mark up, and 8 cents/gallon for the retail mark up. The USDOE (1991c) reports a retail station markup of 9 cents/gallon.

0.31 ***Federal, state, & local gasoline taxes ($/gal)***

This is equal to total motor fuel tax receipts (Federal plus state plus local taxes) divided by total gallons taxed in the U. S., in 1990 (FWHA, 1991).

13,460 ***Manufacturer's suggested retail price (MSRP), excel. options, shipping charges, taxes, year 1990 ($)***

The cost of the whole vehicle, excluding options, in 1990: the cost of the engine, transmission, fuel system, electrical system, exhaust and emissions-control system, plus the cost of the rest of the vehicle.

17,302 ***The full selling price of the vehicle, inc. taxes and fees, year 2000 ($)***

The MSRP in 1990, plus the cost of shipping, the cost of options, and the cost of safety, fuel economy, and emissions changes between 1990 and 2000, multiplied by the sales tax factor.

46.14 ***Cost of engine, transmission, fuel system (inc. fuel and tank), electrical system, exhaust and emission control, 2000 ($-MSRP/hp-engine)***

The Jet Propulsion Laboratory's (JPL) Advanced Vehicle Assessment (Hardy, 1985) indicates a cost of at least $40-MSRP/hp for parts removed from an ICEV. A cost program developed by JPL for the USDOE actually indicates substantially *higher* manufacturing costs for engines and transmissions than are calculated here (Humphreys and Brown, 1990).

515.86 ***Levelized maintenance costs ($/yr.)***

See Appendix B.

0.158 ***Efficiency of year-2000 engine and transmission, unadjusted EPA city cycle***

0.208 ***Efficiency of year-2000 engine and transmission, unadjusted EPA highway cycle***

The estimate of the year-2000 efficiency in the city cycle is very close to the estimate by Bentley et al. (1992). Bentley et al. (1992) estimate an "effective driveline efficiency" for the Ford Taurus of 0.132, in the year 1992, over the EPA composite city/highway cycle. Their estimate is based on the lower heating value of gasoline and in-use fuel economy (which they assume is 15% lower than test-cycle fuel economy). Using the higher heating value and the unadjusted fuel economy, their estimate would be about 0.142 for 1992. They assume a 10% improvement by the year 2001, resulting in a driveline efficiency of 0.156.

0.045 ***Power-to-weight ratio of gasoline vehicle (engine-hp/lb-loaded-driving-weight)***

This is a relatively high power-to-weight ratio. For the 1991 model year, the ratio stood at 0.0369 hp/lb for the 2500-lb class, 0.0367 for the 2750-lb class, 0.0422 for the 3000-lb weight class, and 0.0447 for the 3500-lb class (Heavenrich et al., 1991). The ratio has been rising steadily for most weight classes.

Table A.3. Parameters for the fuel-cell and battery-powered vehicle.

FCEV	BPEV	Vehicle initial cost and operating costs: input data
20.00	20.00	Cost of electric motor, electronics package, transaxle, and miscellaneous parts ($-OEM/max.-kW-motor)
500	500	Cost constant for electric drivetrain ($-OEM)
0.90	0.90	OEM cost of adding extra structural support ($/lb)
0.00	0.00	Cost of oil (fraction of oil cost of gasoline ICEV)
1.33	1.33	Ratio of life of EV or FCEV to life of ICEV (mileage basis)
6.50	6.50	Length of time carrying insurance against damage to own vehicle (yrs)
0.75	0.75	Scheduled maintenance cost of the EV, excluding the fuel cell and hydrogen storage system (fraction of the scheduled maintenance cost of an ICEV)
0.60	0.60	Unscheduled maintenance cost of the EV, excluding the fuel cell and hydrogen storage system (fraction of the scheduled maintenance cost of an ICEV)
0.10	0.10	Annual maintenance cost of fuel cell stack and auxiliaries (fraction of annual maintenance cost of BPEV)
0.06	0.06	Annual maintenance cost of reformer and auxiliaries (fraction of annual maintenance cost for a BPEV)
0.02	0.02	Annual maintenance cost of hydrogen storage system (fraction of annual maintenance cost of BPEV)
0.50	0.50	Inspection and maintenance fee (fraction of gasoline vehicle $/yr. fee)
1.00	1.00	Tax analog of retail tax on gasoline (cents/mi, relative to gasoline tax in cents/mi)
Vehicle efficiency parameters: input data		
0.89	0.89	Once-through efficiency of electric motor, EPA unadjusted city-cycle efficiency (But/mi basis)
0.92	0.92	Once-through efficiency of electric motor, EPA unadjusted highway-cycle efficiency (Btu/mi basis)(
0.94	0.94	Once-through efficiency of motor controller & inverter (electronics) (Btu/mi basis)
0.95	0.95	Once-through efficiency of motor-to-wheels transmission (Btu/mi basis)
0.135	0.135	Fraction of once-through city-cycle energy returned from battery or fuel cell back through the battery to the battery terminals by regenerative braking.
0.018	0.018	Fraction of once-through highway-cycle energy returned from battery or fuel cell back through the battery to the battery terminals by regenerative braking.
0.90	0.90	In-use mi/kWh divided by EPA unadjusted mi/kWh, city driving, year 2000
0.77	0.77	In-use mi/kWh divided by EPA unadjusted mpg, highway driving, year 2000
Vehicle weight and performance parameters: input data		
0.80	0.80	High-end acceleration of EV relative to high-end acceleration of ICEV
26.8	26.8	Speed at which acceleration of EV and ICEV are compared (meters/s)
0.50	0.50	Maximum power required by vehicle accessories, excel. air conditioning (kW)
4.35	4.35	Weight-to-power ratio of added EV components: motor, electronics, transaxle, etc. (lb/kW-max.-from-motor)
0.06	0.06	Weight compounding factor (lbs extra structure per lb additional vehicle weight)
0.05	0.05	Reduction in weight of chassis, body, and interior of EV, compared to ICEV (fraction of curb wt. of ICEV)
(100)	(100)	Cost of extra weight reduction measures in the EV, beyond those used in baseline ICEV ($)
0.23	0.23	Coefficient of drag (Cd)
200	200	Cost of difference between Cd of EV and Cd of baseline ICEV ($-MSRP)
250	250	Minimum acceptable total vehicle range, using fuel cell and battery (mi)
Vehicle initial cost and operating costs: calculated results		
11.2	11.2	Age of vehicle when it is scrapped or sold (yrs)
73.07	77.36	Insurance payments for first n years, with coverage for damage to own vehicle ($/month)

434.16	387.64	Levelized maintenance costs ($/yr.)
159,600	159,600	Life of the vehicle to scrappage or resale (mi)
14,270	14,270	Distance driven per year, with "mileage" discount rate applied (mi)
309	367	Shipping cost for electric vehicle ($)
(3,082)	(2,653)	MSRP of added EV equipment minus MSRP of removed ICEV equipment ($, exc. retail tax)
14,053	14,622	Selling price of the EV, excel. battery, fuel cell, & fuel storage, but inc. sales tax ($)
25,446	28,247	Full retail price of complete EV, inc. taxes ($)
Vehicle efficiency parameters: calculated results		
0.90	0.90	Net efficiency of motor, electronics, transmission, EPA unadjusted city cycle (Btu/mi basis)
0.84	0.84	Net efficiency of motor, electronics, transmission, EPA unadjusted highway cycle (Btu/mi basis)
0.69	0.69	Average in-use once-through efficiency of motor, electronics, and transmission system
707	771	Vehicle efficiency, EPA unadjusted city cycle (net Btu/mi, based on net energy from the battery or fuel cell)
574	629	Vehicle efficiency, EPA unadjusted highway cycle (net Btu/mi, based on net energy from the battery or fuel cell)
4.42	4.05	Vehicle efficiency, in-use city & highway driving (mi/kWh from the battery or fuel cell terminals; based on net kWh from battery, after regenerative braking)
3.59	3.28	Vehicle efficiency on battery, in-use city & highway driving (mi/kWh from the outlet)
592	n/a	Vehicle efficiency on fuel cell, in-use city & highway driving (mi/million Btu-fuel, HHV)
0.347	0.614	Net efficiency of powertrain, inc. battery or fuel cell, in-use city & highway driving (Btu/mi basis)
Vehicle range, power, and weight: calculated results		
196	0	Required vehicle range on fuel cell and hydrogen or methanol (mi)
54	250	Required vehicle range on battery at max. acceptable depth of discharge (DoD) (inc. mileage during reformer warm up) (mi)
73.1	84.6	Maximum mechanical power at wheels, when not using air conditioning (kW)
2,584	3,074	Curb weight of the vehicle (no payload, full fuel tank) (lb)
2,730	3,224	Actual EPA test weight of vehicle (one passenger, 40% full fuel tank) (lb)
2,884	3,374	Loaded driving weight of vehicle (curb weight plus 300 lbs)

Documentation to Table A.3.

20.00	***20.00***	***Cost of electric motor, electronics package, transaxle, and miscellaneous parts ($-OEM/max.-kW-motor)***
500	***500***	***Cost constant for electric drivetrian ($-OEM)***

Hamilton (1988a) reviews previous cost estimates, including those made for the Jet Propulsion Laboratory's Advanced Vehicle Assessment (Hardy, 1985), discusses the state of the art and expected improvements, and then projects that the electric motor, electronics package, and a single-speed transaxle together will cost $24/kW_{peak}$ at the retail level by the year 1995. Hamilton's estimate appears to incorporate an MSRP/OEM ratio of 1.50:1 (he and the USDOE [1990b], which uses his work, use a ratio of 1.50 to estimate the MSRP of batteries); if he does use 1.50:1, then his estimate is equivalent to $16/kW_{peak}$ at the OEM level. Hamilton's estimates, which assume "significant cost reductions" by the year 1995, may be conservative for the year 2000.

At least two other estimates are similar to Hamilton's. In his recent analysis of the cost of fuel-cell vehicles, Kuhn (1992) assumes that the motor, controller, and transaxle could be manufactured for $11/peak-kW (from the motor) in the year 2000 (1990$). General Motors (1992) cites Jet Propulsion Laboratory estimates of $4-10/kW$_{peak}$ for switched-reluctance motors, and $2.5-3/kW$_{peak}$ for ac induction motors. (I assume that these are manufacturing costs, not retail-level prices.), However, J. Wallace (1992a) of Ford Motor Company, and a source from another major auto company (who wishes to remain anonymous), believe that it will be "difficult" to reduce the OEM cost of the motor and controller (transaxle not included) to less than $20/kW.

Given these estimates, I assume a fixed manufacturing cost of $500 (OEM), and then an additional cost of $12 (OEM)/kW$_{peak}$ for the motor, electronics, and transaxle in the year 2000. (If this estimate of $500 plus $12/kW is expressed entirely in $/kW, then the total for the vehicles in this analysis is about $18/kW.) I estimate that the miscellaneous components added to the EV -- the emergency battery, the heater and air conditioning, the cooling for the inverter and motor, the driveshaft, the charger box, the vacuum pump for the brakes, the driveshaft, the state-of-charge indicator for the battery, and wires and cables -- will add $8/kW to this total. (Note, though, that no state-of-charge indicator developed so far has proved satisfactory over all types of driving, and over the full battery life [Burke, 1991b].) The total is thus $500 plus $20/kW. .

0.90 0.90 OEM cost of adding extra structural support ($/lb)

Passenger vehicles will require extra structural material to support the battery, fuel cell, and hydrogen storage equipment,. Carriere and Curtis (1984) estimate that chassis material costs between $1.50 and $2 per pound. In the cost program the extra structural weight is determined by multiplying a weight compounding factor by the extra vehicle weight.

0.00 0.00 Cost of oil (fraction of oil cost of gasoline ICEV)

Electric motors do not require regular oil changes.

1.33 1.33 Ratio of life of EV or FCEV to life of ICEV (mileage basis)

This is my estimate of how the long life and reliability of the electric drivetrain might increase the life of the entire vehicle.

Electric motors are not subject to such extremes of heat, pressure, vibration, and mechanical movement as are engines, and as a consequence last many times longer than engines used in the same applications. This longer life has been demonstrated in both stationary and mobile applications. Hamilton (1988a) reports that the mean time between failures for motors and controllers in industrial forklifts exceeds 20,000 hours, which is about 4 times the life of most ICEs. Hamilton (1988a) also states that:

"...the Dairy Trade Federation reported in 1980 that EVs used to deliver milk door-to-door outlast comparable diesel vehicles...15 years vs. 5 years. These vehicles...are designed for and operated in grueling start-and-stop service seven days a week...[and] they constitute the only large fleet of on-road electric vehicles in the world (over 30,000 in 1980). Moreover, they represent the only sizeable on-road application where electric and ICE propulsion compete on reasonably equal footing, i.e., with comparable production volumes and mature technology (p. 19)".

George Steele, manager of the 74-vehicle (as of 1984) electric fleet of the Southern Electricity Board in the United Kingdom, stated in 1984 that:

"It is generally recognized that electric vehicles should perform economically and efficiently in fleet service much longer than their conventional counter-parts, but only if due provision is made to ensure that the onset of rust or other premature decay does not preclude these considerable savings from accruing to the electric vehicle fleet operator.

These benefits can be obtained by careful attention to such items as paint specification and the use of high-quality bodywork materials e.g. by ensuring special rust preventative treatment is used on all vulnerable areas and that full use is made of long-lasting materials such as glass re-inforced plastics (p. 3)".

Steele (1984) summarized the performance of his own EV fleet as follows:

"The longer vehicle lives predicted for electric vehicles -- so necessary for equating whole-life cost comparisons -- seem to be fully justified so far".

Based on these experiences with vehicles, and on widespread experience with electric motors, I think that is reasonable to assume that: a) electric motors will last much longer than the ICEs that they will replace, in essentially any kind of vehicle and any kind of application; and b) in at least *some* kinds of commercial fleets, EVs will outlast their ICE counterparts. However, to generalize from all kinds of motors and some kinds of fleet vehicles to all kinds of passenger vehicles, I must address at least these four issues:

i). There is no significant on-road experience with advanced electronics packages (inverter/charger and motor controller packages). The electronics in future passenger vehicles will be different from, and used differently than, the electronics in the forklifts and commercial vehicles mentioned above. These electronics will have to be designed to handle sustained high voltages and currents, extreme fluctuations in power, complex power flows, and a lot of vibration and shocks, under a wide range of weather conditions -- and without requiring sophisticated routine maintenance. Although advanced electronics generally can be made to be very robust, I am reluctant to simply assume that the life of the vehicle electronics routinely will match the life of the electric motor itself. I do expect, though, that electronics packages will last at least as long as any of the major components of the ICE system. In any case, there will be at least one tradeoff between life and cost: the lower the maximum voltage the lower cost, but also the shorter the life, because the system will be operating closer to its capacity more often.

ii). The average life of the EV probably will be less than the average life of its drivetrain. Although many and perhaps most vehicles are scrapped because of the actual or impending failure of some costly part of the drivetrain (the engine or transmission), many vehicles undoubtedly are scrapped for other reasons, such as major body or frame damage, failure of the steering or the suspension, or just overall deterioration. Thus, if EV drivetrains last, say, two or three times as long as ICE drivetrains, the whole EV will last considerably *less* long -- say, 50% longer than the comparable ICEV.

Note that I do consider rust to be a major determinant of vehicle life. I agree with Steele's (1984) remarks quoted above: vehicles can be made to be rust proof, at low cost, either by rust-proofing metal, or by using non-metallic parts.

iii). It is possible that even if EVs last considerably longer than ICEVs, consumers will not value the extra life as much as they "should," according to a rational cost accounting. Whereas many commercial and institutional buyers perform lifecycle cost calculations that explicitly account for the expected life of the vehicle, nearly all other buyers consider reliability and reputation for longevity only *qualitatively*. Moreover, individuals are more concerned than are commercial and institutional buyers with style and newness per se, and these aesthetic attributes will deteriorate as rapidly in an EV as in an ICEV. It therefore is probable that EVs will depreciate faster in the private-vehicle market than in a fleet-manager's lifecycle cost accounting.

Nevertheless, consumers do consider and value vehicle longevity. For example, there is evidence that many people who buy diesel vehicles value the longer life and lower maintenance costs (see the discussion of maintenance costs in Appendix B).

iv). There is a *remote* possibility that, in order to prevent customers from hanging on to cars longer and buying new vehicles less frequently, automakers will *collude* and all agree to design EVs somehow to have the same life as ICEVs. It is important to note that for this to happen, automakers must actually *collude* : any individual automaker that decided unilaterally to make short-lived EVs, in order to maintain annual vehicle sales, would find itself without customers, because buyers obviously would prefer the longer-lived EVs (all else equal). In fact, in the absence of collusion, the incentive actually works in the other direction: if buyers appreciate the longer life, then the companies with the reputation for building the longer-lived vehicles will sell more vehicles, all else equal. (Mercedes Benz does not appear to be upset that it has a reputation for building long-lasting automobiles.)

Collusion of this sort is very unlikely, for several reasons. First, it is very difficult to arrange and enforce. Second, it is illegal and therefore risky. Third, and most importantly, automakers really don't have any reason to collude in the first place, because they are more interested in total dollar sales than in the number of units sold. EVs will retail for more than ICEVS, so that even if fewer of them than ICEVs are sold, total dollar sales will not necessarily be lower.

Based on this analysis, I think that household EVs might last as much as 50% longer than ICEVs, on average. Hamilton's (1988a) analysis for the U. S. Department of Energy (1990b) assumes conservatively that EV would last 25% longer than ICEVs. In my base-case analysis, however, I assume only a 33% longer life. Moreover, as discussed in Appendix B, I estimate a maintenance schedule for EVs that explicitly assumes that very old EVs occasionally will require additional expenditures to maintain the parts it will have in common with ICEVs (the body, interior, chassis, brakes, etc.). I also have assumed that the BPEV and the FCEV would be driven more miles per year than would an ICEV, because they would be more reliable and have lower operating costs.

6.50 6.50 Length of time carrying insurance against damage to own vehicle (yrs)

This period is longer than the period assumed for the baseline ICEV (Table A.2), because the EV has a higher initial cost, and presumably would be worth insuring against collision damage for a longer period.

0.75 0.75 Scheduled maintenance cost of the EV, excluding the fuel cell and hydrogen storage system (fraction of the scheduled maintenance cost of an ICEV)

0.60 0.60 Unscheduled maintenance cost of the EV, excluding the fuel cell and hydrogen storage system (fraction of the scheduled maintenance cost of an ICEV)

See Appendix B.

0.10 0.10 Annual maintenance cost of fuel cell stack and auxiliaries (fraction of annual maintenance cost of BPEV)

0.06 0.06 Annual maintenance cost of reformer and auxiliaries (fraction of annual maintenance cost for a BPEV)

0.02 0.02 Annual maintenance cost of hydrogen storage system (fraction of annual maintenance cost of BPEV)

The maintenance cost of the FCEV is assumed to be equal to the maintenance cost of the BPEV plus increments to account for the cost of maintaining the fuel cell, the reformer, and the hydrogen storage system. See the brief discussion in Appendix B.

0.50 0.50 Inspection and maintenance fee (fraction of gasoline vehicle $/yr. fee)

Assuming that half of the I & M fee for gasoline ICEVs is emission-related, and half is safety-related, then the I & M for EVs would be half the fee for gasoline ICEVs, because there would be no emissions inspection for EVs.

1.00 1.00 Tax analog of retail tax on gasoline (cents/mi, relative to gasoline tax in cents/mi)

I assume that the new fuels or the new vehicles would be taxed so that the same amount of revenue would be generated, per km of travel, as would have been generated by the gasoline tax. I expect that, because of the difficulty of taxing electricity used at home to recharge BPEVs, the tax most likely would be something like a mileage tax paid at the time of vehicle registration.

0.89 0.89 Once-through efficiency of electric motor, EPA unadjustedcity -cycle efficiency (Btu/mi basis)

0.92	***0.92***	***Once-through efficiency of electric motor, EPA unadjustd highway-cycle efficiency (Btu/mi basis)***
0.94	***0.94***	***Once-through efficiency of motor controller and inverter (electronics) (Btu/mi basis)***
0.95	***0.95***	***Once-through efficiency of motor-to-wheels transmission (Btu/mi basis)***

I have specified component efficiencies separately for city and highway driving because the efficiency of electric motors is a function of torque and rpm, and the efficiency of electronics is a function of power (voltage and current), among other factors.

Bullock (1989) shows that above 2000 rpm, the efficiency of an ac permanent-magnet motor increases with increasing power. At 500 rpm, efficiency decreases with increasing power. Burke and Henriksen (1989) show that generally the efficiency of transmissions and motor/controller systems increases with increasing constant vehicle speed. Seto et al. (1990) show a highly nonlinear efficiency map (torque vs. rpm) for a small brushless dc motor, although generally when both torque and rpm increase (i.e., when power increases), the efficiency increases. The efficiency of the dual-shaft electric propulsion ac powertrain increases with increasing torque and rpm (up to about 6000 rpm), and hence with increasing power (Kelledes, 1988). The ac motor in the ETX-II is 76.6% efficient at 500 rpm and 77 ft-lbs of torque, 95% efficient between 4000 and 7000 rpm and 50 to 80 ft-lbs of torque, and 92.7% efficient at 11,000 rpm and 34.9 ft-lbs of torque (Ford and GE, 1989). Various test results and other estimates are summarized below. My estimates assume that the state of the art in motors and electronics in the year 2000 will be at least as good as the best performances reviewed here. I assume a direct-drive transmission, which is more efficient than most of the technologies reviewed here. My estimates are in line with the values achieved by the GM Impact, which has a motor efficiency of 90 to 95%, and a direct-drive transmission that is 94-98% efficient (GM, 1990; Wyczalek, 1991).

Efficiency of components of electric drivetrain

Vehicle (Reference)	Controller	Inverter	Motor	Trans & Wheels
ETV-1 (Kurtz, 1981; dynamometer)[a]				
45 mph	0.99		0.89	0.87
SAE J227a D	0.99		0.84	0.92
Generic estimate (Bentley and Teagan, 1992)				
year 2001	0.94		----------- 0.80 -----------	
year 2020	0.96		----------- 0.88 -----------	
ETX-I (Ford and General Electric, 1987; simulation)[b]				
FUDS		0.94	0.87	0.88
ETX-II (Fenton & Sims, 1990; dynamometer)[c]				
25 mph	0.92	0.88	0.95	0.80
35 mph	0.97	0.95	0.92	0.82
45 mph	0.98	0.97	0.88	0.89
55 mph	0.95	0.97	0.80	0.92
FUDS	0.96	0.97	0.87	0.83
SAE J227a D	0.98	0.96	0.88	0.89
DSEP (Hamilton, 1988; simulation)[d]				
35 mph			0.79	
55 mph			0.86	
FUDS			0.79	
SAE J227a D			0.86	
G-Van (Hamilton, 1988; simulation)[e]				
35 mph			0.87	
SAE J227a D			0.88	
TEVan (Hamilton, 1988; simulation)[f]				
35 mph			0.84	
55 mph			0.88	
FUDS			0.76	
SAE J227a D			0.87	
DSEP minivan (Burke and MacDowall, 1991; dynamometer)[d]				
20 mph	-------------- entire powertrain: 0.53 -----------------			
40 mph	-------------- entire powertrain: 0.76 -----------------			
55 mph	-------------- entire powertrain: 0.83 -----------------			
Mercedes 307 (Falt et al., 1990; field test?)[g]				
a city cycle?		0.97	0.89	0.90
1980 Suzuki van (Gosden , 1990; dynamometer)[h]				
SAE J227a-C	-------- 0.97[i] --------		0.89	0.95

[a]DC-motor, transaxle.

[b]Single-shaft ac powertrain.

[c]Integrated permanent-magnet ac motor and automatic transaxle, and transistorized inverter. Ford and GE (1989) had projected 0.94 for the inverter, 0.92 for the motor, and 0.84 for the drivetrain, over the FUDS.
[d]Three-phase ac induction motor, transistorized inverter, two-speed automatic transaxle.
[e]dc motor, chain and sprocket transmission.
[f]dc motor, electronic two-speed transmission, combined controller, charger, dc-dc converter.
[g]3-phase GTR inverter, 3-phase ac induction motor.
[h]MOSFET inverter, permanent-magnet ac motor.
[i]Controller and inverter.

0.135	*0.135*	***Fraction of once-through city-cycle energy returned from battery or fuel cell back through the battery to the battery terminals by regenerative braking.***
0.018	*0.018*	***Fraction of once-through highway-cycle energy returned from battery or fuel cell back through the battery to the battery terminals by regenerative braking.***

The amount of energy that can be recovered from regenerative braking is a function of the amount of braking in a drive cycle, the efficiency of the drivetrain, the maximum allowable regenerative power, and other factors. My estimate of energy recovery by regenerative braking over an urban drive cycle is based on the following tests or estimates of regenerative energy recovery:

Estimates of energy recovered by regenerative braking over various drive cycles

Source	Vehicle	Drive Cycle	recovery[a]
Kurtz (1981)	ETV-1	SAE J277a D	15%
Ford and GE (1987)	ETX-I	FUDS	14%
Fenton and Sims (1989)	ETX-II	FUDS	5%[b]
Burke and MacDowall (1991)	DSEP	FUDS	5%
Bentley et al. (1992)	generic	city/highway	8-16%
Wyczalek and Lilly (1992)	modeling	"urban"	23%
Wyczalek and Lilly (1992)	modeling	"suburban"	7%
Gosden (1990)	Suzuki van	SAE J227a C	19%
Clean Fuels Report (1991)	G-van	SAE J227a C	11-24%[c]

[a]For the ETV-1, ETX-I, ETX-II, Suzuki van, the modeling results of Wyczalek and Lilly (1992), and the estimates by Bentely et al. (1992), the % recovery shown here is defined as the amount of energy (in wh/mi) retured all the way back to the battery terminals (but *not* through the battery and back out to the terminals) divided by the wh/mi energy consumption measured coming out of the batteries at the battery terminals, multiplied by 100. (This also is how I define my estimate. Of course, in my calculation of net energy use, I do account for the battery in-out efficiency.) Burke and MacDowall (1991; DSEP) do not define their estimate (they referred to is simply as "energy recovery"). In their analysis of CO_2 emissions from EVs and FCEVs, Bentley et al. (1992) assume that the "regeneration fraction of gross battery energy" will be 6-12% (1995 to 2020), over a combined/city and highway cycle. They include energy lost in battery charging and discharging -- that is, their fraction is equal to regenerative energy returned all the way back through the battery, divided by battery output. If the cyclic efficiency of battery charging and discharging (they assume 75%) is removed, the estimate becomes 8% - 16%, as shown above. This implies that 20% or more energy would be recovered over FUDS. Wyczalek and Lilly (1992) define energy recovery as the amount of energy returned to the battery divided by energy consumption *into* the battery (not out from the battery terminals). I converted this to an energy-consumption-measured-coming-out-of-the-battery-terminals basis by assuming a battery efficiency of 0.90.
[b]Ford and GE (1989) projected 14% recovery over FUDS.

[c]The amount of regenerative braking energy depended on the use of power steering (PS), power brakes (PB), and air conditioning (a/c), as follows (I assume that dc kWh regeneration is measured going into the battery):

	PS/PB on	PS/PB off	a/c on	a/c off
dc kWh discharge	36.2	37.6	32.6	36.9
dc kWh regeneration	7.1	9.2	3.6	5.9
% regeneration	19.6	24.5	11.0	16.0

Because there is much less braking over the highway test cycle than the city test cycle, I assume that very little regenerative braking energy will be recovered.

Occasionally, the amount of regenerative energy available might exceed the available rechargeable capacity of a peak-power battery in an FCEV. This could happen in a driving cycle that involved low-power starts and stops that rarely called on the battery's peaking power, and hence did not deplete the battery enough to make room for regenerative recharging. I do not consider such situations formally in my model.

0.90 0.90 In-use mi/kWh divided by EPA unadjusted mi/kWh, city driving, year 2000

0.77 0.77 In-use mi/kWh divided by EPA unadjusted mpg, highway driving, year 2000

I assume that the difference between test-cycle and in-use energy consumption, in city driving, would be *less* with EVs than with ICEVs; that is, I assume that on the road, EVs would come closer to their city-cycle test results than would ICEVs. Some of the factors that cause ICEVs in the real world to fall short of their city-cycle fuel economy -- for example, more time spent idling and more stopping and starting in the real world than in the tests -- would not cause a difference between real-world and test cycle energy consumption with EVs, because EVs do not consume energy while idling or decelerating, and do not need to "warm up". However these factors are much less important in the highway cycle, and hence should not affect the EV in-use/test shortfall relative to the ICEV shortfall.

I am not aware of any recent data comparing EV efficiency on the FUDS or SAE D cycle with in-use efficiency. Five EVs tested between 1978 and 1984 had in-use mi/kWh efficiency that was 0.66 to 0.79 times the mi/kWh efficiency measured over the SAE C cycle on a track (Labelle, 1985). For three of the vehicles, the SAE C track energy consumption was measured between 1978 and 1981, and the in-use energy consumption was measured up to 1984. For two of the vehicles, both kinds of energy consumption measurements were made in 1980. Thus, the data and the vehicles are now over 10 years old. All the vehicles had lead-acid batteries and dc motors; most were conversions, with relatively "low-technology" components, and correspondingly low power and short range. Labelle (1985) suggests that some of the vehicles were repaired frequently. Consequently, these efficiency shortfall data really do not apply to advanced-technology vehicles tested over the SAE D cycle or the FUDS. It is worth noting, though, that the most advanced vehicle in the group, a vehicle made by Unique Mobility, not only had the lowest energy consumption both on the track and in use, but also was closest to its track results, in use.

0.80 0.80 High-end acceleration of EV relative to high-end acceleration of ICEV.

26.8 26.8 Speed at which acceleration of EV and ICEV are compared (meters/s)

The peak-performance ratio is the ratio of the high-end acceleration capability of the EV to the high-end acceleration capability of the ICEV, and is used to find the peak power of the EV, given an ICEV with a known peak power. Put another way, the ultimate purpose here is to determine the peak EV-motor power that will provide a specified level of performance relative to the performance of an ICEV with a known peak power, accounting for vehicle weight, rolling resistance, and aerodynamic drag. This specified relative level of performance is the high-end acceleration ratio. I will calculate this ratio here at 60 mph (26.8 meters/s). Note that I am not measuring, or comparing, 0 to 60 mph acceleration time. Rather, I am comparing the acceleration when the engine peak power is applied at 60 mph. Thus, if the peak-performance ratio is 0.80, it means that the acceleration of the EV when the peak EV-motor power is applied at 60 mph is 80% of the acceleration of the ICEV when the peak engine power is applied at 60 mph.

0.50 0.50 Maximum power required by vehicle accessories, exc. air conditioning (kW)

From An and Ross (1991).

4.35 4.35 Weight-to-power ratio of added EV components: motor, electronics, transaxle, etc. (lb/kW-max-from-motor)

I estimate this as the sum of the lb/kW$_{max}$ weight of the motor, the electronics package (the dc-ac inverter, motor controller, and dc-dc converter), the transaxle (excluding the drive shafts), and the miscellaneous equipment (the back-up battery, the charging receptacle, the heater/air conditioner, the vacuum pump for the brake assist, the cooling equipment for the motor and electronics, the drive shafts, and connecting cables and wiring).

Motor: The 52-kW ac permanent-magnet motor in Ford's ETX-II weighs 2.2 lbs/kW$_{peak\text{-}motor}$ (Patil and Davis, 1988). The 85-kW ac-induction motors in the GM impact weigh 1.94 lbs/kW$_{peak\text{-}motor}$ total, including the weight of the gearbox-transmission (Wragg, 1991). Unique Mobility is designing a high-energy dc brushless permanent-magnet motor that will weigh only 0.70 lb/kW (Anderson and Cambier, 1990). BMW has built a motor + controller system that weighs 2.2 lb/kW (Braess and Regar, 1991). Hamilton (1988a) projects 2.2 lb/kW by the year 1995.

Electronics package: The GM Impact's state-of-the art electronics package (charger, dc-to-ac inverter, and dc-to-dc converter) uses dual MOSFET inverters and weighs only 0.72 lbs per maximum kW from the motor (General Motors, 1990). Hamilton (1988a) has projected 0.55 lb/kW for advanced electronics packages by 1995.

Transaxle: The transaxle in the ETX-II weighs 2.3 lbs/kW$_{peak\text{-}motor}$ (Patil and Davis, 1988), and the transaxle in the dual-shaft electric-propulsion system weighs 2.0 lbs/kW$_{peak\text{-}motor}$ (Kalns, 1988). Hamilton (1988a) projects about 0.80 lb/kW for fixed-gear transaxles by 1995. The transmission in the GM Impact consists of a gearbox, the weight of which is included in the estimate above for the motor, and a driveshaft connecting the gearbox to the wheels.

(See Burke and Henriksen [1989] for a summary of the weight and power of the motor, controller/inverter, and transaxle for the Ford ETX-I, the Ford ETX-II, the DSEP vehicle, and the Chrysler TEVan.)

Miscellaneous. The miscellaneous components in the ETX-I weighed about 217 lbs, or 5.8 lbs/kW (Ford and General Motors, 1987). About half of this weight was in a very heavy battery for the electrical system, and in a heavy heater. The miscellaneous components in the ETX-II apparently weigh about 5.3 lbs/kW (Ford and General Motors, 1989). The GM Impact uses only a very small emergency backup battery, and a heat pump heater/air conditioner (Wragg, 1991). The miscellaneous equipment in the Impact probably weigh 140 to 180 lbs, or about 1.9 lb/kW. (And the Impact has over twice the maximum power of the ETX-I.)

Summary. The overall specific weight depends on the design of the powertrain. Some advanced BPEVs will use two lightweight electric motors, one over each front wheel (GM, 1990; Anderson and Cambiers, 1990; Nissan, 1991; Sato et al., 1990), and an integrated controller-inverter-charger package with advanced inverter electronics. The Ford and GE Modular Electric Vehicle Program is using an ac induction motor, a transistorized inverter, and a single-speed transaxle (Burke, 1991b). All of these configurations will be relatively light. For the year 2000, I assume 1.9 lbs/kW for the motor/transaxle assembly, 0.55 lbs/kW for the electronics package, and 1.9 lb/kW for miscellaneous equipment, for a total of 4.35 lbs/kW. In a recent analysis done for the USDOE, Bentley and Teagan (1992) assume 3.8 lbs/kW in the year 2001 and 2.9 lb/kW in the year 2020 for the motor, controller, and transmission (this estimate apparently excludes what I refer to as "miscellaneous equipment").

The following two tables show weight breakdowns for the ETX-I and ETX-II.

Weight of ETX-I (excluding battery) and comparable Mercury Lynx-7 ICEV

Subsystem	Lynx	ETX-I	difference	difference due to:
	---------- Weight, lbs		------------	
body	1038	1121	+83	extra structure for battery[a]
engine	309	296	-13	EV powertrain vs. ICE engine
emission control	26	0	-26	no emission control in EV
transmission	154	25	-129	EV transaxle counted in powertrain
clutch	16	0	-16	no clutch in EV
exhaust	29	0	-29	no exhaust system in EV
fuel tank and fuel	94	2	-92	no fuel tank and lines in EV
heater/vents	20	60	+40	extra heater in EV
electrical	43	57	+14	larger aux. battery in EV
other[b]	498	507	+9	extra cables, etc. in EV
TOTAL	2227	2066	-161	
TOTAL w/out extra structure for battery		1983	-244	

From Ford and General Electric (1987).

[a]Battery and tray weighed 1237 lbs.

[b]EV does not have 23-lb. spare tire. Note that this "other" category is different from the "miscellaneous" category defined above.

Weight analysis for the ETX-II (excluding battery) and comparable Ford Aerostar van (lbs)

Weight item	ICE Aerostar	ETX-II
Weight of components common to both vehicles	2062	2062
Weight of the ICE system removed	992	
Weight of the EV components added		628
Total vehicle weight	3054	2690
Difference in weight		-364

From Ford and General Electric (1989).

0.06 0.06 Weight compounding factor (lb added structure/lb additional vehicle weight)

The ETX-I had 83 lbs of extra body structure for a battery and tray that weighed 1237 lbs (Ford and GE, 1987; see above), or 0.067-lbs structure/extra lb. I assume 0.06.

0.05 0.05 Reduction in weight of chassis, body, and interior of EV, compared to ICEV (fraction of curb wt. of ICEV)

Because it is so important to achieve high fuel efficiency and light weight in an EV, in order to reduce the size of the very costly energy-storage and power-provision systems needed to supply a given range and performance, drag and weight reduction likely will be pushed further in an FCEV or BPEV than in an ICEV. Svantesson (1992) of Volvo Corporation has stated that "since battery energy is scarce, it is of utmost importance to reduce all energy consuming parameters -- mass, drag, and rolling resistance". Recently built or planned vehicles are indeed following this precept. The General Motors Impact (Wyczalek, 1991; GM, 1990), and Nissan's "Future Electric

Vehicle" (Tange and Fukuyama, 1992) have used extreme energy-saving designs to reduce energy consumption by more than 50%, compared to more conventional electric vehicles. Energy Partners, a Florida-based company designing and building a fuel cell vehicle, is planning to use lightweight plastic/composite materials extensively (Ewan, 1991). Nippon Steel of Japan has built an experimental BPEV with a low Cd and a body that weighs about 250 kg less than the body on a comparable conventional car (Sato et al., 1990).

I assume that an aggressive effort to reduce the weight of the body, chassis, tires, and bumpers in the FCEV would result in a further weight reduction for these components equal to 5% of the curb weight of the year-2000 ICEV (which already hypothetically has some weight-reduction measures built in to it, compared to the 1990 ICEV).

(100)   (100)   Cost of extra weight reduction measures in the EV, beyond those used in baseline ICEV ($)

As noted above, in Table A.3, the substitution of plastic/composite materials for steels probably would reduce, not increase, the price of the vehicle (ACEEE, 1990; EEA, 1990). Qualitatively accounting for the increase in the price that would result from an increased demand for plastics, I assume that the further use of plastics in place of metals in the FCEV or BPEV, beyond what I have assumed would be used in the baseline year-2000 gasoline ICEV, would reduce the MSRP of the vehicle by $100.

0.23   0.23   Coefficient of drag (Cd)

As noted above, the high cost of storing energy and providing power in EVs makes energy-saving measures more valuable in an EV than in an ICEV. Thus, I expect that EVs in general will have a lower coefficient of drag than will the comparable ICEVs. EEA notes that several experimental vehicles already have Cds less than 0.20. The GM Impact has a Cd of 0.19 (GM, 1990). I do not think it unreasonable, then, to assume that the FCEV and BPEV would have a Cd of 0.23.

200   200   Cost of difference between Cd of EV and Cd of baseline ICEV ($-MSRP)

Ledbetter and Ross (1990) estimate that reducing the Cd from 0.37 to 0.30 would add $80 to the price of the vehicle. I assume that marginal cost of reducing the Cd increases with decreasing Cd, so that going from 0.28 Cd of the ICEV to the 0.23 CD of FCEV might add $200 to the price of the vehicle.

250   250   Minimum acceptable total vehicle range, using fuel cell and battery (mi)

See text for explanation.

73.07   77.36   Insurance payments for first n years, with coverage for damage to own vehicle ($/month)

Insurance costs are a function of many factors, including the amount and kind of protection, the value of the vehicle, the characteristics of the drivers and the area where the vehicle is driven, and the amount and kind of driving. Although any of these factors may or may not be systematically different with EVs than with ICEVs, the only difference which can be estimated confidently is that related to the value of the vehicle. EVs, with their very expensive batteries, fuel cells, and hydrogen storage equipment, will cost considerably more than comparable ICEVs, and consequently collision-damage insurance, which is based on the value of the vehicle, will be higher.

Typically, coverage for collision is carried for the first 5 to 8 years of the vehicle's life, depending on the value of the vehicle. The cost program takes as input data the monthly insurance rate with collision insurance, the number of years collision is carried, and the monthly rate without collision insurance, for the baseline ICEV. The total monthly insurance rate after collision insurance is dropped is assumed to be the same for the ICEV and the EV. The total rate with collision coverage (higher for the EV) is calculated by multiplying the difference between the with and without collision rates (this difference is equal to the cost of collision insurance) by the ratio of the initial cost of the EV to the initial cost of the ICEV. This procedure assumes that the collision-damage insurance premium is proportional to vehicle replacement cost. (In reality, the ratio of collision-damage insurance premiums for two vehicles will be less than the ratio of vehicle value [all else equal], because many kinds of accident damage cost the same regardless of the value of the vehicle. Consequently, my assumption overestimates the insurance rate for the EVs.) The baseline insurance rates for the ICEV are shown in Table A.2.

434.16 387.64 Levelized maintenance costs ($/yr.)

See Appendix B.

159,600 159,600 Life of the vehicle to scrappage or resale (mi)

This equal to the baseline life of the ICEV (Table A.2) multiplied by the relative life factor of this table.

14,270 14,270 Distance driven per year, with "mileage" discount rate applied (mi)

Santini and Vyas (1988) have estimated the relationship between miles per vehicle and operating cost (in cents per mile). As one would expect, vehicles with a lower operating cost are driven more miles per year, all else equal. However, Santini (personal communication, October 6, 1991) also notes that vehicles with a higher initial cost will tend to be driven less, because the higher initial cost translates into higher monthly loan payments, which, given a fixed budget, reduces the amount of money that can be spent on fuel and vehicle operation. I do not account for this latter effect here.

309 367 Shipping cost for electric vehicle ($)

I assume that the shipping cost is a function of the weight of the vehicle and the distance of the shipment. Assuming that shipment distances do not depend on the type of vehicle, I calculate the shipping cost of the BPEV or FCEV as

$$Sev = Sg \times Wev/Wg$$

where:

Sev = shipping cost of the FCEV or BPEV ($)
Sg = shipping cost of the baseline gasoline ICEV ($)
Wev = curb weight of the FCEV or BPEV (lbs)
Wg = curb weight of the baseline gasoline ICEV (lbs)

(3,082) (2,653) MSRP of added EV equipment minus MSRP of removed ICEV equipment ($, exc. retail tax)

My estimates here result in an EV selling price, excluding the battery, fuel-cell system, or hydrogen-storage system, that is substantially less than the ICEV selling price. Previous comparisons put the selling price of a BPEV (excluding battery) very close to the price of the ICEV. Ford and GE (1987), developers of the ETX-I, suggested that advanced electric vehicles (EVs) would cost no more than comparable ICEVs, excluding the battery, at a "reasonable production volume". Similarly, a weight and cost model developed by General Research Corporation (Carriere and Curtis, 1984) projected that the initial cost of EVs and ICEVs would be close, assuming high-volume production. Ken Winters, manager of Chrysler's Pentastar EV program, stated in 1989 that if EVs are produced in the same quantity and manner as ICEVs, they should have the same selling price, excluding the battery (Winters, 1989). More recently, the U. S. DOE (1990b), using work by Hamilton, estimated that BPEVs will cost $660 less than comparable ICEVs, excluding the cost of the battery. Nevertheless, I believe that the detailed, bottom-estimates of the cost of the ICEV and the BPEV presented here are more accurate.

0.90 0.90 Net efficiency of motor, electronics, transmission, EPA unadjusted city cycle (Btu/mi basis)

This is the calculated overall efficiency of the EV powertrain, over the EPA's city-driving test cycle, without adjustment for the difference between energy consumption over the test cycle and actual energy consumption on the road. The calculation is based on component-by-component efficiency estimates, and accounts for the energy recovered by regenerative braking. The estimated overall net efficiency of 90% is 5.7 times higher than the estimated 15.8% overall unadjusted city-cycle efficiency of the engine and transmission in the comparable year-2000 ICEV (Table A.2). Is this factor of 5.7 reasonable? To check this, I compared the reported mi/kWh energy efficiency of 13 EVs with the reported mpg of the comparable ICEV, over the same or similar test cycle, with the effect of differences in vehicle weight netted out. (I removed the effect of weight differences because the object here is to determine the relative powertrain efficiency, for comparison with the component-by-component calculation. I assumed that each 1% decrease in weight reduced fuel consumption [Btu/mile)] by 0.54% [Energy and Environmental Analysis, 1990].) The results of this comparison are summarized in the following table. As shown in the table, the city-cycle efficiency of the EVs, expressed in mi/Btu, and measured from the battery terminals is 4.4 to 6.3 times higher than the mi/Btu efficiency of the ICEV, over the same or similar driving cycle, when the efficiency of the EV is normalized to the weight of the EV. The average of the 13 calculated efficiency ratios is 5.4 (as is the average with the high and the low efficiency ratios removed). It thus appears that the relative component-by-component efficiency advantage estimated here (5.7) for future, advanced EVs -- is consistent with the overall efficiency advantage achieved by experimental EVs tested to date (5.4).

Ratio of energy efficiency of EVs to energy efficiency of comparable ICE vehicles, city driving

ELECTRIC VEHICLE					ICE VEHICLE				EFFICIENCY RATIO[a]	
	miles/kWh									
Vehicle	battery[b]	outlet	Drive cycle[c]	Test wt. [battery wt.][d] (lbs)	Vehicle comparable to EV	mpg	Drive cycle[c]	Test wt. (lbs)	EV to ICEV	notes
ELVEC-EV	(4.13)	2.79	SAE D	3600[992]	subcompact	33.0	FUDS	2300	5.7	e
Audi	2.30	1.38	city	4630[1100]	Audi 100	16.8	city	3500	5.8	f
ETV-1	3.41	--	FUDS	3960[1090]	'79 Ply. Horizon	27.6	FUDS	2500	5.7	g
ETV-2	3.14	--	FUDS	3920[1066]	'79 BMW 320i	26.0	FUDS	2750	5.3	h
Yr. 2000 EV	(4.63)	3.33	SAE D	2560[400]	Year 2000 ICEV	35.6	FUDS	2110	5.3	i
CitySTROMer	3.51	2.07	SAE C	3671[--]	'85 VW Golf GTI	28.3	FUDS	2500	5.5	j
Griffon van	(1.66)	1.03	Urban	6775[2500+]	'84 GMC vans	17.5	FUDS	4200	4.4	k
4-seat BMW	(3.73)	2.35	ECE	3600[584]	'86 BMW 3 series	27.0	comb.	3100	5.5	l
ETX-I	2.99	--	FUDS	3800[1237]	'83 Ford Escort	28.0	FUDS	2500	4.8	m
ETX-II	2.50	--	FUDS	4500[1100]	'88 Ford Aerostar	18.0	FUDS	3500	5.8	n
G-van	1.77	--	SAE D	7780[2540]	'89 GM G-van	17.0	FUDS	4750	4.8	o
TEVan	3.31	--	FUDS	4948[1770]	'89 T115 minivan	23.0	FUDS	3500	6.3	p
DSEP	2.58	--	FUDS	5300[1600]	'89 stretched T115	20.0	FUDS	3850	5.6	q
AVERAGE:									5.4	
AVERAGE, without high and low value:									5.4	

[a]Calculated as: $(0.125/ICEV_{mpg})/((1/EV_{mi/kWh})*(1-0.54(1-ICEV_{wt}/EV_{wt}))/293.1)$, where 0.125 is the million Btu/gallon heating value of gasoline, 293.1 is kWh/million Btu, and 0.54 is the percent decrease in fuel consumption per 1% decrease in weight. See also Wang and DeLuchi (1992).

[b]EV battery efficiencies shown in parentheses were calculated by dividing the reported efficiency from the outlet by the combined efficiency of the charger and the battery, as reported in the reference.

[c]FUDS is the Federal Urban Drive Schedule, which is used by the EPA to measure "city" fuel economy. I use the unadjusted EPA city fuel economy, for proper comparison with the unadjusted SAE test results. The SAE cycles are urban test cycles designed specifically for EVs. The SAE D cycle has higher average speed and power than the FUDS, but lower maximum speed and power. The SAE C cycle is less demanding than the SAE D cycle. The European ECE cycle is a composite of FUDS and the U. S. highway cycle

[d]Battery weight is included so that one can check if EV test weight less battery weight is close to ICEV test weight, which it should be.

[e]EV characteristics are from an EV simulation model called "ELVEC" (Hamilton, 1980b). The ICEV and EV were assumed to have equal payload volume, payload, and acceleration times. The EV is assumed to have a range of 100 miles in a the SAE J227a/D cycle. Hamilton (1980b) gives 2.79 from the outlet, including regenerative braking, and specifies 0.90 charger efficiency and 0.75 battery efficiency. The weight and efficiency of the ICEV are as specified by Hamilton.

[f]EV data are from Mueller and Wouk (1980a), who reported 1.38 mi/kWh from the outlet in what apparently was a test in urban traffic. They calculate energy use from the batteries by assuming a combined 60% efficiency for the battery and the charger. The fuel economy for the Audi ICEV was reported in Mueller and Wouk (1980b), for driving in city traffic. It is not clear if the EV had regenerative braking.

[g]ETV-1 data are from Kurtz (1981). The weight and efficiency of Horizon ICEV are from 1979 EPA emissions and fuel economy test data, with the following adjustment: the ETV-1 had exceptionally low aerodynamic drag; I assume that if the Horizon ICEV had the same low coefficient of drag, fuel economy the city cycle would have been 15% higher than as measured by the EPA in 1979 (24 mpg). The ETV-1 was 11% more efficient in the SAE D cycle than the FUDS cycle. Efficiency estimate for ETV-1 accounts for energy returned to battery by regenerative braking.

[h]ETV-2 data are from AiResearch (1981). The ETV-2 used a flywheel to improve acceleration and increase range. Energy from regenerative braking went to the flywheel rather than the battery. In the SAE D cycle, the ETV-2 achieved 3.64 mi/kWh, 16% better than in the FUDS. The authors state that the ETV-2 was comparable to a BMW 320i; I assume 1980 model year and use 1980 EPA test results for weight and fuel economy. The 1979 BMW ICEV weighed the same as the 1980 model but achieved only 18 mpg in the city cycle test.

[i]All ICEV and EV data are from ELVEC and EVWAC computer simulations, by General Research Corporation (Carriere et al., 1982). The EV and the ICEV have the same acceleration. The EV uses a Li-me/Fe-S battery, and has 150-mi range. The EV and the ICEV have the same acceleration and the same interior capacity. Carriere et al. specify 3.33 mi/kWh from the outlet, including regenerative braking, and 0.72 combined battery and charger efficiency. They gave curb weights of 2260 lbs (EV) and 1810 lbs (ICEV); I assume that the efficiency data were reported with an additional 300 lb test payload, as used by the EPA and by Hamilton (1980b), who also used ELVEC.

[j]EV data are from Driggans and Whitehead (1988a). The STROMer was built from a Golf CL. However, EPA data are available only for the Golf GTI. I assume 1985 model year. Efficiency data include energy returned by regenerative braking.

[k]Griffon data are from Driggans and Whitehead (1988b). The Griffon is a Bedford van, and the EPA does not report test data for Bedford vans. I have assumed that the Griffon is comparable to 1984 GMC vans, and have used 1984 EPA weight and fuel economy test results. Griffon efficiency figure includes regenerative braking. The battery wt. is modules only; it does not include auxiliaries or tray. The test cycle is the TVA's urban cycle. The Griffon was 27% more efficient in the SAE C cycle. Data in the reference indicate that combined battery/ charger efficiency was 62%.

[l]EV data are from Angelis et al. (1987), who expect the EV to achieve 190 Wh/km in the ECE cycle, from the outlet, with an additional 75 Wh/km required for battery heating. I assume a combined battery and charger efficiency of 0.63 for Na/S batteries. Regar (1987) reports that the vehicles being tested are converted BMW series 3 cars; I use EPA weight and fuel economy data for 1986 BMW series 3 vehicles. Since the ECE is similar to a combination of FUDS and the highway cycle, I use the unadjusted EPA combined mileage result. The 3300 lbs given by Angelis et al. for calculating energy consumption appears to be curb wt; I have assumed they added 300 lbs test weight for the actual efficiency calculation. The BMWs have regenerative braking (Haase, 1987), which apparently was included in the efficiency goal.

[m]ETX-I are data from MacDowell and Crumley (1988). The ETX-I was stated to be comparable to a Mercury LN7 or Ford Escort; I used EPA weight and fuel economy results for a 1983 Escort. The EPA test weight of 2500 lbs (2200 lbs curb weight plus 300 lbs payload wt.) is consistent with 2224 curb weight reported by Ford and GE for the ICEV, before it was converted to the ETX-I. ETX-I data include split regenerative braking.

[n]ETX-II data are from Stokes et al. (1988), and Patil and Davis (1988). The efficiency figure for the ETX-II is a goal, and appears to include regenerative braking. However, it is not clear if this includes energy required to heat

the Na/S battery. The ETX-II will be built from a Ford Aerostar van; I use 1988 EPA fuel economy and weight data for the Aerostar. The fuel economy for 1987 was 20 mpg.

[o]G-van are characteristics from Hamilton (1988b). Test weight is curb weight plus test payload. Electricity consumption data are from computer simulations run by Hamilton (1988b). The estimate accounts for regenerative braking. Hamilton's simulation of energy consumption over the C cycle (the value shown here is for the D cycle) was extremely close to the consumption measured for the C cycle at the TVA test track.

[p]TEVan characteristics are from Hamilton (1988b). Test weight is curb weight plus test payload. Electricity consumption data are from computer simulations run by Hamilton (1988b). The estimate accounts for regenerative braking. Simulation results are close to Chrysler projections. I used mpg and weight results for the Chrysler Caravan.

[q]DSEP characteristics are from Hamilton (1988b). Test weight is curb weight plus test payload. Electricity consumption data are from computer simulations by Hamilton (1988b). The estimate accounts for regenerative braking. I used mpg and weight results for the heavy Chrysler Caravan, since the DSEP is a heavier version of the TEVan.

73.1 84.6 Maximum mechanical power at wheels, when not using air conditioning (kW)

I calculate the peak power of the EV motor given the peak power of the ICE, the desired high-end acceleration of the EV relative to the high-end acceleration of the ICEV (see above), and the mass, drag, and rolling resistance of the EV and ICEV. I begin with the basic physics equation that describes the force needed at the wheels to move a motor vehicle (on a level surface):

$$Fw = I + D + R$$

where:

Fw = force needed at the wheels to drive the vehicle

I = force to accelerate the vehicle, equal to m*a, where m = vehicle mass and a = vehicle acceleration

D = force to overcome aerodynamic drag, equal to $1/2*p*A*Cd*V^2$, where p = the density of air, A = vehicle frontal area, Cd = coefficient of drag, and V = velocity

R = force to overcome rolling resistance, equal to m*g*Cr, where m = vehicle mass, g = gravitational constant, and Cr = coefficient of rolling resistance

Substituting m*a for I, and expressing the equation in terms of acceleration, a, we have the following, for a gasoline vehicle (subscript g) and a FCEV or BPEV (subscript e):

$$a_g = (Fw_g - D_g - R_g)/m_g$$
$$a_e = (Fw_e - D_e - R_e)/m_e$$

Let us define an acceleration ratio, K, equal to a_e/a_g. (This will be the high-end acceleration ratio of this table.) Thus, $a_g = a_e/K$. With this relationship, we have:

$$a_g = (Fw_g - D_g - R_g)/m_g = (Fw_e - D_e - R_e)/(m_e*K)$$

Now, power at the wheels, P, is the product of force F and velocity V: P = F*V. Thus, F = P/V. Substituting P/V for F in the preceding equation, and assuming that the equations will be evaluated at the same velocity V for both vehicles, we have:

$$(P_g/V - D_g - R_g)/m_g = (P_e/V - D_e - R_e)/(m_e*K)$$
$$(P_g/V - D_g - R_g)*(m_e*K/m_g) = P_e/V - D_e - R_e$$
$$[(P_g/V - D_g - R_g)*(m_e*K/m_g) + D_e + R_e] *V = P_e$$

We now have an expression for the power of the EV, P_e, in terms of vehicle mass (m_e and m_g), aerodynamic drag (D_e and D_g), rolling resistance (R_e and R_g), the power of the gasoline vehicle (P_g) and relative acceleration rate (K) at the velocity V. To solve for P_e we must specify the velocity at which we are relating the power of both vehicles. For vehicles similar to the ones in this analysis, (e.g., $Pmax_g$ = 101 kW at the wheels, and $Cd_e < Cd_g$), we have the following for $Pmax_e$ (kW at the wheels), as a function of velocity V and the performance ratio K:

	K=1.00	K=0.95	K=0.90	K=0.80	K=0.60	K=0.40
1 mph	94.24	88.41	82.63	71.51	50.85	32.10
15 mph	94.30	88.44	82.71	71.67	51.17	32.56
30 mph	94.18	88.42	82.79	71.95	51.79	33.46
45 mph	93.84	88.29	82.88	72.43	52.96	35.20
60 mph	93.17	88.01	82.96	73.21	54.93	38.18
75 mph	92.20	87.57	83.04	74.24	57.67	42.36
90 mph	90.59	86.82	83.12	75.89	62.14	49.26

There are three things to note about these results. First, when the performance of the EV is set equal to, or very close to, the performance of the EV (K=1.0 or 0.95), the peak-motor power required to match (or nearly match) the performance of the ICEV decreases as velocity increases, because the EV in this example has a lower aerodynamic drag, and hence has to do less work to overcome wind resistance. Second, if the peak performance of the EV is much less than the peak performance of the ICEV (K=0.60 or 0.40), then the peak-motor power required to provide the low-level of performance increases as velocity increases, because the wind-resistance term (D) (in the low-performance case) has increased in importance relative to the acceleration term. Third, because these results do not account for differences in the torque curve of EVs and ICEVs, they are not valid for the low-rpm regions where the ICEV has less than full torque available, but the EV has full torque available.

BATTERY COST

The cost of a battery is directly related to the number of cells, and therefore indirectly related to the desired range: the greater the desired range, the more stored energy needed, and hence the more cells required. In a battery-only EV with a range of 100 miles or more, an advanced battery will cost $1000s of dollars. In an FCEV, however, the battery will provide peak power, not range, and hence will contain many fewer cells, and be much less expensive.

In this model, the life-cycle battery cost is estimated as a function of: battery OEM (original equipment manufacturer) cost in $/kWh, $/kW, and $ (a cost constant); cycle life; battery efficiency; energy density in Wh/kg; power density in W/kW; total energy and power capacity; and disposal cost ($/kWh). My analysis assumes that if the vehicle is scrapped before the battery, the value of the battery is directly proportional to its remaining life. This assumption is reasonable given the high cost of batteries, and further assuming that the life of the battery can be measured and that batteries will be easy to install and remove.

Table A.4. Parameters for batteries and battery recharging.

FCEV	BPEV	Battery parameters: input data
6.50	6.50	Battery-power cost coefficient, original equipment manufacturer (OEM) ($/kW)
90.00	90.00	Battery-energy cost coefficient, OEM ($/kWh)
500.00	500.00	Battery cost constant, including tray and auxiliaries, OEM ($)
10.00	10.00	Cost of battery disposal, including recycling cost and any salvage value, as an addition to the retail price of the battery ($/kWh)
800	800	In-use battery life (cycles to 80% depth of discharge specified below)
0.80	0.80	Average DoD throughout battery life (based on total battery capacity)
0.90	0.90	In-use battery energy efficiency, not inc. any energy required for temperature management (kWh out at battery terminals/kWh in from charger)
4	4	Thermal loss (Watts lost per kWh of battery)
36	36	Average hours of heat loss per week (after reaching lowest allowable temp.)
2	2	Number of weeks per battery cycle (in case where battery must heat itself)
1.00	1.00	Depth of discharge (DoD) at desired driving range on battery
0.05	0.05	Weight and size of battery tray and auxiliaries (fraction of weight and size of battery)
5	5	Warm-up time of fuel/cell reformer system, to be provided by battery power (minutes)
Battery recharging: input data		
7.00	7.00	Price of residential electricity at outlet (cents/kWh)
0.90	0.90	Efficiency of the battery charger (kWh to battery/AC-kWh to charger)
230	230	Recharging voltage
50	50	Recharging current (amps)
0	200.00	Full cost of installing a recharging station in home ($/vehicle)
30.00	30.00	Amortization period for recharging station (yrs)
Battery: calculated results (400-km range)		
9.4	58.8	Nominal battery discharge capacity, to provide driving range (kWh)
86.6	123.3	Maximum power of battery (kW)
135	135	Battery life (months)
177	273	Volumetric energy density, inc. jacket and thermal management, but exc. tray and electrical auxiliaries (Wh-discharged/liter)
101	151	Mass energy density, inc. jacket and thermal management, but exc. tray and auxiliaries (Wh-discharged/kg)
719	301	Specific power, inc. jacket and thermal management, but exc. tray and auxiliaries (W_{peak}/kg)
2.51	7.98	Volume of battery, exc. tray and electrical auxiliaries (ft^3)

264	904	Weight of battery, exc. tray and electrical auxiliaries (lb)
4,205	13,625	Retail price of battery, inc. tray and electrical auxiliaries ($)
177	111	Calculated manufacturing (OEM) cost of battery, expressed as $/kWh, exc. recycling
1.84	9.37	Weekly energy required to balance thermal loss from battery (kWh)
Battery recharging: calculated results (400-km range)		
8.67	68.7	kWh at battery terminals (from fuel cell or charger, going into battery) needed to supply battery energy not supplied by regenerative braking (not counting thermal losses)
0.57	7.33	Recharging time needed to provide kWh not provided by regenerative braking (hours)

Documentation to Table A.4

6.50	*6.50*	***Battery-power cost coefficient, original equipment manufacturer (OEM) ($/kW)***
90.00	*90.00*	***Battery-energy cost coefficient, OEM ($/kWh)***
500.00	*500.00*	***Battery cost constant, inc. tray and auxiliaries, OEM ($)***

In support of the Jet Propulsion Laboratory's Advanced Vehicle Assessment (AVA), a battery review board projected that lithium/iron-sulfide batteries would cost $70/kWh, $10/kW, and $750 fixed cost per battery (1982$) to manufacture in the early 1990s (Hardy and Kirk, 1985). I have chosen cost coefficients (in 1990$) for the bipolar lithium/disulfide battery that are close to the coefficients estimated in AVA and that result in a total battery cost that is reasonable when compared with estimates for other advanced batteries (see below).

My cost coefficients are meant to include the cost of the battery tray, electrical auxiliaries, thermal enclosure, and heating system, and of marketing and servicing the battery.

10.00	*10.00*	***Cost of battery disposal, including recycling cost and any salvage value, as an addition to the retail price of the battery ($/kWh)***

Patil et al. (1991) believe that initially battery recycling would cost $30 to $50 per kWh, but that the cost eventually would decline to $10 to $20 per kWh, and perhaps lower. We assume that this cost includes any credit for salvage value.

800	*800*	***In-use battery life (cycles to DoD specified below)***
0.80	*0.80*	***Average DoD throughout battery life (based on total battery capacity, including any energy needed for heating)***

As shown in Table 2, researchers project that Li/S batteries will last for at least 1000 cycles. However, Burke (1991b) notes that "field experience with lead-acid batteries in vehicles and the limited laboratory data available show that battery life on the FUDS or SFUDS is much shorter than that found from constant-current discharge testing" (p. 19). I assume that this will apply to at least some extent to the high-temperature peak-power battery considered here, and so assume a life less than 1000 cycles.

0.90	*0.90*	***In-use battery energy efficiency, not inc. any energy required for temperature management (kWh out at battery terminals/kWh in from charger)***
4	*4*	***Thermal loss (Watts lost per kWh of battery)***
36	*36*	***Average hours of heat loss per week (after reaching lowest allowable temp.)***
2	*2*	***Number of weeks of per battery cycle (in case where battery must heat itself)***

I begin by assuming that a high-temperature Li/S battery would have a constant-current test efficiency of above 90% (see the estimates and discussions of battery efficiency in Table 2.), and an in-use efficiency of 90%. Next, I account for energy required to maintain the high operating temperature. The U. S. Advanced Battery Coalition (ABC) has established a goal to limit heat loss to 3.2 watts per kWh of battery. This goal has not yet been achieved; I assume 4.0 watts/kWh (I also assume that the battery will be heated by 100%-efficient electrical heating). If the vehicle typically was idle for no more than 48 hours per week, and if the battery could cool for 12 hours before reaching the minimum allowable temperature, than 36 hours of heating typically would be required every week. In the base case, I assume that the energy required to heat the battery would come from the wall outlet. In the worse case, the battery would have to heat itself, and would not be recharged from the outlet until it had been 80% discharged (due to driving and heating). To calculate the heating energy required from the battery in this worst case, one must know how many weeks before the battery is recharged. I assume two weeks.

1.00 1.00 Depth of discharge (DoD) at desired driving range on battery

This is just a convention, or definition: I define "driving range" as the range provided by using all the available energy in a battery.

0.05 0.05 Weight and size of battery tray and auxiliaries (fraction of weight and size of battery)

My estimate.

5 5 Warm-up time of fuel/cell reformer system, to be provided by battery power (minutes)

As mentioned in the text, methanol reformers require a few minutes to warm up from cold to their operating temperature. Assuming that motorists would not want to have to wait for the reformer to warm up, and that it would be too expensive to keep the reformer on standby, the battery would have to provide all of the motive power while the reformer was warming up. This extra start-up energy demand would be in addition to the peak-power energy required from the battery over the driving trip.(Actually, not all of this warm-up-time energy would be additional, because during the 5 warm-up minutes there probably would be some peak-power demand from the battery anyway. I ignore this.) To calculate the extra battery energy required while waiting for reformer to warm up, I multiply the warm-up time (in hours) by the average mph driving speed and the average kwh/mi energy consumption rate from the battery. This extra energy requirement would make the battery in the methanol FCEV larger and more costly than the battery in the hydrogen FCEV.

7.00 7.00 Price of residential electricity at outlet (cents/kWh)

This is my estimate of the price of off-peak electricity to the residential sector. The EIA (1990a) projects an average price of 8.0 cents/kWh in the residential sector in the year 2000

0.90 0.90 Efficiency of the battery charger (kWh to battery/AC-kWh to charger)

The efficiency of the recharging depends on the type of charger, the charging algorithm, and the type of battery. External (off-board) chargers typically are 85 to 87% efficient (Chan et al., 1990; Hamilton, 1988a). In 1983 Thimmesch reported that an onboard charger integrated with the inverter was 86% efficient charging a lead/acid battery (Thimmesch, 1983). More modern inverter/charger packages presumably can do better. As shown above, most electronics packages are more than 90% efficient, and presumably could be nearly as efficient when run "in reverse," as chargers, especially if no low-power trickle charging was required. Angelis et al. (1987) note that sodium/sulfur batteries can be charged at constant power, apparently without a trickle or equalization charge period. This eliminates the low-efficiency, part-load charging. Braess and Regar (1991) and Angelis et al. (1987) state that present onboard chargers for Na/S batteries are 90% efficient, and Braess and Regar (1991) state that the efficiency should be improved to 97%.

Hamilton (1985) assumes a 90% recharging efficiency in his analysis of the energy use of EVs. Bentley and Teagan (1992) and Bentley et al. (1992) assume a recharging efficiency of 90% in the year 2000, and 92% in the year 2020.

230 230 Recharging voltage

50 50 Recharging current (amps)

This is the typical maximum current and voltage available on a separate household circuit. I believe that most households would want a 240-volt, 50-amp circuit for recharging EVs, because a 120-volt circuit in many cases would not provide enough power -- that is, would not recharge the vehicle fast enough. As shown below, only very efficient vehicles, or vehicles with relatively short driving ranges, could be recharged in less than 8 hours with a 120-volt circuit. A 240-volt circuit provides twice the power of a 120-volt circuit, and would cut recharging time in half. I believe that most households would find this desirable.

Required voltage and amperage as a function of vehicle efficiency, range, and recharging time.

	Recharging time (hours)				
	2	4	8	12	16
50-mile range, 4.5 mi/kWh (small car)	120/46	120/23	120/12	120/8	120/6
75 -mile range, 4.5 mi/kWh (small car)	240/35	120/35	120/17	120/12	120/9
150-mile range, 4.5 mi/kWh (small car)	cant'do	240/35	120/35	120/23	120/17
50-mile range, 1.5 mi/kWh (van or truck)	can't do	240/35	120/35	120/23	120/17
150-mile range, 3.0 mi/kWh (midsize car)	can't do	can't do	240/26	120/35	120/26
75-mile range, 1.5 mi/kWh (van or truck)	can't do	can't do	240/26	120/35	120/26
150-mile range, 1.5 mi/kWh (van or truck)	can't do	can't do	can't do	240/35	120/35

Each voltage/amperage number pair in the table provides the power needed to deliver the amount of energy required to completely recharge the battery in exactly the number of hours shown. I assume that the battery is charged at full power throughout the charging period. (With some batteries, the last 10 to 15% of the energy must be delivered at low power --- a "trickle" or "finishing" charge -- in order to equalize cell voltages. I do not account for this.) Amperages shown are the *actual* current requirements, not the nominal circuit ratings. Generally, the nominal circuit rating must be higher than the maximum expected demand. I assume that if the power demand exceeds 6.0 kW (120 volts/50 amps) then a 240-volt circuit must be used, but that a home cannot be wired for more than a 12.0 kW (240/volt/50 amp) circuit. Note that 110-volt and 220-volt circuits would require about 10% more amperage to satisfy a particular recharging time, or would take about 10% longer to recharge the battery.

0 200.00 Full cost of a recharging station in a home ($/vehicle)

The cost of the set up would depend on the capacity of the electrical the panel, the length of the run from the panel to the recharging station, the construction of the house, the prevailing wage rates, the type of load-management and safety equipment used, and other factors. The table below summarizes estimates from the literature, and from conversations with electricians and building inspectors across the United States. These estimates indicate that retrofitting an existing house with a 240-volt EV-recharging circuit would cost at least $200 if the installation was relatively simple, and up to $500 if the installation was complex. Building a recharging circuit into a new home at the time of construction would add at least $100 to the price of the home. Safety and load-management devices could cost an additional $300; however, it is not clear if a safety device would be necessary, or how much of the cost of a load-management device should be charged to the EV, since the device might replace the ordinary electric meter that serves the whole house. I assume that it would cost $100 to add an extra circuit to a new home at the time of construction, and an *incremental* $100 for a load-management device in place of an ordinary electric meter. The total -- probably a low-end total -- would be $200.

Installation costs for personal EV recharging outlet, parts and labor (1990$)

	Existing house	New house
Estimates from the literature:		
240-V, 30-amp[a]	220-550	100-190
240-V, 50-amp[a]	310-650	180-230
Safety device[b] (optional?)	110	110
Load management device[c] (optional)	160	160
Total, with 30-amp	*490-820*	*370-460*
Total, with 50-amp	*580-920*	*450-500*
Estimates from electricians[d]		
i) Install a 240-volt, 40-amp outlet; panel has an extra slot for a breaker, and existing service entrance is adequate	~200-300[e]	50-150[e]
ii) If a new subpanel is needed, add:	~100[f]	
iii) If service entrance must be increased, add:	~400[f]	

[a]The cost estimates are originally from Harshbarger (1980). I have updated them to 1990$ using estimates in Hamilton (1988) and the Consumer Price Index (CPI) for home maintenance and repair (USDL, 1991), and have rounded to the nearest 10$. (Harshbarger's estimates also are shown in Hamilton (1988) and in DOE (1990) in 1987$.) The low end of the range for the existing house assumes that the existing panel can accommodate a 240-volt breaker without modification; the high end assumes that a new sub-panel is required, and that more wire (from the panel to the outlet) is required. For the new house, the low end corresponds to a 20-foot run in a garage; the high end corresponds to a 38-foot run in a carport (units in carports require extra weatherproofing). The original estimates in Harshbarger (1980) were calculated from specific data on the amount and price of labor and hardware.

[b]This cost estimate is from Hamilton (1988; see also DOE, 1990), updated to 1990$ (using the CPI for home maintenance and repair [USDL, 1991]) and rounded to nearest $10. The safety device is a ground-fault interrupter, meant to prevent the leakage of hazardous currents.

[c] This cost estimate is from Hamilton (1988; see also DOE, 1990), updated to 1990$ (using the CPI for home maintenance and repair [USDL, 1991]) and rounded to nearest $10. The load-management device is a time-of-use electric meter, which apparently would allow the household to program the recharging of the electric vehicle and prioritize shutdown of recharging and other appliances in the event of a circuit overload. Since this meter would replace the ordinary residential meter, its cost should be allocated to the whole house, not just to the electric vehicle. However, the cost shown is the total cost of the meter, not the allocated cost. (See Hamilton, 1988).

[d]These estimates are based on conversations with electricians, electrical contractors, and building inspectors in northern California and elsewhere. Estimates include $30-$50 for a building permit and inspection fee, to retrofit an existing house. The cost of safety devices and load-management devices is not included here.

[e]The low end of range is for easy installation of outlet close to the panel; the high end is for difficult installation far from the panel.

[f]Electricians and building inspectors felt that in most cases a new subpanel would not be required.

30.00 30.00 Amortization period for recharging station (yrs)

I assume that the recharging circuitry will be put in when the structure is built. The cost therefore will be included in the price of the structure and will be amortized over the typical 30-year loan period.

86.6 123.3 Maximum power of battery (kW)

The maximum power of the battery is equal to: the maximum power required at the wheels of the vehicle (Table A.3), divided by the once-through efficiency of the electric powertrain (Table A.3), plus the power required by accessories, less the net maximum power output of the fuel cell (In the case of the FCEV) (Table A.7). As noted above, the maximum power required at the wheels is calculated from the power of the ICEV (Table A.2) and the desired performance of the EV relative to the ICEV (Table A.3). The once-through efficiency of the powertrain is calculated from component-by-component efficiency assumptions (Table A.3). The net maximum power of the fuel cell is calculated as the gross maximum power less the power required by the auxiliaries (Table A.7). The gross maximum power of the fuel is an input variable. I choose the gross fuel cell power so that the resulting combination of fuel-cell peak power, battery peak power, and battery energy storage result in the lowest lifecycle cost for the FCEV, subject to constraints on the battery power-density to energy-density ratio.

177 273 Volumetric energy density, incl. jacket and thermal management, but exc. tray and electrical auxiliaries (Wh-discharged/liter)

101 151 Mass energy density, inc. jacket and thermal management, but exc. tray and auxiliaries (Wh-discharged/kg)

719 301 Specific power, inc. jacket and thermal management, but exc. tray and auxiliaries (W_{peak}/kg)

2.51 7.98 Volume of battery, exc. tray and electrical auxiliaries (ft^3)

264 904 Weight of battery, exc. tray and electrical auxiliaries (lb)

The power and energy density of a particular battery or not fixed, mutually independent parameters. Rather, they are inversely and non-linearly related: one can design a particular battery to have relatively high energy density and relatively low power density, or vice-versa. Power density and energy density are related quantitatively by the "Ragone function". I developed a Ragone function for the Li/S battery assumed here, using the following performance projections made by Nelson and Kaun (1991):

(W/kg)	*(Wh/kg)*	*(Wh/l)*
318.7	141.6	256.6
319.7	142.1	252.2
339.4	150.8	271.0
558.0	111.6	206.0
657.0	109.5	188.4
718.7	119.8	205.7

Includes jacket, bus bar, heating and cooling

Nelson and Kaun (1991) made these projections for six different configurations of a bipolar Li/S battery, for different electric vehicle applications. I fit a continuous function to these data, and used this function to calculate the battery weight, volume, energy, and power parameters.

177 111 Calculated manufacturing (OEM) cost of battery, expressed as $/kWh, exc. recycling.

This $/kWh manufacturing (OEM) cost is back-calculated from battery characteristics and the total battery retail price above. It compares well with other estimates of the cost of manufacturing advanced batteries, shown in the table below:

Estimates of the cost of manufacturing advanced batteries

Source	battery and type of estimate	$/kWh
USDOE (1991a)	monopolar Li-Al/Fe-S, high production levels	96
USDOE (1991a)	Na-metal/Cl, high production levels	128
USDOE (1991a)	Na/S, high production levels	96
Quinn et al. (1989)	Na/S, 6600 batteries/yr.	112
Liljemark (1992)	Na/S, large-scale production	200
Hirabayashi et al. (1992)	Na/S, 100000 batteries/yr.	146
Hirabayashi et al. (1992)	sealed Pb/acid, 100000 batteries/yr.	75
GM (1992)	sealed Pb/acid	<150
GM (1992)	high-temp Li/S_2	150-500
Belanger et al. (1991)	Lithium/polymer	100-150
Burke (1992)	advanced batteries, USABC goals	100-150
Nichols (1992)	long-term USABC goals	50
Trippe and Blank (1992)	double-layer ultracapacitor	<2000

USABC = U. S. Advanced Battery Coalition. Estimates are in 1989 to 1990 dollars.

In this analysis, the back-calculated $/kWh cost of the large Li/S battery in the BPEV is towards the low end of the range of the cost estimates shown above for various advanced batteries. This is reasonable, because the estimates in the table above are for batteries designed for use in BPEVs. The back-calculated $/kWh cost of the peak-power battery in the FCEV is substantially higher than the $/kWh cost of the BPEV battery, but this also is reasonable, because the FCEV battery contains relatively little energy (the denominator of the back-calculated $/kWh term), but a lot of power (and total battery cost is a function of the amount of power, as well as the amount of energy), and also has fixed-cost peripherals. One would expect that a battery designed to provide maximum *power* would be relatively expensive per unit of *energy*.

0.57 7.33 Recharging time needed to provide kWh not provided by regenerative braking (hours)

For the BPEV, the time shown is that required to recharge a fully depleted battery at the voltage and current assumed above. For the FCEV, the time shown is that required to replace the net drawdown (if any) of the peak-power battery, at the recharging current and voltage above. The peak-power battery in the FCEV might not have any net drawdown at all (that is, the battery might finish a trip with at least as much energy as it started with), because the amount of energy available from regenerative braking might be equal or exceed the amount required for peak-power over the trip.(The battery in the BPEV, on the other hand, always will have a net drawdown during a trip, because it must supply all of the driving energy, including the "net" work required to move the vehicle after regenerative braking. In the FCEV, the hydrogen fuel cell could supply the "net" energy needed to move the vehicle, after regenerative braking replenished the energy provided by the peak-power battery.) Note that the peak-power battery in the FCEV need not be recharged from a wall outlet: the fuel cell could recharge the battery when the vehicle was idle. This would reduce the range of the FCEV, and would be more costly than recharging from the outlet, because electricity produced from solar-electrolytic hydrogen (which itself originally would be produced from electricity) would be more expensive than electricity from the outlet, but it would completely free the FCEV from recharging. Alternatively, one could constrain the size of the peak-power battery in the FCEV to hold no more energy than typically could by provided by regenerative braking. This would result in a higher lifecycle cost, because the fuel cell would have to have more than the economically optimal amount of power (because the battery would be smaller), but again would completely free the vehicle from having to recharge from the outlet.

Table A.5. Cost parameters for hydrogen and methanol production, distribution, and vehicular storage.

Hydrogen and methanol production and distribution: input data	
17.93	Cost of hydrogen production, inc. on-site storage, and compression for pipeline transport ($/million Btu, HHV)
1.05	Cost of hydrogen distribution ($/million Btu, HHV)
10.60	Cost of methanol production, plant gate, ($/million Btu, HHV)
0.13	Cost of methanol distribution ($/gallon)
0.08	Cost of methanol retailing ($/gallon)
0.0645	Higher heating value of methanol (million Btu/gallon)
Hydrogen and methanol and storage: input data	
0.05	Salvage value of hydrogen container at end of life (fraction of initial cost inc. taxes)
300,000	Life of hydrogen container (mi)
8,000	Storage pressure of hydrogen onboard the vehicle (psi)
59.73	Cost of carbon-wrapped aluminum-lined container ($-OEM/ft^3/1000 psi)
4.97	Weight of carbon-wrapped aluminum-lined container (lb/ft^3/1000 psi)
1.325	Size of carbon-wrapped aluminum-lined container (ratio of outer volume to inner volume)
40.00	Cost of methanol storage tank ($-MSRP).
0.40	Weight of liquid-fuel tank (lb-fuel/lb-tank)
Hydrogen and methanol production and distribution: calculated results	
23.74	Cost of hydrogen delivered to motorist, exc. taxes ($/million Btu)
13.86	Cost of methanol delivered to motorist, exc. taxes ($/million Btu)
Hydrogen vehicular storage system: calculated results (400-km range)	
0.33	Hydrogen fuel energy needed, full tank (million Btu)
0.38	Methanol fuel energy needed, full tank (million Btu)
2.47	Weight of hydrogen in a full tank (kg)
2.88	Inner capacity of hydrogen storage tank (ft^3)
3.81	Volume of hydrogen storage system, exc. valves, regulators, & fuel lines (ft^3)
147	Weight of hydrogen storage system, inc. valves, regulators, fuel lines (40%-full tank) (lb)
2,692	Retail price of hydrogen storage system, inc. valves, regulators, & fuel lines ($)

Documentation to Table A.5.

17.93 Cost of hydrogen production, inc. on-site storage, and compression for pipeline transport ($/million Btu, HHV)
1.05 Cost of hydrogen distribution ($/million Btu, HHV)

I have chosen middle-of-the-road estimates for solar-photovoltaic hydrogen, based on the cost ranges of Table 9.

10.60 Cost of methanol production, plant gate, ($/million Btu, HHV)
0.13 Cost of methanol distribution ($/gallon)
0.08 Cost of methanol retailing ($/gallon)
0.0645 Higher heating value of methanol (million Btu/gallon)

The cost of methanol production is based on the analysis if Larson and Katofsky (1992). I assume that methanol distribution and retailing will cost the same per gallon of fuel as gasoline distribution and retailing (Table A.2).

0.05 Salvage value of hydrogen container at end of life (fraction of initial cost inc. taxes)

This is assumption. I have tried to make the container life and salvage value mutually consistent: in this case, I assume a long life (see below) and a relatively low salvage value at the end of life.

300,000 Life of hydrogen container (mi)

The life of the hydrogen storage system is important because it determines the amortized cost-per-km of the system. High-pressure vessels can be expected to have a very long life. For example, one manufacturer warrants its composite cylinders for compressed-natural gas for 10,000 cycles, which implies a lifetime of on the order of 100 years (DeLuchi et al., 1987). And because the containers will be relatively expensive, there will be an economic incentive to keep using them, even after the end of life of the vehicle. I assume that hydrogen containers will last 2 to 3 vehicle lifetimes, and will be transferred between vehicles at little extra cost.

8,000 Storage pressure of hydrogen onboard the vehicle (psi)

This pressure appears to represent a good balance between cost (which increases with increasing storage pressure) and bulkiness (which decreases with increasing storage pressure). As the storage pressure increases, the cost and weight of the hydrogen-storage container increase, but the bulk decreases. The greater weight of the hydrogen container increases the energy consumption and reduces the performance of the vehicle; this in turn necessitates a more powerful motor and battery and a larger hydrogen storage system to maintain the original driving range and performance. The following series of numbers shows the relationship between the hydrogen storage pressure, the breakeven gasoline price, the total selling price of the vehicle, and the total volume of the fuel-cell-plus-battery-plus-hydrogen storage system, taking into account all the interactions between size, weight, performance, range, and cost:

pressure (psi)	b.e. price ($/gallon)	vehicle selling price ($)	system volume (liters)
3,000	1.32	25,019	355.8
4,000	1.34	25,096	318.5
5,000	1.36	25,178	296.9
6,000	1.38	25,265	283.2
7,000	1.41	25,355	274.0
8,000	1.43	25,446	267.5
9,000	1.46	25,538	263.0
10,000	1.48	25,630	259.7
11,000	1.51	25,722	257.4
12,000	1.53	25,815	255.8

The range and the peak-performance of the FCEV are held constant at every pressure. The "b.e. price" is the breakeven gasoline price.

I chose 8,000 psi because it appears that at around this pressure non-ideal gas behaviour begins to noticeably limit the benefits of increasing the pressure. For example, it costs about $0.05/gallon and $180 to go from 6000 psi to 8,000 psi and from 8,000 psi to 10,000 psi, but from 6000 to 8,000 the system volume is reduced by 16 liters, whereas from 8,000 to 10,000 it is reduced by only 8 liters. I think the 16-liter reduction is worth the cost, but that the 8-liter reduction is not.

59.73 Cost of carbon-wrapped aluminum-lined container ($-OEM/ft^3/1000 psi)

4.97 Weight of carbon-wrapped aluminum-lined container (lb/ft^3/1000 psi)

1.325 Size of carbon-wrapped aluminum-lined container (ratio of outer volume to inner volume)

I commissioned an industry consultant to estimate the size, weight, and OEM selling price of hydrogen pressure vessels of several sizes and operating pressures (Price, 1991). The consultant has developed a model, used by the pressure-vessel manufacturing industry, that calculates the OEM selling price of pressure vessels as a function of the type of liner (e.g., aluminum or plastic) and the type of fiber overwrap (e.g., kevlar or carbon), the maximum capacity and operating pressure of the vessel, the safety factor (the ratio of the calculated burst pressure to the maximum storage pressure), the quantity of vessels produced per year, and other factors. Using the estimates provided by the consultant, I calculated the following measures for carbon-wrapped aluminum containers, at four pressures:

tank pressure (psi)	$\$/ft^3/1000$ psi	$lb/ft^3/1000$ psi	ratio of outer displacement to inner
6,000	61.78	5.40	1.259
7,000	60.42	5.07	1.289
8,000	59.69	4.97	1.327
9,000	58.98	4.82	1.360

note: ft^3 refers to the inner capacity of the container. "lb" and "$" here refers to the weight and cost of the container only; no auxiliaries are included. In the final cost and weight calculations I assume that valves, regulators, and fuel lines weigh 30 lbs and cost $72 at the retail level.

I then fit continuous functions to these estimates (using regression analysis to find the functional form with the highest R^2):

$$\text{Cost } (\$/ft^3/1000 \text{ psi}) = 73.86+-0.1580314379*(\text{pressure})^{0.5}$$
$$\text{Weight } (lb/ft^3/1000 \text{ psi}) = 7.8206+-0.0319090832*(\text{pressure})^{0.5}$$
$$\text{Outer volume:inner volume} = 1.1109+1.8066E-06*(\text{pressure})^{1.3}$$

These equations reproduce the original estimates very closely (generally to within 1% or better), and produce plausible results for a limited range of pressures outside the original range used to estimate the equations. I use these equations to calculate the cost, weight, inner capacity and outer displacement of the containers, for the selected input pressure.

40.00 ***Cost of methanol storage tank ($-MSRP).***

The methanol tank would be smaller than the gasoline tank in the baseline ICEV, and therefore should cost slightly less. Data from L. Lindgren (ACEEE, 1990) indicate that a gasoline tank costs about $50.

0.40 ***Weight of liquid-fuel tank (lb-fuel/lb-tank)***

See DeLuchi (1991) for documentation.

2.47 ***Weight of hydrogen in a full tank (kg)***

2.88 ***Inner capacity of fuel storage tank (ft^3)***

3.81 ***Volume of fuel storage system, exc. valves, regulators, & fuel lines (ft^3)***

147 ***Weight of fuel storage system, inc. valves, regulators, & fuel lines (40%-full tank) (lb)***

These results were calculated using the equations shown above. As mentioned above, in the final cost and weight calculations I assume that valves, regulators, and fuel lines weigh 30 lbs and cost $72 at the retail level.

Table A.6. Cost and performance parameters for the hydrogen refueling station.

Compressor cost: input data	
300	Fixed cost of compressor ($/hp, 1975$)
2.10	Compressor cost per unit of output ($/hp/million standard ft^3 [SCF] of hydrogen/day, 1975$)
2.07	Ratio of PPI for current year to PPI for 1975
0.070	Cost of electricity to the commercial sector ($/kWh)
0.05	Annual cost of servicing, labor, and new parts (fraction of initial cost)
0.20	Salvage value of compressor (fraction of initial cost)
Compressor power requirement: input data	
288.80	Initial temperature of hydrogen (degrees K)
50	Initial pressure of hydrogen (psi)
1.05	Compressor output pressure divided by vehicular storage pressure
0.85	Compressor efficiency
4	Factor increase in compression ratio per compressor stage
Storage and refueling equipment: input data	
0.27	Cost of storage cascade, including manifolding, support, safety equipment, and transportation ($/SCF/1000-psi storage)
0.016	Storage capacity of station (SCF) divided by total SCF demanded during peak period
0.10	Gas deliverable from storage at max. vehicular storage pressure (fraction of total SCF of storage)
10,000	Cost of refueling equipment, including meters and safety equipment ($/refueling line)
0.15	Salvage value of storage and refueling equipment (fraction of station initial cost)
0.02	Annual cost of servicing, labor, and new parts (fraction of initial station cost)
Land, building, and other initial costs: input data	
0.15	Other station capital and engineering cost (fraction of cost of compressor and storage and refueling equipment)
20,000	Cost of buildings ($)
2,500	Cost of hook up to gas line ($)
200,000	Price of land ($/acre)
4500	Land required for buildings, exits and entrances (ft^2)
150	Land required per refueling bay (ft^2/bay)
50.0	Land required for gas storage (ft^2 land/1000 SCF storage x 1000 psi pressure)
0.03	Real rate of change in value of land (fraction of original cost per year)
Hydrogen throughput: input data	
12	Number of refueling lines (or bays)
400	Rate of delivery of gas to vehicle (SCF/minute [SCFM])
2.5	Average length of time spent pulling in and out of refueling bay, removing and replacing pump, and paying (minutes)
0.33	Ratio of average non-peak demand to peak demand (assume peak demand = station capacity)
2.00	Hours of peak (maximum) demand rate
20	Hours open per day
360	Days open per year
0.75	Fraction of tank filled per refueling
Operating costs: input data	

7.50	Wage rate ($/hr)
1.50	Average number of shifts per hour
1.60	Overhead on salaries (multiplier)
5,000	Other station operating cost: supplies, water, sewage, garbage, etc. ($/yr.)
Compressor: calculated results	
1,020	Compressor power needed (kW)
2,101	Required capacity of compressor (SCFM at 1 atm, 293.15 K)
3.03	Ratio of compressor capacity (SCFM) to non-peak hydrogen demand (SCFM, per non-peak operating hour)
1.00	Ratio of compressor capacity (SCFM) to peak hydrogen demand (SCFM)
7.9	Average compressor operating hours per operating day
4	Number of stages of compression
Hydrogen: calculated results	
8,400	Final pressure of hydrogen from compressor (psi)
1.38	Hydrogen compressibility factor
1.47	Ratio of specific heats of hydrogen
Demand for fuel: calculated results	
115,084	Hydrogen throughput (million Btu/yr.)
$3.60 \cdot 10^8$	Hydrogen throughput (SCF/yr. at 1 atm, 293.15 K)
779	SCF per vehicle (at 1 atm, 293.15 K)
2,101	Maximum hydrogen demand rate in an hour (SCFM at 1 atm, 293.15 K)
4.5	Vehicles per hour per refueling line, non-peak hours
13.5	Maximum station capacity (vehicles per refueling line, one hour; assume this is peak)
1,286	Average number of vehicles per operating day
4.45	Total refueling time per car, inc. pulling into bay, delivering fuel, and paying (minutes)
Storage system and land: calculated results	
39,492	Required hydrogen storage capacity at station (SCF)
0.1	Non-peak demand provided by station storage (hrs.)
0.150	Land required (acres)
Cost: calculated results	
48	Cost of compressor engine ($/hp, 1975$; based on a regression of $/hp and hp)
949	Compressor cost ($/kW)
968,515	Capital cost of compressor ($)
88,373	Capital cost of storage cascade ($)
176,533	Other station capital and engineering cost ($)
30,005	Cost of land ($)
1,405,926	Total initial cost of station, inc. all equipment, installation, and engineering cost ($)
419,456	Total station operating cost ($/yr.)
127,414	Levelized total initial cost, including resale of land and equipment ($/yr.)
4.75	**Hydrogen retail mark up, before all taxes, $/million Btu**

Documentation to Table A.6.

300 ***Fixed cost of compressor ($/hp, 1975$)***

2.10 ***Compressor cost per unit of output ($/hp/million standard ft^3 [SCF] of hydrogen/day, 1975$)***

I derived these coefficients from a cost-function graph presented in Darrow et al. (1977). Compressor manufacturers I have spoken with recently have confirmed the results estimated here (Barker, 1991; Tothe, 1991; Ward, 1991).

2.07 Ratio of PPI for machinery in 1990 to PPI for machinery in 1990

From U. S. Department of Labor data (USDL, 1990, 1989b). This is used to update the 1975-$ estimates above to 1990-$.

0.070 Cost of electricity to the commercial sector ($/kWh)

This is the commercial-sector price projected by the EIA (1990b) for the year 2000.

0.05 Annual cost of servicing, labor, and new parts (fraction of initial cost)

This is the maintenance-cost factor estimated by two major compressor manufacturers, Dresser-Rand (Tothe, 1991) and Norwalk (Barker, 1991).

0.20 Salvage value of compressor (fraction of initial cost)

This is my estimate, based on my conversations with compressor manufacturers. Dresser-Rand states that compressors will last at least 20 years (Tothe, 1991).

288.80 Initial temperature of hydrogen (degrees K)

I assume that hydrogen would be delivered to the refueling site by underground pipeline, and hence would equilibrate to the temperature a few feet below the surface of the earth. The year-round average temperature underground is about 289 K, or 60 degrees F.

50 Initial pressure of hydrogen (psi)

In urban areas, gas is delivered via pipeline to end users at pressures ranging from just above atmospheric to several atmospheres. The feeder lines running along the streets generally operate at least 50 psi. The higher the inlet pressure the better, because the less compression work has to be done. I assume that at least 50 psi would be available at most hydrogen refueling sites.

1.05 Compressor output pressure divided by vehicular storage pressure

The compressor and the intermediate storage tanks must have a slightly higher maximum pressure than the maximum desired pressure of the vehicular storage tanks, in order to ensure a reasonable rate of gas flow to the vehicle.

0.85 Compressor efficiency

This is the efficiency assumed by Ogden and Williams (1989) in their calculations of the cost of hydrogen compression.

4 Factor increase in compressin ratio per compressor stage

According to the Institute of Gas Technology, there is one stage per each factor of 3 to 5 increase in the compression ratio (Blazek, 1992). I assume one stage per factor of 4 increase in the ratio.

0.27 Cost of storage cascade, including manifolding, support, safety equipment, and transportation ($/SCF/1000-psi storage)

I asked CP Industries, a major manufacturer of steel pressure vessels, to estimate the cost of a storage system designed specifically for hydrogen storage at 8,400 psi. They estimated that an 8-vessel assembly, with a maximum working pressure of 9,300 psi, a typical working pressure of 8,400 psi, and a test pressure of 13950 psi, would cost $112,000, excluding delivery and installation (Carozza, 1991). The assembly would include shut off valves and spring-loaded relief valves, but no manifolding between vessels. Each vessel would have an inner capacity of 12.5 ft^3, for a total of 100 ft^3 for the 8-vessel assembly. At the design pressure of 9,300 psi, the system would store 44,400 SCF of hydrogen. These figures indicate a cost of $0.27 per SCF of hydrogen per 1000 psi maximum storage pressure. Delivery, installation, and manifolding would increase this figure somewhat, but presumably volume orders and competitive bidding also would reduce it. I assume $0.27/SCF/1000-psi for an installed system including manifolding and safety devices. This cost factor probably is valid only for systems similar to the one assumed here.

0.016 Storage capacity of station (SCF) divided by total SCF demanded during peak period

0.10 Gas deliverable from storage at max. vehicular storage pressure (fraction of total SCF of storage)

10,000 Cost of refueling equipment, including meters and safety equipment ($/refueling line)

According to one supplier, a custom-produced complete refueling system designed to deliver 400 to 500 SCFM of natural gas at 3,600 psi would cost about $11,000 (Patterson, 1991). Similarly, Blazek et al. (1991) report $12,500/hose for a complete state-of-the art mass-flow natural gas delivery and metering system (including readouts for price, quantity, and total sale), from the same company. A system custom-made for higher pressures (8,000 to 9,000 psi) would cost more. However, mass-produced systems presumably would cost considerably less than custom-made systems. Considering these factors, I estimate $10,000 dollars for mass-produced very-high-pressure hydrogen refueling equipment.

0.15 Salvage value of storage and refueling equipment (fraction of station initial cost)

0.02 Annual cost of servicing, labor, and new parts, for storage and refueling equipment (fraction of initial station cost)

As noted above, compressor manufacturers estimate that service, labor, and new parts for compressors amount to 5% of the initial cost annually. This percentage should be less for refueling and storage equipment, since the storage equipment has no moving parts and should not require a significant amount of maintenance.

0.15 Other station capital and engineering cost (fraction of cost of compressor and storage and refueling equipment)

The cost of setting up a station probably is a function of the number, size, weight, and complexity of the pieces of equipment. However, most analysts do not estimate set-up costs in detail, but instead either estimate the total dollar set-up cost directly, or express the set-up cost as a fraction of the capital cost of the equipment. For example, in a recent analysis, Taylor et al. (1992) assume that for a compressed-natural-gas station, the cost of setting up the station will be 25% of the combined capital cost of the compressor, storage system and dispenser. However, because the cost of setting up a station is not purely a function of the cost of the equipment being set up, applying this percentage probably will overstate the cost for hydrogen, because the capital cost of the equipment of a hydrogen station will be far higher than the cost for a CNG station. I assume that the set-up cost for a hydrogen station would be 15% of the capital cost.

20,000 Cost of buildings ($)

I assume that the site would have one building of about 400 ft^2, containing a cashier's counter, bathrooms, snack machines, and tools, and that construction would cost $50/$ft^2$.

2,500 Cost of hook up to gas line ($)

My estimate.

200,000 Price of land ($/acre)

My estimate of the price of commercial/industrial land on the urban periphery.

4500 Land required for buildings, exits and entrances (ft^2)

150 Land required per refueling bay (ft^2/bay)

My estimates. These two land requirements are additive. The total amount of land used by the station is equal to the these two land requirements plus the land required for gas storage (estimated below). The total amount of land is multiplied by the land price to obtain the total land cost.

50.0 Land required for gas storage (ft^2 land/1000 SCF storage x 1000 psi pressure)

This metric is multiplied by the amount of hydrogen storage, in 1000 SCF, and divided by the storage pressure, in 1000 psi, in order to obtain the total amount of land devoted to gas storage. I multiply by the amount of storage because the greater the amount of hydrogen stored, the larger or the more the containers required, and hence the more land needed, all else equal. I divide by the storage pressure because the higher the storage pressure, the smaller or the fewer the containers needed to store a given amount of hydrogen, and hence the less the land requirement. The hydrogen storage system designed for this study by CP Industries (Carozza, 1991) has eight bottles, each measuring about 13 inches in diameter by 28 feet long, arranged in two rows of four. The eight-bottle unit has a total footprint of about 240 ft^2 (30 ft. by 8 ft.), and holds 44,400 SCF at 9,300 psi. This results in 50 ft^2 per 1000 SCF x 1000 psi. Note, though, that this applies only to the 4-wide by 2-high stacking of this particular design. If additional bottles were added as a third row on top of the second, or if the unit were stood upright instead of laid "flat", the land requirement as expressed here would be less.

0.03 Real rate of change in value of land (fraction of original cost per year)

At the end of the life of the refueling station the land will be sold. The value of the property at the time of sale will be equal to the value at the time of purchase multiplied by i^n, where i is 1+the yearly change in land value, and n is the life of the station (the number of years between the sale and the initial purchase of the property). The difference between the purchase price and the present value of the sale price (in purchase-year dollars) is the net cost of the land. If the land appreciates in value at a rate greater than the desired rate of return on investment, then the cost of the land will be negative (i.e., it will yield a net return).

12 Number of refueling lines (or bays)

This is my assumption. In this cost model, the greater the number of refueling lines or bays, the lower the per-unit cost of hydrogen, because the station fixed costs are spread out over a larger hydrogen demand. However, hydrogen stations cannot be indefinitely large. I chose the number of refueling bays so that the resultant daily number of vehicles refueled is about what one might expect to find at a busy, relatively large gasoline refueling station.

400 Rate of delivery of gas to vehicle (SCF/minute [SCFM])

The higher the rate of delivery the shorter the refueling time, but the more costly the compressor system. I chose a rate that results in a refueling time comparable to the time it takes to refuel a gasoline vehicle. Note that in this model the cost of the compressor is calculated as a function of the amount of hydrogen delivered per day, which in turn is a function of the SCFM rate.

2.5 Average length of time spent pulling in and out of refueling bay, removing and replacing pump, and paying (minutes)

My estimate. This is used to calculate the maximum number of vehicles that can be accommodated in an hour, which in turn is part of the calculation of the total number of vehicles refueled over the course of a year.

0.33 Ratio of average non-peak demand to peak demand (assume peak demand = station capacity)
2.00 Hours of peak (maximum) demand rate
20 Hours open per day
360 Days open per year
0.75 Fraction of tank filled per refueling

All of these are part of the calculation of the annual demand for hydrogen, which in turn is the denominator in the estimated $/million-Btu-hydrogen selling price. The values shown here are my estimates or assumptions about typical demand patterns and hours of operation. The estimate of the amount of the tank filled per refueling is based on the results of a survey reported in Turrentine et al. (1992).

7.50 Wage rate ($/hr)
1.50 Average number of shifts per hour
1.60 Overhead on salaries (multiplier)
5,000 Other station operating cost: supplies, water, sewage, garbage, etc. ($/yr.)

These are my estimates or assumptions. All of these are part of the calculation of the yearly operating cost of the station.

4 Number of stages of compression

I calculate the number of stages as:

$$\log(CR)/\log(F)$$

where:

CR = the compression ratio (compressor output pressure divided by compressor input pressure)

F = factor increase in the compression ratio per stage.

I round fractional results greater than 0.35 up to the nearest integer.

1.38 Hydrogen compressibility factor

1.47 Ratio of specific heats of hydrogen

Calculated as a nonlinear function of the temperature and pressure of hydrogen, using data from the National Bureau of Standards (Hilsenrath et al., 1955) and CP Industries (Dowling, 1991).

4.75 Hydrogen retail mark up, before all taxes, $/million Btu

This is equal to the total annual cost (levelized total initial cost, plus annual operating costs) divided by the annual hydrogen throughput in million Btu.

Table A.7. Cost parameters for the fuel cell.

Materials costs: Input data	
6.00	Membrane price ($\$/ft^2$)
1.50	Total membrane area/active membrane area
750.00	Catalyst price ($US/troy-oz)
0.100	Total catalyst loading (mg/cm^2)
0.30	Flow-field cost ($/lb)
0.90	Flow-field volume (cm^3/cm^2)
1.50	Flow-field density (g/cm^3)
0.0311	Other areal materials cost ($\$/cm^2$)
10.00	Total cost of materials for heat, air, and water management system ($/kW)
12.00	Total cost of materials for reformer + CO control ($/kW)
6.00	Total cost of extra vehicle electronics needed because of fuel cell system ($-MSRP/kW-max.-from-fuel cell)
Labor costs: input data	
0.830	Assembly and installation of fuel cell and auxiliaries (hrs labor/kW_{peak} (gross), fuel cell)
0.250	Assembly and installation of reformer system (hrs labor/kW_{peak} (gross), fuel cell)
10.00	Wage rate, exc. overhead ($/hr)
2.10	Overhead on labor: benefits, operating costs, supervisor salaries, plant costs (wage multiplier)
1.00	Specific weight of fuel cell stack (kg/kW)
1.00	Specific weight of heat, air, and water management systems for fuel cell (kg/kW)
1.50	Specific weight of reformer and associated systems, and CO control (kg/kW)
Energy efficiency: input data	
0.10	Average energy consumption of fuel-cell auxiliaries, hydrogen case (fraction of fuel-cell gross output)
0.20	Maximum energy consumption of fuel-cell auxiliaries, hydrogen case (fraction of fuel-cell gross output)
0.10	Average energy consumption of fuel cell auxiliaries and reformer, methanol case (fraction of fuel cell gross output)
0.20	Maximum energy consumption of fuel cell auxiliaries and reformer, methanol case (fraction of fuel cell output)
0.86	Ratio of fuel-cell efficiency on methanol to efficiency on hydrogen (Btu-fuel/Btu-electric basis)
Fuel cell life and power: input data	
1,250	Current density at designated maximum power of fuel cell (mA/cm^2-active membrane area)
0.550	Operating voltage per cell at fuel-cell maximum-power point
25.0	Maximum gross power from fuel cell stack (kW)
0.05	Fuel cell salvage value (fraction of initial cost inc. taxes)
1.00	Ratio of fuel-cell calendar life to vehicle calendar life
0.06	Volumetric power density of fuel cell (ft^3/kW_{peak} (gross) fuel cell)
0.06	Volumetric power density of all fuel cell auxiliaries (ft^3/kW_{peak} (gross) fuel cell)
0.10	Volumetric power density of reformer and associated auxiliaries (ft^3/kW_{peak} (gross) fuel cell)
Calculated results (power results based on peak, gross fuel-cell output)	
11.2	Fuel cell calendar life (years)

7,519	Hours of vehicle use sustained by fuel cell
0.458	Net efficiency of fuel cell, auxiliary, and reformer system (Btu-fuel/Btu-electricity-to-powertrain, HHV)
688	Power density (mW/cm^2)
3.51	Cost of catalyst ($/kW)
14.09	Cost of membrane ($/kW)
46.54	Cost of other materials, inc. flow field ($/kW)
3.00	Volume of fuel cell stack and associated water, heat, and air auxiliaries (ft^3)
110	Weight of fuel cell stack and associated auxiliaries (lb)
2.50	Volume of methanol reformer system (ft^3)
83	Weight of methanol reformer system (lbs)
74.13	Total materials cost for fuel-cell system, inc. auxiliaries, but exc. fuel cell electronics ($-OEM/kW)
17.43	Total labor cost for fuel cell and reformer system, exc. fuel cell electronics ($-OEM/kW)
4496	Retail price of fuel cell stack and associated auxiliaries (in both methanol and hydrogen cases) ($)
817	Retail price of methanol reformer system ($)
179.83	Total retail price per kW of hydrogen fuel-cell system, inc. electronics and sales tax ($/kW)
212.50	Total retail price per kW of methanol/reformer/fuel-cell system, inc. electronics and sales tax ($/kW)

Documentation to Table A.7.

6.00 Membrane price ($/ft^2)

This estimate assumes that large quantities of the membrane would be produced. Currently, the Nafion membrane made by Dupont sells for about $60/ft^2, and the experimental membrane made by Dow is not even a commercial product. However, General Electric (1981) wrote in 1981 that "since the basic elements from which Nafion is produced are inexpensive, the ultimate cost will undoubtedly follow the trend of Teflon which went from hundreds of dollars a pound to cents per ft^2 of 5-mil sheets as production increased and competitive materials were made available" (p. 69). Although a PEM may never be as inexpensive as Teflon, because of the additional technology required to make the PEM, the assumption that mass production would greatly reduce the price seems sound. Dow has said that the price of its membrane is fundamentally linked to the volume of production, and would decline considerably if large quantities of the membrane were produced (Gunsher, 1991). DOW said that there are no technical reasons for the price to remain extremely high, and that they intend to price their membranes competitively (Gunsher, 1991).

Furthermore, it might be possible to produce other types of membranes at very low cost. In its cost analysis for PEM fuel cells, General Electric (1981) assumed the use of a trifluorostyrene material that would cost about $6/ft^2 in 1990 dollars. Similarly, A non-fluorinated, simple-hydrocarbon membrane probably could be produced for less than $7.50/ft^2, but it is not known if a hydrocarbon membrane would perform satisfactorily and last long enough. Scherer (1990) states that "synthesizing less costly hydrocarbon membranes... will be a challenge for polymer-and electro-chemists" (p.1013).

In a recent analysis of the cost of FCEVs, Kuhn (1992) assumes that the membrane for a PEM fuel cell would cost $5/ft^2 (1990$) in the year 2000, assuming 100,000 units/year.

"Nafion" and "Teflon" are registered trade names.

1.50 Total membrane area/active membrane area

0.30 Flow-field cost ($/lb)

0.90 Flow-field volume (cm^3/cm^2)

1.50 Flow-field density (g/cm^3)

0.0311 Other areal materials cost ($\$/cm^2$)

These estimates were provided by Keith Prater of Ballard Technologies (Prater, 1991b). According to Ballard, these "technologies and cost factors have been demonstrated in one form or another and are believed to be achievable in near term products".

750.00 Catalyst price ($US/troy-oz)

The price of platinum now stands at about $500/troy-ounce (Commodity Research Bureau, 1990; 1.0 troy ounce = 0.0311 kg), but can be expected to rise as European automobile manufacturers, in response to emission standards recently adopted by the European Economic Community, increase their use of platinum-bearing catalytic converters (Loebenstein, 1990). (When the United States began using catalytic converters in the 1970s, the price of platinum increased sharply [Commodity Research Bureau, 1990].) Moreover, the manufacture of FCEVs instead of ICEVs could increase platinum demand per automobile. In 1989, the United States automobile industry consumed 18.8 million grams of platinum (Loebenstein, 1990), and produced 9.5 million light-duty vehicles (LDVs) (Motor Vehicle Manufacturers Association, 1990) -- about 2 grams per LDV. The fuel cell modeled here would require almost twice this amount -- around 3.6 grams. This increase, combined with the increased demand by European automobile manufacturers, would cause the price of platinum to rise.

However, the rise would be attenuated by several factors: the availability of other noble metals, such as palladium, for catalytic converters in ICEVs and possibly for fuel-cell catalysts; the possibility of recycling platinum; and the price incentive to further reduce platinum loading in fuel cells. Stonehart (1990) states, with regards to phosphoric-acid fuel cells, that the platinum can be recovered easily, and that alloys of platinum and palladium perform better than does pure platinum. If these findings could be applied to PEM fuel cells, the total cost of the catalyst would decline considerably, because palladium costs only 1/4 as much as does platinum (Loebenstein, 1990), and because demand for platinum and hence the price of platinum would fall. Nevertheless, I assume that the catalyst in a PEM fuel cell would be 100% platinum, and that fuel-cell manufacturers would face a platinum price 50% higher than today's price (in 1990$).

Of course, if the fuel cell were sized to meet the peak power demand of the vehicle, the total platinum content would be much higher. A 100-kW (gross) fuel cell, with 0.1 mg/cm^2, would have about15 grams of platinum, an order of magnitude more than in current ICEVs. On the other hand, an increase in the kW/cm^2 current density of fuel cell, or a decrease in the mg/cm^2 platinum loading, would reduce the total amount of platinum.

0.100 Total catalyst loading (mg/cm^2)

Catalyst loading have declined by an order of magnitude over the decade, and are now down to 0.1 mg/cm^2. Researchers at Los Alamos National Laboratory (Wilson et al., 1991) have concluded that PEM fuel cells "can operate on very low platinum loading (0.1 gm/cm^2) while achieving high performance" (p. 4) for at least 2000 hours. Lower loading probably will be achieved by the year 2000.

10.00 Total cost of materials for heat, air, and water management system ($/kW)

General Electric (1981) estimated $\$8/kW_{peak}$ in 1981 dollars, or about $12/kW in 1990 dollars, for the materials in the compressor/expander, condenser, air/water separator, reaction air cooler, exhaust air-water economizer, anode exhaust gas dryer, anode humidifier, and circulation pump. The most expensive items were the circulation pump and the condenser. Kuhn assumes that it would cost $\$3/kW_{peak}$ (1990$)to manufacture 100,000 units of fuel cell "peripherals" per year.

12.00 Total cost of materials for reformer + CO control ($/kW)

General Electric (1981) estimated that the materials in a reformer system for a 20-kW fuel cell would cost $216 in 1981$, or $303 in 1990$ (using the GNP price deflators) -- $15/kW.

Swan (1989) estimated that a methanol reformer would cost \$40/kW_{peak} (1989\$), including construction, overhead, and liability. In Swan's analysis, this implies a materials cost of \$20/kW.

However, until quite recently, there has been virtually no effort to develop methanol reformers for FCEVs, and so it is likely that a serious R & D effort (such as the USDOE is beginning to sponsor) will significantly improve reformer technology and reduce costs. I expect that advanced reformers will cost less and perform better than the reformers available when GE (1981) and Swan (1989) made their estimates.

6.00 Total cost of extra vehicle electronics needed because of fuel cell system (\$-MSRP/kW-max.-from-fuel cell)

Fuel-cell vehicles with a peak-device will require power-sharing and load-leveling algorithms and controls. I assume that these will be available at a reasonable cost (e.g., \$150 for a 25-kW fuel cell).

0.83 Assembly and installation of fuel cell and auxiliaries (hrs labor/kW_{peak} (gross) fuel cell)

General Electric (1981) estimated that it would take 17.5 hours to assemble a 20-kW PEM fuel-cell stack and 0.83 hours to assemble the fuel-cell auxiliaries (excluding the components related to methanol reforming), for a total of 18.33 hours. I assume that by the year 2000 this could be reduced by 15%, to 15.6 hours. However, the fuel cell in the GE analysis had a platinum loading higher than I have assumed. It might take extra time to prepare and apply the very small amounts of catalyst that now are being used in laboratories; I assume an additional 0.5 hours per fuel cell. I assume further that it would take an additional 0.5 hours to assemble the GE fuel cell into the vehicle. The total labor requirement for the 20-kW GE PEM fuel-cell design would be 0.83 hrs/kW.

Note that the cost of equipment and facilities used to manufacture the fuel cell is accounted for in the ratio of the retail price to the manufacturing cost. (The manufacturing cost as defined here is essentially a variable manufacturing cost.)

0.250 Assembly and installation of reformer system (hrs labor/kW_{peak} (gross), fuel cell)

General Electric (1981) estimated that it would take 31.5 minutes to assemble individual components of the reformer system for a 20-kW fuel cell. This results in 0.03 hours assembly/kW. It probably would take an additional several hours to assemble the system and install it into the vehicle. I assume 5 hours for the 20-kW system, or 0.25 hours/kW.

10.00 Wage rate, exc. overhead (\$/hr)

2.10 Overhead on labor: benefits, operating costs, supervisor salaries, plant costs (wage multiplier)

These are based on the values used by L. Lindgren in his detailed analysis of the cost of manufacturing an automobile (ACEEE, 1990).

1.00 Specific weight of fuel cell stack (kg/kW)

In 1990, Ballard's PEM fuel cell with a "Dow-2" membrane had a specific weight of 3.87 kg/$kW_{max.}$ when running on hydrogen and air (Ballard, 1990). However, the latest Dow membrane has worse performance, and as a result the specific weight of the latest Ballard fuel cell is about twice as high (Prater, 1992). Billings (American Academy of Sciences, 1991) reports that his "LaserCel" has a specific weight of 0.81 kg/kW. Meyer (1990) projects a specific weight of 0.91 kg/kW to 4.5 kg/kW for an SPE fuel cell being designed by International Fuel Cells Corporation, operating on hydrogen and oxygen (not air). Maceda (1991) projects 2.5 kg/kW for a PEM stack, now being designed by H-Power, that uses the Nafion membrane and runs on hydrogen and 30 psia air. Lemons (1990) specifies 1.67 kg/kW_{peak} as a design parameter for an automotive fuel cell (including assembly hardware and pressure housing). Appleby (1990) believes that 0.75 kg/kW can be achieved.

1.00 Specific weight of heat, air, and water management systems for fuel cell (kg/kW)

1.50 Specific weight of reformer and associated systems, and CO control (kg/kW)

In 1981, General Electric published a detailed analysis of the cost and weight of a 20-kW fuel-cell stack, reformer, and auxiliary system for motor vehicles. Using GE's component-by-component analysis, I calculate 1.50 kg/kW for the fuel-cell auxiliaries, and 1.65 kg/kW for the reformer. However, as discussed below, there has until quite recently been no serious effort to develop fuel-cell auxiliary systems. Engineers are just now beginning to do so, and R & D over the next decade certainly will improve performance and reduce costs.Similarly, as discussed above, reformer technology certainly will improve over the next decade; I assume a 10% reduction, to 1.50 kg/KW.

0.10 Average energy consumption of fuel-cell auxiliaries, hydrogen case (fraction of fuel-cell gross output)

0.20 Maximum energy consumption of fuel-cell auxiliaries, hydrogen case (fraction of fuel-cell gross output)

PEM fuel cells generally have a circulation pump for water management, and an air compressor to increase the partial pressure of oxygen at the air electrode. (An increase in the partial pressure of oxygen increases the current density and the power density.) Water content in the fuel streams must be maintained at a partial pressure of at least 400 mm mercury, to prevent dehydration of the membrane and the consequent large increase in resistance. To do this, the system must be pressurized, and water must be constantly supplied to the anode. At the same time, water must be removed, to prevent water from accumulating at the cathode and blocking the flow of gas (Springer et al., 1991; USDOE, 1991b). As Springer et al. (1991, p. 2334) put it, "water management within the fuel cell involves walking a tightrope between two extremes".

The amount of energy required for air compression is a function of the output air pressure, the ratio of oxygen into the fuel cell to oxygen consumed by the fuel cell, and other factors. Most fuel-cell systems tested to date use air compressed to 20 to 50 psia (1.4 to 3.4 atm). Using the equation given by General Electric (1981), I calculate that air compression to 50 psia for a 20-kW PEM fuel cell would require a 2-kW compressor (assuming that air enters at 1 atm, that the compressor is 82% efficient, that the cell voltage is 0.72, and that 1.5 times as much oxygen is taken in as is actually consumed by the fuel cell). However, the air system for the 20-kW SPE fuel-cell system being developed for the Energy Partners "Green Car" requires 3.5 kW to compress air to only 30 psia (Jones, 1991). (It is possible that the ratio of oxygen in to oxygen consumed is much higher for the Green-Car system than for the GE system.) The cooling water system in the "Green Car" requires about 1 kW of the fuel cell output.

In their own analysis, GE (1981) assumed a partial pressure of oxygen of 1.30 atmospheres, and a ratio of 1.5 moles of oxygen in to the fuel cell for every mole of oxygen consumed. This required a total air pressure of 10 atmospheres, which in turn required a 4.98-kW air compressor, for a 20-kW fuel cell stack. They calculated that an air expander, working off the fuel-cell exhaust, could supply 3.37 kW of the required 4.98 kW. The remaining compression power was to be supplied by a steam expander, with steam being generated from some of the waste heat of the fuel cell and from the waste heat of the exothermic shift reaction in the methanol reformer. With this design, none of the gross electricity output of the fuel cell was required as compression energy, and air was compressed at a minor cost. However, as mentioned, the GE analysis was for an SPE fuel cell using reformed methanol. In a hydrogen (no-reformer) system, such as is considered here, there would be no shift reaction, and hence no such waste heat to produce steam. (On the other hand, more waste heat from the fuel cell would be available, since none would be diverted to drive the reforming process, as it was in the GE analysis.) According to GE's calculations, the total waste heat from the fuel cell would generate enough steam to make 1.23 kW, short of the additional 1.61 kW needed (4.98 total requirement less the 3.7 provided by the air expander) to compress the air to 10 atmospheres.

Swan et al. (1991) gives the following equation for determining the effective voltage requirement of the air compressor (I have added the Ec term, to account for the efficiency of the compressor):

$$Vc = 1.287/(3600 \times Ec) \times S \times Cp \times T \times [(Po/Pi)^{(k-1)/k} - 1]$$

where:
Vc = the effective air-compressor voltage, accounting for the efficiency of the compressor
Ec = the efficiency of the air compressor (0.82; General Electric, 1981)
S = the number of stoichiometric mixtures, or the ratio of the amount of oxygen input to the amount required by reaction stoichiometry (a design variable)
Cp = specific heat, Joules/gram-Kelvin (1.004 for air)
T = temperature of air at compressor inlet, ^{o}K (298)
Po = air pressure at compressor outlet, psia (a design variable)
Pi = air pressure at compressor inlet, psia (14.7)
k = specific heat ratio (1.4 for air)

This equation gives the following results for Vc as a function of S an Po:

Calculation of Vc as a function of S and Po

	Absolute pressure of outlet air, psia (Po) ---					
	24.7	29.7	34.7	44.7	54.7	64.7
S						
1.0	0.021	0.029	0.036	0.049	0.059	0.069
1.5	0.031	0.044	0.054	0.073	0.089	0.103
2.0	0.042	0.058	0.073	0.098	0.119	0.138
2.5	0.052	0.073	0.091	0.122	0.149	0.172

With these data, one can calculate the effective "net" voltage of the fuel cell (net of the effective air compressor voltage, Vc), simply by subtracting Vc from the gross fuel cell voltage at each point in a V-I plot (Swan et al., 1991). One can then translate a plot of net voltage versus current density into a plot of net power versus current density. I have done this using V-I data plotted for 6 different Po (24.7, 29.7, 34.7, 44.7, 54.7, 64.7 psia, as above), for a Ballard PEM fuel cell with the DOW membrane (performance data at different output pressures from Ballard, 1991).

Net power (gross power less power required for air compression) watts/ft,^{2} as a function of Po and current density, PEM fuel cell using DOW membrane, S = 2.0

	----- Absolute pressure of outlet air, psia ------					
Amps/ft^2	24.7	29.7	34.7	44.7	54.7	64.7
50	39.9	39.5	39.4	38.9	38.1	37.8
100	76.8	76.4	75.7	75.2	73.4	72.8
300	205.6	202.2	205.3	206.2	201.3	198.7
500	304.1	300.0	311.2	316.2	309.1	305.2
700	364.9	361.1	386.7	399.3	391.4	388.8
900	390.0	381.5	411.7	447.7	435.7	444.1
1000	385.3	391.9	407.4	453.4	435.1	452.4
1100	358.9	381.6	385.5	409.6	386.2	417.4

Note that up to about 200 watts/ft^2, there is no advantage to air compression, because the increase in power density due to the greater partial pressure of oxygen is equal to or less than the power requirement of the air compressor itself. However, as the peak power of the fuel cell is approached, the energy benefit of compression exceeds the energy cost. The data used here indicate that the biggest net benefit and the best system performance (above 200w/ft^2) is obtained at around 45 psia, or about 3 atmospheres pressure. Swan et al. (1991), who first presented this idea, report similar findings.

As Swan et al. (1991) note, these findings suggest that it would be best to have a variable-speed "smart" air compressor, programmed to operate at the optimal point depending on the load. Such a compressor might not even operate at low loads. However, at maximum load, the compressor might require about 20% of the gross output of the fuel cell. (For example, for S = 2.0 and Po = 44.7 psia, Vc = 0.10 volts. If the maximum gross output occurred at 0.50 volts [gross], then the effective compressor voltage would be 20% of the gross fuel cell voltage. Similarly, Amplett et al. [1991b] estimate that air compression can require up to 15% of the fuel cell output. However, they also report that this can be reduced to 3% if there is good energy recovery.) One implication of this is that the drive-cycle-average energy requirement of the air compressor, relative to the average energy output of the fuel cell, will be much less than the maximum energy requirement relative to the maximum fuel cell output. I have assumed that here.

If hydrogen were stored on board the vehicle as a highly compressed gas, the potential expansion work available as the hydrogen pressure was stepped down from storage pressure (up to 10,000 psia) to fuel-cell pressure (about 50 psia) could supply a small part of the energy required to run the auxiliaries. The expansion work could be used either to compress the air directly, or to drive a generator that would charge the battery, which then would supply electricity to the compressor motor. In the design of such a system, one would have to consider the drop in available expansion work as hydrogen was consumed and the storage pressure (input to the expander) declined, and the drop in the temperature of the hydrogen as it was expanded. Waste heat from the fuel cell also could be captured and put to work, although at the low temperatures of PEM fuel cells, not much work is available. *I assume, though, that the amount of energy that could be recovered from hydrogen expansion , from waste heat from the fuel cell, or from air expander using fuel cell exhaust would be equal to the amount of energy required to run auxiliaries other than the air compressor.* Prater (1992) states that the subsystems used for gas control, water collection, stack cooling, and system control in a 5-Kw fuel cell consume 250 kW, or 5% of the fuel cell output. As mentioned above, the cooling-water system in the Energy-Partners' Green Car requires 1 kW.

Fuel cell stacks and auxiliaries are only now beginning to be designed as integrated systems, and it is likely that much can be done to minimize the weight, bulk, and economic and energy cost of compressing the air, cooling the fuel cell, and managing water. Amplett et al. (1991b) state that "efficient air compressors and maximum possible energy recovery from pressurized waste gas streams will certainly be key features of a successful integrated reformer/SPFC system" (p. 647). Srinivisan et al. (1989) note that high-power density PEM fuel cells will require "novel thermal and water management techniques" (p. 1628), and cite as an example an internal evaporative cooling technique which simultaneously maintains the fuel cell operating temperature and manages the water and moisture content, without the use of cooling plates in the stack. Another interesting possibility is passive water removal using hydrophilic separator plates (Baldwin et al., 1990). The use of very thin membranes -- desirable in any case because of the lower resistance -- also could simplify water management: Springer et al. (1991) found that with a thin (50-micron) membrane, the back-diffusion of water from the cathode to the anode supplied all the water needed at the anode, thereby eliminating the need for active water transport.

0.10 Average electricity consumption of fuel cell auxiliaries and reformer, methanol case (fraction of fuel-cell gross electricity output)

0.20 Maximum electricity consumption of fuel cell auxiliaries and reformer, methanol case (fraction of fuel-cell gross electricity output)

0.86 Ratio of fuel-cell efficiency on methanol to efficiency on hydrogen (Btu-fuel/Btu-electric basis)

I assume that the energy needed by the reformer comes from either methanol fuel, reformer gas, or heat recovery, but not from electricity supplied by the fuel cell. This means that the auxiliary *electricity* demand on the fuel cell is the same in the methanol case as in the hydrogen case. However, the overall fuel-to-electricity efficiency of the methanol/refomer/fuel-cell system will be less than the overall fuel-to-electricity of the hydrogen/fuel-cell system, because some of the energy in the methanol fuel will, in one form or another, be used in the reforming the reaction. For example, a much-cited analysis by Kumar et al. (1989) indicates that a PEM system with a reformer has an overall efficiency (methanol to electricity, HHV) of 30% -- much less than the typical efficiency of a hydrogen fuel-cell system. Another paper by Kumar et al. (1988) states that a PEM fuel cell has a gross efficiency of 40.3% on methanol, including air compression, but excluding reforming and fuel vaporization. The efficiency with reforming and vaporization is 34.4%. Although advances in reformer technology and in heat management and heat recovery will improve the net efficiency of the methanol/reformer/fuel-cell system, it still will be less efficient -- I assume 15% less efficient, in relative terms -- than the hydrogen/fuel-cell system.

1,250 Current density at designated maximum power of fuel cell (mA/cm^2-active membrane area)

0.550 Operating voltage per cell at fuel-cell maximum-power point

This performance is approximately 25% better than the present performance of the Ballard PEM fuel cell using the DOW experimental membrane (Ballard, 1991, 1990; Prater, 1990). However, Cisar (1991) of Dow Chemical reports 1,600 at 0.55 volts for a Dow XUS013204.10 membrane on 30 psig air and 30 psig hydrogen in a single-cell stack. I assume that such performance will be commercially available within the decade. Bentley et al. (1992) assume 540 mA/cm^2 in the year 2001 and 2150 mA/cm^2 in the year 2020. Maceda (1991, 1992) states that H-Power has achieved nearly the same performance with Nafion as with the Dow membrane.

25.0 Maximum gross power from fuel cell stack (kW)

Note that the fuel cell does not by itself provide the maximum power desired. The maximum net power from the fuel cell, plus the maximum power from the peaking battery, together provide the maximum power needed to run the vehicle, accessories, and fuel-cell auxiliaries. Through iterative calculations, I have found the combination of fuel-cell maximum power and battery maximum power that, subject to certain constraints on the specific power and specific energy of the battery, results in the lowest overall vehicle lifecycle cost per km.

0.05 Fuel cell salvage value (fraction of initial cost inc. taxes)

My estimate.

1.00 Ratio of fuel-cell calendar life to vehicle calendar life

The life of a fuel cell is a function of many factors: the thickness and composition of the membrane, the amount and stability of the catalyst, the quality of the whole fuel cell assembly, the air pressure and operating temperature, the reliability of the auxiliaries, the characteristics of the operating environment (vibrations, shocks, moisture, heat, etc.), and so on. In space applications, fuel cells have been designed to last for tens of thousands of hours (Appleby, 1992). However, such performance requires relatively high-quality -- and hence relatively high-cost -- membranes and assemblies. Ideally, one would find the combination of initial cost and lifetime that resulted in the lowest lifecycle cost, in automotive applications. Unfortunately, not much is known about how fuel cells will stand up in automotive applications, and hence it is not yet possible to design fuel cells for the lowest-lifecycle cost. For example, the relationship between catalyst loading and fuel cell lifetime performance is only now being investigated. Nevertheless, I assume that it would be easy to make a fuel cell that lasted as long as the vehicle (between 5,000 and 10,000 hours of operation) without resorting to extraordinary life-extending designs or unusually high loading of noble-metal catalysts. Appleby (1992) states the mechanical parts of fuel cells are likely to limit the life of the whole system

0.06 Volumetric power density of fuel cell (ft^3/kW_{peak} (gross) fuel cell)

Ballard's PEM fuel cell stack with a "DOW 2" membrane had a specific volume of 0.09 ft^3/kW_{max} when running on hydrogen and air. (Ballard, 1990). However, the latest Dow membrane has lower performance, and as a result the latest Ballard stack has about twice the specific volume (Prater, 1992). Billings (American Academy of Sciences, 1991) reports that his "LaserCel" has a specific volume of 0.09 ft^3/kW, and that Treadwell's PEM fuel cell has a specific volume of 0.15 ft^3/kW. Meyer (1990) projects a specific volume of 0.03 ft^3/KW to 0.15 ft^3/kW for an SPE fuel cell being designed by International Fuel Cells Corporation, operating on hydrogen and oxygen (not air). Maceda (1991) of H-Power projects 0.067ft^3/kW for a PEM stack that uses the Nafion membrane and runs on hydrogen and 30 psia air. Lemons (1990) specifies 0.04 ft^3/kW_{peak} as a design parameter for an automotive PEM fuel cell operating on hydrogen and air. Appleby (1990) believes that 0.03 ft^3/kW can be achieved.

0.06 Volumetric power density of all fuel cell auxiliaries (ft^3/kW_{peak} (gross) fuel cell)

Data and diagrams in the literature indicate that the fuel cell auxiliaries take up about as much space as the fuel cell stack itself. Maceda (1991) of H-Power has confirmed this as a rule of thumb. However, Appleby (1992) states that in general, auxiliaries "will have a weight and volume which is less than that of the stack itself" (p. 226).

0.10 Volumetric power density of reformer and associated auxiliaries (ft^3/kW_{peak} (gross) fuel cell)

My estimate here is a bit lower than other estimates in the literature. Kumar et al. (1988) show that, in a 60-kW-fuel-cell system, a fuel vaporizer and reformer displace 190 liters, and a CO-removal device 60 liters, resulting in about 0.15 ft^3/kW. Patil and Huff (1987) use a value of 0.36 ft^3/kW for a total PEM fuel-cell-plus-reformer system; the reformer probably accounts for 0.15 to 0.20 ft^3/kW. My estimate assumes that progress in reformer technology will reduce somewhat the bulk of reformers.

46.54 Cost of other materials, inc. flow field ($/kW)

By comparison, Kuhn (1992) estimates a manufacturing cost of $8/kW for "fuel-cell stack plates" (100,000 units/year,1990 dollars). H-Power has suggested that it can manufacture these components for much less than I have assumed (Maceda, 1992).

74.13 Total materials cost for fuel cell, inc. auxiliaries, but exc. fuel cell electronics ($-OEM/kW)

Others have estimated lower costs. Appleby (1990) believes that the materials in an advanced, mass-produced PEM fuel cell could cost $10/kW or less.

179.83 Total retail price per kW of fuel cell and reformer system, inc. electronics and sales tax ($/kW)

In this section, I review several previous estimates of the cost of fuel cells. (As noted throughout, I have used parts of some of these estimates here.)

i). In 1981, General Electric (GE) analyzed in detail the cost of producing SPE fuel cells. They considered material, labor, and overhead costs, for producing 1000, 10000, and 100,000 20-kW SPE units per year. The results are shown in the two tables below.

General Electric's (1981) estimate of the cost of manufacturing SPE fuel cells[a]

Units per year:	1,000	10,000	100,000
$/kW, 1981$	238	164	141
$/kW, 1990$[b]	333	294	197
materials cost, %	55%	73%	82%

[a]Fuel cell stack cost only. Includes materials, labor, and overhead. Excludes cost of reformer, air compressor, fuel storage, water management, and electronics. Excludes profit.

[b]Updated to 1990$ using GNP price deflators (*Statistical Abstract of the United States, 1990; Survey of Current Business, 1991).*

The GE estimate has been widely cited (Werbos, 1987; Huff et al., 1987; Huff and Murrray, 1982). Huff et al. (1987) multiply GE's estimate (based on 100,000 units/year) by 1.7, to account for manufacturing profit and the cost of installation, and arrive at an installed cost of $280/kW (their original estimate; not converted to 1990$) for a complete PEM system (fuel cell, reformer, and associated components). Werbos (1987), citing Huff et al. (1987) and GE (1981), states that "it now seems reasonable to project a cost of $2500 for a complete automotive powerplant" (p. 13; Werbos original estimate, not converted to 1990$). This is within the range stated by GE (1981). Huff and Murray (1982) cite GE's estimate of the cost of producing 1000 complete systems/year, excluding installation and profit.

ii). More recently, Swan (1989) has calculated a production cost of $162/peak-kW (1989$) for PEM fuel cells. He assumed that the price of the electrolyte would be 1/5 the present price for large orders of Nafion, but that the price of platinum would be twice as high as at present, due to the increased demand. His estimate, converted to 1990$, is shown below.

iii). Ballard Power Systems, one of the leading developers of PEM fuel cells, has estimated the current cost of its PEM fuel cell, and projected the cost in the near term "assuming cost factors that have been demonstrated in one form or another and are believed to be achievable in near term products" (Prater, 1991). Many of Ballard's projections are used in this analysis. The Ballard estimates also are shown below.

iv). Other people have remarked on the likely cost of fuel cells, without showing details. Nuttal and McElroy (1983) state that with reduced catalyst loading, and a lower cost electrolyte, a PEM fuel cell could produced at "an acceptable manufacturing cost," (p. 7), depending on production volume. They based this assessment on 0.75 gm-platinum/cm^2, a value which has been beaten by nearly an order of magnitude, as noted above.

Appleby (1990), suggests that ultimately, an alkaline system could be produced for "only a few dollars per kW" (p. 275), and that a PEM system may cost about the same.

Summary of previous estimates of the cost of fuel-cell stacks, 1990$[a]

Cost item	GE (1981)[b]	Swan (1989)[c]	Ballard (Prater, 1991) near term[d]	long term[e]	This report
Power density, peak-mW/cm^2	589	1000	540	540	688
Total catalyst loading[f], mg/cm^2	0.81	0.80	0.10	0.01	0.10
Platinum price, $/troy-oz.	622	1055	800	800	750
Membrane cost, $/ft^2	8	10.22	75	5	6
<u>Calculated results</u>					
Catalyst cost, $/peak-kW	67	27	5	< 1	4
Membrane cost, $/peak-kW	27	11	224	11	14
Other materials cost, $/peak-kW	68	45	59	4	46
SUBTOTAL, materials, $/peak-kW	162	83	288	16	64
Factor for labor, overhead, etc.[g]	x 1.22	x 2.00	not estimated		2.23[h]
TOTAL $/peak-kW (exc. tax)	197	166			143[i]

[a]I have updated all the costs in GE (1981) and Swan (1989) except the platinum price to 1990$ using the GNP price deflators (*Statistical Abstract of the United States, 1990; Survey of Current Business, 1991).* The estimates by Ballard (Prater, 1991) are used as given. All estimates are for the fuel-cell stack only; air, water, cooling, and electronic auxiliaries are not included.

[b]Based on 100,000 units per year.

Catalyst loading: GE believed, in 1981, that there was no technical reason that 0.81 gm/cm^2 could not be achieved. Note that this has already has been beaten by nearly an order of magnitude.

Platinum price: as assumed by GE. The current price is about $500/troy-oz.

Membrane cost: GE assumed a Nafion substitute that another source estimated cost $2/ft^2 in 1975. GE inflated this to 1981 dollars at 12%/year, probably because in 1980 inflation in the U. S. was quite high. I have updated the original 1975 estimate ($2/ft^2) to 1990$.

GE apparently assumes that the total area of the membrane is exactly equal to the active area.

Other materials: collectors, backing, end plates, tie plates, insulation.

Labor, overhead, etc.: GE includes labor and factory overhead (based on 100,000 units per year), but not profit or "manufacturing yield".

[c]Power density: Swan's assumption regarding specific power is a performance goal, and assumes technological breakthroughs.

Catalyst loading: Swan shows 0.40 mg/cm^2, but this appears to be per electrode, so that the total loading (there are two electrodes) is 0.80 mg/cm^2.

Platinum price: He assumes that the extra demand for platinum by fuel cell manufacturers will cause the price of platinum to double, to $1055/troy-oz. He assumes no recycling.

Membrane cost: He assumes that very large scale production and the use of thin membranes will bring the cost of Nafion down by a factor of 5, from $550/m^2 to $110/m^2. He appears to assume that the total area of the membrane is exactly equal to the active area. I updated his estimates to 1990$.

Other materials: bipolar plate, electrodes. I back-calculated this from Swan's $/kW and mW/cm^2 data, and updated to 1990$.

Labor, overhead, etc.: Swan labels this "construction, overhead, and liability". He assumes that this is equal to materials cost.

Swan also estimated the cost the reformer ($40/kW), the subsystems (tanks, pumps, etc.; $50/kW), and the cost of the electric motor and controller ($20/kW).

[d]Ballard believes that the near term estimates "represent technologies and cost factors which have been demonstrated in one form or another and are believed to be achievable in near term products". All are numbers are as supplied by Ballard (Prater, 1991).

The near-term membrane $/kW cost assumes 1.50 cm of membrane per cm of active area.

[e]Longer-term cost targets. Assumes 1.10 cm of membrane per cm of active area.

[f]The total amount of electrocatalyst (anode + cathode) divided by the total cm of active area.

[g]Excluding taxes.

[h]Note that this ratio -- the retail price to the materials cost -- is not the same as the ratio of the retail price to the manufacturing cost (discussed above), because in the latter ratio the labor cost already is included in the manufacturing cost.

[i]The difference between this estimate and my $180/kW estimate for the whole fuel cell is that the latter includes the cost of all auxiliaries -- $25/kW -- and the 7% sales tax.

It is interesting to note that these estimates differ considerably in detail, but produce fairly similar bottom-line total costs.

APPENDIX B: MAINTENANCE AND REPAIR (M & R) COSTS FOR EVS AND ICEVS

Maintenance and repair (m & r) costs are the sum of all expenditures for parts and labor, except expenditures for tires, accessories, and oil, which in this analysis are covered separately. Expenses covered by insurance also are not counted. In this appendix, I estimate the yearly amortized cost of maintenance and repairs for gasoline ICEVs, and then estimate the maintenance cost of EVs relative to this baseline.

Maintenance and repair costs for gasoline vehicles

There are two primary sources of information about m & r costs for light-duty gasoline vehicles: cost estimates by the Federal Highway Administration of the U. S. Department of Transportation (USDOT, 1984), and survey data from the Bureau of Labor Statistics of the U. S. Department of Labor (USDL, 1989a). This analysis updates and adjusts the USDOT estimates, using the data from the USDL and other sources.

The USDOT has estimated year-by-year m & r costs for large, intermediate, compact, and subcompact automobiles, and for passenger vans, for the Baltimore area, in 1984 (Table B-1). They define maintenance and repair costs as I have here, as excluding tires, oil, accessories, and costs covered by insurance. They also distinguish between "scheduled" and "unscheduled" costs: "scheduled" costs are the cost of services explicitly suggested or required by the owners manual (e.g., checking the emission control system, changing the oil, tuning up the vehicle, checking the brakes). Costs contingent upon the outcome of an recommended inspection, and all other m & r costs, are considered "unscheduled". For example, if the manual recommends periodic brake checks, and states the conditions under which brakes should be replaced, but does not explicitly establish a replacement interval, then the cost of the inspection is considered scheduled maintenance, but the cost of the replacement is considered unscheduled (because the replacement per se is not explicitly scheduled in the manual). Included under unscheduled maintenance are any repair costs that result from an accident and are not covered by insurance.

To estimate m & r costs, USDOT consulted repair manuals, service managers of major dealers, personnel in the automotive industry, and published statistics. They assumed that *all* labor was done by a professional mechanic, at $26/hour (in 1984). They used retail prices for parts. However, they excluded labor and parts costs for those repairs covered by a normal vehicle manufacturer's warranty (but *not* an extended, 5-year/50,000-mile warranty).

The USDOT data must be adjusted in several ways in order to be up-to-date and otherwise appropriate for this study. In the following sections I address several issues associated with using these data.

1). *Generalizing from the Baltimore area to the whole U. S., in 1984.* The USDOT estimates are based on prices in the Baltimore area in 1984. The first step, then, is to generalize these estimates to the nation as a whole. In 1984-85, households in the Baltimore area had 1.7 vehicles and spent $515/year on maintenance and repairs, or $303/vehicle (USDL, 1989a) (note that the definition of m & r is not very important here, since we are interested in relative costs). In 1984 and 1985, all urban households in the U. S. owned 1.9 vehicles, and spent about $480/year, or $250/vehicle (USDL, 1989a). This suggests that the Baltimore-area estimates should be multiplied by 250/303 = 0.83, to yield nationwide average estimates

2). *Updating to 1990$.* The Consumer Price Index (USDL, 1991) has an index for automotive "maintenance and repair," but their definition of "maintenance and repair" does not include everything that I include. The expenditures that I count as m & r but that the CPI does not apparently are in another CPI category, called "other parts and equipment".

From 1984 to 1990, the price of m & r, as defined by the CPI, rose 25.3%, while the price of other parts and equipment rose only 8.7%. To combine these two inflation rates into a single inflation figure for m & r as *I* define it, the rate for each CPI category must be weighted by the portion of total m & r expenditure (as I define it) that it accounts for.

The CPI shows that consumers spent 2.2 times more on m & r (as defined in the CPI) than on "other private transportation commodities," which is the category that contains "other parts and equipment". Assuming that expenditures on "other parts and equipment" were 40-50% of expenditures on "other private transportation commodities," then expenditures on m & r (as defined by the CPI) were about 5 times expenditures on "other parts and equipment." Thus, the weighted-average price of m & r (as defined by the CPI) and other parts and equipment combined rose by 0.833 x 0.253 + 0.166 x 0.087 = 22.5%. I therefore multiply the 1984 national m & r values (as defined here) by 1.225, to obtain 1990 values.

3). *Accounting for the effect of a manufacturer warranty.* The USDOT estimates exclude m & r costs covered by a "normal" manufacturers warranty (as opposed to an extended, 5-year or 50,000-mile warranty), because consumers do not pay these covered m & r costs when they incur them. However, as DOT notes, a warranty is not free: a consumer pays for a warranty either directly (in the case of some optional extended warranties), or indirectly, in the form of a higher vehicle price. In either case, one would expect the actual price of the warranty, or the implicit price embedded in the vehicle price, to be greater than or equal to the net present value of the m & r expenses the warranty is expected to cover (otherwise, the manufacturers would lose money on the warranty). This means that vehicles with much lower-than-average expected m & r costs (such as EVs) should have a lower (actual-or implicit-) price warranty. This effect should be accounted for.

To properly account for this, one must know either the implicit or explicit price of the warranty, or the expected cost of the m & r it covers (on the assumption that the price of the warranty is about equal to its cost). Unfortunately, DOT's analysis does not specify the warranty or its implicit price, or the cost of the m & r it covers. Therefore, I have assumed that on average a typical manufacturer's warranty covers $75 dollars (1990$) worth of m & r expenses in the first 12,000 miles. I will add this to the first-year totals of Table B-1.

4). *Do-it-yourself maintenance and repair.* DOT assumed that all m & r was done by professional mechanics. However, many consumers do minor servicing, such as tuning the car and changing the oil, themselves. Presumably, these consumers feel that what they pay for parts and tools, plus the total value of their time, is less than what they would pay a professional for the same service (plus the time cost of having a car serviced professionally). This means that the DOT assumption -- that all work is done professionally -- overestimates the actual consumer cost of m & r.

To quantify this overestimation, one would have to know how much consumers spend on tools and parts, how much time they spend on the repair job, how they value the time spent servicing their vehicle, and how much they would have spent to have the job done professionally. It is virtually impossible to quantify these factors. The value-of-time problem alone is severe, as some consumers despise repair work (and so have a high time cost) and some may actually enjoy it (and so have negative time cost).

Rather than guess at the extent of overestimation, I let the DOT estimate stand as an overestimate in this respect -- to be balanced, generally, by way in which DOT underestimates costs (discussed next).

5). *Cost of time associated with having car serviced by a professional mechanic.* The DOT estimates do not include the psychic "cost" of discovering and dealing immediately with a automotive problem, the value of the time required to take a car to and from a mechanic, or the value of the inconvenience of being without the car (if one does not get a replacement from the shop). These nonmarket costs might be a nontrivial fraction of the cash outlays for m & r. Rather than attempt to quantify them, though, I omit them and let them counterbalance the overestimate (discussed above) that is built into the DOT estimate.

6). *Portion of m & r costs attributable to accidents.* DOT assumes that the typical motorist will be responsible for one accident during the time she or he carries collision insurance, and hence have to pay, once, the deductible portion of the insurance, which DOT assumes to be $100. It appears that DOT assumes that this expense is occurred in the fourth year. DOT assumes that there are no more accident-related expenses over the life of the vehicle.

If EVs are sufficiently like gasoline vehicles, then driving patterns and behavior will not change as a result of a switch to EVs, and hence the frequency and cost of accidents should not change. I assume this to be the case here. This means that the cost of repairing accident damage will not change, which in turn means that the $100 deductible expense will be incurred by EVs in the fourth year, too. Since this is a fixed (probabilistic) expense for both types of vehicles, and is unrelated to the reliability and design of the powertrain, I will remove it from the m & r expense series, and place it under insurance costs.

7). *Comparison of USDOT data with data from the USDL and the U. S Government Accounting Office.*

i). As noted above, consumers in Baltimore reported spending $303 on m & r and tires per vehicle per year in 1984-85 (USDL, 1989a). The USDOT (1984) estimates are much higher than this: $606 for m & r and tires per vehicle per year, for a mid-size vehicle, in Baltimore in 1984; $522/year for a compact vehicle, and $586/year for a subcompact.

However, there are two strong reasons to expect the DOT estimates to be much higher than the USDL consumer-expenditure estimates. First, the USDL figures include only what consumers actually pay for parts and professional labor; they do not include the cost of any labor done by the consumers themselves. The DOT estimates, on the other hand, assume that all labor is performed by professional mechanics. If consumers perform a substantial amount of repairs themselves, then one would expect the DOT estimates to be much larger than the USDL estimates.

Second, the USDL estimates cover only direct, at-the-time payments for m & r, and hence exclude all costs covered under all warranties, whereas the DOT estimates exclude only costs covered by short-term warranties. If many people had extended warranties in 1984, and if many costs were covered by these warranties, one would expect the USDL estimates to be significantly less than the DOT estimates.

Of course, it is possible that DOT simply overestimates m & r expenses. Without being able to quantify the differences between the DOT and the USDL estimates, though, it is impossible to assess this possibility.

ii). The U. S. Government Accounting Office (GAO, 1991) reports that the fleet of vehicles operated by the General Services Administration has a m & r cost of 5 cents per mile. This results in about $500/year, using the 10,000 mile/year basis of the USDOT analysis. This $500/year figure is close to, but actually a bit higher than, the updated USDOT (tire cost excluded). Since the GSA presumably charges all labor time, this is a good validation of the USDOT estimates.

8). *Future maintenance and repair costs.* Ideally, one should compare the m & r costs of EVs with the m & r costs of ICEVs in the future target year of the analysis. One might do this by projecting future m & r costs for ICEVs, based on historical trends in real m & r costs, and anticipated new forces in the future.

Table B-2 shows that from 1984 to 1989, *reported direct* m & r expenditures per vehicle remained relatively constant, in 1990$. Although it is possible that *total* expenditures (direct cash expenditures, plus do-it-yourself costs, plus the actual or implicit price of warranties) did change appreciably, because of a systematic bias in reporting, or because warranties covered increasingly more or less repair work, or because consumers were doing more or less work themselves, I do not have reliable evidence of such effects. I therefore assume that real total expenditures on m & r have been relatively constant in the recent past.

It is possible that the cost of maintaining and repairing increasingly stringent and sophisticated emission control equipment will raise overall m & r costs over the next decade. However, any such trend is likely to be dampened somewhat by the use of on-board emission control diagnostic systems, which will help keep the systems operating properly.

This brief analysis suggests that there is little ground for projecting a radical change in real m & r costs in the future. Therefore, I use assume that m & r costs in the target year of this analysis will be the same in real dollars as I have estimated they were in 1990.

Summary. This analysis starts with USDOT (1984) estimates of the cost of scheduled and unscheduled m & r in Baltimore, for several vehicle types (Table B-1). These figures are then generalized from Baltimore to the U. S., updated to 1990 labor prices and parts prices, and adjusted to account for the effect on m & r costs of manufacturer warranties and collision insurance. My adjusted 1990 estimates are shown in Table B-3. The DOT estimates are roughly consistent with expenditure data form USDL surveys, when important differences between the two data- collection methods are accounted for.

Maintenance and repair costs for electric vehicles

Eventually, when EVs are produced and serviced and maintained in large numbers, they will have lower m & r costs (excluding tires and oil) than ICEVs, because electric drivetrains are simpler and more robust than ICE drivetrains. Many cost analysts have assumed that the m & r costs for EVs will be about half the costs for comparable ICEVs (GM, n.d.; SERI, 1981; Asbury et al., 1984; Edwards, 1984; Cohen, 1986; Humphreys and Brown, 1990; Morcheoine and Chaumain, 1992). For example, in an analysis done in support of the introduction of 300 commercial EVs in Britain, Edwards (1984) assumes that EVs will have 50% lower m & r costs than comparable ICEVs. Similarly, a cost model developed by the Jet Propulsion Laboratory for the USDOE assumes that total maintenance costs per mile for a Pb/acid-battery EV will be 40% lower than the costs for an ICEV (Humphreys and Brown, 1990). General Motors (n.d.) asserted that "G-Van owners could save up to 50% on normal maintenance operations" (p. 2).

There is a fair amount of evidence of lower m&r costs. Kocis' (1979) survey of consumer experience with EVs found that EV operators considered maintenance and operating costs to be substantially lower than for ICEVs. The electric milk delivery fleet in England was reported to have 35% lower m & r costs than the comparable ICEV fleet (Hamilton, 1984). A utility in the U. K. reports that EVs have 60% lower unscheduled maintenance costs than comparable diesel-powered vans . Marfisi et al. (1978), using data compiled by Hamilton (1974) on the percentage of engine-related business at auto repair shops and parts stores, estimated that per-mile maintenance costs for the EV would be 66% lower than those for comparable ICEVs (they excluded tires, as I do, but included oil).

A recent comparison of the Griffon electric van with conventional ICE vans showed that the Griffon had only a 25% lower maintenance cost-per-mile than the ICEVs, excluding battery watering and oil, but including tire cost (Brunner et al., 1987a, 1987b). Further analysis showed that costs related to the engine were only about 24% of total maintenance costs for ICEVs, a figure sharply lower than that estimated in Hamilton et al. (1974) and Marfisi et al. (1978). Part of this relatively high m & r cost for the Griffon vans was attributable to unfamiliarity with EVs. More importantly, however, the authors note that the ICE vans were withdrawn from service and sold before accumulating 60,000 miles, which was about when major transmission and engine repairs were expected. This suggests that the electric Griffon's m & r advantage was greater over the second 60,000 miles of both vehicle's lives, and that it averaged better than 25% lower m & r costs over the whole of both vehicles' lives.

In sum, both engineering analyses and operational data show that electric-motor vehicles have considerably lower m & r costs than ICEVs. It probably is reasonable to assume that EVs have a greater advantage with respect to unscheduled costs (such as unexpected motor or transmission problems) than scheduled costs (such as checking the brakes).

My assumptions for maintenance and repair

Based on the preceding analysis, I assume that a BPEV with a maintenance-free battery would have 25% lower scheduled m & r costs, and 40% lower unscheduled m & r costs, than a comparable ICEV, up to the life of the ICEV. These assumptions are more conservative than many others in the literature; however, I feel that they are realistic. I start by making assumptions for BPEVs, rather than for FCEVs, because all the available evidence and analyses pertain to BPEVs, and not to FCEVs, which will have two additional large and expensive components: a fuel cell, and a fuel storage/processing system. I specify a "maintenance-free battery" because advanced batteries, such as the ones assumed in this analysis, will be maintenance free. Finally, I start with an assumption that applies "up to the life of the ICEV," because that typically is the basis of cost comparisons reported in the literature. To estimate the relative m & r costs of FCEVs, or of BPEVs or FCEVs with a longer life than ICEVs, additional assumptions are necessary:

i) FCEVs will have two kinds of additional m & r costs: those associated with the fuel cell stack, and those associated with the fuel storage or processing system (the hydrogen storage system or the methanol reformer). I assume that these costs will be related to the complexity of the system, and express them as a fraction of the annual m & r cost of the BPEV. I estimate that it will cost less than $40/year to maintain PEM fuel cells, and very little to maintain high-pressure hydrogen storage tanks, which are extremely simple and rugged .(Hydrogen tanks might need to be leak-tested occasionally.)

ii) I assume that the m & r expenditures in most of the out years of the life of an EV (the years beyond the life of the ICEV) will be relatively small, because of the high reliability of the electric drive. However, the parts that an EV will have in common with an ICEV -- the suspension, body, interior, brakes, frame, and more -- will continue to deteriorate, and be prone to failure. The owner of an old EV either will have to pay a large amount of money occasionally to maintain and repair these parts, or else scrap the vehicle. I assume that in a few of the out years, there will be a relatively large expenditure on the body, interior, chassis, etc. With this in mind, I have estimated the m & r expenditure schedule shown in Table B-3. (Note that I have, in fact, tried to make the assumption about vehicle life consistent with the m & r cost schedule, by accounting for the inevitable deterioration of the parts that EVs will have in common with ICEVs.)

The final assumed and calculated m & r costs, for BPEVs, are shown in Table B-3. (Increments for fuel cells or fuel storage systems are not shown here.)

Do consumers recognize and evaluate maintenance and repair costs?

I have argued here that fuel-cell vehicles will have considerably lower m & r costs than ICEVs, and that this cost reduction will partially offset the higher initial cost, from a life-cycle-cost point of view. Now, it is widely accepted that many fleet operators calculate life-cycle costs explicitly, and so can be expected to account for the m & r cost reduction of EVs in the way I have here. Unfortunately, though, the fleet-vehicle market is tiny compared to the household-vehicle market, and most households apparently do not do calculate life-cycle costs *explicitly.* (For example, Patil and Huff [1987] argue that "life cycle costs are not usually used to determine economic feasibility in passenger car applications" [p. 998]).If households do not even *qualitatively* weigh running costs against initial costs, then either the maintenance cost reduction of EVs will not be realized, or else it will have to be translated into a purchase incentive. It is of some interest, then, from both an analytical and a policy-making standpoint, to find out if consumers are likely to weigh lower m & r costs against higher a initial cost.

To address this question econometrically, one would need to know, for a large set of vehicles, the selling price and all attributes of the vehicles, including m & r costs, that determine consumer utility. There would have to be reasonable variation in the expected m & r costs, and one would have to believe that buyers were aware of differences in m & r costs. Unfortunately, it is not likely that buyers choosing among spark-ignition vehicles consider m & r costs, because m & r costs are not posted on the vehicle, are not evident by inspection, and generally are not well known. However, diesel vehicles do have appreciably lower m & r costs than gasoline vehicles (Redsell et al., 1988), and buyers choosing between spark-ignition (gasoline) and compression-ignition (diesel) vehicles are aware of this (Kurani and Sperling, 1989).

It might be worthwhile, then, to try to find the implicit price of lower maintenance costs and longer vehicle life, by comparing purchases of diesel vehicles and gasoline vehicles. For my purpose, though, it is sufficient to note that car buyers do indeed take account of reduced m & r costs. The case of diesel vehicles is enlightening. Light-duty diesel vehicles are harder to start, noisier, dirtier, and up to $1000 more expensive than their gasoline counterparts, but have lower fuel and m & r costs (Kurani and Sperling, 1989). Buyers of light-duty diesel-fuel vehicles expect the lower fuel and m & r costs to compensate for the disadvantages, including the higher initial cost (Kurani and Sperling, 1989). Kurani and Sperling's (1989) survey of diesel-car buyers shows clearly that people who chose diesels over gasoline vehicles did so in part because of the lower maintenance costs of the diesel.

Of course, one could argue that the people who choose diesels probably are unusually concerned about maintenance (and fuel) costs. This probably is true. However, EVs are likely to have much lower m & r costs than even diesels, and so will appeal to people who are less concerned with m & r costs. Interviews of participants in a recent EV test-drive clinic do suggest that consumers will recognize the lower m & r costs of EVs. Turrentine et al. (1991) write:

"The initial inspection of EVs convinced some participants that the motor was so simple there would be little to repair...When asked to reflect upon maintenance costs of EVs, many thought about electric appliances such as their refrigerator and commented that there was little that could go wrong" (p. 30).

It appears, then, that consumers very likely will account for the lower m & r costs of EVs. (Whether they do so explicitly, using the rate of interest used here, is another question, which I do not address.)

Table B-1. FHWA (USDOT, 1984) estimates of year-by-year scheduled and unscheduled maintenance costs for three vehicle types (1984$).[a]

			Midsize 21 mpg		Compact 26 mpg		Subcompact 27 mpg	
Vehicle age (yrs)	Yearly VMT	Cum. VMT	sched. maint.	unsched. maint.	sched. maint.	unsched. maint.	sched. maint.	unsched. maint.
1	14500	14500	65	12	35	10	28	9
2	13700	28200	108	48	110	45	74	40
3	12500	40700	111	364	93	218	111	319
4	11400	52100	108	306	82	226	56	325
5	10300	62400	66	897	50	510	65	684
6	9700	72100	232	733	169	613	187	1036
7	9200	81300	66	1101	35	1461	56	1289
8	8700	90000	109	516	109	561	54	519
9	8200	98200	111	239	81	122	107	198
10	7800	106000	144	15	83	10	136	9
11	7300	113300	24	11	35	7	51	6
12	6700	120000	24	11	35	7	17	6

[a]The midsize vehicle weighs less than 3500 lbs, the compact less than 3000 lbs, and the subcompact less than 2500 lbs. The estimates are based on parts prices and labor rates (26.33/hour) in Baltimore, Maryland, in 1984. VMT = vehicle miles traveled. sched. maint. = scheduled maintenance. unsched. maint. = unscheduled maintenance. These are the original USDOT FHWA estimates; none of the adjustments discussed in the text have been made.

Table B-2. U. S. average annual expenditures per vehicle, from consumer expenditure surveys,1984-1989.[a]

	Insurance		Other[b]		Maintenance and Repair[c]	
Year	current$	1990$	current$	1990$[d]	current$	1990$[e]
1984	$183	$300	$71	$99	$253	$301
1985	$201	$299	$79	$105	$255	$298
1986	$213	$283	$84	$107	$257	$293
1987	$231	$283	$80	$97	$257	$285
1988	$254	$290	$89	$103	$277	$299
1989	$288	$308	$94	$103	$281	$292

[a]1984-1986 expenditure data (in current dollars) from USDL (1989). 1987-1989 expenditure data (in current dollars) from USDL (data transmittal, 1991). I have adjusted current or nominal dollars reported in the expenditure surveys to 1990$ using the consumer price index for each expenditure category (USDL, *CPI Detailed Report*, 1991). (The USDL shows the index as of December of each year; I have used the midpoints between the December indices to represent the calendar-year averages.) See also notes c and d.

[b]Expenditures on leased and rented vehicles (including trucks), inspection fees, state and local registration fees, driver's license fees, parking fees, towing charges, and tolls.

[c]Expenditures on all maintenance, repairs, and parts, including batteries, tires, transmission fluids, oil changes, exhaust system repairs, brake work, auto repair policies, and much more.

[d]We adjust the "other" current-$ expenditures reported in the expenditure survey to 1990$ by applying price indices from the CPI category (USDL, *CPI Detailed Report*, 1991) that most closely matches the "other" category in the expenditure surveys. The CPI price category called "automobile fees," which includes registration, licensing, inspection, and "other automobile-related fees," appears to be identical to the "other" expenditure category from the consumer expenditure surveys.

[e]We adjust the "m & r" current-$ expenditures reported in the expenditure survey to 1990$ by applying price indices from the CPI category (USDL, *CPI Detailed Report*, 1991) that most closely matches the "m & r" category in the expenditure surveys. The CPI has a price category called "automobile maintenance and repairs," and a category called "other private transportation commodities." This second category includes tires, oil, coolant, and other parts, products, and equipment. These two CPI categories -- m & r, and "other private transportation commodities" -- appear to correspond to the single "m & r" category in the consumer expenditure surveys. Hence, the two CPI indices that cover the m & r category of the expenditure surveys must be combined into a single index, by weighting each CPI-index category by its relative importance. The relative importance of each of these two categories of the CPI is defined as: expenditures in each category divided by the sum of expenditures in both categories. According to the CPI "relative importance" index, consumers spend 2.2 times as much on maintenance and repairs (as defined by the CPI) as on "other private transportation commodities" (USDL, *CPI Detailed Report*, 1991). Hence, I multiply the m & r CPI by 0.69, and the "other..." CPI by 0.31, and

sum, to get a weighted CPI to apply to the m & r category defined in the USDL consumer-expenditure survey.

Table B-3. My estimated and assumed maintenance and repair costs for ICEVs and battery-powered EVs, as a function of vehicle VMT (1990$).[a]

	ICEV maintenance costs		EV maintenance costs	
Cumulative VMT (miles)	scheduled	unscheduled	scheduled	unscheduled
14,500	66.34	86.79	49.76	52.08
28,200	110.04	48.75	82.53	29.25
40,700	113.11	369.84	84.84	221.91
52,100	110.11	210.64	82.59	126.38
62,400	67.02	912.16	50.27	547.29
72,100	235.71	745.60	176.78	447.36
81,300	67.35	1,119.69	50.51	671.81
90,000	110.57	524.55	82.93	314.73
98,200	112.55	243.45	84.42	146.07
106,000	146.72	15.07	110.04	9.04
113,300	24.49	11.13	18.37	6.68
120,000	24.52	11.58	18.39	6.95
126,200			40.00	30.00
132,000			40.00	30.00
137,500			40.00	150.00
142,700			40.00	30.00
147,700			30.00	75.00
152,700			30.00	30.00
157,700			30.00	30.00
162,700			30.00	30.00
167,700			30.00	250.00
172,700			30.00	50.00
177,700			30.00	50.00
182,700			30.00	50.00
187,700			30.00	50.00
192,200			30.00	50.00
196,700			30.00	50.00
201,200			30.00	250.00
205,700			30.00	50.00
210,200			30.00	50.00
214,200			30.00	50.00
218,200			30.00	50.00
222,200			30.00	50.00
226,200			30.00	50.00
230,200			30.00	50.00

[a]Based on data from USDOT (1984), USDL (1991, 1989) and other sources. See the text for an explanation of the methods and data sources used.