**RESEARCH AND DEVELOPMENT OF
PROTON-EXCHANGE-MEMBRANE (PEM)
FUEL CELL SYSTEM FOR
TRANSPORTATION APPLICATIONS**

**FUEL CELL INFRASTRUCTURE
AND COMMERCIALIZATION STUDY**

CONTRACT NO. DE-AC02-90CH10435

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OFFICE OF TRANSPORTATION TECHNOLOGIES**

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FOREWORD

This report documents the results of "Research and Development of Proton-Exchange-Membrane (PEM) Fuel Cell System for Transportation Applications" performed by the Allison Gas Turbine Division of General Motors Corporation under contract DE-AC02-90CH10435. The objective during Phase I was to develop a methanol-fueled 10-kW fuel cell power source and evaluate its feasibility for transportation applications. Specifically, this report documents the results of a study undertaken to describe and prepare preliminary evaluations of the manufacturing facilities, infrastructure, and commercialization processes which will be required for the successful development of fuel cell engines for commercial and private vehicles.

This work was funded by the U.S. Department of Energy (DOE), Energy Efficiency and Renewable Energy, Office of Transportation Technologies, Office of Propulsion Systems, Electric/Hybrid Propulsion Division. Project and technical management was provided by Dr. Pandit Patil and Mr. Robert Kost of DOE's Office of Transportation Technologies with technical oversight and advice provided by Mr. Clinton Christianson and Dr. James Miller of Argonne National Laboratory. Dr. Howard Creveling and Dr. Robert Sutton of Allison Gas Turbine Division of General Motors were the Program Manager and the Technical Director, respectively, for this project.

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I. OBJECTIVES

This paper has been prepared in partial fulfillment of a subcontract from the Allison Division of General Motors under the terms of Allison's contract with the U.S. Department of Energy (DE-AC02-90CH10435). The objective of this task (*The Fuel Cell Infrastructure and Commercialization Study*) is to describe and prepare preliminary evaluations of the processes which will be required to develop fuel cell engines for commercial and private vehicles. This report summarizes the work undertaken on this study. It addresses the availability of the infrastructure (services, energy supplies) and the benefits of creating public/private alliances to accelerate their commercialization. The Allison prime contract includes other tasks related to the research and development of advanced solid polymer fuel cell engines and preparation of a demonstration automotive vehicle.

The commercialization process starts when there is sufficient understanding of a fuel cell engine's technology and markets to initiate preparation of a business plan. The business plan will identify each major step in the design of fuel cell (or electrochemical) engines, evaluation of the markets, acquisition of manufacturing facilities, and the technical and financial resources which will be required. The process will end when one or more companies have successfully developed and produced fuel cell engines at a profit.

A number of possible approaches to the commercialization of electrochemical or fuel cell engines are described. Regulatory and market changes which will influence the market are summarized. Discussions are included of competitive propulsion systems, their development status, costs, and benefits. The term electrochemical engine, or fuel cell engine, is used to describe the total propulsion package. The fuel cell itself bears the same relationship to an electrochemical engine as the piston and cylinder do to an internal combustion engine.

This study addressed the status of the information which will be required to prepare business plans, develop the economic and market acceptance data, and to identify the mobility, energy and environment benefits of electrochemical or fuel cell engines. It provides the reader with information on the status of fuel cell or electrochemical engine development and their relative advantages over competitive propulsion systems. Recommendations and descriptions of additional technical and business evaluations (scenarios), that are to be developed in more detail in Phase II, are included.

II. SUMMARY AND CONCLUSIONS

This Summary and Conclusions Section provides an introduction to this report. This section also serves as an Executive Summary for those readers who desire to understand the implications to the United States of the use (mandated or economically driven) of advanced propulsion and energy systems.

This paper describes the manufacturing facilities, infrastructure, and commercialization processes which will be required for the successful commercialization and development of fuel cell engine propulsion systems. It summarizes available information on fuel cell engine propulsion systems, their development status, costs and benefits, and the availability of supporting services (in particular, fuel supplies). Several processes which could be used to accelerate the development and commercialization of fuel cell engines are described. The kinds of information which public and private decision makers require to justify their investments in fuel cell engine research and development include:

- The extent to which transportation needs may be better served by fuel cell engine powered vehicles
- The external forces (economic and regulatory) which influence the introduction of fuel cell engines and compatible energy supplies
- Knowledge of competitive propulsion systems and their relative technical and economic benefits in selected vehicle applications
- The functions or infrastructure (fuel supplies, maintenance, etc.) which will be required for the public to effectively use fuel cell engines
- The processes required to develop commercial versions of fuel cell engine propulsion system powered vehicles.

The objective of this program task was to identify problems and describe the processes which, if implemented, will accelerate the commercialization of fuel cell engine propulsion systems. It includes recommendations for further analysis including the development of additional technical, marketing, and economic information. Strategies which could minimize inadvertent delays, which may be caused by "non technical barriers" such as government procurement regulations, are discussed.

The terms electrochemical engine (ECE), fuel cell engine, fuel cell propulsion system, or fuel cell engine propulsion system are used interchangeably when the entire propulsion system is being discussed.

As noted in the Table of Contents, this Study addresses six (6) major topics:

- **TRANSPORTATION REQUIREMENTS**
- **ENERGY AND ENVIRONMENTAL CONCERNS**
- **CHARACTERISTICS OF ADVANCED PROPULSION SYSTEMS**
- **COST AND AVAILABILITY OF COMPATIBLE ENERGY SYSTEMS**
- **MARKET FOR ADVANCED PROPULSION SYSTEMS**
- **COMMERCIALIZATION PROCESS.**

The transition to electrochemical engine use in ground vehicles can be considered to be divided into two stages or generations:

- Production of electrochemical engines which can achieve virtually zero emission environmental and/or energy efficient mandated goals more economical and effective than competitive propulsion systems (battery/electric)
- Production of electrochemical engines which provide superior performance and costs to competitive propulsion systems.

The discussions in this paper concentrate on the first, or environmental/energy driven stage, based on the assumption that if the energy and environmental benefits of fuel cell engines are to be obtained in a timely manner, government support will be required. If the first stage is successful, the second stage should follow in a decade or more without further need for major government sponsorship.

2.1 PERSONAL TRANSPORTATION REQUIREMENTS

The Transportation Requirements segment of this Study illustrates the need to evaluate how electrochemical engines within vehicles could improve the movement of people and goods and how that will influence transportation requirements and markets. Improvement of U.S. transportation systems is a national priority. Effective transportation not only improves personal mobility, but will be necessary if the nation is to remain economically competitive in the production of goods and services. There are at least three primary incentives for the development and commercialization of advanced propulsion systems such as fuel cell engines:

- Mobility improvements for people and goods
- Emissions reductions
- Petroleum consumption reduction.

This section of the report describes typical current and future transportation requirements and the ability of existing vehicles (commercial and private) to satisfy these needs. Fuel cell engine propulsion systems will be more than substitutes for gasoline engines; they can make it possible to improve the operation and attraction of personal and commercial vehicles while meeting energy and environmental objectives.

Automobile designers (stylists) will find ways to take advantage of the performance and packaging flexibility of fuel cell engines. While the first generation of cars powered by ECEs may not be significantly different in appearance from conventionally powered cars then in production, subsequent generations may be very different. Fuel cell engine advantages include:

- The ability to be packaged in a very different manner than internal combustion engines. Fuel cell engines may be located in areas of the car which today's designers would not consider
- Low noise levels which will make conversation easier and reduce the need for (and weight of) sound insulation
- More response to driver input, e.g., provision of better road feel; four wheel drive and braking and torque control may be easier to provide with electric drive

- Longer life and less maintenance (fewer, if any, emissions checks): fuel cell engines will extend the useful life of cars
- The ability to be designed to fail "softly", thus insuring the ability to limp home, or off a congested freeway to a safer location
- A modular nature which would make it possible to produce a wide variety of propulsion systems, tailored to specific vehicle sizes and missions, for much less cost than would be possible with internal combustion engines. This should increase the variety of cars which would be available to the public.

Fuel cell engines can also improve the attractiveness of public transit; they do not have the noise and odor of diesel engines. Fuel cell engines should make it possible to improve passenger ride quality; for example, acceleration jerk, which is annoying to seated and dangerous to standing passengers, could be eliminated. ECEs will also eliminate the need for third rails or catenaries for rail transit systems, thus reducing costs, maintenance, and visual clutter.

ECEs may be relatively more important for freight systems. The U.S. Dept. of Energy estimates that the energy consumed by commercial vehicles will exceed that of light vehicles by the year 2010; the proportion of noxious emissions produced may be even greater. This prediction will be true even if the weight of trucks and trailers were slightly reduced; the purpose of commercial vehicles is to transport heavy loads which are a large share of the total weight.

The first commercially viable application for fuel cells may be in locomotives. The first ECE powered locomotives may appear to be an extension of existing diesel locomotive design and technology, but subsequent locomotives may be very different and involve designs which minimize maintenance costs (of the track as well as locomotives), improve enroute performance, provide the railroads with greater flexibility, and make them more competitive.

Electrochemical engines will have reached maturity when a typical automobile or truck buyer walks into a dealer and selects an ECE propelled car or truck over one with a "conventional" heat engine.

2.2 ENERGY AND ENVIRONMENTAL CONCERNS

The Energy and Environmental Concerns segment of this Study describes the regulatory environment (and standards) in which fuel cell engines and their competitors must comply and compete.

The increases in the U.S. automotive energy consumption regulations appear to have three causes:

- First - Concern over another supply interruption
- Second - The international balance of trade of which oil is a major part
- Third - The perception that we have become a wasteful society.

The public's concern that the U.S. (and the world) is in immediate risk of running out of petroleum or other useful forms of fossil energy is misplaced. To the contrary most energy authorities believe that there is enough fossil fuels (crude oil and natural gas) to last for about a

century (refer to Section VI). Before that is exhausted, other fuel supplies based on renewable sources (biomass, solar, geothermal), which can provide essentially unlimited supplies, can be produced at competitive costs. In the author's opinion the existing world's supply of fossil fuels will probably never be consumed because alternatives will become more economic.

Fuel cell engines may make it possible to alleviate some of the public's concerns over pollution. At present, the mandated emission requirements which must be met by future vehicle propulsion systems include the National Air Quality standard and the emission requirements established by the California Air Resources Board. The national, or federal, air quality standards for automobiles call for reductions in non-methane hydrocarbons (NMHC), carbon monoxide (CO), nitrogen oxides (NOx), and particulates (PM) in a two stage, or two tier process.

- Tier 1 is to go into effect in 1996. It requires that the non-methane hydrocarbon emissions be below 0.25, CO be below 3.4, and NOx be below 0.4; all values are in grams per mile
- Tier 2 may be mandated by 2003, if implementation of Tier 1 has not made a major improvement in regional environments. Tier 2 standards reduce each of the Tier 1 requirements by 50%.

Federal standards for air quality in major cities such as Los Angeles are the basis of the propulsion emission requirements promulgated by the California Air Resources Board (CARB). They are the most stringent and are intended to accelerate technology and provide the base standard which may be adopted by other states. These state environmental regulations currently require an increasing share of new cars sold to achieve ultra low emission (ULEV) and zero emission (ZEV) standards according to the following schedule:

1997	2% to be ULEV's
1998	2% to be ULEV's and 2% to be ZEV's
2001	2% to be ULEV's and 5% to be ZEV's
2003	15% to be ULEV's and 10% to be ZEV's

Table II-1. Summary of California Private Vehicle Emission Standards

The ULEV's are to have an average emission level $(\%CO + \%NOx + \%HC)/3$ less than 2.3% of an unregulated (1964) gasoline engine. Each company which supplies cars to the California market would be required to sell at least this share of ULEV's and ZEV's. It is expected that the use of alternative fuels or reformulated gasoline will be required to meet ULEV standards with piston engines. Most flexible fueled cars, which can operate on either methanol or reformulated gasoline, will probably qualify as at least low emission vehicles (an LEV's average emission level is approximately 4.8% of an unregulated gasoline engine).

There have also been several legislative initiatives directed at increasing automobile vehicle mileage standards. Senator Brain's "Motor Vehicle Fuel Efficiency" Act S-279 called for a 20% increase in fuel economy by 1996 and a 40% improvement by 2001 for cars sold by each manufacturer. Related House bills; The "Motor Vehicle Fuel Efficiency" Act HR 446, or the Boxer bill, would require increases of 20% by 1996 and 60% by 2001 over each manufacturers 1988 cafe levels. Other house bills, HR-560 (by Pannetta) and HR 612 (by Clinkmann), called for similar fuel economy improvements.

The legislative initiatives have been supplemented by the White House-sponsored "Clean Car" or "New Generation of Vehicles" initiative. This initiative has the objective of demonstrating a "family car" with one third the energy consumption of existing cars (that is, the energy equivalent of 82.5 mpg or 0.012 gallons per mile on gasoline). The project is a joint activity of the three major U.S. automobile manufacturers, federal laboratories, and the U.S. Departments of Energy and Commerce. It is directed by a senior executive of the Department of Commerce. The February 22nd (1993) paper from the President's Office of Science and Technology Planning, which initiated this activity, apparently was originally intended to accelerate the commercialization of fuel cell engine propulsion systems. The "New Generation Car" program has now been expanded to include near, mid, and long term objectives.

2.3 CHARACTERISTICS OF ADVANCED PROPULSION SYSTEMS

The Characteristics of Advanced Propulsion Systems segment of this Study was expanded at the suggestion of DoE management to include more information on competitive propulsion systems. It will not be possible to predict the market penetration of fuel cell engines unless the estimates consider other existing and future technologies which provide the same function. This section of the report describes the status of competitive power plants such as: advanced piston engines, battery/electric drive, external combustion engines, and alternative fuel engines. These engines establish the performance and cost levels which electrochemical engines must meet or exceed.

The U.S. Government (Dept. of Energy) has sponsored the development of a number of propulsion technologies including:

- Advanced Piston Engines
- Battery Electric Propulsion
- Gas Turbines
- Stirling Engines
- Electrochemical Engines (Fuel Cell Engines).

The internal combustion engine is approaching the theoretical efficiency limit defined by the second law of thermodynamics. Predictable improvements in engine performance (and improvements in vehicle design) are unlikely to achieve emission or fuel consumption levels which will alleviate the public's concerns. The cost of the equipment to "clean up" piston engines tends to increase exponentially as efficiency requirements increase and allowable emissions are reduced. Improved piston engines and gas turbines "may satisfy" some of the need for emission reductions before fuel cells become economically competitive. If fuel cell engine cost targets are not achieved, piston or gas turbine engines may be the propulsion systems of choice [36].

The electrochemical energy conversion process avoids the second law of thermodynamics which limits the theoretical efficiency of internal combustion engines to about 40% (practical peak efficiencies are generally much lower). Individual fuel cells have demonstrated efficiencies over 70% during bench tests. Complete fuel cell engine propulsion systems are expected to achieve efficiencies in the mid 40% to low 50% range. Since automobiles operate primarily at low power (15-20% of maximum peak power) where fuel cell engines are most

efficient, the range of a fuel cell engine powered vehicle could be nearly twice that of a similar internal combustion engine propelled vehicle using the same energy (fuel).

All fuel cell engine "fuel cell" components operate by electrochemically combining a fuel (hydrogen in most cells) with oxygen from air in the presence of a catalyst. The fuel cell components continue to produce electrical power as long as fuel and air are supplied. The "fuel cell" components of interest include:

- Phosphoric acid cells (PAFC) originally developed for stationary power and now being demonstrated in buses
- Polymer, or proton-exchange-membrane (PEM), cells have been used successfully in submarines and some preliminary ground vehicle demonstrations
- Molten carbonate (MCFC) and solid oxide (SOFC) cells are high temperature operating cells that do not require precious metal catalysts or, in some cases, reformers. They may be able to reform hydrocarbons internally
- Alkaline Fuel Cells (AFC) are primarily used in space and submersibles because of electrolyte carbon dioxide poisoning from the air; there has been some limited interest in using scrubbers to allow AFC applications in bus fleets in Europe.

The various names (phosphoric acid, solid polymer, etc.) refer to the kind of electrolyte. Each type of fuel cell is at a different development status and will require somewhat different development strategies. Phosphoric acid fuel cells are closest to commercialization. The DoE/DoT PAFC buses are currently being demonstrated. All elements of the solid polymer or proton-exchange-membrane cells have been successfully demonstrated. Ballard has a PEM fuel cell demonstration bus which uses stored hydrogen as its fuel. Molten carbonate cells are in the demonstration phase, while solid oxide cells are still in the research stage; several years of continued research will be required to resolve SOFC material problems [43]. At this time the kind of fuel cell system which will ultimately be commercialized, for specific applications, cannot be predicted with confidence.

2.4 COST AND AVAILABILITY OF COMPATIBLE ENERGY SYSTEMS

The Cost and Availability of Compatible Energy Systems segment of this Study summarizes the cost and availability of fuel/energy systems and how their use will influence the economics and emissions of "conventional heat engines". Emphasis is also given to the changes in the energy production and supply infrastructure which will be required to meet the needs of electrochemical and other advanced propulsion engines.

The automotive and energy companies have worked together to develop the first generation of reformulated gasoline for use in internal combustion engines which provides some environmental improvements at relatively low costs. Even closer control of gasoline constituents could further reduce emissions, but this would result in increased costs in engine design and fuel processing.

The use of methanol and/or ethanol in piston engines may be mandated in a number of states. Methanol, either as M-85 (15% gasoline) or M-100 offers some environmental improvements in piston engines; but the magnitude of the improvements appears to be small, particularly for cars equipped with computer controlled fuel injection systems. As a result, there is the risk that

few, if any, benefits will be perceived by people living in the communities where its use may be mandated. Mandating methanol (or ethanol) as an environmental solution for piston engines could be a technical (performance-wise) achievement and a political failure.

Methanol will not be a competitive internal combustion engine fuel until the cost of fuel per mile is equivalent to petrochemical based fuels. This may be achieved when gasoline reaches \$1.50 per gallon (assuming that the cost of natural gas from which methanol is made remains below \$2.50 per trillion cubic feet). The higher efficiency of fuel cell engines would make methanol cost competitive when gasoline is less than \$1.00 per gallon.

Natural gas engines can probably be designed to meet California's low emission vehicle (LEV) or possibly even ultra low emission vehicle (ULEV) standards. The low energy density of natural gas, even in high pressure tanks, means that most natural gas propelled vehicles will only have the energy equivalent of three to four gallons of gasoline; consequently these vehicles will experience limitations. Their acceptability will be improved if they can be dual fueled, i.e., with gasoline or methanol for example.

Gas turbines can use a wide variety of fuels (they are insensitive to cetane or octane ratings). They may be designed to use fuels made from the balance of the barrel (after more demanding fuels are made) and still be economically practical.

The primary source of electricity to recharge battery/electric cars will be the electrical utilities. The California utilities report that they have adequate capacity (during off-peak periods) although the increased demand for electrical power in other regions of the nation has lead to brown and black-outs.

Fuel cell engines "may" require new fuels. The choice of the "best" fuel is not clear at this time. Candidates include methanol, natural gas, hydrogen, and even gasoline, each of which has its benefits and problems. The first generation of fuel cell engines may use methanol or gasoline, although natural gas and hydrogen appear to be desirable for some applications.

- *Methanol or gasoline are preferred for private automobiles because they are liquids which can be sold and stored in a manner which is familiar to car owners. Methanol can be easily dissociated into hydrogen and carbon dioxide. Gasoline is more difficult to reform; fuel processing into hydrogen and carbon dioxide requires so-called partial oxidation reformers which are still in very early development.*
- *Natural gas (methane) may be the preferred fuel for some commercial applications such as railroads. Simple steam reformers for Proton-Exchange-Membrane fuel cells may require nearly pure methane without butane or higher hydrocarbons.*
- *Hydrogen can be a true zero emission fuel, but it has storage and low density problems which make it difficult to use as a fuel for private cars or trucks. The cost of developing the processing and distribution system requires further analysis.*

It has been suggested that the ideal fuel for a fuel cell engine propulsion system would be a "hydrogen carrier"; a liquid which can be easily separated from its hydrogen content on-board the vehicle. In this respect methanol can be considered to be a "hydrogen carrier". The potential to develop innovative fuels such as "hydrogen carriers" needs further evaluation, as does the technical and economic feasibility of developing fuel supply production, distribution, and retail infrastructures for each candidate fuel other than gasoline.

2.5 MARKET FOR ADVANCED PROPULSION SYSTEMS

The Market for Advanced Propulsion Systems segment of this Study discusses the market for cars, trucks, and other vehicles which may be powered with fuel cell engines. While some preliminary estimates of market sales based on compliance with state and federal regulations are included, it was not possible to effectively address all of the factors which will influence the total market for fuel cell engine powered vehicles during this phase of the program. A computer model is discussed which will make it possible to evaluate the influence on fuel cell engine requirements and sales as a function of changes in national economic growth, vehicle cost, and fuel cell engine (and competitive power plant) cost and performance. A discussion is included on the use of sensitivity studies to illustrate the uncertainties in available information and identify the technical, design, or manufacturing opportunities where the greatest progress in commercialization per dollar can be attained.

An effective (logically consistent) method of describing potential markets is to prepare scenarios which illustrate alternative future economic developments and the use of advanced propulsion systems and transportation technologies. Three scenarios make it possible to consider a range of assumptions regarding economic growth, regulations, technology, and availability. A large number of scenarios could be considered; for simplicity, four are suggested:

- First - Assume the continuation of historic technical, regulatory, and economic conditions and vehicle markets, and then use these trends to provide a basis against which to compare other scenarios
- Second - Assume that "second best" technologies are adopted to meet California's transportation system emission control/time objectives, and that many other states adopt the same emission control/time goals
- Third - Assume that the time required to meet California's emission goals are modified to permit the commercialization of the first generation of fuel cell engines
- Fourth - Assess the impact on fuel cell engine (and other propulsion system) markets if new and innovative transportation systems (automobiles and transit) and traffic management concepts are introduced.

The scenarios will:

- Illustrate the uncertainties in the market and the economics and the need for a robust development and commercialization program
- Identify those aspects of electrochemical engine development and commercialization where resources should be concentrated to obtain the greatest benefits, including a reduction in development time.

The use of such scenarios can illustrate how the transition to fuel cell engine propulsion could occur, how long it could take, and what benefits would be provided. Preliminary assessments indicate that a commitment to the development and commercialization of fuel cell engine propulsion systems must be robust; that is the plan must be able to accommodate major changes in performance and demand. Scenarios, such as those described above, are summarized in Section VII and will be developed in detail during Phase II of this program.

The size of the market for first generation fuel cell engines will depend on the relative costs and performance of fuel cell engines as compared to other low or zero emission propulsion systems. If California becomes the only state to enforce a Zero Emission Vehicle regulation approximately 1% of the total light vehicle production would be ZEV's, a market which fuel cell engines should capture as soon as they are available. If half of the states adopt regulations similar to California the total market for ZEV's would be on the order of 5% of the U.S. light vehicle fleet, or approximately 400,000-500,000 light vehicles per year.

2.6 COMMERCIALIZATION PROCESSES

The Commercialization Processes segment of this Study includes a description of possible commercialization strategies and the preparation of business plans to define the commercialization processes and resources which would be required to commercialize fuel cell engines. It identifies the material which should be included in business plans for electrochemical engines and the vehicles which would utilize them.

The commercialization of advanced propulsion systems such as electrochemical engines would normally be undertaken by the private sector. The commercialization would first occur in high value, low risk applications such as remote power and/or pleasure boats. Some of this type of commercialization is starting and at least one company claims to be making a profit in the sale of small fuel cells to power hand held electronic equipment, etc. However, in the case of fuel cell engine propulsion systems the uncertainties appear to be so high that interested manufacturers are unlikely to make major investments until there is a better understanding of the benefits and costs of such systems.

There are several possible strategies for the development and implementation of a process to make fuel cell engines available on an expedited basis such as:

- Development by one or more of the major automobile companies
- Establishing fuel cell companies
- Creating joint private-public partnership or affiliations.

The U.S. DoE, which sponsors most of the fuel cell engine research, has suggested that research laboratories and private companies which have complementary capabilities could band together, in teams, to develop specific categories of fuel cell engines for selected applications. Each participating organization should have some "ownership"; that is, it should benefit from the success of the program. For example, each program could be a source of support and technical recognition for federal laboratories. The industrial company's incentives would include the sale of fuel cell engines or components and/or increases in the market for fuel cell engine powered vehicles that they manufacture.

Logically, the first application of electrochemical engines should be in vehicles where the economic requirements are most easily satisfied or where the public need is most evident. The locomotive appears to meet the first requirement, transit buses the second. However, the DoE is currently emphasizing the replacement of conventional gasoline engines by fuel cell engines in private passenger vehicles in an attempt to achieve near-term maximum reductions in emissions and energy consumption (foreign oil dependency). When, and if, the energy consumption and emissions from commercial "vehicles" exceeds that from private passenger cars this strategy may have to be reconsidered.

The commercialization process will start with the preparation of business plans which identify the resources required (technical and financial), how they will be obtained, and how the development and commercialization program will be organized. The plans will contain the information which private decision makers need to justify investments in the electrochemical engine business, and which public sector decision makers require to justify their support for processes which will accelerate the commercialization of fuel cell engines.

The business and financial analyses included in the business plans will require projections of potential markets (and benefits) and how they will change with: uncertainties in costs, performance, and acceptance of electrochemical engine propelled vehicles.

A description of the market and commercialization process can be found in a separate report "Fuel Cell Commercialization Process" (January 25, 1994). Related papers which have been prepared to summarize the commercialization processes for electrochemical engine propelled vehicles (light vehicles and locomotives) for other clients are listed in the Reference section of this report.

2.7 CONCLUSIONS

The interest in electrochemical engines for propulsion will increase as people become aware that fuel cell engines have the potential to make major contributions to future environmental and economic requirements, such as:

- The demonstrated capability to meet the requirements for economic and performance improvements relative to internal combustion engine propulsion systems
- The demonstrated capability to meet the requirements for reduced fuel consumption and emissions at the lowest social and economic costs.

Both of these capabilities are consistent with national goals. The strategy for developing and implementing fuel cell engine propulsion systems will differ with each vehicle application as a function of travel requirements, as well as the environmental, technical, and economic objectives.

At the present time, public and private investments in fuel cell engine research and development are much too small to meet the time objectives for developing low emission and efficient cars, buses, and trains. Serious private sector efforts to develop and produce fuel cell engines will not be undertaken until the business risks are reduced to a level comparable with other business investments. This requires evidence that there are applications in which fuel cell engines are superior to existing or potentially "competitive" alternative propulsion systems, such as gas turbines and battery/electric propulsion.

Investments in fuel cell engine development present a number of risks, each of which must be satisfactorily addressed, including:

- Technical - Will the performance capabilities be achieved?
- Economic - Will the costs be competitive?
- Scheduling - Are the present schedules consistent with the time required to develop reliable, economical fuel cell engine propulsion system?

Business -	Can the manufacturers make a profit?
Political -	What problems will be solved and/or generated by sponsoring fuel cell engine development initiatives?
Societal -	Will there be perceived societal concerns? Could elements of fuel cell engine performance, operation, or manufacturing be unacceptable to user or the general public?

Government support will be particularly important during the early stages when the economic and technical viability of the use of fuel cell engines has not been confirmed.

The useful information that has been obtained in performing this Study does support the contention that fuel cell engine based propulsion systems could become the dominant propulsion system for all ground vehicles within twenty to thirty years. In this connection, it is appropriate to make several observations:

- Most public and private decision makers do not know what fuel cell engines are, the image is one of a different kind of battery
- The technical risks are low; fuel cell engines will work
- Initial assessments have indicated that the Proton-Exchange-Membrane (PEM) fuel cell engine system has advantages in operability, efficiency, and packaging over the other types. The development of fuel cell engine systems is at an early stage and, with "breakthroughs", other types could become the fuel cell engine propulsion system of choice
- The primary barriers to fuel cell engine commercialization are cost, demonstration of adequate performance and efficiency in a production prototype, and resolution of fuel infrastructure issues
- It is probable that the goal of costs competitive with existing engines will not be achieved until fuel cell engines have been in production and deployed in response to environmental and/or energy efficient requirements
- Fuel cell engines will probably be commercialized in two stages, first when they are competitive with other ultra low emission technologies and second, when they are competitive with "conventional" engines for most vehicles
- The business risks are high, initial profitability is a question
- The public and private sector decision makers' (political) risks are difficult to assess. If fuel cell engines do not work well promoters will be at risk. If decision makers opt for "second best" solutions to the environmental concerns, and fuel cell engines are developed in a timely manner, it will appear that they used poor judgment
- Care must be taken to ensure that the program will not be in jeopardy, particularly if some of the optimistic schedules for the early deployment of fuel cell engine powered vehicles are not met
- Due to the low level of effort in the U.S., the U.S. may have to purchase fuel cell engines from other nations, e.g., Germany or Japan
- When their performance and economic benefits are confirmed the author believes that fuel cell engines should become the dominant propulsion system for ground vehicles.

The low emission levels and high efficiencies of fuel cell engines have the potential to essentially eliminate the public concern over the contribution of automobiles (including trucks and buses) to air pollution and energy consumption. Government support for expediting the development of fuel cell engine propulsion systems and their use in ground vehicles can be justified because that should make it possible to achieve national energy and environmental objectives at the least economic and societal costs.

Most of the published projections of the market for electrochemical engine powered vehicles, for the next three and a half decades, appear to be based on conservative assumptions of their relative efficiency and costs. It is the author's intention to make adjustments to these data during the next phase of the GM program. Assumptions will be made regarding a logical range of performance and cost of fuel cell engine powered transportation vehicles, transportation trends, and energy consumption, so as to permit inclusion of transportation technologies which were not considered in most of the referenced sources.

If the cost of electrochemical engines is reduced to a level competitive with other heat (or internal combustion) engines, it is the author's opinion that fuel cell engines should capture the majority of the vehicle market, i.e., five to ten million light vehicles per year.

Since the available information on the market for, and benefit of, fuel cell engines is inadequate for business planning purposes, a more comprehensive market assessment should be conducted during the subsequent phases of the program. Four activities which are recommended for the next phase include:

1. Conduct parallel or competitive studies on candidate fuel cell engine types to select the most appropriate for specific vehicle applications
2. Research on fuel supply systems including the potential use of new fuels, as well as the fuel production, distribution, and retail infrastructure
3. Completion of the market assessment for fuel cell engine propulsion systems and their potential benefits in terms of energy consumption, emissions, and mobility
4. Preparation of business plans which will identify each step in the development and commercialization process of fuel cell engines.

The transition to fuel cell engine propulsion systems will have a short term economic cost. ECEs will displace and obsolete other technologies. But, like previous transitions, the long range benefits will be substantial. Previous energy-power plant transitions include: wood to coal, coal to oil, steam to diesel locomotives, and aircraft piston engines to gas turbines. Subsequently, it also became cheaper to develop other energy supplies, which incidentally were easier to use and had environmental benefits.

The development of fuel cell engine propulsion systems is taking place in parallel with other programs to reduce the emissions (and improve efficiency) of piston engines, to reduce the cost of gas turbines, and to extend the range of battery/electric vehicles. It is appropriate to ask if the industry, or nation, has adequate resources to effectively pursue a multiplicity of parallel programs?

Even if delayed, the potentially superior economics and societal benefits of fuel cell engine propulsion systems (or any other superior system) could result in their being the power plant of choice for most future ground vehicles.

III. TRANSPORTATION REQUIREMENTS

The purpose of this section of the report is to describe how changes in transportation requirements may change the use of, and market for, electrochemical engine powered vehicles. The information presented in this section will be used in preparing the transportation demand, system performance assumptions, and market assessments that are discussed in Section VII.

Improvement of U.S. transportation systems is a national priority. Effective transportation not only improves personal mobility, but is necessary if the nation is to remain economically competitive in the production of goods and services [47,48]. There are at least three primary incentives for the development and commercialization of advanced propulsion systems, such as fuel cell engines:

- Mobility improvements for people and goods
- Emissions reductions
- Petroleum import dependency reductions.

The introduction of fuel cell engine propulsion systems can provide major benefits in terms of personal mobility and the movement of goods. Fuel cell engine powered vehicles should not simply be a re-powered version of existing cars and trucks. ECEs can provide vehicle designers with the opportunity to create new concepts; fuel cell engines should also contribute to reducing operating costs and extending overall vehicle life. The vehicles of interest in this program task include personal cars, and light and heavy trucks. The locomotive fuel cell program is also discussed, even though locomotives were not included in the original program objectives.

The benefits of fuel cell propulsion systems can be illustrated by considering two contrasting potential scenarios:

- Fuel cell propulsion systems are not developed
- Fuel cell propulsion system development is accelerated.

If fuel cells are not commercialized in a timely manner, environmental requirements may impose increasingly severe restrictions on both the design of vehicles and conventional propulsion systems; this, in turn, may effect personal travel styles.

In the absence of fuel cell engines it may be necessary to impose mobility constraints such as mandating employers to encourage car pooling and/or impose user fees on cars to meet environmental standards and reduce petroleum consumption. These actions will reduce the mobility of people and goods by discouraging the use of automobiles for "unnecessary" or "excessive" travel and force the use of public transit and/or car and van pooling, restricted parking, etc. Special circumstances would be required to avoid the development of public opposition to these kinds of measures. Even in California, where people tend to be more environmentally conscious, recent surveys have indicated that citizens will continue to find ways to maintain the personal freedom and mobility provided by their private automobile.

The interest in electrochemical engines will increase as people become aware that such engines can provide economic and performance advantages over internal combustion

propulsion systems. This developing interest, and increased R&D, should make it possible to meet the requirements for reducing fuel consumption and emissions at the lowest social and economic costs. The strategy for developing and implementing fuel cell engine propulsion systems will differ with each vehicle application as a function of travel requirements, as well as environmental, technical, and economic objectives.

Government support for expanding the development of electrochemical engines, and their subsequent use in ground vehicles, should be based on the recognition that such engines represent one of the best ways of achieving national energy and environmental objectives. There will, consequently, probably be two (2) stages or generations that will occur during the commercialization of fuel cell engine propulsion systems:

- Stage I - Occurs when fuel cell engines can satisfy virtually zero emission environmental/energy efficient mandated regulations better than other advanced propulsion systems
- Stage II - Occurs when fuel cell engines can provide performance and costs superior to competitive advanced propulsion systems.

Logically, fuel cell engines should be introduced sequentially, starting with applications which are believed to be more economically competitive with existing internal combustion engines, such as:

- First - Railroad locomotive
- Second - Buses and rail transit
- Third - Heavy trucks
- Fourth - Private automobiles.

Some authorities suspect that buses, rather than locomotives, may become the first commercial fuel cell engine powered application because of the desire to eliminate diesel odor and noise, both of which are objectionable to the general public. At present, however, the DoE is emphasizing the development of fuel cell engines for private automobiles since the goals are to minimize emissions, energy consumption, and foreign oil dependency. Replacement of the conventional gasoline engine in passenger vehicles is currently believed to be one of the best ways to accomplish these goals. As total energy consumption and emissions of commercial vehicles increases and possibly surpasses that of private vehicles, this strategy may have to be reexamined.

Of the 3.5 billion person miles traveled in 1990, 70% were by personal car, 15% were by personal truck, 9.7% were by air, 3.5% were by bus, 0.7% were by rail, and 0.3% were by motorcycle. Trucks provided 16% of the ton miles of freight movement (or 36% of the total tonnage moved), while rail accounted for 23% of the ton miles of freight movement (or 27% of the total tonnage moved). The balance of freight movement was by water or pipelines.

Expressed in terms of energy consumption, 49% of the total energy used for transportation was consumed by automobiles. Of that amount about 17% was consumed by light trucks, 9% was consumed by aircraft, about 0.4% was consumed by passenger rail, with less than 0.1% being consumed by motorcycles. Of the remaining 51% of the total energy used for transportation, 15% was consumed by heavy trucks, 18% was consumed by railroad freight operations, approximately 6.5% was consumed by ships, approximately 4% was consumed by pipelines,

while about 3% each was consumed by military and off-highway (farm and construction) vehicles. Electrochemical engines could be used in all of these applications (including pipelines, which are the only major use of electrical power for transportation) [109].

The U.S. DoE forecasts that the energy consumption by commercial vehicles will exceed that of light (personal) vehicles by the year 2010. If some of the advanced vehicle and highway infrastructure concepts discussed in this section are implemented, commercial vehicle energy consumption may exceed that consumed by light vehicles several years earlier.

3.1 PERSONAL TRANSPORTATION REQUIREMENTS

The existing personal transportation system, primarily personal automobiles, is a major generator of regional air pollution. As a consequence, use of advanced propulsion systems should provide significant environmental benefits without restricting personal mobility. Personal travel can be divided into several categories, all defined under urban travel:

- Commuting or work related
- Personal/business travel to friends, recreation, etc.
- Shopping travel to stores, etc.
- Intercity work or pleasure.

People appear to have two budgets for personal transportation:

- Cost as a percent of household disposable income
- Time limitations, including average time for different trips.

For several decades the average household's expenditure for transportation has been remarkably consistent when measured in terms of percent of disposable household income. The average household spends about 14% of its disposable income on all forms of transportation. About 57% of that is spent on the purchase of cars and gasoline [77,79].

Likewise, average travel time has also been remarkably consistent. While there are great variations by individuals, world bank studies [111] indicated that the average commute time is similar across social classes in all industrialized societies, though it is somewhat longer in developing economies. This is not surprising as time cannot be banked or saved for tomorrow.

3.1.1 Urban Travel

Travel times and distances differ significantly for each category of urban travel. The results of a 1967 study by the Stanford Research Institute are summarized in Table III-1. The distribution is surprisingly similar for different size cities. Only in very large cities, such as New York, is the commuting time longer. Most of those longer trips are by high income and two professional person households [133]. In 1990 there were 143 million passenger cars registered in the United States. Of the 9.3 million cars sold in the U.S. in 1990 about one quarter were imported. The median age of automobiles in the U.S. increased from 4.9 years in 1970 to 6.5 years in 1990. This trend is expected to continue to increase at a similar rate (7.8 years by the year 2000) as the requirements to maintain emission and energy standards for the "life" of the vehicle are increased. Fuel cell engine propulsion systems could accelerate this trend to increase vehicle life [73].

Commuting travel, that is travel to work and/or work related destinations, amounted to 21.2% of the total personal vehicle trips and 26.8% of the total vehicle miles traveled in 1990. The average automobile commuting trip in the U.S. takes about 24 minutes and is 11 miles in length, Table III-2. The average household generated nearly 4,800 miles of commuting in 1990, up 16% since 1970 (1990 Nationwide Personal Transportation Study, Summary of Travel Trends) [77]. Studies by the Federal Highway Administration and others estimate that the time lost in congested traffic will more than double by 2020; however, there are reasons, discussed below, to doubt if this will actually occur.

<u>Commute Time</u>	<u>Work</u>		<u>Personal Business</u>		<u>Shopping</u>	
	<u>Increment</u>	<u>Sum</u>	<u>Increment</u>	<u>Sum</u>	<u>Increment</u>	<u>Sum</u>
0-5 min.	7%	7%	29%	29%	57%	57%
5-10 min.	16%	23%	24%	53%	24%	81%
10-15 min.	2%	45%	13%	66%	10%	91%
15-20 min.	25%	70%	11%	77%	6%	97%
20-25 min.	5%	85%	9%	86%	2%[1]	100%
25-30 min.	7%	92%	7%	93%	---	---
30-35 min.	5%	97%	5%	98%	---	---
35+ min.	3%	100%	2%	100%	---	---

[1] Over 20 minutes

Table III-1. Typical Urban Trip Travel times by Purpose, One Way

<u>City</u>	<u>Auto</u>	<u>Transit</u>	<u>Average</u>
Chicago	23.0 min.	44.0 min.	26.4 min.
Dallas	22.7 min.	40.7 min.	23.2 min.
Los Angeles	22.1 min.	39.0 min.	22.8 min.
New York	26.3 min.	46.0 min.	34.0 min.
San Diego	19.5 min.	39.5 min.	19.6 min.
San Francisco	21.3 min.	33.2 min.	24.4 min.
Washington, DC	25.0 min.	38.4 min.	26.2 min.

Source 1990 census, University of Southern California

Table III-2. Average Work Trip Times by Mode in Selected Cities, 1990

There is increasing evidence that there is a feedback to congestion. The average trip time in Los Angeles decreased from 23.7 minutes in 1980 to 21.1 minutes in 1984. Of the 20 largest U.S. cities, according to P. Gordon of USC, individual commute time decreases were statistically significant in all but five. It appears that when trip times exceed people's acceptable time budgets, people relocate or take jobs nearer home [105]. This occurs even if the jobs or places to live are less desirable; this relocation is usually overlooked in estimating the time cost of congestion.

Approximately 5.5% of all urban trips use public transit. The average commute trip by public transit takes 35 to 40 minutes but is less than 9.5 miles long. The percent share of travel by public transit appears to be closely related to people's disposable personal income. If disposable household incomes increase by 1% per year through the year 2000, the use of conventional public transit could be expected to decrease to less than 5% of the total number of urban trips.

Approximately 24% of all work trips today occur by car or van pooling. The average car or van pooling commuting trip length and time is about half that between a personal car and public transit. Personal business travel includes travel to stores, churches, doctors, personal friends, etc. These trips now make up more than 20% of all personal vehicle trips. This is the most rapidly increasing category, such trips have more than doubled since 1970. The average vehicle occupancy on personal business trips was 1.6 in 1990, down from an average of 2.0 in the late 1970's. The average personal business trip by automobile is about 7 miles in length and requires 10 minutes. Personal business trips are estimated to consume 30 to 35% of the fuel used by automobiles. Trips for shopping represent the shortest of all trips. They average about 5 minutes in time and 1 to 1 1/2 miles each way. Only about 11% of the total automobile travel mileage is currently for shopping, but this is rapidly increasing. Shopping trips per household have nearly doubled since 1970. Vehicle occupancy during shopping trips averages 1.5 persons. Shopping trips consume a disproportionate quantity of fuel and create a disproportionate quantity of emissions because the engines are not fully warmed-up by the time the trip is completed. The remaining (approximate) 25% of all household based trips are for social and recreational purposes. These average about 12 miles in length with 2 or more people per car or van.

Intercity travel, that is travel for pleasure, family business, or business trips represents an increasing share of personal trips. The purposes and modes used are summarized in Table III-3.

	Pleasure	Business	Vacation	Other	Total
Personal Vehicle	77%	58%	74%	83%	73%
Airplane	18%	37%	20%	135%	22%
Bus/Train/ Other	5%	4%	2%	4%	6%
Total trips/ millions	460	155	420	280	661

Source: U.S. Travel Data Center, 1990 Travel Market Report, Appendix F [79].

Table III-3. Mode of Intercity Travel by Purpose, 1990

The average intercity trip length in 1990 was 900 miles; this is up from 790 miles traveled in 1974. If this rate of increase continues the average intercity trip length should reach 1100 miles by the year 2030. The share of intercity travel by air is expected to continue to increase to 30-35% of the total number of travel modes by 2030.

3.1.2 Personal Vehicle Choice

Perhaps the most difficult, yet important, area of uncertainty to interpret regarding the market for advanced automobiles and energy systems is:

To what degree will the U.S. public change its driving habits and life styles to adapt to changes in regulations or differences in the performance of alternative fuel vehicles compared to conventional gasoline fueled vehicles?

There are two possibilities:

First - A continuation of present driving patterns

Second - Acceptance of changes to meet environmental requirements.

If a large portion of the U.S. public insists on maintaining its historic driving pattern the reductions in performance and range inherent in the use of some alternative propulsion systems, such as battery/electric and compressed natural gas, may cause significant buyer resistance to those particular alternative propulsion systems.

The typical western American city reached maturity after the automobile (which provides a high level of mobility) was in wide use. These cities, and the suburban ring around older cities, are relatively low density with a multiplicity of origins and destinations not easily served by public transit or vehicle pools. Urban traffic congestion, coupled with the public's desire for a less crowded environment, has been a major factor in the development of ring or edge cities.

While transportation using bicycles and walking has advantages for a small (and decreasing) portion of the urban trips which can be made (in an acceptable time) by such modes, new towns, with the ambiance and distances of small communities, continue to be built. Even if all new construction were mandated to be within existing city limits it would take several decades for the average urban density to increase to the level where the use of bicycles, walking, etc., could provide acceptable travel times for a majority of trips.

Improved mobility for people and goods may also be provided by changes in highway and street infrastructures and the use of innovative vehicles designed to serve specific kinds of travel. The construction of freeways is approaching saturation and encountering serious opposition.

Any attempt to extrapolate or predict future transportation requirements from existing driving patterns or to predict changes in the methods by which automobiles will be purchased must be performed with caution. Different people accept change differently. There have been numerous attempts to classify people by their life styles and to estimate how people in each of these classifications decide on which cars to purchase and which trips to make. SRI (Stanford Research Institute) studies regarding Values and Life Styles [100], for example, divided people within one work force group into nearly a dozen categories from sustainers to emulators and achievers. These dozen categories are condensed into four, more basic, categories in Table III-4:

The description "survivors and sustainers" is self-explanatory, very few of these people can purchase new cars. People categorized as "belongers" are sometimes described as Chevrolet and Apple Pie types. The "early intenders", that is, people who will purchase the first of a new

design, or a type which is environmentally superior, are included within the "experiential and societal" category. The "achievers and emulators" are those people who have "made it", or want others to think that they have.

	<u>Share 1990</u>	<u>Number 1990</u>
Survivors, Sustainers	11%	13.2 Million
Belongers	39%	46.8 Million
Experiential, Societal	21%	25.2 Million
Achievers and Emulator	29%	<u>35.8 Million</u>
Total in work force		120.0 Million [100]

Table III-4. SRI Values and Life Styles Characteristics

Even if it were understood how to identify the people who would purchase environmentally benign cars, market predictions would have to be able to project how the number of people in each category will change with: time, economic growth, societal developments, and political reactions to such changes. What is clear from these kinds of studies is that the number of people who will select products for their innovative designs is relatively small and will decrease significantly if the rate of economic growth decreases.

SRI studies imply that only 3 to 5% of the potential purchasers of new cars would be expected to be "early intenders". A similar number of others may be sufficiently concerned over the environment to purchase environmentally benign cars without financial or legal incentives. Thus, only 6 to 12% of the new car buyers may be expected to give major consideration to energy and environmental concerns with respect to their decision regarding which new car to purchase. Canada discovered that only about one quarter of the people who purchased compressed natural gas vehicles, even when the government encouraged its use, fell into this class [13].

There are a few auto performance enthusiasts, and a few environmentally concerned car buyers, who are also concerned about an engine's performance. However, it appears that most people do not care how a car performs as long as it provides economical and reliable service. It would undoubtedly be helpful to those who make advanced product decisions if they fully understood the values that potential new car buyers place on car performance parameters such as range between refueling and/or acceleration for merging into traffic. Very little of the research performed in this area in the last decade is in the public domain. A summary report was prepared by Melvin Cheslow in 1983-84 [35]. This report includes the results of a number of separate studies concerning what people will pay for automotive performance improvements.

The range of prices people will pay for specific performance improvements is large and depends on the buyers income, family size, education, and other factors. Some of the conclusions of Cheslow's studies are summarized in Table III-5. The original reports should be consulted before trying to interpret the results in terms of present day markets.

The projected "willingness to pay" for improved mileage (which averaged \$45 for a one mile per gallon improvement) is approximately the same as the cost of the fuel which would have been saved over the first two and a half years of the vehicles life, given fuel prices at the time the

study was made. Oil prices have declined significantly since the Cheslow paper was prepared. The data probably overstates what people will now pay for improved mileage. These conclusions need to be reviewed and updated in view of more recent conditions.

Increase fuel mileage by 1 mpg	\$15	to	\$150	above 30 mpg
Reduce 0 to 60 mph by 1 sec	\$45	to	\$500	below 20 second
Increase range by 50 miles	\$900	to	\$1,600	above 300 miles

Table III-5. What People will Pay for Performance Improvements

These studies indicated that most people will pay more for increasing range (a larger fuel tank?) than for comparable improvements in fuel economy. This may reflect the inconvenience of refueling. Many people appear to think of fuel economy as the distance between trip to the gas station. Automobile companies have found that people complain when their new cars will not go at least 300 miles without refueling. It is not clear whether the ability to refuel (recharge batteries) at home would offset this concern.

As previously described, over the past several decades families have spent about 14% of their disposable income on transportation. Of this amount 57% goes for the purchase of new cars plus gas and oil, about half of which is used toward the purchase of the car itself. U.S. Congressional Budget Office (CBO) projections of disposable income for 1997 indicate an increase of 8 to 10% over 1990. This study assumed a 2.5% per year increase in the Gross Domestic Product. Other studies of GDP growth during the period between 1990 and 2001 project increases between 2.0% to 2.8%. For simplicity, GDP growth bounded between 2.0% and 3.0% per year may be used to illustrate the market uncertainties in the scenarios described in Section Seven [137].

Most people or families reduce their travel and purchases of fuel as the price of fuel (in dollars per mile terms) increases. The short term elasticity of consumption to price has been estimated by various observers as ranging from 0.4 to 0.6 (that is, a 4% to 6% reduction in consumption following a 10% increase in gasoline price). Since (in the U.S.) the family budget for transportation and purchase of cars has been essentially constant for decades in terms of percent of disposable income, increases in expenditures on fuel will probably cause a reduction in expenditures (purchase, insurance, maintenance) on cars. This occurred in the late 1970's and early 1980's when oil prices were high. Still, it is surprising how many people will pay from 20 to 40 cents more per gallon for high octane unleaded gasoline which very few cars actually require. In any event, it is estimated that a 25% increase annually in cost (to the user) per mile would cause a 9 to 15% reduction in the money annually available to spend on new or used cars.

In the absence of a mandate to accelerate propulsion technology the cost of conventional cars (with the same accommodations, amenities and performance) in real terms, should decrease gradually over the next several decades. If historical trends continue, the constant dollar price of a new standard four door sedan would decrease at an average rate of 1% to 2% per year. This rate of decrease should level-off toward the end of the time period of interest (2030) assuming no increase in environmental or efficiency standards. This price trend is consistent with the experience with other manufactured products (refrigerators, ships, tanks, etc.). Manufacturing costs tend to reduce asymptotically toward material costs as more units are built.

The cost of pollution control equipment should also decrease at a similar rate during periods when environmental standards are unchanged.

3.1.3 Automobile Ownership and Use

The number of cars owned per household has steadily increased for several decades (since the 1940's) as indicated in Table III-6. Increased disposable household income, which has caused more multiple car ownership, is also responsible for developing new car ownership concepts, for example:

In the 1920's-1950's

Few households had more than one car (more had none); the one car belonging to the household was selected to meet the maximum need of the household. Most commuting was by public transit

In the 1960's-1990's

More households have two cars, an image car and a utilitarian car

In the 2000's and beyond

Households will probably have a multi-car fleet with specialized vehicles for commuting, shopping, family travel, etc.

<u>Year</u>	<u>None</u>	<u>One</u>	<u>Two</u>	<u>Three +</u>	<u>Total Vehicles</u>	<u>House-Holds</u>
1969	20.6%	48.4%	26.4%	4.6%	72.5 million	62.5 million
1977	15.3%	34.6%	34.4%	15.7%	120 million	75.5 million
1983	13.5%	33.7%	33.5%	19.3%	144 million	85.4 million
1990	9.2%	32.8%	38.4%	19.5%	165 million	93.3 million

Table III-6. Percent of Households with More Than One Car

In the first stage of automobile ownership, purchased cars were usually selected to meet the most extreme need of the households. Many station wagons were purchased with a family vacation in mind. People spent 10 to 12% of their disposable income on transportation, including purchases of other transportation services and transit fares.

In the second stage of automobile ownership cars were purchased to meet two needs: first, for image (depending on the owner, a Corvette, Cadillac, or Geo Metro) and second, for utility. A utility vehicle could include a utilitarian type car, a light truck, a van, or a used car. People spent 12 to 14% of their disposable income on transportation, about 57% (or 8% of their total disposable income) of that amount went for the purchase of cars, fuel, and oil.

In the third stage of automobile ownership people may purchase (or lease) specialized vehicles which can meet specific needs more economically than traditional products (or used cars). Families will probably continue to spend about 8% of their total disposable income on car ownership and direct operating costs. The trend to multiple car availability in each household will increase due to a continuing increase in disposable household income. The number and

type of vehicle choices will be tailored to the family's needs, commuting, shopping, family travel, etc.

If one assumes that the "extra" cars in multiple car households are used only on week days, then, using the average vehicle mileage data presented in Table III-7, the average second car travels 33 to 50 miles per day, the average third car 18 to 34, the average fourth car 14 to 34, and the average fifth car 15 miles per day [41].

The public's acceptance and use of cars which are designed for specific travel purposes, as well as improvements in road infrastructure and mass transient effectiveness and appeal, could change the size of the market for fuel cell engine powered vehicles. Potential transportation system concepts, therefore, which may significantly influence both the design requirements for advanced propulsion systems and regional air quality include:

- Image Cars
- Utilitarian Cars
- Single passenger commuters
- Runabouts, Shoppers, or Neighborhood cars
- Improved public transit.

<u>Number of Cars per Household</u>	<u>First</u>	<u>Second</u>	<u>Third</u>	<u>Fourth</u>	<u>Fifth</u>	<u>Total</u>
1	11.5	---	---	---	---	11.5
2	15.5	8.4	---	---	---	23.9
3	17.5	9.9	4.9	---	---	32.3
4	18.8	11.6	7.1	3.8	---	41.3
5	20.3	12.8	8.9	5.1	3.9	51.0

Table III-7. Average Vehicle Miles Traveled per Year, per Car, Thousands of Miles

In addition, adaptive traffic signal controls and intelligent vehicle and highway systems (IVHS) could potentially provide significant reductions in energy consumption by minimizing time delays at stop lights and the need for frequent acceleration and braking. Such systems could provide information on the location of accidents and/or congestion and suggest appropriate routes, thus reducing total travel time and travel errors which frequently accompany the first trip to a new destination. Telecommuting may also make it possible to avoid a trip, or at least to time it so as to minimize congestion and pollution.

Light Vehicles (Cars and Trucks). As discussed, the increasing number of households with multiple cars is making it possible for people to purchase cars for specific kinds of trips. The cars in a two car household frequently fall into two categories, image and utilitarian. Image cars can be large luxury cars, or Geo Metros, depending on the image the owner desires to project. Utility cars include used cars, four wheel drive vehicles, light trucks, vans, etc.

Fuel cell engine propulsion systems will provide automobile designers with new opportunities. The first generation of fuel cell engine powered cars will probably be similar to "standard" gasoline powered cars, but successive designs will take advantage of the unique performance and packaging capabilities of fuel cell engines. The low noise of ECEs, for example, may permit installation of the cells themselves under seats or in other places where "heat" engines would not normally be considered. Such fuel cell engine powered vehicles may have more useful room than vehicles with "conventional" power plants, assuming that stricter energy and environmental constraints may be mandated in the near future.

Automobile manufacturers (U.S. and foreign) are currently concerned about their ability to sell enough battery/electric cars to meet proposed California Air Resources Board's Zero Emission personal vehicle standards. These standards, as of 1994, require that 2% of the cars sold in 1998 be Zero Emission Vehicles (ZEV). This share of ZEV's rises to 10% by 2003.

There is little question concerning the ability to build an adequate number of battery/electric cars. The question is, will enough people buy them? The useful range of battery/electric cars, using currently available batteries, will be less than 80 miles (future batteries may provide a 100 to 150 mile range). The cost of battery/electric cars will be much higher than comparable gasoline cars. Batteries must be replaced every few years (depending on mileage, average depth of discharge, etc.). While battery life and reliability will improve, ownership costs will continue to be much higher than those of similar gasoline (or natural gas) powered internal combustion engine vehicles.

In urban regions which do not meet federal standards (such as Los Angeles and others) the economics (under mandated environmental constraints) of fuel cell engine propelled vehicles need only be equal to or superior to that of batteries or other low emission vehicular power plant systems.

Single Passenger Commuters. The average commuter car only carries 1.2 people, including the driver. In more than 80% of work trips, people travel alone [77]. Consequently, single passenger (or two passengers in tandem) commuter cars could meet the needs of the majority of commuters.

Several automobile companies have been or are working on candidate concepts, for example the GM "Lean Machine" which is capable of very high (per passenger) mileage (150 mpg or 120 mpg with air conditioning) and proportional environmental improvements. The California Dept. of Transportation considers this one of a class of "narrow lane" vehicles. This "vehicle" should qualify for ULEV classification with reformulated gasoline. Two lean machines can run side by side on a single lane. Up to four times as many can be parked in the same space that one conventional car requires. In regions where additional freeway capacity is needed, narrow (4 to 5 ft) low weight bearing lanes can be added at less cost (capital and societal) than conventional freeways. These lanes would be used only by such narrow cars and motorcycles. Their high maneuverability and coordinated turns (people do not slide across their seats) make these cars fun to drive. It should be possible to make them as safe as small conventional cars [96]. Product clinics regarding the "Lean Machine" have been conducted by GM in cooperation with the California Department of Transportation. While some of the data is proprietary to GM, it was observed that there is a surprisingly high level of interest in purchasing such a machine, depending on price. The price of these "narrow lane vehicles" could be at or below the costs of conventional vehicles depending upon the pricing strategy of the manufacturer and the

probability of selling additional high profit margin conventional vehicles. One working assumption is that (in large cities where parking space is a concern) up to 30% of the work trips could be made using this class of narrow lane vehicle.

Runabouts or Shoppers. Over half of the vehicle trips in most communities take less than 10 minutes. These involve trips to stores, public transit stops, and personal business (including about one fourth of the work trips). Vehicles used for these type of trips could be electric powered, simple and reliable, and need have only about a 30 minute battery charge duration. Battery charge duration in these vehicles is a more appropriate measure than range.

Vehicles of the type described above can carry two passengers at speeds up to 45 mph, have full automotive amenities, be used on arterial streets, but not on freeways. They should be very reliable and able to meet all motor vehicle safety objectives. The market penetration of such vehicles will be based on the manufacturer's ability to provide a product which will be less costly and more reliable than old used cars. If one assumes that: this type of electric vehicle would only be sold to households with two or more other cars (and/or to the elderly who might not otherwise be licensed to drive); that they are very reliable and had automobile like amenities (cooling systems); and were priced below a typical old used car, it is logical to assume that they would be used for 30% of shopping and similar trips.

The California dept. of Transportation has evidenced a willingness to cooperate with local utilities and interested manufacturers to conduct demonstrations to determine if a market for a low cost, moderate performance "Shopper" or regional electric vehicle could be developed.

Other alternative automobiles, such as "neighborhood cars" may supplement the runabouts in low density areas. They would be very simple vehicles, with top speeds less than 10 mph, used for short trips where there are paths or lanes dedicated to their operation. Such vehicles could carry two passengers, mix with pedestrians, and provide a few amenities such as shelter from weather. They also can be powered with (existing) batteries. These cars could also improve access to public transit in low density residential areas. It may be possible for them to be used by people who are not qualified to use conventional cars; for example, golf carts and motorized bicycles (mopeds) presently serve that purpose. In general "neighborhood" vehicles are primarily replacements for walking.

3.1.4 Acceptability of Personal Vehicles

The economic viability of vehicles designed to use alternative fuels and the willingness of the public to purchase them will depend on whether a cost penalty, or service loss (if any), is associated with their use. The total user (or life cycle) costs of alternative fuel vehicles will be a weighted combination of several tangible and intangible factors including:

1. The service the vehicle can provide
2. The purchase price of the vehicle
3. The operating and maintenance costs (including fuel and other expendable materials) of the vehicle
4. The cost of owner equipment, if required, to charge or refuel the vehicle
5. Reliability costs (inconvenience) of the vehicle

6. The cost of insurance for the vehicle
7. The resale value and/or disposable cost of the vehicle.

Service. People select cars for the service (or image) they provide. Any operational limitation to a car's usefulness such as passenger capacity, range, traffic, merging capability, package space, etc., is subjective and difficult to define, but will be a major factor in owner acceptance. The kind of car selected will depend on whether the car is to be used for commuting, shopping, or some combination of family uses.

Purchase Cost. The first question asked by most car buyers is "how much does it cost." Market experience indicates that the sale of cars is relatively insensitive to price changes of 2-3% or less, or about \$200-\$500.00. The cost assumptions used for the "conventional family sedan" in this study are based on cars such as the Chevrolet Lumina or Ford Taurus. The average price paid for a new car in 1991 was \$16,700.00, although some small cars could be purchased for as little as \$7,000.

The base price (in constant dollars) of conventional cars should decrease about 1% per year if there are no major technology changes or added technical features. This could be offset by the introduction of new technologies required to achieve air quality goals with gasoline, by the introduction of alternative fuels, or by the introduction of advanced power production systems. Vehicle redesign (such as larger fuel tanks, etc.) to achieve similar range per refueling may also increase the overall vehicle cost.

Operating Costs. Operating and maintenance costs are the sum of the retail price of the fuel consumed plus the price of expendable items like oil and tires. The amount of fuel consumed will vary with the vehicle's fuel efficiency and the type of trips for which the automobile is used.

The use of alcohol fuels may permit the design and use of engines with higher compression ratios than current gasoline engines. This will increase the engines power and improve acceleration characteristics. Methanol may provide 7% to 10% more power than the same engine operating on gasoline. It is debatable if the improved performance of piston engines using methanol would justify higher vehicle and/or fuel prices. Further, undesirable emissions such as NO_x may increase with increasing compression ratios.

Refueling Equipment Costs. The cost of owner equipment, such as that required to recharge or refuel the car, may be significant for battery and natural gas or hydrogen powered vehicles, but negligible for gasoline or methanol powered vehicles. The need or ability to provide home (or business) "recharging" facilities can be important with respect to the public's acceptance of alternative "fueled" engine systems, such as compressed natural gas or hydrogen powered engines or battery/electric vehicles. If hydrogen or other high pressure or cryogenic fuels are selected, the refueling station (and car) may have to be equipped with automatic disconnects to reduce potential hazards to the operator.

Reliability. The perceived costs of poor reliability (inconvenience) are subjective, dependent upon the frequency with which technical problems prevent the completion of a trip. The annoyance which occurs with the cancellation of a trip, or the time lost in obtaining repairs, will impact public acceptance. Additional studies are required to address the question of the additional amount an owner will pay so as to avoid a trip for repairs.

Insurance. Insurance and perception of risk will play a major role in the economics and acceptance of advanced propulsion systems and alternative fuels. Insurance represents a significant portion of the cost of ownership for many people. Given present trends, the relative cost of insurance is probably going to increase. The safety of some gaseous fuels has been questioned, as has the accident risk of vehicles whose acceleration capabilities may be limited by alternative fuels. Insurance companies usually overestimate such risks until they have sufficient data on accidents or other maintenance problems on which to base their rates.

The cost of insurance will differ with the users (and insurance companies) perception of the risks associated with the introduction of new fuels. Insurance company estimates of the costs of insurance for some recent innovative cars have been as high as \$1000 per month because of the vehicle's performance or major systems vulnerability. In some cases the insurability of the vehicle itself has still not been determined.

Resale. Resale value and or disposal costs are important to new (and used) car purchasers. The resale value of the vehicle to a second owner is a function both of the vehicle's perceived value and the expected costs of maintaining it. This perceived value will also be influenced by the availability of alternative fuel refueling facilities if the vehicle is dedicated to a specific fuel. The final disposal cost of the car and its materials must also be considered, particularly if the propulsion system incorporates hazardous or non-degradable materials.

The Zero Emission Vehicle requirements established by CARB are a concern to the automobile manufacturers since they question whether they will be able to sell adequate numbers of battery/electric cars to meet the mandated share of the market. This has caused the automobile companies to consider using fuel cell engines as the vehicle's power source, even if they have a higher initial cost. Fuel cell engine powered vehicles appear to be one of the best alternatives to meet emission (and probable future energy consumption) standards while still providing consumers with cars of acceptable performance.

3.2 ADVANCED PUBLIC TRANSIT

There has been very little innovation in buses or other public transit equipment since the start of the century. The uncertainties in the public transit market made it difficult to maintain production capacity. Public transit is at a disadvantage in most modern American cities, particular those in the west because of their low population density. For example, nearly half of all public transit trips are in two eastern cities, New York and Philadelphia. Work trips by public transit can take more than twice as long as by car, buses must often travel farther with fewer passengers. As a result, the use of buses does not always reduce pollution or energy consumption. Public transit use also decreases almost directly with increases in disposable income. World Bank data indicates that a 1% increase in household disposable income leads to a 1% decrease in the use of public transit in all but the most densely populated major cities. Most of those type of cities have rail transit which provides both travel time and convenience competitive to the automobile; modern rail transit also helps to reduce traffic congestion and avoid the hassles associated with parking. There has been little expansion of public transit services in the last several decades within the United States (the exception has been the construction of a few rail systems and the introduction of articulated buses). The major difficulty in attracting people to use public transit is the fact that in most situations the travel time by transit is significantly longer than by private car (or car or van pool). Further, the public's choice

of public transit over automobiles is not linear with trip time. A study based on data from a number of public transportation studies, primarily the Chicago Area Transit Study, indicating a rider's decision to use public transit as a function of perceived trip time and cost relative to a car, is summarized in Table III-8.

However, emission regulations are being established that will effect mass transit propulsion systems; for example, a requirement has been established in Los Angeles to replace diesel buses with zero emission buses on 30% of the city's bus lines by the year 2000. Such zero emission transit vehicles (in the locality) could be provided through the use of trolley buses. The cost of installing and maintaining the catenaries (estimated at 600 million dollars) could be avoided if fuel cell engine powered buses could be made available in reasonable quantities within this time period. Similar savings could be achieved if the replacement schedule could be modified to permit development of fuel cell engine powered buses within a reasonable time period [30,101].

Perceived Trip Time[1]	Perceived Costs [2]			
	<u>Twice</u>	<u>Same</u>	<u>Half</u>	<u>Free</u>
-30 min.	75-80%	82-87%	90+%	90+%
-15 min.	25-35%	50-60%	82-87%	90+%
same	6-8%	12-18%	25-35%	90+%
+15 min.	<1%	6-8%	10-15%	80-90%
+30 min.	<<1%	4-6%	8-12%	40-50%
+45 min.	<<<1%	1-2%	6-8%	20-30%

Notes: [1] waiting valued 2.5 times on vehicle time

[2] perceived costs for car include gasoline, parking fees, etc.

Table III-8. Rider's Decision to Use Public Transit as a Function of Perceived Trip Time and Cost Relative to a Car

Serious consideration is being given to a two step program in which a small fleet of phosphoric acid fuel cell engine powered buses would replace some of the diesel engine powered buses to demonstrate the potential of fuel cell engine powered buses. The phosphoric acid fuel cells in the buses would then be replaced by proton-exchange-membrane fuel cells if and when that particular type of fuel cell's superior performance, cost, and reliability has been confirmed.

The low emission levels and noise of fuel cell engine propulsion systems will make fuel cell engines attractive for local bus operators and government decision makers, even if the initial costs are somewhat higher than that of diesel engine powered buses. Demonstrations of both the DoE/DoT phosphoric acid fuel cell engine/battery and Ballard (stored hydrogen) PEM fuel cell powered buses occurred during 1994 and 1995. New transit buses which use advanced propulsion systems can provide more attractive transportation services; they will also be more acceptable in residential neighborhoods.

In many large cities with rail transit it is possible to provide competitive rail transit travel to other mass transportation or private vehicle travel times if the time to travel: to rail stations or bus

stops; for parking; traffic congestion; etc., are all included. Use of electrochemical engines by rail transit would avoid the need for electrification (third rail or catenary), thus reducing both the construction and maintenance costs of rail transit.

3.2.1 Advanced Traffic Control Systems

Intelligent Vehicle Highway Systems (IVHS) should improve personal mobility while at the same time reducing congestion, energy consumption, and air pollution. Adaptive traffic signal systems which adjust signal timing to favor higher streams of traffic will reduce traffic delays and start and stop driving which consume a disproportionate quantity of fuel. Automated highway systems may be able to increase vehicle capacity and relieve the driver of some driving related tasks. Assessments, by local authorities, of the reductions in energy consumption made possible by improved traffic signal controls range from 5 to 20%. The actual values are uncertain since available computer models are not designed to address these kinds of changes.

Traffic information and routing systems will enable travelers to avoid congestion (or accidents) and reduce excessive travel by identifying the best route to selected destinations. Some studies have shown that traffic information systems can save up to 40% of the driving distance to new destinations and reduce travel time an average of 5 to 7% for trips to known destinations. Adaptive traffic signals and information systems should reduce idle time on an average trip by 10 to 20% depending on the community. Such systems can provide a corresponding reduction in travel times and proportionate reductions in emissions and fuel use.

Unfortunately, the computer models used to project regional pollution levels are not able to accurately project the benefits of these systems. Some progress is being made in developing improved models but the benefits they project are, at best, only representative of what may be possible. Some authorities think that real time traffic signal systems and related traffic information could improve the fuel consumption of cars in cities to the point that energy consumption in city and rural driving would be essentially identical [18,88].

Telecommuting. Telecommuting, that is the use of telephones and other communication and control devices to contact customers or other employees, is still in an early stage of acceptance. These devices will make it possible for people to change where they live and work. Satellite offices can be located where they will be more convenient for employees and customers. Many workers will be able to commute, when necessary, at times when traffic congestion is low. Coupled with computer controls for manufacturing, these new technologies will make it possible to locate facilities, plants, stores, and offices almost anywhere that convenient access to highways and railroads exists.

Road Pricing and Environmental Fees. Increases in gasoline taxes and implementation of road pricing should encourage people to travel in off-peak travel periods and to purchase more energy efficient cars. Road pricing fees would be charged for entering congested areas on a time of day basis. Such fees are being seriously considered as a way to reduce congestion and minimize the need to construct additional freeways. The use of electronic license plates, which would be necessary for road pricing, has already started at some existing toll locations (bridges, etc.) where the time savings would be beneficial to the driver. The use of electronic license plates reduces the costs of toll collection and may reduce the need for additional highways. Road pricing on a larger scale will probably begin with trucks and commercial vehicles which

will pay a fee for entering congested regions; fees would be high at peak travel hours and lower, or perhaps non-existent, in the morning hours [88].

Environmental fees, combined with road pricing and the cars actual emission data, can provide incentives for a driver to use the most efficient vehicle available for each kind of trip, without excessively penalizing those cars which receive little use.

These regulations may accelerate the growth of rim cities and nearby small cities which have been stagnant in recent years. A number of proposed new towns are being designed to combine the amenities of a small city with access to work and shopping either by walking or using innovative transportation vehicles. The city locations are being selected for ambiance and quality of life.

The changes in energy consumption, pollution, and mobility that innovative vehicles and control systems provide have not been included in past energy or transportation forecasts prepared by the U.S. DoE or U.S. DoT, in part, because the public acceptance (and availability) of these products has not been confirmed.

3.3 FREIGHT SERVICE IMPROVEMENTS

In the early part of the next century, by 2010, the energy required for commercial vehicles is projected (by the U.S. DoE) to exceed that consumed by light or personal vehicles. This will increase the pressure to reduce the emissions generated, and the energy consumed, by commercial vehicles; this is a more difficult task than that for personal vehicles because the mission of commercial vehicles is to transport heavy loads. Consequently, there is relatively less to gain by improvements in structure or design. It will not be possible to make as much improvement in the energy consumption of commercial vehicles as in personal cars. A 3,000 lb. car for example carries on average less than 300 lb. of useful load, about the average weight of two passengers. The purpose of a truck or train, on the other hand, is to move heavy loads which may exceed 75% of the total weight of the loaded vehicle. Improved aerodynamics, lower rolling resistance, and decreased weight will all help, but major improvements will require low emission and efficient power plants such as electrochemical engines.

Mode	% Ton Miles	% Revenues	Cost per Ton Mile	Ton Miles/ Gallon
Local Truck	7.4 %	35.0 %	27.0 cents	tbd
Intercity Truck	17.0 %	48.0 %	20.0 cents	Tbd
Railroad	26.0 %	11.0 %	3.0 cents	307
Pipelines	18.0 %	3.5 %	1.5 cents	tbd
Domestic Water	30.0 %	3.2 %	0.8 cents	tbd
Domestic Air	0.2 %	0.8 %	34.0 cents	tbd

Total ton miles (1986) — 3.1 billion

Total revenues (1986) — 235 billion dollars [133]

Table III-9. Modal Share of U.S. Freight

The American freight system is made up of at least six (6) major elements: trucks (local and intercity), railroads, pipelines, domestic water, and domestic air. Railroads continue to provide the majority of the intercity ton miles, (26+%) versus 18% for trucks, but generate only 11% of the revenue compared to the 48% generated by trucks, Table III-9. Freight rates continue to be very competitive and most are decreasing; for example, the average railroad freight rate has decreased by 5% since 1980.

Of the 53 million trucks in use in 1990, the majority were used for urban delivery. Urban delivery trucks generated approximately 465,000 million miles of vehicle travel while vehicle intercity trucks generated an additional 140,000 million miles. Trucks generate about 30% of the total urban mileage and probably cause 20 to 25% of the traffic delays. The average age of trucks in service is about 16 years as compared to private car average age (1990) of 12 years. In 1990, intercity movement of high valued freight (electronic equipment, perishables) involved the use of nearly 2.2 million trucks. The number of intercity trucks (class 7 & 8) is expected to increase from about 2.2 million to between three and four million by the year 2020 (depending on the effectiveness of rail competition).

3.3.1 Advanced Truck/Truck Traffic Control Concepts

Improved freight shipment systems and new equipment technologies for trucks include the use of dispatching and scheduling systems which route truck movements to avoid congestion or peak traffic periods. These systems can improve the utilization of trucks as well as reduce energy consumption, traffic congestion, and pollution. The use of advanced freight technologies will be assumed in Scenario Four (see Section VII) as will innovative local distribution systems.

Very little emphasis has been applied to the use of fuel cell engine propulsion systems within heavy trucks. Most truck buyers are very cost conscious; they will not risk investing in new and different technologies until there has been extensive field experience. Truck fuel cell engine propulsion systems could be derived from bus fuel cell engine programs since the power ranges are similar. The primary competitor may be the gas turbine which could provide a more cost competitive solution to energy and environmental concerns for many heavy truck applications.

The unique characteristics of fuel cell engines and electric drives could, however, lead to entirely new truck design and propulsion concepts. For example, operators have experimented with providing power to the trailer wheels to improve overall hill climbing and acceleration characteristics. This can also be accomplished with electric drive. Electric drive could be advantageous to both the truck operator (less driving time and lower maintenance costs) and to the general public driving passenger cars on the same roads by reducing current traffic congestion and delays caused by conventional heavy trucks.

U.S. DoE projections of reduced truck energy use and emissions are based on the assumption that fuel cell engine systems will power approximately 20% of the commercial trucks (class 5 and above) by 2015 and 40% by 2020 [137].

3.3.2 Advanced Rail/Rail Traffic Concepts

Railroads services are becoming more efficient, both in equipment utilization and in energy usage. In 1980 1,710,000 rail cars and 28,000 locomotives (rated at 65 million hp) were in use.

By 1988 equipment was reduced to 1,240,000 rail cars and 19,700 locomotives (rated at 57 million hp). Some of the reductions in equipment were the result of railroad consolidation, but most were the result of improved utilization. The revenue ton miles per locomotive improved about 1.5% per year and should continue to do so through the 1990's.

Piggyback, that is trailer on flat car, services have increased about 10% per year for the last several decades. The fuel economy of a piggyback train equates to about 12-14 trailer miles per gallon compared with 5.2 trailer miles per gallon for a class 8 (over 33,000 lb.) intercity truck.

A new category of equipment has been introduced in the last six (6) years which is even more efficient. Vehicles that appear to be simple highway trailers actually have two sets of running gear, tires for roads and steel wheels for railroads. These have demonstrated fuel economy benefits on the order of 25 trailer miles per gallon on high speed intercity services. These "railroaders" can be transferred from rail to road and back on almost any level surface. Adaptation of this concept may expedite delivery and reduce congestion of existing freeways and streets by operating dual mode trailers and highway (class 6-8) tractors on existing, under-utilized railroad right-of-ways in cities. If these new service concepts are attractive to shippers, their higher energy efficiency (410 Btu/ton mile compared to approximately 3,500 btu per ton mile for conventional trucks) could lead to a 10% to 15% reduction in intercity freight energy consumption; this is so even if no improvements in propulsive efficiency, such as would result if fuel cell engines were utilized, occurs [57].

Additional high value and/or perishable goods might be attracted from trucks to rails if trains could run at high speeds. Expedited service at 150 mph on tangent track railroad systems appears technically feasible, although the economics have not yet been fully evaluated. Some studies imply that it may be possible to divert up to 20% of over 300 mile trips from truck to rail if shorter rail trip times were combined with more effective control of scheduling and makeup of trains in the rail yards, Table III-10. Intercity movement of commodities such as coal, grain, etc., will be dependent on the progress in reducing energy consumption (and policies with respect to use of low sulfur coal).

Trip Length	One Day	Two Days	Three Days	Four Days	Five Days	Six Days
300 miles	16-20%	7-10%	present	----	----	----
1000 miles	N/A	30-40%	20-30%	10-20%	10%	present

Current average truck time on 1000 mile trip is 2.5 days with 8 hr. uncertainty

Current average rail time on 1000 mile trip is 6 days with 2 days uncertainty

Current average truck time on 300 mile trip is 1 day with negligible uncertainty

Current average rail time on 300 mile trip is 3.5 days with 1 day uncertainty

Table III-10. Modal Share Truck vs. Rail Delivery Time, Percent Diverted from Truck for Different Trips Assuming Improved Rail Delivery.

The initial use of electrochemical engine powered locomotives may be in regions which have not achieved federal air quality standards. The South Coast Air Quality Management District (SCAQMD) of Los Angeles has established a goal of reducing pollution from railroads by 90% by the year 2010. They are seriously considering banning diesel locomotives from their area of responsibility.

The low emission approach first considered by the South Coast Air Quality Management District was to use electric locomotives. This would require construction of electrical distribution systems (catenaries or third rails). The cost and time of constructing the infrastructure to use electric locomotives has been estimated at 4.6 billion dollars and 18 years, respectively. This estimate requires consolidation of some lines and would still not provide for electrical power on most branch distribution lines. Despite this investment the electrification strategy would only reduce railroad emissions by 70%. It is reasonable to assume that equivalent (or greater) emission reductions could be provided by fuel cell engine powered locomotives at a lower cost [64, 99].

Introduction of fuel cell engine propulsion systems for locomotives at about the year 2000 should also lead to significant reductions in freight service energy consumption as indicated in Table III-11. The assumptions in Table III-11 are based on first generation fuel cell engine costs of about \$750 per kW. Fuel cell engine manufacturing studies indicate that the cost of the second generation fuel cell engines should be about \$250 per kW. This is still higher than diesel engines which cost about \$150 per kW. The diesel engine's fuel costs are based on diesel fuel at \$0.75 per gallon and 30% average thermal efficiency. The first generation locomotive fuel cell engine methanol costs are based on methanol at \$0.50 per gallon and 50% average thermal efficiency. It may be possible for second generation fuel cell engine propulsion systems to achieve average efficiencies of 55+%.

	Capital Cost Power plant	Annual Fuel Cost	20 Year Total
Diesel Locomotives	\$336,000	\$315,000	\$6,620,000
1st Generation Fuel Cell Locomotives	\$1,230,000	\$254,000	\$6,310,000
2nd Generation Fuel Cell Locomotives	\$410,000	\$220,000	\$4,810,000

Table III-11. Relative Economics of Fuel Cell Engine and Diesel Locomotives

This very preliminary comparison will be revised based on the information being developed in an ongoing fuel cell engine powered locomotive study. Items which may change the actual numbers, but probably not the relative levels, include the use of selected railroad duty cycles incorporating realistic levels of idle and part throttle time (diesel locomotives idle from 45% to 55% of the time and incorporate part throttle 17% of their operating time on long internodal runs). Fuel cell engines can probably be shut off for most of the idle time. Fuel cell engines for locomotives may incorporate batteries, ultra capacitors, or flywheels for regeneration. Currently, trains brake between 4-20% of their operating time, generating wasted energy, some of which could be recovered by regenerative techniques.

The process of demonstrating and commercializing fuel cell engine powered locomotives will include: tests of prototype systems on modified locomotive(s), demonstrations of preproduction locomotive(s) in revenue service, and creation of manufacturing capability. Phosphoric acid cells will probably be available first and, thus, may be used to meet the schedule for the first

generation locomotives which would be used in the Los Angeles basin and other non-compliance regions.

Stage II, or second generation, fuel cell engine powered locomotives should be economically superior to diesel locomotives for almost all railroad uses. They may use Proton-Exchange-Membrane (PEM) fuel cells. Preliminary economic and cost studies imply that PEM fuel cell systems will be at least economically competitive and perhaps even superior, on a life cycle cost basis, with diesel engines in locomotives. If PEM fuel cell engine powered locomotives were in general use railroads would not have to change locomotives when entering SCAQMD territory.

If the results of the initial use of fuel cell engine propulsion in locomotives are positive the entire stock of diesel locomotives may eventually be retrofitted or replaced with locomotives powered by electrochemical engines.

The third phase of fuel cell locomotive development would take advantage of the fuel cell engine's operating characteristics to create an entirely new type of locomotive. These could be as different from current diesel locomotives as diesel locomotives were from steam locomotives.

3.4 SUMMARY OF PLANS FOR INNOVATIVE VEHICLE DEMONSTRATIONS

The U.S. Departments of Energy and Transportation are sponsoring the development and demonstration of fuel cell engine powered buses. Other demonstrations such as "station" cars and fuel cell engine powered locomotives are being discussed with state and local governments, advocacy groups, and potential manufacturers. The California Department of Transportation (Caltrans) is developing useful information on the acceptance of problems with, and benefits of, single passenger commuters, neighborhood cars, shoppers, advanced public transit, improved freight services, and similar concepts. The results of those studies will be used in the assessments discussed in Section VII to project how travel demand could change and the implications that portends for advanced propulsion systems.

IV. ENERGY AND ENVIRONMENTAL CONCERNS

This section of the report provides an overview of the public's environmental and energy concerns, describes what facts are known, what regulations are in place, and what regulations will probably be mandated for future vehicle, truck, and railroad locomotive engines. This section also summarizes the information on possible future regulations that will be used for the development, during Phase II, of future scenarios; the use of and development of such scenarios are described in more detail in Section VII.

Societal concerns that are contributing to the introduction of laws and regulations which will require the automobile and energy companies to produce a significant number of low emission/energy efficient cars and compatible fuel supplies include:

- Concern regarding the health problems caused by regional air pollution
- Concern that the U.S. is running out of energy, or importing an excessive amount of petroleum products
- Concern over the international balance of payments
- The need for competitive fuels which could help provide a price cap on the world price of crude oil.

Public concern over emissions and energy consumption has lead to the imposition of a number of legislative initiatives directed at forcing or accelerating processes which will reduce emission levels in "non-compliance" regions to levels deemed acceptable by the Environmental Protection Agency.

The Federal initiatives for improving vehicle technology fall within the responsibility of a number of departments and activities. The most important include:

- The *New Generation or Clean Car* initiative started by the Presidents Office of Science and Technology Policy, which has now become the responsibility of the Department of Commerce
- Existing laws and regulations including the Intermodal Surface Transportation Efficiency Act (ISTEA), The Clean Air Act Amendments (CAAAAs)-1990, Alternative Motor Fuels Act (AMFA)-1988, Energy Policy Act (EP Act) 1992, and Executive Order 12759-1991
- Defense Conversion Programs in which a significant amount of money is being made available for programs to develop information or dual use products which take advantage of prior defense research
- Initiatives by the Department of Energy and Department of Transportation which have been authorized by prior legislation
- Initiatives by the Congress to mandate higher "technology standards" and to create the mechanisms that will make it possible to accelerate the commercialization of advanced technologies with significant societal benefits.

Industry is much more confident with economically driven than with mandated initiatives. Government mandates could be reversed or significantly modified by the next administration. As a result the automotive and energy industries will be reluctant to make commitments to technologies that require both long lead times and substantial investments to commercialize.

Government agencies, on the other hand, have societal obligations to reduce pollution; obligations which may be potentially difficult to meet if fuel cell engines are not developed in a timely manner.

The vehicles of interest in this study include personal cars and light and heavy-duty trucks. Non-transportation energy uses have not been considered except to the degree that they may provide both early market opportunities and experience which could accelerate the availability of electrochemical engines for private automobiles and light trucks.

The primary regulated pollutants generated by spark ignition engines include NO_x (Nitrous oxides), CO (Carbon Monoxide), and UHC (Unburned reactive organic hydrocarbons gases, also defined as ROG) which primarily result from incomplete combustion and/or evaporative losses.

Carbon monoxide is a known poison. CO emissions tend to be more serious in cold weather, particularly in regions where there are frequent temperature inversions. Unburned hydrocarbon emissions combine with NO_x in the atmosphere in the presence of sunlight to form ozone (O_3). Ozone is a lung irritant and causes respiratory problems. NO_x is a reactant in the formation of ozone and therefore is one of the primary pollutants targeted for reduction. Unfortunately, NO_x emissions from an engines tend to increase as the combustion temperatures, hence, efficiency increase.

Electrochemical engines can potentially provide significant benefits in terms of reduced energy consumption and emissions. However, many questions remain: are there better short term solutions such as improving existing engines; are there competitive propulsion systems which can meet the standards more easily; what will it cost to develop fuel cell engine propulsion systems which meet the standards; when will they be competitive with other propulsion systems?

4.1 TRANSITIONS TO ELECTROCHEMICAL ENGINES

As noted earlier, the transition to the use of electrochemical engines and alternative fuels for vehicles propulsion will probably come in two steps:

- First - The near zero emission environmental/energy efficient mandated transition
- Second - The economic transition.

The economically driven transition will occur (in the absence of regulations) when the overall costs of fuel cells, on a per mile basis, are less than the overall costs of competitive engines which use petroleum derived fuels. There is little existing incentive for individuals to purchase or use low pollution propulsion systems in the absence of regulations. If there were no government support or mandates, the timing of the economic transition to new energy propulsion systems would depend on how well private companies anticipate the need for such propulsion systems and then, when they decide to develop such energy resources and propulsion systems.

Available data on the world energy resources indicates:

- That the world's petroleum resources are large enough that economic production could continue through at least the middle of the next century (refer to Section VI)
- That the cost of petroleum derived fuels will not increase significantly until the middle of the next century when low cost resources (outside of OPEC) are exhausted.

As a result, petroleum and natural gas based fuels will continue to provide the lowest cost energy for many decades. Other fuels derived from non-petroleum resources (biomass, etc.) should be economically competitive in the latter half of the next century. The economic transition to non-hydrocarbon based energy systems will, therefore, require a period of several decades. For a significant time both petroleum derived and alternative fuels should be available to users at about the same cost per mile traveled. Similar transitions have occurred in the past; examples are the change from wood to coal to oil to natural gas for heating, and the change from coal fired steam to diesel or electric locomotives.

Automobiles and trucks are one of the largest sources of air pollution. To alleviate the public's concerns federal and state governments are establishing regulations for allowable levels of noxious emissions from automobiles, trucks, etc. These regulations currently mandate the use of low emission propulsion systems; such regulations may include improvements to present systems or the future use of new technologies such as fuel cell engines.

Since it is impossible to exactly predict the type or timing of regulations that may be passed by the legislatures, planning for fuel cell engine commercialization must allow for changes in: regulations, funding for the development of new technologies, the economic environment, and public acceptance. Scenarios can provide tools to illustrate the effect of alternative futures and response strategies which provide improvements in fuel economy and emissions. By addressing the interaction of the pertinent variables it will be possible to provide estimates of the range of performance requirements, markets, and availability. The uncertainties which should be addressed include:

- Changes in emission regulations
- Changes in fuel consumption standards
- Changes in the economic environment
- Changes in the cost of fuels
- Changes in vehicle and propulsion technology
- Changes in societal acceptability.

New technical data are still being developed regarding: health problems due to pollution; the sources of emissions; and the technologies for moderating environmental problems which could, with time, change the requirements as they are now interpreted.

4.2 FEDERAL EMISSION REQUIREMENTS

4.2.1 Regional Emission Level Classifications and Regulations Established by the Clean Air Act Amendment and the EPA

The Clean Air Act Amendment of 1990 established a series of classifications for regional ozone and carbon monoxide emission levels based on the levels of the most serious emissions; it then

established dates at which these serious levels are to be reduced to "acceptable" levels. These emission level regional classifications are summarized in Table IV-1.

	Class	Level ppm	Attainment Date
Ozone	Marginal	0.121 to 0.138	3 years
	Moderate	0.138 to 0.160	6 years
	Serious	0.160 to 0.180	9 years
	Severe 1	0.180 to 0.190	15 years
	Severe 2	0.190 to 0.280	17 years
	Extreme	0.280 and above	20 years
Carbon Monoxide	Moderate	9.1 to 16.4	December 31, 1994
	Serious	16.5 and above	December 31, 2001

Table IV-1. Classifications of Regions by Emission Levels of Ozone and Carbon Monoxide

The Environmental Protection Agency (EPA) has also developed regulations requiring the use of cleaner burning fuels (or low emission engines) in the 1990's; such regulations stipulate:

- Those areas not in compliance with CO standards, but in compliance with ozone standards, to use oxygenated gasoline in the winter beginning in 1992;
- The areas which are not in compliance with CO standards, and have an ozone problem that is classified as serious, moderate, or marginal, can request the use of reformulated gasoline (opt-in) before the 1998 deadline for compliance;
- The areas which are not in compliance with CO standards and contain ozone levels classified as extreme or severe to be required to use wintertime oxygenated gasoline beginning in 1992 and reformulated gasoline beginning in 1995;
- The areas which do not exceed CO standards, but have extreme or severe ozone problems to be required to use reformulated gasoline starting in 1995.

The scope of the environmental problems as perceived by the U.S. Environmental Protection Agency (EPA) can be illustrated by identifying the states, regions, and cities which are not in compliance with the federal regulations. The number of days per year (averaged over the past 10 years) that the emission levels have exceeded national tolerances in ten of the major U.S. cities are summarized in Table IV-2.

Washington DC had on average 29 days per days per year which exceeded federal standards in the early 1980's, 16 days per year in the later half of the 1980's, and only 11 such days in 1991. In 1991 Los Angeles averaged 37 very unhealthy days per year, while Washington DC averaged less than 1 very unhealthy day per year. The overall state and city compliance records are summarized in Tables IV-3 and IV-4.

4.2.2 Private Passenger Car and Light and Heavy Duty Vehicle Current and Proposed Emission Standards

The national air quality standards for automobiles require reductions in non-methane hydro-

Los Angeles	201	New York	40	Houston	31
Philadelphia	30	Washington DC	23	Detroit	11
Dallas	8	Chicago	7	Boston	5
		San Francisco	2		

Table IV-2. Average Days per Year Cities were in Excess of Federal Emission Standards, 1980-1990

States Which Comply with Ozone and CO ^[1]		States with Extreme Ozone Noncompliance		States with Marginal Compliance	
Idaho	0.63 ^[2]	Texas	8.65 ^[2]	Oregon	1.83 ^[2]
Wyoming	0.29	California	17.10	Utah	0.86
N. Dakota	0.37	New York	8.81	Arizona	1.95
S. Dakota	0.42	Pennsylvania	6.42	Missouri	2.74
Nebraska	0.91	Connecticut	2.51	Louisiana	2.00
Kansas	1.40	Wisconsin	2.74	Michigan	5.68
Iowa	1.86	Illinois	6.46	Indiana	3.22
Arkansas	0.93	Delaware	4.08	Ohio	7.57
Mississippi	1.45	Maryland	2.94	Kentucky	1.90
Total	8.26	DC	0.24	Tennessee	3.53
		Total	59.97	Mississippi	1.45
				Alabama	2.72
				W. Virginia	0.82
				Virginia	3.81
				N. Carolina	3.71
				S. Carolina	1.89
				Massachusetts	3.28
				Florida	8.97
				Total	57.93

[1] These states consume 7.2% of gasoline in the U.S.

[2] Number of Cars registered in each state in 1991, millions

Table IV-3. Emission Compliance Records by States

Cities with Extreme Ozone Noncompliance	States with Noncompliance Cities Ozone and Carbon Monoxide	
Los Angeles [1]	Washington (2) _[2]	Oregon (4) _[2]
San Diego	California (8)	Nevada (2)
Houston	Montana (1)	Utah (1)
Chicago	Colorado (3)	New Mexico (1)
Milwaukee	Texas (1)	Minnesota (2)
Grand Rapids	Wisconsin (1)	Ohio (2)
Baltimore	Tennessee (1)	New York (2)
New York	Pennsylvania (1)	Massachusetts (1)
Philadelphia	Connecticut (1)	Maryland (1)
Total 9	North Carolina (2)	
	Total 37	

[1] Designated Extreme, All Others Severe

[2] Number of Non Attainment Cities in Each State

Table IV-4. Emission Compliance Records of Cities

carbons (NMHC), carbon monoxide (CO), nitrogen oxides (NOx), and particulate matter (PM) in a two stage, or two tier process, which is depicted in Tables IV-5 and IV-6.

The allowable Tier I emissions are approximately 5.5% of an unregulated 1965 gasoline engine, (3% of HC, 4% of CO, 10% of NOx). Tier II would be approximately half of that.

<u>NMHC</u>	<u>CO</u>	<u>NOx</u>	<u>PM</u>
0.25	3.0	0.4	0.8

All covered vehicles must meet these standards for five years or 50,000 miles
The standards for the period between 1991 and 1996 are 26% lower

Table IV-5. Tier I, National Tailpipe Certification Standards, Private Cars, 1996, Grams per Mile

<u>NMHC</u>	<u>CO</u>	<u>NOx</u>	<u>PM</u>
0.125	1.7	0.2	0.8?

Table IV-6. Provisional Tier II Tailpipe Certification Standards, Private Cars, 2003, Grams per Mile

The Tier II standards may be promulgated after an EPA and Office of Technology Assessment study of the tail pipe emission improvements resulting from Tier I standards implementation. EPA must submit a report to Congress no later than June 1997 and determine within three calendar years after the report is submitted, but no later than December 31, 1999, whether Tier II standards should be promulgated.

Tier I emission standards, involving non-methane hydrocarbons (NMHC), carbon monoxide (CO), nitrogen oxides (NOx), and particulate matter (PM), have also been established for light duty (truck) vehicles, Table IV-7, while heavy duty vehicle emission standards (particulate matter, NOx, and HCHO, all in ppm) have been established through 1998 and are summarized in Table IV-8.

	NMHC	CO	NOx	PM
Light Duty Vehicles	0.25 gm/mi.*	3.4 gm/mi.	1.0 gm/mi.	0.08 gm/mi.
Trucks <6,000 lb.				
0-3,750 lb. LVW	0.31	.2	1.25	0.10
3,759-5,750 lb.	0.40	5.5	0.97	0.10
Trucks >6,000 lb.				
3,750-5,750 lb. ALVW	0.46	6.4	0.98	0.10
>5,750 lb.	0.56	7.3	1.53	0.12

*Grams per mile

Table IV-7. Tier 1, Light Duty Truck Tailpipe Certification Standards

Model Year	Particulates		NOx	HCHO
	Bus	Truck		
1985	-----	-----	10.7	-----
1988	0.60	0.60	10.7	-----
1990	0.60	0.60	-----	
1991	0.25	0.25	5.0	
1993	0.10	0.25	5.0	-----
1994	0.05 [1]	0.10	5.0	0.10
1998	0.05 [1]	0.10	4.0	0.10

[1] EPA can relax to 0.07 if 0.05 is not attainable, all data in ppm.

Table IV-8. Federal Heavy Duty Vehicle Emission Standards

4.2.3 Use of Alternative Fuels, Advantages and Disadvantages

The National Energy Strategy includes mandates for the use of alternative fuels in commercial trucks and light vehicles. The mandates are to apply to:

- Fleets of ten or more vehicles in the 21 most polluted cities
- Fleets of 230 or more vehicles in cities with populations over 250,000 [76].

The only fleet vehicles which would be exempt would be intercity passenger buses, multi-unit trucks over 26,000 lb., rental vehicles, emergency vehicles, and law enforcement vehicles. Ten percent (10%) of the purchases of applicable vehicles would be required to be alternatively fueled by 1995, increasing to 90% by 2000. Purchases of city buses would not be covered until the year 2000 at which time 50% would be required to be operating on alternative fuels; by the year 2003, 90% of all city buses would be required to be alternatively fueled, Table IV-9.

<u>Year</u>	<u>Buses</u>	<u>All Other Vehicles</u>
1995	not covered	10% of new vehicles purchases
1996	not covered	15% of new vehicles purchases
1997	not covered	25% of new vehicles purchases
1998	not covered	50% of new vehicles purchases
1999	not covered	75% of new vehicles purchases
2000	50% of new purchases	90% of new vehicles purchases
2001	75% of new purchases	same
2002	80% of new purchases	same
2003	90% of new purchases	same

Reference [15]

Table IV-9. National Energy Strategy, Alternative Fuel Fleet Mandates

Preliminary studies of these requirements indicate that 12,000 to 15,000 fleet cars and 8,000 to 10,000 trucks would have to be equipped to use alternative fuels to meet the federal standards. The stricter California Air Resources Board standards could require that 500,000 to 550,000 commercial vehicles in California operate on alternative fuels.

However, neither reformulated gasoline nor low sulfur diesel will be allowed to qualify as an alternative fuel. In addition an executive order was signed in April, 1991 which requires federal agencies operating fleets of 300 or more vehicles to reduce their gasoline and diesel fuel consumption by 10% by 1995.

Other pollutants which are receiving increasing attention include carbon dioxide, CO₂; no standards currently exist but CO₂ is considered to be one of the primary elements involved in the "greenhouse effect". Particulate matter (PM) has been difficult to eliminate from diesel exhaust but has never been a serious problem for gasoline engines.

While the control of ozone is indirect, concern over local ozone levels is one of the major factors behind the regulations. As described in Section 4.2.1 ozone levels exceed federal standards in many cities throughout the nation. Formaldehyde, which is produced in the exhaust of methanol engines, particularly during cold start-up, is at present unregulated; however, standards are being proposed for California.

The actual level of air quality improvement which can be achieved through the use of alternative fuels and improved engine emission controls will depend on factors which are difficult, or nearly impossible, to control. Examples include, poor repair, mis-repair, and deliberate tampering with air quality equipment to get higher performance or slightly greater fuel economy. Emissions during accelerations are much higher than during steady-state. The emissions from cars (for example in California) and trucks registered in other states cannot be legally regulated. The extent of this problem is debatable but some California authorities have estimated that out of state unregulated vehicles could generate emissions equivalent to those from all "properly" controlled California registered cars and trucks by the year 2003.

Despite the uncertainty about alternative fuel health benefits, public opinion in the United States appears to favor encouraging the increased use of such fuels. For example, recent interviews of 1,200 people by representatives of the Union of Concerned Scientists found that 67% of the people interviewed were strongly in favor of providing incentives for alternative fuel use and development while less than 10% expressed any opposition. Renewable energy research would be allocated the largest (or second largest) share of the Department of Energy's research and development dollars by 75% of those interviewed [120].

The U.S. Clean Fuel Enhancement Act of 1991 authorized \$10 million for each fiscal year beginning in FY 1992 through FY 1994 for research and demonstrations related to improving natural gas and other alternative fueled vehicle technologies. It also provides an investment tax credit of 20% through December 2001 (less in subsequent years) for the purchase of qualified clean burning vehicle fuel equipment, including both the vehicle and fuel supply system. Further, the Act established a fee/bate program to provide incentives to the purchasers of vehicles that produce carbon dioxide emissions below specified limits. In a related area it authorized \$27 million dollars for the year 1992, \$36 million for 1993, and \$41 million for 1994 for continued and expanded research development and demonstration of the availability of natural gas from existing and non-conventional sources.

It is unlikely that there will be any relief from such current and future standards unless serious attempts to accomplish them have been conducted and the technology to achieve the desired results is proven to be impractical or unavailable. Recent studies indicate that the automobile companies have been conditioned to expect increasingly severe environmental standards. A recent series of interviews published by J.D. Power and Associates of automobile and advertising agency executives on the future importance of "green marketing" found that:

- 6% felt that it will be much more important in 1996
- 50% felt that it will be somewhat more important in 1996
- 23% felt that it will be somewhat less important in 1996
- 10% felt that it will be much less important in 1996.

Table IV-10. Automotive Executive Expectations on the Importance of Environmental Characteristics In Marketing Cars

4.3 STATE ENVIRONMENTAL STANDARDS

4.3.1 Sources of Emissions within Non-Attainment Regions of California, Mobile Source Contribution

The requirements for low emission propulsion systems is led by California which has (in Los Angeles) the most severe regional air quality problem in the United States. The extent to which transportation (on-road and other mobile sources) is a source of emissions can be illustrated by the emissions from six (6) non-attainment regions in California in tons of pollutant per day, as depicted in Table IV-11.

In the California air basins, mobile sources are responsible for 47% of the HC emissions, 85% of the CO emissions, 73% of the NOx, 60% of the SOx, but only about 5% of the particulate

emissions (PM10). This level of emissions can be incrementally reduced by further improvements in existing engines, or by the use of fuels which reduce pollution. It can be reduced significantly by the use of battery and/or fuel cell type engines, both of which are low or near zero pollution propulsion systems.

	<u>HC</u>	<u>CO</u>	<u>NOx</u>	<u>SOx</u>	<u>PM10</u>
Stationary Sources	1,860	2,090	804	183	3,710
On Road Source	1,375	9,945	1,680	110	152
Other Mobile Sources	250	1,550	450	175	58
Total	3,485	13,395	2,934	470	3,920

Table IV-11. California Emissions from Six Non Attainment Regions, Tons Per Day

4.3.2 California Passenger Car and Light/Heavy Duty Vehicle Current and Proposed Emission Standards

The California vehicle emissions standards are divided into four categories: transitional low emission vehicles (TLEV), low emission vehicles (LEV), ultra low emission vehicles (ULEV), and zero emission vehicles (ZEV). The emission standards for each category, as a function of vehicle mileage, are shown in Tables IV-12 and IV-13.

<u>Requirements</u>	<u>NMHC</u>	<u>CO</u>	<u>NOx</u>
1960's Base	10.6000	84.00	4.10 (Illustrative only)
93 National	0.250	7.00	0.40
TLEV	0.125	3.40	0.40
LEV	0.075	3.40	0.40
ULEV	0.040	1.70	0.20
ZEV	0.00	0.00	0.00

The formaldehyde emissions are not to exceed 0.015 gm/mi. for TLEV and LEV or 0.008 gm/mi. for ULEV

Table IV-12. Emission Requirements for California Cars and Light Trucks, Grams per Mile at 50,000 Miles

The ULEV's are to have an average emission level $(\%CO + \%NOx + \%HC)/3$ less than 2.3% of an unregulated (1965) gasoline engine. Each company which supplies cars to the California market will be required to sell an increasing share of ULEV's and ZEV's beginning in 1997 and 1998, refer to Section II or Table IV-17. It is expected that the use of alternative fuels or reformulated gasoline will be required to meet ULEV standards with piston engines. Most flexible fueled cars, which can operate on either methanol or reformulated gasoline, will probably qualify as low emission vehicles (an LEV's average emission level is approximately 4.8% of an unregulated 1965 gasoline engine) [143].

<u>Requirements</u>	<u>NMHC</u>	<u>CO</u>	<u>NOx</u>
TLEV	0.156	4.20	0.60
LEV	0.090	4.20	0.30
ULEV	0.053	2.10	0.30
ZEV	0.0008	0.00	0.00

Table IV-13. Emission Requirements for California Cars and Light Trucks, Grams per Mile at 100,000 Miles

The California Air Resources Board (CARB), the official state body which set these standards, will require each car manufacturer to guarantee that cars will pass smog check inspections until they are 3 years old. The manufacturers can sell any combination of cars (except ULEV's and ZEV's) as long as the fleet average non-methane-hydrocarbon or organic gases (NMOG) emission standard is not exceeded. This standard decreases each year starting at 0.25 gm/mi. in 1994, decreasing to 0.202 gm/mi. in 1997, then to 0.073 gm/mi. in 2000, and finally to 0.062 gm/mi. in 2003.

The CARB rules will also make car manufacturers liable for all defects related to emission control during that time and require them to pay for any parts that cost more than \$300 to replace during the first 7 years or 70,000 miles. To ease the manufacturer's problems CARB allows vehicles with slightly higher emissions (in gm/mi.) to qualify as low emission vehicles prior to the imposition of the full standards as indicated in Table IV-14.

<u>Requirements</u>	<u>HC</u>	<u>CO</u>	<u>NOx</u>
before 1995 TLEV	0.188	3.4	0.40
before 1998 LEV	0.100	3.4	0.30
before 1998 ULEV	0.058	2.6	0.30
ZEV	0.0008	0.00	0.00 [143]

Table IV-14. Emission Requirements for California Cars and Light Trucks, Grams per Mile Prior to Dates Indicated

The emissions generated by cars are a function of the original equipment, the age, and the maintenance state of the cars. It is recognized that older cars generate a disproportionate share of the automotive emissions in most regions. For example, the California Air Resources Board recommends the use of the following pollution characteristics, Table IV-15, when the emission levels of the existing vehicle fleet are projected. The emission rates of the older vehicles certainly contribute disproportionately to the total amount of pollutants emitted by mobile sources.

Finally, California has also established heavy duty vehicle emission standards as presented in Table IV-16.

Model Year	Emission Rates, Grams per Mile		
	ROG	NOx	CO
Pre 1972	12.30	3.00	75.0
1972-74	9.80	3.20	59.0
1975-81	3.70	2.30	27.6
post 1981	0.84	0.78	8.3
New 1992	0.47	0.34	3.8

Table IV-15. Emission Characteristics of Older Cars.

Model Year	Particulates		NOx	HCHO
	Bus	Truck		
1985	-----	-----	5.1	-----
1987	0.60	0.60	6.0	-----
1991	0.10	0.25	5.0	-----
1993	0.10	0.25	5.0	0.10
1994	0.10	0.15	5.0	0.10
1996	0.10	0.10	5.0	0.05
Reference-Federal Heavy Duty Vehicle Emission Standards				
1993	0.10	0.25	5.0	-----
1998	0.05 ^[1]	0.10	4.0	0.10

[1] EPA can relax to 0.07 if 0.05 is not attainable

Table IV-16. California Heavy Duty Vehicle Emission Standards

4.3.3 Strategies for Operating Alternative Passenger and Light Duty Vehicles and the Use of Alternative Fuels to Meet Emission Standards

The industry is hoping that a new category which might be described as "near ZEV" will be established between ULEV and ZEV for hybrids and other very low emission propulsion systems such as fuel cell engines. The initial expectation was that only battery/electric cars would qualify as ZEV's. The maximum practical range with batteries that are expected to be available by 1998 is less than 100 miles. Their limited range make it highly unlikely that battery/electric cars will be found acceptable for most commuting, or as a family car. Electrochemical engine propelled cars, which are fueled with hydrogen, should qualify as zero emission vehicles. ECE cars which use methanol (reformed into hydrogen and carbon dioxide) will have much lower emission levels (estimated at 0.002 gm/mi. HC, negligible CO, and 0.001 gm/mi. NOx) than required to qualify as an ULEV, but may still not initially qualify for ZEV status. The California Air Resources Board standards are unique in that they mandate that a minimum share of the cars, i.e., the ULEV and ZEV vehicles sold by each automobile manufacturer in California meet the appropriate air quality level classification, Table IV-17. The

objectives were based on studies which considered all local pollutants and how they would have to be reduced to meet federal regional air quality standards.

<u>Year</u>	<u>1993 Federal</u>	<u>TLEV</u>	<u>LEV</u>	<u>ULEV</u>	<u>ZEV</u>	<u>Fleet Average NMOG^[1]</u>
1994	80%	10%	---	---	---	0.252
1995	85%	15%	---	---	---	0.231
1996	80%	20%	---	---	---	0.225
1997	73%	----	25%	2%	---	0.202
1998	48%	----	48%	2%	2%	0.157
1999	23%	----	73%	2%	2%	0.113
2000	----	----	96%	2%	2%	0.073
2001	----	----	90%	5%	5%	0.070
2002	----	----	85%	10%	5%	0.068
2003	----	----	75%	15%	10%	0.062

[1] NMOG in gm/mi.

Table IV-17. Annual Share of Sales of Low and Zero Emission Vehicles, California Air Resources Board Requirements

Some automobile manufacturers have expressed the hope that the California regulators will consider more flexibility in the mix of cars and the implementation time schedule if it is found that other combinations will meet the regional emission objectives for the years identified. For example, a higher percentage of ULEV's and fewer ZEV's could in principal provide the same total emissions. However, given the political emphasis in California on building battery/electric cars it may be unlikely that such a strategy would be accepted unless there has been a serious attempt to sell an appropriate number of ZEV's. The requirement for zero tailpipe emission cars is apparently at least partially politically and societally motivated, and not entirely based on stringent health or technical requirements.

Even though not specifically mandated, the assumption (in discussions with California environmental officials) has been made that transitional and low emission vehicle standards (TLEV, LEV) could be achieved with reformulated gasoline, ULEV's would require alternative fuels, and ZEV's would have to be battery/electric powered. Recently, CARB has implied that there could be two modifications to the ZEV standards. The first would take into account the use of a combustion space heater at low temperatures. The second modification is more comprehensive; emissions for ZEV's could be defined in terms of the total energy cycle which includes the emissions from the electrical utilities in California used to provide the electricity for battery charging. Current estimates by the California Air Resources Board indicate that the power plant emissions attributable to a battery/electric car (which uses 0.24 kW-hr/mile and operates within the South Coast air basin) are 0.0008 grams per mile NMOG and 0.007 grams/mi. NOx. (By comparison ULEV standards are 0.040 gm/mi. NMOG and 0.2 gm/mi. NOx). Hybrid (battery plus internal combustion engine) vehicles may qualify as ZEV's if a method is developed to monitor how they are operated (that is, on the battery only in restricted

regions) [143]. Fuel cell engine powered cars, operating on reformed methanol, emit only slightly more NMOG and less NOx emissions than a ZEV when the total energy cycle emissions are considered.

California authorities (South Coast Air Quality Management District) have prepared estimates of the penetration of alternative fuels/energy resource powered vehicles for their studies of air quality benefits in the Los Angeles region. The vehicle ownership and use assumptions, by environmental characteristics, which were required to meet federal regional environmental standards are summarized in Tables IV-18 and IV-19. There appears to be little prospect of achieving the proposed level of use of battery/electric cars (or eliminating as many diesel engines as indicated); the latter may be of less concern, considering the recent improvements in diesel engine emission characteristics [97].

	Electric (Battery)	Alternative Fuels	Natural Gas	Diesel
Passenger Cars	50%	25%	25%	0%
Light Duty Trucks	35%	33%	32%	0%
Commercial Trucks	0%	50%	50%	0%
Buses	30%	70%	0%	0%
Locomotives, Catenary	?%	?%	?%	0%

Table IV-18. South Coast Air Quality District Estimates, Percentage of Vehicles by Fuel/Energy Class Required in Use by 2010 to Meet Air Quality Standards.

	Electric (Battery)	Alternative Fuels	Natural Gas	Diesel
Passenger Cars	50%	35%	35%	0%
Light Duty Trucks	35%	33%	32%	0%
Commercial Trucks	0%	50%	50%	0%
Buses	30%	70%	0%	0%
Locomotives	0%	?%	?%	10%

Table IV-19. South Coast Air Quality District Estimates, Percentage of Vehicle Miles Driven in 2010 by Each Fuel/Energy Class to Meet Air Quality Standards.

It may not be possible to sufficiently reduce the air pollution levels in some regions of the country (particularly Los Angeles) through the total elimination of automobiles, most industrial facilities, two cycle engines, etc., to meet the federal air quality objectives. One study reported by the California Air Resources Board assumed that there were no cars or trucks, no gasoline refining, and no distribution or marketing of vehicle fuels in the Los Angeles basin. This scenario would only reduce the peak ozone level from 0.270 ppm to 0.206 ppm while the annual time above 0.12 ppm ozone would only decrease from 2,500 to 1,750 hours [32].

4.3.4 Effects of Other States Adopting California Emission Standards

A group of Northeast States is considering the adoption of at least a portion of California's automobile emission standards. The automobile manufacturers are contesting their right to do

so on the basis of the fact that this creates a third family of emission standards which was banned by the Federal Clean Air legislation. Other industry concerns include the economic damage that these mandates could impose on the industry and the affected regions. In February, 1994 the New York court held that these states had the right to require the same standards as California. As of late 1994 nine other states and the District of Columbia have expressed strong interest in adopting the tougher California standards rather than the Federal Emission Standards. The U.S. DoE (in 1994) estimated that states representing about 1/3 of the U.S. automobile market would eventually adopt California's environmental standards. States representing half the automobile market are reported (in 1994) to be seriously considering adopting the California standards [1].

The reason that other states concerned with their environmental problems are potentially planning to adopt the California Emission strategy is based on Federal regulations that limit a state or region's choice to one of two sets of standards, either the Federal environmental standards or those of California's, even if there were more cost effective approaches. There are two explanations for this limitation:

- First- To prevent each state from developing its own standards which would make the manufacturers problems nearly impossible
- Second- To insure that there is a "level playing field" and that all states are equally penalized, economically.

The automobile industry has justified its resistance to the proposed mandates on the economic basis that they must limit their ability to provide products which their customers would buy. The Motor Vehicle Manufacturers Association is currently (1994) challenging the New York effort to adopt California Standards on the basis that such rules should be approved by the legislature rather than by the Environmental Review Board. Even the California regulators are concerned; they recognize that the industry (automobile companies and fuel suppliers) may not be able to provide all, or even a portion, of the desired California products in time to meet environmental objectives if other major states adopt the same time schedules.

The primary criteria for energy and emission controls have been established by the federal government in the Clean Air Act and its amendments. But, in parallel, several state governments have developed performance requirements and unrealistic time schedules which can only be met by making substantial investments in technologies that do not have the same performance potential as fuel cell engines. Examples include the railroad and transit bus emission reductions in California which are required to achieve regional environmental goals. The expenditures in the Los Angeles region alone for electrification is estimated to exceed 5 billion dollars. Such investments justify support for more effective, lower cost alternatives which fuel cell engine propulsion systems could provide. This has led to increasing interest in fuel cell engine propulsion systems by California agencies, in particular the South Coast Air Quality Management District.

4.3.5 Costs to Achieve California Passenger and Light Duty vehicle LEV and ULEV Emission Standards

Alternative strategies for responding to the ZEV requirements, which are allowable under California rules, include:

- Building and/or selling battery/electric powered cars

- Building and/or selling fuel cell engine powered cars
- Building and/or selling hybrid/battery/electric powered cars
- Purchasing environmental credits.

The cost of achieving LEV and ULEV emission standards with "conventional" piston engines involves controversial assumption and computations. The industry currently (1994) has little confidence that it can achieve ULEV standards without vehicle or engine downsizing and/or the use of alternative "clean" fuels. There are still many technical unknowns. It is difficult, if not impossible, to project the costs of the technologies which would be required [60].

The cost extrapolation presented in Table IV-20 is a summary of cost estimates prepared as part of a study for the California Energy Commission. A regression analysis of the equations within the study, which related environmental protection equipment cost to air quality requirements, was utilized. This technique was used because there is little technical information on the cost of the equipment which would be required to meet higher emission standards. More detailed information is presented in the next section. These projections are at best indicative; major cost reductions would be required to be acceptable.

Year	GM Estimate [34]	U.S. Dept. Of Commerce Estimate [37]
1971	\$50	\$15
1984	\$730	\$950
Extrapolations Below Based on Regression Analysis of pre-1984 Costs		
'93 National	\$1,500	\$2,000
'96 National	-----	-----
TLEV	\$2,000	\$3,500
LEV	\$3,000	\$3,600
ULEV	\$6,000	\$7,500

Table IV-20. Estimates of the Incremental Costs per Car to Achieve California Emission Standards

Many people in the automotive industry question the actual costs and benefits of increased environmental standards. The Environmental Protection Agency estimates of the cost for mobile source environmental pollution control in the United States were \$1.3 billion in 1972, increasing to \$7.5 billion in 1987. The cost is projected to be \$11 billion in 1995 and \$14 billion in the year 2000. Other estimates are much higher; the cost of pollution control for Los Angeles alone (from all sources) is estimated to be \$13 billion per year. The estimates of benefits range from \$3.7 to \$20 billion per year [19,26,37].

The automotive industry at this time has limited resources to devote to the development of a new fuel and propulsion system which will not be used in production for at least 10 years. The resources are, however, now being fully devoted to incremental solutions. It will be difficult to develop a total new propulsion system and at the same time make improvements in conventional engines and propulsion systems that may mandated by environmental and energy regulations.

4.4 FUEL CONSUMPTION STANDARDS

The energy shocks of the 1970's led many people to believe that we are rapidly running out of economical energy supplies. The public now appears to be less concerned over running out of petroleum, or other useful forms of fossil energy, since prices dropped in the mid 1980's. But concerns over the international balance of payments and the potential economic impact of an energy supply interruption continue to be high. Most energy authorities believe that the world has adequate supplies of fossil energy to last at least to the middle of the next century, refer to Section VI. In fact, new discoveries and new production technologies should enable petroleum reserves to last not only to the middle of the next century, but perhaps even into the 22nd century. Before the reserves are exhausted, other fuel supplies, based on renewable sources (biomass, solar, geothermal) that can provide essentially unlimited supplies, will be able to be produced at competitive costs. The world's supply of fossil fuels will probably never be consumed because alternatives will become economically attractive prior to fossil fuel depletion.

Even if there is no immediate shortage of petroleum products, there is still strong support for increases in the U.S. automotive energy consumption regulations. This support appears to have three causes:

- First- Misunderstanding of the availability of low cost energy
- Second- The international balance of trade, of which oil is a major part
- Third- The perception that we have become a wasteful society.

Environmental groups and others concerned about energy independence are pushing for higher automobile mileage standards. These efforts have received the support of many people in the U.S. Congress; legislation has been introduced in both the U.S. House and Senate to raise Corporate Average Fuel Economy (CAFE) standards.

Public opinion in the United States appears to favor increasing fuel economy; for example, an interview of 1,200 people by representatives of the Union of Concerned Scientists found that 84% were strongly in favor of increasing the federal fuel economy standard for automobiles to 40 miles per gallon by the year 2000. Eighty nine percent of those interviewed said that they would still support the higher standards even if a new car would cost \$500.00 more. On the other hand, life cycle economics appear to be more important. The Analysis Group discovered that fewer than 75% of the people would support a \$0.30 increase in gasoline taxes to encourage conservation.

4.4.1 Federal Fuel Economy Initiatives

There are a number of proposals to mandate increases in the fuel economy of private automobiles. Congress for several years has considered mandating a 40 mpg average (or equivalent) for passenger vehicles. The *New Generation of Vehicles* initiative is directed in part at demonstrating a "standard family sedan" with nearly one third the fuel consumption as is now mandated, or approximately 80.0 mpg (0.0125 gallons per mile).

The existing automobile corporate average fuel economy regulations, CAFE, have been in effect since the 1970's; these regulations mandated increasing fuel economy until it reached a level of 27.5 mpg (0.036 gallons/mile). The manufacturers had initial difficulties in achieving this level while still producing a product that met customer needs. Finally, a combination of

computer fuel controls, catalytic converters, and new and innovative designs incorporating reduced vehicle weight made it possible to achieve current CAFE standards. An additional factor has been CAFE driven; lower prices and profits on efficient cars have encouraged people to purchase smaller cars. Another major factor in meeting the CAFE standards has been the price of gasoline. When gasoline prices were high people purchased relatively fuel efficient cars. Current gasoline prices are the lowest in memory, and people are at the moment much less concerned about fuel economy.

The fuel economy bills which have recently been considered by the U.S. Senate include the following:

- **The Motor Fuel Efficiency Act-S279 (Brian bill).** This bill would require each manufacture to reduce fuel consumption by the same percentage. The bill calls for a 20% decrease by 1996 and a 40% decrease by 2001. The Secretary of Transportation would be permitted to raise or lower the statutory standards to the "maximum feasible level". However, this flexibly is limited to not less than a 15% decrease from 1988 fuel consumption levels by 1996 and to not less than a 30% decrease from 1988 fuel consumption levels by 2001. It also increases the penalties for manufacturers who fail to meet such CAFE Standards.
- **The CAFE Standards in the National Security Act of 1991-S1220 (Johnson Bill).** This bill calls for a percentage increase over each manufacturer's 1990 CAFE levels (for both passenger cars and light trucks). The requirements are to be set by the Secretary of Transportation at the "maximum feasible level" by 1996 and again in 2002. The Secretary is to consider four (4) criteria: 1) technology feasibility, 2) economic practicality, 3) the effect of other Federal motor vehicle standards on fuel economy, and 4) the need of the country to conserve energy resources.

Similar U.S. house bills include:

- **The Motor Vehicle Fuel Efficiency Act HR-446 (Boxer Bill).** This bill would require each manufacturer to increase CAFE levels 20% by 1996 and 60% by 2001 compared to 1988 standards. Failure to achieve requirements for more than 2 years would double the penalties starting in 1996.
- **The National Energy Policy Act (Pantetta Bill).** This bill calls for a 20% CAFE increase by 1996 and a 40% increase by 2001 compared to the 1988 CAFE standards.
- **The Motor Vehicle Conservation Act HR-612 (Glickman Bill)** This bill calls for a 25% increase by 1996 and a 50% increase by 2001 compared to the 1988 levels.

All of these bills have provisions intended to encourage the use of alternative fuels or to develop and sell battery/electric cars. The high durability standards called for in these bills, combined with the mandated increase of a car's ability to maintain its efficiency and environmental characteristics for an increasing share of its useful life, would have three secondary effects:

- First-* The useful life of all cars would have to be extended, perhaps to 150,000 or more miles by the early part of the 21st century
- Second-* The design freedom of vehicle manufacturers will become limited. As cars are forced to become more alike in configuration and quality, designers will be

increasingly challenged to devise features and appearances which set individual models and companies apart

Third- Important innovations in vehicle technology will tend to be delayed. Innovations which represent significant departures from existing technologies will require longer times to demonstrate compliance with more stringent regulations.

4.4.2 Taxes and Other Incentives

The emission and energy standards being proposed are intended to accelerate the development of low emission propulsion systems. This, however, may not be the most effective strategy in the long run in terms of environmental improvement per dollar investment.

An alternative to mandates would encourage the transition to low emission propulsion systems by providing economic incentives such as: increases in the price of fuel, imposition of emission fees, or the provision of taxes or credits based on actual emissions created by each vehicle. Increasing the price of fuel alone will tend to reduce fuel consumption and encourage the development of more efficient propulsion systems, but will not necessarily lead to more environmentally acceptable engines and/or vehicles.

It is more difficult to explain the benefits of economic incentives than mandates. But incentives will be more long lasting and cause less societal disruptions. Mandates frequently have secondary effects which reduce their effectiveness. These are seldom considered when they are proposed. A major advantage of incentives is that they encourage the development of new technologies (like fuel cell engines) which may not have been feasible at the time the standards were established. Incentives apply to all vehicles, new and old, thus encouraging their replacement with even newer, low polluting efficient vehicles.

Fuel	Federal Tax, Cents/Gallon	
Gasoline	14.0	
Diesel Fuel	20.0	
Special Fuels	14.0	
Gasohol	8.6	At least 10% Methanol or Ethanol in Gasoline
Diesohol	14.6	Mixture of 10% alcohol not derived from petroleum or natural gas
Ethanol	8.6	At least 85% alcohol not derived from petroleum or natural gas
Methanol	8.6	At least 85% alcohol not derived from petroleum or natural gas

Table IV-21. Federal Tax Rates on Motor Fuels, Cents per Gallon

Taxes will probably continue to be an increasing portion of the price consumers pay for gasoline or other transportation fuel. The federal tax rates on motor vehicle fuels are summarized in Table IV-21 above; state taxes should be added to these prices. As described above, alternatives to mandates by providing tailored economic incentives may require a reevaluation of the methods by which the nation taxes fuel usage.

The cost of personal travel per mile will be increased by the cost of pollution control equipment. This, coupled with higher energy taxes, will make it necessary for car owners and drivers to reevaluate how they allocate their personal finances. If the combined effects are to reduce the economic growth of the nation, disposable family incomes will decrease, and in the short term the use of energy (and pollution production) will decrease proportionately.

Experience in the 1970's, with two energy price peaks, indicate that people will continue to expend approximately the same portion of their disposable income on transportation. Expenditures on cars dropped when prices of gasoline rose. The public accomplished this by buying smaller, less expensive cars or holding existing cars longer. If both fuel and car prices increase, people will probably purchase even smaller cars or retain their existing cars for even longer periods of time. The short term result of the public retaining older cars for longer time periods is counterproductive. But, by the early part of the next century, this effect may become less significant as low emission cars (with increased life and durability) become a significant portion of the fleet [2]. Several studies have indicated that the most cost effective way of obtaining an early reduction in emissions is to reduce the number of older, high polluting, cars. One method to accomplish this is to provide cash for the repurchase of older cars, similar to the process conducted by UNOCAL in 1990 when they bought 8,000 pre-1972 vehicles for \$700.00 each. The environmental credits for this program were primarily used by UNOCAL to offset the environmental pollution of its manufacturing or processing facilities.

The automobile industry, using studies by economists inside and outside of government, is attempting to convince regulators that some of the more strict proposed regulations/mandates would actually be politically counterproductive. The industry points to both loss of jobs and personal choice if the average car which could be purchased was about the size of the smallest available today. Laws requiring much higher fuel economy (approaching 40 mpg) might have been passed by this time if it were not for the multi-billion dollar losses which the U.S. automobile companies recently experienced, and the small group of state and federal officials who understand the consequences to the nation, the industry, and their districts. The industry's financial problems and capabilities are discussed in more detail in Section VIII.

V. CHARACTERISTICS OF ADVANCED PROPULSION SYSTEMS

This section of the report describes some of the factors which may influence the introduction, mandation, selection, and use of advanced propulsion systems. The basic conditions which are used for comparing the performance and availability of different advanced propulsion systems are described. The discussions address the status of each competitive power plant and their probable public acceptance considering performance and service requirements for each power plant. This information provides the background data for the assumptions used in the proposed scenarios to be developed in Phase II (as summarized in Section VII) and the commercialization process outlined in Section VIII.

The evaluation of commercialization processes for fuel cell engines will require consideration not only of their benefits but the relative performance of contemporary competitive power plants. Thus, this study must address the potential for the commercialization of all candidate advanced power plant systems. It is therefore necessary to identify the primary propulsion system competitors and compare their performance and economic characteristics with potential fuel cell engine propulsion systems. The propulsion systems of interest include:

- Piston engines which can use reformulated gasoline, diesel fuel, methanol (M-85), natural gas, liquefied petroleum gas, and hydrogen
- Gas turbines which can use gasoline, methanol (M-85 or M-100), turbine fuel, natural gas, and liquefied petroleum gas
- Fuel cell engines which can use hydrogen from reformed methanol, natural gas, or other hydrocarbons depending on the reformer's capabilities
- Battery/electric (including hybrid/electric systems) which obtain their charge from local utilities or on-board (hybrid) engines.

Each of these advanced propulsion/energy systems is discussed in terms of how it differs from piston engine/gasoline fueled propulsion systems. The emphasis is on fuel cell engine propulsion systems. Other propulsion systems are included if they have a cost, performance, or fuel usage advantage [3].

The U.S. DoE is sponsoring, or has sponsored, propulsion system research and development on a number of propulsion technologies including:

- Improved gasoline and diesel propulsion piston systems, including their potential use of alternative fuels
- Gas turbine propulsion systems
- Stirling (external combustion) engine propulsion systems
- Battery/electric propulsion systems
- Electrochemical engine (fuel cell engine propulsion) systems.

Each of these propulsion concepts have some characteristics which make it attractive and worthy of being considered for additional development. Several of the advanced propulsion systems have the potential to significantly reduce emissions.

5.1 ADVANCED PISTON ENGINE PERFORMANCE AND EFFICIENCY

The internal combustion engine is approaching the theoretical efficiency limits imposed upon it by the second law of thermodynamics. While some improvements in both engine performance and vehicle design are possible they are unlikely to achieve the kind of emission or fuel consumption levels required to alleviate the public's concern. The cost of the equipment to "clean up" piston engines tends to increase exponentially as efficiency requirements increase and allowable emissions decrease.

Even though piston engines (gasoline and diesel) have been under development for over 100 years there are still some (limited) opportunities for efficiency improvements. The potential for internal combustion engine technology improvements is relatively well understood. The theoretical limits to internal combustion engine efficiency, the second law of thermodynamics, were defined nearly 150 years ago. For example, an ideal gasoline engine using air could theoretically be about 60% efficient, based on the lower heating value of the fuel. This efficiency cannot be obtained with real engines. Even the best existing piston (diesel) engines used for stationary steady-state power, where weight and size are not considerations and power transients are seldom important, rarely exceed 45% efficiency. The best practical piston engines used in transportation applications can probably achieve efficiencies between 30 and 35%. Above that level it becomes increasingly difficult to make significant improvements [10,12].

Large improvements in piston engine efficiency are frequently quoted by advocates for specific devices or engine improvements. However, even when technically viable, such improvements may not be additive as the engine's efficiency approaches the maximum permitted by the second law of thermodynamics. Any practical combination of "improvements" is unlikely to increase peak efficiency by more than 10%, (or about a 20% decrease in fuel consumption). The fuel consumption of gasoline fueled piston engines, in particular, is a compromise between efficiency and environmental standards; most such engines could yield 5 to 7% higher mileage if it were not for the losses due to the controls required to meet emission requirements [9].

5.1.1 Projected Performance, Efficiency, Emissions, and Cost of Passenger Cars with Advanced Spark Ignition Engines

The fuel economy of standard passenger cars has improved steadily. Incremental improvements have been made over the years in engine efficiency, weight, reliability, and power. Prior to the enactment of the CAFE standards, a standard car's fuel economy (corrected for weight, emission systems, etc.) improved between 1% and 2% per year in gallons per mile (gal/mi.) [6,92]. Projected fuel economies are illustrated in Table V-1 should this trend continue.

An illustration of the fuel consumption reduction possible with reduced performance is depicted in Table V-2. The fuel economy of a car which gets 20 mpg can be increased to about 26-27 mpg if a smaller engine is installed; however, the vehicle will then require twice the time to accelerate from 0 to 60 mph. "Consumer willingness to pay" studies indicate that slower accelerating cars must be priced \$3,500.00 to \$4,000.00 lower than higher performing vehicles.

<u>Year</u>	<u>1% per year</u>	<u>2% per year</u>
1988	0.038 gal/mi., 26.0 mpg	0.038 gal/mi.[1], 26.0 mpg
1994	0.035 gal/mi., 28.5 mpg	0.033 gal/mi., 30.5 mpg
1999	0.033 gal/mi., 30.3 mpg	0.029 gal/mi., 33.5 mpg
2004	0.031 gal/mi., 33.25 mpg	0.027 gal/mi., 37.0 mpg
2008	0.030 gal/mi., 33.33 mpg	0.024 gal/mi., 41.5 mpg

[1] gal/mi. is also abbreviated as gpm

Table V-1. Trends in Automobile Fuel Efficiency, Corrected for Size, Performance, etc.

<u>Type of Vehicle</u>	<u>Acceleration</u> <u>Zero to 60 mph</u>	<u>Fuel Economy</u> <u>Miles per Gallon</u>
Standard Sedan[1]	7 seconds	20 mpg, 0.050 gal/mi.
High Mileage Sedan[1]	15 seconds	26-27 mpg, 0.037 gal/mi.

[1] Same vehicle weight, different power

Table V-2. Effect of Acceleration Capability on Fuel Economy

Car manufacturers that attempted to reduce mileage by compromising vehicle performance were criticized by car buyers, particularly during the early 1970's. This was before other approaches, such as computerized fuel control, were adequately developed.

The National Research Council (NRC) report "Automotive Fuel Economy, How Far Should We Go", published in 1992, projected the "technically achievable" fuel economy levels for model year 2006 vehicles and the incremental cost (price) for achieving such levels [11]. A summary of their conclusions is presented in Table V-3.

<u>Vehicle Size Class</u>	<u>Highest Confidence</u>	<u>Lowest Confidence</u>	<u>1990 EPA Actual</u>
Subcompact	39 mpg, \$500-\$1250	44 mpg, \$1000-\$2500	31.4 mpg
Compact	34 mpg, \$500-\$1250	38 mpg, \$1000-\$2500	29.4 mpg
Midsize	32 mpg, \$500-\$1250	35 mpg, \$1000-\$2500	26.1 mpg
Large	30 mpg, \$500-\$2500	33 mpg, \$1000-\$2500	
<u>Light Trucks</u>			
Small Pickup	29 mpg, \$500-\$1000	32 mpg, \$1000-\$2000	25.7 mpg
Small Van	28 mpg, \$500-\$1000	30 mpg, \$1000-\$2500	22.8 mpg
Small Utility	26 mpg, \$500-\$1250	29 mpg, \$1250-\$2500	21.3 mpg
Large Pickup	23 mpg, \$750-\$1750	25 mpg, \$1500-\$2750	19.1 mpg

Table V-3. National Research Council 2006 Fuel Economy and Incremental Cost Projections

The NRC report defined "technically achievable" as any technology currently (1992) being employed in one or more mass production vehicles, somewhere in the world, that would pay for itself on the basis of fuel saved at projected prices of \$5.00 to \$10.00 per gallon or less (1990\$). It appears unlikely that the cost increment as a function of vehicle size would be as consistent as the estimates imply. The University of Michigan Center for the Study of Automotive Transportation - Delphi Seven Survey of industry decision makers estimated that by 1998 U.S. cars, on average, could achieve 29 mpg (Japanese vehicles 34 mpg). By the year 2003 U.S. cars could achieve 32 mpg while Japanese vehicles were assumed to be able to achieve 35 mpg on the same CAFE duty cycles.

The costs of efficiency improvements (and environmental equipment) are controversial. Not surprisingly, local, state, and federal government regulator's cost estimates are usually low while the auto industry's forecasts are higher. The industry estimates include allowances for the difficulty in developing new commercially viable products (reducing failures, extending operating life, etc.) and the uncertainty of manufacturing costs. Estimates of future manufacturing prices are difficult to project with confidence; even during production, bids on certain parts from apparently equally qualified suppliers can differ by a factor of two.

A study for the California Energy Commission took a different approach. The historical data regarding the changing costs of emission equipment as standards increased was evaluated. A regression analysis of these costs as a function of a pollution level index was prepared and then extended forward to achieve the proposed costs and standards. The index was a simple average of the three primary noxious pollutants, $(\%HC + \%NO_x + \%CO)/3$. This approach was based on the assumption that the cost of reducing each kind of pollutant would be similar. While the results of this approach are subject to debate, no better data existed at the time. The results of this study are presented in Table V-4. The projected prices (presented in Table V-4), of course, will be unacceptable. Better solutions will have to be found; as discussed later in the report, these "regression costs" represent unrealistic projections.

The emission levels, historic costs, and projected emission control costs presented are all for a "standard" family sedan. The profit on an alternative fuel car may be low or non-existent depending on the manufacturer's need for CAFE credits that the use of alternative fuels would provide. Further, the existing CAFE rules fine a manufacturer \$5.00/car for every 0.1 mpg that the manufacturer's fleet fuel economy is below the required CAFE level. Several European manufacturers have elected to pay the fines rather than redesign to meet the standards; this is a major problem for "single class" car manufacturers. Jaguar paid \$5.5 million in 1990 while Mercedes paid more than \$20 million in the same year.

The estimates of the incremental cost of cars to meet both the U.S. Tier I and, particularly, the California Energy Standards are, not surprisingly, controversial. Table V-5 below, extracted from a Sierra Research paper [142], illustrates a different range of cost estimates. The California Air Resource Board (CARB) has developed their own cost estimates which are presumed to be installed retail price increases; but, Sierra Research points out that in some of the previous estimates, for example, the cost of electrically heated catalyst systems has been underestimated by as much as half the cost of the part, before installation, that the manufacturer would have to pay. In addition, there must be allowances for installation labor (typically equal to the purchase part price), research and development costs, overhead, and dealer markup. The manufacturer's costs shown in the table below are a weighted average of cost estimates provided by automobile manufacturers; these are even higher than Sierra

Research's estimates. Part of the difference is due to the fact that Sierra Research's estimates are for an average cost over the 1995-2010 time period and reflect "experience curves". Sierra Research assumed that total costs follow a typical "learning curve" and decrease 5% per year in the absence of changes in requirements which mandate new technologies. The manufacturer's costs do not reflect that optimism. As is evident in the Table V-5, the cost differences are large and all are different from those presented in Table V-4.

Emissions					Cost to Attain	
Year	HC	CO	NOx	(H+C+N)/3	GM ^[1]	U.S. Dept. of Commerce ^[2]
Base Conditions-Unregulated Engine						
1960's gm/mile	10.6	84.0	4.1	100%	no air quality equip. installed	
Standards, Percent of Unregulated Engine						
1966	59%	61%	100%	73.3	\$30	\$15
1971	27%	41%	100%	56.0	\$50	\$40
1974	21%	33%	76%	43.3	\$70	\$100
1975	13%	18%	76%	35.6	\$210	\$210
1976	11%	18%	41%	26.0	\$180	\$340
1981-84	3%	4%	24%	10.3	\$730	\$950
Extrapolations Based on Regression Analysis					[3]	[4]
Tier I U.S.	2.3%	4%	9.7%	5.3	\$1500- 2000	\$1500-\$2500
TLEV	1.1%	4%	9.7%	4.9	\$2000- \$3500	\$3500-\$7000
LEV	0.7%	4%	9.7%	4.8	\$2300- \$3800	\$4000-\$7500
ULEV	0.3%	2%	4.8%	2.3	\$6000- \$7500	Illogical

[1] Development of U.S. Vehicle Regulations, Technologies and Costs [34]

[2] Expenditures for Abating Pollutant Emission from Motor Vehicles [37]

[3] Regression Formula, $Y\$ = (21.98) X^{-1.562}$

[4] Regression Formula, $Y\$ = (16.118) X^{-1.890}$

Table V-4. Cost of Air Quality Equipment vs. Percent Reduction in Pollution Index, 1984 Dollars

Useful estimates of the cost variance required to meet future energy and environmental standards as a function of different propulsion systems will be very important in developing a commercialization strategy for fuel cell engine propulsion systems. For example, if the cost

estimates for a battery/electric car with a 40-kW propulsion system is over \$50,000, a fuel cell engine propulsion system which costs less than \$1,000 per kW would have a 25% cost

Vehicle Standard	CARB Estimates	Sierra Research Estimates		Manufacturer's Estimates	
		California	Nation	California ^[1]	Nation ^[2]
TLEV	\$105	\$464	\$344	\$862	\$666
LEV	\$146	\$1,019	\$775	\$1,689	\$1,291
SMALL ULEV	\$214	\$757	\$610	\$2,982	\$1,668
LARGE ULEV	\$214	\$1,475	\$1,347	\$2,799	\$2,229
ZEV (Small)	\$1,436	\$21,034	\$12,588	\$56,641	\$34,145

[1] Assumes cars are only built for California

[2] Assumes similar cars are required in half the U.S.

Table V-5. Estimates of the Incremental Costs of Meeting CARB'S Vehicle Standards

advantage; at \$300 per kW the fuel cell engine propulsion system would have more than a \$40,000 cost advantage.

It is possible that even the manufacturer's estimates of costs to meet the CARB standards will be low considering the potential changes in the air quality regulations to include both acceleration and the difference between "test procedure" emissions and "actual on-road" emissions [6]. Information based on these estimates must be combined with additional assessments of parts costs to develop low and high projections for the costs of vehicles which could meet various proposed state and federal standards.

5.1.2 Projected Emissions and Costs Using Diesel Engines

Diesel engines for transportation can be grouped into three basic categories:

- Light duty or automotive
- Heavy duty truck and bus
- Locomotives.

The diesel engine has become the dominant power plant for heavy commercial vehicles. Essentially all of the class 7 and 8 trucks (heavy intercity highway tractors) are diesel powered, as are almost all railroad locomotives. There is almost no U.S. automotive diesel production, although diesel powered cars are still imported, primarily from Europe.

Many of the same practical design considerations which limit the ability of spark ignition engines to achieve energy and environmental goals apply to diesel engines. The diesel engine has two additional environmental problems which were not a concern for gasoline engines, particulates and sulfur compound emissions. The manufacturers of diesel engines have made remarkable progress in achieving air quality goals during the last decade. There have been improvements in the design of the combustion chamber and control of fuel injection timing, as well as benefits from the use of low sulfur fuel.

Use of low sulfur fuels (0.05%S) by 1994 is mandated by the U.S. Congress. This fuel should be available nationally for automobiles and trucks. It may also be used for locomotives. California regulations require even lower sulfur fuels (0.02%S). Low sulfur fuels (0.01%S) have been found to reduce particulates by 23% and NOx by 8% on heavy (locomotive) engines, with offsetting increases of 8% in HC and 6% in CO. Retarding the injection timing about 4° from peak power timing has also reduced NOx about 20% [52].

Like other internal combustion engine performance projections, results of emission and efficiency tests can be highly variable. Tests of 15 locomotive engines showed a variation of 12% in NOx, 44% in CO, and 27% in HC emissions [64].

Other approaches to reduce diesel emissions which are being considered include:

- Water addition
- Particulate traps
- Ammonia injection into the catalytic reactor
- Selective catalytic reduction
- Injection of RAPRENOx
- Increased after-cooling
- Oxygen enrichment.

The costs of most of these approaches has not been fully defined. Particulate traps are expensive and most require some form of regeneration as they accumulate particulates. The addition of RAPRENOx, or isocyanic acid, can provide reductions of NOx of 80 to 90%. After-cooling of heavy duty engines has been shown to reduce NOx by 15%, HC by 30%, and CO emissions by 59%, while improving the specific fuel consumption by 2 to 3% [52].

5.1.3 Performance, Efficiency, and Availability of Advanced Piston Engines, Including the Use of Alternative Fuels

<u>Fuel</u>	<u>Vehicle Price</u>	<u>Fuel Cost per Mile</u>	<u>Environment % Emissions</u>	<u>Operability</u>	<u>Range</u>	<u>Source of Fuel</u>
Gasoline	100%	100%	100% ^[1]	Good	300 mi. ^[3]	retail
Gasoline	>100%	100%	2-3% ^[2]	Acceptable	300 mi.	retail
Reformulated	100%	125%	<<gasoline	Acceptable	300 mi.	retail
M-85	>100%	>gasoline	<gasoline?	255 mi. ^[3]	retail	retail
M-100	>100%	>gasoline	<gasoline?	Cold start?	150 mi. ^[3]	retail
Natural Gas	>110%	<gasoline	<<gasoline	Power loss?	100 mi.	home?
LPG	>110%	<gasoline	<gasoline	Good	>150 mi.	?
Hydrogen	>110%	>>gasoline?	NOx only?	Good	?	?

[1] Percent of an unregulated gasoline engine

[2] Assuming best available vehicle environmental control technology

[3] Typical tank size to provide acceptable range on gasoline

Table V-6. Use of Alternative Fuels in Piston Engines

Detailed realistic assumptions regarding the potential improvements to, and costs of, piston engine powered vehicles are discussed in Section VI.

Improvements in car design, including reductions in weight and drag, can also reduce energy consumption and, indirectly, pollution. Further reductions in emissions may require the use of alternative fuels; projected results and costs of using various fuels are illustrated in Table V-6. The major advantage of gasoline and diesel engines and their current compatible fuels include public acceptability, cost of the vehicle, continued use of existing facilities (service, processing, manufacturing), and the availability of skilled service personnel.

The near doubling of fuel efficiency of the average U.S. automobile since the first energy shock (1973) [12] was made possible by a number of design changes including:

- The use of catalytic converters
- Reduction in vehicle weight
- Improved tires and aerodynamics
- Compromises in vehicles performance
- Lower prices (and profits) on small, efficient cars.

About 15% of the fuel consumption improvement can be credited to the use of catalytic converters [33,37] which offset the engine compromises that would otherwise have been required to meet environmental standards. Most of the rest of the gain has come from performance compromises and reduced weight. Some CAFE improvement has also come from a strategy in which the price (and, hence, resulting profit) of smaller cars that produce high mpg has been reduced to encourage people to purchase such vehicles.

The time and costs of the research to improve the combustion and emission characteristics of advanced spark ignition engines will depend on the specific concept(s) being investigated and the objectives. As an approximation, a major automobile engine redesign may require 3 to 5 years and cost up to \$1.0 billion. This includes the testing required to confirm the product's performance and reliability when installed in typical vehicles. Manufacturers have to conduct preproduction tests of new engines slated to be installed in new vehicles intended for production, a process which can take several years. The testing of several improvements can usually occur in parallel and may include tests and demonstrations required to obtain governmental approval. Not until these tests and demonstrations are complete will the manufacturers have sufficient confidence to initiate the development of production versions for sale to the public. Then, the manufacturers will have to acquire (or modify) their manufacturing facilities to build the new systems.

Production costs include research, direct labor, materials, the amortized costs of the facilities, and other costs incurred prior to entering production. The incremental costs of advanced combustion engine propulsion systems cannot be estimated without more knowledge of the specific concept that will be used, and that probably will not be available until the first series of field tests is complete.

Post sale costs include warranties and other costs related to customer satisfaction. Increasingly, emphasis will be given to disposal costs. Uniquely future valuable materials (such

as platinum in catalytic converters) and other materials may require special attention during their disposal.

As previously stated, another of the techniques by which the emission levels of conventional piston engines can be reduced is to use other fuels, such as reformulated gasoline, methanol, ethanol, or natural gas. Beginning in 1993, CAFE credits may be obtained by selling alternative fueled automobiles. Alternative fuels are currently (1994) defined as ethanol, methanol, other alcohols, and/or mixtures containing 85% or more by volume of these fuels with other fuels such as gasoline. Different credits are available for Flexible Fuel Vehicle (FFV's) and Dedicated Alternative Fuel Vehicles (DFV's). The CAFE rating of a dedicated alternative fuel vehicle is determined by dividing the fuel economy achieved through use of the alternative fuel (such as methanol) by 0.15. That is, an alternative fueled vehicle that has a fuel economy of 20 mpg would be entered into the CAFE calculations as if it had a fuel economy of 133.33 mpg. The formula for FFV's is, however, specified by Title V of the Environmental Act. For these vehicles there is a maximum fleet increase cap which can be obtained by a manufacturer selling FFV's; this fleet increase cap is currently set at 1.2 mpg. For example, a company CAFE average of 28 mpg could only be raised to 29.2 mpg [5,40].

The first stage in the transition to environmentally acceptable fuels and propulsion systems started with the elimination of tetraethyl lead. The next stage is the introduction of reformulated gasoline. These are tailored fuels which will have some of the pollution troubling ingredients removed. An alcohol, or ether, is usually substituted to maintain the desired octane levels. The relative benefits, availability, and problems with alternative fuels are discussed in Section VI.

Emissions from spark ignition engines could essentially be eliminated using hydrogen. If gaseous hydrogen is not available, a reformer (similar to those required for fuel cell engines) could be used to generate hydrogen from methanol or appropriate hydrocarbon fuels. This would permit a significant increase in thermal efficiency, "theoretically" to about 50% at a 15:1 compression ratio, though response times may suffer due to the presence of the on-board reformer. Some investigators feel that a true 40%-45% level of thermal efficiency could be obtained at compression ratios nearer to 11:1. If stratified charge engines are utilized, NOx could theoretically be controlled to below 10 ppm at effective equivalence ratios below 0.40. Estimates exist that NOx from a hydrogen fueled high compression, stratified charge spark ignition engine would be 0.005 grams per mile, including allowances for oil leakage. As discussed later in Section VI this scenario suffers from the size of the on-board tank if hydrogen is used directly, and by the lack of an existing infrastructure for hydrogen distribution. If reformers are utilized methanol becomes an attractive fuel if, or when, a methanol infrastructure becomes available; if the response of the reformer is not adequate some type of hybrid vehicle (on-board batteries for load leveling and start-up) may be required. The concept certainly has attracted considerable interest; cost, performance, and reliability will be the overriding factors determining the ultimate usage of this concept.

5.2 ADVANCED GAS TURBINE ENGINE PERFORMANCE, EFFICIENCY, EMISSIONS, AND COST

Gas turbine engines can be designed to have emission characteristics below those required to meet California Ultra Low Emission Vehicle (ULEV) Standards. However, their development and production costs have yet to be fully evaluated.

Gas turbine engines can use nearly any liquid fuel and produce very good emission characteristics. The efficiency of gas turbine engines at peak power is good, but tends to fall off rapidly as power is reduced. Generally, gas turbine engines are excellent design point engines, ideal for aircraft use; but, in cars, they operate at 20 to 30% of their peak power for a majority of their operating time. Gas turbine engine automotive usage requires unique smaller designs combined with transmissions, the addition of some type of variable geometry, and very high turbine inlet temperatures, all optimized for automotive purposes. Over 1,370°C turbine inlet temperatures within an uncooled blade gas turbine engine have recently been achieved by the utilization of a ceramic hot section (refer below).

Typical emission characteristics measured during recent research on automotive gas turbine engines were shown to be superior to other internal combustion engines. Emission levels of 0.05 gm NOx, 0.02 gm HC, and 1.5 gm CO have been demonstrated using turbine fuel. It appears that gas turbine engines should be able to meet California's ULEV standards without any after-treatment. These characteristics are discussed in more detail in Section 5.2.1.

The U.S. DoE AGT-100 and AGT-101 programs led to prototype gas turbine engine designs which were capable of providing 32 mpg compared to 25 mpg for the same vehicle with an equivalent gasoline spark ignition engine on EPA duty cycles. The next stage, the DoE Advanced Turbine Technology Applications Project, has already achieved turbine inlet temperatures of 1,370°C. Vehicles ("family sedans", 3,000 lb., 100 hp engine) with these turbine engines should provide 36 mpg or more (equivalent gasoline fuel) on the federal combined urban/highway fuel economy cycle [49].

5.2.1 Performance, Emission Characteristics, and Cost of a Gas Turbine Engine, Use of Alternative Fuels, and Acceptability as a Propulsion System

The advantages of gas turbine engines include their "relative simplicity", the probability of public acceptance, acceptable cost of the vehicle, probable low cost of fuel, continued use of existing facilities (service, processing, manufacturing), and "general" availability of skilled service personnel. Their potential high power output and compact size also make them attractive for heavy duty commercial vehicles.

Engine Type	Emissions[1]			
	HC	CO	NOx	
Unregulated Automobile	10.6	84.0	4.1	gm per mi.
CARB ULEV Requirement	0.04	1.70	0.20	gm per mi.
Gas Turbine	0.02	1.50	0.05	Using diesel
Gas Turbine	0.015	1.00	0.005	Using methanol

[1] Emissions in grams per mile

Table V-7. Typical Emission Characteristics of an Automotive Gas Turbine, Grams per Mile

In moderate volumes gas turbine engines are expected to cost more than piston engines which provide the same power. Some authorities believe that in very large volumes they may cost

less than equivalent piston engines. The key elements requiring additional research include the hot section and the processes for producing and testing ceramic turbine wheels and other hot elements at low cost.

Emission standards and gas turbine engine emission characteristics on two very different fuels are presented in Table V-7 above. Results presented in Table V-7 clearly indicate that gas turbine engines can indeed meet CARB ULEV standards on diesel fuel (barely) and on methanol fuel (easily). A more comprehensive table of alternative fuel usage in gas turbine engines is presented in Table V-8 below.

Gas turbines may benefit (economically) from the use of designated fuels (such as aircraft jet fuel). Unknowns include the cost (or price) of fuels for the balance of the hydrocarbons in a barrel of crude after the more volatile elements have been removed. This price will no doubt be a market function. At this time there is no indication that gas turbines will be produced as a prime mover for use in passenger cars, although they may be cost competitive in heavy duty trucks and other commercial vehicles.

<u>Fuel</u>	<u>Vehicle Price</u>	<u>Fuel Cost per Mile</u>	<u>Environmental % Emissions</u>	<u>Operability</u>	<u>Range</u>	<u>Access to Fuel Supply</u>
Gasoline	?	100%	1.5% [1]	good	300 mi. [2]	stations
Reformulated	?	125%	?	good	300 mi.	same
Turbine Fuel	?	<100%	1.0%	good	>300 mi.	same
M-85	?	>gasoline	<gasoline	good	225 mi. [2]	same
M-100	?	>gasoline	1.0%	good	150 mi. [2]	same
Natural Gas	?+10%	<gasoline	<<gasoline	good	>100 mi.	home?
LPG	?+10%	<gasoline	<gasoline	good	>200 mi.	

[1] Environmental index (HC + NOx + CO)/3, % unregulated gasoline

[2] Typical tank size to provide acceptable range on gasoline

Table V-8. Use of Alternative Fuels in Gas Turbine Engines

The factors which a purchaser of a gas turbine engine propelled car must consider are summarized below.

- The purchase price of the car will increase by the cost of the gas turbine propulsion system and auxiliaries. However, the low weight and simplicity of the drive system may permit offsetting cost reductions. If production approaches a million turbine engine powered cars per year the cost increment could still be of concern to the average new car buyer, that is, if there is more than a 5% difference between a gas turbine engine propelled car and an equivalent spark ignition gasoline propelled car.
- Cost of fuel and other expendable materials should be somewhat lower than for a gasoline engine if a special fuel is produced for use in gas turbines. If hydrogen is used as the fuel, the costs (while unclear at this time) will probably be much higher. Other costs, such as vehicle maintenance should be the same or lower.

- Cost of insurance may be initially higher due to concern about system unknowns. After on-road experience, the insurance costs should be comparable, possibly lower, than for a piston engine powered car.
- Limitations of the cars usefulness should be negligible; gas turbine engines should be easier to maintain than conventional engines, whether fueled with gasoline or an alternative fuel. Thus, fewer limitations than a conventional piston engine powered car should be expected.
- Reliability experience has been outstanding in aircraft and stationary power plants. There should be fewer operating problems than with internal combustion engines. There may be starting problems at cold temperatures; however, a more serious problem may be the initial non-availability of trained service personnel.
- Resale value may be a limiting factor if the service facilities for these vehicles are not available nationwide.

Since there are several remaining problems in the development of low cost, reliable, high producible ceramic gas turbines it is difficult to project when, or if, automotive gas turbines would be available at reasonable costs.

5.3 ADVANCED STIRLING (AND OTHER ALTERNATIVE) ENGINE PERFORMANCE, EFFICIENCY, EMISSIONS, AND COST

Stirling engines have recently undergone a resurgence in interest because they have some attractive properties including: the ability to use a wide range of fuels, very low noise levels, and low emissions. The efficiency of Stirling engines can be high, but researchers have not been able to show that they have significant (if any) practical efficiency advantages over conventional engines.

The Stirling engine's primary advantages include its ability to use any heat source, (gaseous, liquid, or solid), and its low noise level. Since the burner-heaters operate at near ambient conditions, control of emissions is relatively easy. There need be no noxious emissions and little if any NOx. Stirling engines may be attractive for series/hybrid electrical vehicles where the engines are run at relatively constant power/speed to maintain the charge on the batteries. Subsequently, there have been several government sponsored Stirling engine development programs. Most of the government sponsored research has been aimed at achieving high theoretical efficiencies.

In the last 10 years Dr. Meijer, who devised the first modern Stirling engine, has developed a simplified version which should have high reliability [103]. Recent estimates of the production cost of this Stirling engine indicate that the basic engine (without accessories, radiator, etc.) could be sold at a cost equivalent to that of a similar size diesel engine. The price of a 70 hp natural gas fueled Stirling engine was estimated at \$6,300/unit based on production of 10,000 units annually.

The balance of system costs will be higher than for comparable diesel engines. The Stirling engine requires much larger radiators since it has no working fluid (like piston and turbine engines) in which waste heat can be rejected. There is little information to substantiate the life cycle costs. Reviews of the most recent designs indicate that they should have a long life and low maintenance costs.

It is also possible to operate a Stirling engine in a zero pollution mode by using stored heat. A car using aluminum oxide pellets was built in the 1960's. This car has a range (70 miles) comparable with a lead acid battery; use of a phase change material like lithium fluoride for heat storage could essentially double the range (approximately 150 miles). The relative performance of various thermal energy storage devices (including Stirling engines), battery systems, and flywheels is summarized in Table V-9 [103].

Device Type	Temperature Range	Watt Hours per Lb	Watt Hours Per Cu Inch	Assumed Efficiency
Lithium Fluoride	800°F-1700°F	540	19[2]	40% efficient[1]
Aluminum Oxide	800°F-2100°F	47	6.7[2]	40% efficient[1]
Silver Zinc Battery		40.5	2.4	90% efficiency[3]
Lead Acid Battery		9	0.7	90% efficiency
Flywheel		8.3	1.6	~100% efficiency
Compressed Gas		7.8	0.33	~100% efficiency
Super Capacitors	available information needs confirmation			

[1] Includes Stirling engine efficiency

[2] Includes weight and volume of thermal storage unit

[3] Does not include control system losses

Table V-9. Relative Performance of Unconventional Energy Storage Systems

5.4 BATTERY/ELECTRIC AND HYBRID/ELECTRIC PROPULSION SYSTEMS

Most major automobile manufacturers are developing some type of battery/electric vehicle to meet the California ZEV requirements. However, they have little confidence that the public will purchase enough "conventional" or pure battery/electric cars to meet the California ZEV objectives. This has led to increasing interest in niche vehicle markets such as industrial vans and neighborhood cars, and, at least, to the consideration of accelerating fuel cell engine technology development.

Battery/electric powered vehicles are thought to be the only vehicles which offer the promise of zero emissions. The major advantage of battery propulsion as envisioned by most advocates is the ability of battery/electric powered cars to operate with essentially no emissions impact on the local environment. The standards do not yet include the pollution generated at the electrical power station. If utility emission controls are not improved, use of battery/electric vehicles could actually increase NOx emissions slightly and SOx emissions several fold. However, if more stringent (planned) stationary power plant standards are enacted, emissions from power plants will be much lower. In this case there could be a total decrease in atmospheric emissions; for example use of ZEV's, including the emissions generated from the power plant, could result in 80% less NOx being generated compared to an equivalent number of gasoline engine powered cars [29].

Unfortunately, battery/electric powered vehicle range limitations present a serious marketing problem. The automobile manufactures are concerned that optimistic projections of the sale of large numbers of battery/electric vehicles, particularly passenger cars, are misleading. Using

the "purchaser willingness to buy" criteria, discussed earlier, battery/electric powered cars which provide less than 100 miles useful range must cost from \$3,000 to \$5,000 less than gasoline engine powered cars if many are to be sold to willing buyers. This is in agreement with a Charles River Associates study (1976-78) which found that people would pay \$6,500 to increase the range of a battery/electric car from 50 to 200 miles. This "willingness to pay a substantial price differential" is overstated as the price of gasoline has decreased since the study was made. What has not been demonstrated is whether "no hassle" daily recharging at home will offset some of the concerns about range. It will take a large scale demonstration, such as GM is conducting with the Impact battery/electric vehicle, to determine the actual importance of these concerns.

Several companies have reported that they can design battery/electric cars which will be capable of 120 miles, or more, between recharges. This is usually the distance which the car would run, starting with new fully charged batteries before the batteries are exhausted at a constant 40 to 50 mph using no accessories or headlights, etc. Considering the need for passenger heat and air conditioning, lights, and the need for reserve energy, the practical range would probably be half of that.

As noted earlier studies have shown that public acceptance of cars is significantly influenced by the useful range. Owner complaints are frequent on gasoline powered cars which have less than 300 miles range. While this observation is at best illustrative there have been several studies of the public's concern over a vehicle's range. The problems of "range" facing battery/electric powered vehicles may be alleviated by:

- The ability to charge at home, thus, usually having fully charged batteries at each trip start
- Siting of recharging facilities at places of employment, stores, etc.

The availability of recharging facilities should provide driver/operators with the confidence of being able to complete a trip. Another factor which would improve operator confidence includes quick response by repair or recharging trucks in case of electrical power depletion of the vehicle while on a trip [51].

The standards for home recharging units proposed by the American Battery Consortium is 6.6 kW at 220 volts and unity power factor. The recharging units should be able to operate at 95% efficiency. Home recharging facilities should present few technical problems (they are estimated to cost \$1,000 to \$1,500) [29]. The concerns which have been expressed include limitations in charging during peak demand on the utility supplying the electrical power, and the ability of states (or other governments) to collect taxes for construction and maintenance of roads, etc., as they now do from fuel taxes. In California, variable rates and charger timing controls are being considered to insure that battery recharging occurs at off-peak periods for the utilities so that new, larger capacity power plants do not have to be constructed.

Public, or opportunity, recharging facilities at offices, recreation centers, stores, etc., present similar problems. The economics of such recharging facilities have not yet been adequately defined, nor has the responsibility for installation, maintenance, or collection of costs from users. To provide power sources during peak electrical demand periods, consideration is being given to the use of banks of less sophisticated storage batteries to store power at the

recharging point. Some designs of recharging facilities which are being evaluated include automatic (safe) electrical connections.

The manufacturing cost of the vehicle structure may be from 30% to 50% higher (for a car with about 80 miles maximum range) than that for a conventionally powered car. This increment will in part be due to the use of more exotic materials and in part to the lower production volume. In addition, the original costs of electric drive systems (not including the batteries) will probably always be somewhat higher than equivalent mechanical drive systems. According to Charles Macey, TRW has spent nearly \$10 million per year for 10 years to bring an electric power steering system to the point of commercialization. It still costs \$120 per unit compared to a target of about \$80.

Battery/electric vehicle designers have concentrated on reducing the weight and size of the equipment and structure in the vehicle in order to achieve performance (range and acceleration) which they feel would be acceptable to an adequate number of customers. Most of the size and weight reduction techniques could also be applied to conventional or liquid fueled vehicles, although the benefits of exotic materials would be less economically attractive for the gasoline engine powered car.

The life cycle costs of batter/electric cars will probably be higher than comparable gasoline cars. Direct operating costs, including the cost of electrical power, should be lower than an equivalent gasoline engine powered car on a per mile basis, and maintenance costs may even be lower. However, the major cost outlay will be for the batteries which must be replaced every few years (depending on mileage, average depth of discharge, vehicle range, etc.). Cost estimates for battery replacement range from \$10,000 to \$30,000, or approximately \$0.10 to \$1.00 per mile. Some of the concern over high initial and battery replacement costs may be moderated if the batteries are leased on a kilowatt hour delivered basis. The lessor would then replace the batteries at the appropriate time in their life cycle. The replacement costs would be included in the lease payments. While battery life and reliability will be improved, total ownership costs of battery/electric powered vehicles will still be much higher than those of similar gasoline (or natural gas) engine powered cars.

5.4.1 Battery Specifications, Type, Projected Costs, and Their Acceptability as a Propulsion System

The research and development of high energy batteries has been difficult; efforts are continuing, most of which are being coordinated by the American Battery Consortium which includes as members both the U.S. automobile manufacturers and the U.S. DoE. Performance objectives for both near-term and long-term developmental batteries are presented in Tables V-10 and V-11 below.

However, these objectives are not met by any available battery system. More realistic performance levels for the first generation of battery cars are summarized in Table V-12 for selected batteries. For several decades the objective of advanced battery research and testing has been to increase the energy storage and consequently the range of battery/electric vehicles. There has been considerable speculation concerning the development of batteries with greater energy density. Several battery concepts hold the promise of doubling (or more) the range of electric vehicles, but have not yet demonstrated the life required to be cost competitive. The results to date have not been encouraging. The most attractive recent

development appears to be the lithium polymer battery which is described in more detail following Table V-12.

Battery Characteristics	Mid Term	Long Term
Specific Energy Wh/kg	80 (100 desired)	200 C/3 Discharge Rate
Energy Density Wh/L	135	300 C/3 Discharge Rate
Specific Power W/kg	150 (200 desired)	400 80% DOD/30 seconds
Power Density W/L	250	600
Cycle Life	600	1000 80% DOD
Ultimate Price--\$/kW hr	<150	<100
Operating Environment	-30 to + 65°C	-40 to + 85°C
Recharge time	<6 hr.	3 to 6 hr.
Continuous Discharge	75% in one hour	75% in one hour (of rated capacity)
Power & Capacity Degradation	20%	20% (of initial rating)

Table V-10. American Battery Consortium, Primary Battery Performance Objectives

Battery Characteristics	Mid Term	Long Term
Efficiency	75%	80% C/3 6 hr charge
Self Discharge	<15% in 48 hr.	<15%/month
Maintenance	None	None (qualified mechanic only if required)
Thermal Loss	3.2 W/kW-hr	3.2 W/kW-hr
High Temp. Batteries	15% capacity	15% capacity (48 hr period)
Abuse Resistance	Tolerant	Tolerant

Table V-11. American Battery Consortium, Secondary Performance Objectives

Battery Type	Energy-Wh/kg	Power-W/kg	Recharge Cycle Life	Life Costs-Cents/kW hr
Lead Acid	22-36	80-100	500-700	8-12
Adv. Pb/Acid	35-40	200-300	600-1000	12-15
Ni/Cd	50-55	165-225	2000-3000	30-50
Ni/Fe	50-55	80-110	900-1200	40-80
Na/S	85-195	140-145	300-500	20-150
Li/AlSO ₂	80-95	400-600	120-150	?

Table V-12. Typical Battery Performance and Costs

These performance projections were obtained from a number of sources. They should be considered to be nearer term objectives or goals. Some improvements are possible but it is probable that the higher performance levels may never be attained. Even if major gains are

achieved there will be performance limitations (like rapid self-discharge) which will make it difficult to take advantage of the battery's performance.

The theoretical problem in increasing battery energy density can be illustrated by the fact that batteries must contain both the oxidizer and the fuel. An internal combustion engine consumes eight times as much oxygen (by weight) as gasoline; this oxygen comes from the air. Certain metal/air (zinc and aluminum) batteries might be considered pseudo fuel cells since they take advantage of the oxygen in the air.

It is probable, then, that the first generation of battery/electric powered vehicles will use conventional lead acid batteries. The lead acid batteries will be replaced when superior battery technologies (or fuel cell engines) are developed. Some of the attractive battery candidates at this time include zinc nickel oxide and lithium polymer batteries. Recent performance estimates for lithium polymer batteries by Valence technology, Inc., a developer, indicate that they could "theoretically" achieve an energy density of 205 Wh/kg (383 kW/L). Valence projects a self-discharge rate of less than 1% per month for these batteries. The self discharge of lead acid batteries range from 4 to 8% per month while other batteries (Nickel Cadmium, etc.) have even higher self discharge rates, 5 to 20% per month.

A 1988 study by Wm. Hamilton provided the following comparison (Table V-13) for various battery/electric powered vehicles as compared to an "unrealistic" conventional gasoline engine powered car which would sell for about \$6,700 [28].

	Internal Combustion	Lead Acid	Nickel Iron	Sodium Sulfur
Sale Price	100% ^[1]	125%	165%	185%
Life Cycle Costs	100% ^[2]	95%	105%	120%
Range, Miles	300	65-75	110-115	210-214
Battery Life	N/A	4 years	9.5 years	10 years

[1] \$6,700

[2] \$0.15/mile

Table V-13. Estimated Relative Costs of Gasoline and Electric Cars with Selected Batteries

While studies such as this imply that the costs of battery/electric vehicles could be somewhat (barely) equivalent to gasoline engines powered cars, the automobile companies have not reached similar conclusions, even using the extended battery life assumptions assumed in many studies. One such example of the projected costs of more realistic priced gasoline, natural gas, and battery/electric powered vehicles is presented in Table V-14.

It is generally accepted that battery/electric cars will be about one and one-half or more times as expensive to operate than gasoline cars at current oil prices (\$1.00-\$1.30 per gallon). They may be equal or less expensive to operate if, or when, gasoline exceeds \$2.00 per gallon retail, with or without additional taxes [28].

Many of the regulatory requirements such as the federal safety standards for electrical powered vehicles have been addressed. Safety considerations will be important from both the standpoint of the probable regulations which could limit the usefulness of the battery/electric vehicle, or impose additional costs. These include the risk of electrocution when working on the

electrical system, spillage of corrosive or otherwise hazardous material during maintenance, or accidents. The time which will be required to create new safety regulations and get them approved is estimated to be two to three years. This must be accomplished before battery/electric powered vehicles could be sold to the general public.

There is not enough experience with accidents with battery electric vehicles for insurance companies to establish rates with any degree of confidence. Some of the initial contacts with insurance companies by potential manufacturers of battery/electric vehicles have led to estimates of rates higher than those of equivalent gasoline engine powered cars because expensive electronic equipment may be located in places vulnerable in an accident. Other technical risks which must be resolved include the development of a superior battery system and effective, safe, and economic recharging facilities.

	Energy-Fuel Type		
	Gasoline	Natural Gas	Electric
Initial Capital Costs	\$14,000	\$14,000	\$14,000
Alternative Incremental Costs of Power Source	\$0.00	\$1,000	\$7,850
Total	\$14,000	\$15,000	\$21,800
Operating Costs (Cents per Mile)			
Energy	3.62	1.58	2.86
Energy Taxes	1.24	1.24	1.24
Recharging/System Considered	not required.	0.67	included
Oil etc.	0.17	0.15	much lower
Tires	0.40	0.40	0.50
Maintenance	1.74	1.65	1.10
Total	7.17	5.69	5.70
Total Capital And Operating Costs			
Cents/Mile (18,500 Miles Per Year)			
Total	17.69	16.96	22.12-26.13

Source: Hamilton [28]

Table V-14. Economic Comparison of Conventional Gasoline, Natural Gas, and Battery/Electric Vehicles

The factors which a purchaser of a battery/electric propelled vehicle must consider are summarized below.

- The **purchase price** of most battery/electric vehicles will be greater than that of comparable chemically fueled vehicles. While subject to discussion and further analysis, the price premium for the same size and performance car (100 mile range, nominal acceleration) is probably on the order of 40%, although some investigators

have argued that the life cycle costs (including energy and maintenance, etc.) should be about 20% lower and the useful life about 20% longer [29].

- The **total operating cost** per btu of electrical energy is, and will remain, higher than that of chemical fuels (\$0.05 per kW hr is usually assumed in comparative studies). However, the "in-vehicle" propulsion system efficiency can be significantly higher than an internal combustion propulsion system, so that the distance traveled per btu in the battery should be greater than the distance provided by a similar number of Btu's in the gasoline tank.
- There is very little **reliability** data and no useful **safety record** on battery/electric cars which the insurance companies can use to estimate their costs. The small number of battery/electric vehicles which have been built, with the exception of GM's Impact vehicle, have been limited in performance. Most did not attempt to meet motor vehicle safety objectives. Batteries have some additional hazards; if not vented properly, lead acid cells have been known to explode with sufficient force to damage a vehicle.
- The major **acceptability** problems with battery/electric vehicles will continue to be the limitations on range and the time required to recharge the vehicle. Users would have to adapt their life styles to limited total trip distances or, more likely, have a conventional car available. In terms of the ability to start and complete a trip within its range the battery/electric car should be as or more reliable than a gasoline, or alternative fueled, car.
- The cost of **home recharging equipment** has been addressed in several battery/electric car studies. An estimate of \$1,000 to \$1,500 for a home recharging station appears reasonable.
- **Resale** value of a battery/electric car may be limited unless there is a very large mandated market.
- **Disposal or recycling** costs could be high if toxic materials are used in the batteries.

Fuel cell systems could indirectly contribute to the increased use of battery/electric cars. Fuel cell power plants can also be used as stationary sources for electrical power production. This may be a logical use for phosphoric acid or other fuel cell systems which do not meet the packaging or operational characteristic requirements for automobiles and trucks. A combination of such high efficiency electric power production plants and battery/electric vehicles could produce overall high efficiencies and near zero global emissions.

5.4.2 Hybrid/Electric Propulsion Systems and Their Acceptability as a Propulsion System

One way of alleviating the range concerns with battery/electric cars would be to use a combustion driven engine (operated when required) to maintain the charge on the battery, in other words, a hybrid propulsion system. There are two categories of hybrids.

- **Series Hybrid.** All "engine" (combustion plus battery) output is converted to electrical energy, which is used to drive the wheels.
- **Parallel Hybrid.** Mechanical and electrical energy both are used to drive the same or separate wheels. Unique power transfer connections are generally required in such a device.

As the internal or external combustion engines utilized within the hybrid/electric propulsion systems described within this section are directly connected to alternators, they convert their output energy entirely to electricity. Thus, hybrid/electric propulsion systems described in this report are "series hybrids". This is also true of an electrochemical engine (fuel cell engine system)/battery powered hybrid/electric as there is no mechanical output from the electrochemical (fuel cell) engine. In fact, an internal/external combustion engine/alternator or electrochemical engine combination with a flywheel is still a "series hybrid". While the flywheel stores input energy as "kinetic energy", energy is transferred to and from the flywheel in the form of electricity utilizing electric motor/generators units.

The environmental implications of the various hybrid/electric concepts are significantly different. Internal or external combustion engines for series hybrid/electric vehicles can be designed to operate at a single speed-power point, selected for minimum fuel consumption or minimum emissions. The emissions should be lower than would be possible with conventional piston engine propulsion systems. Hybrid/electric vehicles may be classified as ultra low or near zero emission vehicles, not zero emission vehicles. Use of alternative power plants such as gas turbines and Stirling engines and alternative fuels would further lower emissions, but not to ZEV levels. There is some possibility that a "hybrid" classification may be approved, with requirements closer to ZEV's than to ULEV's. If ways were found to insure that hybrid/electric engines operated on battery power only in critical regions (but primarily on internal combustion engines for rural trips) there is also a possibility that they could be given some (partial) credit toward meeting the ZEV quotas. Several control possibilities include:

- Recording clocks which indicate what portion of the time the car is operated on battery power alone
- Passive (radio) signals which could be monitored by local police
- Regional sensing devices which would disable the internal combustion engine in critical areas
- Environmental/road pricing schemes which would record the total time that the vehicle is in critical areas (congestion or environmental) and charge the operator a fee (probably monthly) based on where the car was operated, what time of day, and what mode of operation the car utilized (such as, pure battery only, etc.).

All of these require some measure of vehicle status data, recordings, or real time controls from the local government or infrastructure. Similar proposals have been subject to criticism because of the concern over privacy.

The energy/power ratio of the "active engine" (combustion or electrochemical (fuel cell)) compared to the storage device (batteries, flywheels, supercapacitors) is a function of the vehicle emission design and trade-off studies. Should the storage batteries provide enough power to provide (or aid in achieving) acceptable acceleration? Should the engine provide enough power for an extended hill climb? As an example, the relative power requirements for hill climbing and acceleration of a "conventional family sedan", with standard belted tires, are presented in Tables V-15 and V-16.

Studies of hybrid battery/electric propulsion systems have assumed that their original costs will be from 10 to 40% higher than similar cars with gasoline engines. The maintenance costs will probably be higher due to the need to maintain two different kinds of propulsion systems.

Hybrids could potentially be the worst of both systems unless unique design strategies are employed. Hamilton [28] points out that the potential market for the hybrid/electric vehicle, as determined by their ability to meet most travelers needs, should be three times that of pure battery/electric vehicles.

<u>Grade</u>	<u>Speed</u>		
	<u>25 Mph</u>	<u>45 Mph</u>	<u>65 Mph</u>
0%	2-5 hp	8-10 hp	18-20 hp
2%	4-6 hp	12-15 hp	25-27 hp
4%	8-10 hp	18-20 hp	32-35 hp
6%	12-15 hp	28-30 hp	40-45 hp
8%	15-18 hp	30-35 hp	55-58 hp

Table V-15. Power Required for Various Grades and Speeds, 3000 Lb. Car, 0.3 Cd

<u>Weight</u>	<u>Power</u>		
	<u>50 hp</u>	<u>100 hp</u>	<u>200 hp</u>
2000 lb..	10-12 sec	6-7 sec	5-6 sec
3000 lb..	16-18 sec	8-9 sec	7-8 sec
4000 lb..	23-25 sec	10-12 sec	9-10 sec
5000 lb..	35-40 sec	13-15 sec	11-13 sec

Table V-16. Acceleration Time to 60 Mph, for Different Vehicle Weights and Power Levels

Hamilton also calculated that hybrid/electric vehicles could be used by 45% of all households, perhaps more, depending on the size of the engine. But, he estimated that the sale of hybrid/electric vehicles would only attract 5% of the market because of their higher initial cost and the increased maintenance problems which could potentially occur with the use of two different propulsion systems. The U.S. DoE projections are more generous, assuming about 17% of the light vehicles manufactured in 2015 will be hybrids, with sales of such vehicles projected to exceed 20% of the market by 2030 [137].

The development of electric drive systems for either battery/electric and/or hybrid/electric cars is complementary to the development of fuel cell engine propulsion systems. The drive systems and some of the energy monitoring controls will be similar. Automotive electrical (fuel cell or battery) propulsion systems will use batteries (or high performance ultracapacitors, flywheels, etc.) to store energy during regeneration braking and, in some instances, to provide peak acceleration power.

5.5 ELECTROCHEMICAL ENGINE (FUEL CELL) PROPULSION SYSTEMS

5.5.1 Fuel Cell Engine Propulsion Systems and their Operating Conditions

All fuel cells operate by electrochemically combining a fuel (hydrogen in the cells of immediate interest) with oxygen from air in the presence of a catalyst. They will continue to produce

electrical power as long as fuel and oxygen are supplied. Fuel cells are the energy conversion element of an electrochemical engine, much like pistons and cylinders are the energy conversion elements of an internal combustion engine.

Most fuel cell engine propulsion systems require hydrogen fuel or the use of an on-board reformer to disassociate a hydrogen rich material such as methanol or natural gas into hydrogen and carbon dioxide. The fuel processing system also includes unique devices downstream of the reformer to remove any residual compounds, carbon monoxide, etc., as performance can be degraded by such materials. There are several types of reformers, some small and rapid in response, others more complex and more efficient. The choice of fuel will depend on the relative economics, size, and efficiency of the fuel processing process.

The electrochemical process avoids the second law of thermodynamics which limits the "theoretical efficiency" of internal combustion engines to about 60% (practical peak efficiencies for gasoline engines are much lower, typically 30-35%). Individual fuel cells have demonstrated efficiencies over 70-80% during bench tests. Complete fuel cell engine propulsion systems are expected to achieve efficiencies in the high 40 to low/mid 50% range; this overall efficiency includes the balance-of-plant efficiencies involving: conversion of fuels such as methanol to hydrogen, air turbocompression, cooling, and other systems.

Research and tests of prototype fuel cells have been in process for decades. For decades advocates have also promised that they were less than ten years away. Fortunately, recent technical developments are very encouraging. Even so, the fuel cell development process is expected to be similar to that of other advanced energy conversion systems. There will probably be several generations of increasingly more effective and competitive designs [36,75].

Since vehicular engines are primarily operated at low power (15-25% of maximum power), where fuel cells are most efficient, the range of a fuel cell engine powered vehicle (using methanol) could be nearly twice that of a similar internal combustion engine propelled vehicle (using methanol), or about the same range as the internal combustion engine propelled car on gasoline with the same size fuel tank.

In a typical PEM type of fuel cell, hydrogen atoms are stripped of their electrons on the anode. The protons migrate through the electrode to the cathode where they combine with oxygen to form water. The flow of electrons (external to the cell) from the anode to the cathode provides the electrical power. Fuel cells generate essentially zero noxious pollutants. Auxiliary equipment and elements of the fuel processing system may create a very small level of emissions. Different fuel cells of interest, which also utilize various electrolytes and migrating species, include:

- **Phosphoric acid fuel cells (PAFC's)** which are in production for stationary power and are also being used in demonstration buses
- **Solid polymer or Proton-Exchange-Membrane fuel cells (PEM's)** which have been used successfully in submarines and buses but have not yet entered volume production
- **Solid oxide fuel cells (SOFC's)** which may provide cost advantages if they can reform hydrocarbons internally; they may not require precious metal catalysts or reformers
- **Alkaline fuel cells (AFC's)** which are primarily used in space where ultra pure fuels and oxygen can be used to avoid carbonate "poisoning" of the KOH electrolyte.

The various names (phosphoric acid, solid polymer, etc.) refer to the kind of electrolyte. Other fuel cells, such as molten carbonate, are under development for utilities and may have some application if solutions to the cost, packaging, material compatibility, and life problems are solved.

Alkaline fuel cells were among the first used and have demonstrated efficiencies equal to or slightly greater than PEM cells. They are extensively used in space and the German Navy has used them to power an experimental submarine. They require pure hydrogen and oxygen because even trace hydrocarbon compounds and carbon dioxide can "poison" the electrolyte and rapidly degrade performance. As a consequence, they have been given limited consideration for production vehicles; even alkaline fuel cell hydrogen/air buses being developed in Europe require scrubbers on the air to remove trace quantities of CO_2 from the air. CO_2 in reformat presents unique fuel cell performance degradation problems.

Most research and development of phosphoric acid fuel cells has been directed toward their use for electrical power generation by utilities. Because of their "availability" PAFC's were selected for the first generation of fuel cell bus demonstrations scheduled for 1994. They require either hydrogen fuel or the use of an on-board reformer to disassociate methanol or natural gas into hydrogen and carbon dioxide.

Proton-exchange-membrane (PEM) type polymer fuel cells were originally developed by General Electric for space power in the 1950's. Major improvements in power and reductions in cost have recently resulted from the development of new membrane materials and reductions in Pt catalyst loading. They will be smaller, lighter, more efficient, and less costly than phosphoric acid cells [95,141] and virtually as efficient as alkaline fuel cells. Further, they produce half of their rated power at ambient temperatures, thus reducing cold start-up requirements. Like the phosphoric acid fuel cells, PEM fuel cells require hydrogen fuel or the use of an on-board fuel processing system to disassociate a hydrogen rich material such as methanol or natural gas into hydrogen and carbon dioxide. The choice of fuel will depend on the relative economics, size, and efficiency of the fuel processing system; for transportation applications pure methanol presently appears to be the fuel of choice because of the ease with which methanol can be reformed.

However, if a lack of methanol infrastructure appears to be an impediment to fuel cell commercialization, special partial oxidation fuel processors that can reform gasoline may have to be developed.

The operating temperatures, projected mass and volume densities, start-up times, and dynamic response for various fuel cell systems, operating at peak power conditions, are presented in Table V-17 below. The latter operating condition is used to correlate with internal combustion engine rating techniques. The fact that this table is relatively incomplete reflects the early state of development of fuel cell engines and the uncertainty (or lack of comparability) of the available information. Solid oxide fuel cells appear promising from the standpoint of cost, efficiency, and size. Unlike the previously mentioned fuel cells they can reform most conventional fuels internally (methanol, natural gas, pure kerosene, etc.). The differential expansion of different ceramics used within the cells has been a major problem in their development. It is reasonable to expect that these problems will eventually be overcome; however, there is no basis for estimating when that development may occur. One major problem with solid oxide fuel cells may be their time required to warm-up during a starting cycle, as the cell operates near 1000°C .

PROJECTIONS

		Operating Temp	Mass Density kg/kW		Volume Density kW/Ft ³		Start-Min.		System Dynamic Response
Type	Fuel		Cell	System	Cell	System	Cold	Standby	
KOH	H ₂	80°C	----	----	10	?	fast	----	fast
PAFC	MEOH	200°C	----	----	3	0.5	300	15	slow
	NG		---	---	---	---	---	---	slow
	H ₂		---	---	---	---	---	---	medium
PEM	MEOH	80°C	~1.35	~3.0	~20	~6.0	2	<<1	good
	NG		?	?	?	?	----	----	good
	H ₂		~1.2	storage dependent	~22	?	<<1	fast	fast
PSOFC	MEOH	1000°C	----	----	----	2.3	100	1	fast
	HC		----	----	----	----	----	----	----
MSOFC	MEOH	1000°C	----	----	20?	----	----	----	----
	HC		---	---	---	---	---	---	---

H₂-Hydrogen, MEOH-Methanol, NG-Natural Gas, HC-Wide cut hydrocarbon fuels
PSOFC-Planar Solid Oxide Fuel Cell, MSOFC-Monolithic Solid Oxide

Table V-17. Performance Characteristics of Various Fuel Cell Systems

Fuel cell engines share a characteristic with other electrical power devices. Maximum continuous power is set by cooling requirements. Significantly higher peak power (nearly 40%) can be produced for some limited time if the temperature does not exceed specified transient limits. This is also true for conventional internal combustion engines.

5.5.2 Emission Characteristics of Fuel Cell Systems

The projected automotive and locomotive emission characteristics of PEM and phosphoric acid fuel cells, using reformed methanol from on-board fuel processors, are presented in Table V-18. The reduction in projected emission compared to unregulated engines (or even CARB ULEV passenger car requirements) is remarkable.

Additional information regarding automotive fuel cell engine emission requirements, as compared to gasoline automobile engines and the CARB standards, is presented in Table V-19. Any fuel cell type operated on stored hydrogen will qualify as a ZEV.

5.5.3 Operational/Cost Characteristics of Various Fuels Being Considered for Use in PEM Fuel Cell Propulsion Systems

M-85 and other grades of methanol for use in internal combustion engines will not be acceptable for fuel cells. M-85 contains up to 15% gasoline and additives to improve lubricity, etc., which would contaminate current electrochemical engine fuel processing systems. Pure

Automotive	Grams per Mile			
	HC	CO	NOx	SOx
Unregulated-pre 1965	10.6	84.0	4.0	----
CARB ULEV requirement	0.04	1.70	0.20	----
PEM fuel cell using methanol	0.002	----	0.001	----
Phos. acid fuel cell using methanol	0.015	<0.001	0.001	----
Locomotive	Grams per 1000 Btu of Fuel Consumed			
Average unregulated	130.0	587.0	1676.0	236.0
PEM fuel cell using natural gas	0.2	----	1.4	0.01
Phos. acid using methanol		3.6		

Table V-18. Projected Emission Characteristics of Different Fuel Cell Engine Applications, Using Reformed Methanol or Natural Gas Produced by On-board Fuel Processors

	Emissions			
	HC	CO	NOx	
Unregulated automobile	10.6	84.0	4.0	
CARB ULEV requirement	0.04	1.70	0.20	
PEM fuel cell	0.002	0.00	0.001	using methanol
Phos. acid fuel cell	0.015	0.0001	0.001	using methanol
Any fuel cell (ZEV)	0.00	0.00	0.00	using methanol

Table V-19. Projected Emission Characteristics of Fuel Cell Engine Systems, Grams per Mile

Fuel	Vehicle Price	Fuel Cost per Mile	Environment % Emissions	Operability	Range [2]	Retail Sale of Fuel
Gasoline	---	---	N/A	---	---	---
Reformulated	---	---	N/A	---	---	
M-85	---	---	N/A	---	---	
M-100	>100%	<gasoline [3]	.003% [1]	start delay?	>300 mi.	station
Hydrogen	?	>>gasoline	zero	?	150 mi.	?
Natural Gas	110%	<gasoline	<<gasoline	?	>100 mi.	home?
LPG	N/A	---	---	---	---	---
Battery	May be required for starting and peak power in some applications					

[1] Environmental index (%HC+%NOx+%CO)/3 --% of unregulated gasoline engine emissions

[2] Tank which will provide 300 miles on gasoline with a piston engine.

[3] Assumes use of PEM fuel cell system

Table V-20. Fuel Options for PEM Fuel Cell Propulsion Systems

methanol is an attractive fuel because it is a liquid and disassociates "easily" into hydrogen and carbon dioxide. Its use is consistent with the public's understanding of a fuel. Hydrogen is an ideal fuel but it is difficult to store and transport and it is also potentially dangerous. Hydrogen can be stored in systems such as zeolite and activated charcoal; however, such devices can store only a very small percent of hydrogen by weight (usually less than 3%). This justifies a close look at other fuels which may be easier and less costly to transport. On balance, the total system for on-board methanol reforming may be more efficient than the use of hydrogen (Table V-20 above).

Little consideration has been given to unique fuels or hydrogen generation systems (such as reacting steam on iron to form iron oxide and release hydrogen) for fuel cells. These concepts may provide superior performance and economics, but will require rethinking of the entire fuel supply system and infrastructure.

5.5.4 Developmental Approach to Produce Fuel Cell Engine Systems and Their Acceptability as a Propulsion System

The development of fuel cell engines and their production for and use in vehicles must be addressed as a system. The fuel cell itself is only a portion, although a most important one, of the system. The other critical elements include:

- The electrical drive system
- The fuel supply system
- The fuel reformer or on-board fuel processor
- The balance-of-plant components such as air handling, controls, etc.

The experience in developing electric drive systems for battery/electric and hybrid/electric cars will be transferable to fuel cell propulsion systems. Depending on the duty cycle, batteries may be required or desired to provide power for initial operation if the fuel cell engine system requires too long to meet customer expectations for cold start-up.

It appears probable that the first generation of fuel cell engine powered automobiles (and buses) will have a nearly even mix of batteries and electrochemical engines. The batteries can serve three major functions:

- Provide hotel loads for lights, air conditioning, etc.
- Provide operating power during start-up which is estimated to be thirty seconds to two minutes for PEM cells (depending on the type of reformer utilized), and much longer for the other fuel cell types
- Provide energy storage for regeneration.

Fuel cell engine/battery powered "hybrids" will be appropriate for vehicles which have significant stop and go operation. Super capacitors and/or flywheels may also be of interest; all such storage devices can also be used for load leveling the fuel cell engine systems. In cars the peak power from the batteries and the fuel cell would be about the same. Locomotives and trucks can take advantage of batteries to store braking energy, but the fuel cells and reformers would have to be sized for maximum power as both kinds of vehicles spend long periods at full power to accelerate and climb long grades.

The fuel supplies and electrochemical engine system must be developed in parallel. To a greater extent than most other power plants, the characteristics, cost, and availability of a suitable fuel will influence the final choice of fuel cell type. Reformer research appears to be as, if not more, challenging than the development of the fuel cell portion of the entire electrochemical engine.

The factors which a purchaser of a fuel cell engine powered car must consider are summarized below.

- Initially, the use of fuel cell propulsion systems will increase the ***purchase price of the vehicle*** (primarily because of the fuel cell propulsion system and electric drive). Even if the cost of the fuel cell engine system itself could be reduced to below the cost of an equivalent gasoline engine, the cost of the electrical drive system will probably remain higher than that of a mechanical drive system. Offsetting the higher original cost will be improved fuel economy, lower emissions, and lower maintenance costs. The cost to produce vehicles to be used with fuel cell engine propulsion systems will depend on the production volume achieved. Even if the production volume approaches a million vehicles per year for each major manufacturer the cost increment will probably still be of concern to the average new car buyer (that is, more than a 5% difference between a fuel cell engine powered vehicle and an equivalent performance gasoline engine powered vehicle). The manufacturer could set the price of the car to the consumer above or near the cost of production. Prices could be nearer the cost of production if the sales of more expensive "conventional" large cars increase as a result of the sales of high mileage or alternative fueled cars.
- Initially, ***cost and availability of alternative fuels and other expendable materials*** (if alternative fuels are utilized) will be higher because of their special handling and limited market. By 2020 fuel costs per mile should be lower than that for a gasoline engine if methanol is used. A fuel cell engine powered car will use about half the methanol compared to that of an internal combustion engine powered vehicle. If hydrogen is used as the fuel, the costs (while unclear at this time) will probably be higher. ***Other costs***, such as vehicle maintenance, should be lower due to the fundamental simplicity of the fuel cell engine.
- ***Cost of Insurance*** may be initially higher due to insurance companies concerns regarding the new propulsion system unknowns and the lack of data on actual damage or other hazards. After experience, the insurance costs should be no higher, and possibly lower, than that for an internal combustion engine powered car.
- ***Limitations to the cars usefulness*** should be fewer than with an internal engine powered car, particularly where there are mandated regulations designed to limit the use of cars with internal combustion engines. Fuel cell engine powered cars should be as or more reliable than conventional cars, whether fueled with methanol or some other fuel alternative. A major concern will be the availability of skilled maintenance personnel to repair fuel cell engine powered cars during their introduction period.
- ***Reliability*** will probably be greater than with internal combustion engines; initial life experience has been outstanding. There should be few starting problems.
- ***Cost of equipment to refuel the vehicle*** will probably be inconsequential as it is unlikely that many private owners will provide their own fuel supplies, although this may be tempting for cost and convenience reasons.

- **Resale value** could be a limiting factor if service facilities for these vehicles are not available nationwide.

5.6 SUMMARY OF PROPULSION SYSTEMS CHARACTERISTICS

The existing and proposed benefits of each category of propulsion system will be based on its relative cost, life characteristics, energy consumption, emissions, and configuration (ability to be able to be installed in a vehicle). The propulsion systems of interest in this paper include the following.

- **Spark Ignition.** The "conventional" piston engine has been successful because of its low cost, relative reliability, and ability to meet the performance and packaging requirements for personal automobiles. It has been under development for more than a century and is approaching its practical limits of efficiency. Further reductions in emissions will be costly and will probably require specialized fuels (second phase reformulated gasoline, etc.).
- **Diesel Engines.** Heavy duty diesel engines have dominated the heavy truck market (also locomotives and many vessels such as tugboats) because of their excellent life characteristics and ability to use a relatively low cost hydrocarbon fuel. They weigh about twice as much as a spark ignition engine of the same power (but lower torque) rating. There has been considerable concern over their emission characteristics and remarkable progress has been achieved in reducing diesel emission and particulates; however, these reductions are now approaching the limit of practicability. Diesels are somewhat more efficient (in terms of miles per gallon) than spark ignition engines, but about half the difference is due to the approximately 10% higher energy density of the diesel fuel.
- **Gas Turbines.** Gas turbines may provide some unique advantages for heavy duty vehicles (high efficiency and power for hill climbing, etc., in a compact package). Their emission characteristics are excellent. They can probably meet all but zero emission standards without exhaust after-treatment. They are also being considered for use in hybrid/electric propulsion systems. Their manufacturing cost remains a question.
- **Stirling (External Combustion) Engines.** Stirling engines should generate the lowest level of emissions of any "thermal or heat" engine since the burners operate at near ambient pressure. The efficiency of the newest designs is similar to the best internal combustion engines. The new designs are remarkably compact and nearly noiseless. Costs appear competitive with diesel engines although they require much larger radiators since they cannot reject waste heat to the working fluid as do internal combustion engines.
- **Phosphoric Acid Fuel Cell Systems.** The most highly developed fuel cell. Most research has been based on their use for stationary electrical power generation. They are also being used in the DoT/DoE bus demonstration. They appear to require much larger volumes, produce lower ideal efficiency, and are estimated to be much more costly than other competitive fuel cells.
- **Polymer or Proton-Exchange-Membrane (PEM) Fuel Cell Systems.** The PEM fuel cell system appears to have the primary characteristics required for vehicle propulsion. It has a greater efficiency than internal combustion engines, is compact, and should be very reliable (potentially longer lived than the vehicles they power). There appear to be

no show-stopping barriers to reduce PEM fuel cell engine system costs to a level competitive with spark ignition engines on a life cycle basis.

- **Solid Oxide Fuel Cell Systems.** This system is not yet developed to the point where it can be considered for vehicle propulsion. When it is developed it may be more compact and lighter, but always less efficient than a PEM system. Solid oxide systems do have the potential advantage of being able to use unreformed hydrocarbons although system studies indicate that the use of reformers may improve overall performance and life.
- **Alkaline Fuel Cell Systems.** These are widely used fuel cells for space applications where they operate on pure hydrogen and oxygen. If the problems with carbon compound poisoning are resolved they could become one of the fuel cell systems of choice.

Each class of advanced power plant differs significantly in the way it uses fuel, and in the characteristics of the fuel which provide the highest level of performance (and competitive economics). For example, unlike piston engines which require carefully specified fuels (for cetane or octane ratings, etc.), gas turbine engines can utilize almost any gaseous or liquid fuel.

VI. COST AND AVAILABILITY OF COMPATIBLE ENERGY SUPPLIES FOR ADVANCED PROPULSION SYSTEMS

This section of the report discusses potential fuels for electrochemical engines, the potential need to construct new fuel supply systems, and the availability of critical materials. Information was obtained both from reviews of recent energy literature and from meetings with energy research, production, and retail companies. This information provides the background data for the assumptions used in preparing estimates regarding the spread of fuel costs and fuel availability that will be utilized in the proposed scenarios to be developed in Phase II (as summarized in Section VII).

The cost and availability of a suitable fuel may become the pacing item in the deployment of fuel cell engine powered vehicles as alternatives to conventional options. The fuel of choice may be different for specific types of fuel cell engine propulsion systems and/or whole classes of vehicles. Several observations are appropriate.

- The preferred fuel for fuel cell engine powered locomotives will probably be methanol, natural gas (CNG or LNG), or diesel (if it can be successfully reformed)
- The preferred fuel for busses will probably be methanol (although some of the initial fuel cell system demonstrations use hydrogen) or diesel, again, if it can be reformed.
- The preferred fuel for trucks has not been identified. Use of diesel or gas-oil which has been the preferred fuel in the past is being challenged by environmental rules. Further, diesel fuel, as stated, is very difficult to reform; however, partial oxidation fuel processors may be able to be developed to accomplish this process.
- The preferred fuel for the first generation of light vehicle ECEs will probably be methanol or, more likely, due to the existing infrastructure, gasoline if a suitable partial oxidation fuel processor can be developed. Other fuel systems may subsequently be developed which provide superior performance and lower costs.

In order to obtain information to develop a fuel supply assessment, contacts were initiated with several of the major oil companies to determine what their strategy would be if advanced propulsion systems (gas turbines, external combustion or fuel cell engines) became widely accepted and therefore a major share of their market. The companies contacted included: Amoco, Arco, BP, Chevron, Conoco, Exxon, Shell, Skelly, Tenneco, Texaco, and Sun. One or more meetings were held with all but Texaco and Sun. Excellent cooperation was received. Some companies suggested opportunities for research and provided different views on the performance/commercialization of fuel cell engines. These contacts have led to a series of joint meetings between interested energy companies and the U.S. automobile companies. The energy companies point out that, because their investment time horizons are much longer than those of the automobile companies, they would like the auto companies to cooperate with them to project fuel needs for the next 10, 20, 30 years, and longer.

All parties recognize that it becomes increasingly difficult to project costs and markets as the time span regarding the future is increased. Studies which establish: probable bounds of fuel costs and availability, the sensitivity of the market to incremental changes in energy distribution costs, and the efficiency of advanced engines will help both industries (and the government) determine where and how to invest their research and development funds.

Most energy authorities believe that there are adequate fossil fuel (petroleum) resources in the world to permit the continued use of gasoline and other petroleum derived fuels for many decades. However, since the majority of the low cost petroleum resources are in the Persian Gulf area, it is usually assumed that the low cost non Persian Gulf oil resources will be depleted first. The nations in the Persian Gulf (Organization of Petroleum Exporting Countries or its successors) will then have the ability to reduce production to raise prices [39,72].

In the late 1980's the industry believed that environmental regulators might be receptive to reducing the stringency of fuel economy standards if this would permit reduced emissions. This approach was side tracked by a combination of the Persian Gulf war, aggressive lobbying by environmental groups, and concern over petroleum's share of the international balance of payments. Some industrial decision makers (automotive and energy) continue to think (hope) that when (if) the government recognizes the societal costs of mandating both high energy and environmental standards, the environmental rules will be modified to practical, achievable levels.

The professional staffs of the regulators appear, however, to believe that the use of new fuels and systems will provide health and other benefits which will offset their higher costs. A review of existing regulations should be prepared to insure that the laws as they exist (or are planned) do not inadvertently inhibit use of improved fuel/propulsion systems. The energy industry will continue to be reluctant to expend significant amounts of money on new fuel systems until they are convinced that new propulsion systems which use such fuels will be economically competitive in the absence of mandates. If there were no regulations the transition to alternative fuels would occur naturally when the economics of the advanced systems become clearly superior to propulsion systems which use petroleum derived fuels. The question is then:

"When will advanced propulsion systems become less costly to the user than gasoline or diesel engines using petroleum derived fuels?"

Estimating the time at which this may occur will require an understanding of the life cycle costs of the advanced propulsion systems relative to existing gasoline and diesel engines. A study of the life cycle costs should address the original cost of the propulsion systems, the cost of fuel, and the entire system operating costs. The engine-fuel combinations of interest in this paper include those described in the previous section:

- **Spark Ignition.** Using reformulated gasoline, methanol, ethanol, propane, or hydrogen
- **Diesel Engines.** Using conventional and low sulfur diesel fuel
- **Gas Turbines.** Using tailored ground vehicle fuels, aircraft jet fuels, and diesel or spark ignition engine fuels
- **Stirling Engines.** Using tailored fuels, diesel, or spark ignition engine fuels
- **Phosphoric Acid Fuel Cell Systems.** Using methanol, natural gas, hydrogen, "hydrogen carriers" or possibly reformed gasoline from advanced fuel processors
- **Polymer or Proton-Exchange-Membrane Fuel Cell Systems.** Using methanol, natural gas, hydrogen, "hydrogen carriers", or possibly reformed gasoline from advanced fuel processors
- **Solid Oxide Fuel Cell Systems.** Using methanol, ethanol, natural gas, or a wide range of hydrocarbons

- **Alkaline Fuel Cell Systems.** Using pure hydrogen and oxygen or CO, CO₂ scrubbed reformat and air.

The questions to be addressed in selection of appropriate fuel supply systems for advanced power plants include the following.

- How tolerant are the various engines to fuel characteristics such as octane, cetane, vapor pressure, variation of other fuel characteristics, etc.?
- What capability exists to produce suitable fuels, including refining, processing capacity, and distribution?
- What resources can be used to provide suitable fuels such as fossil fuels or renewable fuels, etc.? How long will they last and at what cost?
- What will it cost (resources, time, money) to create the capability to provide new fuels with new characteristics suited to advanced power systems?
- What modifications will be required to existing fuel distribution systems?
- What modifications will be required to existing retail sales systems?

The energy conversion reaction in most fuel cells is the combination of hydrogen and oxygen to create water. The questions to be addressed in selecting an appropriate fuel supply for fuel cells include those stated below.

- What is the most effective way of storing and transporting the required energy, as a liquid or gas, or as a chemical, such as methanol?
- What is the cost and availability of the fuel?

The majority of low cost petroleum resources are in the Persian Gulf area, a fact which gives the Organization of Petroleum Exporting Countries (OPEC) nations a chance to manipulate oil prices (through control of production) to their benefit. The price of petroleum products will increase as the low cost non-Persian Gulf oil resources are depleted. World oil prices should not rise exponentially after 2000 (as some forecasts predict) if the facilities to produce alternative fuels such as methanol, etc., are planned sufficiently in advance of the time at which the alternative fuel will cost the same to the consumers, in terms of dollars per mile driven [90]. Continuing research by the energy companies, government, and university laboratories must lead to the development of other useful, lower cost, or less environmentally damaging energy delivery systems.

Any of the advanced propulsion systems (and their compatible fuels) could become the dominant propulsion system in the U.S. (and other nations) depending on: its ability to meet energy and environmental goals, its cost, the ability of the energy companies to rapidly develop adequate fuel production capacity, and the ability of vehicle manufacturers to create and sell the product(s).

The change to entirely new kinds of fuels, such as methanol and hydrogen, will use little of the nation's existing production and refining capability. Each of the existing and projected "new fuels" cost, availability, and infrastructure is discussed in detail in the following sections.

6.1 GASOLINE

Both the automotive and energy industries are interested in the continued use of gasoline as the primary vehicle fuel. This will probable require changes in the fuel and advancements to engine systems to achieve the mandated reductions in emissions. The environmental objectives can, in theory, be achieved by modifications of the fuel (reformulated gasoline), by modifications of the engine, or, more likely, by a combination of both.

In 1990 the U.S. consumed approximately 17,000,000 barrels of crude oil per day out of a world consumption of about 55,000,000 barrels per day. Those U.S. petroleum reserves which can be processed at competitive costs are expected to be adequate for 27 years (95% probability) to 32 years (5% probability) at the present production rate. New discoveries and recovery technologies are expected to increase U.S. production capability to 30 to 40 years [3,90]. Depending on the success in locating new, economical resources, U.S. oil production can be expected to drop from 10 million barrels per day in the late 1980's to 8 to 9 million barrels per day by 1995, 4 to 9 million barrels by 2000, and 2 to 8 million barrels per day by 2010 [4,61,81,82]. The proven and projected reserves and years of production (at the present consumption rate) for several regions are presented in Table VI-1.

<u>Region</u>	Billion Barrels of Oil/Years Production [1]			
	Proven Reserves	Projected Additional Reserves (Probability)	New Technologies	Total Life [1]
U.S.	48/16 yr.	33/11 yr. (95%) 48/16 yr. (5%)	14/5 yr. (95%) 27/9 yr. (5%)	32 yr. (95%) 41 yr. (5%)
North America (Including U.S.)	83/19 yr.	67/15 yr. (95%) 121/27 yr. (5%)	--- 330/73 yr. (5%)	34 yr. (95%) 119 yr. (5%)
Middle East (91% OPEC)	585/114 yr.	66/13 yr. (95%) 122/24 yr. (5%)	--- 2 to 3 times (5%) ^[2]	127 yr. (95%) 138++ yr. (5%)
World Total	922/43 yr.	275/13 yr. (95%) 547/25 yr. (5%)	--- 371/17 yr. (5%)	56 yr. (95%) 85 yr. (5%)

[1] Years production at present production rate

[2] Not included in total estimates

OPEC has 80% of the proved capacity; it is estimated to have 25% of the projected reserves at 95% probability and 53% at 5% probability. Source: C. Masters, D. Root, & E. Attanasi, July, 1991 [116]

Table VI-1. Expected Life of Oil Resources, Millions of Barrels of Oil

The life projection presented in Table VI-1 were based on present rates of production; these rates are not expected to remain constant. For example, the existing and planned production capacity for gasoline fuels is summarized in Table VI-2 [116].

The uncertainty in the demand for petroleum derived fuels after 1995, combined with strict environmental standards that may inhibit new refinery construction (and make some older

refineries uneconomic to operate), makes the prediction of future U.S. refinery capacity difficult to ascertain with any degree of confidence. For economic and environmental reasons the majority of new petroleum production and refinery capacity may be constructed overseas.

	<u>1985</u>	<u>1990</u>	<u>1997</u>	<u>2000</u>	
Domestic U.S.	17.5	18	?	?	million barrels per day
Middle East	4	5	?	?	million barrels per day
World Total	72	74	?	?	million barrels per day [112]

Table VI-2. Refinery Production Capacity

The capacity to produce refined petroleum products is expected to remain relatively constant during the time period of interest as described within this report. The requirement for increased gasoline production capacity will be partially offset by increases in the use of methanol, ethanol, and ether derivatives, in particular MTBE (Methyl Tertiary Butyl Ether), as octane enhancers for use in Clean Gasoline programs. MTBE is significantly less corrosive than methanol and has superior cold starting characteristics, etc. Cost breakthroughs in the production of MTBE could significantly change the composition of both M-85 and reformulated gasoline.

6.1.1 Future Cost of Gasoline

In 1990 gasoline prices varied from \$1.10 to \$1.45 depending on the octane rating, region of the United States, and various state and local taxes. The cost of crude oil landed in the United States ranged from \$18.00 to \$23.00 per barrel during 1991. Current dollar prices in 1993 were as low as \$14.00 barrel. Many energy price forecasts call for crude oil prices to reach \$30.00 per barrel some time between the year 2000 and 2010 and to increase at a rate of 1 to 2% per year in subsequent years. This is unlikely to continue because the price of crude oil (and thus gasoline) are bounded by two considerations:

- The lower long run bound is set by the cost of discovery and production of crude oil outside of the Persian Gulf area
- The upper long run bound is based on the maximum revenue which can be generated by the oil producing nations (OPEC).

The lower long run price bound (cost of discovery and production) is generally understood to be approximately \$5.00 to \$7.00 per barrel (1988\$). There is evidence that the high price of crude oil will peak at that price which generates the maximum revenue for Saudi Arabia, approximately \$30.00 to \$35.00 per barrel (1992\$). If prices were to rise above the "long run bound" the substitution of alternative fuels and conservation efforts would decrease petroleum consumption faster than revenues of the oil producers increase with price. One of the major incentives for the oil producing nations (OPEC) to increase production is to inhibit the development of alternative fuels.

Oil prices will probably become more variable in the future (like other commodities). Prices could rise above and fall below these bounds temporarily (such as over a year). When prices are at or below the lower long run bound there will be little further exploration. There will be upward price pressure as the low cost resources are exhausted. When prices are at or above the upper bound there should be additional exploration and reopening of "shut in" wells to increase the supply, thus reducing costs [39].

The upper price bound should produce an average retail gasoline price between \$1.30 and \$1.50 per gallon by 2008 (1988\$) assuming present taxes are not increased. If oil prices are near or at the lower bound, the retail price of gasoline could be as low as \$0.75 per gallon, not including any increases in taxes. State and federal taxes, in combination, could increase gasoline retail prices (unleaded self service) from \$0.80 to \$1.75 per gallon by 1997 and further increase them to \$1.00 to \$1.95 per gallon by 2008 [19].

The price of regular (self service) unleaded gasoline, as determined by leaders of the automobile companies and major suppliers for the Delphi 7 study of the University of Michigan Center for the Study of Automotive transportation, was estimated to be \$1.75 per gallon in 2003 (premium would be \$2.00). The uncertainty of future oil prices is emphasized by a recent Energy Modeling Forum study on international oil supplies and demands (1991) in which a number of energy economists estimated the clearing price of petroleum. This study is summarized in Table VI-3 and also includes forecasts from the Gas Research Institute, Data Resources Inc., and the U.S. Department of Energy [61].

Year	GRI	EIA	ICE	CERI	FRE	PRNBU	DRI	NEP-89	Low	High
1985	----	----	----	----	----	----	----	29.44		
1990	18.33	----	----	----	----	----	22.93	----	18.5	23.0
1995	19.74	19.75	19.00	19.75	32.50	41.00	20.41	21.23	19.0	41.0
2000	22.30	30.00	20.50	24.50	40.00	40.00	23.70	26.89	20.5	40.0
2005	27.80	45.00	----	28.00	45.00	59.00	28.29	45.16	28.5	59.0
2010	34.60	50.00	----	31.50	49.00	70.00	31.38	48.74	31.5	70.0
2015	To be developed									
2020	To be developed									

FROM ENERGY MODELING FORUM REPORT [62,65]

EIA-Energy Information Administration, (M. Rodekoher)

ICE-Massachusetts Institute of Technology, (N. Choucri)

CERI-Canadian Research Institute, (A. Reinsch)

FRB-Federal Reserve Bank of Dallas, (S. Brown)

PRNBU-University of Pennsylvania, (S. Pauly, etc.)

OTHER SOURCES

GRI-Gas Research Institute Report, April, 1991 (T. Woods)

DRI-DRI/McGraw Hill, Energy Review, Second quarter, 1992

NEP-89-National Energy Policy Plan Projections, U.S. Department of Energy, Unpublished, 1989

Table VI-3. Projected Crude Oil Prices, 1990 Dollars per Barrel

6.2 REFORMULATED GASOLINE

The perception that gasoline is a simple chemical with some additives to vary its characteristics, on a seasonal basis, is an oversimplification. Actually, gasoline is a complex mixture of different hydrocarbons (and additives). The variability of its properties is illustrated by a recent sampling of retail gasoline stations by the Motor Vehicle Manufacturer's Association; the results of their sampling are summarized in Table VI-4.

Specific gravity (weight per gallon)-----	varied more than 10%
The hydrogen/oxygen ratio-----	varied nearly 30%
Reid vapor pressure in winter-----	varied from 9.0 to 16.6 psi.
Reid vapor pressure in summer-----	varied from 7.5 to 12.5 psi.
The percent aromatic-----	varied from 12% to 54%
The percent olefin-----	varied from 1% to 20%

Table VI-4. Typical Gasoline Composition Variation

The recognition that reducing some of the components of gasoline and producing more consistent formulations would reduce pollution led to the formation of joint Automobile Company/Oil Company Air Quality Improvement Programs to develop reformulated gasoline. This effort is still continuing; some of the results are now reaching the market in the form of "environmentally benign" fuels. The approval of reformulated fuels will make it possible to partially reduce some emissions without major investments in new processes and distribution systems which would be required in a transition to alternative fuels.

The parameters which will be reduced, or more tightly controlled, in reformulated gasoline include: the aromatic content (<20%), the olefin content (<5%), and T-90 (the temperature at which 90% of the gasoline has boiled off) to <280°F. Some elements such as benzene will be eliminated [7,8,9].

The modification of refineries to produce even reformulated gasoline fuels has been costly. The prices of cleaner versions of gasoline and diesel fuels will undoubtedly increase. Recent estimates of the incremental cost of reformulated gasoline, by the Auto/Oil Air Quality Improvement Research Program, range from 4 to 17 cents per gallon. Other estimates are as high as 25 cents per gallon. Part of the cost uncertainty is the market uncertainty regarding the "usefulness of the remainder of the barrel" which is not used for gasoline or other vehicle fuels. Energy companies are concerned that they will be faced with a sequential series of even tighter fuel (gasoline) specifications, i.e., reformulated gasoline II, III, etc., each of which will require costly facility changes. If so, the energy companies need time to amortize their investments in reformulated gasoline I, and to modify or construct new processing facilities.

The economics of reformulated gasoline would appear to be superior to other alternatives (per unit emission reduction) because it can use the distribution system which is in place. The energy companies can make use of much of their existing capital investments (in refineries, etc.) [45].

Factors influencing the acceptability of reformulated gasoline include the following.

- The purchase price difference of a vehicle using reformulated gasoline compared to a standard gasoline powered vehicle should not be a significant decision factor.
- The cost of reformulated gasoline should be only \$0.10 to \$0.20 higher than for conventional low lead regular. This translates into an increased annual cost per car of \$50 to \$75.

- Insurance on cars using reformulated gasoline and fuel supply systems should be little different than present gasoline vehicle insurance costs.
- The usefulness of cars using reformulated gasoline should be unchanged compared to present vehicles.
- The reliability of vehicles using reformulated gasoline should be similar to current vehicles. The difficulty in predicting the life of the emission equipment could make this an important question for the first buyers, but, by the year 2000 problems should be fully resolved.
- The resale value of vehicles using reformulated gasoline should be similar to current vehicles; this will depend on the public's perception of life and reliability.

6.3 DIESEL FUEL AND MIDDLE DISTILLATES

The availability and composition of diesel fuel will be regulated by the same factors that pertain to gasoline. Diesel fuel can be purchased by fleet operators, under contract, at about \$0.40 per gallon. The average retail price of diesel was \$0.99 in 1992. Low sulfur diesel fuel will cost up to \$0.25 per gallon more than current prices.

The potential development of multi-fuel partial oxidation type reformers may provide the basis for a major change in the availability and cost of transportation fuels. Ideally, the reformer would be able to determine what the fuel is, how to reset the reformer to produce hydrogen with the least energy loss, and deliver the hydrogen to fuel cells. It is theoretically possible to develop reformers which could process any liquid hydrocarbon fuel including: methanol, ethanol, middle distillates, gas oil, etc. This could provide major savings in terms of the percentage of a barrel of oil which can be used since there will be less need for precise control of fuel composition to achieve octane or cetane ratings, etc. It may be possible that the least costly (and least polluting) near term fuel under such a scenario would be a middle distillate; it could then be replaced by biomass derived, or other sustainable, fuels when they become economically competitive. However, it must be reemphasized that while "theoretically possible" to develop, no middle distillate (much less flexible fuel) compact reformer has, as yet, been successfully demonstrated.

6.4 METHANOL

Since methanol is a liquid it can replace gasoline in most private car and commercial vehicle applications. Problems involving methanol usage include starting difficulties at low temperatures and a lower energy content (approximately half that of gasoline) which limits vehicle range if larger fuel tanks are not provided. These problems apply to conventional heat engine powered vehicles; the increased efficiency of a fuel cell engine system offsets range limitations. There are, at present, two views on the use of methanol in piston engines:

- The environmental benefits of methanol are thought to be significant
- In the long run the increasing cost of crude oil will probably require the transition to methanol (or some other alternative fuel).

The use of methanol instead of gasoline in private cars is expected to occur in one or both of two stages:

- First, by mandates which require efficiency or environmental performance levels which can be achieved only with methanol (or similar alternative fuels)
- Second, by economics when the long-term cost of petroleum derived fuel (gasoline) exceeds that of methanol made from natural gas.

Most environmental studies assume that retail methanol for automobiles will contain about 15% gasoline and other additives (M-85). The environmental benefits are expected to increase as the use of methanol increases. However, some studies indicate that most of the environmental benefits can be achieved at about M-50 [94]. Recent tests also indicate that emission benefits derived from the use of methanol may be negligible in conventionally powered cars equipped with the most recent electronic fuel controls and direct injection.

Methanol's most important physical characteristics, and its comparison to gasoline, are summarized in Table VI-5. The higher octane rating of methanol will permit the design of engines (dedicated to methanol) to have higher compression ratios; consequently, power and efficiency should be increased.

Lower Heating Value, Btu/lb.	8,600.	46% of Gasoline
Lower Heating Value, Btu/gallon	57,000.	49% of Gasoline
Vapor Pressure, psi. (100°F)	4.6	5% to 51% of Gasoline
Octane Number Research	112	112% to 132% of Gasoline
Motor	91	99% to 111% of Gasoline
Heat of Vaporization (Btu/gal)	500	290% of Gasoline

Table VI-5. Physical Characteristics of Methanol

It has been suggested that because of the higher performance of methanol engines there could be a significant weight reduction (smaller engine) with a methanol fueled car. This benefit is limited by the fact that the payload (passengers and cargo) is one of the dominant portions of the weight of a modern passenger car.

<u>Component</u>	<u>Gasoline Car</u>	<u>Methanol Car</u>	<u>Percent, Methanol Car Compared to Gasoline Car</u>
Engine and drive train	759 lb.	650 lb.	86%
Body and suspension	1750 lb.	1675 lb.	96%
Fuel including tank	120 lb.	185 lb.	154%
Passengers (4)	600 lb.	600 lb.	same
Weight Empty	2515 lb.	2325 lb.	92%
Weight with Fuel	2610 lb.	2485 lb.	95%
Weight Fully Loaded	3210 lb.	3085 lb.	96%

Table VI-6. Illustration of Potential Weight Saving with Dedicated Methanol Engines

Table VI-6 above, adapted from a recent report [70], illustrates the potential weight savings for a small car that could provide the gasoline equivalent of 27.5 mpg fuel economy and a range of about 400 miles between refueling. These weights do not represent any specific car. Major changes in any design element will not significantly change the conclusions. The indicated weight reduction in the engine and drive train would be difficult to achieve in production [20,21].

The creation of a methanol fuel distribution system which can serve the entire U.S. would require several decades. Energy companies have questioned the economics and technical viability of a significant increase in the use of methanol. They are unwilling to commit the significant investments required to build the processing, distribution, and retail facilities until they are convinced that there is a viable, sustainable market. One major oil company has indicated that it does not intend to open any additional retail outlets for methanol [68,69,70].

There is also increasing evidence that the benefits of methanol in recent cars (with computer fuel controls and fuel injection) are minor. Unfortunately, the mandates or regulations which directly or indirectly require the use of methanol are not likely to be reversed with experience.

The technical risks (fuel storage and supply) which must be resolved include the compatibility of methanol with the fuel systems at service stations and those on-board the vehicle. On-board vehicle storage of methanol should not be a significant problem as it has been successfully accomplished in many test and pre-production vehicles. The material selections must be carefully made as methanol is highly corrosive.

6.4.1 Methanol Production Capacity

Methanol production capacity has increased at the rate of 6% per year since 1983. Most of the new capacity is being used to produce MTBE. This rate of growth is expected to decrease to 4% per year in the 1990's. Future growth will be constrained by the availability of isobutylene which is also used in making MTBD. In a 1989 paper Carmen DiFiglio (U.S. DoE) estimated that it would require nearly 15 to 20 years (until 2005 to 2009) for the world methanol production capacity to reach between 7 to 26 million barrels per day, equivalent to 3.5 to 13 million barrels per day of petroleum. The time and capacity difference estimates depend on the levels of national priority and government interest to provide some offset of the economic risks the energy companies would have to assume to build new methanol production facilities [106].

The existing and planned production capacity for methanol is presented in Table VI-7.

Country	Year						
	1992	1994	1996	1998	2000	2015	2030
Domestic U.S.	107.8	120.9	159.5	159.5	159.5	?	?
Canada	46.5	52.0	52.0	52.0	67.9	?	?
Mexico	3.7	3.7	21.6	21.6	21.6	?	?
World Total	544.4	635.4	726.6	731.6	790.7	?	?

Table VI-7. Methanol Production Capacity, Thousands of Barrels per Day

There is some concern about the ability of the industry to even produce methanol in adequate quantities for California. Chevron estimated the cost of new methanol from natural gas facilities to meet California's needs (alone) at 25 to 70 billion dollars (1990\$) [47]. If there are only 1 million methanol cars in use it would require about 15% of the existing world methanol capacity (about equal to that which was shut down in 1991). Higher rates of consumption can be expected if additional states elect to meet the proposed objectives of the California Air Resources Board.

The resulting demand could require the construction of more methanol facilities than are now scheduled. Previous studies have indicated that, if a national priority was established, adequate capacity to meet the total anticipated U.S. demands for all light vehicles could be constructed in less than ten years. This would require rapid regulatory and financial approvals and support from both the automotive and energy companies. For economic reasons it is anticipated that the majority of new methanol capacity will be constructed overseas in the Persian Gulf, or in areas where there is little domestic demand for natural gas for heating or electrical power generation [68,104].

6.4.2 Methanol Distribution Capability

Methanol is presently being distributed to those retail dealers taking part in methanol fuel demonstrations using tank trucks and tank cars in a manner similar to gasoline and diesel fuel. Considerable attention has been given to the problem of using existing intercity pipelines and distribution systems for the large quantities of methanol which would be required to meet California and other national requirements.

Problems will undoubtedly be encountered during the transition to methanol. Extreme care would be required to avoid water dilution and other contaminants. This would involve cleaning, or replacing, much of the present fuel distribution infrastructure and (at first) movement of small, uneconomic methanol lots. Since methanol has approximately 1/2 the energy capacity of gasoline, pipe lines and storage areas will have to be increased in size; other provisions (primarily to avoid contamination with water) will also be required. Resizing of pipe lines and storage areas could be avoided only if fuel cell engine powered vehicles become readily available.

Some tests by oil companies appear to confirm that existing oil pipelines could be used, but other oil companies question the feasibility of lining pipes or their ability to sell methanol at a profit due to overall cost and questionable benefits. Additional studies will be required to determine the cost (estimated at several billion dollars) and payment strategy to undertake the transition from gasoline to methanol. However, by 2008 most of the technical distribution problems should be understood and systems or materials developed to avoid them. The cost of methanol distribution should then be only slightly greater than that of gasoline on a volume basis and, thus, not a major factor in the price to the consumer.

6.4.3 Retail Methanol Capacity

The only existing retail stations in the U.S. selling methanol (M-85) are those which have been opened in California (51 as of January, 1992) primarily in support of the California Alternative Energy program. None of these would be justified on an economic basis as the demand is below that justified for the installation of tanks and pumps. The introduction of cars or propulsion systems which can only use methanol will require the development of retail

networks. In critical non-compliance areas (such as Los Angeles) methanol could be available from retail stations such as those described above. In other areas of the country, where there will be only a limited initial demand for the fuel, selected stations may have methanol available in package or drums, etc. Modern versions of the gravity feed systems like those which were developed for early (1920's) gas stations may even be feasible. These could be low cost, reliable, and suitable for stations which serve only a few car per day.

6.4.4 Methanol Costs and Safety

Today, methanol can be purchased under contract, in large quantities, for about \$0.40 per gallon. Information provided by major chemical engineering companies indicates that methanol could be produced in world scale plants at a cost of 28 to 30 cents per gallon, not including profits, taxes, or transportation. A representative of Ocelot, a chemical company, stated that it could sell methanol at 31.78 cents per gallon landed in California and earn a 10% return on investment [69].

A 1985 study of the profitability of methanol as a heat engine powered vehicle fuel assumed that: 1.7 gallons of methanol would provide the same range as 1 gallon of gasoline, that distribution costs would be the same per gallon as gasoline, and that taxes would be on a btu basis. The price to the consumer of neat (100% pure) methanol or methanol additive fuels includes distribution costs, retail costs, taxes (and relative tax expenditures), and profits. These estimates were based on an assumed facility cost of \$10,000 per barrel per day and an operating cost of \$0.08 per gallon; \$0.31 per barrel was assumed for distribution and profit, and \$0.90 per barrel for tax. On an equivalent energy (per mile traveled) basis this results in a cost equivalent of \$1.16 per gallon for gasoline (assuming \$1.40 per trillion cubic feet (tcf) of natural gas, the feed stock for the methanol production). The capital costs were based on the 10th facility. The results of these studies are summarized in Table VI-8.

Equivalent Retail Gasoline Price per Gal.	Annual Return on Investment						
	\$1.00	\$1.10	\$1.20	\$1.30	\$1.40	\$1.50	\$1.60
Natural Gas Price							
\$1.00/MMbtu	10%	15%	20%	25%	---	---	---
\$1.50/MMbtu	7%	12%	17%	22%	27%	---	---
\$2.00/MMbtu	3%	8%	13%	18%	23%	28%	---
\$2.50/MMbtu	---	5%	10%	15%	20%	25%	30%
\$3.00/MMbtu	---	2%	7%	12%	17%	22%	27%
\$3.50/MMbtu	---	---	3%	9%	14%	18%	23%
\$4.00/MMbtu	---	---	---	5%	10%	15%	20%

Table VI-8. Estimated Profitability of Methanol Production as a Function of Natural Gas Costs, Annual Return On Investment

On this basis methanol should be economically competitive with gasoline when the retail price of gasoline reaches and stays at or above \$1.50 per gallon, even if the cost of the natural gas feedstock increases. This price would provide a 15% to 20% return on investment [104]. Using the same basic economics and cost approach, methanol, made from coal in quantities that provide the same distance traveled as a gallon of gasoline, was estimated to have a gasoline equivalent cost of \$1.21 per gallon.

Many people have expressed safety concerns over the use of methanol because of its reputation as a poison and the serious injuries (and deaths) from episodes when it was mistaken for ethyl alcohol and internally consumed. This same scenario might be encountered when siphoning what one believes is "gasoline". This risk can be minimized by adding a bad tasting additive to methanol. Even if one were to ingest a dangerous quantity of methanol there are effective, simple procedures for eliminating it from a person's body before the eyes experience irreplaceable damage. Users, station proprietors, and others should be well versed on these procedures. Concerns over repeated exposure need further assessment; there can be significant hazards to humans in large spills. But, the data provided by a chemical company (DuPont) indicate that lifetime exposures, below a maximum equivalent to a few ounces per day for a normal weight man, is probably not life threatening. Some authorities believe that methanol is actually less toxic than gasoline. This is uncertain because there is better toxicity data on methanol than on gasoline.

Methanol is a biodegradable volatile and not toxic to most primitive life forms, although large spills could still be a problem. One government energy researcher, however, estimated that if the Exxon Valdez had been filled with methanol instead of crude oil when its hull ruptured in Alaska waters, at most only a few fish and mammals would have been killed. Further, there would have been virtually no long term effects to the fish runs, mammals, or beaches.

The cost to produce cars which can use methanol will decrease significantly with increasing volumes of production. If by 2001 the production level for standard four door methanol fueled family sedans approaches a million cars per year it is reasonable to expect that incremental costs will be below the decision threshold of the average new car buyer. That is, less than a 5% difference in cost will exist between a methanol fueled car and an equivalent performance gasoline fueled car.

Cheslow's paper [35] indicated that people, at least during one period of time, would pay from \$900 to \$1,600 for a 50 mile increase in range. However, this "willingness to pay" estimate probably does not work in reverse (reduction in range), but assuming that it does and that the same size fuel tank in a car that has a 300 mile range on gasoline is retained for methanol usage, the car would have about a 175 mile range on methanol. On this basis the methanol fueled car should be priced \$2,000 to \$2,500 less than the gasoline car to attain the same market penetration. Obviously, it appears preferably to have a larger fuel tank. While the forecasts of the incremental cost of cars which use methanol are debatable, the conclusion that acceptable methanol fueled cars should have larger fuel tanks is supportable. The tanks will be larger and probably heavier, thus methanol fueled cars may have to be slightly larger to provide the same interior and luggage space [70].

Cars designed for California and other states, which propose the use of methanol to meet air quality requirements, may be of limited use in the remainder of the United States if drivers have difficulty getting fuels with the octane rating for which they are designed. This could reduce the

value of the cars to the owner and, in particular, the price of used cars. The traditional transfer of used cars from eastern states to California could be significantly reduced or eliminated.

6.4.5 Factors Influencing the Acceptability of Methanol as an Automobile Fuel

The major factors which might influence the willingness of a car buyer to purchase and use a methanol fueled vehicle are presented below:

- The **vehicle purchase price** difference between a methanol fueled and standard gasoline powered sedan should not to be a significant decision factor when volume production of the methanol fueled cars is in place. The price a purchaser will be asked to pay will depend on the pricing philosophy that the company will elect and the need for fuel economy credits. If the sale of additional alternative fuel vehicles is required to comply with government regulations the cars could be sold at a low profit (potentially even a loss) since this may permit the sale of more expensive, conventional vehicles. The cost of the air quality equipment will probably be somewhat lower than that required to achieve the same standards (LEV) with gasoline.
- By the second decade of the 21st century **retail methanol and associated expendable material prices** could be similar to those of gasoline on a cost per mile basis. This would represent the start of a period of possibly several decades in which the price of the two fuels would be competitive on a cost per mile basis.
- While the lack of a visual flame can be a safety problem it can be resolved by use of additives. This should reduce or eliminate any **insurance bias against methanol**. Retail service stations may find their insurance premiums lowered because of the reduced risk of contamination to ground water and lower life forms from spillage and tank leakage.
- **Performance (range) limitations** should not be significant if the on-board fuel tank is large enough and there are a sufficient number of service stations to provide access to methanol fuel. The use of the vehicles cannot be limited by lack of access to fuel. Cold starting problems should be resolved before methanol fueled cars are released for public sale.
- The difficulty in predicting the life of methanol engines could make **reliability** an important question for the first buyers, but, by the year 2000 such problems should be fully resolved.
- **Resale value** will depend on the public perception of vehicle life and reliability and the availability of service stations.

Estimates of the total sale of cars which are dedicated to operating on methanol will be discussed in more detail in Section VII.

6.5 ETHANOL

Ethanol is an attractive conventional engine powered vehicle fuel. It can be made from many feed stocks, including natural gas, but the majority of the ethanol produced in the United States is made from corn products. In Brazil ethanol is made from sugar cane. If all available U.S. corn crop land were used to produce ethanol from corn the annual production could exceed 10 billion gallons or, energy wise, only approximately 10% of the gasoline required in the United States.

Today, the cost of ethanol produced from corn in the U.S. is about \$1.28 per gallon. Research has demonstrated that ethanol from wood could be produced at \$1.35 per gallon. If future research activities are successful it may be possible to reduce the costs of ethanol from biomass to about \$0.60 per gallon. At this price ethanol would be cost competitive with gasoline.

Ethanol's most important characteristics and its comparison to gasoline are summarized in Table VI-9.

Lower Heating Value, Btu/lb	11,600	62% of Gasoline
Lower Heating Value, Btu/gallon	76,000	65% of Gasoline
Vapor Pressure, psi. (100°F)	4.6	35%-51% of Gasoline
Octane Number		
Research	111	111%-122% of Gasoline
Motor	92	100%-112% of Gasoline
Heat of Vaporization (Btu/gallon)	90	230% of Gasoline

Table VI-9. Physical Characteristics of Ethanol

The increased use of ethanol in private cars has come about because of economic incentives, including tax credits, which encourage the use of ethanol/gasohol as a replacement for tetraethyl lead in gasoline; ethanol is one of the lowest cost octane improvers to replace tetraethyl lead.

Recent planned increases in ethanol capacity (from agricultural products) have largely been based on both the need to replace tetraethyl lead in gasoline to improve octane and the economic incentives provided by the tax breaks. There is increasing interest in ETBE (Ethyl Tertiary Butyl Ether) as an additive for use in the Clean Gasoline programs. ETBE has similar energy/weight and octane characteristics to ethanol but is significantly less corrosive.

6.5.1 Distribution Capability and State Incentives

Ethanol can be distributed by the same processes (pipelines, tank cars) as gasoline and diesel fuel. Since ethanol has approximately 3/4 of the energy capacity of gasoline, pipelines and storage areas will have to increase in size; other provisions, such as avoiding water contamination, will also be required. At this time the capacity to distribute ethanol does not appear to be a restriction to its use in either the U.S. or Canada. Ethanol is not available as neat alcohol (E-100) or E-85 in the United States although equivalent fuels are being used in Brazil.

The tax incentives which have been responsible for the increased use of ethanol as a motor fuel include:

- The economic incentives, including the tax credits provided for the use of ethanol (gasohol), as a replacement for tetraethyl lead in gasoline
- The state and local mandates which require efficiency or environmental performance levels which can be achieved only with ethanol (or similar alternative fuels).

The mandates may be augmented by taxes and other economic incentives to encourage the purchase of ethanol fueled vehicles. The existing state incentives are summarized in Table VI-10.

Oxygenated Fuels	Ethanol Incentives	
Alaska	Alaska	Minnesota
California	Hawaii	Iowa
Nevada	Idaho	Missouri
Utah	Montana	Ohio
Arizona	Wyoming	Virginia
Colorado	North Dakota	South Carolina
Nebraska	South Dakota	Delaware

Table VI-10. States with Alternative Fuel Mandates or Incentives

The basic characteristics of ethanol as a fuel and the potential reactions of vehicle owners are similar to those with methanol, with two exceptions. First, the energy density of ethanol is midway between methanol and gasoline. Second, there is concern that the subsidies on ethanol (equivalent to more than \$0.50 per gallon of ethanol), which now make grain produced ethanol competitive with gasoline may be lifted in the future.

6.5.2 Factors Influencing the Acceptability of Ethanol as an Automobile Fuel

- The ***purchase price difference*** between an ethanol fueled and standard gasoline powered sedan should not be a significant decision factor when volume production of ethanol fueled cars is in place.
- The ***cost of ethanol and other expendable materials*** would be much higher except for federal subsidies. If these are eliminated it is likely that the use of ethanol would rapidly decrease.
- ***Insurance costs*** for ethanol fueled vehicles and ethanol fuel supply systems should be little different than for present gasoline fueled vehicles and gasoline supply systems.
- Ethanol fueled vehicles should experience no ***useful limitations***; performance should be similar to present gasoline fueled cars except for a reduction of about 1/3 in range because of the lower energy content. This could be alleviated through the use of a larger fuel tank.
- The difficulty in predicting the ***life and reliability*** of the emission equipment could make this an important question for the first buyers, but, by the year 2000 the problems should be fully resolved.
- ***Resale value*** will depend on the public's perception of vehicle life and reliability.

6.6 NATURAL GAS

Natural gas is considered to be a desirable alternative fuel because of its anticipated environmental benefits and low operating and maintenance cost. Its relatively current limited

use in vehicles is due to the low density of natural gas storage systems which limit the vehicle's range. Natural gas can be attractive as a fuel for commercial vehicles which accumulate only 30 to 100 miles per day. Only 30 to 40 thousand CNG vehicles (mostly light commercial trucks) are in operation in the United States.

Information provided by natural gas advocates implies that there can be a 73% reduction in hydrocarbon and a 90% reduction in carbon monoxide emissions but only nominal reductions (possibly an increase) in NO_x emissions. Since methane is less reactive (as a pollutant) than other hydrocarbons, the amount of unburned methane which can be allowed is higher than that for other unburned hydrocarbons [48]. At least this is so if greenhouse gas effects are discounted.

There are two different approaches to the use and storage of natural gas on-board vehicles: the first is compressed (CNG) in which the gas is stored in pressurized tanks, and the second is liquefied natural gas (LNG) in which the natural gas is cooled to the temperature at which it liquefies (below -260°F) so that it can be stored in insulated tanks. The primary physical properties of natural gas and its comparison to gasoline are summarized in Table VI-11 below [59].

Lower Heating Value, Btu/lb.		21,300	114% of gasoline*
Lower Heating Value, Btu/gallon	LNG	74,500	64% of gasoline*
	CNG	25,609	22% of gasoline*
Vapor Pressure, psi. (100°F)		N/A	(gasoline, 91 psi.-100 psi.)
Octane Number,	Research	120	120%-132% of gasoline*
Boiling Range		-259°F	(gasoline, 90°F-400°F)

* Not including tank weight or volume

Table VI-11. Natural Gas Characteristics

Most U.S. natural gas is used for heating or energy (electric) generation (97%), approximately 3% for petrochemical processing, and a negligible amount directly for transportation. An increasing quantity of natural gas is being used to make methanol which in turn is processed into MTBE and used as an octane improver; MTBE may become a major element in reformulated gasoline.

The higher octane rating and lower emissions of natural gas give it several potential advantages over gasoline. The primary constituent of natural gas is methane although other materials (butane, hydrogen, etc.) can also be present. It has been reported that some pipeline "natural gas" distributed in metropolitan areas also contains carbon dioxide to maintain similar Btu/cu-ft levels when large amounts of hydrogen are present.

Demonstrations of natural gas fueled vehicles in California and Colorado have encountered fuel metering (and probably emission level) problems due to the variability of the energy content of the gas available. Better control of the gas composition may be required if the full environmental benefits of natural gas are to be achieved.

Conversions of conventional cars include either the addition of a compressed natural gas (or liquefied natural gas) tank and supply system to deliver the fuel to the engine. On-board vehicle storage has not been found to be a major problem. However, due to the low energy density (even with high pressure tanks) the car may only have gas storage capacity equivalent to three or four gallons of gasoline. The size of the compressed natural gas tank usually limits the range of CNG vehicles to 100-150 miles. Converted engines operating on compressed natural gas usually lose some peak power, variously estimated as 10% to 15%, due to intake air displacement.

The cost of air quality control equipment for natural gas propelled vehicles will depend on the emission requirements. Preparing estimates of these costs is complicated by the lack of useful data on the emissions from unregulated natural gas car engines and the fact that the available estimates of the cost of air quality equipment are at best preliminary.

Most natural gas conversions to date are "dual fueled" so that they can be switched from natural gas to gasoline or some other fuel on demand; the operator of a dual fuel car is able to switch to the other fuel to travel longer distances. Methanol and/or ethanol are logical "second fuels" for compressed natural gas fueled cars since all of the fuels have similar octane ratings.

6.6.1 Natural Gas Production Capacity

In 1990 approximately 17 trillion cubic feet of natural gas (or 18 quads equivalent energy) were produced in the United States. There has been only limited importation of natural gas into the U.S. (1.4 tcf). The anticipated production capacity for natural gas in trillion cubic feet per year for the U.S., Canada, and Mexico is presented in Table VI-12.

Recent increases in natural gas production capacity in the U.S. have been limited because of existing on-line reserves (natural gas glut) and the cost of deep drilling required to locate economical reserves. Increases in drilling costs will require well head natural gas prices to be similar (per Btu) to crude oil if production capacity is to increase. GRI (Gas Research Institute) projections anticipate between 1.9 and 2.3 trillion cubic feet of natural gas will be imported annually in 1995. The price is expected to range from \$2.28/MMbtu (1988\$) for Norwegian gas in the year 2000 to \$4.56/MMbtu for Algerian gas in the year 2010 [4]. Facilities exist to import natural gas from Algeria, the Caribbean, Nigeria, Norway, or Indonesia. There has been little use of these facilities (all of which are on the east coast of the U.S.) for several years.

<u>Country</u>	<u>Production Capacity, tcf/yr.</u>			
	<u>1989</u>	<u>1995</u>	<u>2000</u>	<u>2010</u>
Domestic U.S., lower 48	16.6	16.2	17.6	18.2
Alaska	0.4	0.3	0.4	1.7
Imports	1.3	2.3	2.8	2.8
Canada	to be determined	to be determined	---	---
Mexico	to be determined	to be determined	---	---
Rest of World	to be determined	to be determined	---	---

Table VI-12. Existing and Anticipated Natural Gas Production in the U.S., Canada, and Mexico

Economic studies indicate that the total distribution cost from resource to vehicle would be less if the natural gas were converted to methanol at the point of origin. It could then be shipped in conventional tankers. The insurance costs would also be lower than for liquefied natural gas shipment [66].

The expanded exploration for oil in the world which followed oil price increases in 1973 and 1970-80 led to a substantial increase in the world's proven petroleum reserves. An accompanying major surprise has been the discovery of unexpected reserves of natural gas, some in the United States, but most overseas. Henry Linden (recently retired head of the Gas Research Institute) has been quoted as estimating that there is ten times more energy in natural gas reserves in the world as there is in known crude oil reserves. Not only were more natural gas reserves discovered than expected, but the resources (while still significant in Russia and the Persian Gulf) are more widely dispersed.

The existing U.S. reserves, at competitive costs, are expected to be adequate for 34 years (95% probability) to 39 years (5% probability) at the present production rate. Additional discoveries are expected to increase the total time that economical supplies of natural gas would be available in the United States to between 50 to 65 years [116]. The proven and projected reserves and years of production (at the present consumption rate) for several regions are presented in Table VI-13.

The use of natural gas propelled vehicles in California would consume only a small portion of the existing U.S. natural gas production. This could be augmented by importing supplies from Canada and Mexico. Studies have indicated that adequate natural gas capacity to serve 25% of the U.S. cars and light truck fleet could be developed in approximately 10 years; this time estimate, of course, depends on the level of national priority assigned.

Trillion Cubic Feet of Natural Gas/Years Production^[1]				
Region	Proven Reserves	Projected Reserves (Probability)	New Technologies	Total Life
U.S.	272/16 yr.	210/18 yr. (95%) 400/23 yr. (5%)	not determined	28 yr. 39 yr.
North America (Including U.S.)	440/21 yr.	580/28 yr. (95%) 930/44 yr. (5%)	not determined	49 yr. 65 yr.
Middle East	1247/441 yr.	1120/396 yr. (95%) 1825/645 yr. (5%)	not determined	837 yr. 1086 yr.
World Total	4040/61 yr.	5200/78 yr. (95%) 8460/128 yr. (5%)	not determined	139 yr. 189 yr.

Notes: [1] Years production at present rate

Source: C. Masters, D. Root, & E. Attanasi, Science, July, 1991

Table VI-13. Expected Life of Natural Gas Resources, Trillion Cubic Feet of Natural Gas

6.6.2 Distribution Capacity

The majority of U.S. households are served by natural gas for heating and cooking. Nearly 95% of the homes in California have access to natural gas. Some concern has been expressed by industry personnel concerning the life expectancy of existing natural gas pipelines and their ability to maintain their integrity. These existing natural gas distribution systems (pipelines) reach a majority of the households and businesses in the area of the nation (cities) where environmental improvements are a major concern. The existing infrastructure can be used if only a relatively small portion of the vehicles in the United States use natural gas. Even then, the development of a natural gas retail distribution system will involve both technical and economic risks which must be resolved before there will be adequate quantities of natural gas available for natural gas fueled vehicles.

6.6.3 Retail Sales Capability

There are a growing number of natural gas stations in the United States (13 in Michigan, 94 in California, 3 in the District of Columbia, and 14 in Virginia as of 9/93). The development of increased gas production and distribution capabilities in the United States will depend on the number of vehicles which are converted to use natural gas as a fuel. Advocates of natural gas believe that it can be distributed at home as well as by the same retail stations which sell gasoline and diesel fuel. Most existing natural gas fleets have their own recharging facilities which cost from \$1,000 to \$1,500 per vehicle for fleets of 35 to 40 vehicles. Cost estimates of a home recharging system range from less than \$1,000 to several thousand dollars depending on the storage capacity and recharging times. There are some serious safety concerns which must be overcome, although the safety record to date has been good.

Some studies by oil companies have questioned the economics of retail stations. Mass production of compressors and other charging equipment could reduce the capital cost of the equipment to the point that retail sales would be economically competitive.

6.6.4 Cost of Natural Gas

Historically the cost of natural gas (in terms of equivalent energy content) has been 10 to 20 % less than for the same energy content in petroleum. Recent studies by the National Petroleum Council estimated that the cost of natural gas will approach that of petroleum (per Btu) in the next decade. The cost of drilling the deep wells required to maintain production make it doubtful that adequate wells could be drilled at current prices.

The existing and anticipated well head costs of natural gas (per tcf) are presented in Table VI-14. Cost data for projections beyond 2015 will be developed in cooperation with responsible industry organizations such as the Gas Research Institute.

<u>Well Head Costs, \$/tcf</u>								
<u>1990</u>	<u>1995</u>	<u>2000</u>	<u>2005</u>	<u>2010</u>	<u>2015</u>	<u>2020</u>	<u>2025</u>	<u>2030</u>
\$1.80	\$1.68	\$3.56	\$3.91	\$4.17	---	---	---	---

Table VI-14. Existing and Anticipated Natural Gas Well Head Costs, Dollars per Trillion Cubic Feet

Retail prices for natural gas will differ widely depending on the pipeline capacity available, taxes if imposed, etc. Examples of costs for the U.S. west and east coasts are shown in Tables VI-15 and VI-16.

A 1980 study of the requirements for use of natural gas in private cars indicated that an investment of between 30 to 50 billion dollars (1980\$) would be required to provide the capacity to operate 5% of the U.S. passenger car fleet on natural gas. This was estimated to reduce petroleum consumption between 3% and 3.5%. If all vehicles associated with houses now supplied with natural gas (approximately 55 million cars) were operated on natural gas, U.S. petroleum consumption would be reduced by about 30%. This was estimated to cost about 260 billion dollars (1980\$); roughly 1/3 of the cost would be for vehicle conversion, 1/3 for home recharging units, and 1/3 for increases in natural gas wells and distribution pipelines.

U.S. West Coast Natural Gas Prices, \$/Therm									
	1990	1995	2000	2005	2010	2015	2020	2025	2030
Residential	\$0.56	\$0.63	\$0.85	\$1.21	\$1.59	\$1.96	\$2.44	\$3.02	\$3.74
Commercial	\$0.49	\$0.55	\$0.77	\$1.10	\$1.46	---	---	---	---
Industrial	\$0.38	\$0.42	\$0.61	\$0.91	\$1.22	---	---	---	---

Table VI-15. Regional Natural Gas Prices, Dollars per Therm, U.S. West Coast (Pacific Pad)

U.S. East Coast Natural Gas Prices, \$/Therm									
	1990	1995	2000	2005	2010	2015	2020	2025	2030
Residential	0.68	0.86	1.12	1.54	2.00	---	---	---	---
Commercial	0.54	0.61	0.83	1.18	1.55	---	---	---	---
Industrial	0.40	0.45	0.65	0.96	1.26	---	---	---	---

Table VI-16. Regional Natural Gas Prices, Dollars per Therm, U.S. East Coast (Middle Atlantic Pad)

6.6.5 Compressed Natural Gas Storage Systems

The cost of vehicles dedicated to use compressed natural gas will be higher than existing gasoline powered cars (but may be less than similar gasoline fueled vehicles equipped with sophisticated environmental controls to meet ULEV standards). The costs include a larger engine to offset the loss of power experienced when a gaseous fuel is utilized. Theoretically, there should be an improvement in engine efficiency, but this has not been found to be the case by all investigators.

Purchase prices of CNG fuel systems for vehicles installed by independent converters range from \$1,500 to \$2,000 (1987\$). For this price they provide a tank (usually mounted in the trunk) with a capacity equivalent to 3 to 4 gallons of gasoline. While there are no available estimates of the cost of vehicles from original equipment manufacturers, the incremental cost should decrease by 1/3 to 1/2 in volume production [53].

If the gas were to be stored at 2,000 psi. pressure in a steel tank about 12 inches in diameter and about 35 inches long, the tank would weigh about 56 kg (125 lb.). The effective Btu per pound to compress the gas would be on the order of 2,000 to 3,000, or about 1/10th of the energy per pound of the fuel itself. Depending on the size and design of the tank the total volume displaced by the tank may be 10 to 20 percent larger than its internal capacity. More fuel can be stored by using larger tanks or by increasing pressure, both of which have limited practicality. If normal interior and trunk space is maintained, the car will probably have to be somewhat longer and heavier than a gasoline or methanol fueled car.

Researchers have been seeking more effective ways of storing natural gas. One storage concept discussed in the literature, but not proven, is the use of zeolite or activated carbon to absorb the natural gas at near ambient pressures. This technology may provide significant advantages in weight and volume, but neither the practicality of the concept nor the life of the storage medium has been demonstrated. A "theoretical comparison" of gasoline, pressurized natural gas, and a zeolite storage system which would provide the same range is summarized in Table VI-17.

	Fuel Storage Systems			
	Pressure	Fuel lb..	Total lb..	Volume cu ft
Gasoline	ambient	37	47	2 cubic feet
Pressure tank	2,300 psi.	33.6	560	7 to 9 cubic feet
Zeolite	300 psi.	33.6	510	3 to 4 cubic feet

Table VI-17. Alternative Compressed Natural Gas Storage Systems

6.6.6 Liquefied Natural Gas Storage Systems

The major advantage of using LNG in vehicles is the extended range that it can provide over compressed natural gas. Liquefied natural gas has about 2/3 of the energy density of gasoline (btu/gallon). However, the required insulated tanks require 25 to 40% more volume than the fuel alone. Therefore, the effective density is less than half the energy per unit volume of gasoline. The installation is also complicated by the fact that the tanks should be spherical or cylindrical, or nearly so, to ensure efficient thermal control. The insulation characteristics of the tanks can be tailored to the specific mission of the vehicle. Some super insulation is capable of maintaining the gas in the liquid state for weeks without boil-off; however, these tanks can be very expensive. Beech Aircraft estimated the cost at \$1,500 each for short time (days) storage tanks for a passenger car compared to \$18,000 (1981\$) for long term (one week) storage tanks which could provide enough fuel for a 300 mile range for a class 7 or 8 truck.

Liquefied natural gas fuel supply systems will, therefore, generally be more costly than compressed natural gas systems and, thus, probably not cost competitive for most urban vehicles. The energy required for liquefaction is greater than that required to compress natural gas. In some gas producing regions it may be possible to take advantage of the natural gas clean up processes which lower the temperature of the gas to remove water and other undesirable materials. In such cases liquefaction may require very little additional cooling of the gas.

The fuel can be injected into an engine as a liquid in an LNG system. Direct injection requires less power than a CNG fuel system, utilizing a pressure pump (similar to, but technically more complex than a gasoline or methanol pump). There may still be some slight performance losses as the liquefied natural gas requires more energy to raise it to the combustion temperature in the cylinder; however, this is primarily offset by the octane rating of the fuel, which permits higher compression ratios, and decreased compression energy due to fuel vaporization/cooling effects during the compression stroke.

6.6.7 Operating Costs and Safety considerations of Natural Gas Fueled Vehicles

The operating costs of a natural gas vehicle should be lower than that for a gasoline fueled vehicle because of the lower cost per Btu of natural gas today and the excellent life characteristics demonstrated by most natural gas conversions.

Safety considerations will be important. Existing regulations intended for residential or industrial applications could limit the usefulness of natural gas as a vehicle fuel or impose additional costs. These regulations address fuel handling and storage, including materials and construction techniques, as well as shipment limitations. At this time there is little evidence that natural gas retail outlets would create additional hazards (probably fewer since the gas would quickly evaporate). An analysis of accidents sustained by the approximately 30,000 unit natural gas fueled vehicle fleet, which has been in use for the last several decades in the United States, supports the conclusion that the fuel will seldom be a contributing factor to the severity of an accident [98]. Unfortunately, there have been two recent accidents with production light trucks in which there was an explosion after refueling was completed. The reasons are not yet understood but may have been the result of either over-pressurizing the tank, concurrent or separate heat and mechanical damage, or simple carelessness.

The natural gas utilities are promoting the increased use of natural gas as a fuel. In this effort they hope to sell 5,000 natural gas vehicles per year in the United States (725-850 in California alone) [48]. This is only part of the approximately 21,000 U.S. utility vehicles which could be converted to natural gas. The utilities are also encouraging the use of natural gas vehicles by their 40,000 employees in California.

Canada had taken the leadership in encouraging the use of alternative fuels by providing credits to the car owner starting back in the 1970's. This was done in the belief that this would encourage the development of an alternative fuel capability in Canada. These incentives have since been reduced with the result that the number of cars converted to natural gas has decreased significantly [13].

6.6.8 Factors Influencing the Acceptability of Natural Gas as an Automobile Fuel

The level of acceptance of natural gas fueled passenger cars will partly depend on the willingness of people, and the safety, to recharge the vehicles at home. This may partly offset some of the public's opinion over having to stop frequently to refuel or recharge the vehicles.

- The cost to produce and, hence, the ***purchase price*** of vehicles which can use compressed natural gas will decrease significantly as the production volume increases. However, assuming that the production level for standard natural gas fueled four door sedans approaches a million units per year, the cost increment will still probably be higher than the decision threshold for the average new car buyer (that is more than a

10% difference will exist between a natural gas fueled and an equivalent performance gasoline car).

- The **direct cost per Btu of natural gas and other expendable materials** will probably be lower than that of any other alternative fuel, although this advantage will be offset by the added cost of compression and storage equipment. The life cycle costs will be lowest for those users who have consistent low mileage daily travel requirements (50 to 100 miles).
- The cost of owner equipment to recharge or refuel the vehicle will be significant for a user who intends to recharge at home (\$1,500 to \$2,000 per vehicle) or at a factory or office building.
- Dedicated natural gas fueled passenger cars face similar, but less severe, **limitations to their usefulness**, as battery/electric cars as a result of their limited range (normally less than 150 miles). This can be offset by dual fuel systems and by the fact that recharging is a relatively fast process.
- Natural gas fueled passenger car should have advantages in **reliability and availability**, particularly if they are recharged at home (or at the work place).
- Based on California experience **insurance costs** may be lower than for gasoline cars; natural gas has demonstrated a lower risk of fire in an accident than gasoline.
- **Resale value** may be limited unless the vehicles can be converted to liquid fuels or are dual fuel in design.

6.6.9 Factors Influencing the Acceptability of Natural Gas as a Commercial Transportation Fuel

The acceptability of natural gas propelled vehicles by commercial operators will depend on the relative economics of natural gas and petroleum fuels. Most car and truck fleet or public transit operators make careful assessments of the benefits of any change before making commitments. Since the selection or change is site or route specific it is difficult to project the degree of economic benefits. Natural gas buses may present a specific problem since most city buses now are at (or exceed when loaded) legal axle weight limits. The tanks required for natural gas could increase the axle weight.

Liquefied natural gas (more correctly liquefied methane) has been chosen by several railroads for their future propulsion systems. Burlington Northern Railroad is in the process of testing the first commercial unit (two locomotives separated by a liquefied natural gas tender). Other railroads such as the Union Pacific have expressed similar interests. The railroads have several reasons for this decision:

- Locomotive life cycle operating costs should be lower
- Railroads own or control at least a portion of the natural gas resources
- Emissions are much lower from natural gas fueled engines than from conventional diesel engines.

The Federal Environmental Protection Agency is planning to establish emission standards for locomotives in 1994.

6.7 LIQUEFIED PETROLEUM GAS (PROPANE)

Liquefied petroleum gas (LPG) is the most widely used alternative fuel in the United States and many other nations. Conversions to LPG are relatively straight forward; range is only slightly degraded and LPG usage provides operating as well as economic and maintenance advantages. It is estimated that there are 300,000 LPG vehicles in the United States and an additional 140,000 in Canada.

Propane (the primary ingredient in LPG) has been successfully used in many buses and taxicab fleets. Since the LPG supply now available exceeds the existing demand for home heating, stoves, etc., a much larger portion of the fleet (in California) could be fueled with liquefied petroleum gas without increasing production capacity. Use of liquefied petroleum gas is of interest to automobile owners and truck operators because of its apparent economic advantages and the simplicity of operation and conversion relative to compressed natural gas vehicles. The emission advantages using LPG as an automotive fuel have not been a factor to date in the creation of the U.S. fleet of LPG vehicles. Propane advocates report that it would be easier to achieve environmental standards with propane than with gasoline. In a 1989 paper developed for the California Energy Commission the unregulated air pollution emissions from a propane fueled vehicle were stated to produce 50% less hydrocarbons, 70% less carbon dioxide, and 43% less NO_x emissions than a gasoline fueled vehicle. These "data" need verification; if confirmed, the cost for pollution control would be similar to or less than that for methanol [14]. Proponents believe that there could be one million LPG vehicles in California by 2001 and two million vehicles by 2007. Seventy-five percent of this fleet would consist of conversions of existing commercial and private vehicles [63].

The composition of liquefied petroleum gas varies both geographically and seasonally. Typically, there is a small amount of butane in LPG, the content of which can run as high as 10%. The variability of LPG energy content and physical characteristics could lead to the requirement to develop a specification for LPG used as a vehicle fuel. The physical characteristics of propane are summarized in Table VI-18.

Engine compression ratios, when LPG is used as the engine fuel, can be greater than those utilized with gasoline because of the increased octane rating. There may also be some reductions in the cost of catalysts and a slight reduction possible in the size and weight of engines required to achieve a desired level of acceleration performance. The higher octane rating will provide power increases similar to those with methanol.

Lower Heating Value, Btu/lb.	19,800	106% of gasoline
Lower Heating Value, Btu/gallon	82,000	49% of gasoline
Vapor Pressure, psi. (100°F)	N/A	(Gasoline, 91 psi. -100 psi.)
Octane Number, Research	104	104%-114% of gasoline
Boiling Range	-44°F to +31°F	

Table VI-18. Characteristics of Propane

While the liquefied petroleum gas available for vehicle use is primarily propane there are economic incentives to increase the amount of butane in future supplies (particularly if butane is

eventually removed from gasoline to lower the vapor pressure of gasoline). Butane has not previously been considered as a desirable fuel for vehicle propulsion, in part because it liquefies at 32 degrees Fahrenheit; it has a very low vapor pressure and is often hard to meter and ignite at lower temperatures.

Existing safety regulations which may impact the use of LPG include restrictions on the transportation of LPG through tunnels, etc. Many of these regulation were originally based on the use of LPG for home heating and cooking.

The modifications to vehicles to use propane have usually been made by small companies or by vehicle owners. Propane vehicles require pressurized tanks, usually mounted in the trunk, and modified fuel control and fuel supply systems. Dedicated propane vehicles can be designed to provide ranges similar to that of most liquid fueled vehicles, but usually with a loss of storage or other space on the vehicle. Most conversions reduce the range to about 2/3 of that of a conventional gasoline fueled automobile. The incremental weight for a steel tank which contains the equivalent of 3 gallons of gasoline would be on the order of 50 lb. (23 kg). This represents a tank approximately 13 inches (320 mm) in diameter and 30 inches (750 mm) long. Advanced tank designs (such as filament wound tanks) could reduce the empty weight of the tank by about 40%.

6.7.1 Production Capacity

Approximately one third of the 950,000 barrels of propane supply per day in the U.S. originates as a byproduct of petroleum refineries; the remainder is produced along with natural gas. Additionally, 75,000 barrels of propane per day are imported. Most of the propane used in California is associated with gasoline refining. Since much of the available liquefied petroleum gas in the U.S. is a co-product of the production of crude oil and natural gas, its availability and cost is a function of petroleum production.

<u>Liquefied Petroleum Gas Production</u>						
<u>Country</u>	<u>1990</u>	<u>1992</u>	<u>1994</u>	<u>1996</u>	<u>1998</u>	<u>2000</u>
<u>Domestic U.S. [1]</u>	850	*	*	*	*	920
<u>International [2]</u>	*	*	*	*	*	*

[1] Billion barrels per day

[2] Billion barrels per year

* To be obtained

Table VI-19. Existing and Anticipated Liquefied Petroleum Gas Production

Over half of the propane consumption in the U.S. is used in the production of plastics (primarily ethylene). About 250,000 barrels per day are used for heating and cooking. About 50,000 barrels per day are used for propulsion or other energy conversion operations. Future production estimates are summarized in Table VI-19 above. Future production capacity is uncertain as it is in part dependent on what actions are taken by petroleum refiners. Because most propane is a co-product with petroleum, many forecasters assume that the LPG capacity can only be increased by making coincident increases in crude oil production capacity. However, a 1991 paper by R. Webb estimates that the available supply of LPG for transportation could be increased through the use of unconventional sources as presented in Table VI-20 below. These estimates must be considered to be speculative until further studies yield more information.

LPG Production Source	Alternative Production Sources of LPG		
	Millions of Barrels	Availability Year	Cost per Gallon
Conventional	12	1990	
Market displacement	70-105	1991-1995	\$0.25-\$0.40
Increased recovery	280-350	1991-2000	\$0.40-\$1.00
Alaska north slope	23	1991-2000	\$1.00-\$1.05
Devonian shale	23	2000+	\$1.05-\$1.10
Synthesis	110-220	2000+	\$1.10-\$1.35

Table VI-20. Potential Sources of Liquefied Petroleum Gas

6.7.2 Distribution Capability

Transportation costs for LPG have been higher than for gasoline as LPG is usually shipped in tank cars and trucks. However, it should be possible to adapt natural gas pipe lines to the transportation of LPG if appropriate safety precautions (and inspections) are taken. The pipeline capacity would have to be increased if a significant increase in LPG use is contemplated.

6.7.3 Retail Capacity

Most propane is purchased from industrial suppliers or from convenience stores which sell it as "bottled gas" for cooking and heating. The advocates of liquefied petroleum gas expect it to be distributed through retail dealers as is done for gasoline and diesel fuel. There are 51 retail propane vehicle refueling stations in California which have been opened in support of the California Alternative Energy Program.

6.7.4 Costs of Liquefied Petroleum Gas Fuel

Historically the cost of liquefied petroleum gas (in price per unit energy content) has been substantially less than that of petroleum. LPG fuel prices should change in a manner similar to gasoline since they are subject to some of the same supply concerns. Major portions of the market for LPG are different from the gasoline market however, as a result there has been significant differences in costs per energy content. The price of LPG should, over the long run, approach that of gasoline on an energy equivalent basis. In 1990 the price of LPG in California was equivalent to \$0.26 to \$0.34 per gallon of gasoline. Some forecasts, such as that performed by the California Energy Commission Delphi IV Study, project increases to only \$0.41 to \$0.52 by the year 2000. These prices will increase if significant quantities of propane are used for vehicle propulsion. The anticipated well head costs of propane (per equivalent gallon of gasoline) are presented in Table VI-21 .

Retail prices for liquefied petroleum gas will differ widely in different parts of the U.S. depending on the distribution process (tank car or pipeline), type and quantity of taxes imposed, etc. Since the probable prices of LPG will be related to the availability and, hence, price of petroleum and natural gas products, it should be possible to develop logical projections of lower and upper bounded future price trends.

<u>1990</u>	<u>1995</u>	<u>2000</u>	<u>2005</u>	<u>2010</u>	<u>2015</u>	<u>2020</u>	<u>2025</u>	<u>2030</u>
\$0.30	*	\$0.46	**	**	**	**	**	**
* To be determined			** To be obtained					

Table VI-21. Existing and Anticipated Liquefied Petroleum Gas Costs, Dollars per Equivalent Gallon of Gasoline

6.7.5 Factors Influencing the Acceptability of LPG as a Vehicle Fuel

The factors which a purchaser of a liquefied petroleum gas propelled car would have to consider are summarized below:

- The ***purchase price*** of the vehicle will increase by the size of, and difficulty of incorporating, LPG tanks (modifiers currently charge \$1,000 to \$2,000). The cost to produce the vehicle for use with LPG will depend on the volume of production achieved. Even if production by a major manufacturer approaches a million vehicles per year the cost increment will probably still be of concern to the average new car buyer (that is, more than a 5% difference between a LPG car and an equivalent performance gasoline car).
- ***Fuel and other expendable materials costs*** should be somewhat lower for LPG than for gasoline but will approach gasoline in price if a large number of vehicles use LPG. Other costs should be the same or lower compared to gasoline fueled vehicles.
- ***Insurance costs*** may be higher due to concerns about the use of a pressurized flammable liquid which is heavier than air. Propane has a reputation for detonating when exposed to heat in depressions or in locations where it may puddle.
- LPG cars will be somewhat ***limited in their usefulness*** compared to cars propelled by gasoline because of the reduced range (2/3 or less for the same tankage space). This problem can probably be alleviated by unique designs of the tankage and vehicle. By 2020 it is probable that a sufficient number of filling stations would be selling LPG to overcome concerns concerning its availability.
- There should be fewer operating problems (***high reliability***) with LPG than with gasoline or methanol fueled vehicles as the life experience with existing propane vehicles has been outstanding. There should be few starting problems.
- It is unlikely that many private owners will pay for the ***cost of equipment to recharge or refuel*** their vehicle (i.e., provide their own fuel supply) although this may be tempting for convenience reasons. It may be an important cost for fleet operators (but much less so than for natural gas or battery/electric vehicles).
- ***Resale value*** will be a limiting factor if the service facilities for these vehicles are not available nationwide.

6.8 METHYL AND ETHYL TERTIARY BUTYL ETHERS

Methyl tertiary butyl ether (MTBE) is being used in substantial quantities for octane improvement for gasoline. MTBE is equivalent in octane to methanol but is less corrosive. The characteristics of ethyl tertiary butyl ether (ETBE) are similar to ethanol; it is more costly but it does have the advantage of a higher heating value. TAME (tertiary amyl methyl ether) has

similar characteristics. Some of the properties of each of these compounds is presented in Table VI-22.

<u>Additive Property</u>	<u>MTBE</u>	<u>ETBE</u>	<u>TAME</u>
Octane	107	119	106
Reid Vapor Pressure, psi.	8 psi.	6 psi.	3 psi.
Boiling Pt, °F	131	162	187
% H ₂ by weight	18	16	16

Table VI-22. Characteristics of Tertiary Ethers

Anticipated production capacities for MTBE and TAME are summarized in Tables VI-23 and VI-24.

<u>Country</u>	<u>1992</u>	<u>1994</u>	<u>1996</u>	<u>1998</u>	<u>2000</u>	<u>2010</u>	<u>2020</u>	<u>2030</u>
Domestic U.S.	183.5	321.6	355.0	365.7	378.2	?	?	?
Canada	12.2	12.2	12.2	12.2	23.8	?	?	?
Mexico	1.0	4.6	4.6	5.7	5.7	?	?	?
World Total	343.3	581.4	667.8	749.6	797.6	?	?	?

Table VI-23. MTBE Estimated Production Capacity, Tons per Year

<u>Country</u>	<u>1992</u>	<u>1994</u>	<u>1996</u>	<u>1998</u>	<u>2000</u>	<u>2010</u>	<u>2020</u>	<u>2030</u>
Domestic U.S.	8.9	26.7	28.7	28.7	28.7	?	?	?
World Total	12.6	48.1	50.1	50.1	50.1	?	?	?

Table VI-24. TAME Estimated Production Capacity, Tons per Year

Ethyl tertiary butyl ether, which is derived from biomass ethanol, is much higher in price and not expected to be a significant factor in the fuel additive market.

6.9 ELECTRICAL POWER

In most areas in the U.S. the electrical capacity is adequate to meet the need for off-peak energy consumption battery/electric vehicle recharging; but, because of delays (regulatory and financial) in construction of planned new electrical capacity, some regions are already experiencing power supply shortages during peak energy consumption periods (particularly on hot summer days or during scheduled or unscheduled power plant shutdowns). The major California Utilities (Southern California Edison (SCE), PG&E) have stated that there is adequate electrical capacity for all of the mandated battery/electric vehicles to be supplied by the existing (or planned) utility generating capacity during off-peak "power" (primarily late night) periods. They have expressed concern, however, over permitting recharging during the day and, in particular, during peak day time consumption periods as this would probably require construction of additional generating facilities. Some utilities (SCE and PG&E) have suggested that the utilities could achieve the desired air quality improvements more cost effectively (in tons

of pollutants reduced per dollar) by subsidizing battery/electric powered cars and light trucks than by equivalent investments in cleaning up their existing power plants.

6.9.1 Cost of Electrical Power

The cost of electrical power used in most recent battery/electric vehicle studies is assumed to escalate with the average rate of inflation. Recent studies have used electric power costs ranging from 4 to 8 cents per kilowatt hour. In California the present cost of electricity ranges from 8.6 to 10.85 cents per kW-hr for residential users and from 3.7 to 4.98 cents per kW-hr for commercial and industrial users. The assumption of constant dollar rates for recharging may be unrealistic in light of the increasing environmental control costs for utilities (estimated at 25 to 50% of the current rate in some areas) and recent electrical demand increases (not including power for battery/electric cars) which have surpassed the GDP growth rate. This recent demand growth is more rapid than predicted. The anticipated national average cost per kW-hr for retail household prices is presented in Table VI-25. An indication of the potential difference in prices in selected areas of the nation is presented in Tables VI-26 through VI-28. Cost trends beyond 2015, and the probable range of future prices, will be developed in cooperation with electrical and energy economic forecast organizations and the DoE.

<u>1990</u>	<u>1995</u>	<u>2000</u>	<u>2005</u>	<u>2010</u>	<u>2015</u>	<u>2020</u>	<u>2025</u>	<u>2030</u>
8.58	7.04	8.34	10.74	13.84	*	*	*	*

* To be determined

Table VI-25. Anticipated National Electrical Power Household Prices, Cents per Kilowatt Hour, Average U.S.

Retail prices for electrical power will differ widely depending on the base power source (coal, natural gas, water, nuclear, etc.), the distance from the generation site (approximately 10% loss per 1,000 miles), and taxes if imposed, etc.

	<u>1990</u>	<u>1995</u>	<u>2000</u>	<u>2005</u>	<u>2010</u>	<u>2015</u>	<u>2020</u>	<u>2025</u>	<u>2030</u>
Residential	10.0	10.5	11.8	14.84	18.77	*	*	*	*
Commercial	9.0	9.6	11.1	14.1	17.93	*	*	*	*
Industrial	7.3	8.2	9.7	12.5	15.94	*	*	*	*

* Projections to be developed

Table VI-26. Estimated Electrical Costs, U.S. West Coast (Pacific Pad #2), Cents per Kilowatt Hour

	<u>1990</u>	<u>1995</u>	<u>2000</u>	<u>2005</u>	<u>2010</u>	<u>2015</u>	<u>2020</u>	<u>2025</u>	<u>2030</u>
Residential	7.2	7.6	9.9	12.87	16.58	*	*	*	*
Commercial	6.3	7.2	9.0	11.90	15.24	*	*	*	*
Industrial	4.4	4.9	6.2	8.00	10.11	*	*	*	*

* Projections to be developed

Table VI-27. Estimated Electrical Costs, U.S. Midwest (West North Central), Cents per Kilowatt Hour

	<u>1990</u>	<u>1995</u>	<u>2000</u>	<u>2005</u>	<u>2010</u>	<u>2015</u>	<u>2020</u>	<u>2025</u>	<u>2030</u>
Residential	10.3	10.0	10.8	13.2	17.30	*	*	*	*
Commercial	9.3	9.4	10.3	12.8	16.19	*	*	*	*
Industrial	6.1	6.5	7.6	9.7	12.39	*	*	*	*

* Projections to be developed

Table VI-28. Estimated Electrical Costs, U.S. East Coast (Middle Atlantic), Cents per Kilowatt Hour

Preferential or subsidized prices are proposed for initial battery/electric vehicle users. They are unlikely to be continued if the demand for electrical power requires construction of new facilities.

6.10 HYDROGEN AS A POTENTIAL VEHICLE FUEL

While this commercialization study did not require addressing hydrogen as a vehicle fuel, hydrogen's apparent environmental benefits have led to increasing public (and political) interest in its use as a vehicle fuel. In principle, the emissions from a hydrogen powered fuel cell engine propulsion system will only be water (and carbon dioxide if produced from methanol reformation).

6.10.1 Hydrogen Production and Distribution/Storage Capacity

- Hydrogen can be produced and supplied to an engine system in three different ways:
- From a national or regional processing center (electrolysis, etc.)
- From a refueling station (site reformation)
- Internal to the vehicle (on-board reformation).

The first method, producing hydrogen at a national or regional processing center will require the creation of a major new distribution system. Initially, H₂ could use the excess capacity (if any) of natural gas pipelines and cryogenic trucks. The costs of truck distribution, in particular, would be much higher than that of equivalent liquid fuels. As demand increases it will be more economical, and safer, to develop a system of pipelines. These will have to be large in size, about four times the cross sectional area of pipelines currently delivering an equivalent amount of energy in natural gas. There will be major energy losses accompanying this process. Some authorities estimate that pumping, compression, and liquefying losses could be equivalent to 40 to 50% of the total energy contained in the delivered hydrogen.

Producing the hydrogen at a refueling station (from natural gas) will alleviate some of the infrastructure construction problems, but as demand grows it will then be necessary to build new natural gas pipelines to provide the natural gas feedstock for hydrogen generation. Locating fuel processing plants at filling stations to produce H₂ from methanol or natural gas will create other problems. Reformers (processing plants), if not properly designed and maintained, may generate noxious emissions as well as carbon dioxide. They may be perceived as a hazard and subject to the same regulations as a chemical plant. Further, the hydrogen and/or reformat will have to be stored at the refueling station; this will require additional compressed gas or cryogenic liquid facilities. The refueling of a car with a gaseous or cryogenic liquid also creates potential safety problems. In all probability, if this approach is utilized, the ultimate

solution will be to develop automatic filling facilities so that private owners will not be exposed to the very cold (cryogenic) or high pressure hydrogen. Even a small leak of a cryogenic fluid can cause severe injuries.

Producing the hydrogen on demand aboard the vehicle from methanol, natural gas, or some other energy resource simplifies the distribution problem but adds to the complexity and cost of the on-board equipment. This may provide the highest overall energy system efficiency as some of the waste heat (or unused hydrogen) from the fuel cells can be used to supply heat to the fuel processing process. Storage of pure hydrogen fuel at a refueling site or on-board a vehicle presents a number of technical problems; the density of hydrogen is very low and it can cause embrittlement in many metals. The potential storage weight, volume, and cost for various hydrogen storage systems are summarized in Table VI-29.

<u>Fuel Type</u>	<u>Weight</u>	<u>Volume</u>	<u>Container Cost</u>
Gasoline	1	1	1
8000 psi. (C-Al tank)	9.5 times	4.8 times	200 times
Liquid Hydrogen	6.5 times	2.2 times	75 times
FeTi Metal Hydride	10.8 times	22.6 times	220 times
Iron Oxidation Reduction	5.8 times	6.8 times	25 times

Information adapted from DeLuci and Ogden, 1992

Table VI-29. Characteristics of Hydrogen Storage Systems, Relative to Gasoline

6.10.2 Cost of Hydrogen Fuel

The cost of hydrogen fuel in small quantities is high. A recent projection of the production costs of hydrogen using four different processes is summarized in Table VI-30. While additional information to fill in all of the scenarios will be sought, it is unlikely that additional meaningful information will be obtained.

<u>Facility Size</u> <u>(Million Cu Ft/Day)</u>	<u>Steam Reforming</u>	<u>Partial Oxidation</u>	<u>Coal Gasification</u>	<u>Electrolytic</u>
0.0075	---	---	---	\$50
0.030	---	---	---	\$35
0.60	---	---	---	\$10
1.0	\$17	---	---	---
5.0	---	---	---	---
10.0	\$10	---	---	---
25.0	---	---	---	\$5
50	---	\$13	\$15	---
100	\$6	\$11	\$14	---
200	---	\$10	\$11	---

Table VI-30. Estimated Production Cost of Hydrogen, Dollars per Million BTU

6.11 OTHER POTENTIAL FUELS

Discussions with energy and chemical companies indicate that there are some potential energy concepts which warrant further exploration; the potential benefits of other fuels has not been fully explored. Candidates include heavier hydrocarbons and designer hydrocarbons or hydrogen carrier chemicals. If they prove attractive they may change the choice of a particular fuel cell propulsion system for specific vehicles. Ideally, there could be some chemicals which can transport more hydrogen (per weight or volume) than can be stored under pressure and which can be reformed (stripped of their hydrogen) with less energy loss than occurs when methanol or natural gas is reformed.

An illustration of a potential innovative "fuel" or hydrogen carrier is methylcyclohexane. MCH disassociates into hydrogen and toluene in the presence of a catalyst and heat (600°K). The toluene (described as the exhausted carrier) would be recycled and reconstituted back to MCH external to the vehicle. The vehicle's tank would have two parts, one for MCH and one for toluene. The refueling process would occur in two steps; the first would involve the return of the toluene (exhausted carrier) to the processor (perhaps at a filling station) while the second step incorporates the refill of the tank with MCH [136]. Unfortunately, the energy required to separate the hydrogen from MCH is high and the energy density is low. The on-board vehicle storage tanks would have to be excessively large if a normal (300 mile plus) range is required. While MCH is not economically or technically attractive it has been mentioned to suggest to researchers that other materials may provide improved performance. Since hydrogen carriers would be recycled their costs could be initially high relative to conventional fuels. The advantages of this kind of process is that the products of "reformation" would only be hydrogen and the exhausted carrier. There would be no carbon dioxide or carbon monoxide. Since the carrier and the "exhausted carrier products" should all be liquids, normal types of tanks and controls would be applicable.

Some other fuels have been suggested which appear unlikely candidates for environmental reasons (due to the fuel, not the exhaust products) such as ammonia and hydrazine.

6.12 TOTAL SYSTEM ENERGY AND EMISSIONS

A proper evaluation of the suitability of alternative fuel-energy conversion systems includes an analysis of all elements within the system such as the cost and energy consumed in: production, processing, retailing, and storage at the refill site and/or on-board the vehicle(s).

The total energy required to create the fuel used in the vehicle is the sum of all of the incremental energy losses in each stage from production, processing (refining), distribution, and retail sales. Data in Table VI-31 above indicates that (on average) the delivery of one million Btu's of gasoline to a car requires that the process start with about 120-125 million Btu's of crude oil. At the same time approximately 150 million Btu's of natural gas are required to produce and deliver 100 Btu's of methanol to a vehicle's fuel tank.

A second assessment prepared by ARCO of the overall fuel delivery and (various) engine system efficiencies is also summarized below in Table VI-32.

<u>Fuel</u>	<u>Feedstock Recovery</u>	<u>Transport</u>	<u>Fuel Production</u>	<u>Distribution</u>	<u>Compression</u>	<u>On-Vehicle Liquefaction</u>
Reformulated Gasoline	2.5%	1.1%	18.4%	0.8%	N/A	N/A
Standard Gasoline	2.6%	1.2%	14.5%	0.8%	N/A	N/A
Low Sulfur Diesel	2.9%	1.3%	7.0%	0.9%	N/A	N/A
Fuel Oil/Crude	3.2%	1.4%	7.0%	1.0%	N/A	N/A
Natural Gas	2.8%	--	2.4%	3.6%	5%	20.2%
Methanol/Natural Ga	7.9%	2.1%	35.1%	3.8%	N/A	N/A
Methanol/Coal	1.5%	0.2%	44.4%	1.9%	N/A	N/A
Methanol/Wood	6.2%	1.7%	43.5%	2.4%	N/A	N/A
Ethanol/Corn	10.0%	2.5%	58%	2.7%	N/A	N/A
Hydrogen from???	---	---	---	30%	30%	31%

Source Derived form Table 3, Emissions of Greenhouse Gases From the Use of Transportation Fuels and Electricity, Argonne National Laboratory, ANL/ESD/TM-22, November, 1991

Table VI-31. Percent Net Energy Consumed During Production and Distribution of Various Candidate Fuels

<u>"Fuel"</u>	<u>Production Processing and Delivery</u> [1] [2]	<u>Engine Drive Efficiency</u>	<u>Overall Efficiency</u>
Gasoline	85.6	12.7-17.1	10.9-14.6
Reformulated Gasoline	83.6	12.4-17.1	10.4-14.3
Methanol form natural gas	60.7	14.7	8.9
M-85	64.4	13.6	8.8
Ethanol	36.6	14.3	5.3
Gasohol-19% ethanol	80.7	12.7	10.3
CNG	80.6	10.8-12.8	8.7-10.3
Battery/Electric	25.7-30.7	59.5-72.0	15.3-22.1
Hydrogen from Natural Gas	80.6	20.8	16.8
Hydrogen from Solar	21.8-72.8	33.7[3]	7.3-24.5
Electrolytic Hydrogen	16.2	33.7[3]	5.5

[1] Present efficiency

[2] Assumed improvements

[3] Low efficiency fuel cell

Table VI-32. Assessment of the Overall Fuel Delivery and "Engine System Efficiency" Prepared by ARCO

An assessment of the environmental impact of alternative fuels must also consider the pollution generated during the processing of the fuel. While this is usually very localized, and can be treated with processes which would be unworkable for automobiles or trains, it is important to recognize the need for such assessments.

6.13 CRITICAL MATERIALS IN NEW ENGINE SYSTEMS

While the cost and availability of most minerals (iron, copper, etc.) have decreased in the recent past, and are expected to do so in the future, there are some materials, such as the platinum group metals used in phosphoric acid and PEM fuel cells, which may increase in price. Approximately half of the platinum group metals come from South Africa and most of the remainder from the ex-Soviet Union. The costs of these metals may be expected to increase if the use of fuel cell engine propulsion systems increase. The recent price history of these metals is presented in Table VI-33.

<u>Year and Price Ratio</u>	<u>Platinum \$</u>	<u>Palladium \$</u>	<u>Rhodium \$</u>
1983	380-480	97-170	300-400
1984	270-410	111-162	400-800
1985	245-375	91-130	700-1200
1986	350-675	94-151	1200-1400
1987	465-630	108-160	1200-1250
1988	440-620	112-147	1200-1250
1989	470-615	129-181	1200-2200
1990	380-530	81-138	2200-7000
1991	330-425	79-102	1600-5800
Price Ratio 1991/1983	.86-.88	.81-.60	5.3-14.5

Source: Englehard precious metal prices

Table VI-33. Prices of Platinum Group Metals, Dollars per Troy Ounce

The rapid price increase of rhodium in 1988 and 1989 was in part due to the fact that catalytic converters require a disproportionate share of rhodium, that is, more than the proportion that is normally found when mining platinum base materials. This emphasizes the need for additional research on non-precious metal catalysts or fuel cells which utilize very low loadings of platinum. Fortunately, PEM fuel cell engine systems utilize little or no rhodium and have demonstrated the ability to perform with low Pt loadings.

6.14 SUMMARY - EVALUATION OF FUEL INFRASTRUCTURE

The availability of economic fuels for fuel cell engine propulsion systems (or other advanced engine systems) has not yet been systematically investigated. While some cost and performance information is available on the obvious choices, methanol, natural gas, distillate, and hydrogen, the costs and feasibility of creating a system to produce, distribute, and sell

adequate quantities of the selected fuels have not been addressed. There are several steps involved to adequately determine the feasibility of alternative fuel usage.

- Identify the optimum fuel-propulsion system combinations, develop suitable system elements, and demonstrate their operation and economics
- Estimate the economic requirements, costs of discovery (if new fuels are involved), cost of production and or refining facilities, additional distribution networks, etc. This may also involve the evaluation of materials which could act as hydrogen transporters; their technical and economic feasibility for use in advanced engine systems, particularly fuel cell electrochemical engines, needs to be determined
- Determine the requirements for the fuel energy distribution system, anticipate consumption by region, number of retail stations required, cost of converting existing stations (or building new retail stations)
- Evaluate the impact on the energy industry, sources of capital, probable profitability, etc.

There are no useful estimates of the time and costs of developing this information, it may take several years and cost thousands of dollars to develop such information. If the energy companies are convinced of the future viability of fuel cell engines (or other advanced engine systems) they will invest in the development of proprietary technologies for production of new fuels and the creation of the required production and retail infrastructures. At this time, neither the engine system(s) or the appropriate fuel(s) of the future has been selected. When this information becomes available the extent of the role that energy companies, exploration, production, refining, distribution, and retail may play in determining the development of new fuel(s) for new engine system(s) can be determined [5].

VII. MARKET FOR VEHICLES WITH ELECTROCHEMICAL ENGINES

This section of the report includes a summary of some of the Department of Energy forecasts predicting sales of vehicles with advanced alternative propulsion systems, including those with fuel cell (electrochemical) engines, and a description of the market and benefits analysis (scenarios) to be conducted in Phase II of this program.

The potential initiation of the market and support infrastructure for the accelerated development of fuel cell engine propulsion systems (electrochemical engines) will depend on the benefits such systems can provide in terms of their impact on personal mobility and freight movement, as well as their ability to meet future energy and environmental objectives. Methods to develop data projections involve the preparation of logical scenarios of future economic and technical developments in combination with other predictions that project the potential changes in importance of certain key elements that may influence public and private decision makers.

7.1 ALTERNATIVE PROPULSION SYSTEM MARKET PROJECTIONS

Several forecasts of markets for light vehicles which would utilize alternative fuels and propulsion systems currently exist. The actual market at any time in the future will depend on:

- The state of development of fuel cell engine and other alternative propulsion systems
- The cost to buyers of fuel cell engine propulsion systems and conventional propelled vehicles
- The disposable family income
- The rate of economic growth
- Actual energy prices
- Federal and state energy and environmental regulations
- Changes in urban development including construction of edge and/or new cities
- The public's acceptance of new transportation technologies such as improved public transit or alternative automobiles.

Much less attention has been given to estimating potential markets for commercial trucks, buses, and locomotives than light vehicles, although enough is known of these markets to make reasonable estimates of their potential size.

The first electrochemical engine applications to be commercialized may be utilized in buses and/or locomotives. Utilization of electrochemical engines in buses will probably occur due to their unique (but small) market based on their current use of diesel engine systems which have particular emission (and odor) problems. Locomotives could be the first application where the use of electrochemical engines may be economically justified; heavy duty trucks (classes 5 to 8) may possible be the next application. The introduction of electrochemical engines for light duty (passenger car and pickup truck) type vehicles would benefit from the experience in these markets. As discussed earlier, the introduction of fuel cell engine propulsion systems for light duty vehicles will probably be driven by one of two possible scenarios:

- Environmentally driven reasons which assume that the first generation of fuel cell engine propulsion systems will cost less and provide more acceptable performance than battery/electric or other advanced low emission propulsion systems
- Economically driven reasons which assume that, after development, electrochemical engines will compete economically with "heat" engines and provide other advantages such as responsiveness, reliability, low noise, etc.

The development of the first generation of electrochemical engines will require some form of support until they become economically competitive and government sponsorship is no longer necessary. However, the full benefits of electrochemical engines will not be realized until the second generation of such engines has been developed.

The size of the market for the first, or environmentally driven, generation of electrochemical engines for light vehicles will depend on energy and environmental regulations, and any subsidies or support which the government (state and/or federal) may provide. This market could range from 1 to 10% of the total U.S. light vehicle market depending on the success, or lack thereof, that "new conventional engines" achieve in reducing emissions and energy consumption. This first market for electrochemical engines should be relatively cost insensitive. The size of the environmentally driven market was illustrated earlier by summarizing the requirements and projected size of a fleet (and its use) of vehicles with alternative propulsion systems. To review:

- The California Air Resources Board (CARB) requirements call for 2% of the cars sold by all major manufacturers to be zero emission cars by 1998, 5% by 2001 and 10% by 2003. California regulators recognize that battery/electric propulsion systems will not meet all transportation needs, so they project that 25% to 70% of "conventional vehicles" will be powered by alternative fuels (25% to 50% by natural gas). Their emission forecasts are based on the assumption that there will be no resident (California) diesel trucks or cars but 47% of the miles driven by trucks will still be diesel engine powered transient (out of state) vehicles. These estimates are based on compliance with mandates, not a detailed assessment of the market.

7.1.1 Estimated Future U.S. Market Penetration of Advanced, Alternative Vehicles Utilizing Fuel Cell Engine Propulsion Systems

The U.S. Department of Energy has conducted a number of studies to obtain a better understanding of the size of the markets for various future propulsion systems. Tables VII-1 to VII-6 are illustrative of the DoE projections. The estimates of the sale of advanced vehicles in the U.S. automobile fleet, prepared by a number of forecasters in 1992, are summarized in Table VII-1. The market share estimates of the vehicle market powered by "internal combustion", battery/electric, hybrid/electric, and advanced engine systems were described in a memo by J. Maples, October 1, 1992. The "advanced engine or vehicle" category includes vehicles powered by electrochemical engines, gas turbines, and other "new" propulsion systems [24,139].

Heat engines (internal combustion) include gasoline, diesel, natural gas, and methanol fueled piston (or gas turbine) engine systems. It would appear that the 2010 penetration of fuel cell engine powered vehicles (assuming that this includes buses and locomotives) is reasonable on a percent of installed power basis. The 2030 projection for fuel cell engine market penetration, Table VII-2, on the other hand, is either way too low or way too high depending on the level of

investments in fuel cell engine propulsion system research and commercialization and the success in cost reduction efforts.

Year, 2010	Market Share Estimates		
	Base Case	High Subsidy	Double Gasoline Price
Gasoline/diesel	22.4%-34.8%	26.1%-27.4%	14.5%-18.2%
Alcohols	21.1%-26.6%	22.4%-26.6%	20.8%-43.2%
Dual fuels	20.0%-27.1%	21.2%-30.1%	13.9%-30.7%
Natural gas	4.1%-9.1%	4.3%-13.6%	6.4%-15.6%
Battery/electric	0.1%-2.6%	0.1%-2.7%	0.1%-3.9%
Hybrid/electric	2.5%-6.6%	2.5%-6.9%	3.6%-7.6%
Advanced	4.9%-8.1%	6.2%-11.1%	7.3%-12.0%
Year, 2030			
Gasoline/diesel	14.9%-19.5%	11.1%-13.3%	3.3%-6.5%
Alcohols	16.5%-23.7%	13.0%-24.1%	13.9%-27.0%
Dual fuels	12.3%-17.4%	13.9%-27.0%	10.7%-23.6%
Natural gas	4.1%-9.1%	4.3%-13.6%	6.4%-15.6%
Battery/electric	3.4%-14.7%	3.3%-14.3%	7.6%-14.5%
Hybrid/electric	15.7%-17.3%	15.1%-16.8%	19.6%-18.6%
Advanced	15.6%-17.2%	19.8%-21.7%	18.4%-19.3%

Table VII-1. U.S. Department of Energy, 1992 Market Share Estimates

The high subsidy case assumes a \$2,000 subsidy for natural gas, dual fuel, and alcohol fueled vehicles, and a \$4,000 subsidy for battery and hybrid/electric, and advanced vehicles. The columns do not add to 100% because the selected data is taken from different market penetration estimates for "battery/electric vehicles". High and low estimates were selected from a series of DoE sponsored models including DAS (Halling Decision Analysis Corp.), IDEAS (J, Gienzer, AVS Corporation), and DVSAM (Argonne). In most cases the high estimates of the battery/electric vehicle market penetration were projected by the DAS model, while the low estimates were projected by the DVSAM model.

Engine Type	2000	2010	2020	2030
Internal combustion	<100%	76%	60%	67%
Battery/electric	<1%	2%	3%	3%
Hybrid/electric	0%	19%	23%	23%
Fuel cell	0%	3%	5%	7%

Table VII-2. AVS 1993 Estimates of Market Share if Advanced Technologies are Available

A second set of U.S. DoE estimates of market share, which specifically addressed the fuel cell engine propulsion system market, is presented in Table VII-2 above. These estimates were obtained from a presentation to the U.S. DoE Transportation Technologies Contractor's meeting in October, 1993. The estimates are based on a survey of energy-propulsion forecasters and other authorities [2,7].

A third set of DoE forecasts is included in the U.S. Department of Energy, Office of Transportation Technologies report on its Five Year Transportation Program Plan (December 8, 1993 draft). Data include projections of the sales of various kinds of propulsion systems for light personal vehicles (cars, vans, pickup trucks) and medium and heavy duty commercial trucks. These forecasts are summarized in Tables VII-3, 4, and 5, respectively.

<u>Year</u>	<u>Conventional</u>	<u>CNG/LPG</u>	<u>Flexible Fuel</u>	<u>Battery/ Electric</u>	<u>Dedicated Ethanol</u>	<u>Dedicated Methanol</u>	<u>Hybrid/ Electric</u>	<u>Fuel Cell/ Electric</u>
1995	81%	--	18%	--	--	1%	---	---
2000	75%	3%	20%	--	--	2%	---	---
2005	60%	5%	20%	2%	1%	2%	10%	---
2010	45%	12%	20%	2%	2%	2%	15%	2%
2015	35%	13%	25%	2%	2%	2%	17%	4%
2020	20%	20%	25%	2%	3%	3%	20%	7%
2025	20%	17%	25%	2%	4%	4%	20%	8%
2030	20%	15%	25%	2%	4%	5%	20%	9%

Table VII-3. Market Penetration by Fuel/Propulsion System, Light Duty Vehicles

When fuel cell engine propulsion systems become economically competitive with heat engine propulsion systems, battery/electric and hybrid/electric vehicle sales will probably be replaced almost entirely by fuel cell engine powered vehicles. The 2030 production volume of fuel cell engine powered vehicles, assuming economic success, could at least be the sum of the three electric vehicle categories as presented both by John Maples (Table VII-1) and the data in Table VII-3 above. This represents between 30 and 45% of all light vehicle sales. This translates into four to seven million U.S. cars and light trucks per year. If the costs do not come down, the market size will be based on environmental regulations, not economics. The uncertainty about future changes in regulations affects the accuracy for predicting the probable market penetration of first generation electrochemical engine powered passenger vehicles.

The U.S. DoE anticipates that the primary future alternative fuels used by medium duty commercial trucks will be compressed and/or liquefied natural gas. They also assumed fuel cell engines would first be available for these commercial vehicles in 2010, resulting in a significant penetration of the market (40%) by 2020, Table VII-4.

The Dept. of Energy forecasts for heavy duty trucks (primarily class 7&8), Table VII-5, are based on the assumption that the low emission, high efficiency (LE-55) diesel and fuel cell propulsion engines find acceptance in this market starting in 2000 and 2010, respectively. The LE-55 advanced large diesel engine utilizes ceramics and high temperature compatible

lubricants to offset the increased heat transfer potential and wear at its anticipated higher operating temperatures. Again, a significant fuel cell engine penetration of the market (40%) is predicted by the year 2020.

<u>Year</u>	<u>Conventional</u>	<u>CNG</u>	<u>LPG</u>	<u>Fuel Cell Engine</u>
1995	99%	1%	--	--
2000	85%	10%	5%	--
2005	65%	22%	13%	--
2010	49%	33%	17%	1%
2015	25%	36%	18%	20%
2020	-- %	40%	20%	40%
2025	To be developed %			
2030	To be developed %			

Table VII-4. Market Penetration by Fuel/Propulsion System, Medium Duty Truck Vehicles

<u>Year</u>	<u>Conventional</u>	<u>LE-55</u>	<u>Fuel Cell Engine</u>
1995	100%	---	---
2000	98%	2%	---
2005	80%	20%	---
2010	58%	40%	2%
2015	29%	50%	21%
2020	0%	60%	40%
2025	To be computed		
2030	To be computed		

Table VII-5. Market Penetration by Fuel/Propulsion System, Heavy Duty Truck Vehicles

A preliminary estimate of the overall market for fuel cell engine powered applications is presented in Table VI-6. This table indicates price and annual sales projections of fuel cell engines for both non-transportation (military, recreation, power generation, etc.) and transportation applications of interest in this paper. The annual market for each category of application is estimated as a function of price range in terms of dollars per kilowatt. Based on this assessment the total annual market for fuel cell systems of all types could be between 40 and 50 billion dollars per year.

7.2 DEVELOPMENT OF MARKET AND BENEFIT SCENARIOS

The use of scenarios will make it possible to consider a very wide range of technical, economic, and political uncertainties. Given the period of time (40 years) which this study considers, it is impossible to predict specific outcomes; but, it is probably possible to estimate the upper and

lower bounds of each major parameter. These "bounds" can then be incorporated into logically consistent scenarios to project potential vehicle markets, fuel requirements, and energy and environmental benefits. Hopefully, these "bounds" will be wide enough to encompass all potential futures.

<u>Application</u>	<u>Annual Sales</u>	<u>Target Price</u> ^[1]	<u>Year</u> ^[2]	<u>Fuel Cell System Sales</u> ^[3]
Military	Not defined	\$1,500/kW \$1,125/kW	1997 2000	Not definable
Recreation	Not defined	\$500-\$1000/kW \$200-\$500/kW	1997 2000	Not defined
Electrical Power Generation				
Utility	---	\$500-\$1000/kW	1995-98	\$10-\$30 Billion
Utility and Cogeneration	---	\$500-\$750/kW	2000	\$20-\$40 Billion
Household Power	---	\$50-\$100/kW	2020	\$2-\$4 Billion
Maritime	Not defined	\$1000/kW	?	Not defined
Locomotives	250/yr. 1000/Yr.	\$400/hp ^[4] \$200/hp ^[5]	2000 2005	\$200-\$400 Million \$200-1250 Million
Buses	---	---	---	---
Trucks	10,000/Yr. 200,000/Yr.	\$200/hp \$100/hp	2005 2010	\$250-\$400 Million \$10-\$20 Billion
Automobiles	100,000/Yr. 10,000,000/Yr.	\$250/hp ^[6] \$50/hp ^[7]	2010 2015	\$2-\$4 Billion \$10-\$15 Billion

[1] Price for fuel cell engine and drive train only
 For locomotives approximately 2/3 of the cost is for the fuel cell engine
 For trucks approximately 1/2 of the cost is for the fuel cell engine
 For cars approximately 1/3 of the cost is for the fuel cell engine

[2] Target price-may not be realizable

[3] Sale of fuel cell engine propulsion systems (including electric drives)

[4] Stage I economics, competitive with electrification

[5] Stage II economics, competitive with diesel engines

[6] Stage I economics, competitive with battery/electric cars

[7] Stage II economics, competitive with gasoline engines

Table VII-6. Preliminary Fuel Cell Powered Applications Market Estimates

The scenarios will assume:

- Different rates of development of fuel cell engine propulsion systems and other alternative propulsion systems based on available funding and technical success
- A range of incremental costs to buyers of fuel cell and conventional engine propelled vehicles
- Two different rates of economic growth
- A range of energy prices

- Low and high assumptions regarding the requirements of federal and state energy consumption and environmental emission regulations
- Low and high assumptions regarding the acceptance of fuel cell engine powered propulsion for trucks and locomotives
- The difference in personal transportation requirements in response to two possible types of urban development, edge and new cities.

During the next phase of the study the findings outlined in the previous sections will be used to construct four scenarios, each of which describes a potential level of use of vehicles propelled by advanced propulsion systems. The range of underlying assumptions will be broad enough to identify both the uncertainties in the projections and the commercialization strategies which must be sufficiently robust to account for uncertainties in economics, technology, and the regulatory environment.

A very large number of scenarios could be developed to illustrate alternative conditions. However, for simplicity four scenarios will be utilized as they appear to illustrate the most logical futures:

1. Extension of historic trends - (Conventional)
2. Compliance with the CARB environmental standards and time schedule
3. Compliance with the CARB standards, but incorporation of revised time schedules to permit the introduction of fuel cell engine propulsion systems, etc.
4. Scenario 3, but with the addition of innovative personal and freight transportation concepts.

7.2.1 The First Scenario - Extension of Historic (Conventional) Trends

This scenario will be based on the continuation of existing or evolutionary trends in the development of advanced vehicles and propulsion systems. No significant increase in regulations are assumed beyond those in place in 1994. Comparisons will be prepared from data published in other studies and the analysis (derived from household disposable income) used in this scenario.

7.2.2 The Second Scenario - Compliance with California Environmental Standards

This scenario will be based on the assumption that strict California environmental standards are imposed, and met, in California and approximately half-of the other states. The scenario will also assume that there are no restrictions on the availability of alternative fuels or vehicles which can use them. Further, it will be assumed that people accept the probable compromises in vehicle design, performance, and mobility required to achieve these standards. Feedback, or reductions in vehicle sales and miles driven with increased fuel cost (per mile driven or ton mile), will be included in the estimates of vehicle sales and fuel consumption.

7.2.3 The Third Scenario - Compliance with California Standards, but with a Revised Time Schedule to Permit Use of Fuel Cell Engine Propulsion Systems

This scenario will be based on the assumption that the introduction of advanced propulsion systems, fuel cell and/or gas turbine engines, etc., for various vehicles will occur on a time schedule consistent with the completion of the research and development required for such advanced propulsion systems. This scenario will also include allowances for the time to build

advanced propulsion system manufacturing facilities and assumes that California, and the other states which adopt California environmental standards, phase in and adapt the standards on a basis consistent with the availability of suitable advanced propulsion system products.

7.2.4 The Fourth Scenario - Impact of Innovative Transportation Concepts

This scenario encompasses the third scenario but also includes assumptions on the commercialization of innovative automotive concepts, smart highways, and innovative freight systems discussed earlier. Taxes, fees, or other incentives which may be instituted to encourage people to meet California environmental standards will also be considered.

7.3 COMMON ASSUMPTIONS/SCENARIO DESCRIPTIONS

Each of the scenarios will include two subcases, low and high economic growth coupled with low and high energy prices. Other forecasts will be used to project gross domestic product, total population growth (working age), the number of people employed, and the number of households within the U.S. The average, or base dollar, amount used for family income projections was approximately \$15,200 in 1985. The range of forecasts by the Energy Information Administration, DRI, Wharton, and the Presidents Council of Economic Advisors are summarized in Table VII-7.

<u>Forecast Organization</u>	<u>Real GDP</u>	<u>Labor Force</u>	<u>Productivity</u>
EIA	1.8%-2.4%/year	1.0%-1.3%/year	0.8%-1.1%/year
DRI	1.7%-2.5%/year	1.0%-1.3%/year	0.7%-1.2%/year
Wharton	2.1%-2.9%/year	1.2%-1.5%/year	1.0%-1.4%/year
CEA	2.1%/year	not forecast	not forecast

Table VII-7. Range of Forecasts by the Energy Information Administration, DRI, Wharton, and the Presidents Council of Economic Advisors

U.S. Congressional Budget Office (CBO) projections of disposable income for 1997 predict an increase of 8 to 10% over 1990. This report assumed a 2.5% per year increase in the Gross Domestic Product. Other projections of GDP growth during the period between 1990 and 2001 predict increases of 2.0% to 2.8% [62,72,113,115]. Since the 1940's the U.S. car market has changed almost directly with the level of personal disposable income. For decades families have spent about 14% of their disposable income on transportation. Of this amount 57% (8% of the total disposable income) goes for the purchase of new cars plus gas and oil.

The underlying conditions from which the projections in other scenarios will be derived will be based on generally accepted forecasts of vehicle fleet size, trip generation, and energy demand. Existing reports, such as Argonne National Laboratories Report ANL/ESD-9, will provide the basis for comparison. Its projections will be updated to evaluate the impact of higher energy efficiency (CAFE) standards and the mandated use of alternative energy advanced propulsion systems to achieve environmental goals. The projections of automobile energy consumption will be based on logical extensions of existing information on travel patterns, domestic (commuting, shopping etc.) and intercity travel. The projections will reflect the way household travel decisions vary with disposable income.

For simplicity:

- The percent of disposable income devoted to purchase (or lease) of cars will be held constant
- Travel, and automobile purchase price assumptions, will be varied to maintain a constant percent of disposable income
- Disposable income will be derived from assumptions on the rate of change of gross domestic product
- Person miles traveled will be a function of projected locations of homes, work sites, commercial, and recreational centers
- The length and duration of trips will be modified to account for the adoption of new technologies (such as improved communications and highways)
- Vehicle miles traveled (VMT) will be a function of personal disposable income, the economics of the advanced propulsion systems, the purchase and operating cost of cars (or other vehicles), and the cost and availability of fuels.

A simplified illustration of the logic which can be used to project future markets for private cars and other vehicles powered by advanced propulsion systems is illustrated in Figure VII-1. Freight transportation is likewise based on gross domestic product changes and the trends in the movement of major goods categories. Existing information on both shipper movements and total percent of an industry's earnings devoted to transportation will be assumed to remain essentially constant. Similar relationships have been developed for truck and railroad movement of freight. The buyers of freight transportation equipment (trucks and railroad equipment) are very sensitive to costs, service potential, and ability to earn a reasonable return on their investments. For the sake of this study a simplified market and benefits logic scheme similar to that illustrated by Figure VII-1 will be used to project changes in the volume of freight movement and the potential market for fuel cell engine systems and compatible fuels for commercial vehicles. The simplified logic diagram for this assessment is presented in Figure VII-2.

National (and state) aggregated approaches, starting with economic growth of national and household incomes, make it possible to account for changes in energy and vehicle cost as new technologies and new means of transportation are introduced. This approach includes developments which are not usually incorporated in more widely used analysis techniques; most of the current analysis techniques incorporate additional details on only some, or a very few aspects, of the projected scenarios.

Figure VII-1. Logic Diagram, Automobile Fleet Size, Energy Consumption, and Pollution Generation

Figure VII-2. Commercial Vehicle Propulsion System Economic and Market Assessment, Simplified Logic Diagram

7.3.1 First Scenario - Extension of Historic Trends

This scenario assumes the continuation of existing or evolutionary trends in vehicle design and use. It also assumes that there are no significant increases in energy or environmental regulations. The economic projections will be derived from federal reports on energy cost, price, vehicle travel, etc.

Since the absolute levels of personal and goods movement cannot be predicted with confidence, it appears to be useful to indicate how different assumptions can change a generally accepted forecast such as the projections presented in ANL/ESD-9 [4]. The forecasts of transportation demand will be based on projections of:

- The changing demand for travel, by purpose
- The changing requirements for goods movement, by category
- The purchase and operating costs of the vehicle.

These projections, in turn, will be sensitive to the cost of energy which will be based on projections of:

- The retail price of gasoline and diesel fuels
- The total vehicle fleet configuration (in particular, automobiles and personal trucks)
- The availability of alternative fuels as a function of time
- The retail price of alternative fuels
- The actual consumption of alternative fuels.

The base conditions and trends in automobile ownership and energy consumption used in this scenario have been derived from several federal reports including: The Forecast of Transportation Energy Demand Through 2010 [41], The National Energy Outlook with Projections to 2010, and The Transportation Energy Data Book, Edition 12.

The projections in these reports assumed that the energy efficiency standards will continue to be set at the national level and that the improvements will be gradual (because of technical and economic limitations). All of the reports assumed continuation of existing technologies, with only minor changes in regulations, and no new transportation concepts.

The typical assumption in these reports was that advanced and improved four stroke internal combustion engines would continue to be the primary power plant for both cars and trucks. Two stroke engines (projected to potentially have 15% better efficiency) are assumed to be used in less than 5% of the cars. Other changes include an assumed reduction in the average vehicle drag coefficient to 0.3 Cd which, in combination with improved four stroke engines, would improve fuel economy (miles per gallon) about 3.5%. While the estimates in these reports provide the "accepted base projections" for this study, it should be pointed out that any significant improvements in the performance of conventional internal combustion engines will be difficult to achieve. The future market projection for automobiles and trucks is presented in Table VII-8, taken from Reference 41.

A range of energy prices will be utilized; the high price bound will be based on continued price manipulation by the OPEC nations, the low price bound will be based on a "free" market. The high price estimates will assume continued control of crude oil production by the Organization

of Oil Exporting Nations to maximize their profits. The long term upper bound will be defined by the cost of alternative fuels. The low price will assume a near open (competitive) market for crude oil.

Year	Personal Cars	Fleet Cars	Light Trucks	Heavy Trucks₍₁₎
1985	122,300,000	8,900,000	23,500,000	17,300,000
1990	140,400,000	9,200,000	29,600,000	19,700,000
1995	150,600,000	9,900,000	35,400,000	21,300,000
2000	161,500,000	10,800,000	39,600,000	23,700,000
2010	184,700,000	13,000,000	44,600,000	28,800,000
2020	Not estimated	Not estimated	Not Estimated	Not Estimated
2030	---	---	---	---

(1) Class 6, 7, and 8

Table VII-8. Projected Number of Automotive Vehicles in U.S. Fleet, Present Trends

Historically (before the first energy shock of 1973), on an equalized basis (same weight, same acceleration, same accessories), the fuel economy of a U.S. automobile improved at 1 to 2% per year in terms of gallons per mile (gal/mi.). The projections in this scenario assume continuation of this underlying trend. Advances in technology should tend to improve regional air quality, even if improved environmental control standards are not mandated. But, the rate of improvement will be much slower. A number of sources were used to project the probable future fuel economy of automobiles and trucks under this scenario; the results are summarized in Table VII-9. The table reflects estimates from both the sources and the author regarding the changes in fuel economy levels for these vehicles; mandates, even current CAFE standards, for major changes were not considered in order that fuel economy projections for this scenario represent the worst case "base" condition.

Year	Automobiles/Projector		Light Trucks/Projector
	ANL	DEI	ANL
1985	17.9	00.0	13.6
1988	---	20.0	---
1990	19.1	21.1	14.5
1995	20.3	23.1	15.4
2000	21.0	24.3	15.7
2010	24.3	27.2	17.7
2020	---	---	---
2030	---	---	---

Table VII-9. Projections of the Fuel Economy of Personal Cars and Trucks, Miles per Gallon

It is anticipated that the average fuel economies of cars and, hence, the vehicle fleet may be lower than these projections which will be used as the low fuel economy case in the scenarios. The annual fleet average travel, as depicted in Table VII-10, will be adjusted as a function of energy cost (budget) so that, as costs change, trip lengths and frequency will also change (0.6 elasticity, see below) as people make adjustments to maintain their budget. Any balance of money is assumed to be used to acquire new cars. These assumptions will be adjusted for each successive year as the energy consumption and emission production of the U.S. vehicle fleet are projected.

The use of gasoline and other fuels is sensitive to price. A short term energy use/price elasticity of about 0.6 is assumed (that is, fuel use decreases 6% for a 10% increase in price). Long term elasticity (10 year) will be assumed to be 1.0 [38].

<u>Model Year</u>	<u>Annual Mileage</u>	
Fleet Average 1992	9,800	
New 1992	13,000	132% of 1992 average
Pre 1972	4,500	46% of 1992 average
1972-74	4,700	48% of 1992 average
1975-81	6,500	66% of 1992 average
Post 1981	10,500	107% of 1992 average

Table VII-10. Average Annual Mileage by Model Year Age Groups

The information developed for Scenario One will be presented in the form of sensitivity plots. These plots will include assumptions on the lower and upper bounds of the parameters of interest with information presented for even increments between the lower and upper bounds. For example, fuel consumption may be shown at a range of propulsion system efficiencies from 20 to 50% at 5% increments. These sensitivity plots make it possible to identify incremental changes which would be caused by changes in parameters such as: emission levels as a function of power, fuel cost per mile, changes in vehicle purchase price, and the introduction of innovative transportation services. This approach will illustrate the robustness of the propulsion and transportation system concepts being evaluated, rather than develop specific detailed projections.

7.3.2 Second Scenario - California Automotive Emission Standards

This scenario is based on the assumption that strict California environmental standards will be met by the best available methods, i.e., the use of small internal combustion engine cars, hybrid and battery/electric cars. There will be two cases considered:

First --- Proposed California emission standards and timing will be adopted

Second --- Approximately half of the other states adopt the same California requirements.

The underlying assumption of this scenario is that people will accept the compromises in vehicle design and performance required to achieve these standards, and that there are no limits on the availability of alternative fuels or products. Two levels of economic growth and energy (gasoline) prices will be assumed. The gasoline prices were described in the gasoline portion of Section VI of this report. One assumption not involved in this scenario is that

accelerated development of fuel cell engines (and other advanced low emission power plants) could make it possible to achieve pollution objectives sooner than would be the case if the development of fuel cell engines continued on their present pace. Under this "Scenario Two", however, the majority of technical and financial resources will be directed at "second best" concepts, which will not provide the energy efficiency or environmental benefits of fuel cell engines. While the impact of introducing fuel cell type engines is considered in this scenario, later scenarios consider their impact in more detail.

Economic constraints discussed previously will be included; that is, as the cost of vehicles and energy increase, the total sales and use of cars (and trucks) will decrease. The analysis process and assumptions will be the same as were used for Scenario One. The prices of vehicles will be projected in ten year intervals through 2030. Two forecasts will be prepared based on low and high economic growth levels combined with two different assumptions regarding vehicle price. Light vehicles will be divided into personal and fleet cars and light trucks (and vans). Use and cost of heavy duty (class 7&8) trucks will be also be estimated as will the use and price of other related vehicles like buses and locomotives. The total number of cars sold will be estimated to be a function of their average price and the average percentage of disposable income which the typical household has to spend on transportation. For example, an average of 8% of total household disposable income has been used to purchase and operate cars.

Year	Other		TLEV		LEV		ULEV		ZEV		Total	
	[1]	[2]	[1]	[2]	[1]	[2]	[1]	[2]	[1]	[2]	[1]	[2]
1994	986-1100		110-115		---		---		---		110-1220	
1995	950-1060		168-185		---		---		---		1120-1250	
1996	910-1020		225-255		---		---		---		1140-1280	
1997	855-915		---		290-365		23-26		---		1170-1310	
1998	570-650		---		570-645		24-27		24-27		1190-1350	
1999	275-390		---		885-1005		24-27		24-27		1210-1300	
2000	---		---		1190-1365		25-28		25-28		1240-1420	
2001	---		---		1135-1315		63-73		63-73		1260-1460	
2002	---		---		1095-1275		129-150		64-74		1290-1500	
2003	---		---		985-1165		196-235		130-160		1310-1588	
2005	To be determined		---		---		---		---		To be developed	
2010	To be determined		---		---		---		---		To be developed	
2020	To be determined		---		---		---		---		To be developed	
2030	To be determined		---		---		---		---		To be developed	

Other: Conventional cars which meet federal standards

[1] Low economic growth, high oil prices

[2] High economic growth, low oil prices

Note: These are preliminary tables which will be changed as additional information is developed

Table VII-11. Estimate of California Mandated Car Sales, Scenario Two, Thousands of Vehicles

Using this relationship, and assuming that the average cost of cars changes as described earlier in this section of the report, the total sales of cars in California would be predicted to be as indicated in Table VII-11 above; the projected car sales for the U.S. as a whole are presented in Table VII-12.

These assumptions will be modified to account for the introduction of fuel cell engine powered and other low emission/low fuel consumption vehicles after 2005. These estimates (and related low and high boundaries) will be combined with assumptions on vehicle life and typical mileage driven as a function of vehicle age and capability; then, estimates can be prepared of the probable vehicle miles traveled by each car category, accounting also for the capabilities of each car category.

National sales of cars which meet the California standards can be estimated (Table VII-12) by assuming that the states which already have extreme or severe environmental pollution by federal standards adopt the California standards. These states include: Texas with 8.6 million cars, California with 17.1 million cars, New York with 8.8 million cars, Pennsylvania with 6.4 million cars, Connecticut with 2.5 million cars, Wisconsin with 2.75 million cars, Illinois with 6.4 million cars, Delaware with 4 million cars, Maryland with 2.9 million cars, and the District of Columbia with 250,000 cars. These nine states (and the District of Columbia) have a combined total of 60 million cars.

Year	Other		TLEV		LEV		ULEV		ZEV		Total	
	[1]	[2]	[1]	[2]	[1]	[2]	[1]	[2]	[1]	[2]	[1]	[2]
1994	13.9-14.7		0.66-0.73		---		---		---		14.6-15.8?	
1995	13.7-14.9		1.03-1.13		---		---		---		14.6-16.0?	
1996	13.6-14.8		1.36-1.48		---		---		---		15.0-16.3?	
1997	14.0-15.4		---		1.04-1.14		0.14-0.15		---		15.2-16.7?	
1998	13.1-14.7		---		1.98-2.21		0.15-0.16		0.15-0.167		15.4-17.2?	
1999	9.8-11.2		---		5.33-6.05		0.15-0.17		0.15-0.17		15.5-17.5?	
2000	8.3-9.6		---		7.07-8.16		0.15-0.17		0.15-0.17		15.7-18.1?	
2001	8.6-9.6		---		6.77-7.83		0.37-0.43		0.37-0.43		16.0-18.5?	
2002	8.4-9.9		---		6.61-7.80		0.75-0.89		0.37-0.44		16.1-19.0?	
2003	8.6-10.3		---		5.74-6.87		1.14-1.37		0.76-0.91		16.3-19.1?	
2005	To be developed		---		---		---		---		To be developed	
2010	To be developed		---		---		---		---		To be developed	
2020	To be developed		---		---		---		---		To be developed	
2030	To be developed		---		---		---		---		To be developed	

[1] Low economic growth, high oil prices

[2] High economic growth, low oil prices

Note The estimated car volumes in this table are illustrative and will be changed as more information is obtained

Table VII-12. Estimate of National Car Sales, Assuming that States with Extreme Non-Compliance Adopt California Mandates, Scenario Two, Millions of Vehicles

The national vehicle miles traveled by each category of car or truck (TLEV, LEV, ULEV, ZEV, etc.) will then be estimated using similar assumptions to those used to generate the projections for California.

Sales (and fleet size) of vehicles which can meet each emission standard (TLEV, LEV, ULEV, ZEV, etc.), as well as projections of the mix of car size and propulsion system type, will be estimated for the period of interest (1990-2030).

The projection will assume two levels of prices for fuel cell engine system propelled cars. The first generation of such vehicles will be incorporated into this projection only if their economics are superior to other low or zero emission vehicles. The lower cost second generation fuel cell engine system powered vehicles will encourage the transition of all vehicles to electrochemical engines. All ULEV and ZEV vehicles are projected to be fuel cell engine powered by 2020; this is also expected to be true for many cars and trucks even when emission requirements are not the major deciding factor in deciding what vehicle to acquire. The projections will incorporate both low and high fuel cell engine system costs as well as low and high economic growth rates. The estimate of miles traveled by fuel cell engine system powered cars will be a function of their estimated percentage of the fleet mix per household and the travel propensity of vehicle owners as estimated from their disposable family income.

The initial estimate of truck sales and vehicle miles traveled by both truck and rail will be computed using extensions based on existing truck sales for the assumed low growth version of this scenario. Projections for a high growth case will use modified assumptions regarding the potential diversion of truck to rail by assuming significant (but possible) improvements in railroad attractiveness to shippers. The potential vehicle miles traveled by truck will be based on an assumed relationship between the changes in gross domestic product and the quantity of freight movement. The historic relationships described in reference papers will be extended to new economic, vehicle, and energy/cost situations.

The number of fuel cell engine system powered trucks will depend on the specific regulatory energy and environmental mandates and the projected rate of development of fuel cell engine propulsion system competitors such as gas turbines for trucks. The number of urban and intercity trucks will be based on historic trends of truck sales and fleets as a function of economic activity. The total energy consumption by fuel cell engine system powered truck vehicles will be a function of their efficiency, size of the fleet, and number of miles traveled. Estimates will be prepared regarding energy consumption by engine type, and the energy and environmental characteristics of each vehicle fuel system at 10 year intervals beginning in 1990 and extending to 2030.

The actual estimate of the split between diesel, gas turbine, and fuel cell engines for trucks will be based on the assumption that both turbine and fuel cell engines will achieve the required air quality standards for class 7 and 8 trucks and that, due to engine size and costs, relatively low emission gas turbines will capture a significant portion of the future market. The fleet size and annual sales will be based on the buyer's preference assuming that the previously discussed estimates of the production and operating costs of automotive and truck gas turbines are achieved.

The potential commercialization of alternative fuels/engines for cars or trucks will depend on mandates and federal regulations. The underlying question is how the public will perceive the

difference between competitive propulsion systems. While some forecasts indicate fractional markets for a number of candidate systems and/or types of fuel, entry cost (research, development, design, and production capacity) make this unlikely. It is probable that one propulsion/fuel system will provide the best performance at the lowest ownership cost, given the energy and environmental requirements; this system will become the dominant power plant.

The price of propulsion systems will be assumed to include the amortization of private investments in research, development, manufacturing process, etc. These forecasts will assume that government support is available for fuel cell engine research and development through the point that the business risks have been reduced to a level comparable with other private sector investments. Estimates of the cost of private sector contribution to the research and commercialization efforts will include the costs to complete the: required research; engineering development and demonstration; acquisition of manufacturing facilities; and the development of fuel processing, distribution, and retail facilities.

The costs of continued research on, and manufacture of, battery and hybrid/electric technologies and production of advanced piston engines required to either satisfy future regulations and/or facilitate the transition to fuel cell engines will also be addressed. In each case low and high estimates of the cost and time will be prepared.

The total fuel consumed in California will be based on estimates of the mileage of the existing and projected fleets of cars, by age, energy consumption, and miles driven.

7.3.3 Third Scenario - California Standards with Modified Schedules

This scenario assumes that the California environmental standards are mandated, but that the time at which the mandates become effective are revised to permit the development of fuel cell engine and alternative fuel systems on a schedule that would minimize the technical and political risks during their introduction. The construction of facilities to produce the quantities of methanol and natural gas required is expected to take several decades. The delays in the creation of adequate methanol (or other alternative fuel) capacity will be the primary difference between Scenarios Two and Three.

This scenario also includes allowances for the time required to complete research, development, testing, and product improvements to eliminate probable initial failures prior to making major public commitments to new technologies. The projections of market, energy use, etc., in this scenario will be based on the assumption that the other states which adopt California's environmental standards phase them in and adapt them to their needs utilizing a schedule that adequately permits the development of new technologies and fuel systems.

7.3.4 Fourth Scenario - Modified Schedules and Innovative Transportation Concepts

This scenario is based on the assumptions of Scenario Three and that a series of innovative transportation concepts are made available to the public, including: alternative automobiles, smart highways and routing systems, and innovative freight systems. Many (but not all) of the "vehicles" may use fuel cell engine power plants. Fuel cell engine system introduction will be assumed to occur on a reasonable (timely) schedule. Scenario 4 also assumes that tax and similar incentives are instituted to encourage people to meet the desired environmental standards. This is assumed to occur first in California, then spread to other states. The

vehicles and propulsion systems which will be considered in evaluating alternative future scenarios include the following concepts.

Alternative Automobile Concepts. Performance, costs, energy consumption, and estimated pollutants will be projected for each of the following car concepts.

- **Conventional "family" cars**, in which applicable propulsion systems include gasoline and natural gas powered internal combustion engines and/or battery/electric and fuel cell engine powered systems.
- **Personal trucks and vans**, in which applicable propulsion systems include gasoline and natural gas powered internal combustion engines and/or battery/electric and fuel cell engine powered systems.
- **Narrow (half width) cars**, which are two passenger (tandem) freeway compatible, motor vehicle safety standard qualified cars. Applicable propulsion systems include gasoline and natural gas powered internal combustion engines and/or battery/electric and fuel cell engine powered systems. While approximately 80% of the commuting trips could be satisfied by use of a single passenger (or two in tandem) commuter car, it is unlikely that more than half the households (those who now own two or more cars) would purchase them. For the sensitivity assessment this analysis will assume two levels of commuter car sales and use:
 1. That half of the two car households will purchase a commuter car and use it for 80% of their commuting
 2. That 10% of the car households will purchase a commuter car and use it for 50% of their commuting.

Offsetting this, the use of fuel cell engine propulsion systems could improve the performance and acceptability of "conventional " family sedans. Family sedans with fuel cell engines could have lower maintenance costs, longer life expectancy, and more freedom of packaging which could lead to new and unique configurations. These facts may alter the need for commuter cars.

- **Runabouts** are two passenger battery/electric cars having at least 30 minutes of operation at 45 mph. These are motor vehicle safety standard qualified cars. Applicable propulsion systems again include gasoline and natural gas powered internal combustion engines and/or battery/electric and fuel cell engine powered systems. As previously discussed, data indicate that half of the trips in most urban areas could be made in less than 10 minutes (one way) by runabouts (shoppers, public transit access, or neighborhood cars). A preliminary study by Southern California Edison, Caltrans, and South Coast Air Quality Management district indicated that 10% of the households would purchase such a car if priced below utility or used cars. Nearly 50% of the households indicated that they would seriously consider purchasing such a vehicle. The acceptance was almost independent of household income or other car ownership. Additional demonstrations will be required to quantify the potential market. Fuel cell engines could increase the usefulness of these cars; costs should be lower than for battery/electric powered versions. For the purposes of this scenario two levels of neighborhood car sale and use will be assumed:
 1. That 40% of the households will purchase such cars and use them for 80% of their short trips

2. That only 10% of the households will purchase such cars and use them for 50% of their short trips.

These assumptions will be addressed for both low and high economic growth situations.

Advanced Traffic Control Systems. The effect on performance, cost, energy consumption, and estimated pollutants will be estimated for each of the following transportation control systems, using both conventionally propelled and the "best" alternative propulsion system powered cars and trucks:

- Smart highway systems (IVHS)
- Adaptive traffic signal systems
- Traffic information and routing systems
- Road or congestion pricing systems
- Environmental fees based on use of road pricing information.

Advanced Public Transit. Performance, cost, energy consumption, and estimated pollutants will be projected for each of the following public transit categories:

- **Rail transit**, for which propulsion system candidates include diesel engine, catenary, fuel cell engine, and battery/electric powered systems
- **Transit buses**, for which propulsion system candidates include diesel engine, catenary, fuel cell engine, and battery/electric powered systems
- **High speed passenger rail systems**, for which propulsion system candidates include turbine engine, catenary, fuel cell engine, battery/electric, and magnetic levitation powered systems.

Two cases for public transit use will be assumed in the scenario. The low use case will assume that public transit utilization is inversely proportional to the level of personal disposable income (1% decrease for 1% increase). In the second (high use) case the present level of public transit use (as a function of family disposable income) will be assumed to double where innovative new systems are implemented. For the purposes of this assessment the sensitivity of energy consumption and emissions from public transit use will be assessed by making two further assumptions:

- That transit use continues to change in proportion to changes in disposable income
- That transit use can be increased 50% (to an average of about 15% of total ridership) by improved services and access, decreased trip times, etc.

Projections will be prepared for ridership by conventional bus, heavy rail, light rail, and commuter rail at ten year increments from the present time to the year 2030. Assumptions regarding public transit use will be combined with projections coupled to the change in urban structure (toward "edge" cities), estimated number of trips, and total fuel consumption of conventional and alternative automobiles. In the low use case no high speed passenger systems are assumed to be developed. On the other hand, the high economic growth case will assume that use of high speed ground passenger systems replaces 25% of all trips less than 300 miles in length on major proposed routes. Airlines will continue to dominate longer trips.

Advanced Freight Systems. Performance, cost, energy consumption, and pollutant levels will be projected for each of the following truck and railroad freight systems considering both conventional (diesel) and advanced propulsion systems.

- **Local truck movement**, for which propulsion system candidates include diesel engines, gas turbine engines, fuel cell engines, and battery/electric powered systems. Petroleum, methanol, and natural gas may all be considered as potential fuels for each system, except, of course, for the pure battery/electric system which is recharged by electricity from a central power station.
- **Railroad based local freight distribution systems**, for which propulsion system candidates include diesel engines, gas turbine engines, fuel cell engines, battery/electric powered systems, and electric catenaries. Potential fuels for the non-pure electric systems again include diesel, methanol, natural gas, and even hydrogen.
- **Expedited, 150 mph railroad freight systems**, for which propulsion system candidates include diesel engines, gas turbine engines, fuel cell engines, electric catenaries, and magnetic levitation powered systems.

The low use case scenario will assume that only evolutionary improvements will be made in freight delivery systems. The high use case scenario assumes that both the routing of delivery trucks and the time of day in which deliveries are made are optimized. Further, the high use case scenario assumes that the railroads will use low emission locomotives and improve service so as to attract 20% of the high valued shipments over 300 miles presently being transported on trucks. The same analysis techniques will be used as in the previous scenarios. The major change will be the preparation of estimates of the mix of alternative cars and trucks as well as diversion of goods to rail shipment. In each case a range of assumptions regarding prices, penetration of the freight market, and performance of competing transportation modes will be assumed.

Projections will be developed of the truck sales (and fleet) by propulsion system; i.e., diesel engine, fuel cell engine, gas turbine engine, etc. Different fuels will also be considered. The assumptions that account for improvements in freight handling systems, in particular increased use of railroads, will also consider the expected potential reduction in total energy consumption.

7.4 SUMMARY COMPARISON OF EMISSION LEVELS AND ENERGY CONSUMPTION BY SCENARIO

A comparison of the emission levels and energy consumption for the four scenarios will be prepared. It will reveal how the scenarios influence the use of fuels, vehicle mileage, vehicle sales, etc. The fuel consumption and emissions, presented by vehicle/engine type, will be the sum of that for all ground transportation modes, including cars, buses, trucks, and trains. The findings will be summarized by scenario, type of vehicle, type of propulsion system, and type of fuel. The results will be presented in 10 year increments as a function of the type of fuel used (reformulated gasoline, methanol, ethanol, natural gas, electrical power, hydrogen, etc.).

The estimates of emission levels will be a function of vehicle efficiency, emissions, miles traveled, and the size of the fleet of specific categories of vehicles. For older vehicles the estimates developed by the California Air Resources Board will be used. The emission data will illustrate the relative magnitude of the changes in the more important emissions: carbon monoxide, carbon dioxide, nitrous oxides, aldehydes, and particulates on an aggregate

(national or California) basis. The study will not address the relative importance of these emissions or how the improvements will benefit selected regions of the nation. It would be desirable to time weight the emission reductions (much like the value of future earnings is discounted). Near term emission reductions would be more valuable than higher emission reductions at a later date.

VIII. POTENTIAL COMMERCIALIZATION STRATEGIES FOR ELECTROCHEMICAL ENGINES

This section of the report discusses some aspects of the process of commercializing new products, in particular, advanced or alternative propulsion systems within the United States. The discussion includes the requirements for government sponsorship, private sector investment and risk taking, and the need to develop consumer confidence in those products which use innovative propulsion technologies.

8.1 POTENTIAL PROBLEMS IN COMMERCIALIZING ALTERNATIVE PROPULSION SYSTEMS

The commercialization of electrochemical engines can be divided into two (2) stages or time frames:

- First -- Their use to achieve mandated (environmental and/or energy efficiency) goals
- Second -- Their acceptance by buyers as superior engines to competitive propulsion systems.

Ideally, the commercialization of a new technology would normally be undertaken when developers identify a niche where the technology provides superior performance or economics compared to competitive technologies; then, at that point a product could be built and sold for a profit. In this case, however, the initial opportunities will be those where the fuel cell engine provides value which is not easily replicated by other advanced energy conversion technologies. Examples include military applications, battery applications where continuous power is required (such as hand tools), luxury applications such as auxiliary power for yachts and other recreational vehicles, and stationary power at either remote sites or at those sites which are not well served by existing utilities. These types of applications, as well as fuel cell engine usage in heavy commercial vehicles such as locomotives, buses, and trucks, will probably be commercialized before fuel cell engines for light vehicles become economic. Such commercialization of fuel cell engines for commercialized vehicles would provide experience in fuel cell engine system manufacturing and use which can be applied to the development of competitive fuel cell engines for light vehicles. The non-mandated commercialization of fuel cell engines will occur when vehicle purchasers perceive that the cost and utility of the new technology is preferable to that of existing engines or other competitive propulsion systems. If there is adequate time and public acceptance the economic transition to fuel cell engine propulsion will occur, probably over a period of several decades.

The cost of developing electrochemical engines, combined with market risks, make it doubtful that private industry will make major investments in their development without some form of government support. Government support will be particularly important during the early phases when the economic and technical viability of the use of fuel cell engines has not been confirmed. Advocates of advanced technologies criticize the automobile industry because of its apparent reluctance to build and market battery/electric cars; in the minds of such advocates the automotive industry has an image of resisting building cars that meet "societally beneficial" energy and environmental standards. It may be impossible for the industry to present its case effectively, but it is evident that, to date, it has not. Industry spokespersons emphasize that the industry will produce any product on which it can make a profit. The industry will resist

producing vehicles at a loss, even if mandated. However, while all of the industry's expenditures on advanced propulsion systems are not public record (some may not even be internally identifiable), the known expenditures by the U.S. automobile industry on battery/electric propulsion exceed those by all other agencies, government and private. The industry started work on alternative propulsion systems in the 1960's; a demonstration of a fuel cell powered van was first conducted by GM during this period.

Studies of the automobile industry's capability to respond to the most severe combination of proposed energy and environmental regulations indicate that such regulations could be met by downsizing and restricting performance of conventional cars, coupled with the sale of some battery/electric cars. The sale of "environmental cars" may require subsidized pricing to encourage people to purchase them. This strategy could lead to a reduction in the market for cars and (as a result) large losses for all vehicle manufacturers. After a few years of limited product offerings industry observers expect that public opposition would become strong (as in the cases of the 55 mph speed limit and seat belt interlocks) and that the energy standards would be moderated. The long run beneficiaries could be the companies having large world markets; these are primarily foreign manufacturers.

A study by the University of Michigan's Center for the Study of Automotive Transportation [135] includes estimates that the industry has to invest approximately \$140 billion to develop new automobile models and another \$84 billion to develop new truck models by 1997, or nearly \$45 billion per year. This is about three times the recent investments by the industry in new products. In the same period foreign companies are expected to spend more than \$300 billion (\$225 billion by the Japanese suppliers alone) on new automotive products aimed at the American market. Even with increased American investment, the share of American platforms in the U.S. car market could drop from 70 to less than 50 percent.

The recent downturn in the Japanese economy may, however, make it possible for the U.S. producers to "hold their own". On the other hand, while the details are not well understood it is known that both German and Japanese companies have extensive fuel cell engine system development programs, based in part on prior U.S. findings, which could enable them to penetrate the near zero emission vehicle market.

8.1.1 Private Sector Investment and Risk

Investments in fuel cell engine development present a number of risks, each of which must be satisfactorily addressed, including:

- Technical - Will the performance capabilities and new fuel infrastructure (if required) be achieved?
- Scheduling - Are the present schedules consistent with the time required to develop reliable, economically competitive fuel cell engine propulsion systems?
- Economic - Will the costs be competitive?
- Business - Can the manufacturers make a profit?
- Political - What problems will be solved and/or generated by sponsoring fuel cell engine propulsion development initiatives?

- Societal - Will there be perceived societal concerns? Could elements of fuel cell engine system performance, operation, or manufacture/purchase be unacceptable to users or the general public?

In the writer's opinion these risks can be addressed as follows:

- The **technical risks** are low; fuel cell engines will work.
- The **ability to meet propulsion needs in a timely manner** is questionable. When fuel cell engine system performance and economic benefits are confirmed they should become the dominant propulsion system for ground vehicles; but this confirmation may not occur for a decade or more. The time which will be required for a transition to substantial fuel cell engine usage, on the basis of economics alone, will be too slow to meet the goals defined for reductions in pollution and energy consumption.
- The **economic risks** are higher; costs may not be reduced to competitive levels. The cost of suitable fuels (and the development of the required infrastructure) may be excessive. Advanced competitive power plants may be found to be economically superior, and environmentally acceptable. The wrong fuel cell engine technology may have been selected. Companies may find that they cannot recover their investments in research and development.
- The **business risks** are high; profitability is questionable. The sponsors' (political) risks are difficult to assess. If fuel cell engines are not attractive, promoters will be at risk.
- **Political risks** are difficult to define. If local governments mandate or employ stopgap measures such as battery/electric power or electrification, then change to fuel cell engines in a few years, they will appear to have used poor judgment. The transition to fuel cell engines will have a short term economic cost, it will displace and obsolete other technologies. But, like previous transitions, the long range benefits should be substantial. Previous power plant/energy transitions include: steam locomotives to diesel powered locomotives, aircraft piston engines to gas turbine engines, and the use of wood, then coal, followed by oil and natural gas as fuels for both power plants and home heating. These transitions were based on improved performance (mobility) and economics. Improvements in emissions came as a consequence of other benefits.
- **Another primary societal/political and economic risk** that the present level of effort creates is that the U.S. may find itself in the position of having to purchase fuel cell engines from other nations, e.g., Germany or Japan. Both the German and Japanese governments provide aggressive support for their fuel cell engine propulsion programs. The Japanese government, for example, provides 100% of the funds for basic research, 50% of the funds for technical feasibility demonstrations, and 30% of the funds for market demonstrations.

The U.S. government can create incentives and provide the catalyst (research and development funding) but it can also delay progress. It appears to be necessary for the federal government to subsidize research and to provide seed money where the projected costs and risks are too large for private investors to justify. Government sponsors should review both the procurement processes and the impact of regulations which were designed for different purposes, and which inadvertently can be inhibiting.

8.2 ACCELERATING THE TRANSITION

It is probable (almost certain) that federal and state legislatures will in effect mandate the transition to fuel cell engines (or other equivalent low emission/energy consumption propulsion systems) by enacting stringent emission/energy consumption regulations. This will be justified on the basis of the public's perception (right or wrong) that these regulations can provide significant environmental benefits. Since fuel cell engines offer the potential of achieving environmental and energy conservation objectives with minimal economic or societal cost, some government decision makers may find that support of this technology is "good politics".

Before any significant investment in the commercialization of fuel cell engine propulsion systems should be made, sponsors need a better understanding of the relative advantages of other candidate fuel cell engine types and a determination regarding which candidate or candidates are best suited to differing vehicle applications. This may be accomplished by two parallel programs:

- First - A program directed at developing adequate information to permit selection between candidate fuel cell engine propulsion systems and their accompanying fuel systems
- Second - Another program directed at determining how fuel cell engines would be applied to vehicles, and the benefits and markets for fuel cell engine powered trains, buses, trucks, and cars.

Fuel cell engine research and technical development programs are occurring in parallel with programs that: reduce the emissions (and improve the efficiency) of piston engines, reduce the cost of gas turbines, and extend the range of battery/electric vehicles. It is probably appropriate to ask if the industry, or nation, has adequate resources to effectively pursue a multiplicity of parallel programs. Concentrating efforts on the best solution, even if it takes longer to mature, should have greater long range benefits than expending limited resources on "second best" approaches. Unconcentrated effort may even delay the development of better solutions. The development of fuel cell engines could also alleviate the need for strategies to reduce transportation demand, which are very expensive and unpopular.

Public and private decision makers will need information on:

- The technical and economic requirements for the desired vehicle applications to be achieved
- The total investment required for fuel cell engine system/vehicle research, development, and manufacturing
- The cost and availability of suitable fuels
- The fuel cell engine system/vehicle purchase and life cycle costs, both initial and overall operating conditions
- The requirements to satisfy purchaser/users
- The market for vehicles and for specific kinds of fuel cell engine propulsion systems
- The energy, environmental, and societal benefits of developing fuel cell engine propelled vehicles

- The status of competitive propulsion systems (batteries, gas turbines, etc.)
- The status of foreign competition.

One of the underlying assumptions in this study was that the government (primarily federal) will support acceleration of the fuel cell engine commercialization process because of societal benefits. The need for substantial federal support will continue until the business risks have been reduced to those equivalent to other private investments.

8.3 COMMERCIALIZATION STRATEGIES

If the development and commercialization of U.S. electrochemical engines, compatible energy supply systems, and manufacturing capability is to be accelerated, certain commercialization requirements must occur:

- There must be strong government support, both financial and regulatory
- A ready availability of adequate resources, both manpower and financial
- Approval of processes which will enable developers to avoid non-technical decision making delays
- Public and private support to overcome non-technical barriers to commercialization.

The commercialization process begins with the preparation of a business plan. This plan must identify each step in the commercialization process, the resources (technical and financial) required, and discuss the strategies for minimizing any delay, problems, and or major uncertainties which the program may encounter. Financial projections will be based on estimates of the market size, R&D facilities required, start-up costs, etc., and the expected unit profitability. Projections should include the information which public decision makers need to justify sponsoring fuel cell engine developments, and which private companies need to justify their investment in electrochemical engine commercialization.

At this time, a primary concern regarding the development of the capability to produce and sell fuel cell engine powered vehicles is the lack of a company, or combination of companies, which have both the capability to produce such vehicles and a clearly demonstrated profit potential resulting from their sale. There are a large number of small organizations which foresaw fuel cell engines as the replacement for the internal combustion engine in almost all ground applications such as: passenger car and truck vehicles, recreational equipment, electrical power generation, etc. However, no one organization currently has all of the capabilities that will be required. In summary, these capabilities include:

- Electrochemical research capabilities
- Plastics and composite materials capabilities (for PEM)
- Propulsion system design and manufacturing
- Vehicle design and manufacturing
- Vehicle sales and service
- Alternative (if required) fuel supply infrastructure

There is also no established fuel cell engine system industry. The existing fuel cell companies, International Fuel Cells, Ballard (Vancouver, B.C., Canada), H Power, Energy Research Corp.,

Energy Partners, etc., are small and could have difficulty surviving unless they obtain additional financial support. Ballard has received major (multi-million dollar) investments from Daimler Benz and others, as have some smaller companies. Several major U.S. companies (Westinghouse, Allied Chemical, United Technologies) have internal programs (some partly supported by the U.S. DoE) directed at the development of fuel cell systems for electrical utilities. Other companies such as GM, Dow, and DuPont have explored the potential creation of joint ventures to develop and produce electrochemical engines. Ford's and Chrysler's hydrogen based fuel cell system programs have just been initiated.

None of the major U.S. automobile companies, except GM, has a significant fuel cell engine research program. The growing interest in fuel cell engine development expressed by the automobile companies has been driven by the U.S. DoE, the White House, the Department of Commerce, the Administration's Industry Partnership for the New Generation Vehicle, and increasingly difficult emission/energy consumption specifications. The "new generation car" initiative is leading to increased cooperation between the automobile manufacturers and the fuel cell engine research companies.

8.3.1 Potential Strategies and Processes to Create a Fuel Cell Manufacturing Industry

There are several potential strategies for the creation of a fuel cell engine manufacturing industry including:

- Expanding existing power plant and alternative fuel infrastructure capabilities
- Creation of new fuel cell engine manufacturing corporations
- Creation of affiliations, or vertical teams, including federal research laboratories, energy companies, vehicle manufacturers, and other organizations that can contribute to accelerating the commercialization of fuel cell engines.

U.S. DoE's studies (which tend to emphasize the use of fuel cell engines for automotive vehicles rather than locomotives as a first step) have concluded that the third strategy offers the promise of completing development and commercialization faster and for less cost than do the first two strategies. This strategy assumes that it will be possible to resolve the legal and regulatory problems, such as antitrust, etc. By bringing together people with the required experience and design and production capability it should be possible to avoid some of the delays which appear to be inherent in government contract negotiations. Each participant should have some potential ownership interests such as:

- Federal and private laboratories would obtain support research and credit for technical progress
- Industrial companies would earn profits from the development and sale of fuel cell engines or their basic components
- Energy companies would earn profit from the development and sale of suitable fuels
- Vehicle manufacturers would maintain or increase their market for the categories of vehicles that they produce.

The concept of forming vertical teams was developed in DoE's fuel cell commercialization workshops held in the fall of 1992. The underlying concept is illustrated in Figure VIII-1. The formation of teams or affiliations may require new enabling legislation. Such legislation could establish a national "Fuel Cell Corporation Policy Board" (FCPB) which would have the

Figure VIII-1. Potential Fuel Cell Commercialization Affiliations

responsibility of allocating federal resources to the development of fuel cell engine systems. The policy board would support pre-proprietary research and two or more electrochemical engine developments.

Each team could be developing a different class of fuel cell engine or concentrating on different markets; for example:

- One team could concentrate on the near term development of fuel cell engine propulsion systems for buses and other commercial vehicles
- A second team could concentrate on the development of first generation fuel cell engines for a passenger vehicle market created by regulations
- A third team could be directed towards developing a second generation fuel cell engine system which would be economically competitive in private automobiles
- A fourth team could be directed towards the development of other types of fuel cell engine systems and compatible fuel(s) systems and vehicles.

The make-up of each team should be voluntary, based on the need for a balance of technical and business capabilities. The role of each team would be defined in the business agreement. The team, or affiliations, could include: universities, federal laboratories, material suppliers, energy companies, propulsion system manufacturers, vehicle manufacturers, and sales and service organizations. There could be as few as two public organizations and one private company, or a larger number of organizations, depending on the capabilities of each. Any additional "pre-proprietary" research would be sponsored by the National Fuel Cell Policy Board. Panels made up of "end use" advisors representing drivers or operators would assist in evaluating the actual use of the fuel cell engine propulsion systems.

The activities of each team would be coordinated by and directed by a committee (or board of directors) of "affiliates". This board would be responsible for coordination of efforts and the preparation of budgets, etc. The majority of the members of each team would represent participating organizations. Public sector representatives would be responsible for identifying those regulatory or policy issues which would delay or inhibit progress in the commercialization process. Public sector involvement would phase out when the risks have been reduced and private investment insured. Before the start of commercial sales of electrochemical engines, the teams would become public corporations (or acquired by existing companies). The original agreements should include the terms under which the public corporations would be formed, and the share of the earnings to which each participant would be entitled. It has been suggested that some portion of the profits (proportionate to the federal investment) could be returned to the federal government for use in sponsoring similar initiatives in other fields. Figure VIII-2 was extracted from the National Program Plan, Fuel Cells in Transportation, February, 1993 and is another way of illustrating the same concept.

The commitment to commercialization must be robust; that is, the plan must be sufficiently flexible to accommodate significant changes in fuel cell engine propulsion system design, performance, and costs. The scenarios described in the previous chapter can provide information which public and private decision makers can use to evaluate the impact of externalities (regulations, fuel prices) and progress in fuel cell engine cost reduction.

Figure VIII-2. Exhibit 11 & 12, The National Fuel Cell Program Plan, Fuel Cells In Transportation

The cost and performance criteria will differ significantly for each market, e.g., locomotive, bus, truck, or automobile. The commercialization process can be described as consisting of a series of steps:

First -	Confirm technical feasibility
Second -	Confirm economic feasibility
Third -	Demonstrate usefulness in selected vehicles
Fourth -	Develop commercial versions
Fifth -	Develop fuel cell engine production capabilities
Sixth -	Produce fuel cell engines, compatible vehicles, and energy systems
Seventh -	Sell to willing users
Eighth -	Provide maintenance and service.

Confirmation of Technical Feasibility. The basic technical feasibility of the types of fuel cell engine systems of interest (PAFC, PEM) has been demonstrated. They are being used when cost is not an objective (military and space programs and some government sponsored bus demonstrations). Electrochemical engines can provide significant efficiency and environmental improvements compared to other competitive propulsion technologies.

Before major investments should be made it will be necessary to determine which fuel cell engine propulsion system will be best suited for a given application. The first generation fuel cell engines will meet environmental objectives; the second generation of electrochemical engines must be economically competitive. The problem is complicated by the fact that, at this time, the "best" fuel cell system for each type of "vehicle" has not been established. Several programs should proceed in parallel to obtain enough information to define the technical and economic potential of each candidate fuel cell engine propulsion system. In summary, the major remaining technical challenges are:

- Development of fuel processor subsystems for complex hydrocarbons (methane, ethanol, gasoline, diesel fuels, etc.)
- Improvement of electrocatalyst performance
- Improvement of cooling and fluid management systems
- Improvement of fuel supply control systems
- Reduction of electrochemical engine and energy/fuel storage system masses and volumes
- Reduction of manufacturing costs
- Improvement of electrical power control systems
- Improvement of start-up and transient response.

A major area of technical effort involves the reduction in the amount of and, hence, cost of the fuel cell electrocatalyst. The primary electrocatalyst used within PEM and PA fuel cells is platinum. Extensive work in process has reduced the quantity of platinum required within present fuel cells by more than an order of magnitude compared to earlier fuel cells. Some studies are still in process to identify the possibility of using non-precious metal catalysts.

Engineering problems occurring during fuel cell engine development will be equivalent to those which would be encountered in any new propulsion system. The research programs required to prove both technical feasibility and the potential to reduce costs to competitive levels will require several million dollars to be spent over the better part of a decade. At this stage industry will be reluctant to invest, because, even if successful, the interest costs may be so high that the first fuel cell engine systems will not be competitive with other propulsion systems.

The business plan should provide for continuous reviews of intended program achievements and for sufficient flexibility (robustness) to adapt to new requirements. Estimates of the cost to develop prototype commercial electrochemical engine versions, and achieve competitive levels (for each candidate fuel cell engine system type) range from 200 to 400 million dollars. An investigation of all candidate fuel cell engine system types in parallel would probably require between \$500 million to \$1.25 billion. This amount will decrease as some of the candidate fuel cell engine system types are dropped from consideration when additional information on their technical and economic feasibility becomes available.

Confirmation of Economic Feasibility. Confirmation of the economic feasibility of fuel cell engines for propulsion requires that it be possible to design such systems to meet all of the performance and other design requirements for selected vehicles, and that costs be reduced to a competitive level. The process of confirming the economic (or market) feasibility will require assessment of:

- The technical risks (life, manufacturing cost, possible new energy/fuel infrastructure, etc.)
- Potential engine/fuel infrastructure production costs and prices
- Potential markets and the performance and cost objectives which must be achieved to be competitive in those markets
- The progress in developing competitive power plants
- The profit potential considering research and development investments as well as the probable cost/price margins of the final product.

While only approximate estimates of the costs of fuel cell engine system development and commercialization programs have been prepared, the total program costs will be in the hundreds of millions to possibly several billions of dollars. The costs can be categorized roughly as:

- Research to prove fuel cell engine/fuel infrastructure technical feasibility
- Demonstrations to prove usefulness
- Product development
- Investments in fuel cell engine/fuel infrastructure manufacturing facilities
- Sales, and after sales, costs.

Reduction of the production costs to a level where the life cycle costs of fuel cell engines (including fuel, maintenance, etc.) will be superior to comparable propulsion systems will require extensive efforts. Several generations of more efficient, reliable, and lower cost fuel cell engine systems will have to be developed to reduce prices comparable to competitive propulsion systems.

Demonstration of Usefulness in Selected Vehicles. Before there will be significant private investment in the development of fuel cell engine propulsion systems investors must be confident that all of the operational and cost problems have been (or can be) resolved. This can be accomplished by construction of demonstration vehicles and their operation in useful service (by private operators, companies, etc.) for a reasonable period of time (more than a year). Demonstrations can be divided into four categories.

1. **Demonstrations of potential usefulness.** This involves use of prototype vehicles and/or fuel cell engine propulsion systems to illustrate how the technology can provide mobility or environmental benefits. The objective is to obtain support for further development of a specific technology. The vehicle and/or propulsion system would be at best "illustrative". The demonstrations probably would not provide full performance capabilities. Some people in the automotive industry refer to such demonstrations as "show cars" to emphasize their preliminary status; the vehicles are also known as "mules". There would be no direct progenies.
2. **Initial Tests.** In these tests an existing vehicle is modified to test the operation of an advanced propulsion system in a real operating environment, without having to achieve competitive cost, reliability, or performance goals. Ideally, this would be accomplished on a proving ground or other site not exposed to public attention.
3. **Initial Demonstration.** These are demonstrations of one or more near final design fuel cell engine propulsion systems in existing or specially designed vehicles that provide near commercial performance. These demonstrations will usually be conducted with the knowledge and participation of the end users such as transit properties, railroads, or selected private citizens.
4. **Pre-production.** These are demonstrations of initial production vehicles in their intended application to identify any unanticipated problems and or needed redesigns before entering full production.

It is probable that major fuel cell engine and drive train system redesigns will be required between each of these stages. The cost of demonstrations are estimated at between 50 to 75 million dollars for a single fuel cell engine/vehicle combination, assuming that the fuel cell engine system and new fuel infrastructure (if required) has been developed under other funding.

Development of Commercial Fuel Cell Engine Designs. The development of a commercial version of a fuel cell engine propulsion system will require several years and cost several hundred million to a billion or more dollars. A major portion of the effort will be directed at measuring and demonstrating reliability, assessing maintenance requirements, etc. The cost for this step could range from 100 million to half a billion dollars depending on the system design and its market. This stage in the commercialization process is unlikely to be pursued unless private industry can foresee a profit potential (or other benefits) and is willing to provide the majority of the funding.

Development of Fuel Cell Engine Production Facilities. The construction of suitable manufacturing facilities (or modification of existing facilities) will take several years and could cost nearly a billion dollars depending on the product type and expected volume. It is probable that new manufacturing processes and facilities will be required. The transition to ECEs may obsolete existing investments by both manufacturers in facilities that produce traditional

engines and by energy companies in facilities that produce traditional fuels. If the transition is anticipated in advance, industries could better prepare by reducing their future investments in facilities that would ultimately be phased out. A range of time estimates predicting fuel cell engine availability in various applications is presented in Table VIII-1.

The "likely" times for fuel cell engine availability presented in Table VIII-1 are based on the assumption that there is at least some increase in the present funding for fuel cell engine development. At this time the funding is inadequate and there is no guarantee that it will be continued. The investment in production facilities must come from private industry once the market and potential profitability have been demonstrated.

	<u>Likely</u>	<u>Expedited</u>
<u>Locomotives</u>		
Feasibility demonstrations	10 years	5 years
Stage I market (vs. electrification)	12 years	8 years
Stage II market	15 years	12 years
<u>Buses</u>		
Feasibility demonstrations		2 years (Phos. Acid)
Economic demonstration (vs. trolley buses)	7 years	5 years (PEM)
Volume production	10 years	7 years
<u>Trucks</u>		
Demonstrations	7 years	3-5 years
Stage II market	may not be achieved	8-10 years
<u>Automobiles</u>		
Demonstrations	5 years	3-4 years (PEM)
Stage I market	10-15 years	7-10 years (PEM)
Stage II market	may not be achieved	10-15 years (?)

- Stage I economics assumes that fuel cell engine powered vehicles are competitive in capital and life cycle costs with battery/electric cars and electrified railroads and public transit systems.
- Stage II economics assumes that costs have been reduced to the point where fuel cell engine capital and operating costs are competitive with or lower than those of equivalent piston engines.

Table VIII-1. Range of Time Estimates for Fuel Cell Engine Availability

Production of Fuel Cell Engines, Vehicles, and Energy Supplies. If plans are well prepared, timely production of vehicles for fuel cell engines should not represent any unusual problems for vehicle manufacturers. The fuel supply and distribution network may be the pacing item as new fuels and their distribution infrastructure may be significantly different from that which the energy industry has accomplished in the past.

Slow recovery of the investment costs, e.g. high interest payments on the accumulated investments, can result in very high additional costs to the producer(s) of these new propulsion

systems. The predicted interest costs allocated to volume production as a function of time and annual units sold are presented in Table VIII-2.

<u>Years from Start</u>	<u>Annual Systems Sold</u>	<u>Interest per System</u>
5	10	\$2,420,000
6	100	\$360,000
7	500	\$135,000
8	1,000	\$50,000
9	5,000	\$18,000
10	10,000	\$6,000
15	100,000	\$1,000
20	1,000,000	\$150

Table VIII-2. Interest Cost Allocated to Volume Production

<u>Year</u>	<u>Research</u>	<u>Production Facilities</u>	<u>Operating Losses</u>	<u>Total Investment</u>	<u>Production</u>		
					<u>Interest Costs</u>	<u>Units Sold</u>	<u>Interest per Unit</u>
1993	\$5	---	---	\$5.0	\$0.37	---	---
1994	\$10	---	---	\$15.3	\$1.15	---	---
1995	\$20	---	---	\$36.4	\$2.73	---	---
1996	\$30	\$10	---	\$79.2	\$5.93	---	---
1997	\$40	\$20	\$1.0	\$156.1	\$11.70	\$1	\$11.7
1998	\$50	\$100	\$5.0	\$322.8	\$24.20	\$10	\$2.42
1999	\$50	\$200	\$25.0	\$622.0	\$46.65	\$100	\$0.466
2000	\$50	\$200	\$12.0	\$900.6	\$67.55	\$500	\$0.135
2001	---	\$100	\$6.0	\$1074.2	\$80.56	\$1000	\$0.080
2002	---	\$50	---	\$1204.7	\$90.35	\$5000	\$0.018
2003	---	---	---	---	---	---	---
2004	---	---	---	---	---	---	---
Total	\$265	\$680	\$49				

Note: These costs were selected to illustrate the magnitude of the research and development investments for relatively low production levels of fuel cell engines, such as those for locomotives. These costs will be revised as more information is obtained.

Table VIII-3. Example of Investment Costs, Fuel Cell Engine Powered Locomotive Development Program, 7.5% Simple Annual Interest, Millions of 1990 Dollars

The interest costs used in Table VIII-2 were based on the judgment of authorities, simplified for the purposes of this illustration. At low annual production levels, typical of buses or locomotives, the interest costs which must be recovered if the investment were made by the

private sector could exceed the manufacturing (and sales) cost of the production propulsion system. Even at 50,000 units per year production the interest charges could exceed \$2,000 per unit. These estimates will be revised as additional information is developed.

The amortization of research and development costs will be a major element in the price of the first generation of fuel cell engines; an estimate of these costs for low volume fuel cell engine powered locomotives is presented in Table VIII-3 above.

The preliminary nature of the cost estimates for the development of fuel cell engines are in part due to the fact that neither the most appropriate fuel cell system nor fuel(s) have as yet been selected. In addition to the development of fuel cell system technology, there must be a similar level of effort applied to the development of new fuel supply systems. This will require research on new fuels, development of production (refinery) facilities, and the possible development of new distribution networks. These activities could cost an additional several billion dollars.

Sales to Willing Users. The size of the market for fuel cell engine propulsion systems will increase significantly as the costs of fuel cell engine systems and related equipment decreases. There will be a small proportion of early buyers who will purchase fuel cell engine powered cars because they want to be the "first on the block" to own one. While at this time there does not appear to be any negatives, societal concerns regarding fuel cell engine systems may develop, particularly if there are serious health threatening problems with certain types of fuel cells or other electrochemical systems (such as exotic batteries) which receive broad publicity. (A strategy which is of interest to most of the fuel cell engine system advocates is to select relatively small, commercially viable markets for initial demonstrations, testing, and commercialization. The railroad locomotive appears to be one of the best opportunities. There is evidence that fuel cell engine propulsion systems, at their present rate of development, could soon be nearly competitive with diesel engines for locomotives).

The size of the automotive market will depend on the ability to reduce the cost of electrochemical engines to the point where they are competitive with conventional propulsion systems. Since the initial cost will probably remain higher than that of conventional engines, potential buyers must be attracted by other factors such as: reductions in operating and maintenance costs, improvements (e.g. low noise) compared to other power plants which meet the same performance level, and legal requirements.

Provision of Maintenance and Service. One of the major problems which must be addressed and resolved is the need for trained personnel to manufacture and maintain fuel cell engine systems. The exact nature of the training which will be required cannot be defined at this time. Essentially, all mechanics and service personnel who are qualified to work on conventional automobiles and automobile engines must be retrained.

8.3.2 Summary, Potential Commercialization Concerns Regarding Fuel Cell Propulsion Systems

The commercialization of fuel cell systems is expected to be approached in two stages:

- Stage I - Competitive with other low emission/energy consumption systems where required by law or mandates

Stage II - Fully competitive with existing (or future) internal combustion propulsion systems.

The first applications for fuel cell systems will be in regions which fail to meet federal environmental standards. The primary competition to fuel cell engine/vehicles will be battery/electric and (possibly) hybrid/electric cars, electrified locomotives, and trolley buses.

One of the most important advantages of electrical propulsion systems (batteries and fuel cell engine systems) is their low emission levels. Fuel cell engine systems also offer the additional advantages of higher efficiencies and much lower total energy consumption than gasoline and/or diesel engines. The total energy consumed per vehicle mile for a fuel cell engine may even be lower than that for pure battery propulsion when utility power plant and distribution losses are included. The low emission levels and high efficiency of fuel cell engine systems have the potential to eliminate the public's concern over the contribution of automobiles (trucks and buses) to air pollution and energy consumption.

The costs of available fuel cell engine systems are several times too high to be considered for passenger cars or light trucks. The costs of "research type fuel cell systems" are presently on the order of \$3,000 per kW. Prices for phosphoric acid systems in small lots for utilities are being quoted at \$1,500 per kW. This compares with \$30 to \$60 (or less) per kW for a proposed ULEV piston engine. Fortunately, there appear to be no technical barriers to significantly reduce the cost of a fuel cell engine to nearly the same level of cost as a gasoline or diesel piston engine of the same power level [144]; in addition, the life cycle costs of the fuel cell engine should be lower. GM's study of PEM systems [144] indicates that the costs could be as low as \$65 per kilowatt for continuous rated power (or the equivalent of \$45 per kilowatt at peak power operation).

Fuel cell engine system designs will undoubtedly differ depending on the application. For example, the membrane on PEM cells for cars may be thinner than the ones for trucks. Thin membranes could save costs and increase performance, but may reduce membrane life expectancy. Less costly membranes, which sacrifice efficiency for cost, may be appropriate for many initial or unique applications.

Similar to internal combustion engines the cost and time requirements for the development of each class of fuel cell engine system type will differ. Phosphoric acid fuel cell systems are the most mature at this time. Solid polymer (PEM) fuel cell systems are operating satisfactorily, but have the potential to produce higher performance at lower cost. Solid oxide fuel cell systems are at the laboratory stage; it is uncertain when their problems (such as differential expansion of dissimilar materials) will be resolved. As a result, only preliminary data exists on the research required to develop solid oxide fuel cells with desirable performance, operating, and emission characteristics.

The cost of developing production versions of each kind of fuel cell system type will require research investments in the range of \$200 to \$300 million per fuel cell engine type. It may take 5 to 7 years to develop and start production of the first generation of a fuel cell engine system for environmentally driven applications, after adequate funding has been committed and an accelerated program approved. The program cost estimates include research and preliminary testing, and any demonstrations required to confirm the performance and reliability of the selected fuel cell engine system in the type of vehicle for which it is intended. Additional funds

will be required to adapt fuel cell engines to a specific vehicle and to develop appropriate manufacturing facilities. A major advantage of fuel cell engines will be their modular characteristics. It should be less costly to produce a family of engines with different power ratings to meet various vehicle requirements. Today, it costs nearly a billion dollars to develop each new version of a "conventional" spark ignition engine and tool it for production.

When tests and demonstrations have confirmed the technical and economic usefulness of fuel cell engine systems, interested manufacturers should have sufficient confidence to design and develop production versions for sale to customers. There is, as yet, insufficient information to accurately determine the costs of fuel cell engine research and development, production design and engineering, facility design and construction, and manufacturing. The development of manufacturing processes and tooling will probably represent a major share (half to two thirds) of the total cost of complete development of each new type of fuel cell engine system. The price for production fuel cell engines will include direct labor, materials, and the amortized charges for research, construction of facilities, and other work undertaken prior to the decision to enter production. The cost of sale will include the distribution cost (delivery to customer), advertising, other costs related to dealer organizations, field service and maintenance, and regulatory compliance or product liability.

Market and profitability criteria, which must be achieved to interest the private sector in investing in the design or manufacturing facilities required to produce fuel cell engines and/or compatible fuels, are based in large part on the return on investment which could be obtained by investing a similar amount of money in other activities (for example, the purchase of government bonds).

8.3.3 Production, Cost, and other Estimates Required to Prepare Market Scenarios

Each candidate fuel cell engine type has different technical problems and will require different times to commercialize; there is insufficient data at this time to make estimates with sufficient confidence to interest investors. However, the estimates presented in Table VIII-4 are representative of the assumptions which must be made to prepare the market scenarios.

Two funding levels are indicated, the first is low but more probable (which is consistent with longer development times), while the second is high but less probable (but which could lead to the availability of fuel cell engine systems which are competitive with batteries for electric cars and catenaries for buses and locomotives in shorter development times [95]).

The preliminary estimates of program costs presented in Table VIII-4 are based on discussions with fuel cell advocates, vehicle manufacturers, energy companies, as well as prior experience in the development of high technology products for vehicles. In most cases the estimates by advocates were the lowest and those by vehicle and engine manufacturers were somewhat higher. These estimates should be used as a rough guide only. The cost estimates and time requirements are intended to be conservative, based on the assumption that it would be preferable to error on the high side rather than have to explain overruns in cost or schedule time. Additional information on costs will be developed during the next stage of this program.

An increase in present program funding will be required to meet even the longer time estimates presented in Table VIII-4. The times (and costs) presented below are based on the assumption that the U.S. DoE will be authorized to provide support and funding for high risk research and

demonstration projects. Present programs, as they now exist, are unlikely to lead to volume production of useful fuel cell engines before the second decade of the next century.

	Cost--Millions \$	Time
Completion of Research on Fuel Cell Engine Propulsion Systems		
Phosphoric acid cells	\$100 to \$200 million	5 to 3 years
Polymer PEM cells	\$150 to \$250 million	7 to 5 years
Solid oxide cells	\$200 to \$400 million	10 to 8 years
Other cells	\$100 to \$400 million	? to ? years
Research on Supporting Technologies		
Methanol reformers	\$10 to \$25 million	5 to 3 years
Natural gas reformers	\$15 to \$30 million	7 to 4 years
Hydrocarbon reformers	\$20 to \$30 million	10 to 4 years
Advanced fuel systems	\$100 to \$200 million	? to ? years
Development and Demonstration of Preproduction Systems		
For buses	\$75 to \$150 million	5 to 3 years
For locomotives	\$75 to \$150 million	5 to 3 years
For trucks	\$100 to \$250 million	? to ? years
Development of Production Capacity		
For each selected fuel cell type	\$1 to \$2 billion	10 to 5 years
For compatible fuels	?\$ to \$?	? to ? years

These estimates are illustrative only and will be revised as additional information is developed

Table VIII-4. Preliminary Estimates of the Cost to Develop Electrochemical Engines

The potential costs of fuel cell engine systems (actually the cost of the fuel cell component only as full engine systems are not commercially available) have been obtained from two sources. The first source is the cost at which they can be purchased today. These costs run from \$1,500/kW to \$3,000/kW, at least as quoted by people who will sell them for demonstration purposes. The basis for these costs is not clear as to whether they include the amortization of research and development activities or are priced below cost to interest future customers. Alternatively, several estimates have been prepared regarding the manufacturing cost of complete fuel cell engine systems assuming very high, 1,000,000 units/year production after a relatively long development cycle.

The primary public source of information regarding high volume estimated factory costs for complete fuel cell engine systems is the recently published GM Study [144]. This study projects a total cost of an electrochemical engine at \$65/kW at continuous rated power or \$46/kW at limited time peak power. The latter cost is a more typical comparison to an IC engine. These costs are based on an ECE designed to provide 60-kW for continuous operation and nearly 85-

kW for limited time peak power. The proposed fuel cell stack consisted of 86 cells with 1 square foot of active area operating at 1100 mA/cm² at 0.7 volts. Peak power (for a limited time) would be attained at 2200 mA/cm² at 0.5 volts. Projected costs from this study, assuming high volume, following a relatively long development cycle, are detailed in Table VIII-5. The manufacturing costs were based on design for manufacturing using automated manufacturing equipment.

The predicted low and high production volume as a function of time, Table VIII-6, was estimated using industrial experience in penetrating new markets. Assumptions include uncertainties in cost, requirements for redesigns, etc. These and other estimated production costs for high volume production obviously assume that the cost of fuel cell engine propulsion systems will decrease with increasing volume of production.

Component	Power Rating	
	Continuous	Peak
Fuel cell stack	\$29.20	\$20.90
Fuel processor	\$18.00	\$12.80
Heat rejection and water management systems	\$3.30	\$2.30
System auxiliaries	\$14.60	\$10.40
Total Cost	\$65.10	\$46.40

Table VIII-5. Estimated Factory Production Costs, 60-kW Continuous, 85-kW Peak Power Rated Electrochemical Engine

Year	Locomotives		Heavy Trucks and Buses		Light Trucks and Personal Cars	
	2,000 hp		300 hp		150 hp	
	Low	High	Low	High	Low	High
1990	0	0	0	0	0	0
1995	0	1	0	10	0	0
2000	0	0	0	50	0	10
2005	0	300	0	1,000	0	50
2010	10	500	50	5,000	0	500
2015	50	700	100	10,000	10	10,000
2020	300	700	1,000	100,000	50	100,000
2025	500	700	10,000	150,000	500	1,000,000
2030	500	500	100,000	200,000	10,000	10,000,000

These costs are for illustrative purposes only. They will be revised when additional information is available

Table VIII-6. Assumed Annual Production of Fuel Cell Propulsion Systems

This has been the cost history experience of most new technologies. For example, the price of electronic technologies decrease rapidly after they first enter production; the VCR is one of the outstanding examples. The first VCR's cost over \$30,000.00 and were sold only to commercial users. Consequently, the initial cost of fuel cell engine systems will depend on the rate of increase of production volume.

The production cost of fuel cell engine systems will decrease with time as production volume and experience accumulate. Estimated production costs as a function of produced volume is illustrated in Table VIII-7. Data within this table are based on production levels of 600 to 700 locomotives per year, 200,000 to 250,000 heavy trucks (class 7 and 8) and buses per year, and 10 to 12 million light trucks and passenger cars per year. The costs were estimated using learning curves for similar products. Costs were assumed to decrease rapidly during initial production. After about 100,000 units of each system were built costs were assumed to decrease 18% each time the production quantity increased by a factor of ten. The range of costs reflects the uncertainties of the estimates.

	<u>Locomotives</u>		<u>Heavy Trucks and Buses</u>		<u>Light Trucks and Personal Cars</u>	
<u>Total Produced</u>	<u>2,000 hp</u>		<u>300 hp</u>		<u>100 hp</u>	
10	\$1,000,000	\$1,500,000	\$300,000	\$450,000	\$100,000	\$200,000
100	\$500,000	\$750,000	\$150,000	\$225,000	\$70,000	\$100,000
1,000	\$250,000	\$375,000	\$75,000	\$110,000	\$24,000	\$36,000
10,000	\$205,000	\$275,000	\$55,000	\$82,000	\$14,500	\$21,500
100,000	\$145,000	\$200,000	\$40,000	\$62,000	\$10,000	\$15,000
1,000,000	\$100,000	\$150,000	\$30,000	\$48,000	\$7,500	\$11,000
10,000,000	\$---	\$---	\$22,000	\$37,500	\$6,000	\$9,000
100,000,000	\$---	\$---	\$---	\$---	\$5,000	\$7,500

Note: The prices assumed for this table are illustrative, they will be revised as more information is obtained.

Table VIII-7. Assumed Production Cost of Fuel Cell Propulsion Systems as a Function of Production Volume.

The assumed production price of fuel cell engine propulsion systems (in various transportation applications) as a function of both time and production volume, Table VIII-8, can be estimated by combining the data presented in Tables VIII-6 and VIII-7.

Assuming that overhead, profit, and delivery costs are equal to production costs, a 112 kW (150 hp) automobile fuel cell engine in high production (circa 2030) should be priced (or factored into the price of a car) at about \$10,000. Lower prices will require new fuel cell engine concepts which, based on past experience with new technologies, will probably occur prior to 2030. Nevertheless, the high costs of fuel cell engines in the first years of significant production indicates why some form of incentive may be required to encourage companies to build, and people to purchase, fuel cell engine powered vehicles. At the present rate of development

commercially competitive fuel cell engines should not be expected to be produced by U.S. companies for twenty or more years. Progress could be accelerated by a national commitment to provide increased financial support to a comprehensive program [103].

Year	<u>Locomotives</u>		<u>Heavy Trucks and Buses</u>		<u>Light Trucks and Personal Cars</u>	
	<u>2,000 hp</u>		<u>300 hp</u>		<u>150 hp</u>	
	<u>High</u>	<u>Low</u>	<u>High</u>	<u>Low</u>	<u>High</u>	<u>Low</u>
1990	NA	NA	NA	NA	NA	NA
1995	NA	NA	NA	\$300,000	NA	NA
2000	NA	\$1,000,000	NA	\$150,000	NA	NA
2005	NA	\$250,000	NA	\$55,000	NA	\$100,000
2010	\$1,500,000	\$230,000	\$450,000	\$40,000	NA	\$17,000
2015	\$375,000	\$220,000	\$225,000	\$30,000	NA	\$12,000
2020	\$275,000	\$205,000	\$82,000	\$26,000	\$200,000	\$8,000
2025	\$200,000	\$175,000	\$40,000	\$22,000	\$48,000	\$6,000
2030	\$200,000	\$175,000	\$30,000	\$20,000	\$12,000	\$5,000

Note: The tables in this are illustrative, they will be revised as more information is obtained.

NA - Not Applicable

Table VIII-8. Assumed Production Cost of Fuel Cell Engine Propulsion Systems as a Function of Both Time and Production Volume

Production of Fuel Cell Engine System Powered Vehicles. The design and development of vehicles which will be powered by electrochemical engines will take much less time, but will follow a similar process. Vehicle development will require on the order of 5 to 7 years from go ahead, not including the construction of preproduction cars for engine tests and demonstrations. Vehicle concept and design studies should be conducted in parallel with fuel cell engine research and development to establish both performance and packaging requirements. Doing so will help to identify vehicle design and operating benefits which the inherent flexibility of electrochemical engines may provide.

8.4 NON-TECHNICAL BARRIERS TO FUEL CELL COMMERCIALIZATION

Many valuable technical innovations are not commercialized because of inadvertent non-technical barriers. The potential non-technical barriers to the commercialization of fuel cell engine systems or other innovative propulsion and transportation systems include:

- Cost of financing research and development
- Product liability
- Need for appropriate regulations
- Risk avoidance in public and private sectors
- Requirement for trained personnel.

Finding ways to overcome or moderate the impact of these "barriers" will be as important to the success of the commercialization efforts as finding technical solutions to the design, infrastructure, and manufacturing problems.

8.4.1 Cost of Financing Research and Development

As illustrated earlier the interest cost on the funds expended during the research and development of an advanced engine is a deterrent to private investment in any product development program which will last more than a few (5-7) years. Preliminary calculations indicate that the interest on the funds spent for research, development, and demonstration of a fuel cell engine system for a locomotive, allocated to each fuel cell propulsion system candidate built for a locomotive, could be higher than the total costs of the equivalent diesel/electric propulsion system now in use.

8.4.2 Product Liability

The increasing number of product liability cases and the size of settlements has led legal advisors to many corporation to recommend against the development and marketing of innovative products. The half-width car project (lean machine) has been delayed more than a decade by concern over product liability, despite its obvious energy and environmental advantages and the probability that it could be made as safe as a conventional car. This product liability concern is unique to the United States. The total cost of tort settlements for the United States was 2.6% of the gross national product in 1987. It has undoubtedly, by now, gone even higher. Litan points out that this is more than six times the relative tort cost in Japan and more than five times the tort cost to either of the economies of the United Kingdom or Germany [66].

A series of workshops (1985-87) managed by the Keystone Center addressed the economic costs of product liability. Studies presented at these workshops indicated that there could be no confidence in the existence of an upper bound to the cost of product liability. Lawyers are very skilled at finding ways to expand the application of existing laws or precedents. To illustrate how large such expenditures could get assume that everyone who was treated for an accident could find someone or some company to blame. Taking the number of people treated for accidents from a presidential study of total injuries, multiplied by the average 1985 announced settlement for accidental types of injury, the total dollar amount came to more than twice the U.S. gross national product. Of course, this is not possible; but it illustrates why liability concerns must be considered when a strategy is being created for commercializing fuel cell systems. Fuel cell engine powered vehicles (like battery/electric vehicles) will create some new problems not previously encountered, particularly during the initial deployment and test phase. Ultimately, they should be less dangerous than internal combustion engine powered vehicles.

8.4.3 Need for Appropriate Regulations

A new propulsion system development program such as that for electrochemical engines may be subjected to existing regulations; these regulations include:

- Safety standards designed for gasoline powered cars
- Fuel storage standards based on current industrial or commercial uses
- Procurement procedures used by industry and government based on very different technologies

- Energy and environmental mandates based on different technologies.

The automotive industry has felt that energy efficiency requirements, in particular, might be moderated if the public were better informed about the ultimate availability of alternative fuels such as methanol and natural gas. The estimates of the availability of new fuels implies that at least for the next century there should be no energy shortage, although there will still be a balance of payment deficient. Education of the public would require a concerted effort by the automotive manufacturers, energy companies, and associated government agencies; this has appeared unlikely in the past but could be an outgrowth of future cooperation regarding the development of new and superior propulsion systems.

The future price and availability of alternative energy systems, coupled with reasonable projections of the economic growth (and increased personal disposable income) of the U.S. and other developed nations, indicates that, if a rational strategy were established by industry and government, the transition to alternative fuels could be market driven during the time period when the cost of gasoline approached that of the alternative fuels. This perception, however, is not shared by most government regulators who feel that they must force the development of this capability. Regulators appear more comfortable with mandates than incentives because of their apparent higher predictability.

8.4.4 Requirement for Trained Personnel

A substantial capability for the maintenance of internal combustion engines has developed over the past 90 years and includes: dealers, service organizations, specialty shops, trained mechanics, etc. The introduction of fuel cell engines or any advanced propulsion or new fuel system in large quantities will require the training (or retraining) of service personnel in both the public sector (transit operators, etc.) and private sector (service stations, repair activities, etc.).

8.4.5 Fuel Cell Sponsorship Risks

Very few companies or people are willing to take the risk of being the first to introduce innovations in the creation, manufacture, or use of new products or processes. Industry decision makers need to be confident in their ability to project profits or obtain other meaningful benefits. Political decision makers (particularly at the local level) often have little to gain and much to lose by promoting innovations in technology or services.

8.5 SUMMARY

Accelerating fuel cell engine system commercialization to satisfy the regulatory requirements will present a number of risks, each of which must be satisfactorily addressed:

- **Technical** Will the performance capabilities and new fuel infrastructure (if required) be achieved?
- **Economic** Will the costs be competitive?
- **Scheduling** Are the present schedules consistent with the time required to develop reliable, economically competitive fuel cell engine propulsion systems?
- **Business** Can the manufacturers make a profit?
- **Political** What problems will be solved and/or generated by sponsoring fuel cell engine system development initiatives?

- **Societal** Could elements of fuel cell engine system performance, operation, or manufacture be unacceptable to users or the general public?

8.5.1 Technical Risks

The technical risk of developing fuel cell engine propulsion systems appears low; although, there will undoubtedly be a period of many years involving many problems and many redesigns before fuel cell engine propulsion systems become sufficiently mature to compete with internal combustion engines.

8.5.2 Economic Risks

The economic risks are greater; the goal of reducing the cost of fuel cell engine systems from the prototype level, where they may cost up to \$3,000.00 per kW, to costs virtually competitive with internal combustion engines will be difficult to achieve. Fortunately, there appear to be no fundamental barriers to achieve nearly equal competitive costs with polymer (and solid oxide?) fuel cell systems for locomotives, buses, and eventually trucks and private cars. Confirmation of this observation should be a major goal of the existing DoE programs.

8.5.3 Scheduling Risks

There are some proposals that imply that fuel cell engine propulsion systems can be used to enable both commercial and private vehicles to meet projected environmental standards, such as those which require a certain percent of zero emission vehicles before the year 2003. The ability to meet these schedules with reliable, economic fuel cell engine systems would be doubtful, even if the funding and program plans were in place, unless there were a national mandate. Even then it is likely that a more realistic time schedule would have to be established for meeting projected environmental standards.

Prototype or interim fuel cell engine propulsion systems can be made available in less time. Demonstrations of these prototypes could convince the concerned public and decision makers that there are viable technical solutions to emission problems. But, there is a risk, as these ECEs will not be fully developed and schedule slippage (or public failures) are possible, if not probable. It may be difficult to convince the public (or political decision makers) that such programs are not really "stunts", and, as such, subject to failures. These demonstrations properly achieved could, however, be an important step in creating public acceptance if they are adequately funded (hundreds of millions of dollars).

8.5.4 Financial or Business Risks

The perceived financial or business risks have limited the willingness of the private sector to invest in fuel cell engine propulsion system research and development. The business risks include the possibility that:

- The cost may not be competitive with existing power plants
- Competitive propulsion systems may be superior
- The company may select the wrong fuel cell technology
- The profit margins may be inadequate; in particular, fuel supplies may not be developed in time
- Unanticipated failures may increase warrantee and product liability costs

- Foreign competition may alter the potential market size.

Preliminary business plan studies indicate that the cost of research on individual fuel cell engine system types will require hundreds of millions of dollars. This, coupled with the time and uncertainty of the market size, make most traditional engine and automotive companies reluctant to invest at the level required to achieve near term commercialization. In addition, the design of useful vehicles to incorporate fuel cell engines will require an additional 100 to 150 million dollars.

Foreign competition in the development and sale of fuel cell propulsion systems can be a business, societal, and political risk. The public is increasingly sensitized to the loss of American developed technology (e.g., the loss of VCR's and most of the entertainment electronic industry to Japan) which implies both economic and job losses.

There is increasing evidence that there will be active competition from both German and Japanese companies. Siemens has developed a PEM fuel cell propulsion system for submarines. While this system is much too expensive to be considered for use in commercial vehicles, even locomotives, this accomplishment confirms the technical feasibility of fuel cell propulsion systems. Siemens has indicated that they intend to aggressively pursue the development of low cost fuel cell propulsion systems. Until recently the major Japanese effort has been directed toward phosphoric acid cells for stationary power. Recent reports, however, indicate that several Japanese companies are seriously addressing the question of fuel cell engine propulsion systems for transportation. Some Japanese car companies have acquired Ballard fuel cells. Mazda, for example, has publicly announced a PEM fuel cell show car concept. While this may be more "show" than substance, the Japanese appear to be getting very serious about the development of fuel cell engines for vehicles. Several Japanese car companies are believed to have substantial internal R&D fuel cell engine programs in place; additionally, a national (NEDO) PEM fuel cell engine system program has also been initiated in Japan.

8.5.5 Political Risks

The political risks are more difficult to assess. They can be divided into two categories:

- The probability of success of accelerated fuel cell engine development and implementation programs
- The negative image which could result from the implementation of lower technical risk approaches, and their ultimate abandonment.

The planned demonstrations of fuel cell engine propulsion systems in prototype buses and cars may lead some government and private decision makers to believe that their implementation could occur sooner than they probably should. Ideally, programs without any failures could, in theory, permit the initial sale of fuel cell engine powered vehicles in five to seven years. However, experience with new technology indicates that up to twice that long will probably be required. Time is required to correct both the problems which will undoubtedly be encountered with such new technologies and required cost reductions. Setting unrealistic schedules, and attempting to meet them at any cost, could lead to failures which could set back the entire fuel cell engine propulsion system program.

Conversely, environmental time schedules which force the use of incremental, or second best, solutions such as railroad electrification, use of trolley buses, and mandated sales of battery/electric vehicles (which probably will not provide adequate range and performance) may lead the public to question the need (and expenditure) for such transition systems. Such systems will not be acceptable to most users/buyers and will eventually be replaced. Their construction and use will be costly to users, local governments, and the nation.

8.5.6 Societal Risks

The societal risks appear low; fuel cell engine powered cars, trucks, buses, and trains will operate in a manner similar to that with which the public is already familiar. Additionally, there will be less noise and no appreciable pollution. The primary concerns may involve initial system failures due to design errors and questions about recycling or disposing of toxic materials used in manufacturing, etc.

8.5.7 Purpose of This Report

The information developed in this report should be considered to be preliminary, subject to updating as additional information is obtained. The objective was to describe the scope of the steps which will be required for commercialization of fuel cell propulsion systems and to identify the type of information which might be required to obtain the support of public and private decision makers.

The information developed regarding the potential size of future vehicle markets, fuel use, and environmental benefits indicate that the advanced propulsion systems discussed in this paper are robust enough to provide significant mobility and environmental benefits, relatively independent of the underlying national economic and regulatory assumptions.

This report should help public and private decision makers identify the regulatory and financial incentives which will be required if fuel cell engine (or other advanced) propulsion systems are to be built, sold, and used. The examples of sales projections, emission benefits, and energy savings are at best illustrative. Other investigators will undoubtedly want to address some elements in more depth, or to address other concerns.

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