Alternative Fuel Vehicle Policy: A Lifecycle Analysis Tool for Emissions, Costs and Energy Efficiency with an Application to the U.S.

by

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ABSTRACT

This thesis makes several alternative fuel vehicle (AFV) policy recommendations to the U.S. to reduce air emissions and increase energy security. It uses a spreadsheet model to compare the lifecycle emissions, energy efficiency, and non-tax/subsidy cost of 17 fuel and vehicle combinations from the extraction of the resource to the use of the vehicle over its lifetime. The model can be programmed for any set of fuel chain or vehicle characteristics, so it is adaptable to scenarios in different countries and levels of technology. Policy recommendations are based on 1 present scenario and 8 possible scenarios of resource prices and technology in the year 2010. All future scenarios assume that the price of natural gas rises at a higher rate than the price of crude oil as a result of higher demand. The analysis indicates that:

- Propane (LPG) is a low-cost, clean burning alternative with limited reserves, and cannot be a mainstream fuel.
- Reformulated gasoline (RFG) provides the most cost-effective reductions in emissions, and limited energy security benefits.
- Alcohol fuel blends offer energy security benefits and slight emissions reductions over RFG for a slightly higher lifecycle cost.
- Compressed and liquid natural gas vehicles offer energy efficiency and energy security benefits while lowering most emissions.
- Direct conversion fuel cell vehicles using methanol or hydrogen offer the lowest emissions, but at a high cost unless optimistic fuel cell cost projections are achieved.
- Vehicles using natural gas and methanol fuels could become more cost effective if natural gas prices do not rise as much as assumed relative to crude oil.

This study finds no pressing environmental or fuel security need that compels a widespread change to more expensive vehicle fuels in the near term. For the long term, the U.S. should prepare infrastructure for the use of alcohol-blended liquid petroleum fuels and natural gas to reduce emissions and increase energy security.

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Acronyms/Units

ABC	Advanced Battery Coalition (same as U.S. ABC)
AFDC	Alternative Fuels Data Center (U.S. DOE)
AFV	Alternative Fuel Vehicle
ANWR	Arctic National Wildlife Reserve
AQCR	Air Quality Control Region (U.S. EPA)
Barrel	42 gallons
BEV	Battery Electric Vehicle
Btu	British Thermal Unit
CAA	Clean Air Act (1970)
CAAA	Clean Air Act Amendments (1990)
CAFE	Corporate Average Fuel Economy
CARB	California Air Resources Board
CFF	Clean Fuels Fleet Program
CG	Conventional Gasoline
CGV	Conventional Gasoline Vehicle
CH2	Compressed Hydrogen Gas
CH4	Methane
CNG	Compressed Natural Gas
CNGV	Compressed Natural Gas Vehicle
CO	Carbon Monoxide
CO2	Carbon Dioxide
DOE	Department of Energy (same as U.S. DOE)
DOT	Department of Transportation (same as U.S. DOT)
E85	85% Ethanol/15% Gasoline Blend
EIA	Energy Information Administration (U.S. DOE)
EPA	Environmental Protection Agency (same as U.S. EPA)
EPRI	Electric Power Research Institute
ETBE	Ethyl Tertiary Butyl Ether
EtOH	Ethanol
EV	Electric Vehicle
FC	Fuel Cell
FCV	Fuel Cell Vehicle
FFV	Flex-Fuel Vehicle
FHWA	Federal Highway Administration
FTP	Federal Test Procedure
GJ	GigaJoule (10^9 Joule), measure of energy
H2	Hydrogen
HC	Hydrocarbon (same as VOC)
HDV	Heavy Duty Vehicle
HEV	Hybrid Electric Vehicle
HOV	High Occupancy Vehicle (Lane)
ICE	Internal Combustion Engine

ICEV	Internal Combustion Engine Vehicle
IEA	International Energy Agency
ILEV	Inherently Low Emission Vehicle
kW	Kilowatt (1/750th Horsepower), measure of power
kWh	Kilowatthour (3.6 x 10^{-3} GJ), measure of energy
LCC	Lifecycle Cost
LCE	Lifecycle Emissions
LDV	Light Duty Vehicle
LEV	Low Emission Vehicle
LH2	Liquid Hydrogen
LNG	Liquefied Natural Gas
LNGV	Liquefied Natural Gas Vehicle
LPG	Liquefied Petroleum Gas (Propane)
M85	85% Methanol/15% Gasoline Blend
MeOH	Methanol
MIR	Maximum Incremental Reactivity
MMBD	Million Barrels per Day
MMBtu	Million British Thermal Units (1.055 GJ)
MOR	Maximum Ozone Reactivity
mpg	Miles per Gallon
MSA	Metropolitan Statistical Area
MT	Metric ton (1000 kg)
MTBE	Methyl Tertiary Butyl Ether
NAAQS	National Ambient Air Quality Standards
NG	Natural Gas (Methane)
NGV	Natural Gas Vehicle
NMHC	Non-Methane Hydrocarbon
NO2	Nitrogen Dioxide
NOx	Oxides of Nitrogen
NREL	National Renewable Energy Laboratory
O3	Ozone
OECD	Organization of Economic Cooperation and Development
OME	Original Manufacturer Equipment
OPEC	Oil Producing and Exporting Countries
PM	Particulate Matter
PM10	Particulate Matter of Size 10 Microns or Less
PNGV	Partnership for a New Generation Vehicle
RFA	Common Type of Conventional Gasoline
RFG	Reformulated Gasoline (Clean Air Act Amendments 1990)
SIP	State Implementation Plan
SO2	Sulfur Dioxide
SOA	State of the Art
TAME	Tertiary Amyl Methyl Ether
TCM	Transportation Control Measure
TDM	Transportation Demand Management

TLEV	Transitional Low Emission Vehicle
U.S. ABC	Same as ABC
ULEV	Ultra-Low Emission Vehicle
VFV	Variable-Fuel Vehicle
VMT	Vehicle Miles Traveled
VOC	Volatile Organic Compound (same as HC)
ZEV	Zero Emission Vehicle

1. Introduction and Findings

1.1 Introduction

This thesis presents a model which calculates the emissions, costs, and energy efficiency of using different vehicle fuels in various kinds of vehicles, and applies the model to United States to provide guidance for alternative vehicle fuel policy recommendations. It concentrates on two themes which motivate the consideration of alternative vehicle fuels: energy security and the emissions of pollutants to the air.

It uses an approach which accounts for all of the emissions, costs, and energy in the fuel production chain, as well as the use of the vehicle, so that all fuel/vehicle combinations can be compared side by side. As much as was possible, no taxes or subsidies were included, so that all the fuels and vehicles could be compared on a "level playing field."

Its presentation is divided in to three general parts: Background, Model, and Policy.

Background of the Problem, Current Policies, and Technology

Chapter 2 describes the motivation for the recent interest in alternative fuel vehicles (AFV) by detailing the emissions and energy dependence problems associated with liquid petroleum fueled vehicles. It then presents the strengths of liquid petroleum vehicles that alternatives would have to match in order to gain acceptance.

Chapter 3 outlines current federal and state government policies which have taken measures to address the problems associated with liquid petroleum vehicle use, spending more time on those policies which explicitly include mention or require the use of alternative fuels or vehicles.

Current and developing fuel and vehicle technologies are presented in Chapter 4, providing a background of technical knowledge which is necessary for understanding the model output and its function. The data presented also provide a basis for assumptions made in the model.

Description and Use of the Model

Chapter 5 on model structure and assumptions show how the real world information about fuel chains and vehicles are analyzed so that the different vehicle types can be compared. Changes can be made in the model by anyone who wants to try different price or technology scenarios.

Model results for the base case scenario combining the current (1997) state of technology in the U.S. and world resource prices are presented next in Chapter 6, with a sensitivity analysis of the model's structure and input assumptions following in Chapter 7. The sensitivity analysis alone can be used to recognize the relative impacts of simple changes in technology and cost, though is no substitute for running the model if multiple or large changes are made.

Use of the Model in Making Policy Recommendations

Chapter 8 presents model results for eight more scenarios of three resource prices in the year 2010 (low, medium, and high) and two states of universal technological development by 2010 in the fuel chains and vehicles (low and high), with two special cases of exceptional cost reductions in fuel cell vehicles and vehicle batteries. The final chapter (9) uses these results to recommend a policy for alternative fuel vehicles in the U.S. in the next 15 years.

1.2 Findings

The results of the scenario analyses show that there is no advantage to a mainstream changeover to alternative vehicle fuels in the next 15 years. The policy recommends however, that the country prepare infrastructure for using liquid and gaseous fuels derived from natural gas, which seems the most likely alternative fuel resource to liquid petroleum, in vehicles similar to today's gasoline vehicles.

2. Transportation and its Fuel in the U.S.

This chapter provides background information about the state of highway vehicle and petroleum use in the United States. It begins with a description of the petroleum-based transportation system, summarizing the demand and supply characteristics of the market, and the emissions from petroleum vehicles. Section three introduces the state of current alternative fuel vehicle (AFV) use and availability in the country, followed in section four by a summary of the current policy directions which influence AFV development. Section 5 outlines the current highway vehicle and fuel market, including the intensity of vehicle use, socioeconomic factors, and possible market niches for AFVs. The final section discusses the technical and market conditions for successful AFV introduction, given the strong position of petroleum vehicles today.

2.1 Petroleum Dependence in Transportation

2.1.1 Overview of Petroleum Dependence

The U.S. vehicle fleet depends on petroleum. The term "petroleum," as used by the U.S. Department of Energy (DOE) Energy Information Administration (EIA), includes crude oil, natural gas and its liquids, other low-pressure liquids, and condensate from refineries. Petroleum fuels include gasoline, reformulated gasoline (RFG), oxygenated gasoline, diesel, propane (liquefied petroleum gas, LPG), and methanol. The roughly 134 million passenger vehicles registered in the U.S. primarily use gasoline. 671,000 buses and 64 million freight trucks predominantly use diesel. About half a million vehicles run on other petroleum or non-petroleum fuels.

This dominant uniform system of petroleum fuel vehicles has advantages of providing high mobility for goods and people on a single fuel and roadway infrastructure. The light weight and high energy content of petroleum derivatives enable vehicles high acceleration, speed, cargo space, long range, and quick refueling procedure. The homogeneous gasoline and diesel infrastructure and composition across regions ensures that freight or passenger travel across the country will not be hindered by inconsistencies in fuel or refueling procedure. Second hand vehicles are available at lower prices for lower income consumers of private transportation. A well-developed replacement parts manufacture and distribution industry, relying partly on the similarity of current vehicles, underpins the maintenance of the fleet.

Major disadvantages of the current system include dependence on foreign countries for oil imports, highly polluting exhaust gases, and in the long term, a non-renewable fuel supply. Despite improvements in vehicle technology which have increased the fuel efficiency of individual vehicles, fuel consumption is at an all-time high and growing because of the increasing number of vehicle miles traveled. The U.S. now imports just under half of its petroleum, but this amount will increase according to the EIA as world oil prices continue to be lower than domestic costs. Most world oil reserves lie under the oil producing and exporting countries (OPEC) (NRC 1990), which presents a political concern for Western countries' vital petroleum supply.

The exhaust and evaporative emissions from petroleum vehicles concern localized urban populations, where most vehicles are driven, and the international community, which suffers an increase in suspected global warming gases from petroleum combustion. Most pollutants emitted by vehicles are also emitted by stationary sources, which complicates policy decisions for reducing emissions. These pollutants can lead to acid rain, ground-level ozone, and health problems for people living in areas of high pollutant concentration. Carbon dioxide, emitted from both vehicles and stationary sources, has been identified as a heat absorbing gas in "greenhouse" theories that correlate an accumulation of such gases with an observed rise in the average surface temperature of the Earth over the last 50 years.

Car manufacturers have made enormous reductions in tailpipe emissions by improving vehicle technology since the 1960s, and recent reformulations of gasoline have reduced emissions even more. The non-crude oil based additives contained in the gasolines have displaced about 3.4% of crude which would otherwise have been consumed as gasoline since 1994 (U.S. DOT 1996b, fig 4-2). But both auto and oil producers claim that further incremental changes will not yield improvements worth the extra cost. Also, the increased total miles driven every year erodes the gains made on the level of the individual vehicle.

2.1.2 Demand for Petroleum in the U.S.

Transportation is the largest and virtually only growth market for oil. Since the early 70's, the demand for energy in transportation (almost entirely for petroleum fuels) has grown at an average annual rate of 1.8% per year in the Organization for Economic Cooperation and Development (OECD) countries. This compares with 2.0% per year in the former communist countries of eastern Europe. In the U.S., pipelines are the only major mode of transport which does not rely on petroleum as a fuel, but they use only 4% of the transportation energy in the U.S., most of it natural gas and electricity. All other transport sectors are almost 100% dependent on petroleum. Transportation is the only sector in the U.S. which consumes more energy today than it did in 1973. As it has in the last 20 years, transportation is expected to be the primary driver of growth in the oil market in the next 20 years (U.S. DOE 1992).

Highway vehicles use 78% of the energy consumed in transportation. Aircraft consume the most energy outside of the highway vehicle sector, and their consumption is growing most rapidly of all sectors. Figure 2.1 illustrates the highway transportation energy use in the U.S. by mode.

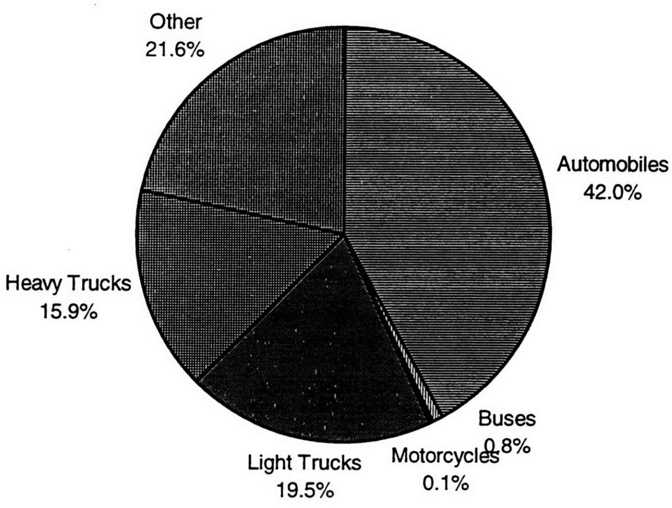

Figure 2.1: Transportation Energy Use in the US by Mode, 1993. Source: DOE Transportation Statistics Annual Report 1996, fig 4-1.

This chart shows the dominant role that automobiles and light trucks play in petroleum consumption, using almost 62% of the approximately 23 quads Btu of petroleum consumed annually in the U.S. transport market. Most of these vehicles burn gasoline or reformulated gasoline (RFG), at a 1994 average rate of 7.6 million barrels of gasoline per day (MMBD) (PennWell Pub. 1996). Light duty trucks are used in a similar way to passenger cars, though they are less fuel efficient, and as such are currently the subject of regulatory debate regarding energy efficiency and emissions. Almost all heavy duty trucks, which use 15.9% of the petroleum, burn diesel fuel (1.8 MMBD of diesel). Alternative fuels must be able to meet this energy demand, plus the anticipated growth, which is currently met by petroleum.

Though total fuel consumption is rising due to more vehicle miles traveled, fuel consumption per vehicle has fallen in the last 20 years. The Corporate Average Fuel Economy (CAFE) standard from the 1975 Energy Policy and Conservation Act forced manufacturers to compliment sales of "gas guzzling" luxury and performance vehicles with more fuel-efficient compact cars. Higher gasoline prices of the mid-seventies drove demand for more efficient cars, too, and both together resulted in raising the average fuel efficiency of new cars. As these cars slowly replaced existing less-efficient vehicles in the U.S. fleet, average fleet fuel economy also rose. This fuel economy improvement has leveled off as consumers have come to prefer less fuel-efficient vehicles in this period of low gasoline prices. Average fleet fuel economy increased steadily from 13.5 miles per gallon of gasoline (mpg) in 1975 to a high of 21.7 mpg in 1991, and has decreased slightly to 21.5 mpg in 1994.(U.S. DOT 1996a) . New cars now average 27.9 mpg, and light trucks average 20.4 mpg (U.S. DOT 1996a). According to DOE, the progress in vehicle fuel efficiency has "stalled." (U.S. DOT 1996a ,p 95) because of the popularity of inefficient sport utility vehicles (mini-vans and 4-wheel drive light trucks) and low relative gasoline prices.

In 1973, transportation in the U.S. used 17.8 quadrillion Btu (1 "quad"= 10^{15}) of petroleum products, 51% of the country's total petroleum consumption. By 1994 consumption had grown to 22.7 quads, 67% of the country's total demand for petroleum and 97% of the total transportation demand for energy. A rule of thumb for thinking about this amount of energy is that a full tank of fuel in a normal passenger vehicle contains about one million Btu (= 1 MMBtu).

2.1.3 The Petroleum Resource Supply

Fossil fuel resources are typically reported in four categories: proven reserves, indicated reserves, inferred reserves, and undiscovered reserves. Crude oil is currently of principal concern in transportation, of course. The categories for reserve estimates indicate a specific status of the reserve. Proved reserves have established extraction infrastructure and are judged to be economically recoverable under existing economic and operating conditions according to geologic and engineering data. Indicated additional reserves refer to crude oil recoverable by enhanced methods which may be too expensive to merit consideration under economic conditions in 1997. Inferred reserves, or probable resources, describe resources which have been identified, but are not yet capitalized for extraction. The inferred reserves will be added to the amount of proved reserves once the infrastructure extensions have been incorporated. Undiscovered resources are informed estimates. Table 2.1 summarizes representative 1987 estimates of oil reserves reported in a National Research Council report on alternative transportation fuels summarizes the US reserves.(NRC 1990)

Table 2.1: Estimates of U.S. Resources of Crude Oil (Billion barrels)

	Reserves			
	Proven	**Indicated Additional**	**Inferred**	**Undiscovered**
Lower 48, Onshore	16.6	3.1	11.2	20.1
Lower 48, Offshore	3.3	0.1	1.6	12.7
Alaska	7.4	0.6	5.5	16.6
Total	27.3	3.8	18.3	49.4

Source: National Research Council (1990).

Both the low and high predictions for total US reserves in the NRC report considered the possibility of doubling the estimated growth in recoverable reserves by employing very expensive recovery technology, costing $40-$50/bbl recovered. Usual moderate recovery costs in the US are $25/bbl.

Some of the potentially recoverable oil may have not be recoverable for reasons other than cost. Environmental concerns about intrusion into or destruction of wilderness areas may prevent the extraction of some reserves. For example, a substantial amount of Alaskan petroleum is located in the 19 million acre Arctic National Wildlife Refuge (ANWR). Whether to open 1.5 million acres of land on the coast of the refuge, the "1002 area," for resource extraction is currently at the center of debate in Congress. The U.S. DOE's EIA (1992) estimates that oil production volumes there could reach a very significant 1 million bbl/day. However, environmentalists claim that the project will block animals' access to the coast and the migratory routes for caribou. In Colorado, where there are large reserves of oil shale (oil within the matrix of layered rock sediments), environmentalists resisted any notion of extracting the reserve during the energy crisis of the late 1970s.

Table 2.2 shows the distribution of proven crude oil reserves as of Jan1, 1997.

Table 2.2: 1997 Proven Crude Oil Reserves by World Region

World Region	Millions of Barrels
Canada	4,894
Western Europe	18,361
United States	22,351
Austral-Asia	42,299
Russia/E. Europe	59,093
Africa	67,555
Latin America	127,943
Middle East	676,352
Total World	1,018,850

Source: American Petroleum Institute (1997)

Most of the world's proven reserves are in the Middle East, with a substantial portion in the Americas. The U.S. Geological Survey estimates the world's estimated discovered and undiscovered reserves of petroleum at 1.5 to 1.6 trillion barrels (U.S. DOT 1996a).

The OPEC countries' majority position in the petroleum supply market potentially gives them substantial power in determining oil prices. Currently, supply easily meets demand. However, according to a U.S. DOT report (U.S. DOT 1996a) OPEC now produces oil at a rate of around 1% of their total reserves per year, and the rest of the world is producing at twice that rate. At these rates, non-OPEC countries would deplete their reserves and encounter higher production costs sooner than the OPEC states would, and may become dependent on dependent on this sole body of suppliers.

Most petroleum used in the U.S. comes from North American fields, but a growing percentage is imported. Oil imports made up 35% of U.S. consumption in 1973, and reached a peak of 47% in 1977. A more fuel efficient vehicle fleet and higher oil prices helped to reduce this dependence to 27% in 1985, partly because more expensive domestic producers could compete in the market at the higher price. But oil price decreases in 1986 have closed many domestic wells and increased imports again to 45% today. With the rapid growth of vehicle miles traveled and a new market for less fuel efficient vehicles emerging in the U.S., the EIA projects that with low oil prices dominating, imports will increase to over 65% by 2010 (U.S. DOE EIA 1992). Even at high oil prices, the EIA predicts that the U.S. will be importing almost 55% of its oil by then.

2.2 Emissions from Petroleum Use in Vehicles

Petroleum products have many characteristics which make them nearly ideal combustion fuels. Most of all, they contain an enormous amount of energy for their mass and volume, so sufficient supplies for people's desired mobility are easy to transport and store in vehicles. However, evaporation and combustion of the fuels emits some gases which have been shown to be harmful to human health, and others which have been implicated in greenhouse warming theories. Mobile sources of pollution are numerous and densely clustered enough that they contribute to a major portion of air pollution, mostly in urban areas. Though it is difficult to estimate the number of people exposed to this urban air pollution, DOE estimates that about ¼ to 1/3 of the population is affected, or 60-80 million people (U.S. DOT 1996a), while the EPA estimates 90 million (U.S. EPA 1993). Highway vehicle transportation, the focus of this thesis, contributes to the largest proportion of mobile source emissions because of the large number and frequent use of the vehicles. However, measurement of emissions and their environmental and health effects does not give very precise results, and most theories of chemical interactions from the source of emission to the effects are extremely complicated and difficult to test. Linking environmental and health problems to particular atmospheric and aquatic emissions has involved as much political negotiation as it has scientific research.

Emissions of carbon monoxide (CO) and hydrocarbons (HC) are particularly high from gasoline powered vehicles, while diesels emit higher amounts of particulate matter (PM). Both types of vehicles emit carbon dioxide (CO2) and steam as byproducts of carbon fuel combustion, and nitrogen oxides (NOx) which result from heating air in the engine. The major pollutants emitted by petroleum vehicles which have elicited concern from scientists, health and environmental activists, and lawmakers are: CO, NO2, HC (or volatile organic compounds, VOC), particulate matter of size less than 10 microns (PM10), lead, benzene and other aromatics, and sulfur dioxide (SO2). CO2, a natural result of complete combustion, has been identified in the last ten years with an accumulation of gases that retain the earth's radiant heat, the so-called 'greenhouse gases', but no vehicle policy currently applies to reducing CO2 emissions from vehicles. There are laws intending to reduce each of the other pollutants both from mobile and from stationary sources.

Table 2.3 outlines the theoretical effects of each pollutant (adapted from Seymour 1992, table 1), the emission source, and the way in which the pollutant either has been or could be controlled.

Table 2.3: Atmospheric Pollutants, Emissions Sources, and Control Measures

Pollutant	Health/Environmental Effect	Emission Source	Controlled by
CO	Interferes with oxygen exchange in blood.	Incomplete combustion of fuel. More from gasoline vehicles than diesels.	Catalytic converter, fuel oxygen additives.
CO2	Greenhouse gas.	Complete combustion of fossil fuel. Buildup avoided by combusting non-fossil (renewable) fuel.	Combustion of renewable fuel, reduction in vehicle miles, increased efficiency, high hydrogen/carbon ratio fuel.
HC	Leads to ground level ozone.*	Incomplete combustion of fuel/evaporation of fuel.	Fuel volatility reduction, catalytic converter, complete combustion.
PM10	Deposited in lungs, can carry toxics to lungs. Possibly carcinogenic.	30-100x higher emissions from diesels than gasoline vehicles. Very high from coal combustion. Includes liquid HCs, carbon particulates, acid aerosols, steam (water).	Filter, leaner burn, lighter molecular weight hydrocarbon fuels
Lead	Implicated in neurological disorders.	Anti-knock compound in gasoline – phased out in 1996.	Replace with octane fuel additive
SO2	Precursor to acid rain, which causes damage to vegetation and buildings.	Combustion of sulfur-rich fuels: diesel, coal. Minor contribution from mobile sources, more from electric power industry.	Remove sulfur from crude before refining into lighter fuels. Use of lighter crudes. Coal "scrubbing."
NOx	Acid rain, ozone* precursor. NO2 most harmful for respiratory distress, brown color.	Product of combustion in the presence of air. Mobile and stationary sources. More a problem with diesels and industrial stationary sources.	Catalytic converter, cooler engine.
*Ozone	Respiratory distress and eye irritation. Symptoms similar to cigarette smoke exposure.	NOx, HC, and sunlight. Not emitted from vehicles.	Reduce HC and/or NOx.

Source: Seymour 1992

The unacceptably high accumulation and recurrent high concentrations of mobile source pollutants attributed to petroleum use motivated federal action in the mid-60s to reduce light-duty vehicle pollution. Pollutant emissions have been reduced since the 1960s with a combination of catalytic treatment of exhaust gases after combustion in the vehicle, and adjustments to the contents of certain chemicals in gasoline. Heavy duty and non-highway vehicles have been controlled to varying degrees by similar policies. However, vehicle miles traveled (VMT) has grown so quickly that emissions reductions from individual vehicles could not compensate for the increase, and emissions of some pollutants have increased despite controlling measures. Table 2.4 summarizes data from the EPA and FHWA (cited in U.S. DOT 1996a) regarding VMT increase and pollutant emissions from 1975-1994. The fact that emissions do not increase with VMT attests to strides in automobile efficiency, emissions control, and fuel reformulations:

Table 2.4: Change in Highway Vehicle Miles Traveled and Total Vehicle Emissions in the U.S., 1975-94

Criterion	% Change, 1970-1994
VMT*	+104.0
CO2**	+38.0
SO2	+25.7
NOx	+0.7
PM-10	-16.7
CO	-31.9
VOC, or HC	-53.0
Lead	-99.2

Source: U.S. DOT 1996a, *80% more vehicles, **U.S. DOT 1996b.

CO, HC, and NOx vehicle emissions were reduced by technologies onboard the vehicle by the Federal Clean Air Act (CAA) of 1970, for vehicles beginning in the model year 1975-76 (which was extended to 1977). This requirement forced the market introduction of large numbers of vehicles catalytic exhaust gas converters in 1977. The catalysts completely combust most of the CO into CO2 in the exhaust pipe, before it is emitted to the atmosphere, reducing CO in the exhaust by 90%.

NOx reductions are difficult to achieve, since any source of heat can cause nitrogen in the air to react with oxygen in the air. The 3-way catalysts introduced in 1981 work with a computerized "closed loop" system to reduce nitrogen oxide emissions. The systems have an oxygen sensor in the exhaust system to control engine air intake and reduce NOx by up to 85% by converting it to nitrogen and oxygen. Roughly, more fuel-efficient engines run leaner and hotter, and produce more NOx. This is an important tradeoff for diesel engines, which emit less particulate matter if they are running more efficiently, but emit more NOx at the higher temperature of the lean air/fuel mixture.

Tailpipe HC emissions have also been further reduced by using computers, fuel injectors, and "closed-loop" combustion strategies to improve the fuel/air ratio in the engine so that fuels burn more completely. These technologies have also resulted in improved fuel efficiency and reduced CO, as well. New requirements to reduce the volatility of gasoline blends are an effort to reduce HC evaporative emissions at refueling stations and from the gas tanks of vehicles.

Lead and sulfur foul the exhaust catalysts in gasoline vehicles, and so had to be eliminated or reduced to near-zero levels in gasoline to be used with the catalytic converters (unleaded gasoline). Lead compounds help to reduce engine "knocking," or pre-ignition of the fuel, however, and had to be replaced with octane-enhancing additives as it was being phased out of gasoline in the 1980s. The market for MTBE (methyl tertiary butyl ether) and ethanol (called gasohol when mixed with gasoline in a 1:9 volume ratio) as gasoline octane additives grew in proportion to the demand for unleaded gasoline. Leaded gasoline has been illegal in the U.S. since January 1, 1996. Sulfur can be reduced in gasoline by buying low sulfur imported crude oil, or by removing sulfur in a series of crude refining steps. Sulfur has been reduced in diesel fuels, as well, to control SO2 emissions.

Roughly speaking, CO2 emissions track energy consumption when fossil hydrocarbon fuels combust. Burning, or oxidizing, fossil carbon and hydrogen releases the energy needed to run an engine, with water and carbon dioxide as the lowest energy chemical byproducts of the reaction. Using more fossil energy requires releasing more CO2. Even storing fossil energy in other media like hydrogen or batteries, or converting the fossil energy to electricity, releases CO2 after the fossil hydrocarbon has been oxidized. This raises issues for alternative vehicle fuels which may have low CO2 emissions at the tailpipe: they may not necessarily emit low amounts of CO2 in a lifecycle sense if the fuels storing the energy have derived that energy from fossil sources upstream of the vehicle. The amount of carbon dioxide emitted depends on the energy demand of the conversion or combustion process and the amount of hydrogen contained in the fossil hydrocarbon. The more energy that can be released from the fuel by oxidizing hydrogen as opposed to carbon, the less CO2 will be produced per unit energy in the fuel. The 38% increase relative to a 104% increase in VMT over the last 25 years shows the increased fuel efficiency of the U.S. vehicle fleet. To further reduce the release of CO2 from petroleum vehicles would require increasing their energy efficiency (decreasing fuel consumption) or decreasing the number of vehicle miles traveled (VMT).

Another alternative for reducing CO2 emissions would be to use carbon sources which do not add new CO2 to the atmospheric cycle. Only biologically derived fuels (fuels made from "biomass") can store energy in hydrocarbons which contain carbon that is active in the atmospheric carbon cycle. Combusting fuels derived from these biological sources, like plants, lichens, fungi, trees, or even some garbage, would add CO2 to the atmosphere which had already been taken away from the atmosphere by the biological source. This avoids adding new CO2 from fossil fuels to the greenhouse gas accumulation. This is the only way to reduce carbon dioxide emissions from combustion to zero. Carbon dioxide will be the most difficult pollutant to reduce, as renewable fuels are limited in supply and very expensive. Its emission will increase with VMT and the inverse of fleet fuel efficiency.

The reductions in mobile emissions have been accompanied by reductions in stationary sector emissions. Despite mobile source reductions, by 1994 mobile sources contributed 78% of CO, 32% of CO2, 45% of NOx and HC, 35% of lead, and 40% of PM-10 emitted to the atmosphere across the country (U.S. DOT 1996a). Carbon monoxide is the signature pollutant of mobile sources because of the hydrocarbon fuel. Highway vehicles alone accounted for 62% of CO and CO2, 32% of NOx, and 26% of HC emissions in the nation, corresponding to 61 million tons CO, 1002 million tons CO2, 7.5 million tons NOx, and 6.3 million tons HC (U.S. DOT 1996a). According to the Bureau of Transportation Statistics (BTS) however, without the reductions in emissions per vehicle-mile since 1970, transportation-source air pollution would be two to four times what they are now (cited in U.S DOT 1996b).

2.3 Alternatives to Petroleum

Fuel alternatives to petroleum could offer advantages in terms of fuel resource independence for the nation, lower air emissions, or lower cost. However, some substitutions may trade-off vehicle performance or serviceability in return for the benefits they confer. And some fuel alternatives have limited reserves themselves, not improving at all on petroleum's supply problem. Most fuel alternatives require a wholly new or retrofitted engine in order to use them. This dependence necessitates considering the fuels and vehicles together in a system. The term, "alternative fuel vehicle" (AFV), then, refers to both the fuel and the vehicle parts of this system. New AFV systems would require new fuel refining and delivery infrastructures because of the fuels' different physical characteristics from gasoline, and a new parts and maintenance support structure for the new vehicle components. These supply networks would probably have to be established across large regions, to preserve the familiar nationwide compatibility provided by the current infrastructure, though regional niche applications of technologies may prove worthwhile. On the political and economic side of AFV changes, new regulations would have to be considered for the different characteristics of the new fuels and vehicle powerplants, for issues ranging from safety to taxation. All of these changes would have to occur in the environment of a deeply and widely established petroleum economy.

True departures from petroleum-based vehicles are not used on a wide enough scale today to have an effect on either petroleum consumption or air pollution. But successful alternatives will be expected to provide substantial improvements to gasoline in these areas. In addition, the fuels which can offer a higher combined resource-to-wheels efficiency and resource availability may stand the best chance of adoption from an energy security standpoint, since those fuels will last the longest. Three important bases of comparison for alternative fuels will be cost, energy efficiency, and the emissions released by using them.

Measuring these characteristics in the vehicle works well for comparing gasoline vehicles to gasoline vehicles. Since all cars use the same fuel from the same sources, comparing the emissions, fuel economy, or cost of two vehicles suffices to identify the superior performer. But in order to be able to compare the emissions, energy efficiency, or cost of using different fuels in different vehicles, this analysis takes into account the entire fuel chain, from resources to the fuel's use in the vehicle. The model corrects for existing price-altering policies to present a "level playing field" for comparing the costs of different systems. This chain analysis also provides insight into the weak links in fuel procurement and utilization: stages of excessive energy loss, emissions, or cost, for consideration in technology policy decisions.

Chapter 3 discusses policies in the U.S. which have tended to introduce alternatives to petroleum.

2.4 Vehicle Use: The Shoes to Fill

2.4.1 Highway Vehicle Ownership and Use in the USA

The car and light truck market in the US offers a lot of potential for AFV growth, given an attractive relationship between price and performance. The same holds in the market for transportation fuels. American consumers spent about $153 billion on new and used personal car purchases in 1994, and $107 billion on gasoline and oil. These individual car purchases included 4.6 million new passenger cars. In addition to the personal market, businesses spent $81 billion on 4.5 million new passenger cars, and governments spent $1.7 billion on 115,000 cars. A total of 9.2 million new passenger cars were sold in 1994, and 5.7 million light trucks (U.S. DOT 1996a). Expenditures on replacement parts for the entire fleet were another $30 billion. These numbers represent not only a potential market for vehicles and fuels, but also the high stakes that automobile and petroleum producers have at risk in vehicle policy decisions.

Most adult Americans will purchase several highway motor vehicles in their lives. In 1994, the average American consumer household spent about $2,725 on new vehicle purchases, and $1000 on gasoline and oil (U.S. DOT 1996b). This represents about 19% of household spending. The average number of vehicles owned per household is about 1.8, but varies by region: 1.5 in the Northeast, where denser settlement supports transit services; 1.8 in the generally poorer South; and 2.1 to 2.2 in the low-density Midwest and West, respectively. Individual households in the West and Midwest not only own more vehicles per capita, they also spend more on gasoline and oil, about $1200 vs. $900 in other regions, because they drive further and more often. Rural residents across the country spend an average of $1200 a year on gasoline and oil for this same reason. Average household vehicle expenditures are 33% lower in the Northeast than in the rest of the country because of the larger number of households which do not own a single or multiple vehicles over which the figure is averaged.

An average passenger vehicle in the U.S. is driven about 12,000 miles per year, which is a mean travel of about 33 miles a day. This average has increased monotonically from 9,000 miles per year in 1980 (U.S. DOT 1996a), possibly indicating a trend in growth of automobile trip length for the future. Of course, there may be no individual vehicle which travels with this annual total and daily average mileage, but for an order of magnitude measure of performance, it is an important average to keep in mind when considering the capabilities of AFV technology. Vehicle range is a common performance limiting factor for many types of alternative fuels.

The statistic means that a portion of vehicles will exceed the need for a 33 mile daily range at least some days of the year. An AFV that would be used as a universal replacement for petroleum vehicles should be capable of at least this range, plus a comfort factor. On the other hand, though the statistic doesn't reveal the number and distance of peak trips when demand for range could be very much more than 33 miles, it shows that vehicles with maximum ranges near this value may find a market if the demand for longer distance travel could be met with another vehicle. This issue ties AFV policy with the idea of individual mobility in general, which can be a very complicated problem. However, as noted above, average vehicle ownership in American households is nearly two vehicles, so if the price of a range-limited vehicle were low enough, these vehicles could potentially find a market in multiple vehicle households. Their success would depend on their user cost and the frequency and distance of the longer trips, information which can only be obtained in expensive travel diary and marketing surveys.

2.4.2 Fleet Vehicles

Fleets employ about 8 million cars, which is 7% of the total cars, and most of the 63 million trucks in the U.S.. These are important figures because current federal policies mandate fleet purchases of AFVs, depending on the size of the fleet, its owner/operator, and the weight of the fleet vehicles. Fleets present a potential niche for AFV designs which require complex, inconvenient, or expensive refueling infrastructure that may not find support from individual consumers. Fleet applications also provide a nearly ideal testing laboratory for AFV performance, since the use and maintenance of the vehicle is closely observed for purposes of managing the fleet. Characteristics of the use of AFVs in fleets can be well correlated with maintenance and fuel needs in a fleet application. Table 2.5 shows the approximate number of fleet cars in the U.S. according to the fleet manager or type of vehicle application.

Table 2.5: U.S. Automobiles in Fleets by Owner and Use, 1994 (U.S. DOT 1996b)

Fleet Owner	Automobiles in Fleet* (Thousands)	Percent of U.S. Total
Individually Leased	3150	2.4
Business Fleets	2600	1.9
Daily Rental	1500	1.1
Government (Non-military)	450	0.3
Utilities	400	0.3
Police	250	0.2
Taxi	150	0.1
Total in Fleets of 10 or more (affected by recent policies)	8500	6.0
Total in Fleets of 4 or more	10500	7.7

***Fleets of 10 or more, except in last row. Numbers rounded to nearest 50,000 vehicles**

As the table illustrates, the policy step toward replacing fleet cars with annual purchases of alternatively fueled vehicles would have minor direct effect on total accumulation of

AFVs because affected fleet vehicles comprise only 6-8% of the total number of vehicles in the U.S.. The schedule of purchases in the combined federal fleet purchase directives is complicated and allows for exemptions from compliance (see Chapter 3), but in general it calls for a growing rate of gasoline vehicle replacement with AFVs each year. The policy can serve as a stimulus to auto and fuel industry innovation and marketing however, and has already resulted in good data for use in future fuel/vehicle system choices.

2.4.3 Socioeconomic Context of Vehicle Use

Emissions and VMT depend on elements external to the fuel/vehicle system which are poorly understood, but which will be continued influences in the future even as vehicle and fuel technologies change. A major driver of vehicle use, the low density settlement patterns around city centers in the U.S., have fostered Americans' dependence on individual automobile use, and exposed more of the population to urban pollution since the early 1950s as population brought mobile source pollution to previously rural areas. In the 1980s, high-tech industries relying less on the freight transport infrastructure and unskilled labor densities found in city centers began moving their offices and production to cheaper-rent areas surrounding city centers. These "office parks" effectively spread cities' economic activity zones to the previously rural regions between suburbs, producing demand for more roadways and more traffic between suburbs.

It is apparently less the case that Americans are moving to urban regions, than that urban centers and their highway-dependent residents are sprawling out into suburbs which had previously been rural areas, which had generated less highway VMT. This "sprawl," common in the West, has increased trip length, vehicle ownership, and road congestion around the city center, though not necessarily in the center. The effect that increased congestion has had on the amount of emissions is unclear, but the increased VMT and population in these expanded regions has raised emissions and exposed more people to mobile source air pollution.

About 80% of the U.S. population now lives in urban and satellite centers as described by Metropolitan Statistical Areas (MSA), which range in population from 200,000 to 20 million. The MSAs are characterized by a center city or conglomeration of trip attractors, and they have been defined such that most commuting trips occur within MSAs as opposed to between them. MSAs are therefore useful transportation analysis and policy-making building blocks for establishing the behavioral trends and the jurisdiction of regulations. MSAs are based on economics, however, and do not often coincide with legal jurisdictions, so implementing policies may imply cooperation between local governments or imposition of rules from a government level with superior jurisdiction.

65% of passenger VMT in the US occurred in MSAs in 1994, and 54% of truck VMT. These statistics have increased in the last thirty years because of growth in MSA populations. This growth has been due to two factors: redistricting the MSAs to reflect changing economic activity zones; and growth of mobility surrounding the economic activity. Both of these increases reflect the increase in suburban-based car commuting, which has extended the geographic boundaries of MSAs, and the broader geographic range of industrial and consumption economies. Despite the reduced roadway efficiencies in these growing centers and their satellites, residents rely on their personal vehicles to commute to work. VMT has increased from 1.1 to 1.6 trillion miles from 1980 to 1994, and the average miles traveled per vehicle, an important performance measure for AFVs to match, rose from 9,100 to 11,800 per year. The drive-alone mode share for trips to work exceeds 75% of trips in most major cities except New York (53%) and San Francisco (70%), which maintain a more extensive transit infrastructure, including commuter rail. These cities can generate higher transit ridership for more economical transit systems partly because their denser populations make transit operation more economically efficient, and partly because access to them via road (across bottlenecks like bridges or tunnels) makes car travel more difficult. Low supplies of parking space and other land-use issues also deter automobile use and ownership in these areas. The structure of a more usual American city however, provides the best access via roadways, which encourages driving a personal automobile.

New traffic in urban areas has grown faster than lane-miles of roadway, increasing congestion in most MSAs since 1982, with a few exceptions (Detroit, Phoenix, and Houston all experienced reductions) (U.S. DOT 1996a). An individual vehicle traveling in congestion has higher emissions per mile than a car driving at normal speed, because of the low number of miles traveled at the lower speed over which to average somewhat higher emissions. Emissions of HC, CO, and CO2 can be much higher during the acceleration and deceleration characteristic of congested flow because of the way cars are programmed to enrich the fuel/air mixture for better performance. Idling engines may also have significantly higher emissions than engines under moderate load (and stationary vehicles, of course, emit infinite per mile emissions!). In a supply and demand consideration of VMT however, congestion works to decrease the supply of roadway and to make travel more expensive, in a temporal sense, also reducing demand for personal vehicle use. This effect may actually result in lowering emissions overall, since more people decide not to drive alone. No one knows for sure what effect congestion has on total urban vehicle emissions.

One important implication of low-density land use policies as they regard alternative fuel vehicle technology, is the necessity of a wider fuel distribution network and of vehicles with a long range, possibly over the national average of 33 miles per day. Current land use suits current petroleum vehicle technology perfectly, and conversely, current living preferences depend on gasoline automobiles and large diesel delivery trucks. Growth in low density housing, office parks, and strip malls is very high in the land-rich Western states. This growth can be counted on to continue at least until the end of the next long-term planning period (2015 for most cities). Some alternative fuel vehicle systems, like electric station cars used for trips to commuter rail stations, for example, may find niche markets in joint land-use/transportation plans which provide refueling or other favorable infrastructure, but large-scale replacement of petroleum vehicles would have to be compatible with the existing sprawl and people's existing driving habits, at least for the first third of the 21st century. Alternative fuel vehicles which can provide the best substitute for petroleum vehicles in these low density areas will find the fastest mainstream acceptance.

2.5 Considerations for Successful AFV Introduction

AFVs' potential benefits over petroleum are primarily lower air emissions and strategic resource management. Under current policies, these benefits are not immediately apparent to, nor realized by, the purchaser and user of the vehicle, since these kinds of benefits are spread over the entire regional or national population. Widespread AFV introduction will therefore only occur if the vehicles and refueling infrastructure can "transparently" replace gasoline vehicles in such a way that they cause minimal changes to people's driving or mobility habits.

The current trends are to drive further and more often, and to purchase larger, utility-style vehicles with large cargo space. This suggests that successful AFVs will have to retain power, cargo space, and a range longer than a day's travel of about 50 miles. The refueling infrastructure will have to be as convenient as the current gasoline refueling stations, and as easily available.

However, American households typically own more than one car, so for AFVs which can match some, but not all, performance characteristics of conventional vehicles, there is potential to find niches in these households for specialized trips. Other niches for AFVs may be in fleet applications, where complicated refueling procedures do not hinder the vehicle operation as much as it would for the owner of a personal vehicle. But the entire fleet market is a small share of the total highway vehicles, and might not achieve great overall reductions in emissions or petroleum imports.

For the present, resource reserves are plentiful and inexpensive, and gasoline vehicle emissions have been controlled very well with exhaust and fuel modifications which are relatively minor compared to changing the national fueling infrastructure to a non-petroleum alternative. These changes have also come at a relatively minor cost compared to present alternative fuel options. The remainder of this thesis presents a basis for comparing fuel alternatives to identify appropriate costs and world conditions in which a change might be desirable or possible.

3. Existing AFV Policies

This chapter begins with an overview of the scope of AFV policy. It then describes in detail the current policies which have had a major effect on AFV development, and which will continue to influence AFVs into the first decade of the next century. The third section outlines current federal government AFV development programs. Section four describes how public technology policy is made in the U.S., and the channels by which it may be influenced. The final section summarizes the important policy thrusts which will continue to influence AFVs throughout the period of consideration of this thesis.

3.1 The Scope of AFV Policy: Overview

This section provides a bird's eye view of the federal policies which have affected alternative fuels or vehicles. Federal AFV policy in 1997 has two major emphases: cleaner urban air and less reliance on imported fuels. A secondary policy direction funds research and development of technologies that reduce transportation CO2 emissions, which are a global warming concern. Vehicle miles traveled and vehicle efficiency strongly influence emissions, so a division between types of policies is not clear. This thesis divides the policies into primary and secondary areas of impact.

State policies aim to comply with federal laws, while California's AFV policies tend to be stricter than or to anticipate federal policy.

AFV policies mix consumer choice with government's goals and technological reality. Often, the best option in any of the three areas is sub-optimal or undesirable in the others. Lawmakers must balance health, environmental, and national strategic needs with concern for preserving individuals' accustomed level of mobility and industry competitiveness. Americans have actually accepted government involvement in consumer choice when to do so was a popular decision. Laws which hint at compromising personal mobility or industry profits are unlikely to gain a popular following. As a result, AFV policies tend toward regulation of the technical components of vehicles and fuels rather than toward measures which may influence consumer behavior. These beliefs are manifested in the U.S. in low federal gasoline and diesel fuel taxes, and some of the strictest vehicle emissions standards and cleanest fuels.

3.1.1 Air Quality Policies

Geographically comprehensive air quality policies have had the most impact on alternative fuels, tending to promote large-scale change by affecting a large market segment of vehicles and fuels at once. Fuel composition and anti-pollution equipment in vehicles nationwide have changed several times since 1970 as a result of Clean Air Act (CAA) directives to the EPA to regulate air quality (Downstream Alternatives 1996). The 1990 amendments to the CAA include further reductions in tailpipe emissions, and very stringent emissions standards for fleet vehicles.

Section 3.2.2 details the history and impact of the CAA on alternative fuels.

3.1.2 Energy and Efficiency Policies

Energy policies intend to reduce petroleum imports by reducing its consumption. They target vehicle efficiency (mileage) or, more recently, fleet vehicles and vehicle use.

CAFE Mileage Standard

The Corporate Average Fuel Economy standard (CAFE) from the Energy Policy and Conservation Act of 1975 does not directly address alternative fuels, but it helped accomplish one of the major goals of AFV policy, which is reducing petroleum imports. It has probably had the most impact in this area of all other policies. Since CAFE was introduced, the average mileage of a new car has increased from 15 miles per gallon (mpg) in 1975 to 26 mpg in 1982 (U.S. DOT 1996a), though it has remained below 28 mpg since then. Fleet average fuel efficiency improvements have saved more than 7 trillion barrels of gasoline since 1975, according to my calculation from annual statistics from the Department of Transportation (U.S. DOT 1996b).

Burning less fuel reduces pollution, so efficiency gains in the last 20 years have also reduced emissions.

Fleets

Policies addressing alternative fuel fleets affect a small proportion of the total vehicles, owners, and fuel consumption. Their intent is to stimulate a market for alternative fuel vehicles which will reduce air emissions and oil dependence, foreign or domestic, by changing fleet fuel consumption to non-petroleum fuel alternatives. These policies include measures in the Alternative Motor Fuels Act (AMFA, Public Law #100-494) of 1988 to encourage coherent vehicle and fuel supply infrastructure development. The Clean Air Act Amendments (CAAA90, Public Law #101-549) of 1990 has a section requiring fleet purchases of AFVs in certain polluted areas. The Energy Policy Act (EPACT, Public Law #102-486) of 1992 introduces more purchase requirements, in some cases superseding those of the CAAA. These laws and regulations have resulted more often in technology demonstration projects because of the relatively controlled environment in which the vehicles operate. Two Executive Orders from President Clinton (E.O. 12844 and E.O. 13031) further modify the federal government's fleet purchases.

Sections 3.2.2 and 3.2.3 detail the content of these laws. Table 3.4 lists the federal fleet purchase requirements in effect until 2004.

Transportation Control Measures (TCM)

The Clean Air Act Amendments of 1990 require states in non-attainment to include transportation control measures (TCM) as part of their air pollution reduction plans. TCMs include behavioral measures like designating higher occupancy vehicle lanes, establishing park-n-ride transit facilities, or requiring large employers to find ways to increase vehicle occupancy on work commutes. TCMs are controversial, and reports conflict about their efficiency in reducing air emissions or improving the efficiency of the transportation system. Many regions dread the organizational challenges imposed by

TCMs, and the EPA has used them as incentives in which exemptions from TCM requirements may be exchanged for participation in alternative fuel vehicle fleet programs. The way TCMs have worked in setting policy is presented in Section 3.2.3 in the subheading for exemptions.

3.1.3 State AFV Policies

State policies tend to emphasize urban air quality in compliance with federal standards because federal sanctions for not complying to air pollution standards would apply the state as a whole, whereas the punishment for failure of a fleet to purchase AFVs will apply only the owners of that fleet. States may either follow CAAA urban air quality mandates in submitting their state plan, or they may adopt California's State Implementation Plan (SIP) without modification.

California has a potentially large amount of power to influence AFV technology because of its large vehicle market. The California Air Resources Board (CARB) regulations of 1990 (included in the 1994 SIP and amended in 1996), treats both air quality and energy source issues at once. One rule originally mandated sales of specific numbers vehicles with zero emissions from the powertrain (ZEV) by the year 1998. The modification of this rule, adopted in 1996, was a compromise with automakers that postponed this requirement to 2003. As battery electric vehicles, ZEVs would emit no pollutants from the powertrain into urban areas, and would consume electricity produced primarily by domestic fuels.

The California Pilot program encourages the production of clean fuels and vehicles, similar to the fleet requirements in the CAAA. It requires 150,000 new vehicles in 1996 to emit less than 0.125 g/mile NMHC, 3.4 g/mile CO, and 0.4 g/mile NOx. The California Pilot program standard permits half as much NMHC emissions as the CAAA standard. The number of vehicles required doubles by 1999. By 2001, the standard for NHMC and NOx will be tightened another 50%, the same as the fleet standards for the CAAA clean fleet program (U.S. EPA, 1994).

Table 3.1: California Pilot Program Tailpipe Emissions Standards

Date	Vehicles Required	NMHC (g/mi)	CO (g/mi)	NOx (g/mi)
1996	150,000	0.125	3.4	0.4
1999	300,000	0.125	3.4	0.4
2001	300,000	0.075	3.4	0.2

Source: U.S EPA 1994

3.2 Major Policies Affecting AFV Technology

3.2.1 Summary of Major Policies Affecting Alternative Fuel Vehicles

This section describes in more detail the major policies which have motivated AFV development. It is divided into sections on air emissions, alternative fuels and fleets, and California's AFV measures. Table 3.2: summarizes the major fuel and vehicle policies in the U.S. mentioned in section 3.1, and the primary or secondary areas of their impact. The table does not intend to show the degree of impact, rather the primary targeted areas within each regulation and the secondary effects that these regulations have caused.

Table 3.2: Primary (1) and Secondary (2) Areas of Impact of U.S. Fuel and Vehicle Policies

Regulation	Fleets	Air Emissions	Fuel/ Resource	Efficiency	Transport-ation Control Measures
CAFE 1975	-	2	2	1	-
AMFA 1988	1	-	1	-	-
CAAA 1990	1	1	1	-	1
EPACT 1992	1	-	1	-	-
EO 1996	1	-	1	-	-
CARB as Adopted in 1996	1	1	2	2	1
CA Pilot Program	1	1	2	-	-

The table shows that many policies focus directly on fleet regulations and fuel types. Air emissions are addressed by fewer policies. However, the number of vehicles affected by each policy is not captured in this table. CAFE and CAAA90 have had widespread impact across the country. From the last chapter, fleet policies impact about 6-8% of the nation's vehicles.

3.2.2 Emissions Policies: The Clean Air Act

The CAA and its amendments primarily address the urban pollution caused by both stationary and mobile emitters. The CAA legislation of 1970 established a regulatory agency in the executive branch, the Environmental Protection Agency (EPA), which it gave the responsibility of identifying and cleaning up the country's polluted air resources. Subsequent amendments have directed the EPA to regulate specific emissions or pollution sources in the nation. Significant amendments were passed in 1977 (CAAA77) and in 1990 (CAAA90). The 1990 amendments contain many of the motivations for AFV development.

EPA and Ambient Air Quality Standards

The EPA established National Ambient Air Quality Standards (NAAQS) in 1971 (Seymour 1992), which set upper limits for airborne concentrations of harmful pollutants. The standards apply to pollutants measured in Air Quality Control Regions (AQCR), which were responsible for reducing their own pollution to levels specified by the EPA. Areas not complying with the standards are called "non-attainment" zones, and the states containing those zones are required to submit a State Implementation Plan (SIP) to EPA which describes the steps the state will take to meet the standard.

EPA originally regulated five air pollutants in 1971, based on their effects on human health: CO, SO2, NOx, oxidants, and hydrocarbons (Seymour 1992). Secondary and tertiary criteria for controlling air pollution included economic and aesthetic degradation of national resources (e.g. cropland and national parks) caused by pollutants. These secondary and tertiary standards were used to regulate SO2 and particulate emissions, respectively.

In 1977, new data motivated the EPA to introduce new NAAQS for lead and suspended particulates, and to revise the 1971 standards, which were set under a strict deadline and were based on unreliable studies (because so little data was available). The hydrocarbon standard was omitted in 1983, but NAAQS for oxidants, particulates, and NOx were narrowed to target ozone (O3), particulate matter smaller than 10 microns in diameter (PM10), and NO2. The six current NAAQS control ozone, PM10, lead, SO2, NO2, and CO, subject to five-year review (U.S. DOT 1996a).

Expanded AQCR Jurisdiction

The 1990 CAAA redefines non-attainment AQCRs as those which contribute to NAAQS violations in *any* AQCR. Thus regions can be considered in non-attainment if they are shown to create pollution problems for other areas, even if their own air is clean. No state within this region shall be considered to have met the NAAQS for ozone until all of them have met the standard. Though this policy addresses the scientific theories of how atmospheric pollution diffuses, it has aggravated relationships between states which are included in or exempt from control zones. This makes enforcement of the NAAQS difficult. (Seymour, 1992).

Improving Efficacy: An Emissions Market, Encouraging State Participation, Air Pollution Science, Enforcement

Market for Emissions Replaces Command and Control

Changes have been added to the CAA which encourage so-called “market solutions” over EPA’s initial “command and control” approach to setting hard standards and deadlines. Command and control deadlines still apply to many regions, programs, and NAAQS, however.

Command and control regulation means that the government agency sets a standard, say for pollution, and a deadline for a region to meet, otherwise the region (or industry, for example) will meet with sanctions.

The 1970 Act used command and control methods. It required the states to control emissions from sectors identified by EPA as problem emitters, outlining their plans for reducing pollution in a State Implementation Plan, or SIP. The SIP had to include a description of the air quality monitoring procedure in the state, an inventory of emissions, a timetable for reducing emissions on a plant-by-plant basis, and the impact such emissions would have on air quality. No new sources of pollution were to be permitted in the state after submission of the SIP without an equivalent "offset" in emissions from another plant or emissions sector (i.e. one unit of added pollution would have to be offset by one unit of pollution not emitted from another sector within the region).

In the 1990 CAAA, emissions permits, credits, and marketable allowances were introduced to counter industry claims of government inefficiency and favoritism in controlling emissions. Emissions credit markets vary by state, and credits may in some cases be transferable over industries, geographic boundaries, or time periods ("emissions credit banking"). The system allows a firm to make a risky investment in new or expensive pollution control measures, for example, while reducing the risk of the investment with the potential market value of the credits it earns by risking the cleaner technology.

State Participation

The administrative changes that the EPA made to the CAA in subsequent amendments can provide a guide for the structure of successful future national-level policies intended to regulate mobile source emissions or fuels. Some of the changes written into the CAA had to do with encouraging reluctant states to participate in programs which were unpopular in their regions.

The marketable emissions was one way to encourage states to participate in the enforcement of the CAAA standards, by relieving state governments of the responsibility of targeting specific emitters for enforcement.

An aim of the EPA's command and control regulation had been to avoid having a federal agency overstep a state government to directly a particular emitter directly, action which could draw accusations of favoritism from individual firms, and which violated many states' sense of federal vs. state government jurisdiction. But this did not work well everywhere. State governments had no desire to appear as the bad guy, but had to regulate specific industries in order to comply with the federal mandates. With such a controlling approach to regulations however, it was difficult to avoid pointing out particular emitting sectors or individual firms as reduction targets.

One easy choice for state politicians was to blame the federal EPA for problems caused by regulating the state's industries. But their easiest alternative was to ignore the regulations as long as possible in order not to upset the constituents. Industries most strongly impacted by the regulations accused EPA of industry favoritism anyway, despite the state's middleman position.

To further reduce pressure on state governments, Congress established guidelines for SIPs to encourage reluctant state politicians to take unpopular stands in mandating emissions reductions by giving them the federal government to blame.

Improving the Efficacy of the CAA

In 1970, state governments proved themselves poorly equipped, scientifically or organizationally, to measure, report, and enforce SIP goals. Partially for this reason, the 1990 amendments have emphasized devising and communicating "scientific" goals like realistic deadlines, research into health effects of pollutants, monitoring techniques, and air quality modeling.

In efforts to improve emissions from old sources as well as new ones, and to encourage the turnover of technology by new purchases, the Amendments recommend vehicle inspection programs, and apply some new requirements to existing stationary emitters.

Enforcement

The CAAA in 1990 increased the power of enforcement for the EPA. Non-attainment states failing to implement a SIP face losing all of their federal highway allotment (except for safety improvement projects) and face an additional 100 percent pollution offset requirement for new emitters entering the region (effectively, a growth restriction requiring 2 unit reductions for each unit increase of a new industry).

Fuels and Vehicles under CAAA90

Title II of the CAAA90 (Provisions Relating to Mobile Sources) addresses vehicles and fuels. Most vehicle-related pollutants will be reduced by more than 40 percent in the Amendments' mobile source provisions (CFDC 1995). The Amendments require two specific alternative fuels, oxygenated and reformulated gasolines, but no non-petroleum fuels or vehicles except in fleets (see below). Fleet vehicles are required to be replaced by alternative fueled vehicles by set schedules, depending on the vehicle application and the level of regional pollution.

The CAAA does require fuels and vehicles in certain regions or service sectors to meet evaporative and emissions standards. For vehicles, a NOx reduction effort requires a 60% NOx emissions reduction for new cars in 1996. The tighter tailpipe standards require a maximum 0.25 g/mile NMHC emissions (from 0.41 g/mile), and 0.4 g/mile of NOx emissions (from 1.0 g/mile). The CO emissions standard remains at 3.4 g/mile. This emphasis intends to reduce urban ozone (see reformulated gasoline, below).

City buses were required by the CAAA to reduce PM emissions by 60%, with the threat of requiring non-petroleum fuel alternatives for noncompliance.

Fuels are regulated in two major programs, oxygenated fuels and reformulated gasoline, and a smaller program reducing road-use diesel sulfur content by 80%.

Oxygenated Fuels Program: Carbon Monoxide

Carbon monoxide (CO) is a poisonous emission resulting from incomplete fuel combustion. Adding oxygen to the fuel can help fully combust it and lower CO emissions. The CAAA require oxygenated fuels to be used in the winter in areas which do not meet the EPA's standard for CO of 9 ppm, measured and averaged over 8 hours, or 35 ppm, measured over 1 hour.(U.S. DOT 1996a) Areas which experience one or more violations per year fail to meet the standard, and must replace all of their gasoline with oxygenated gasoline for the winter months. In 1991, when the CAAA were promulgated by EPA, 39 metropolitan areas (42 urban areas) were identified as CO non-attainment zones, and were required to participate in the oxygenated fuel program. The CAAA mandated that oxygenated fuels be sold in non-attainment areas beginning the first of November in 1992. The program runs each year until the end of February of the following year. Oxygenated fuel directly impacts about 22 million people who live in non-attainment areas. In the first year of the program, the number of days exceeding the CO standard was reduced by 95% in these non-attainment zones (CFDC 1995).

Oxygenated fuel is normal gasoline which contains oxygen to help it burn completely to CO2 and water. The most common oxygen-containing additives are pure ethanol (grain alcohol), and methyl tertiary butyl ether (MTBE), which is derived from methanol. The additives are required in a minimum volume content to ensure that enough oxygen is in the fuel to appreciably reduce the CO. But they are also limited to maximum values because they could potentially damage plastic parts in the fuel lines of unprotected engines. There are also some political influences from the methanol and ethanol fuel manufacturing interests on the minimum and maximum amounts of each additive, each of whom would like to increase market share for their fuel additive. The Clean Fuels Development Coalition (CFDC 1995), an ethanol interest group, estimates that one third of the country's gasoline is replaced by oxygenated fuels in winter, resulting in 100,000 to 200,000 barrels per day of crude oil displaced by the additive (CFDC 1995). This is a very small percentage of the daily crude oil consumption, however (U.S. DOT 1996a).

Reformulated Gasoline (RFG): Carbon Monoxide and Hydrocarbons

The RFG program is the most dramatic step toward alternative fuels that policies have taken so far. 11% of RFG is methanol-based MTBE. The fuel is available in regions across the country during most times of the year, and year-round in some parts of the country. The two phase RFG program in the CAAA attempts primarily to reduce urban ozone by lowering hydrocarbon (HC) emissions from vehicles year-round. The fuel must be used in cities identified to be in non-compliance with the CAAA90 standards for ozone, but other cities may "opt-in" to the RFG sales program. Within the ozone non-compliance zone, all the gasoline is replaced with RFG during the summer months. The program also reduces the heavy metal, aromatic, sulfur, and olefin content of gasoline, and RFG contains a fuel oxygenate to reduce carbon monoxide (CO) emissions. Phase I of the program runs from 1995-1999, and phase II begins January 1, 2000. The RFG program requires a more fundamental change in gasoline than oxygenated fuels does. The gasoline is made differently at the refinery, rather than simply being blended with an additive after it has been delivered to a distribution point.

In 1990, nearly 100 cities exceeded the NAAQS for ozone of 0.12 ppm, defined as the maximum daily one-hour average concentration. Cities fail to attain the standard if they exceed this limit more than once in a year, meaning that they can fail to meet the standard on one day each year and still attain compliance. This included nine "severely" polluted cities, with a population totaling 57 million people, which exceeded the standards by over 50%. The CAAA permits up to 87 other polluted cities to "opt-in" to the RFG program (CFDC 1995) RFG now constitutes about 40% of all gasoline sold in the U.S. (U.S. DOT 1996a). This displaces about 13 million gallons of gasoline, or about 300,000 barrels of crude oil per day (about 0.87 bbl of crude per bbl of gasoline, ADL/Ford model).

Ozone (O3), is not actually emitted by vehicles, though it is regulated by the CAAA90 for its health impacts. It is a result of a chemical reaction in the presence of sunlight between nitrogen oxides (NOx) and volatile hydrocarbons (HC), specifically, non-methane hydrocarbons (NMHC) (or non-methane organic gases (NMOG). Methane in the atmosphere remains non-reactive at ground level. Both NOx and NMHC are emitted in large quantities in urban areas by vehicles, but NOx emissions come from factories and electric power plants, as well. The HC emissions are both a result of unburned fuel passing through the exhaust system of the vehicle, and of the fuel evaporating from storage tanks, during refueling, and from the vehicle as it drives or sits in the sun. The limiting reagents for producing ozone could be either NOx or NMOG, depending on the concentrations of the gases already present in the atmosphere.

Reducing one or the other inputs will reduce ozone only if the conditions permit. CARB has established two scales, based on conditions in which ozone forms, to use for regulating NOx or NMHC emissions. The so-called MIR (maximum incremental reactivity) index identifies the reactivity of an NMHC under atmospheric conditions in which small changes in NMHC concentrations create large changes in ozone. The MOR (maximum ozone reactivity) index identifies the reactivity of the NMOG under conditions in which NOx is the dominant reagent for ozone formation. The RFG program attempts to reduce hydrocarbon emissions under the atmospheric conditions in which the MIR is high. That means that reducing NMHC emissions will reduce ozone under the MIR atmospheric assumptions.(Wang, 1993)

Hydrocarbon and toxic emissions linked to RFG are required to be reduced at least 15% in phase I of the program without raising NOx emissions. Phase I also requires RFG to conform to the EPA's "simple model" of gasoline content. The simple model is a set of regulations indicating maximum and minimum fuel content for particular chemicals that lead to controlled pollutants. In addition, summer grades must meet stricter (i.e. lower) volatility standards. Phase II requires further reductions in HCs, toxic emissions, and

NOx in emissions from vehicles using RFG. It does not specify the content of any additives in the fuel, apart from minimum permissible values of toxics.

After 1998, the EPA's "complex model" for designing gasoline formulations on a computer will afford refiners an alternative to the simple model, possibly resulting in lower cost or more beneficial fuels (Downstream Alternatives 1996). The complex model is a series of complicated equations in a computer model. The equations reflect the results of measurements of the effects on vehicle exhaust composition of changes in components of gasoline. The tests looked at the emissions effects of, among others, oxygen content by oxygenate type, olefin content, vapor pressure (volatility), and distillation characteristics of the gasoline. The programs could enable a refiner to meet the fuel performance standards established by the EPA in a manner most suited to the refinery (Downstream Alternatives 1996).

It is important to note that the RFG resulting from the CAAA contains nothing that is not found in conventional gasoline, and in fact its properties fall within the range of properties observed in normal gasoline blends. The difference lies in forcing the composition of all of the fuel sold in a region to contain the narrowly specified ratios of ingredients which ensure a lower-emitting fuel (Downstream Alternatives 1996).

In the CAAA, the EPA is instructed to implement clean air programs without respect to the cost of the measure. The full cost of the CAAA for formulating and marketing gasolines acceptable to the new regulations has been estimated by an oil-industry sympathetic paper at $70-$100 billion between 1991 and 1999, $34-$38 billion of which would be borne by refiners (Oil and Gas Journal V27, May 1991, cited in Seymour 1992, p.61). Another estimate from OECD, which claims to be conservative, calculates $25-$33 billion for the refiners' share (Seymour 1992). In a fuel market of about $110 billion per year, these costs are less than 3% of revenues if they are spread over a period of RFG consumption of 10 years or more. These refiner costs include increases for capital investment and operating costs for RFG and low-sulfur diesel fuel production, and operating costs for blending oxygenated fuels. The remaining costs reflect an estimated increased consumer expenditure on an price increases for RFG, low-sulfur diesel, and oxygenated fuel of 8.2-11.0 c/gal, 4.7c/gal, and 4-6 c/gal over conventional gasoline, respectively (Seymour 1992).

3.2.3 Fuel Independence: Alternative Fuels and Fleets

Current non-petroleum policies target fleet applications. Fleets are centrally refueled, stored, and maintained, providing the opportunity for close observation of the vehicles under experimental fuel programs. The driving cycles of the vehicle are also well known, and repeated, offering the opportunity for good research on AFV applications.

Fleets: AMFA, CAAA, EPACT

The AMFA of 1988 introduced a federal policy of coherent fuel infrastructure and vehicle development. The CAAA of 1990 sets deadlines for specific minimum purchase requirements for fleets in certain regions. EPACT of 1992 modifies these purchase requirements based on who owns the fleets, and expands the jurisdiction of the mandate. Two subsequent Executive Orders accelerate federal fleet purchase requirements and limit available funding for acquisitions. All the laws maintain incentives and exemptions for the fleets to which they apply.

AMFA

AMFA requires the Federal Government to purchase alternative fuel vehicles, in the maximum number practicable, which use alcohols and natural gas as fuels, and encourages individual consumers to purchase these vehicles . It also encourages the development of facilities for producing and delivering these fuels for use in vehicles (AMFA 1988). Alcohol fuels and natural gas are both domestically produced, though methanol and natural gas are also currently imported.

CAAA Clean Fuels Fleet Program

The CAAA also includes fleet purchase requirements in its Clean Fuels Fleet Program (CFFP), with the emphasis on purchasing clean-burning fuel alternatives (CFDC 1995).

Fleets with 10 or more vehicles and a centralized refueling infrastructure in the 22 "Serious," "severe," and "extreme" ozone non-attainment cities, plus Denver for its CO violations, must purchase clean fuel vehicles beginning in 1998. The light duty vehicles must emit less than one fourth the NHMCs and NOx of non-fleet vehicles (0.075 g/mile and 0.2 g/mile, respectively (U.S. EPA 1994)). 30% of fleet purchases of new passenger cars, light trucks, and vans weighing up to 8500 pounds (light duty vehicles, LDV) must be clean fuel vehicles. This percentage rises to 50% in 1999, and 70% in 2000. Half of heavy duty vehicle (HDV) purchases must be AFV starting in 2001 (seeTable 3.3, below).

"Clean" alternative fuels, according to the CAAA, are limited to methanol, ethanol, and other alcohols, RFG, low-sulfur diesel, natural gas (NG), liquefied petroleum gas (LPG or propane), hydrogen, and electricity. Dual fuel vehicles must use only the clean fuel within the non-attainment areas.

EPACT

EPACT sets purchase requirements for specific types of fleet owner/operators in regions determined on a population, not pollution, basis, with the goal of reducing dependence on petroleum imports. It defines a fleet as 20 or more centrally refueled vehicles, operated in a metropolitan area with a population of at least 250,000 residents, and controlled by a property which owns at least 50 vehicles in the U.S. This expands the jurisdiction of the mandates to over 180 cities. It also establishes federally acceptable definitions of qualifying alternative fuel vehicles, defining alternative fuel as natural gas, propane, alcohol blends of 85% or more by volume, hydrogen, biomass fuels, liquids derived from coal, and electricity (CFDC 1995). RFG and oxygenated fuels are not considered alternatives under EPACT.

Table 3.3 summarizes CAAA and EPACT's purchase requirements (U.S. DOE, AFDC 1997, CFDC 1995):

Table 3.3: Percent of Annual Clean Fuel Fleet Vehicle Purchases Mandated by the CAAA90 and EPACT92

Year	CAAA90	EPACT92			
	Fleet Light/Heavy Duty Vehicles	Municipal and Private Fleets Early Rule/ Late rule (a)	Private-Sector Utility Company Vehicles (b)	Fleet Light Duty Vehicles	
				Federal(c)	State Government(d)
1993		-	-	5,000	-
1994		-	-	7,500	-
1995		-	-	10,000	-
1996		-	30	25	10
1997		20	50	33	25
1998	30	20	70	50	50
1999	50	20	90	75	75
2000	70	30/20	90	75	75
2001	70/50	40/40	90	75	75
2002	70/50	50/60	90	75	75
2003	70/50	60/70	90	75	75
2004	70/50	70/70	90	75	75

Source: U.S. DOE, AFDC 1997

(a) Municipal and private fleet programs must be determined by DOE to be necessary. EPACT gives DOE Secretary two opportunities to rule on AFV purchases for private fleets. If a ruling was made before 12/15/96, left percentage applies. If later (up to 1/1/2001), right column applies.

(b) Electric or natural gas producers and distributors. Date refers to model-year.

(c) Date refers to fiscal year. Numbers for 1993, 94, and 95 are numbers of vehicle purchases.

(d) Date refers to model-year.

Executive Order 12844, signed by President Clinton on April 21, 1993, increased the number of federal clean vehicle purchases or conversions from the EPACT mandate by 50% each year through 1995 (CFDC 1995).

Exemptions to the Fleet Purchase Requirements

Both the CAAA and EPACT fleet purchase requirements exempt certain fleets and vehicles from mandatory participation where to do so would be impractical (U.S. DOE, AFDC 1997). They each provide an exemption for replacing fleet vehicles weighing over 26,000 lbs. (gross vehicle weight), public leased or rented vehicles, vehicles for sale by dealers, law enforcement and emergency vehicles, non-road vehicles, vehicles garaged at personal residences, and vehicles used for OEM testing. In addition, EPACT exempts military vehicles and vehicles which cannot be replaced with an AFV that serves the same function. EPACT's fleet exemptions apply to fuel and vehicle availability. A fleet is exempt from replacing its vehicles if either a refueling and/or recharging station is not accessible within 5 miles of the fleet operating range or base of operations, or a suitable vehicle meeting the "ordinary needs" of the fleet is not available for sale or lease from an OEM anywhere in the USA (U.S. DOE, AFDC 1997).

Incentives for Fleets to Purchase AFVs

Both the CAAA and EPACT establish a system of incentives for fleets to purchase AFVs. The CFFP of the Clean Air Act exempts clean fuel vehicles from transportation control measures (see overview, above), and CFVs which are certified as ILEV (inherently low emission vehicles) are exempt from HOV (high occupancy vehicle) lane restrictions. Title XIX of EPACT adds tax deductions for incremental costs of AFVs (OME and conversions), and for refueling facilities built after June 30, 1993 (U.S. DOE, AFDC 1997), as summarized in Table 3.4.

Table 3.4: Federal AFV Financial Incentives in EPACT92

AFV Category	Tax Deduction Amount ($)
AFVs < 10,000 lbs gvw:	2,000
AFVs 10,000-26,000 lbs gvw	5,000
Trucks/Vans > 26,000 lbs gvw	50,000
Buses seating 20 or more adults	50,000
Electric Vehicles	10% up to 4,000/vehicle
AFV Refueling Facility	100,000

Source: U.S. DOE, AFDC 1997

Purchases are also encouraged via a system of credits. CAAA permits exempt fleets to purchase CFVs and gain credits to sell to covered fleets in the same area. EPACT permits 1 credit per excess AFV purchased in a covered fleet. This credit is then transferable to other control areas. States may modify these credit systems as long as their requirements do not become less stringent than the federal requirement (Colorado Reg. 17, 1996).

Executive Order 13031 in December of 1996 stated that federal efforts to promote alternative fuel vehicles will be coordinated with state, local, and private efforts to ensure that "adequate refueling capabilities exist or will exist" in cities participating in the Clean Cities Program (U.S. DOE, AFDC 1997).

This same order eliminated special funding for federal government AFV purchases, except for battery electric vehicles which were deemed to be behind in development. Agencies must now make their AFV purchases with their normal vehicle budget allotments, except for electric vehicle purchases for which they will be reimbursed the lesser of one-half the incremental price over a comparable conventional vehicle, or $10,000.

Growth in AFV Fleet Purchases

In 1994 there were 8 million vehicles in 89,000 fleets of ten or more vehicles, most of which had fewer than 500 vehicles. The number of fleets was growing at a rate of 1.6% annually, and the number of fleet vehicles was growing at 3.2% (U.S. DOT 1996a). According to assumptions made by the DOE (U.S. DOE 1992a), about 90% of the federal fleet vehicles are covered by EPACT the CAAA, and 70-85% of the state and local government fleet vehicles. The federal assumptions for the turnover period for fleet light duty vehicles (LDV) is 4 or 5 years, and for heavy duty vehicles (HDV), about every 7 (U.S. DOE 1992a). At the AFV purchase rates established by the federal government, complete replacement of the affected petroleum fleets with AFVs would take place very roughly in 8-10 years for car fleets, and 15 years for heavy duty fleets. As a result of this policy, about 1million fleet AFVs would be on the road in 2000, and 5 million in 2005, accounting for exemptions (U.S. DOT 1996a). This is 10 times more than the total number of AFV currently on the road in the U.S., but is less than 3% of the total number of vehicles.

3.2.4 California AFV Policy

California's 1994 SIP included a controversial measure for the seven highest volume sellers of automobiles in the state to market zero emission vehicles (ZEV) at a rate which increased over time. The measure was modified in 1996. A Memorandum of Agreement between CARB and each of the seven manufacturers replaces the 2% ZEV sales mandate for 1998, establishing a Technology Partnership for advanced EV development (CA EPA 1996). This contract, which is enforceable by the state via heavy financial penalties, will place up to 3750 advanced-battery ZEVs with 125-mile ranges in California by 1998. The Partnership, similar to the 1993 Partnership for a New Generation of Vehicles (PNGV) (see below), will also help commercialize the advanced batteries and other critical zero emission propulsion technologies, like fuel cells (CA EPA 1996). The seven manufacturers in the California Partnership also commit to marketing a PNGV-style vehicle in the United States by 2001. This deadline is 3 years ahead of the equivalent U.S. EPA deadline of 2004 set in July, 1994. California would benefit from this rule as people move into the state and register their vehicles. Currently, almost one-fifth of the newly registered vehicles in the state do not meet California's new vehicle emissions standards. California reserves the right to end the suspension and enforce the ZEV mandate as written if the Partnership fails (CA EPA 1996).

CARB's ZEV strategy for the immediate future includes establishing an EV Implementation Advisory Committee, which monitors battery development, a ZEV technology conference, sharing ZEV information at the CARB Internet site (http://www.arb.ca.gov), and promoting research and development of new ZEV technologies.

3.3 Current Federal AFV Programs

According to the DOE, the federal government's role in the AFV technology is to stimulate a market by encouraging concurrent development of vehicles and fuel infrastructure (U.S. DOE 1997). Following is a summary of federal programs intended to bring AFVs to market-readiness. The final section includes a table of the federal investment in these programs for a comparison of their relative emphasis.

3.3.1 Partnership for a New Generation of Vehicles, PNGV

The PNGV is headed by the Department of Commerce and includes U.S. EPA, DOE, DOD, NASA, and NSF, as well as the Big Three car manufacturers (GM, Ford, Chrysler) and the U.S. Council for Automotive Research. Its goal is to create a super-efficient (80mpg), superclean ICEV, and to work on AFV and EV technologies, mostly in an optimization and not innovation sense. The Big Three's compliance with the PNGV objectives are conditional on research progress and on the Northeastern states' abandonment of the ZEV mandate (U.S. GAO 1994). Research directions involve hybrid propulsion systems, methanol and hydrogen fuel cells, materials research, and lightweight structures research.

3.3.2 Biofuels

The biofuels research sponsored by DOE concentrates on lowering ethanol, methanol, and rapeseed diesel conversion costs. Its ethanol cost goal from corn is 70 cents/gallon, down from $1.22, in the next 10 years. Pilot plants for cogenerating electricity are planned for Hawaii sugarcane crops. The biodiesel goal from rapeseed oil is $1.00/gallon from the current $3.50. Methanol can be made from municipal waste or short-rotation tree crops for 84 cents/gallon, with a goal of 50 cents/gallon. Research areas focus on improving the yield of the acreage and the processing stages, as well as speeding catalysis reactions and lowering energy consumption.(U.S. DOE, NREL, 1995)

3.3.3 Advanced Battery Consortium, ABC

The U.S. ABC research program focuses on reducing the cost and increasing the range of electric vehicles. U.S. ABC research directions are covered in detail in Chapter 4.

3.3.4 Clean Fuel Fleets/ Clean Cities Program

The Clean Cities Program combines the Clean Fuel Fleets Program with incentives to increase the number of alternative refueling sites. The DOE reports that its Alternative Fuel Vehicle Deployment Program has helped install alternative fuel stations across the nation, and will initiate a "clean corridor" system of cities participating in the Clean Cities Program in 1997. The project hopes to encourage convenient intercity travel in AFVs by establishing a continuous alternative refueling station network in corridors from coast to coast (U.S. DOE, OTT 1997).

3.3.5 DOE AFV Budget Request for 1997

Table 3.5 (U.S. DOE, OTT 1997) shows the breakdown of the DOE's $262 million budget request for alternative fuel vehicle development. This total request is $50 million more than the 1996 budget. To put it in context, it is about 1/1000th of the total annual expenditure in the U.S. on vehicles, gasoline, and maintenance (Chapter 2).

Table 3.5: 1997 DOE Budget Request for AFV Research and Development

Program	Million $
AFV Development	10.5
AFV R&D	14.5
Biofuels Program	40.5
Electric Vehicle R&D	17.8
Fuel Cell Vehicles	30.1
Heavy Duty R&D	7.1
Hybrid Vehicle R&D	81.7
Light Duty Engine Technology	10.1
Lightweight Vehicle Materials	22.0
Management/Other	11.3
Propulsion System Materials	15.9
Total	262

Source: U.S. DOE OTT 1997

3.4 AFV Policy Summary

Current policies take a wide scope, beyond petroleum fuels and vehicles, encouraging research, development, and marketing of fuel and vehicle alternatives which may have characteristics completely different from the current petroleum combustion-based system. However, they do not clearly emphasize a dominant potential fuel/vehicle technology, partly because it has been difficult to identify the relative potential of systems while many of them remain in an early stage of development. Early identification of the few most likely successful alternatives would help in establishing a policy strategy that could provide a direction certain enough to stimulate investment, but flexible enough to adapt to new technological discoveries.

4. Alternative Fuel Vehicle Technology

Alternative fuel vehicle (AFV) technology which would replace petroleum vehicles concerns not only the design and manufacture of vehicles, but building the supporting network of refueling infrastructure, maintenance centers, spare parts supply chains, and maybe even reforming sales and dealership practices. Consumers may have to adapt to unfamiliar maintenance, starting, or refueling procedures, and to other vehicle characteristics that might not match those of conventional gasoline vehicles (CGVs). New safety concerns will require extensive product testing and demonstrations, and re-training of consumers and emergency response crews. Finally, to minimize manufacturing costs by homogenizing vehicle parts as much as possible, alternative fuel vehicles should be compatible with the support facilities available internationally. This chapter describes the current available and experimental vehicle and fuel technologies, the extent to which they have penetrated the U.S. and other markets, and summarizes the likely near, mid, and long term alternatives.

There are only a few realistic ways to store energy in a vehicle, and then to release it to the wheels efficiently. But different system configurations present critically important infrastructure supply and manufacturing challenges. The combinations of storage methods and powertrain design are nearly unlimited within the constraints dictated by a practical vehicle, so the spectrum of technical alternatives is continuous across its range. This study considers four ways to store energy in a vehicle: as a liquid, compressed gas, chemical potential, or as mechanical motion; and three ways to use it in a vehicle: electric motor, and internal or external combustion engines. Some of these technologies offer cleaner or petroleum-free replacements for petroleum, at no loss in performance or usefulness to the consumer. Others may offer reduced performance or practicality at the benefit of very clean, petroleum-free, or silent ("friendly") operation. One single alternative may not replace petroleum vehicles entirely, but each could find application niches.

4.1 Overview of AFV Technology

Most alternative fuel vehicles used today do not differ much from the gasoline or diesel vehicles they replace. To maintain performance, practicality, and consumer appeal, they still employ the familiar carbon-based fuels, which are combusted in internal combustion engines (ICEV) that are coupled to the wheels via a transmission. The DOE estimates that just over 400,000 of these vehicles are on the road (U.S. DOE, AFDC 1997). Most use LPG or CNG. Battery electric vehicles, which are fairly common, are the most notable exception to this configuration, though at a loss of performance and familiar refueling procedure. There are roughly 2000 EVs on the road in the U.S. today (IEA Annex A 1994, cited in Muntwyler, et al 1996). Hybrid vehicles that combine combustion and electric drives via a generator and electricity storage (in a battery, for example) have just emerged on the market as a performance and emissions compromise. Current experiments with vehicles concentrate on electric drives and electric or hydrogen energy storage systems. One system, called "fuel cells," can produce electricity without combustion from hydrogen-carrying liquid or gaseous fuels. Fuel cells have been used by NASA in space and in stationary generators since the early 1960s, but are only just receiving attention for use in mobile applications.

4.2 Vehicle Technology

4.2.1 Internal Combustion Engine Vehicles

Internal combustion engines provide high power for a low weight. They have been the principal powerplant in motor vehicles in the U.S. since the 1920s, when their superior performance helped them become more popular than steam power and electric vehicles.

The ICEV system has a design advantage in that it allows separate consideration of the power and energy components of the vehicle: power output is determined by the engine characteristics, and energy supply by the size of the fuel tank. Being able to separate these two systems permits flexibility in choosing fuel and engine combinations in a vehicle. ICEs use fuel very inefficiently. They only convert about 35% of the energy in the input fuel to rotating the output shaft, and the rest to heat. The friction in the moving parts of the engines creates a large amount of waste heat. The engines in fact rely on a certain amount of waste heat to keep the cylinders and combustion chambers hot, which promotes a smoother fuel burn and predictable operation (deCicco, et al 1994).

ICEs must be geared to the wheels through a transmission because of the high engine rpm, and because of their variable torque with respect to engine speed. The transmission heats up and loses energy, as well, resulting in even lower efficiency. A standard transmission is about 80% efficient. After power for onboard computers and cabin accessories is removed from the drivetrain, less than 20% of the energy in the fuel is available at the output of the transmission for moving the vehicle.

This kind of engine is generally inexpensive, though this cost depends on the well-established high scale of manufacture. Its computerized electronics and catalytic exhaust treatment, necessary because of its high emissions, add to its expense. The fuel system is very inexpensive and should be easy to modify for other liquid fuels in OEM vheicles. Sperling (1995) suggests that 20% of the cost of a new ICE vehicle is the engine, drivetrain, and fuel system.

4.2.2 Conventional Engine: Otto Cycle

A conventional gasoline engine, also called the otto cycle engine, either has a carburetor or a fuel injection system, and a spark plug to ignite the air/fuel mixture in the engine's cylinder. Fuel injection, or fuel ported, engines have replaced carburetors in most vehicles in the last ten years. Air/fuel ratios, compression ratios, temperature, fuel volatility, and ignition timing in the engine are important determinants of engine efficiency, power, and emissions.

Carburetion vs. Fuel Injection

Appendix 11 contains the details about how otto cycle engines operate. The air/fuel ratio in the carburetor varies according to the fuel demand, as controlled by the position of the accelerator pedal. Its limits of variation can be tuned according to the season and altitude, but this under-the-hood adjustment takes mechanical skills, practice, and a few dirty minutes. The air/fuel ratio settings cannot be adjusted while the vehicle is driving. The fact that the carburetor measures liquid gasoline is crucial in ICEs modified for gaseous or low-pressure liquid fuels, since the higher volume of gaseous fuels will result in too little fuel being admitted to the carburetor for the amount of air which is pulled in. The result is a very lean burn and the familiar loss in power in non-optimized CNG or LPG vehicles. The same thing can happen to very volatile gasolines in high temperature ambient conditions.

In a fuel injected engine, the air/gasoline mixture is constantly adjusted electronically by a computer which measures the presence of oxygen in the air intake system of the vehicle and compares it to the rate at which the fuel pump is providing gasoline. The ratio is also based on the liquid volume of the gasoline. The computer adjusts the mixture for the preset combustion characteristics that reduce emissions and provide the best performance. This type of system can give better fuel efficiency, higher power, and lower emissions than a mechanically carburetted engine. More complicated computer regulation systems may use any number of other sensors, including temperature, exhaust, and/or octane sensors. Such engines rarely need to be tuned, though fuel injectors can become clogged with fuel residues.

Both vehicles are designed so that the air/fuel ratio is enriched, or decreased, for cold starting and accelerating. Fuel in excess of this ratio will be expelled in the exhaust, and emissions of HC and CO (from incomplete combustion of some of the fuel) will be higher during these maneuvers.

Reducing Emissions from ICEs

Since the 1960s, changes in otto cycle engines and their exhaust systems have reduced HC and CO emissions by 96%, and NOx by 76% (this is higher than the table in the background chapter because it addresses individual vehicle emissions, and does not include VMT, which is included in fleet emissions). Early changes included adding a positive crankcase ventilation (PCV) valve and exhaust gas recirculation (EGR) system to burn excess HC in the exhaust. More recent changes include the catalytic exhaust converters previously discussed, evaporative HC adsorbption canisters to control gasoline evaporation from the fuel tank, and air/fuel management computers with sensors in the fuel, engine, and exhaust systems. Putting more valves in per cylinder is a recent industry attempt to improve the performance of an engine while keeping it small for fuel efficiency.

Octane in Otto Cycle Engines

A fuel's octane rating has to do with providing a steady burn in the cylinder's combustion chamber. The octane number is a measure of the anti-knock characteristic of a fuel, and nothing else. Piston engines are designed and tuned so that the air/fuel mixture burns at an even rate across the cylinder, rather than exploding ("knocking"). Knock is an explosion in the combustion chamber resulting from a low octane rating in the fuel, relative to the needs of the engine. It happens when part of the fuel mixture ignites, near the spark plug, but the compression shock wave resulting from this ignition causes the rest of the fuel mixture to explode, rather than to burn evenly. Knocking does not significantly sacrifice engine power or damage the engine unless the knock intensity becomes severe or is permitted for a long period.

Engines designed for higher octane fuels can derive more power and efficiency from this fuel characteristic. They would have a higher compression ratio, and advanced ignition timing. Vehicles with "knock sensors" detect the octane content of the fuel and advance or retard the timing appropriately, possibly providing slightly more power as they control knocking. Other computers which detect barometric pressure adjust the air/fuel mixture and ignition timing simultaneously, for example while climbing to higher altitude.

4.2.3 Diesel Engines

Diesels are usually used in heavy duty vehicles in this country, though they are very popular passenger vehicle powerplants in some European countries because of their low diesel fuel tax there relative to the gasoline tax. Diesel engines do not have spark plugs or a carburetor. Instead, liquid fuel is either mixed with air through a needle valve in the air intake manifold, or is injected into the cylinder by fuel injectors similar to those in otto cycle engines. The needle valve can be set for the desired air/fuel ratio by hand in a tuneup, or adjusted by a computer system. The accelerator pedal position determines the amount of fuel to introduce into the engine, and the needle valve provides the corresponding amount of air.

Diesels rely on higher compression of the air/fuel mixture to cause the mixture to combust spontaneously, usually at a higher temperature than otto cycle engines. The combustion generally creates more NOx because of the higher temperature, but less HC and CO because of a more complete burn of the fuel. The air/fuel ratio in diesels is stoichiometric, at 15:1, but the actual ratio delivered to the engine can be adjusted under the hood or via computer. To prevent knocking or premature combustion, the fuels have a higher octane and cetane rating than gasoline, and a lower volatility.

Diesel fuel is a heavier, more hydrogen-poor molecule than gasoline. Because so much of the energy in the fuel is contained in carbon atoms rather than hydrogen, diesel operation results in a tradeoff of carbon particulate emissions and NOx emissions. Running the engines leaner can oxidize the carbon to create more CO2, but this raises the running temperature and makes more NOx. Running rich lowers NOx by lowering the cylinder temperature with the excess fuel, but it increases PM. Options for lowering emissions include soot filters and catalytic converters for NOx if the sulfur in diesel fuel can be reduced so it does not damage the catalyst. Some fuels can be used in diesel engines at extremely lean mixtures, which allow the excess air to carry away heat and lower NOx production.

Cetane in Diesel Engines

Cetane is a measure of the time delay before a fuel ignites. A high cetane fuel will begin burning sooner in the piston stroke, resulting in smoother combustion, a lower rate of pressure rise, a lower peak pressure in the cylinder, and less noise. Overall, the burn lasts longer in high cetane number fuels, so it can be controlled more easily. Fuels with higher cetane numbers, like octane numbers, can determine engine efficiency and power. They also provide easier starting and faster warmup.

4.2.4 Discussion of ICEV Technology

Internal combustion engines can function on a wide range of liquid and gaseous fuels, and can be optimized to almost any fuel with minor modification. Fuels which would be easily adaptable to this kind of engine include the conventional petroleum fuels (gasoline, reformulated gasoline, oxygenated gasoline, diesel), unconventional petroleum fuels (propane, or liquefied petroleum gas (LPG)), alcohol fuels (methanol, ethanol, or an alcohol with a mixture of gasoline), natural gas (compressed as a gas or cyogenically liquefied), hydrogen (compressed as a gas or cryogenically liquefied), or biologically (biomass) derived fuels like rapeseed methyl ester (derived from vegetable oil). Whether the fuel alternative used an otto or diesel cycle engine would depend on its octane, cetane, and volatility characteristics.

4.2.5 Battery Electric Vehicles and Battery Technology

There are now roughly 2000 battery electric vehicles in the U.S. Unlike combustion engines and their fuels, battery electric vehicles and batteries are inseparable. Batteries are included in this section on vehicles because it is likely that custom-shaped and sized batteries will be furnished with the purchase of a new vehicle in the future as they are today. The model described in this thesis assumes that the new vehicle is produced without a battery however, so that different batteries can be tested in the vehicle model more easily. The "fuel," electricity, and recharging infrastructure, is included below in the "fuels" section.

Battery electric vehicles (BEV) emit no gases, liquids, or engine noise as they drive, and are the only vehicles which currently do not. The electric drive systems are also very energy efficient. Their simple mechanics require very little maintenance beyond checking the tires and windshield wipers, and "fuel" and operating costs are lower than for petroleum vehicles between the "lumpy" cost of replacement batteries. Swiss EV marketers like to call them "friendly" vehicles because of these characteristics. European consumers are generally more supportive of EVs because of the relative higher cost of gasoline and the local environmental benefit of using the EV in urban centers.

BEV Efficiency

The variable-speed motors can drive the wheels directly, with no energy loss to a transmission, giving a motor-to-wheels efficiency of about 60%. EVs carry no power source other than the batteries, which can provide 80% to 85% efficient round-trip energy storage (energy in/energy out again). Increasing average efficiency even more, an EV can use its drive motor as a generator to produce electricity when the vehicle decelerates, regenerating lost battery charge ("regenerative braking"). The energy efficiency of the vehicle could be as high as 50% from the recharge to the motion of the vehicle.

BEV Performance

Electric vehicles cannot perform to the level of petroleum vehicles at the moment because of battery constraints, particularly its low specific energy capacity and heavy weight, and the amount of time it takes to recharge. Batteries have to be voluminous and heavy because they store little energy per unit mass or volume, about 30 times less than gasoline. In order to provide enough range for a serviceable vehicle, the battery must weigh about one third the weight of the entire vehicle. Acceleration may suffer because of the extra weight, but generally power is not a problem with EVs. Of course, frequent acceleration uses the energy in the battery faster than constant speed cruising. The batteries also do not function well in the cold. Their market is therefore restricted to low-emission, short range, or low-noise niches in warm places: mostly as warehouse forklifts and in other indoor applications, and as short-range buses or delivery vans.

BEV Availability and Cost

EVs can be ordered from major automakers, or converted from standard vehicle frames (called "gliders") by smaller firms. Conversion or OEM EVs cost about double the new purchase price of the otherwise petroleum vehicle. Consumers can alternatively purchase conversion kits and expert advice for changing their vehicles over themselves, but these kits also end up costing $5,000 to $10,000 (Sperling 1995). Most BEVs, numbering in the low 1000s, are conversions (Solectria, Corp. 1995). The Big Three (Chrysler, Ford, and GM) sold only 63 BEVs between 1991 and 1996 (Ford Motor Company 1997). To promote EV purchases, most states offer some kind of rebate or tax exemption, usually with a maximum set on the order of $1000, though some states have rebates as high as $4000 per vehicle for single purchases (U.S.GAO 1994). As noted earlier, EPACT favors EV purchases by offering a rebate to EV-purchasing government agencies equal to the minimum of ½ the incremental purchase price of the EV over the petroleum version, or $10,000.

Battery Limitations

BEVs are so expensive because of the large, expensive battery pack they have to carry. Battery packs cost between $6,000 for low-performance lead acid and $20,000 for state-of-the-art nickel metal hydride (NiMH) (GM EV-1 optional battery pack, 5). Even with the large battery, their range is limited to 50-80 miles (80-130km) for lead acid in most mid-sized vehicles, and twice that for NiMH, under prime operating conditions. According to GM, the lead-acid batteries which come standard in their new electric sports car, the EV-1, should last about three years, depending on their treatment, and the optional NiMH batteries should last 10. The low energy content per unit weight (energy density) of batteries has led some EV manufacturers to devise sophisticated electronic energy management systems to maximize the attainable range of each battery charge.

These systems increase the purchase price of the vehicles even more, but have succeeded in increasing battery life, which reduces the average cost of using the EV.

For now, auto manufacturers must wait for battery technology to progress before committing to large scale battery vehicle production. California's 10% ZEV sales mandate still applies to the top seven manufacturers for the year 2003 (Ford, GM, Chrysler, Toyota, Honda, Mazda, and Nissan), and will require them to sell roughly 100,000 zero emission vehicles in the state (U.S.GAO 1994 estimate), but this only equals one half of one percent of the Big 7 combined annual production.

For now, participation in the CARB mandates is optional, but most major car companies are participating for a $5,000 credit from the state per approved vehicle sold, and for future marketing and performance data (Davis et al 1996). Appendix 11 provides a sample of electric vehicles currently offered by the Big 7.

Demonstration Projects

Demonstration projects around the industrialized world concentrate on gathering EV performance data and information about users' acceptance of the unfamiliar technical characteristics of EVs. There are many projects underway in different climate, culture, and geography zones. Some are funded by private sources, but almost all have government support or motivation. Appendix 11 describes some prominent program.

4.2.6 Batteries

In order to reach a wider market, EVs will require cheaper and lighter batteries. Improvements to weight or energy storage capacity that would lighten the battery pack would let the vehicles travel further on a charge and carry more cargo. The poor cold-temperature performance of the battery could be avoided by a battery heater, and the problem could be solved if the battery stored enough energy that the heater could run off of the battery itself. Cost considerations involve purchase cost as well as the number of charging cycles the battery can accept before needing replacement. Research emphasizes lowering manufacturing and materials cost, raising energy density, and increasing the number of recharging cycles before the battery can no longer be charged.

In the U.S., the Advanced Battery Consortium (USABC), a collaboration between U.S. automobile manufacturers, the Department of Energy (DOE), and the Electric Power Research Institute (EPRI), has determined a set of minimum vehicle battery performance characteristics which would result in significant market appeal. USABC has set middle and long-term goals for battery performance for energy density (specific energy), power density (specific power), the number of charging cycles before the battery is dead, and cost. Table 4.1 summarizes the USABC goals.

Table 4.1: USABC Goals for Battery Performance

Battery Performance Parameter	**Units**	**USABC Goal**		**Vehicle Characteristic Affected**	**Vehicle Goal**
		Midterm Criteria	**Long term Criteria**		
Specific Energy	Whr/kg	80-100	200	Driving Range	100 miles
Peak Specific Power	W/kg	150@80%DoD	400	Acceleration, hill climbing	0-60, 12-15s
Lifetime	# cycles	600@80%DoD	1000	Lifecycle Cost	5yr, 10yr
Cost	$/kWhr	<150	<100	Vehicle purchase price, battery replacement	Competitive price

Source: Kalhammer 1996

Energy density refers to the amount of energy the battery can store per unit weight. Current batteries can store about 1/35th the energy per unit weight that gasoline can. Increasing this storage capacity can reduce the weight of a vehicle, improving performance, and lengthen the operating range. Higher energy density is crucial to the viability of electric vehicles.

Peak power density refers to the amount of power, or energy in a small interval of time, that a battery can provide to the motor. This characteristic is important for acceleration and climbing hills. The comparable measure for an ICE vehicle would be a sufficiently large carburetor or fuel line that would admit enough energy to the engine.

The number of charging cycles that a battery can take before it cannot be recharged anymore is important for determining the lifecycle cost of an electric vehicle. A battery pack is very expensive, and won't have to be replaced as often if the energy density is high (enabling less-frequent recharging) and the number of charging cycles is high (more cycles of use before replacing the battery). The abbreviation, "DoD" means "depth of discharge," and refers to the assumption that the batteries will be used each cycle until they contain only 20% of their full capacity before they are recharged. Some batteries will never take a charge again if they are discharged close to 100%.

Finally, the purchase cost of the battery is listed in the table on a per unit energy basis. This is a convenient measure with which to compare batteries because the energy storage capacity of the battery will be the determining factor for its size in all vehicle applications. Comparing the "size" of the battery in each application, then, refers to its energy storage capacity rather than its mass or volume, so the cost measure should reflect this engineering value to be most useful.

These USABC characteristics are based on vehicle performance calculations, and assume certain energy efficiency characteristics of the vehicles. They are also based on likely consumer demand for vehicle performance, which may be in error. Further, the USABC goals do not consider the safety or environmental impact of battery chemistry. It could therefore be possible that batteries may exceed the above specifications and still be a market failure, or that batteries which do not meet the above specifications might still succeed in the market for other reasons than performance in the vehicle. An EPRI paper summarizes a late 1995 CARB panel investigation into the state of development of nine battery types, and their prospects for mass production and market penetration in EVs, based on how they measure up to these USABC criteria (Kalhammer 1996). The spcific results of the paper are presented in Appendix 11. The discussion in the next section is based on the information in that report.

Battery Summary

A rule of thumb for batteries' energy density is that a manufactured battery can potentially reach about 30% of the theoretical maximum energy density for the reactants in the battery. Lead acid and NiCd have been developed to about 30% and 24%, respectively, due to their long-time use. The energy density in these batteries has been maximized, and they will only be improved now with developments in cycle life or cost, since they are both already powerful batteries. Improvements in charging methods could help the lead acid battery's cycle lifetime.

The energy density of NiMH batteries of the AB5 type have met the 30% potential, and should not be expected to improve much. Those of the AB2 type may improve to about 120 Wh/kg, but not enough to meet the USABC long-term goals.

Likewise, lithium ion batteries may be expected to improve to about 140 Wh/kg, but will rely on their exceptional cycle life of more than 1200 cycles to appeal to consumers. NiMH batteries might prove more successful however, because they are closer to large-scale manufacturing and do not have the safety concerns.

Lithium polymer batteries have a 30% theoretical energy density of 270 Wh/kg, and have the same power characteristics as lithium ion batteries, which makes them a likely prospect for longer term introduction. They lag in development at this point, but the small laboratory versions exceed USABC long-term goals for energy and power density.

ZEBRA and zinc/air batteries could each double their already superior energy densities, according to the rule of thumb, and are involved in high profile demonstrations with known manufacturers and fleets. These two are likely candidates for large scale implementation in the mid-term.

Zinc bromide is an unlikely candidate for mobile source applications because of its poisonous electrolyte and because its likely competitor, lead-acid, is well-established.

NaS batteries have a high performance potential, and could win someday based on low price, but for now their development is stalled.

The CARB panel report concludes that battery choice for EVs will likely hinge on cost rather than technical feasibility. It includes a cost and timetable for development that was submitted by each battery manufacturing firm, which is reproduced here in Table 4.2.

Table 4.2: Battery Availability and Cost Projections

	Pilot Scale (Hundreds/yr)		**Production Scale (10,000-40,000/yr)**	
Battery Type	**Year**	**$/kWh**	**Year**	**$/kWh**
Lead-acid	1995	150-300	1997-1998	120-150
NiCd	1995	1000	1997-1998	300-350
ZnBr2	1996	500	1997	100-250
Zn/air	1996	300	1998-1999	90-125
NiMH	1996-1997	450-550	1999-2001	250-350 (AB5) 150 (AB2)
ZEBRA	1996-1997	1000-3000	2000	230-345 175 (100,000)
NaS	1997	1000	2000-2001	250-450 (in 2004) 150 (100,000)
Li Ion	1998-2001	1000-3000	2001-2002	150-200
Li Polymer	1999	750-1500	2002	125-175
USABC				
-mid-term		600 cycles		150
-long-term		1000 cycles		100

Source: Kalhammer 1996

These costs are manufacturers' estimates for very high production volumes. The lowest costs are for production volumes of 100,000 units/year. Note that the NaS project has ended. Lithium polymer, zinc/air, and zinc bromide batteries are the cheapest alternatives per kWh. The NiMH AB2 type and ZEBRA batteries come next. On a charge cycle basis, which includes the number of times a battery can be recharged, NiMH comes out cheapest, at 10 cents per kWh-cycle. Lithium ion is next cheapest at 12-15 cents per kWh-cycle. The rest cluster around 15 cents, except for lithium polymer, which has an unknown lifecycle. USABC does not explicitly consider the per cycle cost in this way, but by dividing $150/kWh by 600 cycles, the per charge (per cycle) cost is 25 cents for the mid term, and 10 cents for the long term. This value is more significant for considering the cost to the EV consumer because it estimates the cost of replacing the vehicle's batteries.

A recent announcement from the DOE (SAE 1996) pledged $106 million to support phase II of the USABC research project. Phase I identified NiMH batteries as the most promising mid-term technology, and lithium batteries as the long-term technology for BEVs. The money will go to safety and durability testing of the NiMH batteries, and to manufacturing process feasibility tests for lithium batteries, according to the announcement.

4.2.7 Hybrid Electric Vehicles

Hybrid combustion/electric vehicles are now arriving on the consumer market from several manufacturers (at least Audi and Toyota), combining a primary source of energy coupled with a mechanism that produces electricity in the vehicle, with an electric drive motor. Hybrid vehicles are part of the U.S. government focus on fuel efficient vehicles in the PNGV program. These vehicles can have many powertrain configurations, and countless mixtures of primary energy sources and devices that produce electricity from them.

Recently, automakers have looked at hybrids as a temporary low emission vehicle until they can develop more competitive electric, or zero emission, vehicles (Sperling 1995; Hong, et al 1996). The currently available vehicles use a gasoline internal combustion engine to generate electricity for an electric drive motor. Employing these two drive systems intends to increase the energy efficiency and emit less pollution than a conventional ICEV by narrowing the range of operating conditions for the internal combustion engine in order to optimize its application. Fuel cells or external combustion engines are other mechanisms currently being researched as realistic components to future hybrid electric vehicles. Fuel cell vehicles will be discussed in the next section.

Series vs. Parallel Configurations

Two main families of configurations of the electric and combustion powerplants are parallel and series arrangements.

Parallel-configured hybrid electric vehicles have both electric and combustion engines driving the wheels. This system presents mechanical complexities and system control challenges for the periods in which the electric motor switches on and off. It can reduce the size of the main power source, which remains the combustion engine, and it uses batteries to power the electric motor during periods when power boosts are needed. This configuration has a strong appeal to mechanically minded automobile companies. The vehicle uses the electric motor for high torque and for regeneration of battery energy while decelerating. This requires an energy storage device capable of high power output, but not necessarily high energy content. The battery pack in this kind of vehicle could be small, or could be replaced by other kinds of high power, low energy storage devices, like ultracapacitors (high power, lightweight capacitors, under development). The combustion engine is kept operating at low rpm, and therefore temperature, when the vehicle is cruising at constant speed. This strategy intends to reduce NOx emissions and fuel consumption (Hong et al 1996).

Series-configured hybrid electric vehicles couple the ICE directly to an alternator or a generator to generate electricity that is immediately used by an electric motor, or is stored in batteries. The electronic energy management system presents design complexities, especially keeping track of the charge of the battery. Much work is being done in this area. This arrangement enables the ICE to run at a constant speed, and to be designed specifically to run at that speed, which would make it much more efficient in average use than a variable speed ICE. It can also be replaced by a more efficient external combustion engine (Sterling cycle or turbine, for example) that might not have enough torque to drive the wheels directly by itself, or by a fuel cell generator. The operating strategy may include turning the ICE off when the batteries are fully charged, or while their charge is above a certain threshold (depth of discharge). The electric motor is the main drive system, which means the batteries for this type of vehicle may have to be larger and store more energy than the ones in the parallel type of vehicle.

In both systems, the size of the electricity storage system, for now batteries, depends on the relative size of the ICE and the energy or power demand of the vehicle. This demand depends strongly on the weight of the vehicle, the application in which it is used, and the driving performance expected from the vehicle. The increased average efficiency of the combustion engine and the excess weight of the battery system are the important numbers to derive from this discussion.

4.2.8 Fuel Cell Vehicles

A fuel cell is an electricity generator which derives its energy from hydrogen-containing fuels without combusting them, and without any moving parts. The fuel cell would be used in a vehicle to charge a battery from which the electric drive motor would run the vehicle. Fuel cells' advantages are a potential generator efficiency of 60% (Borroni-Bird 1996), compared to an ICE efficiency of 35%, low temperature operation which reduces NOx emissions, simple maintenance, and low noise. NASA has over 30 years' experience with hydrogen powered fuel cells in spacecraft, and an engineer at Allis-Chalmers Manufacturing built a fuel cell tractor in 1959 (Sperling 1995). Fuel cell research has been characterized by rapid progress recently (Sperling 1995). Currently in the private marketplace, Ballard Power Systems, GM, Ford/Chrysler, Daimler Benz, and Energy Partners maintain the highest profile development efforts in fuel cells (Sperling 1995). Toyota also has a team involved in basic research (Iwase 1996).

Fuel Cell Function

The fuel cell functions chemically by stripping protons (hydrogen ions) from the molecules in liquid fuels and allowing them to pass through a membrane and an electrolyte to react with oxygen gas, to which the protons are strongly attracted. The movement of the protons (positively charged hydrogen ions) generates a current through electrodes on the fuel and oxygen sides of the electrolyte, and the reaction with oxygen yields water as an exhaust product from the fuel cell. Air may be used at the oxygen electrode to avoid having to carry an oxygen source on board the vehicle, but at a slight efficiency cost. To increase the available voltage from a fuel cell, multiple fuel cells can be "stacked" in series like batteries. An air blower also helps increase voltage by keeping the cell well-oxygenated, but may draw as much extra power as it provides to the cell. To increase the available current, the surface area of each cell membrane has to be increased, making the cell larger.

The electrolytes that have been used for conducting the protons through the cell are alkaline, phosphoric acid, solid polymer, and solid oxide. The most promising type for vehicles appears to be the solid polymer type (Iwase 1996, Sperling 1995).

Fuels for Fuel Cells

The reaction which removes the hydrogen ions occurs at the polymer membrane surface on a catalyst, usually made of platinum in a hydrogen fuel cell. However, platinum catalyst fuel cells do not function well with fuels other than pure hydrogen. This is because the presence of carbon, particularly carbon monoxide (CO), inhibits platinum's catalyzing activity. Fuels other than pure hydrogen have to be reformed in a separate stage in order to extract the hydrogen atoms for use in the fuel cell, and separate them from the resulting carbon, CO, and CO2 reactants in the reformer. Reformers also create NOx and hydrocarbon emissions, and reduce the energy efficiency of the fuel cell vehicle. New research (Iwase 1996) has introduced ruthenium and ruthenium-platinum alloy catalysts which can tolerate CO in the hydrogen fuel, potentially allowing simplifications in the reformer.

Other breakthroughs in fuel cell development include catalysts which permit the use of a mixture of methanol and water as fuel (Seshan 1997, Halper, et al. 1997). Though currently only a laboratory prototype of a few watts, such a fuel cell could improve the efficiency of using methanol in fuel cells, lower NOx emissions, and decrease the system size by eliminating the reforming stage. This could lead to a widespread acceptance of fuel cell vehicles since methanol is easier to use as a fuel than hydrogen.

The major disadvantage to fuel cells is the current density, and therefore the power density, of each cell "stack." The cell has to be made too large and heavy to provide enough power for marketable cars, especially when combined with a reformer. A possible early market would target large vehicles like buses.

H-Power Corporation (Maceda 1996) claims that the efficiency of a methanol fuel cell with a reformer will pay for itself in fuel costs saved over diesel fuel in these larger vehicles. It emphasizes the lifecycle cost of using the fuel cells as its greatest selling point, with durability, environmental friendliness, and low noise (or silence, if there is no air compressor) as secondary benefits. The company claims that fuel cell costs are declining from \$5,000/W to \$200/W, though it was not specific about when the \$200/W version would be available, and in what sizes or what rates of production.

4.2.9 Alternative Fuel Technology

Fuels are the source of energy, and pollutants, associated with vehicles. Choosing a vehicle fuel will depend on the qualities of the fuel and its availability, both based on the resource and the ease of handling and delivering the fuels. The most important fuel characteristics for particulate, CO, and CO2 emissions is the hydrogen to carbon ratio of the fuel. The octane and cetane numbers of a fuel determine the limits of power and efficiency of internal combustion engines. Whether a vehicle can use a catalytic converter for NOx, hydrocarbons, and CO depends on the fuel's sulfur content.

The energy density determines how much of the fuel has to be stored on board the vehicle, which is an important determinant of the consumer appeal of a vehicle.

Table 4.3 lists the energy densities of different fuels and energy storage systems for vehicles.

Table 4.3: Energy Storage Potential of Various Vehicle Fuels and Energy Storage Systems

Type of Fuel	Fuel or Vehicle Energy Storage System	Higher Heating Value (Btu/gal)
Liquid Petroleum	Gasoline	125,071
	RFG	122,190
	Diesel	138,690
	LPG	91,976
Alcohols and Alcohol Derivatives	Ethanol	84,600
	Methanol	64,558
	E85	90,671
	M85	73,635
	MTBE	100,906
Natural Gas	Liquefied (LNG)	93,450
	LNG, including insulated tank	40,000
	Compressed (CNG (3600 psi))	28,000
Hydrogen	Liquid (LH2)	36,000
	Liquid, including insulated tank	15,150
	Compressed (CH2 (6000 psi))	10,600
	Hydrogen Hydride Storage	1500-19,000
Electricity	Battery	270-700 Btu/kg est. 5000-13,000 Btu/gal

Sources: U.S. DOE *Energy Annual Outlook*; Norton 1996 (compressed natural gas), DeLuchi 1989 (hydrogen).

Current resource reserves in North America and the rest of the world for the different fuels investigated here are listed in Table 4.4.

Table 4.4: Estimated Proven Reserves of Fossil Fuel Resource Alternatives in North America and the Rest of the World

Resource	North America (USA, CAN)	Rest of World	Units
Crude Oil	27,250	991,650	Million Barrels
Coal	274,700	862,500	Million Tons
Natural Gas	7,350	198,520	Billion Cubic Meters
LPG	NA	7,170	Million Barrels
Biomass	2.45	NA	Billion Metric Tons/year

Sources: API 1997; National Mining Association, 1996; Price Waterhouse 1995; American Gas Association,1995; U.S. DOE/NREL 1995.

This chapter describes the particular characteristics of each fuel, and its suitability as a fuel for widespread use in vehicles.

Gasolines

RFG and oxygenated gasoline are not very different from ordinary gasoline. But some arguments assert that reformulated (RFG) and oxygenated gasolines count as fuel alternatives because of the large (10-15% by volume) component of non-crude oil, oxygen-enhancing additive they contain. The CAAA counts them as alternatives, but EPACT, the policy regarding vehicle fleet composition, does not. All standard gasoline vehicles can use these gasolines, and since these fuels have been distributed to the most populated parts of the country for emissions reduction, this method of controlling emissions has had the widest reaching emissions and crude consumption reductions of any AFV policy so far. About 40% of gasoline produced is RFG, and another 19% is oxygenated gasoline(U.S. DOT 1996a, table 4-3).

Details about RFG composition and geographical availability are in Chapter 3.

Oxygenated fuel is normal gasoline which contains a minimum of 2.7% by weight oxygen. The most common oxygen-containing additives are pure ethanol (grain alcohol), blended at a maximum 10% by volume (a blend also known as gasohol), and methyl tertiary butyl ether (MTBE), which is derived from methanol, at a maximum of 15% by volume. Other additives include tertiary amyl methyl ether (TAME) at 17.2% by volume, or ethyl tertiary butyl ether (ETBE) at 17.2 percent by volume. The ethanol blend results in a 3.5% oxygen content by weight, and the other blends result in the minimum 2.7% content (Parent, et al 1996). The maximum levels of additives ensure that the fuels are compatible with current vehicles, and more or less pacify the competing ethanol and methanol industries who would like to increase their own market share as additives in oxygenated fuels. The fuels are blended in central gasoline distribution locations, rather than at the refinery or at the gas station. CFDC estimates that one third of the country's gasoline is replaced by oxygenated fuels in winter, resulting in 100,000 to 200,000 barrels per day of crude oil displaced by the additive (U.S. DOE, AFDC 1997), which is less than 1% of the daily crude oil consumption.*

All gasolines have roughly the same energy content (see

Table 4.3). On average, gasoline is a dirtier fuel than newer reformulations because its quality is poorly regulated. The differences between the gasolines are marginal when the fuels are compared to the other fuel alternatives considered in this thesis.

Diesel

Diesel fuel is usually used in heavy trucks in the US. Its use is associated with the high NOx and particulate emissions that result from the higher operating temperatures and the low hydrogen to carbon ratio in the fuel. The fuel has a very high cetane rating for a smooth, efficient burn in the combustion chamber. It is not very volatile or flammable.

Low-sulfur diesel, mandated for use by the CAAA90 at the low rate of 1.4 thousand barrels/day by 1993 (Seymour 1992) , may enable the use of catalytic converters in diesels which reduce NOx emissions.

Diesel's energy density is slightly higher than that of the gasolines.

LPG

The most popular alternative fuel vehicles in the U.S. combust liquefied petroleum gas (LPG, or propane). There are about 350,000 of these vehicles in the U.S., (CA EPA 1997). An LPG trade group in Holland reports that there are almost 4 million LPG vehicles in use in the world, with 2 million of them in Europe (Autolpg, citing BK Gas, 1994 data). The refueling infrastructure for propane in the U.S. is widespread, with about

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* Very roughly, 50% of the petroleum is used in transportation, times 80% that is used for gasoline, times 20% that is oxygenated fuel, times 10-15% of that which is non-crude oil composition = 0.8-1.2% This quick calculation does not account for the different higher heating values of the oxygenated fuel additives, but that is a second order effect because the HHVs of all fuels are the same order of magnitude.

3300 sites spread more densely throughout the Northeast, Midwest, and California, and less densely in the Rocky Mountain and Northwestern states (U.S. DOE 1997).

LPG is a petroleum fuel found in its pure form alongside natural gas deposits, or extracted as a byproduct from gasoline refining from crude oil. However, LPG is a small component of these resources, and has a small estimated reserve of 7170 million barrels (AGA 1995). Currently, 65% of LPG is extracted from natural gas reserves, and 35% from crude oil.

LPG is a gas at room temperature and pressure. It is stored in tanks for use in vehicles, campers, backyard grills, and remote homes as a liquid at 200 psi and ambient temperature. Its energy density is about 2/3 that of diesel fuel or gasoline, but it can combust more efficiently in a properly tuned engine because of its smaller molecule and higher hydrogen content. Claims of equal miles per gallon have not been substantiated, however (CA EPA 1997). Mostly because of the fuel's higher hydrogen content and low volatility, LPG vehicles emit lower NOx, CO, particulate matter, and hydrocarbons than gasoline or diesel vehicles. Its octane rating is similar to gasoline, so it is usually used in spark ignition engines. Service stations require a modest pump and/or pressurized storage tank to dispense LPG. It is commonly dispensed at mainstream service stations.

Some LPG vehicles are dual fuel gasoline/LPG. These vehicles usually suffer from lower power while using the alternative fuel because the engine modifications do not often optimize the engine for the alternative fuel instead of for the gasoline. The engine modification kits available usually only replace the fuel tank and carburetor or the fuel injection computer which adjusts the air/fuel ratio. Conversion to LPG costs $1,000-$2,000, and can be done in one day.(CA EPA 1997).

Natural Gas

At least another 55,000 vehicles combust compressed natural gas in the U.S. (CA EPA 1997). Refueling sites in the U.S. number in the thousands (see U.S. DOE, AFDC 1997), and are private, commercial, and public. Natural gas is a popular alternative fuel in other countries: the countries of the former Soviet Union, Italy, Argentina, and New Zealand have 300,000, 235,000, 100,000, and 60,000 natural gas vehicles, respectively (1992 counts, West Virginia University National Alternative Fuel Training Program, 1997 [WVU NAFTP]).

Natural gas is a non-crude oil, very clean-burning fuel, composed of over 90% methane (CH4) (U.S. DOE, AFDC 1997). It has a high octane rating (130, compared to gasoline's 90), which enables an engine of high compression ratio and the associated efficiency and power benefits, resulting in more miles per unit energy contained in the fuel. This makes natural gas suitable for either diesel or spark ignition applications. However, its very low cetane rating would require modifications in the diesel application (WVU NAFTP 1997). The two characteristics combine to provide high torque development at a higher efficiency than diesel or gasoline fuel, with an increase in NOx emissions, thermal losses, and noise if the engine is operated with this strategy to use the fast burn indicated by the low cetane rating (WVU NAFTP). Natural gas vehicles can be run extremely lean to increase fuel efficiency and reduce NOx by allowing excess air into the combustion chamber to carry away heat.

Natural gas vehicles which do not have a higher compression ratio experience a 10-15% loss in power. Vehicles with an optimized compression ratio may experience an increase in power up to 10% by taking advantage of the higher octane in natural gas (CA EPA 1997). Conversions usually replace the engine computer and fuel injectors or carburetor, and the fuel system. A kit costs $2,500-$5,000. The fuel tanks displace trunk space in dual fuel vehicles, but even in large vehicles like minivans, dedicated CNG vehicles limit the range of the vehicles to under 200 miles (CA EPA 1997). The vehicles' range is about 80-100 miles per natural gas cylinder (U.S. DOE, AFDC 1997).

Refueling stations cost about $300,000 for compressed natural gas (Oregon Office of Energy 1997, De Luchi 1989). They currently enjoy a $100,000 tax deduction from the federal government under the CAAA90 (see Chapter 3). A CNG station compresses the natural gas from its 50psi line pressure to 3,000-3,600 psi in the vehicle. Large compressors can fill a vehicle in a time comparable to that of a normal gasoline pump. Home refueling stations are available for about $3,000-$3,500, which fill a vehicle overnight from the household's natural gas utility connection (CA EPA 1997).

Liquefied natural gas is stored at -260 F at atmospheric pressure, though it remains a liquid up to -117 F. Though it is stored in a double-walled dewar, it is constantly boiling away at this pressure. The tank's extra thickness decreases the effective energy density of this fuel. The boiloff represents an inefficiency in the storage system. It has to be either recaptured or burned in a pilot light for safety reasons. Pilot lights should be familiar from the basement furnaces of many American homes. As a liquid, natural gas is 1/600th the volume of the gas. It weighs half as much as water (CH-IV Corporation 1997). It is not commonly in use as a vehicle fuel.

Hydrogen

Hydrogen is the cleanest burning of the potential vehicle fuels. It can also be used directly in a fuel cell to produce electricity. Pure hydrogen contains no carbon, and would therefore cause no CO, CO2, or particulate emissions from the tailpipe of the vehicle (except for engine parts and oil which deteriorate under normal operation and would exit via the tailpipe). The major hurdles facing hydrogen as a vehicle fuel are its high cost per unit energy, and the related problems of shipping it, storing it at fuel distribution centers, and storing it in the vehicle.

Natural gas is the major source of hydrogen, which is obtained in an energy intensive, two step process of steam reforming and partial oxidation. Hydrogen can also be derived from coal, using the same procedure. Another way to produce hydrogen is through the electrolysis of water, accomplished by passing a current through water. If an electrolysis plant were powered by a solar array, the fuel chain would be truly zero-emission and renewable. About 60% of the current hydrogen production is used in crude oil refineries to manufacture low-volatility gasoline (Simonsen, et al. 1993). Demand for hydrogen in refineries was growing at 3.5% in 1993 as a result of RFG manufacture (Simonsen, et al. 1993). Five states produce two thirds of domestic hydrogen: California, Texas, Illinois, Pennsylvania, and Louisiana (Simonsen, et al. 1993).

Pure hydrogen has a low energy density either as a liquid or a gas, so its storage on the vehicle is difficult. Pure hydrogen would be stored in three ways in a vehicle: as a gas compressed to 5000-6000psi, a liquid at 20K (-253 Celsius, or -423 F), or absorbed under pressure in a metal block, known as hydride storage. Other ways to use hydrogen in vehicles include enriching the liquid fuel with gaseous hydrogen to reduce per mile carbon-containing emissions, or absorbing the hydrogen in a liquid fuel that is not combusted with the hydrogen, but is reformed to release the hydrogen into the engine. This thesis considers only gaseous, liquid, and hydride storage alternatives.

Compressed hydrogen storage takes up a large volume for the energy that is stored in the fuel, and the pressure regulation and storage system adds complexity to the liquid gasoline fuel system. A 5000psi carbon fiber compressed hydrogen storage tank for a vehicle costs about $95/cubic foot of hydrogen, or $1000 for a typical vehicle tank (James, et al. 1994) with a capacity of 15 pounds (6.8 kg) of hydrogen. This type of tank would have a factor of safety of 3, meaning that it could withstand a pressure of 15,000psi before failing. At 5000psi, the full 13.5 cubic foot (380 liters) tank would contain 10.5 cubic feet (300 liters), or 6.7% by weight hydrogen (James, et al. 1994).

Cryogenic storage reduces the volume of the hydrogen fuel of the same mass (energy), and the cost and complexity of its storage in the vehicle, but has problems of efficiency because the fuel will "boil off" out of the tank due to the imperfect insulation around the tank. A cryogenic hydrogen tank capable of carrying the same 15 lbs (6.8 kg) of hydrogen at 20K (-423 F) might cost $300, and would be 16% hydrogen by weight when full (James, et al. 1994). Because of the insulation surrounding the 3.1 cubic feet (88 liters) of liquid hydrogen, the tank would occupy 7.5 cubic feet (215 liters) (James, et al.

1994). Liquid hydrogen is 2.8 times lighter than gasoline per unit energy, but the tank volume for the same energy is 6-8 times larger (DeLuchi 1989). A liquid hydrogen vehicle with the same 260 mile (420km) range as a gasoline vehicle with a 10 kg empty gasoline tank (about 10 gallons) might have a 30-40 kg empty hydrogen tank, with a volume of 80 liters (2.8 cubic feet, 21 gallons) (DeLuchi 1989). The hydrogen would boil off as the hydrogen warmed up, with a loss of between 1 and 11 liters/day. Approximately 10-25% of the liquid hydrogen could be lost to boiloff upon refueling if the vehicle tank is warm when it is refueled (DeLuchi 1989).

Hydride storage methods can reduce the volume of the conventional compressed hydrogen system, but at a cost of increased weight. A hydride tank has a small hollow in the middle of a large block of metal, into which hydrogen is forced under pressure (800-5000 psi). The hydrogen is absorbed from the hollow into the crystalline metal matrix of the tank, and is released by applying heat to the metal block (Deluchi 1989). For example, a magnesium-nickel hydride tank for 15 lbs (6.8 kg) of hydrogen currently costs $2000, occupies 7 cubic feet (200 liters), and can absorb 3% hydrogen by weight (James, et al. 1994). A magnesium tank bonds so tightly to the hydrogen however, that engine heat alone is not enough to release the hydrogen from the hydride (DeLuchi 1989). Generally, the hydrogen capacity of hydride tanks ranges from 0.5%-3% hydrogen by weight, the volume from 3.5 to over 11 cubic feet (100-300 liters), and the weight from 260-1100 pounds (120-485 kg) (DeLuchi 1989). Hydride vehicles suffer range handicaps due to this extra weight, similar to but not as severe as battery electric vehicles, with ranges of 95-200 miles (150-300km) (DeLuchi 1989).

The hydrogen used in a hydride system must be at least 99.999% pure, or else the absorption rate (inverse of refueling time) and capacity can be reduced (Deluchi 1989). Methane and nitrogen deteriorate the absorption rate, and water reduces the capacity of the hydride tank (Deluchi 1989). It takes about 10 minutes to refill a hydride tank to 80% capacity if it has not been damaged. The purity of the hydrogen also affects the number of times the hydride tank can be refilled. Iron-titanium tanks can last up to 4,000 refill cycles with 99.999% pure hydrogen, and 20,000-30,000 cycles if recycled hydrogen is used. This means that the fuel tank could outlast the vehicle, and might be a recoverable cost after the vehicle's lifetime is over (Deluchi 1989). However, the extra purity required in the hydrogen for hydride applications will raise its cost, even over the cost of liquefaction.

Shipping and delivering hydrogen presents other difficulties. Hydrogen has a tendency to be absorbed into the metal matrix of steel fuel tanks and pipelines, weakening the structure and causing cracks. Special treatment of natural gas pipelines, or replacement of their liners, could make them all compatible with hydrogen (DeLuchi 1989). Truck shipment of liquid hydrogen would be the likely mode of delivery to liquid hydrogen refueling stations (DeLuchi 1989), with associated losses of the hydrogen from boiloff during shipment.

As a fuel, hydrogen is 50% more thermally efficient than gasoline, meaning that a vehicle can drive 50% farther per unit of energy contained in the hydrogen fuel than for the same amount of energy contained in gasoline (DeLuchi 1989). Modifications to an internal combustion engines may include a water injection system for each cylinder to reduce backfiring (at est. $75), and a closed loop NOx exhaust reduction system, at $340 (EPA), $725 (General Motors), or $725 (Joint EPA/GM study) (all cited by DeLuchi 1989). The engine would have the same maintenance requirements as gasoline vehicles have, but might require less frequent oil changes (DeLuchi 1989).

Hydrogen has a slightly higher peak flame temperature than gasoline, and a much wider range of flammability in air, however it has to be much more dispersed in the air before it will burn. It burns very fast, so fires are over with quickly, and the heat does not spread as far as the heat from a gasoline flame because of the high heat capacity (WVU NAFTP 1997).

Alcohols: Methanol and Ethanol

Alcohol fuel's strength is that they are not derived from crude oil, and can be used to extend the crude oil resource. Ethanol comes from starch-containing grains, and methanol comes from natural gas or coal. Methanol can also be derived from woody (cellulosic) plant matter. The alcohols have slightly higher octane than average gasoline, so they can provide more power to an engine for a given amount of energy in the fuel if the engine is optimized to a higher octane fuel (WVU NAFTP 1997). However, ethanol has about 2/3 the energy density of gasoline, and methanol about half, on a mass basis.

Today, race cars burn pure methanol mixed with additives to boost power. Ethanol and a chemical derived from methanol, methyl tertiary butyl ester (MTBE) are used as additives to gasoline to raise its oxygen content and lower its CO emissions, as shown in Chapter 3, and above in the RFG section. Ethyl tertiary butyl ester (ETBE), made from ethanol, is another possible gasoline oxygenate/fuel extender in the very near term. About 24% of the world's methanol production is used as MTBE or other fuels (Methanex 1995), and MTBE for gasoline additives is the fastest growing market for methanol at the moment.

Alcohol fuels have been proposed to be used in many ways in vehicles. Initially, to cope with the infrequent availability of alcohol fuels, most alcohol vehicles on the road burn either gasoline or the alcohol. Flex-fueled, or variable-fueled vehicles (FVF, VFV) can burn either gasoline, alcohol, or a mixture of the two. Such vehicles have one fuel tank, into which the owner may fill any mixture of alcohol or gasoline. Dual fuel vehicles have two separate fuel systems: one fuel tank contains the alcohol fuel, and the other contains gasoline. Neither of these vehicles has an engine optimized to run on the alcohol or the gasoline, and the emissions, power, and mileage of the vehicles suffers from this shortcoming.

Other vehicles are optimized to operate on a mixture of 85% alcohol (either one) and 15% gasoline. These mixtures are called E85 and M85. This mixture greatly reduces the amount of gasoline burned per mile of vehicle operation, stretching the crude oil resource, but does not reduce tailpipe emissions as much as using an optimized alcohol-only engine, that is, "E100" or "M100". Pure alcohol fuels, despite their attractiveness as very low emissions fuels, have very poor cold-starting characteristics, and would need engine changes or fuel additives in order to reach mainstream acceptance. For now, the most practical "alcohol fuels" are E85 and M85. If fuel cell catalysts improve, M100 could also be used directly in a fuel cell, without a reformer.

Each alcohol attracts water, and precautions have to be taken in shipment and storage vessels to ensure that water does not build up if the fuel and water separate again while motionless in the tank. Precautions include vacuuming out or heating empty tanks up to dry out water deposits. Both alcohols can make certain types of plastic brittle, requiring the replacement of some fuel system hoses and connectors in vehicles and refueling stations. Also, methanol can corrode the anti-corrosion lining placed inside gasoline tanks in vehicles, so using methanol in a regular vehicle would require changing out the fuel tank. Changes to factory vehicles for alcohol compatibility might cost $0-$300 per vehicle (Wang 1993) .

Tailpipe emissions from methanol are low in hydrocarbons and toxic compounds. NOx emissions are lower because it has a lower burning temperature than gasoline (NREL 1995). Methanol can also be burned extremely lean, with a high air/fuel ratio, which makes its use more efficient than gasoline. Methanol trucks emit much lower amounts of particulate matter than diesel trucks.

There are about 14,000 methanol passenger cars in use in the U.S., mostly in federal and private fleets, and 400 buses, mostly in California (U.S. EPA 1994). There are about 200 M85 refueling stations in the U.S, about 185 of those in California (U.S. DOE, AFDC 1997), and most of the rest in the Northeast and Southeast.

There are about thirty E85 refueling stations in the U.S., concentrated mostly in the Midwest from the Dakotas to Michigan, and south to Kansas and Illinois (U.S. DOE, AFDC 1997).

The alcohol resources are diverse. In general, biomass, as plant matter is called in the fuel industry, has limited resources because of environmental concerns about reducing the biodiversity of natural plant life by cultivating large acreage (NREL 1995), but it recycles CO2, and therefore does not add to a buildup of this greenhouse gas. Planting and using trees (cellulosic biomass) instead of corn or other starchy (food) crop is a more efficient use of land, and may yield higher per acre biomass alcohol production than the starch crops (NREL 1995). Using the coal resource for methanol results in high carbon and CO2 emissions, and is currently not a source of methanol. Natural gas conversion to methanol is inexpensive, but energy inefficient.

Electricity

Electricity production in this country varies regionally. The sources cited by A.D. Little (*Supplement to the Annual Energy Outlook 1993*, EIA, February, 1993) in their fuel chain model show that the fuel use for electricity generation across the nation averages to about 48% from coal, 16% from natural gas, 4% from oil, 2% from biomass, 18% from nuclear energy, and 11% from hydro- or other power sources. The emissions from coal plants can be significant, though they are often removed from the urban region in which air emissions are controlled, and they contain a different set of pollutants than vehicle tailpipe pollutants, so there is a shift in the type of pollution as well. Electric vehicles using coal plants may improve downtown pollution while worsening emissions outside the city, but those electric vehicles using hydro-electric plants are true zero emissions vehicles over the lifecycle.

Battery Chargers and Infrastructure

This section treats electricity as a fuel, and batteries as part of the vehicle (the "tank"). Electric recharging facilities pose a challenge because of the long period of time that the vehicle would occupy the charger. It takes 3-8 hours to fully charge most lead-acid batteries with a slow, or trickle, charger. These chargers cost about $1,000, and use 220 volt circuits, the input voltage to a normal house. State of the art "quick," or, "fast" chargers could cost as much as $10,000, and charge a battery up to 80% capacity in as little as 10 minutes. There are about a dozen fast charger designs ready for the market which enable 50% to 80% battery charges in as little as 10 minutes by pulsing electricity into the vehicle. Some manufacturers even claim that these chargers can increase battery life by reducing the buildup of deposits on the electrodes within the battery during recharging. Appendix 11 has a section discussing California's concerted effort to establish corridors of electric vehicle recharging stations.

4.3 Technical Evaluation of Alternatives

The most likely near term AFVs will still burn fuel in internal combustion engines. Battery electric vehicles may continue to fill application niches, but will have to wait for an industry changeover and battery improvements for their mainstream introduction. Natural gas fuels enjoy the support of government incentives for fleet applications, and will continue to expand their market in this area, especially in heavy duty applications. Hybrid vehicles may provide a demand for batteries that could drive further research, but for now they are novelty vehicles like EVs because of their expense. Fuel cells that run on gasoline may be introduced soon, but fuel cells using methanol or hydrogen require further catalyst and fuel delivery infrastructure development, respectively.

5. Lifecycle Model Description

Because the impact of using a fuel in a vehicle reaches beyond the vehicle itself, this thesis compares the emissions, energy efficiency, and cost of using alternative fuel vehicles by adding the emissions, efficiency, and cost contribution incurred in each stage of fuel production to those of its ultimate use in the vehicle. We recognize that the emissions and costs of each chain in the lifecycle method will vary locally, and that the method does not reveal locally advantageous applications of low tailpipe emission vehicles. However, it does not intend to substitute for local analyses that may identify these applications. Its use for making policy recommendations is on a different level: First, it is a method by which to compare very different fuels and their use in possibly very different vehicles. A tailpipe-only analysis would neglect the magnitude of the displaced emissions or the energy efficiency of using a certain resource. Second, the stage-by-stage analysis and presentation of the results enables the user to quickly identify the location of weaknesses in each chain: highest cost, emissions, or lowest energy efficiency.

This chapter describes the structure and assumptions of the fuel chain and vehicle components of the modified model. The first section describes the fuel chain model: its structure, assumptions, and its output. The next section describes the vehicle model. A final section shows how the results from the two models are presented for analysis.

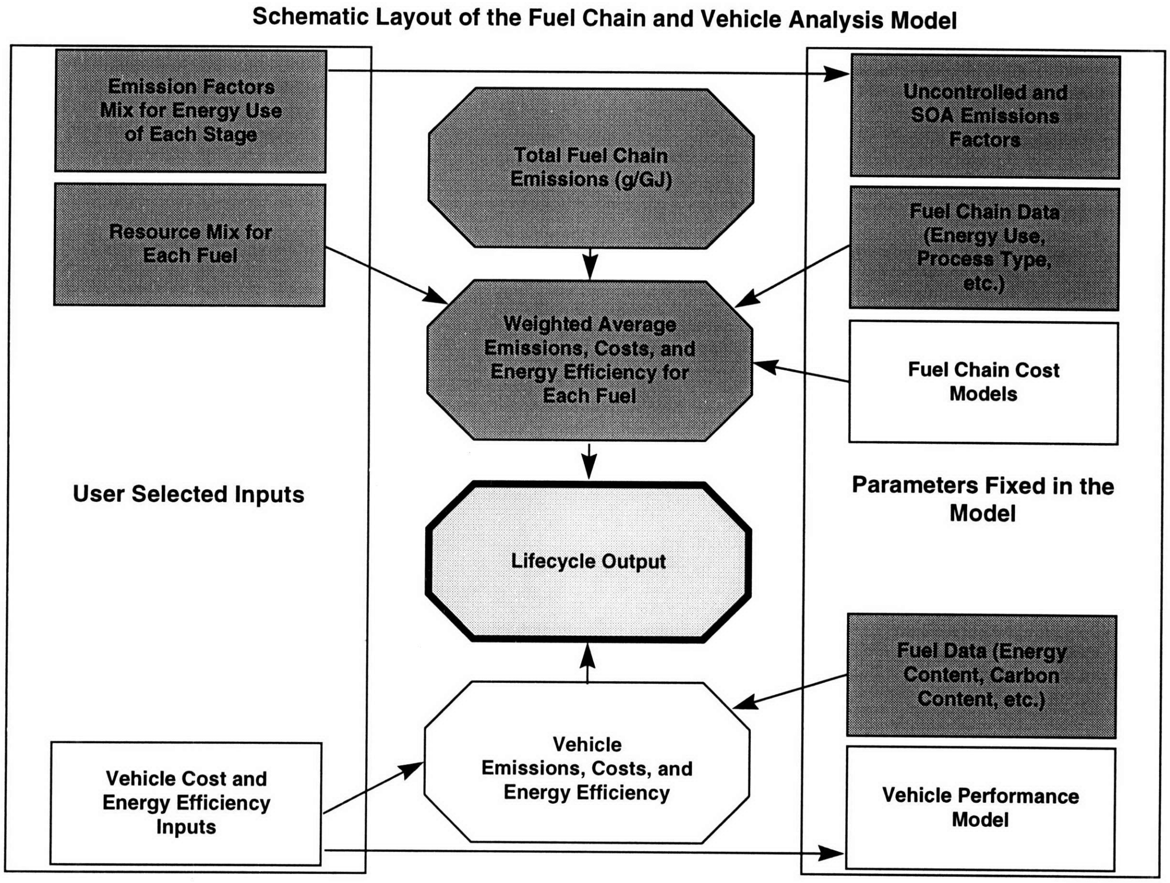
The Integrated Fuel Chain Analysis Model (ifcamv31.xls, referred to as "the ADL/Ford model") was written by Arthur D. Little, Inc. for the Ford Motor Company to compare fuel chain emissions and energy efficiency from the extraction of the fuel's resource to the delivery of the fuel in the vehicle. It runs on the Microsoft Excel spreadsheet program, version 5 or newer. The original version has no costs and no vehicle model.

The modification of the model presented in this thesis, "ifcamv31a.xls," (referred to as, "the modified ADL/Ford model") adds a vehicle model to simulate fuel use in different vehicles over a 12-year lifetime, and cost models for each complete fuel-vehicle chain.

The results represent the total stationary and mobile emissions, cost, and energy efficiency of using particular vehicle technology and fuel combinations over the life of the vehicle. They are described with the term, "lifecycle" analyses because they trace the lifecycle of a resource as it is transformed into the motion of a vehicle over the vehicle service life.

5.1 Structure of the Model

The model has two major data components and two major sub-models. The data includes input variables which the user is intended to be able to control, and model parameters which are more difficult to change, and would normally be fixed. The sub-models include a fuel chain model and a vehicle model. Because the model is programmed into a spreadsheet, changing the fixed model parameters should not be difficult, as long as care is taken not to disturb connections between the worksheets. Some policy analyses will require changing fixed parameters within the model. Figure 5.1 illustrates a schematic diagram of the model structure, showing the separate user inputs, model parameters, fuel chain, and vehicle use components.



Schematic Layout of the Fuel Chain and Vehicle Analysis Model

Figure 5.1: Schematic diagram of the modified ADL/Ford lifecycle model, showing how user inputs and fixed parameters are used in the fuel chain and vehicle models to arrive at lifecycle output. The shaded portion represents original ADL work. The clear boxes are the modifications to the model added in this thesis. The chart presentation is based on schematic of ADL/Ford model in ADL, *Integrated Fuel Chain Analysis Model (IFCAM) User Instructions for Version 3.1*, February 27, 1996.

The fuel chains are each modeled as a series of fuel production stages. Each fuel chain is represented on a separate worksheet, which makes the calculations easy to follow. The efficiency of the process stage and its air emissions are calculated for each stage of the fuel chains, based on published models and data. A linear fuel chain cost model was researched or derived for each fuel and resource combination, and added to each fuel chain worksheet. Their output is based on the user-entered resource (energy) prices and inputs from a separate worksheet of "Fuel Handling Costs" that calculates the cost of transporting and conditioning (e.g. purifying, mixing, liquefying, etc.) the fuel before it can be used in the vehicle.

A single worksheet contains a vehicle model that calculates all outputs related to the vehicle lifecycle, and adds these values to the fuel chain results calculated in the individual fuel chain worksheets.

The incurred AFV lifecycle costs are reported in constant 1996 dollars. Market and regulatory price effects enter the model only as exogenously determined cost inputs to process steps (user-entered).

5.1.1 Definition of Outputs: Energy Efficiency, Emissions, Cost

The efficiency calculates the percent of energy contained in the fuel which arrives out of each processing stage, as a proportion of the amount of energy originally contained in the resource (or fuel) before it entered each stage, plus the energy required to process the fuel (or resource) through the stage. The stage efficiencies are multiplied together to arrive at the overall fuel chain efficiency. The vehicle efficiency is chosen as an average value for its lifetime.

The emissions tracked in the fuel chain are: CO2, SO2, NOx, CO, NMHC, CH4, and PM. Air toxics, like those regulated in gasoline by the CAAA, are not included in the fuel chains. The vehicle model simulates emissions of the same pollutants as the fuel chain, via the tailpipe or evaporation of the fuel.

Lifecycle costs and emissions are reported by the fuel chain model on a per unit energy basis for each delivered fuel. The emissions are calculated in the vehicle model on a per mile traveled basis. The emissions from the vehicles and the fuel chain are added together after the fuel chain emissions are converted to a per mile equivalent value using the efficiency of the vehicle (miles/gallon). The sum is then multiplied by the number of miles traveled by the vehicle to arrive at the lifecycle figure that is in the final output table.

For certain industrial technologies that may be used in common by the fuel chains, for example coal boilers or natural gas turbines, the user selects the percentage of that technology that operates at the "state of the art" (SOA) of lower emissions and higher efficiency, leaving the rest as "uncontrolled," or ,"average" technology. The user also enters the percent mix of the resources used to produce each fuel. For example, methanol may be produced in the model from natural gas, coal, or wood.

5.2 Fuel Chains Analyzed

The modified ADL/Ford model is programmed to analyze different technologies involved in the stages of:

- fuel resource extraction
- resource transport
- refining/processing resources into fuel
- fuel transport
- fuel storage
- fuel delivery to the vehicle.

The model is currently set up to represent the fuel production technology and transportation characteristics in the United States, though any data can be entered into the spreadsheet structure. It relies on published data from the early 1990s which had been presented in technical papers in 1993 and 1994 (U.S. DOE, EIA Annual Energy Outlook, 1993 and 1994 and Supplements; DeLuchi, 1993. See ADL 1996 Bibliography).

The model allows the user to analyze 23 fuel chains which might be likely contenders for providing alternative motor fuels. Table 5.1 presents the chains which are now available for analysis in the modified model.

Table 5.1: Fuel Chains Analyzed in the modified ADL/Ford Model

Energy Resource	Transportation Fuel
Petroleum	Gasoline, M85, E85
	Reformulated Gasoline (RFG)
	Diesel
	Liquefied Petroleum Gas (LPG, Propane)
Natural Gas	Compressed or Liquid Natural Gas (CNG, LNG)
	Methanol, M85
	Hydrogen
	Liquefied Petroleum Gas (LPG, Propane)
Coal	Methanol, M85
	Hydrogen
Cellulosic Biomass (Wood)	Ethanol, E85
	Methanol
Maize (Corn)	Ethanol, E85
Various	US Electricity Mix (1990)
	Northeast Electricity Mix
	NY/NJ Electricity Mix
	Southern California Electricity Mix
US Electricity Mix (1990)	Hydrogen
Northeast Electricity Mix	
NY/NJ Electricity Mix	
Southern California Electricity Mix	
Nuclear Power	
Renewable Electric Technologies	

5.2.1 Interpretation of the Results of the Fuel Chain

Per Unit Energy Comparison of Fuels

The real commodity that a consumer purchases at a refueling station is a mobile energy source, not a volumetric or weight measure of a certain gas or liquid. To reflect this, all fuel costs and emissions in the fuel chain model output are expressed for comparison in units of \$/GJ (1 GJ ~ 1 MMBtu), which is the approximate energy content of a full tank of fuel for an economy-class vehicle with a conventional operating range.* The per unit energy reporting method enables comparisons to be made across gaseous and liquid fuels, and across different in-vehicle energy storage methods. Making such comparisons using

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* One exception to this GJ rule of thumb is a battery electric vehicle, which due to weight constraints and higher efficiency only stores about 10% of this amount of energy. A large sport utility vehicle, on the other hand, could carry as much as 4-5 GJ of fuel in its tank (about 42 gallons, or a barrel of gasoline).

a per unit volume or per unit mass basis would ignore the energy density of the fuel, which can change the real fuel cost dramatically from the apparent per gallon rate with which we are familiar. As will be shown later in this chapter, factoring in the cost of using the fuels in the vehicles can yield lower lifecycle costs for a particular AFV system, even if the fuel is expensive per unit energy.

Emissions from the Fuel Chain

The emissions factors for the stages in fuel processing are automatically weighted according to the user's inputs of the state of the art of the processing technology, and the resources used to produce the fuel. The emissions results are presented in tables expressing the grams of emissions per convenient unit of the fuel, grams per gallon of gasoline equivalent, and grams per Gigajoule (GJ, 10^9 Joule).

Efficiency Calculations in the Fuel Chain

The energy efficiency results are calculated for each stage as the higher heating value of the processed resource or fuel which emerges from the stage, divided by the sum of the energy content of the resource input into the stage and the total process energy used in the stage. The choice of using higher or lower heating values should not make any difference in the results (DeLuchi 1993). The lower heating value omits the energy lost to heating the water formed in the combustion reactants (which does not contribute to useful work in a combustion engine), and the higher heating value includes this energy.

The calculation does not include the energy invested in constructing infrastructure, vehicles, etc., though it does include the energy used by machines involved in each stage.

The efficiency values for all the stages, including vehicle refueling, are multiplied together at the end of the chain to give the fuel chain efficiency. Both emissions and energy models include statistically averaged leakage and other loss rates in their proper location (i.e. storage stage, refueling stage, transfer stage, etc.).

Cost Calculations in the Fuel Chain

Cost calculations do include the cost of constructing new fuel processing or distribution facilities. These costs are also expressed in dollars per unit energy or dollars per volume, which is converted to dollars per unit energy with the appropriate physical property.

5.2.2 Resource Extraction

The original ADL/Ford model includes tables for emissions and energy efficiency of mining, drilling, and other resource extraction processes. It does not include the energy used in construction of the mining infrastructure. The cost of extraction is not explicitly treated in most of the models because it considers the acquisition of the resource at its world market price to include extraction costs. One exception is in the natural gas-to-LPG model, a process in which the LPG is extracted directly from the gas with which it is associated in the ground. In this model, the portion of operating costs of the well which contribute to LPG production are considered the cost of "extracting" the natural gas to make LPG.

5.2.3 Resource Transport

Resources are shipped in the model by modes and over distances which represent the actual distribution of extraction sites and processing plants in the US. Refer to Appendix 13 for a summary of the distances and the percent of resource transported by each mode. Natural gas and liquid petroleum are transported primarily by pipeline, but also by ship, truck, and train. Electricity, of course, is transmitted in high tension wires, which is accounted for in the model by an efficiency loss in the fuel chain. Coal is usually transported by train, and corn and trees by truck only, since biomass processing plants are small and do not demand enough feedstock to merit train shipments. It is important to note that a high proportion of both resources and finished fuels are transported more than once, by more than one mode. Transport modes are treated in more detail below in the fuel transport section.

5.2.4 Fuel Refining

Representative refinery configurations have been modeled to simplify the analysis. It is likely that the representation will not satisfy experts in each fuel field. Refining of crude and processing of coal and natural gas is extremely complex, and varies widely across the country, across fuel companies, and the world. Refineries and reforming plants can be set up to produce different ratios of fuels and other valuable byproducts, at different capacities, depending on the state of the market, on particular regulations, or the price and quality of the input resource. For manageability, the processing stage of each fuel chain has been set to produce at a constant output level, though some chains give the option of choosing between two or more production rates which yield different economies due to scale.

Constant Dollar Stream of Outputs Cost Models for Fuel Production

Most of the production cost models share the logic of representing the capital and lifetime operating costs as a constant dollar, per unit energy sum. They use a capital recovery factor methodology over an output stream of 30 years to account for the depreciation of the capital investment, the opportunity cost of the capital, and economic growth. The resulting average variable cost per unit energy, volume, or mass of fuel produced is added to the cost of the resource consumed per unit energy, volume, or mass of fuel to arrive at the total cost of the fuel per unit energy it contains.

These models were derived by other authors who are experts in their fields, cited in the model and below. Only their per unit of fuel production cost results are used in the modified ADL model. In some cases their calculations were performed for two different capital recovery factors. When this was the case, both models were entered into the fuel chain worksheet, and the conservative model (lowest capital recovery factor) was used in the calculations. The other model is available for use if the appropriate changes are made in the worksheet which reports the final cost of each fuel. The most common capital recovery factor is 20%.

If the user should want to change the per unit of fuel production costs, it is enough to change the fixed or variable cost (either per unit energy, volume, or mass of output) in each model. The simple way that the cost models are structured, the user will have to know what his new input value intends to represent if his results are to have meaning. For example, changing

Petroleum: Gasoline, RFG, Diesel, LPG, MTBE

Processing cost models for the mature petroleum industry are simpler than this because they can rely on the established refining technology rather than improving along a learning curve for new processing plant technologies. Also, the refineries are more numerous and have differing costs across types, so a representation of an "average" refinery falls within a wider uncertainty, allowing for model simplification. The gasoline, RFG, diesel, and LPG (from petroleum) cost model relies on rules of thumb presented in Table 5.2 that have held nearly constant since the mid 1970s (Hadder 1992):

Table 5.2: Rule of Thumb Petroleum Processing Cost Model Used in the Modified ADL/Ford Model

Product	Cost Relationship to Crude Oil
MTBE	28.0 c/gal over Unleaded Regular
Unleaded Premium	4.0 c/gal over Unleaded Regular
Unleaded Regular	3.5 c/gal over #2 Fuel Oil
Jet A	3.0 c/gal over #2 Fuel Oil
#2 Fuel Oil	8% over Crude Oil Price
#6 Fuel Oil	77% of #2 Fuel Oil
RFG	0.11 * Cost/gal MTBE + 0.89 * Cost/gal Unleaded Regular + 1.8 c/gal

Source: Hadder 1992

This model implies a current refiner's cost for MTBE of $0.85/gal, which is about 25 cents less per gallon than the November, 1994 price (U.S. DOE, EIA 1994). To cope with this quickly changing price, the model lets the user enter the price of MTBE into the model inputs* . $0.85 is the cost to the refiner automatically used in the base case scenario (the user entered value is disconnected in this scenario). The other scenarios use the user input value.

RFG contains 11% by volume MTBE, which raises its cost a few cents per gallon. The extra processing cost to reduce volatility and sulfur in RFG adds an average 1.8 c/gal over the production cost of unleaded regular gasoline (OGJ 1994). The cost of diesel is pegged to gasoline at 95% its cost per unit energy, and LPG is pegged the same way at 55%, both picked to match current published costs. (U.S. DOE 1996)

Natural Gas: Methanol, LPG, and Hydrogen

Natural Gas to Methanol

The natural gas to methanol steam reforming model has the option to establish two different sized plants in four operating regions in the world (U.S. DOE 1989). Region I represents developed regions with large natural gas supplies in which transport infrastructure already exists, but land, capital, and labor are more expensive per unit. The DOE suggests only one candidate for this classification, Trinidad. Region II is a developed region with even higher construction costs, because of population density or the need to invest in infrastructure. Region III is a region with large natural gas reserves, but completely lacking in infrastructure for transporting the finished products, housing workers, etc. Region IV refers to offshore locations with no infrastructure, to which producers may be attracted given a high enough natural gas or methanol price.

The hypothetical plants "built" in these locations can produce at 2500 or 10,000 metric tons per day. In the base case, it is assumed that 10% of methanol will come from the large plants. In the case of future technology advances, 40% will come from the large plants.

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* A recent Oil and Gas Journal (7/94) states that MTBE could some day sell for as low as its production cost of near 12 c/gal.

Linear cost models for the manufacturing process are presented in a technical analysis from the DOE (1989). They represent a capital cost of roughly \$600M for the large plant, and \$300M for the small plant. The cost models assume that the larger of these fuel-grade plants provides a lower grade fuel with more impurities, instead of the more pure chemical grade methanol which is commonly provided today for industrial purposes. This change may simplify the distillation and reduce methanol's cost (U.S. DOE 1989). The fuel's primary impurity is water, so it should work with the developing methanol fuel cells. It would certainly work as a combustion fuel in current M85 or M100 engines (U.S. DOE 1989). There is a significant cost reduction in using these large, high technology plants (Chapter 8). Table 5.3 summarizes the natural gas to methanol production model.

Table 5.3: Summary of Natural Gas to Methanol Production Model, Showing Distribution of Manufacturing Facilities and Possible Future Cost Reductions. Cost of Methanol in \$/gal. Cost of Natural Gas (NG) in \$/MMBtu

Production Region		**Methanol Processing Cost (\$/gal) as a Function of Natural Gas Price (\$/MMBtu)**		**% Production in Region**
		2500 MTPD	**10000 MTPD**	
I		0.1 + 0.27NG	0.09 + 0.17NG	5
II		0.1 + 0.30NG	0.09 + 0.19NG	65
III		0.1 + 0.38NG	0.09 + 0.24NG	30
IV		0.1 + 0.53NG	0.09 + 0.33NG	0
% Production by Type of Plant	Present/ Low Tech.	90	10	
	Future/ High Tech.	60	40	

Natural Gas to LPG

The LPG model is built on a DOE report in the same series (U.S. DOE 1996) which analyzes the economic impacts of alternative vehicle fuel consumption on other economic sectors. LPG is different from most other fuels in that its resource is not purchased. Rather, raw natural gas comes up from the well, and LPG is separated from it, along with other "natural gas liquids". The only costs are incurred in operations and economic costs.

The model in the paper presents the plant operating costs and the amount of input gas that is needed to extract liquids from natural gas, all of which depend on the plant configuration and the type of input gas. 5 output liquids are listed from the 6 processes, so cost allocation between the output liquids in each process could be ambiguous. The model in the thesis allocates the operating cost to the output liquids based on the proportion of the energy contained in each one. All of the input energy to the system is in the input natural gas, so this method of cost allocation assumes that processing cost is proportional to energy consumption as the only input to the processes. An additional $2/GJ fixed cost is similar to that assigned to the natural gas to methanol plant model.

Natural Gas to Hydrogen

The natural gas to hydrogen model is a very simple linear production model based on the coal model below. It takes the ratio of the natural gas inputs to hydrogen gas output in the processing step, as given by the ADL part of the model, multiplies this number by the cost per unit input of natural gas, and adds a fixed manufacturing cost which is equal to that of the coal to hydrogen model. This makes sense because both syngas from coal and natural gas must be steam reformed, requiring the same type of installation.

Coal: Methanol and Hydrogen

Coal to Methanol

The coal resource to methanol model simulates a futuristic plant which offers an alternative to cogenerate electricity with the methanol production and sell it to offset costs. It also produces in high volume (5000 metric tons per day), which lowers cost. This type of plant is not in use now, and should only be included in the model when looking at future scenarios. The cogeneration plant also includes a heat-recirculating gasification reactor which improves its efficiency. The cost model is not tied to the user-entered “state of the art” (SOA) proportion however, so for accuracy, the user should choose an SOA percentage for coal boilers which accords with the amount of methanol produced in this “state of the art” cogeneration plant.

Coal to Hydrogen

Coal must be heated to produce a gas called "syngas," which is reformed with steam over a catalyst to form hydrogen. This process is very energy intensive because of the heat required. Coal plants which can co-produce electricity with the leftover heat will be able to sell or use it to reduce costs. This model is very simple, from DeLuchi (1989). It derives a variable cost per unit energy of H2 produced, based on a $300M capital investment and a 15% rate of return. The three models give a high, medium, and low cost output to bracket a range of certainty. The same variable costs are used in the natural gas to hydrogen model because of the similar processes.

Electricity

The price of electricity is set at 7c/kWh for the base case (U.S. DOE, EIA 1992), though the price varies by time of day and by region, up to 35c/kWh. The ADL/Ford model includes electricity production models for the power plants listed in Table 5.1 for use in emissions and energy efficiency analyses, but the cost is not modeled. The user may enter any electricity price in the appropriate input cell, and can model changing prices over the lifetime of the vehicle in the vehicle model, if desired.

Biomass: Ethanol and Methanol

The biomass fuel chains, ethanol and methanol (diesel biofuel has not been included), offer the option of cogenerating electricity during the fuel processing stage and selling or using it to offset costs. These options are not available for analyses in the present, but are used in the "2010" case.

Ethanol from Biomass

Corn for ethanol is transported by truck to the distillery, a distance of 50 miles. Inputs to the distillation process include coal for the boiler that breaks the starches down into fermentable sugars, with the option to use crop byproducts for the boilers at a cost of $0. Corn byproducts (gluten feed) can be sold to farmers for animal feed, which offsets the cost of ethanol production. The going price for this byproduct ranges in the model between $85 and $200/metric ton. (IEA/OECD 1992). The model modifies an OECD model to suit the ADL data presentation in the spreadsheet. It represents a 395 metric ton/day, $100 million plant. The plant has an operating cost of $17,420,000/yr, and variable costs of $50-$100/metric ton of ethanol produced ($50 is used in the model). The conversion efficiency of corn to ethanol is .27-.35kg/kg ethanol (0.35 is used in the model). Two costs give the effect of low and high gluten feed prices on ethanol cost.

Methanol from Biomass

The methanol from trees simulation is a quick model to represent an immature, experimental technology. The model also comes from OECD. Chipping the wood, and then gasifying the wood chips requires a lot of energy, usually electricity. Future installations could cogenerate electricity to use in this process. The small standalone (800 metric tons/day) and large cogeneration (5000 metric tons/day) installations modeled here cost $300M and $660M, respectively, with annual fixed costs of $18,000 and $38,000. The trees arrive via truck, from 50 miles for the small plant, and 100 miles for the large plant. This transport cost is significant because trees are heavy for the energy they contain, and the shipment cost is assumed to be related to the weight of the shipment and its distance. Trees produce methanol in the model at a ratio of roughly 2kg wood:1kg methanol. The user can choose what percentage of biomass methanol is produced by each plant type, though the advanced plant is a future projection, and not available now.

5.2.5 Fuel Storage and Transport

The model accounts for energy and emissions losses in storing and transferring gaseous and liquid fuels from the processing plant to the retail distributor. The average distance and the mode on which each fuel is transported are set parameters for each fuel chain. The model uses published data for average shipment information, using efficiency and emissions data for the US. The costs follow crude, linear hedonistic cost models which express cost in units of $/ton-mile, $/gallon, or $/MMSCF-mile (MMSCF= million standard cubic feet, for gaseous shipments). The coefficients were estimated from the DOT's National Transportation Statistics and NTS Annual Report of 1996. The model costs are summarized in Appendix 15.

Pipelines

Liquid Pipelines

Oil pipelines are assumed to use electricity to run the pumps, at the user-entered market price. They carry crude oil, liquid crude derivatives like gasoline, diesel, kerosene, and heavier fuel oils, methanol, and MTBE. The average shipping distance varies by fuel. The cost of shipping is $0.014 per ton-mile. (U.S. DOT 1996b, derived)

Gas Pipelines

Natural gas pipelines combust some of the pipeline gas to pressurize the system. The costs incurred here are revealed only in a loss in efficiency of 7.5%, or a 7.5% reduction of the natural gas yield after shipment. The average shipping price was calculated from EIA statistics: in 1990 dollars, the delivered natural gas price was $4.00/MSCF. Subtracting the $1.72/MSCF wellhead price and adjusting to 1996 dollars equals $2.54/MSCF transport cost, or $2.40 per GJ. This is derived from a national average value where no average shipping distance is given. The shipping distance is assumed in this thesis to be 1000 miles. As a result of this assumption, some regions may have cheaper shipping costs for natural gas than the model reports, and some regions much higher costs.

Hydrogen shipments are assumed to be made in natural gas pipelines, using electric pumps. These pumps have to be spaced closer together and have to give a higher pressure in order to make the shipment worthwhile on the basis of earnings-per-unit energy shipped, since hydrogen contains less energy per unit volume than natural gas under standard conditions. Upgrading some of the current natural gas pipelines to resist the cracking that hydrogen can cause in steel containers is assumed here to be a cost which will be encountered anyway as the current natural gas pipeline infrastructure is replaced. By one estimate, 85% of the nation's natural gas transmission pipelines will be over 40 years old by the year 2000, and will need to be either replaced or rehabilitated by scraping out the old liner with a water jet and being re-lined (Shannon 1993). Hydrogen transport costs by pipeline are $1.50/GJ (DeLuchi 1989). No extra cost for special upgrades of natural gas pipelines are expected in the model.

Cryogenic Transportation: Hydrogen and Natural Gas

Transportation and retailer distribution costs for the cryogenic liquid fuels, LNG and LH2, were taken from DeLuchi (1989) and account for the cost of double-walled tanks and boiloff losses of the cryogenic fuel. This boiloff characteristic makes long-distance transport of cryogenic liquids less economical than for other liquid fuels, and potentially dangerous, because of escaping gas. This problem presents a tradeoff for distributing these fuels between the expense and losses of storing and trucking the liquid to the retailer, and the expense of storing the gas at the retail site and liquefying it as needed. One way to overcome the safety problem of containing cryogenic liquids is to burn the boiled off gas in the vehicle which is transporting the liquid. LNG is actually a more economical way to ship natural gas across the ocean than CNG, where no pipeline exists, and it is commonly done from North America to Japan (Shannon 1993).

An alternative to transporting cryogenic liquids is to transport the fuels as gases and liquefy them at the retailers'. The model includes estimates by DeLuchi (1989) for hydrogen and natural gas liquefaction and high-pressure compression in the low volumes consistent with the retailer's service scale.

The model allows the user to choose whether cryogenic liquid fuels are shipped to retail stations as liquids, or whether the stations receive the gas in a pipeline and liquefy it themselves. The cost models include the cost of the retailer's compressors on the one hand, and storage tanks and boiloff containers on the other.

Truck Transport

Most fuels are transported to their final retail destinations via diesel truck. The cost of this transport has been modeled by Sperling (1989) as 0.7 c + 0.019c/gal-mile (1989 dollars), or .8c + .022c/gal-mile in 1996 dollars, with constant returns to scale. The average distances transported for each fuel vary by fuel, depending on the location of the fuel blenders and the retail refueling stations.

Ethanol Shipment

Many pipeline operators will not accept ethanol because of the water it could be carrying, and could introduce into the pipeline system. This leaves it to be shipped by train and by truck from its production plants to gasoline blenders. Rolling transport modes are much more expensive than pipelines, and add to the cost of ethanol in the model.

5.2.6 Special Fuel Handling Costs

Some of the fuels require special handling after their manufacture. These include high pressure gases and pressurized or cyogenic liquids.

Natural gas and hydrogen that are to be used cryogenically have to be compressed by expensive and energy-intensive pumps, and then stored in double-walled dewars. The costs and efficiency losses associated with this operation are summarized by DeLuchi (1989) and are included as per unit energy costs to be added to the finished fuels.

Natural gas and hydrogen that are to be used as gases also have to be compressed to very high pressures, about 3600 psi for natural gas (CNG), at $1.30/GJ and 6000 psi for hydrogen (CH2), at $1.50/GJ.

Hydride storage tank systems for hydrogen only require hydrogen to be delivered at 800 psi, but require a hydrogen that is 99.999% pure to preserve the hydride tank, which raises the cost of the hydride hydrogen considerably, so that it is even more expensive than normal CH2 at 6000 psi for the size of station modeled,* at $3.17/GJ.

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* For these special handling procedures for natural gas and hydrogen, the compression, cooling, and purification models include the costs of a retail station serving 200 vehicles/day to 82% of their 210 km range (H2 stations), including compressors, storage tanks, and refueling pumps (see the refueling stations section below).

5.3 Vehicle Model

5.3.1 Overview

The vehicle model worksheet calculates the costs, emissions, and energy efficiency of acquiring and using 17 alternative-fueled and alternative powertrain vehicles over a 12-year lifetime. The vehicle acquisition costs are user-entered in the model. Fuel consumption and maintenance costs are based on data published by the Federal Highway Administration (FHWA) which summarizes the average annual vehicle miles traveled and the average annual maintenance cost over the life of a passenger car. Various data sources were used to estimate a total lifetime representative tailpipe and evaporative emissions profile for each vehicle type, which includes all of the pollutants modeled in the ADL/Ford fuel chains. The user inputs worksheet includes a column for entering the incremental cost of building a refueling station for each vehicle type, expressed on a per vehicle basis, which is added to the cost of the vehicle as a necessary prerequisite to being able to use its fuel.

Vehicles modeled

The seventeen vehicle alternatives modeled include mixtures of fuels and drivetrain types. Some fuels are used by multiple vehicle types, and vice-versa (seeTable 5.4).

Table 5.4: Fuels and Vehicle Types in the Modified ADL Model

Fuel/Vehicle Group	Fuel \ Powertrain Type	Internal Combustion	Electric Drive	Direct Conversion Fuel Cell
Petroleum	Gasoline	X		
	Reformulated Gasoline (RFG)	X		
	Diesel	X		
	Liquefied Petroleum Gas (LPG)	X		
Alcohol Fuels	Methanol	X		
	Methanol		X	X
	M85	X		
	Ethanol	X		
	E85	X		
Natural Gas	Compressed Natural Gas (CNG)	X		
	Liquefied Natural Gas (LNG)	X		
Hydrogen	Compressed Hydrogen	X		
	Compressed Hydrogen		X	X
	Liquefied Hydrogen	X		
	Hydrogen Hydride	X		
Electricity	Battery Electric		X	
	Hybrid ICEV/Electric Vehicle (RFG)	X	X	

All vehicles are assumed to be light duty passenger cars, used the same way according to statistically averaged VMT. Even the diesel, LPG, and CNG fuel/vehicle alternatives refer here to passenger automobiles, though today most of these vehicles in the US are heavy trucks. Diesel and CNG automobiles are commonly used throughout Europe, though, so a comparison with CGVs could be useful. It is easy to modify the model inputs to simulate all heavy trucks or all passenger cars, but dividing fuel/vehicle systems between the two within the model would require more extensive reprogramming.

5.3.2 Vehicle Lifecycle Cost

Only the vehicle purchase and costs of using it are counted in the lifecycle. Associated insurance, vehicle storage, etc. Costs are assumed to be the same across vehicles, and are ignored.

Vehicle Cost

Overview of Vehicle Costs

The model asks for user input price of a conventional gasoline ICEV, and relative likely low and high vehicle acquisition costs of the AFVs. These costs are the differential costs to the consumer between the AFV and a CGV. Options for the low and high costs include aftermarket ICEV conversion costs, new vehicle prices from original equipment manufacturers (OEM), and prices of flex-fueled versions of the vehicles. The high and low values reflect either physical additions to the vehicle, for familiar AFV types, or future uncertainty in cost for the experimental vehicles.

Vehicles with Batteries

The program asks for the cost of hybrid electric vehicles and battery electric vehicles (BEV) without the battery. The model adds the battery cost later, in the vehicle model, since it has to size the battery appropriately to the demanded range and energy consumption characteristics input by the user. The lower OEM value used in the analysis assumes that it costs 20% less to produce a BEV without a battery than it costs to produce an equivalent ICEV (with an engine, of course). The higher cost in the base case of +20% considers a higher performing BEV chassis, which may incorporate lightweight materials or sophisticated electronic controls, for example. The higher cost may be considered to provide slightly added performance, though battery characteristics and vehicle size play a more important role in performance for BEVs than the construction materials. Higher performance for the higher cost vehicle is not modeled.

Hydride Vehicle Cost

The user is not able to determine the cost of the hydride vehicle. This cost based on a hydrogen internal combustion vehicle cost equal to that of a CGV, plus the cost of the hydride tank, which is sized in the vehicle model like the battery for the BEV. Hydride tank costs are is calculated by the model, using data for experimental hydride tanks. Data is sparse enough that no correlation can be made between higher cost and vehicle performance, so the range of expressed vehicle acquisition costs for hydrogen hydride vehicles should be considered to be projections for cost uncertainties only.

Other ICE AFVs: Alcohols, Hydrogen, Natural Gas

The high and low vehicle costs used for the analysis of conventionally functioning ICEVs are based on the best available information from auto manufacturers, conversion kit and labor prices, and other published information. These costs are well-established from many years of experience with alternative combustion fuels. Variations in the price of conversion kits or OEM products stem from the complexity of the engine control systems (which have an effect on performance), the materials of certain fuel systems (like carbon wound aluminum pressure tanks for CNG and hydrogen, as opposed to heavier kevlar tanks), vehicle size, etc. The high and low costs for CNG, LNG, LPG, alcohols and alcohol blends, and CH2 reflect purchase price differentials between available vehicles and new CGVs.

Developing Technologies

Experimental or variable technologies like fuel cell vehicles, hybrids (which can have many drivetrain and fuel storage configurations) and liquid hydrogen have been assigned high and low costs with a wide spread of uncertainty. This spread reflects the optimism of laboratory or entrepreneurial ventures into their development, and skepticism of these predictions. The costs for fuel cells, for example, is cited by the privately funded fuel cell development firm, H-Power Corporation, to be currently $5,000/kW, but falling quickly toward $200/kW.(Maceda 1996) These two values were used in the analysis as the high and low incremental costs for fuel cell vehicles, assuming a 40 hp vehicle (750W/hp). The resulting high and low forecast cost additions for fuel cell vehicle powerplants are then $6,000-$150,000.

Fuel Cost

The fuel cost for each vehicle is calculated based on the vehicle's efficiency (see efficiency discussion, below), and assumes that each vehicle travels the same number of miles every year that the other vehicles travel. The model simply multiplies the miles traveled per year by the energy efficiency of the vehicle and the cost per unit energy of the fuel, as given by the fuel cost models, then discounts the future costs for a constant 1996 dollar representation. The model uses a 10% discount rate, which the user may change. Discounting corrects for the interest and other earnings foregone on money spent today as opposed to in the future. Neglecting dollar discounting would exaggerate the cost of more expensive fuels and maintenance over what they merit in a constant dollar analysis.

The annual miles driven per vehicle simulate passenger vehicle use, and are taken from the FHWA (1992), as presented in Table 5.5. An average vehicle is used less every year.

Table 5.5: Estimated Vehicle Use with Age (U.S. DOT, FHWA 1992)

Vehicle Age (years)	Annual VMT
1	12,900
2	12,600
3	12,300
4	11,900
5	11,500
6	11,000
7	10,600
8	10,100
9	9,600
10	9,100
11	8,700
12	8,200
Total	128,500

These numbers can be changed to reflect other vehicle applications, like fleets or freight hauling service, but the mileage is the same for every vehicle in the model so that the vehicles can all be compared. The declining average use of a vehicle as it ages is significant for vehicles which use higher cost fuels. Since fuel cost is a variable cost, dependent on the number of miles traveled, the incremental cost of using expensive fuels is lowered for every decrease in miles driven.

Maintenance Cost

The maintenance cost for vehicles is also based on the same FHWA publication, and is discounted into the future like the fuel cost. Unlike fuel cost however, maintenance costs increase with the age of the vehicle because more components begin to break down. Different AFVs may have different maintenance costs from CGVs. The model uses the Table 5.6 adjustments for the AFV types. The following discussion justifies these assumptions.

Table 5.6: Model Assumptions of Maintenance Cost Relative to Those of Conventional Gasoline Vehicle Used in the Modified ADL/Ford Model

Fuel/Vehicle Group	Fuel/Vehicle Type	Relative Maintenance Cost
Petroleum	Gasoline	1.00
	Reformulated Gasoline (RFG)	1.00
	Diesel	1.00
	Liquefied Petroleum Gas (LPG)	1.00
Alcohol Fuels	Methanol	1.00
	M85	1.00
	Ethanol	1.00
	E85	1.00
Natural Gas	Compressed Natural Gas (CNG)	1.00
	Liquefied Natural Gas (LNG)	1.00
Hydrogen	Compressed Hydrogen	0.95
	Liquefied Hydrogen	0.95
	Hydrogen Hydride	0.95
Electricity	Battery Electric	0.60
	RFG Hybrid ICEV/Electric Vehicle	1.00
Fuel Cell	Compressed Hydrogen FC	0.60
	Methanol FC	0.60

Electric Vehicle Maintenance Cost Assumptions

Electric and fuel cell vehicles have few moving parts, low operating temperatures, and no oil, filters, or belts to replace. Fuel cell vehicles may have pumps and water tanks which may need attention, however, and electric vehicles are heavier, so they may wear tires and axle bearings more quickly. Neither vehicle will have to pass annual inspections, which can cost near $30-$40 per test. Overall, these vehicles are assumed to enjoy a 40% reduction in standard ICEV maintenance costs each year. Hybrid electric vehicles that use internal combustion engines incur the same maintenance costs as CGVs.

Gaseous Fuel Vehicles Maintenance

Gaseous fuels lack the lubricants for the engine that liquid fuels have, but operators of these vehicles have found that this problem can be overcome with different engine oil. The fuels also foul the engine oil less quickly than gasoline does, so there is a cost savings in oil changes. The higher hydrogen to carbon ratio relative to gasoline of these fuels reduces carbon buildup in the engine, tending to lengthen component life and maintain engine efficiency longer than in CGVs. However, costs will be added for these vehicles because the pressurized or cryogenic tanks are required by DOT to be re-certified every 5 years for steel, 3 years for composite steel or aluminum (U.S. DOE 1996). Hotter engine running temperatures could also require more frequent replacement of spark plugs or glow plugs and wires.(U.S. DOT 1992a). Altogether, maintenance costs for carbon containing gaseous fuels (LNG, CNG, LPG) balances out to be 100% of CGV maintenance costs in the model, and hydrogen fuel vehicles benefit from a 5% reduction in maintenance cost for their carbon-free operation.

Alcohol Fueled Vehicle Maintenance

Alcohol fuels may mix with the oil in engines and break down its viscosity, fouling it more quickly than in gasoline or diesel fueled engines, which would require more frequent oil changes. They also lack the lubricants that gasoline and diesel have, though this can be added to the alcohol fuel. Different engine oil can be used, as well. However, the cleaner burning fuels leave fewer carbon deposits in the engine, resulting in longer life and less frequent spark plug replacement. Overall, alcohol fuel vehicles have the same maintenance costs as CGVs.

Battery Cost

Only battery electric and hybrid electric vehicles replace batteries as an expense above the common maintenance cost, which includes replacement of the starter battery. The size of the battery in kWh (energy) is determined from the efficiency and range of the vehicle, as entered by the user (see the efficiency section below). The BEV range is a user-entered fraction of the CGV range, which is also user-entered. The HEV range on battery alone is a number in miles to be entered by the user. The model calculates from these numbers the required energy to be made available to the wheels of the vehicle. In both HEV and the BEV, all of this energy must be made available by the battery, at an 80% depth of discharge of the battery. Discharging most batteries beyond this 80% "empty" level can damage their ability to accept charge in the future, so this is a safety factor for conserving battery life. This means that the total amount of energy to be stored is 125% of the energy calculated to move the vehicle. The HEV battery size is set at a maximum of 15 kWh, about enough to drive an electric vehicle 30-35 miles under good conditions. This size is consistent with two market-ready hybrids (Audi press release 9/96).

Battery cost calculations are based on battery performance characteristics that are based on USABC goals and industry reports (Ovshinsky 1996), as shown in Table 4.

Table 5.7: Battery Characteristic Choices As They Appear in the Modified ADL/Ford Model, "Vehicle Model" worksheet

Scenario	Energy Density (kWh/kg)	Cost ($/kWh)	Lifetime (Cycles)(80%DOD)
Low Technology and Base Case	0.08	150	600
High Technology Development	0.20	100	1000
Hybrid Battery (30% DOD)			10000

Last row refers to Ovonics hybrid EV battery at 30% DoD (Ovshinsky 1996). Energy density and cost of hybrid battery assumed to be the same as for BEV battery in all scenarios. All other batteries are USABC short and long term goals (Kalhammer 1996).

BEV

In the BEV, the battery cost calculation is straightforward after this. The miles traveled per year divided by the energy available in the battery (the capacity times its depth of discharge of 80%), divided by the efficiency of the vehicle gives the number of recharging cycles per year. The number of cycles the battery can take before it is dead, divided by the number of recharging cycle per year, gives the average battery lifetime. A new battery must be purchased every interval equal to this lifetime. The cost of each battery is simply the $/kWh times the number of kWh capacity that is required. The model loses some accuracy by using a simplified average miles/year calculation instead of the actual number of miles traveled each year. This results in delaying the battery purchases, in the model, which makes them look less expensive because of cost discounting. With the vehicle use patterns assumed for this thesis, this discounted dollar cost savings is very small relative to the additional cost of purchasing a new battery every few years. However, the error introduced by the "annual average " calculation method should be addressed in the program if the vehicle mileage decreases a lot with time.

ICEV/HEV

HEV energy management systems can be very complicated in order to optimize battery life and vehicle performance. The HEV model uses a similar method to the BEV model to find the average battery lifetime, however it assumes that the battery will only be used to 30% of its depth of discharge before the ICE begins to recharge it. This lower depth of discharge per cycle reduces the range of the vehicle under battery power, but increases the number of lifetime recharging cycles before the battery wears out, by a factor of 10. The model manages the energy in the vehicle by asking the user for the percentage of miles expected to be covered by electric-only travel.* The program assumes the vehicle will use the battery power first for this travel, and then will run the ICE to charge the battery over the remaining mileage.

The calculation of the battery lifetime uses the mileage covered under electric power, divided by the efficiency of the electric drive of the vehicle times, 30% of the battery capacity. This kind of hybrid model probably overstates the number of charge cycles that the battery will need, because it is an inefficient way to manage the energy in a hybrid electric vehicle. But the variation in available battery technology could blur the potential accuracy of any such calculation. Some batteries (like NiCds) actually work better if they are more deeply cycled than the ones in this model, and even require being completely discharged occasionally. Lead acids, like the ones in this model, work better if they are kept at a low depth of discharge while the ICE generates power for the electric drive motor. The model can be reprogrammed with more complicated HEV models, and this

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* The CAAA90 requires dual fuel vehicles to travel on the clean fuel only while being used in non-attainment areas.

particular one should not be taken to represent the performance of a whole spectrum of possible configurations of electric hybrid vehicles.

5.3.3 Refueling Station Cost

The cost of the refueling stations propogate in two different ways in the model for presentation purposes, but are only added into the lifecycle cost once. The fuel cost models for hydrogen hydride and LH2, CH2, LNG, and CNG are constant dollar, per unit energy values of the depreciated costs of medium-sized retail stations. The LPG and alcohol fuel station upgrade costs are expressed in constant dollar values on a per vehicle basis, and are entered as user inputs so they are easy to change for sensitivity analyses. However, the station costs for all AFVs are finally expressed in the lifecycle cost as a one-time per vehicle basis cost.

Hydrogen Hydride Station Cost Estimate

As outlined above, hydrogen for hydride tanks must be purified and compressed to 800 psi. DeLuchi (1989) estimates the extra cost of hydrogen hydride fueling stations at $2.73 (1990$) per million Btu (MMBtu ~ 1 GJ) of fuel delivered. The model uses $3 (1994$). The model is based on the cost of a CNG station ($220,000-$300,000) capable of compressing gas to 3000 psi, but that only has to compress the gas to 800 psi. The assumed capital cost of the hydride station is then $85,000. The hydrogen hydride fuel has to be compressed and purified at the station, which adds $.85 per MMBtu.. The cost turns out to be about $200 per 12-year vehicle lifetime, depending on the vehicle assumptions, and is reported in the model as lifecycle vehicle cost. The details concerning hydrogen delivery are described above in the fuel handling section.

LH2, LNG Station Cost Estimate

The LH2 stations should function similarly to LNG stations, compressing and cooling the gas in stages using electric liquefaction compressors. This process, combined with refueling the vehicle, is assumed to proceed at 75%-90% efficient containment of the liquid, which tends to boil off when it comes into contact with a warm vehicle fuel tank (the base case assumes 90%). DeLuchi (1989) presents the results of 10 linear liquefaction cost models. A representative model sets the cost of hydrogen liquefaction equal to the price of electricity times the electrical energy per unit energy of hydrogen, plus fixed costs. The paper presents a version for a large plant (size not indicated) in which the efficiency of using the electricity in liquefying the hydrogen ranges from 0.26-0.33 units of electrical energy per unit of hydrogen energy. The other costs, which include station capital and variable costs, expressed in a per unit energy term, range from $2-$4 per MMBtu of hydrogen liquid. These are the same values used by Union Carbide.

The hydrogen liquefaction process exhibits very strong returns to scale. Future technologies, like magnetic liquefaction, could reduce electricity consumption to 0.25 kWh elect/kWh hydrogen. This thesis uses a midpoint efficiency of 0.3, and a station cost ("other" cost) of $3.30/MMBtu. This is $700 for the 12-year lifecycle.

LNG Station Cost Estimate

The thesis uses a modified version of the LH2 model for the LNG station costs, correcting the per unit energy values for the higher energy content per unit volume of natural gas. The energy consumption factor in the hydrogen model is multiplied by 65% to account for the lower energy requirement for LNG to cool the gas off to only -162C, instead of the -253C required for liquid hydrogen (162/253 ≅ 65%). The station costs should be lower because of less need for powerful compressors. This constant term is set in the model at $1.66 so the processing cost would fall in the middle of the range of total LNG processing costs cited by the DOE of $2.20-2.70/GJ of LNG. (U.S. DOE 1996, 1990 dollars).

CH2, CNG Station Cost Estimate

Stations to compress hydrogen to 6000 psi or natural gas to 3000 psi cost about $220,000 to $300,000 (DeLuchi and Sperling 1989). The CNG model in this thesis assumes that electricity will be used to compress the gases. It multiplies the energy of electricity consumed per unit energy of compressed gas by the cost per unit energy of electricity, then adds a station infrastructure cost per GJ such that this cost equals 65% of the total compression cost (rule of thumb in Sperling, 1989,1989 dollars). This cost is adjusted to $1.44 in 1996 dollars, and can be thought of as the station cost per unit energy of fuel. This cost is about $420 per station per vehicle in the model.

The CH2 station costs are calculated the same way: variable energy costs of the electricity used to run the compressors makes up 35% of the total compression cost, and the other 65% is the cost of the station infrastructure. Station infrastructure costs $2.00 per GJ of CH2 delivered to the vehicle. This station cost is also $420 per station per vehicle in the model.

LPG, Alcohol Station Upgrade Estimates

These fuels require only an upgrade of current gasoline stations, but would not require whole new installations. The cost values used in the analyses for stations delivering these fuels were taken from the DOE assumptions for assessing the costs and benefits of the alternative fuel vehicle fleet policies approved in the late 1980s and early1990s (U.S. DOE 1992). There was no justification for the costs in the report, but they are 10 times less (on a per vehicle or per unit energy basis) than the station costs used for the exotic fuels, LH2, CH2, LNG, CNG, and hydrogen hydride. This makes sense, since the assumed capital cost of the exotic fuel stations was $200,000-$300,000 (Sperling and DeLuchi 1989), an order of magnitude higher than the cost to upgrade a gasoline station for methanol or ethanol has been estimated at roughly $40,000-$45,000 (NRC 1990, Webb, et al 1990), and LPG at $65,000 (AutoLPG Trade Association 1997).)

LPG installations require a storage tank, usually inexpensively added-on above ground, if the space is available, and an uncomplicated pump capable of delivering the LPG to the vehicle at 200 psi. For comparison, car tires usually have 25-30 psi, bicycle tires 50-60, and high-performance bicycle tires 120-170 psi. This pressure is attainable easily and inexpensively, thus the low per vehicle station cost of $58. The per vehicle station cost is $68 in the model for alcohol stations.

Methanol and ethanol stations require replacement of tank liners which may be susceptible to corrosion, and certain rubber parts in hoses and pumps which deteriorate in alcohol. The cost cited above includes upgraded fiberglass underground storage tanks.

Battery Charging Station

The per vehicle costs are higher because of the low number of vehicles that can be serviced by the low energy flow (power) of battery chargers. The model inputs $400/vehicle (Sperling 1995) for a home charger, including an upgrade to 220 volts. Public chargers are covered in detail in Chapter 4.

5.3.4 Vehicle Emissions Model

The tailpipe emissions modeled from the vehicles include the criteria air pollutants in the CAAA90: SO2, NOx, CO, non-methane hydrocarbons (NMHC), and PM, plus methane (CH4) and carbon dioxide (CO2). The tailpipe emissions are recorded in a table for each of the 17 vehicle/fuel combinations on a grams per mile basis. The model assumes that these pollutants represent the lifetime average emissions per mile of the vehicle. Some vehicle emissions increase dramatically as the vehicle's mileage adds up, and some decrease. These changes vary across vehicle fuel, engine, and exhaust catalyst types. The average value assumption is a second best alternative to a mileage-based input structure in the model.

Tailpipe Emissions

Tailpipe emissions cause the most uncertainty in the model. They can be easily changed by entering the desired grams per mile emissions rate for each pollutant in the appropriate vehicle table. Where possible, actual vehicle test results were used for the tailpipe emissions model. Where this data was not available or was incomplete, estimates based either on similar fuels or similar vehicle technology were used as substitutes. Often the data presented in the model as coming from one vehicle type did not come from one single study, let alone one vehicle. Sometimes published data was for a vehicle much larger than the compact-sized vehicles in the model. When it was necessary to use these values, the thesis used a technique to scale reported emissions from one test by the energy efficiency of the test vehicle relative to the vehicle in the thesis model, as indicated by the CO2 emissions, for use in the hypothetical model vehicle.

Besides inconsistent reporting of a standard array of emissions, there is a lot of variation in vehicle tailpipe emissions measurement, as emissions depend strongly on many factors. Major influences include the environmental conditions under which the tests take place, the history of the vehicle and its catalytic treatment system, the test driving cycle, the engine adjustments, and the efficiency of the vehicle. Many different emissions control technologies are available for different prices, and test results do not always clearly state the type of control devices used in the tests. In addition, identical vehicles are simply not available to test with different powerplants and fuels. In making comparisons using emissions test results, one is necessarily comparing different vehicle platforms in addition to different fuel/powertrain systems. Of course, no vehicle will perform on the road as it does in the laboratory, but one would hope at least to be able to compare similar vehicles to each other under similar laboratory conditions.

Emissions Values used in the Model

The NOx, CO, NMHC, and CH4 data for all but diesel, methanol, LNG, and hydrogen vehicles are from Gabele (1995). The test vehicles were the rather large Ford Taurus and Chevrolet Lumina for RFG; Chevrolet Lumina Variable Fuel Vehicle (VFV), Spirit VFV, and Taurus VFV for M85 and E85; Dodge B van and Chevrolet Sierra pickup truck for CNG; and a Chevrolet Sierra pickup truck for LPG. The test was the standard cold start FTP (Federal Test Procedure).

NOx, CO, and NMHC data for methanol vehicles was from Alson, et al (1989) in an unspecified vehicle over the EPA's FTP. The CH4 emissions for methanol come from a Ford research report (1988), cited for both M100 and M85 in CleanFleet (NREL 1995).

The emissions for diesel, except for CO2, come from DOE (1996) for federal requirements for heavy duty diesel truck emissions.

CH4 measurements for CNG and LNG come from the DOE (U.S.DOE 1991), and CH4 for gasoline (van, scaled by CO2 emissions) are from the DOE CleanFleet report (NREL 1995).

The CO2 emissions are from the CO2 content of each fuel as reported in the ADL/Ford model itself, converted from the g/GJ "CO2 content of fuel" into a g/mile measure. The amount of CO2 potentially emitted by each vehicle in the case of complete combustion is adjusted for the amount of uncombusted fuel which is emitted as CO. This is achieved by multiplying the grams/mile of CO emitted by the relative molecular weights of CO2 to CO (=44/28) and subtracting this from the CO2 contained in the fuel.

Efficiency

The user enters the gasoline fuel vehicle range in miles, and efficiency as a percent of the total energy contained in the gasoline which results in the motion of the vehicle, rather than in lost heat. This number is usually below 20%. The computer automatically converts this number in to a more familiar mile per gallon measure, which the user sees immediately, so that he or she can adjust the percent efficiency for the desired miles per gallon target. The model could have been programmed the opposite way. This would be a simple and recommended change for the future. The miles per gallon measure is calculated using assumptions that the vehicles travel the entire range (fuel tank full of fuel) at an average speed of 25 miles per hour, using an average of 4.5 kW of power over the distance to overcome aerodynamic drag and rolling resistance. This is an accurate assumption for the power requirement of a vehicle cruising at 25 miles per hour (Muntwyler 1996). However, the two entries for minimum power required and average cycle speed are highlighted in the vehicle model so that the user can find and change them as desired. The model does not account for efficiency losses in manufacturing vehicle components.

Within the vehicle model, the efficiency of each AFV from the refueling to vehicle motion is related to the efficiency of the CGV as entered by the user, except for fuel cells and battery electric vehicles. The model assumes optimized performance for all fuels, neglecting efficiency losses which are common in converted or flex-fuel vehicles whose mechanical engine parts have not been optimized to perform on the alternative fuel. The details of fuel characteristics in vehicles is described in Chapter 4. Table 5.8 shows the efficiency assumptions used in the model.

Table 5.8: Formulas for Vehicle Energy Efficiency Assumptions Used in the Modified ADL/Ford Model

Fuel/Vehicle Group	AFV System	Vehicle Efficiency, ε, in Percent	Efficiency Relative to CGV (if ε =15%)
Petroleum	Gasoline	ε	1.00
	RFG	ε	1.00
	Diesel	ε	1.00
	LPG	$1.1 \times \varepsilon$	1.10
Alcohol Fuels	Methanol ICE	$1.15 \times \varepsilon$	1.15
	M85	ε	1.00
	Ethanol	$1.4 \times \varepsilon$	1.40
	E85	ε	1.00
Natural Gas	CNG	$1.1 \times \varepsilon$	1.10
	LNG	$1.1 \times \varepsilon$	1.10
Hydrogen	Hydrogen Hydride	$1.5 \times \varepsilon - 0.8 \times$ (% weight increase)	1.29
	Hydrogen CH2	$1.5 \times \varepsilon$	1.50
	Hydrogen LH2	$1.5 \times \varepsilon$	1.50
Electricity	Battery Electric	$70 - 0.8 \times$ (% weight increase)	3.56
	Hybrid Electric	$3.0 \times \varepsilon \times$ BEV efficiency	1.60
Fuel Cell	Methanol Fuel Cell	0.35	2.33
	Compressed Hydrogen Fuel Cell	0.4	2.67

Battery electrics and hydrogen hydride vehicles are very heavy, and suffer a 0.8% loss in efficiency per 1% increase in weight over the weight of an ICEV (DeLuchi 1989). Battery electrics begin at 70% motor-to-wheels efficiency, times 80% round-trip efficiency of battery energy storage (90% charging efficiency times 90% discharging efficiency), and then subtract efficiency for a 4% weight increase in the base case. This percent weight increase is entered by the person running the program, and is not calculated in the program due to the complexity of sizing the battery relative to the rest of the vehicle. The user must take care to check this number before reporting the results of the model, because smaller BEVs or lighter batteries will have a smaller weight increment above CGVs, which will affect lifecycle cost and emissions via this weight increase factor.

The model assumes that hydrogen can provide a 50% gain in efficient combustion of the fuel's energy over gasoline vehicles. However hydrides lose .8% of this efficiency gain times 4 (for a 4% weight gain, adjustable by the user), = -3.2%.

The series hybrid vehicle modeled here drives a generator and an electric motor with an RFG fueled ICE, charging a battery with the excess energy. The ICE/generator is assumed to run at 3 times the efficiency of the conventional RFG engine/transmission combination, however all of this energy is transmitted to the wheels via the electrical system of the hybrid, which has the same efficiency as a BEV.

Performance

The model does not attempt to compare realistic performance measures besides range and efficiency. Most likely, all vehicle would differ in consumer attractiveness for other reasons. But excluding such measures (like payload or handling) should not affect the cost, emissions, or efficiency outcomes.

5.3.5 Range

For simplicity in the model, all ICEVs are assumed to have the range of the CGV entered by the user. This is unrealistic for ranges over about 200 miles for compressed gas fuel systems in smaller vehicles. They would suffer from lost cargo space if they were engineered to have ranges longer than this. Entering longer ranges does not affect the outcome of the emissions, cost, or efficiency of these vehicles, but there are two unused columns of output which display the volume and mass of the fuel storage system, including the tanks, which will exaggerate the real displacement and weight of fuels in a vehicle if the range is unrealistically long.

Cryogenic liquids have smaller volumes than compressed gases, but the insulated tanks are bulky. These vehicles would also most likely have shorter ranges and smaller storage spaces than CGVs. Again, the assumption of range does not affect the outcome of emissions, energy efficiency, or cost.

The BEVs have a reduced range that is calculated as a user-entered fraction of the CGV range. The base case uses 1/6th. The lifecycle emissions and cost are very sensitive to the range of the BEV. The user must ensure that a proper weight handicap (% weight increase) is included in the efficiency of the BEV to correspond to the size of the battery.

5.4 Combining Fuel Chain and Vehicle Emissions into Lifecycle Values

There are several special emissions representations to note. Vehicle NMHCs are corrected for their reactivity in the atmosphere, and therefore their potential to form ozone. The NMHC emissions are added to NOx emissions to present an indicator of the amount of ozone that may form as a result of vehicle emissions. Likewise, CO2 and weighted CH4 emissions are added together to represent total greenhouse emissions.

5.4.1 Ozone Precursor Emissions

The NMHC emissions from the vehicle are adjusted for their ozone-forming reactivity before being added to the fuel chain NMHC emissions by multiplying by the characteristic reactivity adjustment factor for emissions from the particular vehicle type (RAF). The RAF is an index of the likelihood of a vehicle's emissions to form ozone, relative to that likelihood in the emissions from a CGV (Wang 1993). All of the non-petroleum fuels have substantially less ozone-reactive exhaust NMHCs than gasoline vehicles, and their RAFs are less than one. The RAF values used in the model are the same as those used by CARB, and are taken from an Argonne National Laboratory report

(Wang, 1993). The values are roughly equal to EPA results reported in an earlier DOE report (DOE7, 1991). See Appendix 14 for the RAFs used in the model.

Another special lifecycle emission is the "total ozone precursor emissions," which is simply the sum of NMHC and NOx emissions from the vehicle lifecycle. These two chemicals are the primary EPA criteria ozone pollutants (actually, NO_2 is controlled), so representing their total gives a reference for the likelihood of the AFV's contribution to ozone pollution under the assumptions of the CAAA. The combined number has little physical significance, but is useful in policy analysis for quickly separating AFVs which offer significant reductions in total emissions from those offering minor reductions.

5.4.2 Total Greenhouse Emissions

Similarly, the "total greenhouse gas emissions" are reported as the sum of the lifecycle CO_2 emissions and the CO_2-equivalent of methane (CH_4) emissions. Methane absorbs light and radiates the energy as heat, like CO_2, and has a higher capacity for heating the surrounding air. But it is removed from the atmosphere more quickly than CO_2, so it will contribute to the heat content in the atmosphere for a shorter time than CO_2 that is released with it. DeLuchi (1991) reports a table of corrections for adjusting CH_4 emissions to equivalent CO_2 emissions, and justifies a mass-based conversion factor of 9grams CO_2 equivalent per gram of CH_4 emitted to represent a 500 year lifetime of the methane. This thesis uses this value to express the total greenhouse emissions in g/mile as: CO_2 (g/mile) + 9 x CH_4 (g/mile).

The emissions/mile equivalent results must not be taken to mean that this much pollutant is emitted per mile of vehicle operation. The resulting total lifecycle pollutants are merely expressed in g/mile to be added to the emissions from the vehicle model. The total fuel chain emission over the lifecycle are more relevant to consider. It is also important to separate the potential effects of stationary and mobile source emissions, based on their location and the environments they could affect.

The model does not account for any emissions as a result of vehicle component manufacture or delivery.

6. Results for the Base Case

This chapter presents the modified ADL/Ford model's calculations of the 12-year lifecycle cost, air emissions, and energy efficiency of 17 fuel and vehicle combinations in the base case set of technologies and world resource prices. The comparison is based on the tradeoffs between the alternatives' cost, and the emissions or energy efficiency improvement they can offer over current vehicles. They do not consider the consumer appeal of the AFV. Another chapter compares the alternatives again under three scenarios of future world resource prices and different scenarios of technology development to show the model's flexibility, and to see how the attractiveness of alternatives could change under different conditions.

Section two of this chapter describes the base case price and technology inputs. Section three describes the tradeoff methodology with which the alternatives are compared in the thesis, and presents lifecycle results for all 17 alternatives under the base case assumptions. The final section summarizes the strongest alternatives for the lowest cost combined with low emissions, and highest energy efficiency.

The modified ADL/Ford model results show that all AFV types except LPG are more expensive to own and operate than conventional petroleum vehicles. Further, some alternative fuel vehicles offer few emissions or fuel resource advantages over petroleum vehicles when analyzed over the lifecycle. In some cases the options that offer the most significant gains do so only at a very high cost, though with a high uncertainty because either the fuels or the vehicles are technically immature. Moderate to high emissions improvements can sometimes be made at moderate cost increases with more certainty by using proven technologies. Chapter 7 discusses the uncertainty of these results with respect to model behavior and inputs.

6.1 The Base Case Scenario

6.1.1 World Resource Prices in the Base Case

Each of the world scenarios in this thesis use price forecasts from the U.S. DOE Energy Information Administration's (EIA) Annual Energy Outlook (1994). The base case uses current world prices for fossil resources and electricity. The model has a worksheet titled, "Price of Fuel Inputs," in which the user may easily change the prices of any fossil resource, or the price of electricity.

Table 6.1 is a sample of the input table from the modified ADL/Ford model showing the base case inputs.

Table 6.1: Input table from the Modified ADL/Ford Model Showing the Estimated Resource Prices for the Base Case Scenario (1996 $)

Fuel or Resource	Base Case Cost	Units
Crude Oil	$21.00	$/bbl
Diesel	$0.65	$/gal
Gasoline	$0.62	$/gal
Electricity	$0.07	$/kWh
Natural Gas	$1,720.00	$/MMSCF
Corn	$108.00	$/MT
Coal	$22.18	$/short ton
Maize Byproducts H	($200.00)	$/MT
Maize Byproducts L	($83.00)	$/MT
Wood	$50.00	$/MT
MTBE	$0.85	$/gal
Resource X	$1.00	$/unit

The crude, electricity, coal, and gas prices are from U.S. DOE (1992). The base case gas price is similar to the wellhead gas prices in time series data presented in the Methanex Annual Report (Methanex 1995). The current crude price to refiners cited in Oil and Gas Journal Databook (PennWell 1996) is $14/bbl. The DOE values were used however in order to have a consistent reporting year for all resources. Corn, animal feed byproducts, and wood costs are from IEA/OECD (1994). The MTBE price is from Hadder (1992), as described in Chapter 5. According to the EIA, there is currently an oversupply of natural gas production in the world, which is reflected in a low natural gas price relative to crude oil and coal. The diesel and gasoline costs in the table were calculated by the model, and represent the lowest possible cost to a consumer of those fuels.

6.1.2 Technology Assumptions in the Base Case

The base case scenario simulates current fuel production technology in the United States, and the vehicles currently available or likely to emerge in the short term. The costs of the inputs, fuel resource prices, fuel processing and transport costs, and vehicle acquisition (purchase price) and operations cost, correspond to the available technologies.

As described in Chapter 5, the penetration of emissions controls on industry is a user controlled input. The base case uses 50% penetration of emissions controls on all industries. Appendix 15 shows the model's input table for emissions controls in the base case and in the future scenarios that are presented in Chapters 6 and 8.

The base case gasoline vehicle costs $15,000 and is 15% efficient at turning the potential energy in its fuel into kinetic energy of the vehicle. The costs for other vehicles are entered as "high" and "low" cost differences relative to this value. The values used for the base case are presented in Appendix 15.

6.2 Base Case Cost, Emissions, and Efficiency Results

This section presents a summary of the lifecycle results for all the AFVs in the model's base case. Refer to Appendix 16 for detailed results.

6.2.1 Base Case Cost Results

Figure 6.1 ranks the lifecycle costs of the 17 vehicles for the base case scenario. These costs are based on the average of the high and low vehicle costs entered by the user. The variable costs are discounted into the future at a rate of 10%, so future expenditures like fuel contribute less to the total than current expenditures, like vehicle purchases. The fuel cell vehicles have extremely high lifecycle costs ($95,000) because of their experimental status. The high costs of both types of electric vehicles come from replacement battery purchases. Hybrid electric vehicles, fuel cell vehicles, hydrogen hydride, and other vehicles using compressed gas or cryogenic liquid fuels have high vehicle costs to begin with. Hydrogen fuel adds substantial cost to the lifecycle cost of these vehicles.

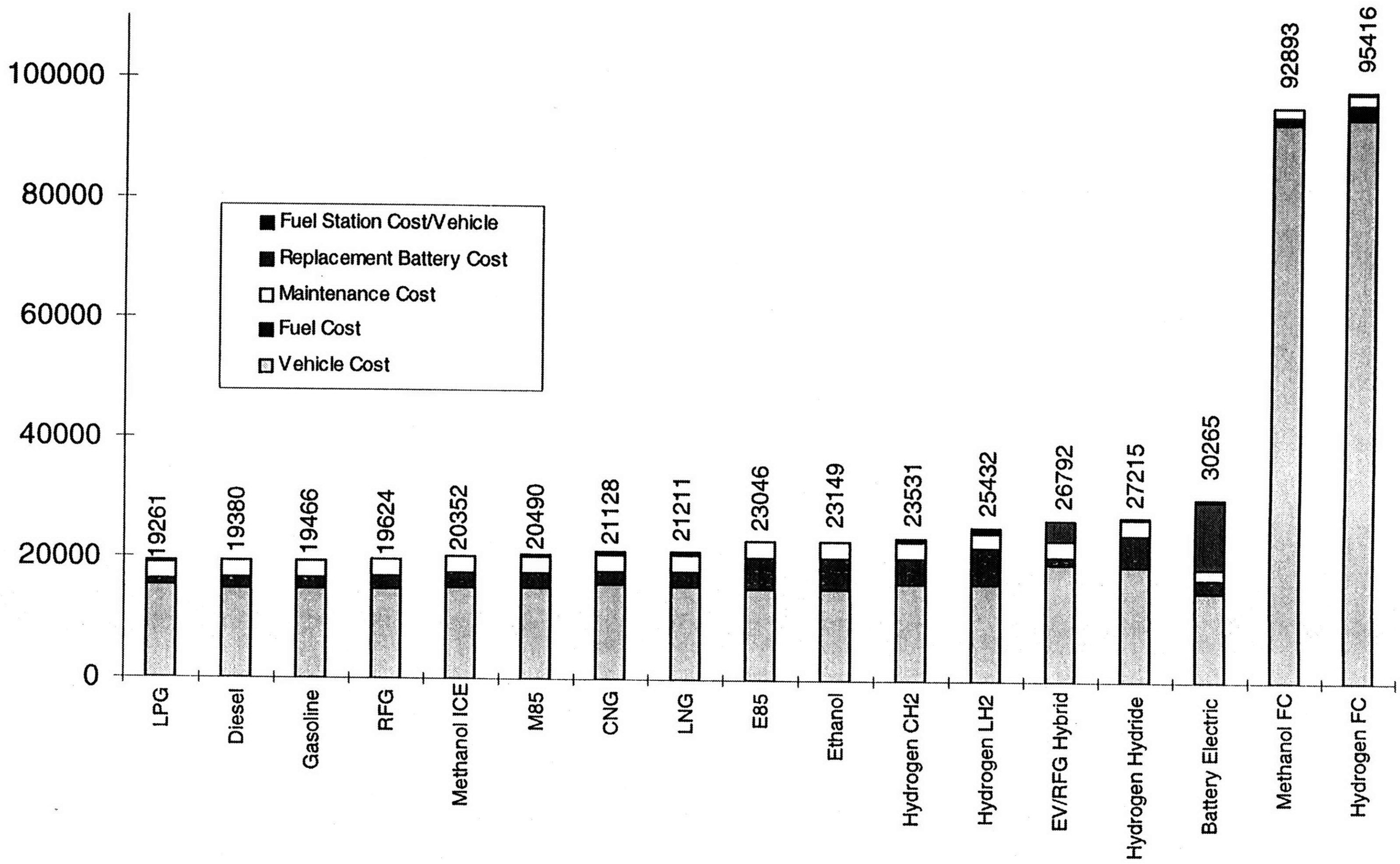

Figure 6.1: 12 year lifecycle cost ranking of the 17 vehicles in the Base Case. Base gasoline ICE costs $15,000. Costs include vehicle purchase and future discounted fuel, maintenance, per vehicle fuel station, and replacement battery costs. There are no taxes included in the costs in this research.

The costs in Figure 6.1 can be divided into four groups: low, medium, high, and very high, for presentation and analysis purposes. Choosing the most suitable alternatives will depend on performance as well as cost, but associating performance with a label that corresponds to alternatives with similar cost can help quickly identify which alternatives might be commercially (and politically) successful.

The summary of this chapter presents lifecycle results in tables which are organized by these cost groups so that best and worst alternatives can be compared alongside each other. The sensitivity analysis in Chapter 7 discusses under which assumptions the costs of particular vehicles may change categories, in other words, have a lifecycle cost which is indistinguishable from the vehicles in another group due to the uncertainty in the model. The low lifecycle cost vehicles are the liquid petroleum vehicles, including LPG. Their costs vary less than $150-$160. Medium cost vehicles include methanol and natural gas combustion vehicles, which are $850-$1700 more. High cost vehicles include ethanol and hydrogen internal combustion, battery electric, and hybrid electric vehicles, at $3500-$11,000 difference in cost. The only very high cost vehicles are the fuel cell vehicles.

The differences in cost should be taken as significant in the context of the model, which assumes that real-life uncontrolled variables, like vehicle operating conditions, do not vary across alternatives, and that therefore there is no unexplained uncertainty across different AFVs. In the real world, of course, $1000 is only 5% of a $20,000 lifecycle cost, and might be considered "noise" in a cost analysis. This means that, even though the average lifecycle costs of two vehicles may vary by $1000, there will be circumstances in real life in which their lifecycle costs will not be distinguishable. The next chapter treats the uncertainty of the model results.

6.2.2 Comparing Alternatives: Plots of the Emissions and Efficiency Tradeoffs

Emissions and efficiency results are reported in conjunction with the vehicle costs in tradeoff curves. This is a practical means of presentation, since a policy consideration of these technologies requires that the costs of each alternative be traded off with the emissions or efficiency improvement it offers. One way to compare the different alternatives is to plot the lifecycle cost of the AFV versus the each of the pollution or efficiency attributes on a graph, as in Figure 6.2.

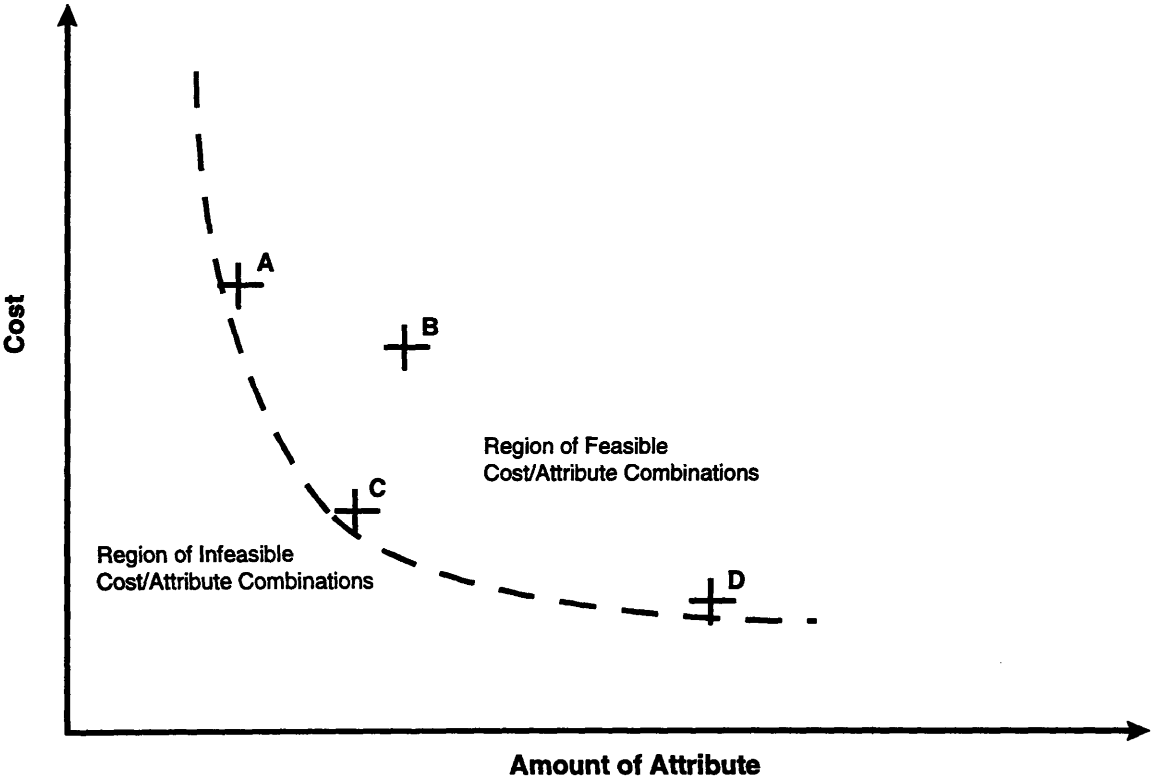

Figure 6.2: Optimal cost/attribute tradeoff curve for an attribute whose cost increases as its amount is reduced.

The attribute in Figure 6.2 costs more in small amounts, and less in larger amounts. For example, the plot might represent the higher costs encountered in lowering the fuel consumption of a vehicle. Points A, C, and D represent the most economical (least cost) alternatives for the amount of the attribute that they provide. Alternative B provides a relatively low amount of the attribute, but at a cost that is higher than what could be achieved with other alternatives, namely alternative C.

On each cost/attribute plot, the points representing combinations of cost and the amount of the attribute will lie above a certain boundary which traces the lowest available cost for a given amount of the attribute. This boundary is known as a “feasibility frontier.” The closer an alternative within this boundary is to the frontier, the more economically efficient the alternative is. This economic efficiency should not be confused with the actual energy efficiency of a fuel chain and vehicle lifecycle. By definition, there are no alternatives below this boundary (they are unknown in current technology).

This thesis estimates the feasibility frontier for each vehicle attribute from the model results of the lowest cost alternatives for the best emissions and efficiency results. There is some uncertainty in determining both what is feasible, and what is optimal (i.e. on the frontier). The uncertainty is discussed in Chapter 7.

All alternatives which lie on the frontier are economically efficient. No alternative can provide a better mixture of cost and performance, so choosing between them becomes a question of the relative values that decisionmakers place on each attribute they trade off. As in Figure 6.2, the attribute-sets which lie within the frontier are less desirable alternatives than those at the edge because they cost more, but offer less emissions or energy efficiency benefit.

Note that the energy efficiency curve will show increasing costs with increasing energy efficiency, turning the plot around from left-to-right.

Similar plots can be used compare the tradeoff of one emission against another, or of emissions versus energy efficiency, to identify the technical tradeoffs associated with the cost tradeoffs.

The cost/attribute curves for all 17 alternatives in the base case (Figure 6.3 through Figure 6.8) present the cost tradeoffs of alternatives relative to:

- the total lifecycle greenhouse emissions (Figure 6.3)
- the total lifecycle ozone precursor emissions (Figure 6.4)
- the total lifecycle particulate emissions (Figure 6.6)

- the total lifecycle carbon monoxide emissions (Figure 6.7)
- the lifecycle system energy efficiency (Figure 6.8).

Similar fuels or powertrain technologies are grouped together in the plots for quick identification and comparison. The boundaries of the groupings qualitatively represent uncertainty in the model output. Fuel cell and hydrogen vehicles are plotted on these charts to provide an indication of future technological goals, but they are presently only experimental vehicles. Their prospects are investigated further under the future scenarios.

Tables of lifecycle costs, emissions, and energy efficiency for the scenario is reported in Appendix 16.

6.2.3 Lifecycle Greenhouse Emissions Comparison

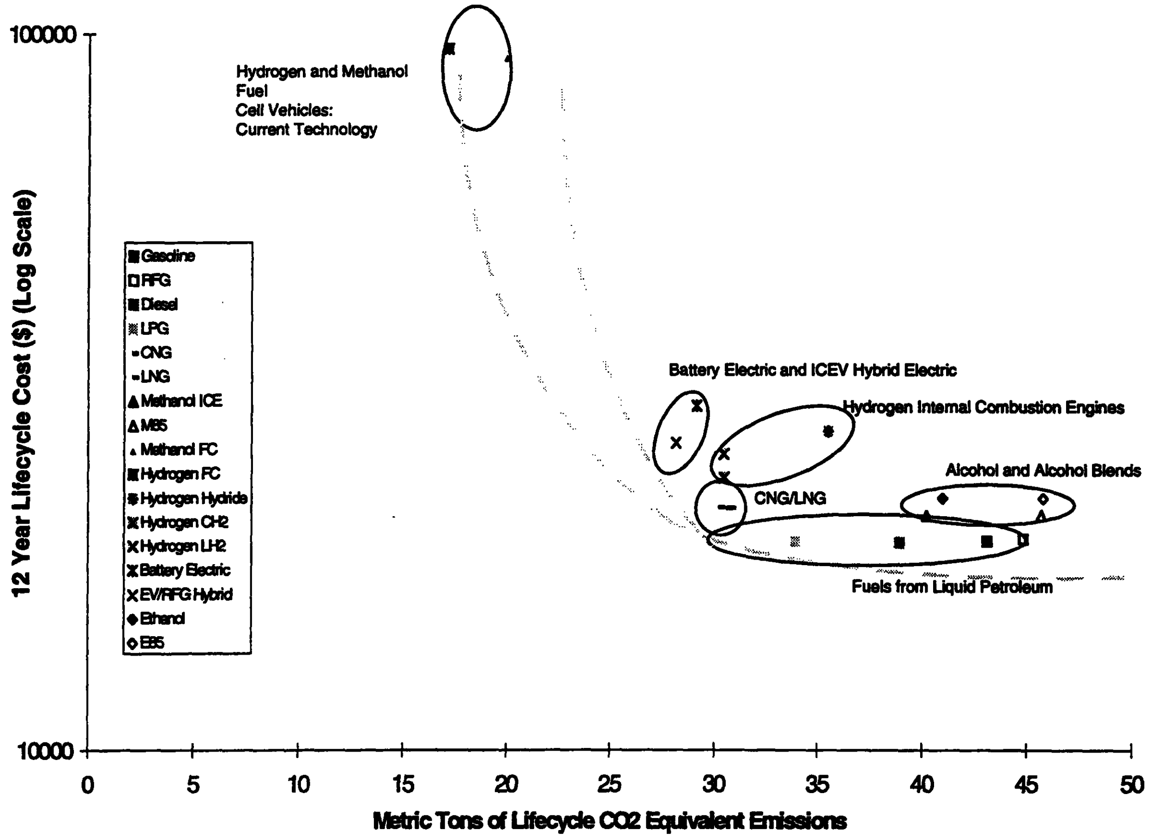

Figure 6.3: Lifecycle cost vs. total greenhouse emissions in the base case. The lower feasibility frontier represents what might be realizable if fuel cell vehicles become market realities at current costs.

Figure 6.3, plotting cost versus total greenhouse (carbon dioxide and methane) emissions (as described in Chapter 5), represents the global impact of using each fuel in a vehicle. Whether the emissions come from the fuel chain or the vehicle does not make a difference in the environmental effect of these pollutants. Lifecycle emissions range from 20 metric tons to 45 metric tons. Two extrapolations of the feasibility frontier show a potential in fuel cells for lowering the cost threshold of emissions improvements from the present frontier.

Recalling the section 6.2.1 cost results (Figure 6.1), conventional petroleum and LPG are the least expensive alternatives, though LPG has 20% lower greenhouse emissions.

The alcohol fuels, both pure and in 85% mixtures with gasoline, are slightly more costly alternatives, but do not reduce total greenhouse emissions over conventional petroleum fuels.

Compressed and liquid natural gas (methane) systems have similar costs to each other, and reduce greenhouse emissions 25% over petroleum systems, despite their high fuel chain emissions of methane.

Compressed and liquid hydrogen fueled vehicles offer the same low greenhouse emissions of natural gas vehicles, but at a higher cost. The carbon from the fossil resource is not emitted from the vehicle, but in the fuel chain, for the same contribution to the greenhouse gas buildup that natural gas vehicles contribute.

Electric and hybrid electric vehicles can lower greenhouse emissions about 30% from conventional gasoline vehicles, but cost about 30% more. Both kinds of electric vehicle reduce greenhouse emissions due to their superior efficiency.

Fuel cell vehicles using methanol or hydrogen show potential greenhouse gas reductions of about 50% from CGVs.

The currently economically efficient alternatives for greenhouse emissions are liquid petroleum fuels, natural gas, and ICEV/EV hybrids powered by RFG. Fuel cell vehicles using methanol or hydrogen could lie on the feasibility frontier, as well.

6.2.4 Ozone Precursor Emissions

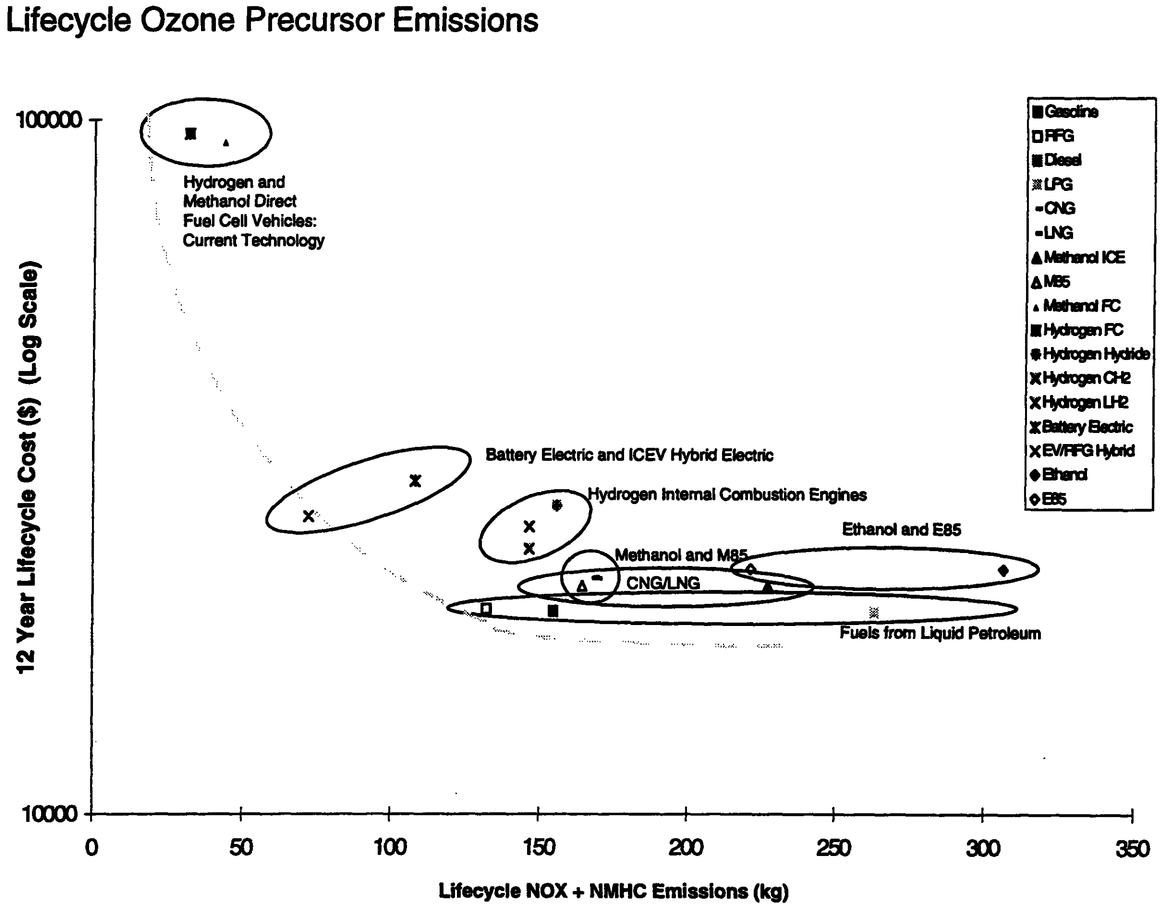

Figure 6.4: Lifecycle total ozone precursor emissions (NOx and hydrocarbon emissions) for the base case.

Ozone precursor emissions from the vehicle and fuel chain are presented together in Figure 6.4 to represent their mutual contribution to the formation of ground-level ozone (see Chapter 2). The lifecycle emissions range from 50 grams to 300 grams for most vehicles.

The diesel fuel chain does not appear on the chart because the high NOx emissions cause the data point to be plotted to the right, off the scale at 700 kg. RFG is the least expensive, low ozone precursor alternative, and its performance is unmatched except for the vehicles with electric powertrains.

Alcohol fuels differ from each other by the emissions from the ethanol fuel chain, but both offer equal or higher lifecycle ozone precursor emissions than gasoline.

Methane and hydrogen fuels add cost over the alcohols, but perform the same as methanol for ozone precursor emissions.

Battery and hybrid electric vehicles can lower ozone precursor emissions about 40% from the average of all other conventional drivetrains, due primarily to improved vehicle efficiency, which lowers NOx, and the use of low-methane content fuels (coal for electricity and RFG for the hybrid).

The experimental fuel cell vehicles may offer an 80% reduction in ozone precursors, due to their low running temperature that cuts NOx, and their efficiency.

The economically efficient alternatives are liquid petroleum fuels, ICE/EV hybrids using RFG, and maybe battery electric vehicles. Hydrogen and methanol fuel cell vehicles could lie on the feasibility frontier.

Fuel Chain vs. Tailpipe and Evaporative Ozone Precursor Emissions

Some fuel alternatives may be able to reduce local ozone precursor emissions where their tailpipe emissions can reduce the total ozone precursor emissions. As long as the fuel chain emissions for the vehicle are displaced away from the region in which the vehicle will be used, these alternatives will be effective at reducing local emissions. Figure 6.5 plots the lifetime stationary fuel chain versus mobile vehicle emissions for each AFV type so these alternatives can be identified.

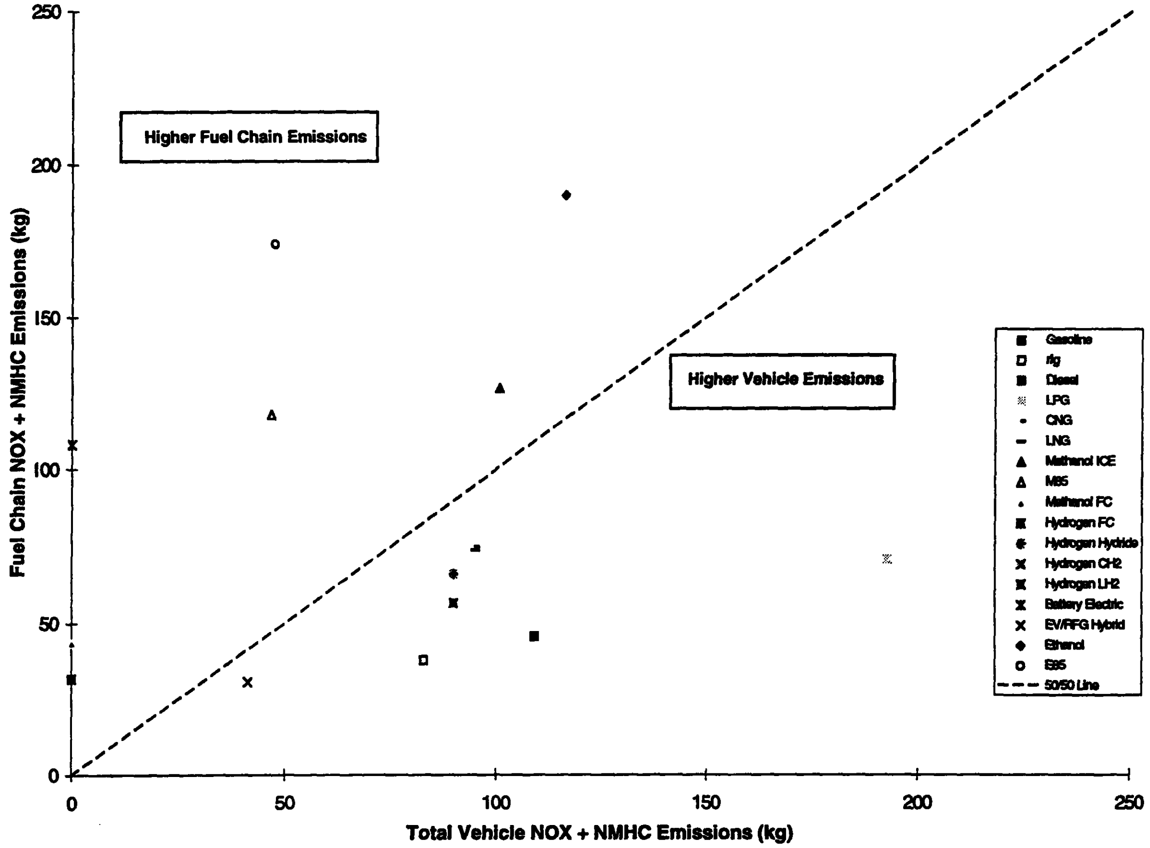

Figure 6.5: Comparison of Fuel Chain and Vehicle (Tailpipe + Evaporative) Ozone Precursor Emissions Components in the Base Case. Points to the left have the lowest vehicle emissions and may be desirable alternatives in ozone polluted cities. Points high on the vertical axis displace ozone precursor emissions toward the fuel chain. Lifecycle emissions are the sum of the horizontal and vertical values plotted here.

The alternatives above the line in Figure 6.5 emit more than half of their pollutants in the fuel chain. Alternatives toward the left have lowest emissions from the vehicle tailpipe and fuel tank. M85, E85, RFG, the RFG hybrid electric, the BEV, and the fuel cell vehicles have the lowest ozone precursor tailpipe emissions. All but RFG and the RFG hybrid emit the majority of their pollution in the fuel chain. M85, E85, BEVs, and FCVs would be most appealing to regions with ozone problems that import these fuels or electricity, but do not produce them.

6.2.5 Particulate Emissions

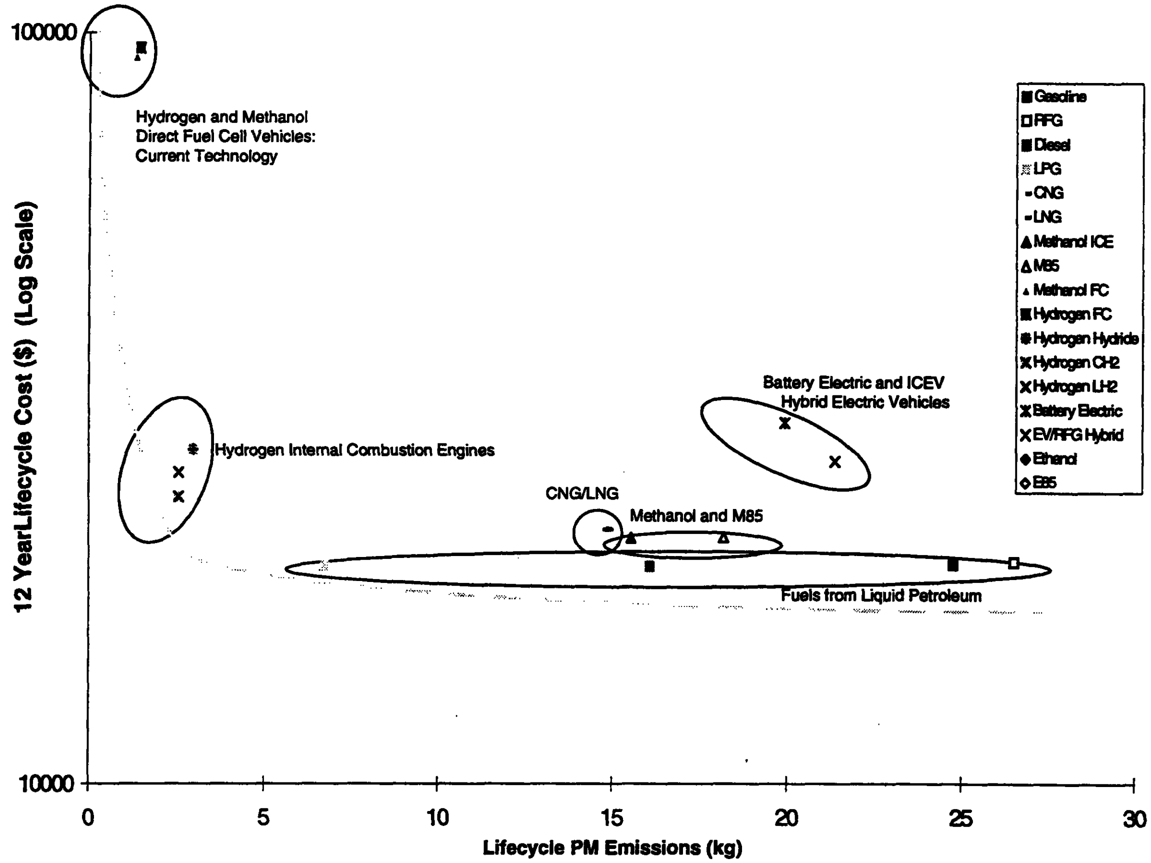

Figure 6.6: Lifecycle cost vs. total particulate emissions for the base case.

Lifecycle PM emissions, shown in Figure 6.6, vary from almost none to almost a kilogram. Except when coal is used in the fuel chain, the PM emissions come primarily from fuel combustion in the engine, rather than from emissions from the fuel chain. Vehicles which do not combust fuel, or which burn fuels that have more energy stored as hydrogen bonds, and less as carbon bonds, have dramatically lower PM emissions from the vehicle. These groups split across the graph from left to right, with LPG in between.

Those vehicles which use coal in their fuel chains will have higher lifecycle PM emissions. These include battery electrics (from electric power) and ethanol vehicles. The high particulate emissions of the ethanol fuel chain result from using uncontrolled diesel engines for the corn harvest, and coal boilers for breaking down starches for fermentation of the corn. Points representing the ethanol particulate emissions fall far to the right of the plot scale, at 270 and 300 kg PM for E85 and E100, respectively. Ethanol vehicles emit the same amount of PM as methanol vehicles. Battery electrics use the U.S. electricity generation mix, which relies on coal for 48% of its energy (ADL/Ford Model). They emit no pollutants as they drive. The particulate emissions control on the coal boilers is assumed to be fairly poor in the base case, and significantly improved in the 2010 cases.

All petroleum fuels have high PM emissions except for LPG, which is very clean because of its high hydrogen content and because of the particular tailpipe emissions used in the model (see Chapter 5). The diesel tailpipe emissions modeled for this thesis use a diesel that is running lean, which causes it to emit high NOx, but low PM.

Methane and methanol PM emissions fall near the average of emissions from petroleum fuels. The methane PM result derives mainly from the tailpipe emissions value, which is higher than many reported natural gas vehicle emissions values. However, this higher value was used because it was measured in the same test in which the other NGV tailpipe emissions were measured (see Chapter 5), and is therefore being used in its proper context with the other emissions levels to represent a true, functioning engine.

Hydrogen PM emissions are very low in the base case, because most hydrogen comes from natural gas. If the source of hydrogen were to change to coal, the PM emissions would rise very quickly (see Chapter 7).

Fuel cell vehicles would lower PM emissions to almost nothing, because they do not combust their fuels. All of the PM emissions for these vehicles result from the fuel chains.

The alternatives on the economically efficient feasibility frontier are liquid petroleum fuels and hydrogen ICEVs. Methanol and hydrogen fuel cell vehicles could lie on the feasibility frontier, as well.

6.2.6 Carbon Monoxide Emissions

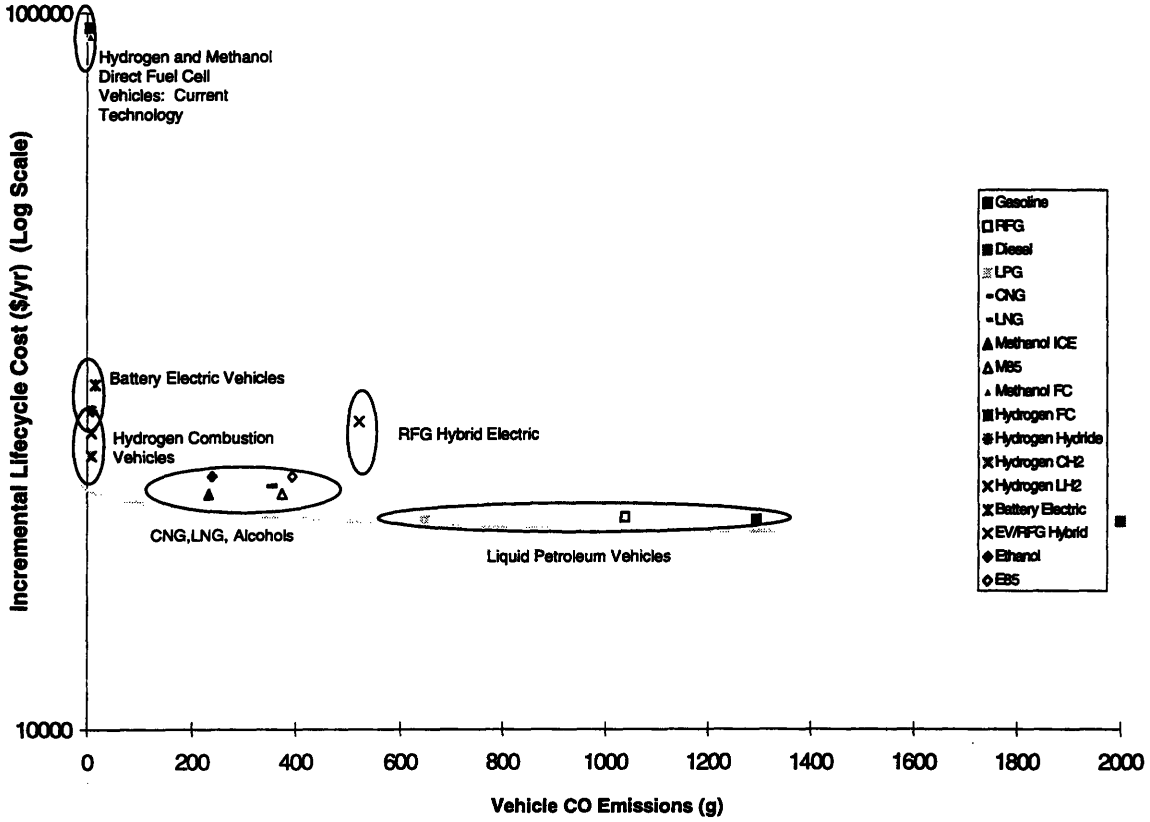

Figure 6.7: Lifecycle cost vs. carbon monoxide emissions from the vehicle.

Carbon monoxide emissions come almost entirely from the vehicle for all vehicle types. Petroleum vehicles emit the highest amounts per mile. Several vehicle types emit no carbon monoxide, but have slight emissions from the fuel chain.

The conventional petroleum fuel vehicles have the highest CO emissions, which are all at least 500% higher than the CO emissions from pure alcohol fuels, and about triple the CO emissions of alcohol/gasoline mixtures. The main emissions strength of fuel alternatives appears to be lowering CO emissions, in fact. M100 gives the lowest CO for its cost on the feasibility frontier. LPG emits 3 times as much CO per mile as M100, but costs $1000 less than M100 over the lifecycle. On the other side of M100 along the feasibility frontier, compressed hydrogen elminates tailpipe CO emissions for a cost increase of $2500 over M100. M85 increases CO emissions over M100 about 100% because of its gasoline component.

All of the vehicles lie on the economic efficiency feasibility frontier for carbon monoxide emissions except the hybrid electric vehicle powered by RFG.

6.2.7 Lifecycle Energy Efficiency

The plot of the lifecycle energy efficiency of each fuel processing chain and vehicle, Figure 6.8, shows the increasing cost of more efficient fuel and vehicle systems. This means that the shape of the plot will be reversed from the preceding plots because on emust pay more to achieve higher efficiency. In this case, alternatives above and to the left of the feasibility frontier are less desirable, and the range of currently impossible alternatives is in the lower right.

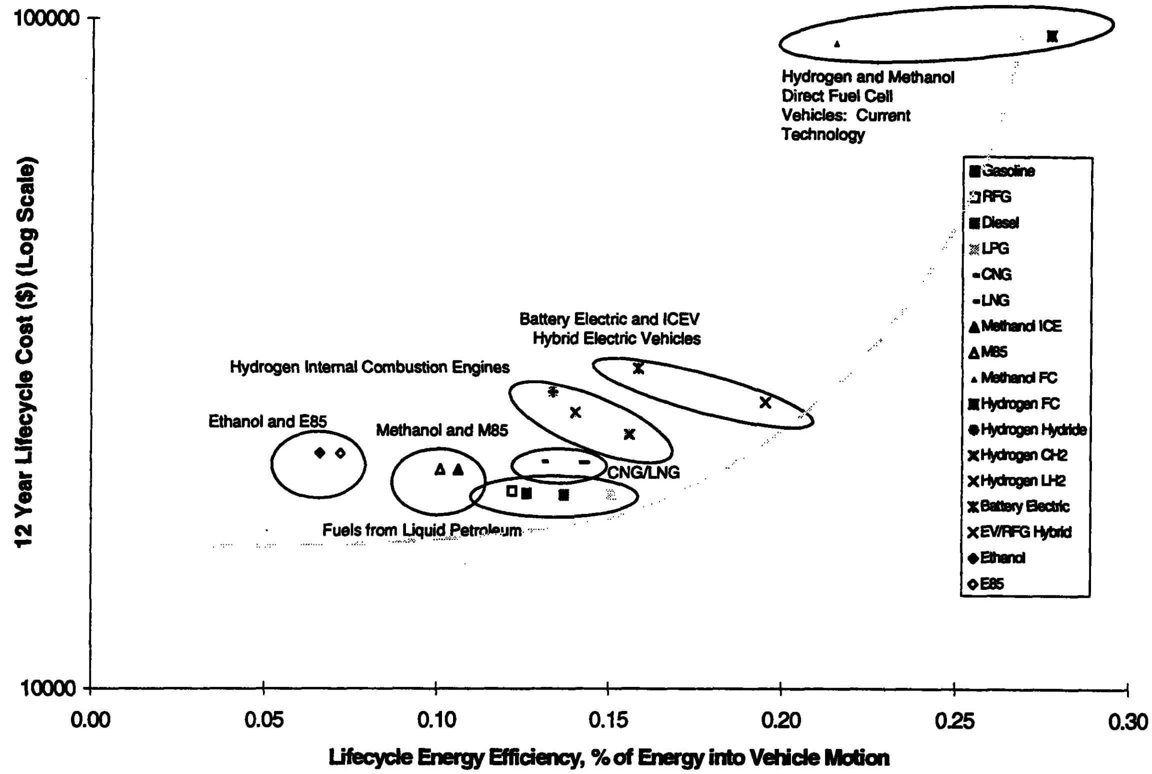

Figure 6.8: Lifecycle cost vs. energy efficiency.

The lifecycle energy efficiency is the ratio of the energy that arrives to turn the wheels of the vehicle to the energy that was originally in the resource, plus the energy required in the fuel chain to transform the resource into fuel.

Lifecycle energy efficiency ranges from a mere 7% for ethanol to nearly 27% for a hydrogen fuel cell vehicle. The most energy efficient alternatives are hydrogen fuels, hybrid electrics, and fuel cell vehicles. The vehicle energy efficiency assumed in the model plays a strong role in determining this final outcome, as described in Chapter 7). Most AFVs can be more efficient than CGVs, but improperly adjusted AFV engines could be less energy efficient than conventional gasoline engines.

The ICE hybrid is more energy efficient than a CGV because the engine runs at its optimum rpm and torque. Torque and rpm are not specified at all in the model, but the engine efficiency that is entered is assumed to occur under these ideal conditions. An ICE hybrid electric could extend petroleum reserves by offering 33% higher fuel efficiency (in this model).

The fuel cell vehicles' lifecycle energy efficiency benefits from the high efficiency of the fuel cell and the electric motor in the vehicle. The hydrogen used in fuel cell vehicles comes from a much more efficient fuel chain than the methanol.

Battery electric vehicle energy efficiency suffers from inefficient electricity transmission and high vehicle weight.

The properly tuned LPG engine is more fuel efficient than a CGV, so its lifecycle energy efficiency is higher despite a similar fuel chain. Unfortunately, despite LPG's high efficiency use of its petroleum resource, its low cost, and its low emissions, the component of petroleum which can be used for LPG is very low, and resources are too limited for LPG's widespread use (see Section 6.2.8).

Conventional petroleum, natural gas fuels, and finally, methanol and then ethanol, are the least energy efficient fuels, in that order. Oil reserves could be more efficiently utilized by electric hybrids. Natural gas vehicles are 50% more efficient at using the natural gas resource than methanol vehicles.

The vehicles on the economic feasibility frontier are liquid petroleum, perhaps methanol fuels, hybrid electric vehicles powered by RFG, and the hydrogen fuel cell vehicle.

6.2.8 Impact of Lifecycle Efficiency on Extending the Fossil Fuel Resource

An AFV and fuel chain with a high lifecycle efficiency indicates that its resource can be used well and that its emissions may be low. But fuel-independence policy is concerned with how the lifecycle efficiency of a particular AFV and fuel chain compares with another in terms of the reserves of a particular resource. A measure of the "usefulness" of a resource in providing vehicle miles, calculated with the lifecycle efficiency and estimates of resource reserves, can help in distinguishing AFV/fuel chains which might conserve crude oil and still provide desired mobility, or vehicle “usefulness”. For example, highly efficient alternative vehicles which have very low alternative fuel resources will not sustain a fuel-independence policy.

By multiplying the lifecycle efficiencies by current estimates of proven fossil fuel resource reserves (see Chapter 4) in North America and the world, Table 6.2 estimates the amount of energy that could be made available as motion by each vehicle type using each resource. This resource “usefulness” statistic is presented in the table as the fraction of the total number of miles that could be driven by each AFV type in exhausting all the reserves of its fuel resource, divided by the total number of miles that could be driven by conventional petroleum vehicles as they exhaust oil reserves. One column presents this calculation for North American reserves, and the other column presents it for the rest of the world. The simple calculation assumes for each combination of vehicles and resources that all of the energy in a resource is used by the vehicle type.

The table does not contain realistic values, since in reality each resource would be used in many other applications than the one vehicle type. But it does provide a thinking aid, a standard for a comparison of the utility that could be expected from each resource in providing transportation, expressed as a fraction of the gasoline system. This standard ballpark-range comparison is helpful for identifyng alternatives that can be used as intensively as current petroleum vehicles.

Table 6.2: Lifecycle Efficiency: Usefulness of resources for each AFV as expressed in total travel miles available to each AFV from each resource, relative to the total travel miles yielded to conventional gasoline vehicles by the petroleum resource

Fuel	Resource	Life-cycle Effic. %	Potential Vehicle Miles Yielded by Resource, Relative to Potential Vehicle Miles Yielded to Gasoline Vehicles by Crude Oil	
			North America	**Rest of World**
Methanol ICE	Coal	10	31	2.7
Hydrogen Hydride		10	31	2.7
Hydrogen CH2		12	36	3.1
Hydrogen LH2		12	36	3.1
Battery Electric		13	39	3.3
Methanol FC		21	63	5.4
Hydrogen FC		22	65	5.6
M85	MIN: Petroleum or methanol	NA	6.7	4.4
Methanol ICE	Natural Gas	11	1.5	1.1
LNG		13	1.8	1.3
Hydrogen Hydride		14	1.9	1.4
CNG		14	2.0	1.5
Hydrogen CH2		16	2.2	1.6
Hydrogen LH2		16	2.2	1.6
Methanol FC		22	3.0	2.2
Hydrogen FC		28	3.9	2.9
LPG	35% Petr./65% NG	15	NA	0.01
RFG	Petroleum	12	1.0	1.0
Gasoline		13	1.0	1.0
Diesel		14	1.1	1.1
EV/RFG Hybrid		20	1.5	1.5
Methanol ICE	Biomass: Max annual supply	1	0.01	NA
Methanol FC		1	0.02	NA
Ethanol		7	0.1	NA

Crude Oil Reserves: API 1997
Coal Reserves: Nat'l Mining Assoc. 1996
Natural Gas Reserves: Price Waterhouse 1995
LPG Reserves: Price Waterhouse 1995
Biomass: USDOE/NREL 1995.

The table shows, for example, that under the above assumptions, using North American coal to provide either methanol or hydrogen in fuel cell vehicles would provide over 60 times more vehicle miles before the resource runs out than using North American petroleum in conventional ICE vehicles would. Alternatively, under the same vehicle use patterns and simplifying assumptions, the coal resource would last 60 times longer when used in these vehicles. This high value reflects the high coal reserves in the United States relative to North America's oil reserves. In the rest of the world, these AFV/fuel chains could extend the vehicle miles to 5.5 times the potential miles of conventional petroleum vehicles. Coal in general provides a huge energy resource in North America, regardless of the fuel derived from it or the type of vehicle which uses the fuel. Coal could also provides the most potential miles as a transportation resource worldwide.

More important for the shorter term, the table shows that LPG's usefulness is limited to 1% of gasoline in the world (no significant accuracy is lost by using world reserves for LPG, the easily available statistic, compared to "rest-of-world" oil results in this table). This means that however long gasoline will last before it runs out, LPG would last only 1% as long if used at the same intensity.

North American natural gas reserves contain about 1.7 times the energy of its oil reserves. This ratio is a bit lower for the rest of the world. This energy store, combined with the generally more efficient use of the resource than crude in all natural gas fuels except methanol, makes natural gas a potential long-term alternative resource. Even methanol internal combustion engines, penalized in the lifecycle by an inefficient fuel chain conversion efficiency, can obtain 1.5 times more use from the North American natural gas resource than gasoline vehicles can from North American oil.

M85 benefits from using coal, natural gas, and oil resources combined to stretch the usefulness of North American oil reserves to almost 7 times their potential when used as gasoline, RFG, or diesel. The oil reserve is the limiting factor in producing this fuel, since the reserves for producing methanol are so plentiful. If coal is omitted from the resource base of methanol, M85 stretches the miles obtainable from gasoline reserves 1.7 times in mixtures with M85, with natural gas as the limiting resource. This strategy for gasoline use would in addition leave 85% of the gasoline for use in gasoline vehicles, for a total extension of 255%. On the world scale, this fuel can stretch conventional petroleum about 4 and a half times until oil is gone, if the coal resource is included for making methanol. This usefulness of the fuel reserves might make M85 a very attractive international motor fuel.

RFG hybrid electrics use their efficient lifecycle operation to extend the potential miles offered by the world oil reserves up to 1.5 times over that of conventional gasoline vehicles. This technology also has the advantage that the ICE could operate on alcohol fuels or alcohol/gasoline mixtures, further extending the usefulness of fossil resources.

Ethanol and other biomass fuels' availability is limited each year. Their total reserves do not come into question, since they are renewable, but they do not fit well in this table of absolute reserves, and require a few comments. Ethanol is the important biomass fuel to consider. The table uses NREL/DOE predictions (U.S. DOE, NREL 1995) for the maximum amount of cellulose (woody plant fiber) that could be grown for fuel use in the U.S. in a year. This amount is reported as 2.45 billion metric tons/year, or 24 billion GJ of potential fuel resource energy. Using the method above, this would translate into enough annual production to provide roughly 10% of the total mileage offered by the proven North American crude oil reserves. However, the same report cites a current annual corn harvest for ethanol production at only 10 million metric tons/yr (400 million bushels), or 89 million GJ of potential energy. The amount of arable land that could be planted with "fuel corn" is very controversial for environmental and economic reasons, so an increase in harvest of 250% (10 million to 2.45 billion metric tons) may present difficulties.

6.3 Conclusions from the Base Case

Most fuel or vehicle alternatives can improve on the emissions or energy efficiency of the current liquid petroleum system, but at a higher cost. The economically efficient alternatives for each lifecycle characteristic modeled are listed in Table 6.3, in order of increasing cost.

Table 6.3: Current or Potential Alternatives that Lie on the Feasibility Frontier for Each Lifecycle Attribute.

Fuel Group	Greenhouse Gas	Ozone Precursors	Particulate Matter	Carbon Monoxide	Energy Efficiency	Fuel Resource Extender
Liquid Petroleum	Yes	Yes	Yes	Yes	Yes	
Methanol Fuels (ICE)				Yes	Yes	Yes
Natural Gas	Yes		Yes	Yes		Yes
Ethanol Fuels				Yes		Yes
CH2, LH2 (ICE)			Possible	Possible		Possible
RFG Electric Hybrid	Yes	Yes			Yes	Yes
H2 Hydride			Possible	Possible		Possible
Battery Electric		Yes		Yes		Yes
Methanol Fuel Cell	Possible	Possible	Possible	Possible		Possible
H2 Fuel Cell	Possible	Possible	Possible	Possible	Possible	Possible

Liquid petroleum vehicles are economically efficient for all of the attributes investigated. Most vehicle types seem to have the same cost tradeoff characteristics for PM and CO, and all but liquid petroleum fuels could potentially extend the fossil fuel resources available for transportation. Of the currently available technologies, natural gas and hybrid electric vehicles are the only ones to compete with liquid petroleum's cost tradeoff for greenhouse gas emissions reductions, and only methanol-fueled ICE or hybrid electric vehicles compete on an energy efficiency basis.

Other alternatives may offer improvements in emissions or energy efficiency, but at a relatively higher cost. Tables 6.8 summarizes how each vehicle compares for each characteristic, divided into categories of low, medium, high, and very high cost. These categories are arbitrarily divided, and refer to the preceding figures.

Table 6.4: Summary of Greenhouse Gas Emissions Levels from each AFV

Vehicle/Fuel Chain Characteristic	Emissions Level or Energy Efficiency	Vehicle Type	Cost Level
Lifecycle Greenhouse Emissions Level	High	Alcohols and Blends	Medium
		Conventional Petroleum	Low
	Medium	Propane (LPG)	Low
		Natural Gas	Medium
		Hydrogen ICE, Battery and Hybrid Electric Vehicles	High
	Low	Fuel Cell Vehicles	Very High
Total Lifecycle Ozone Precursor Emissions Level	High	LPG, Diesel	Low
		E85, E100, M100	Medium
	Medium	RFG, Gasoline	Low
		M85, Natural Gas	Medium
		Hydrogen ICE	High
	Low/Very Low	Battery and Hybrid Electric Vehicles	High
	Very Low	Fuel Cell Vehicles	Very High
Lifecycle Ozone Precursor Emissions from Vehicle Only (Tailpipe + Evaporative)	High	LPG, Diesel	Low
	Medium	Gasoline, RFG	Low
		Natural Gas, M100, E100	Medium
		Hydrogen ICE	High
	Low	M85, E85	Medium
		Hybrid Electric Vehicles	High
	ZEV	Battery Electric Vehicles	High
		Fuel Cell Vehicles	Very High
Lifecycle Particulate Matter Emissions Level	High	Conventional Petroleum	Low
		E85, E100, M85	Medium
		Battery and Hybrid Electric Vehicles	High
	Medium	Propane (LPG)	Low
		M100, Natural Gas	Medium
	Very Low	Hydrogen	High
		Fuel Cell Vehicles	Very High
Lifecycle Carbon Monoxide Emissions Level	High	Conventional Petroleum	Low
	Low	Alcohols, Natural Gas	Medium
		Hybrid Electric Vehicles	High
	Zero	Hydrogen ICE, Battery Electric Vehicles	High
		Fuel Cell Vehicles	Very High

The actual choice of consumers or policy makers may depend on external factors like the local availability of vehicles and fuel, need for local improvements in air quality, etc. Distinguishing individual fuels within each group in Table 6.3 will also be important in decisionmaking, as some fuels give different tradeoffs relative to others within the same group, particularly liquid petroleum.

The important conclusions for each fuel are:

- LPG is a high quality fuel that is used as a widespread basis in the United States already, but its reserves are too low for it to replace other crude oil derived fuels.

- The best performing, all-round alternative for a low cost is RFG.

- Lower ozone precursor and carbon monoxide emissions than RFG may result from the slightly higher cost alcohol blends or natural gas vehicles. These alternatives are only economically efficient for the CO reduction.

- Natural gas vehicles may additionally reduce greenhouse and particulate matter emissions at an economically efficient tradeoff. (See Chapter 4 for more on natural gas vehicle PM emissions).

- Hydrogen fuels could substantially reduce particulate, greenhouse gas, and carbon monoxide emissions at high cost, but would not change ozone precursor emissions from RFG.

- The high cost battery electric vehicles emit an equivalent amount of particulate emitter from stationary sources as conventional petroleum vehicles do from the tailpipe, but zero emissions otherwise.

- Electric hybrid vehicles powered by RFG perform and cost about the same as BEVs, but emit as much tailpipe carbon monoxide as cheaper alcohol or natural gas vehicles.

- Research claims for fuel cell vehicles promise to reduce or eliminate all of these pollutants, though their cost is extremely high in the base case.

7. Sensitivity Analysis

This chapter presents the sensitivity of the lifecycle model's output to user inputs and to the parameters used in the model's structure. Testing the model's response to individual user inputs investigates the robustness of the model under a range of user inputs which might be entered for different policy analyses. Testing the sensitivity of outputs with respect to individual model parameters that the user would not ordinarily change establishes the uncertainty of model output in each scenario.

The first section outlines the two approaches that the thesis uses in the quantitative sensitivity analysis: sensitivity to scenario inputs and sensitivity to parameter assumptions. The next two sections describe in detail the quantitative response of the model: first presenting the responses to changes in parameter assumptions, and then to scenario (user) inputs. The final section summarizes the effect of the model's sensitivity to these components on lifecycle outputs, providing a gauge of the reliability of the model over the range of tested inputs.

Sometimes it is easier to compare the difference in lifecycle costs between a given vehicle and a conventional gasoline vehicle to see if the AFV system can compete on a cost basis. This "incremental," or, "differential," lifecycle cost (LCC) will occasionally be referred to in the following discussion instead of the absolute cost.

7.1 First Order Check

For a first order check, all outputs vary in the intuitive direction in response to changes in inputs. This result is essential for the credibility of the model.

7.2 Approach and Overall Results

The uncertainty of the spreadsheet model was established in a sensitivity analysis of 10 input assumptions in the base case world scenario. Testing 10 more assumptions of scenario input variables gives the model's sensitivity to independent changes in world conditions.

The tests of the sensitivity to the model parameter assumptions ascertain the precision, or high and low bounds, within which accurate output values could lie. Changing parameter assumptions, like the average shipping distance or mode of certain fuels, for example, causes small changes in the model output. The user would not change model parameters unless they unsatisfactorily represent the real world, or unless the user wished to model a scenario which this structure does not account for.

Changing the user-entered scenario inputs individually tests the effects of world scenario changes to identify their relative influence in the model output. This identifies tendencies in the model to react more or less strongly to changes in certain regulatory or market conditions, like a particular sensitivity to changes in gas prices or tailpipe emissions standards. Scenario changes should cause the largest changes in outputs. These values would be the ones most interesting and useful to the user to change.

Table 7.1 summarizes the model parameters which were varied for the sensitivity analysis, divided into influence groups, and outlines the effect that these results might have on decisions based on model output.

Table 7.1: General Areas of Parameter Sensitivity Analysis and Potential Effects of Uncertainty on Determinations

	Input Varied	Lifecycle Outputs Affected	Qualitative Sensitivity	Effect of Changes
Model Parameter Assumptions	Discount Rate	Relative Operating Cost	High	Raising it makes expensive fuel look better.
	Fuel Production Technology	Cost, Energy Efficiency	High for exotic fuels, low for mature industries	Compressed hydrogen can become less expensive than ethanol on LCC basis.
	Fuel Transport Cost	Cost of all but BEV	Low, Significant for CNG, LNG	Inefficient vehicles or high fuel transport costs affected more
World Scenario Inputs	Resource Mix	Emissions, Cost, Energy Efficiency	High if Coal is Involved	Hydrogen, methanol emissions and cost rise if derived from coal.
	Industry Emissions	Selected Emissions	Low except Ethanol	Controlling coal boiler emissions cleans ethanol to competitive PM, NOx levels.
	Resource Price	Selected Costs	High for Low Cost or Low Efficiency Vehicles Low for High Cost or High Efficiency Vehicles	Substantial rise in price of one resource can change recommendation, is unlikely occurrence.
Technology Inputs	Vehicle Tailpipe	ICEV Emissions	High	½ of ICEV emissions. Improvement limited by fuel chemistry.
	Vehicle Cost	Cost	Highest for fuel cell vehicles Low for ICEVs	Large uncertainty in experimental technology cost. Vehicle cost can determined its competitiveness.
	ICE Vehicle Efficiency	ICEV Emissions, Cost, Energy Efficiency	High (1:1)	Increase decreases advantage for cleanest vehicles.
	Battery Technology	BEV, HEV Cost	BEV: High, HEV: Med	Makes EV cheaper but not competitive.

7.3 Sensitivity to Model Parameter Assumptions

This section summarizes the tests of the model's sensitivity with respect to programmed parameter assumptions, which program users would find difficult to change. It refers to parameters in Table 7.1 above the double line. See Appendix 18 for a detailed summary of the tests.

Sensitivity to Discount Rate

The present value discounting in the maintenance, fuel, and replacement battery costs adjusts for the productive opportunities of using the money in other ways between now and when these expenditures must be made. It is necessary for adjusting future expenditures to the value of present money. A gallon of gasoline that costs $1.00 twelve years from now only costs 32 cents in today's dollars at a 10% discount rate. A higher discount rate would indicate that the model user believes that money could earn a lot in investments between now and when it is spent. Higher discount rates will make the differences between future dollar values look smaller than they would look at a lower discount rates.

The model uses 10% for its discount rate. Changing this value by 1% changes the BEV differential lifecycle cost over a CGV by 3% because of the high cost of replacing the battery packs. The discount rate has a large enough effect on the operating costs of vehicles that it can change the relative order of the lifecycle costs. Higher discount rates will favor vehicles with expensive operating costs like BEVs over those with lower operating costs, like LPG.

Sensitivity to Fuel Transport Costs

The model assumes the average truck transport distance for liquid petroleum fuels and methanol to be 50 miles. Changing this distance +50%, to 75 miles, raises the lifecycle costs of each of these AFV types $50, or $25 for fuel cells and ICE hybrids, which are more efficient vehicles. $50 is not enough, by itself, to change the order of the lifecycle costs across AFV types. This 50% increase in the assumption, for example, causing a $50 increase in the lifecycle cost of a CGV, is only 8% of the difference in lifecycle cost between a methanol ICE and the CGV.

Changing liquid fuel per-mile transportation costs by truck +100% from the assumed .022c/gal-mile raises methanol and M85 LCC by $100, and ethanol and E85 LCC by $125. This is a 15% change in the difference in cost over a CGV for the methanol vehicles, not enough to make this parameter assumption a factor in determining the order of LCCs. The ethanol impact is even less, only 2.5% of its incremental cost. The increase in cost derives from the lower energy density of each fuel relative to gasoline, which causes more shipments of fuel to be made. The low sensitivity of the lifecycle cost increment derives from the relatively high cost per unit energy of methanol and ethanol in the first place.

Doubling the cost of barge shipments within the U.S. from the assumed 2.5c/ton-mile value raises petroleum vehicle lifecycle costs $20, and ethanol vehicle costs $13. This an extremely low change which is inconsequential.

Reducing the assumed gas pipeline transport cost by 50%, from $2.54/MSCF to $1.25/MSCF reduces the LCC of CNG and LNG vehicles by $400, and hydrogen vehicles $250-$300. This represents a 25% reduction in the incremental LCC for natural gas vehicles, relative to CGVs. The use of a single shipment cost for the whole nation could mask areas of lower natural gas transportation costs where CNG and LNG might be cost competitive, clean alternatives.

Sensitivity to the Fuel Production Technology

Varying the fuel production technology in the model does not influence the emissions of the fuel chain without simultaneously changing the industry SOA controls on the user input page. Here, varying the fuel production technology refers to changes in cost and energy efficiency in the fuel chain.

Improving the natural gas to methanol technology by modeling a change from 10% large-scale plant production to 50% large-scale plant production reduces the LCC for methanol vehicles $46 and M85 $23. This is an insignificant change.

However, lowering the natural to hydrogen conversion costs to the low estimate model, which reduces the production cost by 60%, reduces the LCC of CH2 vehicles $1450, enough to make them less costly than pure ethanol vehicles in the rank of LCC. Although the other hydrogen vehicles benefit at the same order of magnitude by this cost reduction, they do not come down enough in LCC to change the rank of their cost.

7.4 Sensitivity to Scenario Assumptions

This section analyzes the sensitivity of the model output to variables that the user can, and will likely want to, change in the program. It refers to the variables below the double line in Table 7.1. See Table 18.1 for a detailed quantitative summary of each test.

Sensitivity to Battery Characteristics

The BEV battery lifetime was varied in the vehicle model from the base case 600 cycles to 1000 cycles. This represents the change in technology from the USABC short term battery performance goals to its long term goals. This maximum foreseen improvement in battery performance would lower the incremental lifecycle cost of the BEV up to 40%. In absolute terms however, BEVs would still remain $3000-$6000 more expensive than gasoline ICEVs over the 11 year lifecycle ($275-$550/year). Given no other improvements however, this is enough of a reduction to make low cost BEVs competitive with all hydrogen vehicles, and perhaps ethanol.

The HEV battery lifetime was reduced from its base case value of 10000 cycles to 5000 cycles (50%), reducing the incremental lifecycle cost by 15%, a ratio of 1:0.3. This low sensitivity is because the battery replacement cost for the HEV only contributes about 30% to the lifecycle cost of the vehicle. The 10,000 cycles/lifetime is currently the best available technology. The HEV in this model is probably a good bargain. Lowering the battery lifetime by 20% to conservatively represent today's batteries would result in an additional incremental lifecycle cost of ~20% X 0.3 = 6%=$500, which will not change the HEV rank among AFV lifecycle costs.

Both EV battery costs were also varied from the base case $150/kWh, a realistic price for lead acid, to $100/kWh, the USABC long term goal. No battery maker has predicted that it can make a battery for lower than $125/kWh, however. The BEV incremental lifecycle cost responds at a rate of 1%/1% reduction in battery cost. Incremental HEV costs respond at a rate of 1%/0.3% because battery replacement makes up only 30% of the lifeycle cost of the vehicle due to its smaller size and lower depth of discharge which results in longer life.

Sensitivity to Vehicle Efficiency

Changing the fuel efficiency assumptions of ICEVs results in a 1%/1% change in lifecycle energy efficiency for the affected vehicles. Changing the efficiency of all ICEVs at once from the base case changes emissions at a 1%:1% ratio with the efficiency change, except for NOx and PM emissions, which have lower sensitivities (1:0.4 and 1:0.5, respectively). Changing the efficiency ratio of alternative ICE vehicles relative to gasoline vehicles to investigate the assumption of optimized vehicle performance to the alternative fuels changes incremental emissions relative to a CGV at a 1%:1% rate, and incremental cost at a less than 1%:1% rate for more efficient vehicles than CGVs (gaseous and alcohol fuels), and greater than 1%:1% for equally efficient vehicles. It is unlikely that OEM alternative fuel ICE vehicles will run more than a few percent more or less efficient than a gasoline engine, so the ratio of efficiencies is unlikely to vary as much as 1%. The resulting cost and emissions impacts would not alter the relative strengths of each AFV.

Choosing a high efficiency (e.g. 20%) for ICEVs in the User Inputs worksheet makes EVs and fuel cells relatively less advantageous because they derive most of their advantage from being more efficient vehicles. However, no realistic ICEV efficiency can erase this large advantage except for ICEV/EV hybrids, which share the common problem with the other exotic drivetrains of high cost.

Sensitivity to Resource Price

The model does not exhibit significant sensitivity to changes in coal prices due to the low reliance on the resource for transportation fuels in the resource mix. Changing the corn byproducts price for the ethanol fuel chain, cited by one source as the most significant determinant of ethanol cost (IEA/OECD, 1994), results in only a 0.3% change in incremental lifecycle cost for a 1% change in byproduct price from the $200/ton assumed in the model.

Petroleum cost fluctuations propagate at a 1%:1% ratio to the incremental lifecycle cost of petroleum vehicles (gasoline, RFG, diesel, LPG) because their incremental costs depend only on the relative cost of their fuels.

Natural gas price fluctuations are translated into a 1%:/0.1% incremental cost impact on LNG and CNG vehicles, and a 1%:0.3% impact on methanol ICEs, again because the vehicle cost makes up a smaller component of the incremental lifecycle cost of a methanol ICE, and a larger component of the LNG and CNG vehicles (conversely, the fuel cost is a smaller determinant of lifecycle cost for LNG and CNG vehicles, so they are less sensitive to fuel cost changes).

The petroleum and natural gas price impacts could be significant if the prices of the two resources do not move together because of the close lifecycle costs of liquid petroleum and methanol fuel vehicles.

Sensitivity to Resource Mix

Methanol, hydrogen, and LPG can be manufactured from different sources in the model.

A one percent change in the LPG mix, from 50% natural gas, 50% petroleum, towards a majority of natural gas consumption (51%/49%) raises emissions 0.1%, and incremental lifecycle costs 0.6%, neither of which are a concern in the case of LPG.

Switching hydrogen production 1% toward coal from a 90% natural gas, 10% coal mix increases CO2 emissions 1% and PM emissions 1.5% for hydrogen vehicles over the lifecycle. It also raises their incremental costs 1%. Given the rise in costs, it is unlikely that this shift will occur in the near future.

Methanol can also be made from coal in the model, in addition to natural gas and wood. Wood is such a non-economical choice that it is not part of the resource mix of methanol fuel. Shifting the methanol resource mix 1% toward coal from its 100% natural gas resource in the base case toward coal (99%/1%) will raise the incremental lifecycle costs and greenhouse emissions of methanol vehicles 1%, but will lower NMHC emissions by 0.5%. Methanol processing from both natural gas and coal is about a 52% efficient process, so no changes in efficiency occur. Shifting the methanol manufacturing locations between the four natural gas extraction regions described in Chapter 5 changes the cost insignificantly, as long as the least expensive region I cannot be developed further.

Sensitivity to Tailpipe Emissions

The vehicle tailpipe emissions carry a large potential uncertainty because of the reasons listed in the model description. The weight of the vehicle tailpipe contribution to emissions is summarized in Appendix 14. The zero emissions are precise and accurate by definition.

However for other vehicles, all carbon emissions are assumed to be in the compounds CO2 and CO (see Chapter 5). This methodology double counts the small amount of carbon which is emitted as pure carbon from the tailpipe, however. This is manifested as a minor overstatement of the CO2 emitted by each vehicle by the proportion of 3.67 fewer grams of CO2 emitted per gram of pure carbon emitted. Since the component of PM that is carbon is unknown and small relative to the mass of CO2 which is emitted, this contribution is ignored in the model. For example, even if 0.5 g/mile of PM was emitted as pure carbon, this omission would contribute only a 1.8 g/mile reduction in CO2, roughly 3% of CO2 emissions in the lowest emitting vehicles.

Note that for the ethanol fuel chain, 0 g/mile of carbon dioxide (CO2) are assumed to be emitted as a result of using ethanol in the vehicle, because all of the CO2 in ethanol is part of the present day carbon cycle, and is not released from fossil sources.

However, all the rest of the tailpipe emissions values could vary by as much at 50-80%, based on a literature review (see sources listed in the model description, Chapter 5). Such variation would result in lifecycle uncertainties of plus or minus 50-80% times the proportion of tailpipe emissions versus total emissions. These values are shown in the table in the tailpipe emissions appendix to Chapter 5.

Since the proportion of tailpipe emissions in the total lifecycle emissions from the vehicle are usually large, often more than half of the total emissions in the lifecycle, the choice of tailpipe emissions in the model can result in a plus or minus 25-50% uncertainty in the lifecycle emissions output. This will definitely make some fuel alternatives indistinguishable on an emissions basis from others.

Sensitivity to Vehicle Cost

Users enter a high and low vehicle cost for an AFV conversion, OEM, or dual fuel vehicle. This cost should be the incremental cost between an AFV and a conventional gasoline vehicle. The user also enters an average cost for a conventional gasoline vehicle. The high and low relative vehicle costs should represent uncertainty limits to a range of costs which average to the most likely vehicle cost. A 1% change in the cost of an ICEV yields a 1% change in incremental LCC. Vehicles with expensive maintenance and operations costs, like BEVs, are slightly less sensitive to vehicle cost inputs, at 1%:0.4% change in incremental lifecycle cost. This is a sensitive response, indicating that the range of input vehicle costs should be carefully regarded before relying on model output.

The user could practically determine the lifecycle cost output by his choices of vehicle cost input.

Sensitivity to Industry Emissions

The model shows little sensitivity to industry emissions controls except for controls on coal boilers. Requiring 1% more coal boilers to operate at the state of the art than the 10% which are controlled in the base case gives a 1% reduction in ethanol vehicle lifecycle PM emissions, a 0.2% reduction in ethanol-associated NOx, and a 0.3% reduction in BEV-associated NOx from electricity generation. The maximum available 100% controls on coal boilers could then reduce ethanol vehicle lifecycle PM emissions to the level of CGVs, and NOx levels from ethanol and BEVs by about a third. This could help ethanol a great deal, as it is now a very high lifeycle PM emitter.

7.5 Effect of Inputs and Assumptions on Lifecycle Results

7.5.1 Sensitivity of Lifecycle Cost

The experimental vehicles' lifecycle cost outcomes carry such a wide uncertainty that their future lifecycle costs cannot be discerned from more familiar, and more precisely described, technologies like battery electric vehicles or electric hybrids. In the present day, of course, these exotic vehicles are not even available, and should not be under comparative consideration at all except as a technology goal. However, even the optimistic projections for their introduction in the next 30 years is very much higher than the other vehicles.

More mature technologies, like liquid-fueled internal combustion engines, have less cost uncertainty on the vehicle side, but choosing between them on a lifecycle cost basis is often a matter of tens of dollars per year, which will be blurred by the uncertainty in fuel manufacturing cost and vehicle fuel efficiency.

In-between technologies, like LNG, CNG, and compressed hydrogen, exhibit uncertainty in both vehicle acquisition and fuel costs which is large enough that their lifecycle costs may be considered indistinguishable from the most expensive liquid fueled ICEV configurations under assumptions of low vehicle acquisition price, high volume fuel production, and high vehicle efficiency relative to ICEVs.

7.5.2 Senstivity of Emissions

As described above, lifecycle emissions depend strongly on tailpipe emissions assumptions (see tailpipe emissions analysis section above) and on vehicle efficiency. Liquid petroleum fueled ICEVs have the widest range of tailpipe emissions, partly because of the wide range of representative vehicles reported in the literature used for this thesis. There is also future potential for diesel particulate filters and NOx exhaust catalysts however, which could rein in the high tailpipe emissions for these vehicles and reduce the range of liquid ICEV emissions.

Because all ICEV efficiencies are linked together in the model, there should be some concern that the model neglects explicit treatment of variations in AFV engine performance variation. ICEV incremental emissions would be affected on average 1% per 1% change in drivetrain efficiency relative to the CGV. Likely variation in the assumptions for the efficiency of an alternative fueled ICE relative to a CGV is +/- 10% (WVU NAFTP 1997). This indicates a possible emissions uncertainty of +/- 10% across ICEVs, which is close enough that the resulting lifecycle emissions will overlap for most fuels.

Alcohol fueled vehicle tailpipe emissions vary because of the number of tests reporting results with ambiguous degrees of engine optimization to the fuel. Some of the tailpipe emissions could be reduced substantially, particularly NOx, if the test vehicles used a standard for reporting results only from optimized alcohol fuel engines. A methanol diesel engine should be included in the model, as well, if emissions data can be obtained, because this is a likely use of the fuel, and it could improve on normal diesel emissions.

Very high ethanol particulate emissions occur in the fuel chain, and can be reduced to values approaching conventional-fuel PM emissions with high levels of industry SOA controls.

These improvements could move the alcohol fuel vehicles past conventional petroleum and into contention for cleanliness with the natural gas combustion vehicles. However, average functioning alcohol fuels will still be indistinguishable on an emissions basis from petroleum vehicles, except for LPG.

Natural gas vehicle tailpipe emissions have suspicious CO and PM emissions in the base case scenario. There is no reason for natural gas vehicles to emit more CO or PM per mile than liquid petroleum fuels. It is likely that the test vehicles in the data used for this analysis were running rich, or with too little air for the fuel that was being burned in the engine. Higher NOx and methane (CH4) emissions are to be expected from natural gas, however. The strength of these vehicles is their very low emissions of non-methane hydrocarbons and particulate matter, and the fact that a lower relative proportion of the total lifecycle emissions occur on the road (relatively more is emitted in the fuel chain). This fuel is already the cleanest affordable fuel on a lifecycle basis, and it is presented in a relatively disadvantages light, so changes in tailpipe emissions inputs will probably only be reductions, which would further distinguish this fuel from the rest.

Hydrogen fuels and fuel cell vehicles emit very little from the tailpipe of the vehicle, and a large proportion of their emissions occur in the fuel chain at stationary sources. Tailpipe emissions assumptions will not vary the emissions of the hydrogen vehicles much. Changes in the fuel chain technology would have a larger effect in improving the lifecycle emissions of these vehicles. The lifecycle greenhouse emissions and incremental cost could be improved 10%, and PM by 15%, for hydrogen in the base case if all the hydrogen were produced from natural gas, for example. This would place hydrogen lifecycle emissions close to those of natural gas. Other improvements would be likely if these AFV systems became cheaper.

7.5.3 Sensitivity of Energy Efficiency

The model presents electric and ICE drivetrains. Electric drivetrain vehicles use the energy in their vehicles efficiently through the electric motor. ICEVs use the energy in their vehicles inefficiently, creating a lot of heat that doesn't move the vehicle. Lifecycle efficiency differences between AFV systems within each type of vehicle depend on the efficiency of the fuel chains. Changing the drivetrain efficiency or the fuel conversion efficiency 1% results in a 1% change in the efficiency of using a fuel resource over the lifecycle, since all stage efficiencies are multiplicative. The highest potential for improving efficiency is in the fuel production stage of experimental or developing fuels like hydrogen or methanol.

Differences in efficiency between ICEVs that use different fuels vary between 1% and 3%, so given an uncertainty of +/- 2% in engine efficiency will cause the ICEV alternatives to be indistinguishable on an efficiency basis. Vehicle efficiency improvements up to 10% are possible in ICEVs, which could bring them up to the lifecycle efficiency of BEVs (DeCicco, et al. 1994). Fuel cell vehicles have such high efficiencies that it is certain that neither ICEVs, nor electrics can compete. Hybrid electrics have so many configurations that they could be more or less efficient than BEVs. In this thesis, the hybrid that is modeled has an efficiency as high as fuel cell vehicles because of the assumption that its ICE is 3 times as efficient as a conventionally used ICE. The hybrid efficiency depends on the efficiency assumptions of the electric vehicle technology times the efficiency of a gasoline ICE.

7.6 Conclusions about the Model Output Quality

The value of the model lies in the ability of its users to replace inputs and certain parameter assumptions with updated information, or information intended to represent a certain policy suggestion. This chapter shows that when these changes are entered within realistic bounds, reasonable output results.

Furthermore, the summaries of the model's sensitivity to changes in each individual parameter indicates to the user what kind of changes to expect in the lifecycle output. This should tell the user if it is worth replacing a parameter or changing some structures in the model for one he or she prefers. These sensitivities also show which elements of policies can have the strongest effect on the lifecycle model output. Chapter 8 illustrates an application of the model in scenarios of changed vehicle and industry technology and world resource prices.

8. Results for Possible Future Scenarios

This chapter presents the model results when multiple inputs are changed simultaneously to simulate changes in world resource prices technology between now and 2010. Three realistic sets of fossil resource prices frame an analysis of two possibilities of low and high fuel chain and vehicle technology advancement. For all three sets of world fossil resource prices, and each of the two levels of technology development, the alternatives are compared using the average cost of the two user-input "low" and "high" vehicle costs, as in the base case.

Because of the uncertainty in the cost predictions for immature technologies, and the current interest in zero emission vehicles, two additional analyses investigate optimistic "best case" technology and cost developments in electric drive vehicles. These include fuel cells, battery electric vehicles, and RFG hybrid electric vehicles. Estimated at their lowest possible costs, fuel cell vehicles and battery/hybrid electric drive vehicles are compared to the other alternatives at their average forecast costs, under the conditions of best technology improvements. The scenarios test the possibility of reduced fuel cell and electric vehicle manufacturing costs in an environment of high technological development in the auto and fuel industries. These additional analyses illustrate how the model can be used as a policy tool, and provide more information for the recommendations in Chapter 9.

Altogether, this chapter presents the results of 8 scenario analyses: the combinations of three world resource price scenarios and two technology development scenarios with average forecast technology costs, and two additional special cases of advanced technology with a low cost for battery and fuel cell vehicles (see Table 8.1). Numbers in the scenario names refer to the resource prices: 1 for low, 2 for medium ("reference"), and 3 for high prices.

Table 8.1: Summary of the Future Scenarios Modeled, Compared to the Base Case

Scenario Name	Resource Price	Fuel Chain and Vehicle Technology Improvement	Special Changes
Base	Current	Current	None
2010 1 Low Tech	2010 Low	Low	None
2010 1 High Tech		High	None
2010 2 Low Tech	2010 Medium	Low	None
2010 2 High Tech		High	None
2010 3 Low Tech	2010 High	Low	None
2010 3 High Tech		High	None
2010 2 Fuel Cell	2010 Medium	High	Lowest Cost Forecast for Fuel Cell Vehicles
2010 2 Electric Vehicle			Lowest Cost Forecast for BEV, HEV

Section 8.1 introduces the assumptions of the three resource price scenarios, the two scenarios of technological development, and the low-cost development of electric drive vehicles. Detailed inputs and outputs are in Appendices 15 and 17. Section 8.2 compares the best alternatives under the 2010 scenarios to determine whether the current dominant alternatives are likely to change from the base case. Sections 8.3 and 8.4 present the most favorable outcomes for fuel cell, hybrid electric, and battery electric vehicles. Section 8.5 summarizes the scenario output.

8.1 Scenario Descriptions for 2010

8.1.1 Three Sets of Future Resource Prices

Each set of future resource prices uses forecasts from the USDOE (U.S. DOE, EIA1994). The reference (medium) prices assume that resource prices in 2010 reach the EIA's middle range "reference," or most likely forecast. DOE predicts that natural gas prices will rise quickly relative to oil prices due to increased gas demand which outgrows the current gas oversupply. The low growth case for 2010 assumes that the oil price stays low, and natural gas prices rise more slowly than in the reference case, though still faster than the oil price. The high case assumes higher prices of oil, natural gas, and coal in 2010 that may arise as a result of general growth in energy demand. In all cases, the EIA predicts the price of natural gas to rise from today's low value as the current oversupply shrinks relative to the growing demand, as growth in production lags that of demand. Table 8.2, adapted from the modified ADL/Ford model, summarizes the world prices in each scenario.

Table 8.2: Prices entered in the three 2010 Scenarios with Base Case Values for Comparison

	Base Case Price	2010 Low Price	2010 Reference Price	2010 High Price	Units
Crude Oil	$21.00	$22.60	$33.40	$40.20	$/bbl
Diesel	$0.65	$0.70	$0.99	$1.19	$/gal
Gasoline	$0.62	$0.65	$0.94	$1.13	$/gal
Electricity	$0.07	$0.07	Same	Same	$/kWh
Natural Gas	$1,720.00	$4000.00	$4650.00	$4460.00	$/MMSCF
Corn	$108.00	$85	Same	Same	$/MT
Coal	$22.18	$31.6	Same	Same	$/short ton
Maize Byproducts H	($200.00)	($200.00)	Same	Same	$/MT
Maize Byproducts L	($83.00)	($83.00)	Same	Same	$/MT
Wood	$50.00	$50.00	Same	Same	$/MT
MTBE	$0.85	$0.23	Same	Same	$/gal

The crude, electricity, coal, and gas prices are from EIA Annual Energy Outlook, 1992 (U.S. DOE 1992). The base case gas price is similar to the wellhead gas prices in the Methanex Annual Report, which reports four indexes in a time series over the last 10 years (Methanex 1995). Current crude price to refiners is cited in the Oil and Gas Journal Databook 1996 (PennWell Publishing 1996) as $14/bbl, significantly lower than the $21.00 used in the base case. The DOE value was used however, as it was from the same year as the other resource values. The diesel and gasoline values are the costs calculated in the model. Corn, animal feed byproducts, and wood costs for 2010 are taken from IEA/OECD (1994). The MTBE price is taken from the Oil and Gas Journal (1994) (range is 12 cents to 23 cents).

8.1.2 The Two Cases of Technological Progress

The low technology case, compared to the base case, assumes an increase in the penetration of state of the art emissions controls on basic building blocks of industry, like coal boilers and diesel locomotives, but no improvement in the efficiency, emissions, or cost of vehicle technology and fuel chains. This case reflects an emphasis on tighter emissions restrictions on stationary sources over mobile sources in the early 21st century. Appendix 15 shows the specific input changes made in the SOA controls on industry for all 2010 scenarios.

The high technology case assumes, in addition to the increased SOA controls on industry, that all fuel chains improve to the maximum efficiency and lowest emissions and cost possible in the model, according to the assumptions in Chapter 5. Improvements include cost advantages from an increased scale of production and increased manufacturing efficiency (learning). In the vehicle model, the efficiency of an ICEV is assumed to be 17%, and the higher efficiency and lower emissions of internal combustion engine vehicles cost an extra $1000 over the low technology alternative.

8.1.3 Best Technological Development of Fuel Cells and Batteries

The "best case fuel cell" and "best case electric vehicle" scenarios assume the high technology development for each of these vehicles, combined with the low vehicle cost, instead of the average cost reported for all of the other vehicles. In both of these cases, their costs are assumed to be at the lowest predicted value because of vehicle manufacturing breakthroughs. All of the other vehicles are assumed to have met the highest degree of development in these two scenarios.

In the "best case fuel cell" development scenario, the fuel cell vehicle costs are lowered from a $75,000 increment over a $16,000 conventional gasoline vehicle, to a $2800 increment. This corresponds to lowering the cost of a fuel cell from the mid-range prediction of $2600/W that was used in previous scenarios, to the lowest prediction of $200/W, in a 40 Hp (30 kW) vehicle. This incremental cost includes a 20% reduction in the cost of a conventional gasoline vehicle to simulate the savings from not installing an internal combustion engine and its drivetrain ($3200 worth in a $16,000 vehicle).

In the "best case electric drive" scenario, battery and hybrid electric vehicles include the USABC long-term battery cost and performance characteristics as a representation of possible available batteries in 2010. The improved manufacturing techniques for electric vehicles assume that the vehicle production costs reach the lowest cost assumptions according to the available information from the literature (Chapter 4). The battery electric vehicle without a battery costs 20% less than a conventional gasoline vehicle, or $3200 less than the $16,000 conventional vehicle in this scenario, whereas in previous scenarios it cost the same. A hybrid electric costs $4,000 more than a conventional gasoline vehicle. In previous scenarios it cost $5,000 more. The cost reductions would correspond to high production volume, mature ground-up design, smooth supply of electronic components, simplified assembly (e.g. of plastic parts), etc.

8.2 Results from the Six Scenarios of Prices and Technological Improvement

The changes in relative performance of AFVs associated with the scenario requires a method of comparison like that used in Chapter 6. For the purposes of policy analysis and formulation, it is more important to know the relative performance of alternatives under different scenarios than the details of every change. This section highlights the major changes from the base case that might be expected under the future price and technology scenarios.

Changes in resource prices impact the lifecycle costs of vehicles according to the proportion of the lifecycle cost contributed by the fuel. More efficient vehicles are affected less. Technology changes impact only emissions for most vehicles but do result in cost reductions in electric vehicles as a result of better battery technology. The overall effect of the high technology scenario and higher fossil fuel prices is to bring alternatives together, diminishing their differences in emissions and cost.

The results for the six scenarios are presented in separate plots for high and low technology for each vehicle lifecycle attribute (emissions or energy efficiency). They show that the resource prices in themselves do not result in large lifecycle cost changes, and rarely influence which vehicles end up on the feasibility frontier of the most economically efficient alternatives. Technological improvements in vehicle components and fuel chain processes have a greater individual effect on placing alternatives near the feasibility frontier, particularly for immature technologies. Mature technologies actually become more expensive in the high technology development scenario, because of the cost of components added in order to improve their performance.

8.2.1 Cost Changes in Future Scenarios

The average lifecycle costs in Figure 8.1 are not as sensitive to changes in resource prices as they are to changes in technology or to the cost of added emissions control or efficiency equipment. The alternatives are presented in the same order as in Figure 6.3 for comparison between the base case and the future scenarios. In almost all cases, the change in lifecycle cost is small.

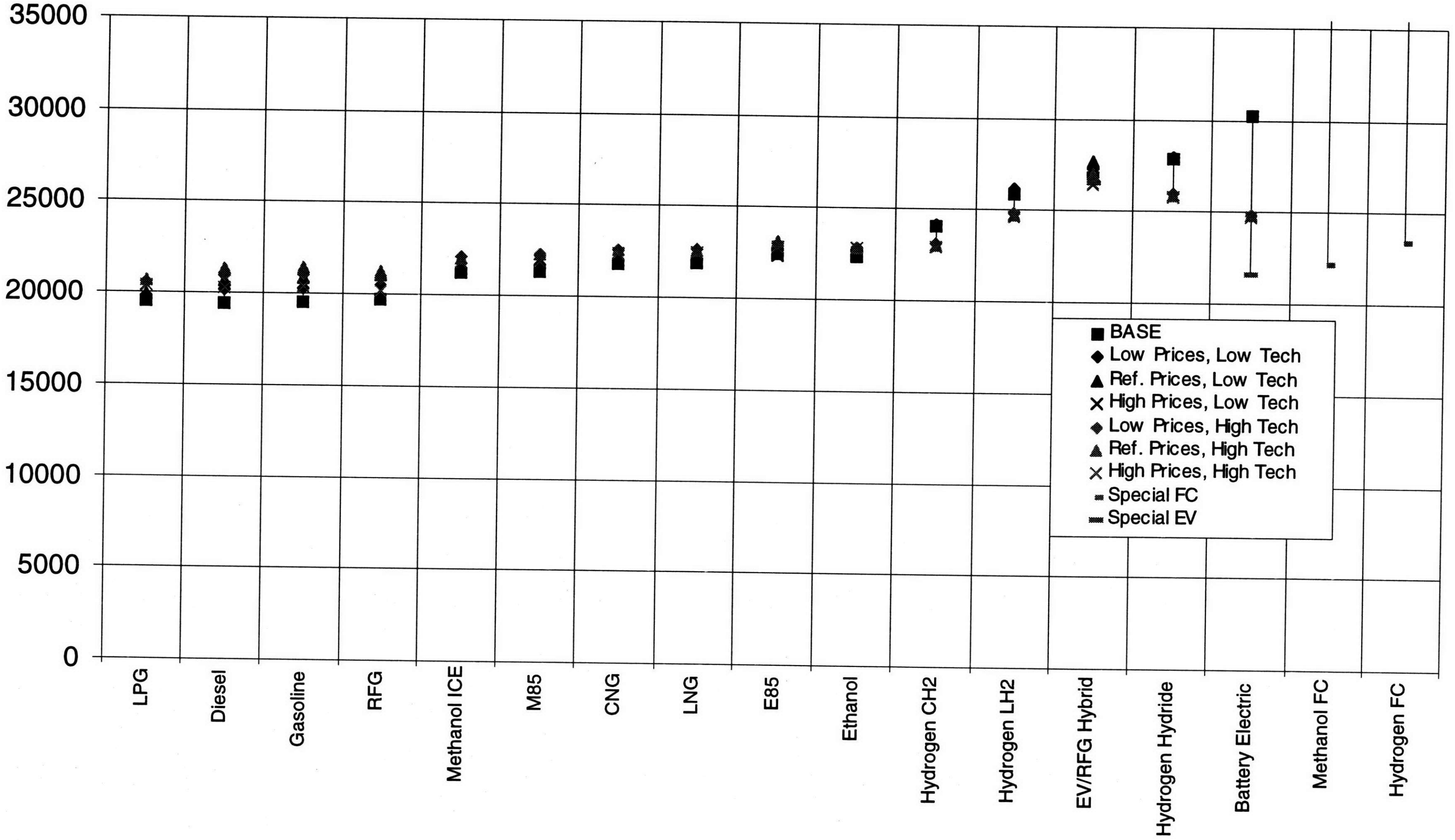

Figure 8.1: Illustration of the changes in lifecycle cost in future scenarios from the base case. Includes the special cases of best case fuel cell and electric vehicle development.

Conventional internal combustion vehicles, in the low cost bracket, become more expensive in the case of high technology because their mature technology is assumed to require added cost to improve on its emissions or energy efficiency, and because these vehicles are sensitive to resource prices.

Alcohol fueled and natural gas vehicles in the middle cost bracket experience a smaller rise in cost because high technology improvements in the fuel chain lower fuel costs, and because fuel costs make up a smaller part of the lifecycle cost of these vehicles (Chapter 7 and Figure 6.3).

The high cost vehicles all experience lower costs under future high technology scenarios. For hydrogen vehicles, this is due to improvements in fuel processing, working along the learning curve. In the case of battery electric vehicles, the cost reduction comes from replacing the USABC mid-term battery with the long-term battery (Chapter 5). The special cases of high fuel cell and electric vehicle development result in extremely high cost savings for fuel cell vehicles, and substantial cost savings for the battery electric vehicle. Hybrid and battery electric vehicles are less affected by changes in resource prices because: 1) hybrid electric vehicles are more fuel efficient than conventional combustion vehicles, and 2) because the EIA price of electricity used for battery electric vehicles barely changes at all in the three future price cases.

The significance of the small cost differences in the medium cost group, in view of the lifecycle cost of over $20,000, depends on the model assumptions as analyzed in Chapter 7 (also see Appendix 18). The relative vehicle lifecycle costs in the model are most sensitive to the following modeling assumptions:

- the discount rate
- predicted fuel production cost
- the assumed efficiency of the vehicle relative to a conventional gasoline vehicle
- predictions of the relative resource prices

- the vehicle prices input by the user

Though the discount rate can cause large changes in the lifecycle costs, the other variables are more likely to be relevant to policy making. Of these, the lower methanol production costs in the high technology case lower the lifecycle costs for methanol fuel blends about $50 from the low technology case (5-10% of the incremental cost over gasoline vehicles, see Appendix 18). Mistakes in the assumption that all alternative-fueled internal combustion vehicles are more efficient than gasoline engines could account for a small share of the cost differential, about the same as improvements to methanol manufacturing.

The relative price rise between crude oil and natural gas has a variable effect on the output. Natural gas prices rise 130-170% in the EIA predictions, and crude prices only 10-90%. The corresponding response in the lifecycle vehicle costs range from a 30% increase to a 40% decrease in the difference in lifecycle costs between the methanol-fueled vehicles and liquid petroleum vehicles relative to the base case. This is because, vehicles which use the natural gas resource are not as sensitive in the model to its price as liquid petroleum vehicles are to the price of crude oil.

All other variables being equal, the rough natural gas prices at which methanol ICE vehicles would have the same lifecycle cost as gasoline vehicles is about $1900/MMSCF in the reference (medium) price case (under $1000/MMSCF for M85 to be price competitive), and $3100/MMSCF in the high price case ($2100 for M85 to break even). The prices at which natural gas vehicles would break even are under $1000/MMSCF in the reference price case (a significant price drop), and $2300/MMSCF in the high price case. This means that if natural gas prices rise only 10% (reference) or 80% (high), in response to the EIA forecasts of a 60% (reference) or 90% (high) increase in crude oil prices), then methanol vehicles could be price competitive with gasoline vehicles.

The vehicle cost that the user inputs can have a large effect on the lifecycle cost of each vehicle. In the case of medium cost vehicles which could compete on a cost basis with gasoline with less than one or two thousand dollars' cost reduction, this input becomes an important source of uncertainty that has to be recognized in recommending policy based on the model.

The incremental lifecycle cost itself will have a different value to different interested parties, so a dollar of methanol is not the same as a dollar of gasoline. For example, when the initial proposals to the CAAA90 were made to include RFG, the predicted cost increase of the fuel was 11 to 12 cents per gallon (U.S. DOE 1994). In the base case scenario in which a conventional gasoline vehicle burns 4280 gallons of gasoline in a lifecycle, this would have been an equivalent discounted lifecycle cost increase of $295-$320 (10% discounting for comparison with the model output), with a large capital investment required of refiners (Seymour 1992). However, a coalition of oil companies supported this fuel despite its increased cost in order to avoid an alternative fuels policy which replaced a large part of the gasoline market with other fuels (Cohen 1995).

8.2.2 Greenhouse Equivalent Emissions

Figure 8.2 and Figure 8.3 show the tradeoff curve for greenhouse emissions in the cases of high and low technology development, for all three price scenarios.

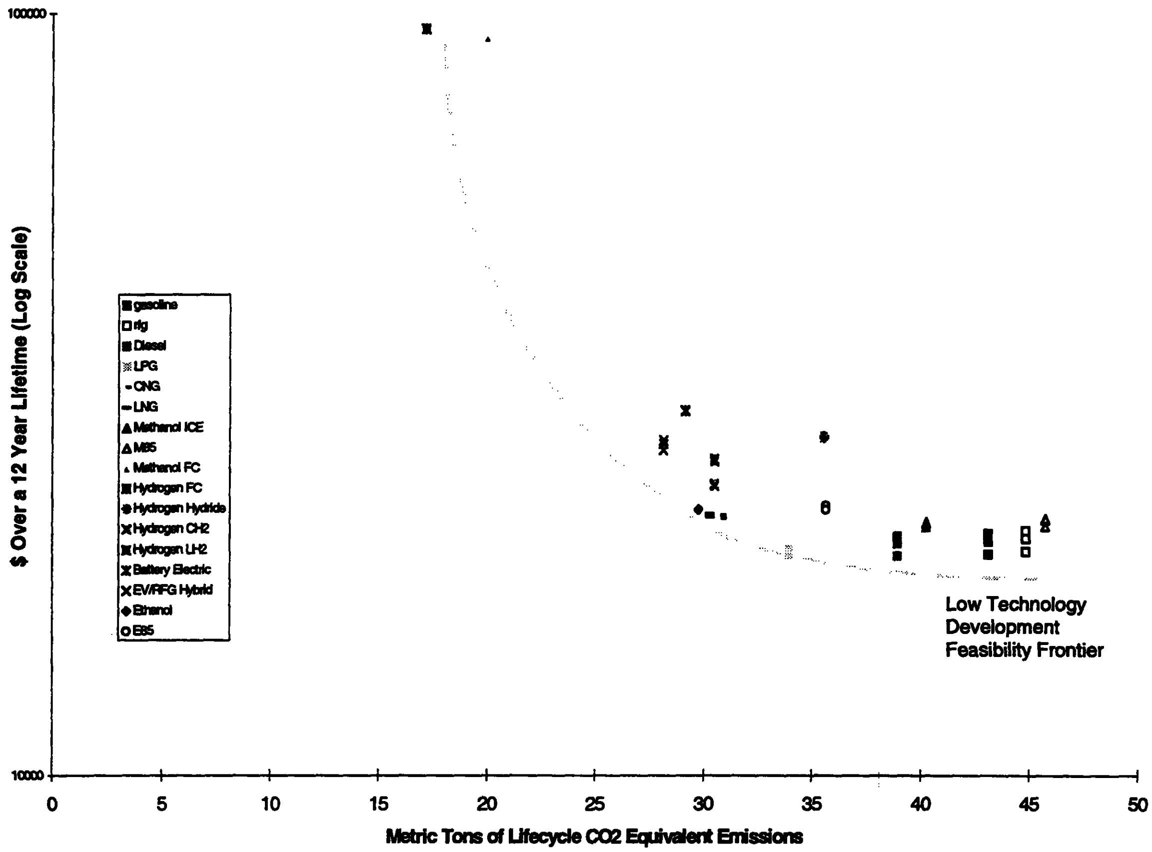

Figure 8.2: Lifecycle greenhouse gas emissions tradeoff curve for three sets of resource prices in 2010, and the case of low technological progress.

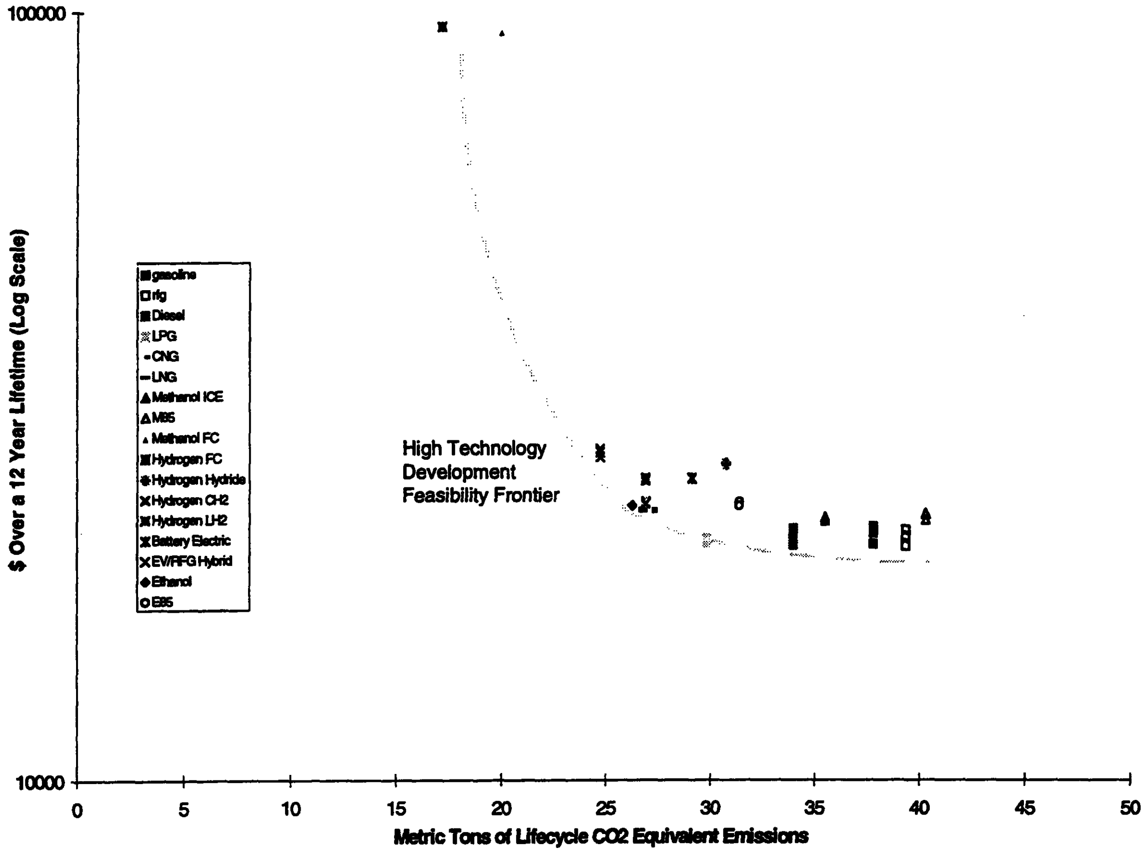

Figure 8.3: Lifecycle greenhouse gas emissions tradeoff curve for three sets of resource prices in 2010, and the case of high technological progress.

In the plots, high technology development is characterized in ICEVs by a left shift, and in battery electric vehicles by a downward (cost) shift.

Improved engine or drivetrain efficiency between the low to the high technology improvement case would likely affect all the ICEVs at once, so it would be unlikely for one type of combustion fuel to be able to dramatically reduce emissions with a high technology improvement while another did not benefit from this same improvement. Improved efficiency would keep the relative lifecycle greenhouse emissions fairly stable across alternatives, which is reflected between Figure 8.2 and Figure 8.3 as a leftward shift of a magnitude proportional to the amount of greenhouse emissions (in other words, higher emitting vehicles experience greater reductions in emissions in the high technology case). The reduction of greenhouse emissions in the higher technology scenario for all combustion alternatives is very roughly 15-20% on average.

Reductions in greenhouse gases are linked to the increased energy efficiency of the vehicles. There is a slight emissions improvement for BEVs in the future scenarios because of electricity fuel chain improvements, but BEV efficiency was not assumed to increase for the high technology case, since current vehicles are already very efficient in order to maximize performance with constraints of today's batteries. The new batteries do not improve the energy efficiency of BEVs in the model, though in real life there could be a savings of up to 3% due to the lower weight of a smaller battery (see Chapter 5). Therefore, greenhouse gas emissions for battery electric vehicles do not decrease dramatically in the future over the base case, and battery electric vehicles do not approach the feasibility frontier for greenhouse gas emissions.

Note that if the greenhouse emissions from M85 remain at the low technology level, its contribution to global warming gases would be higher than any other alternative. Gasoline and other conventional petroleum fuels could also be bad greenhouse emitters, even if vehicle efficiency improves to17% used in the high technology case. The lifecycle greenhouse emissions from liquid petroleum and methanol fuels are 30% higher than the emissions from both types of electric vehicles, hydrogen, and natural gas ICEVs.

At the feasibility frontier, fuel chain improvements in either the low or high technology development case bring pure ethanol to an economically efficient position. This is because of its zero lifecycle carbon dioxide emissions when it is used as a fuel, which leaves only the CO2 used in manufacturing the fuel as emissions. In the high technology development case, in which hydrogen processing costs come down, compressed hydrogen in an ICEV is also economically efficient. Liquid petroleum, natural gas, and the RFG hybrid electric vehicles remain on the frontier for both the low and high technology development cases.

8.2.3 Ozone Precursor Emissions

The average reductions in ozone precursor emissions from the base case as a result of the assumed technology improvements are small, and are due to NOx reductions from improved vehicle efficiency in most vehicles. Coal fuel chain controls for BEVs and ethanol vehicles are responsible for reducing the NOx emissions of these vehicles. Average lifecycle ozone precursor reductions from the base case are 5% for most vehicles, and 10% for ethanol and BEVs.

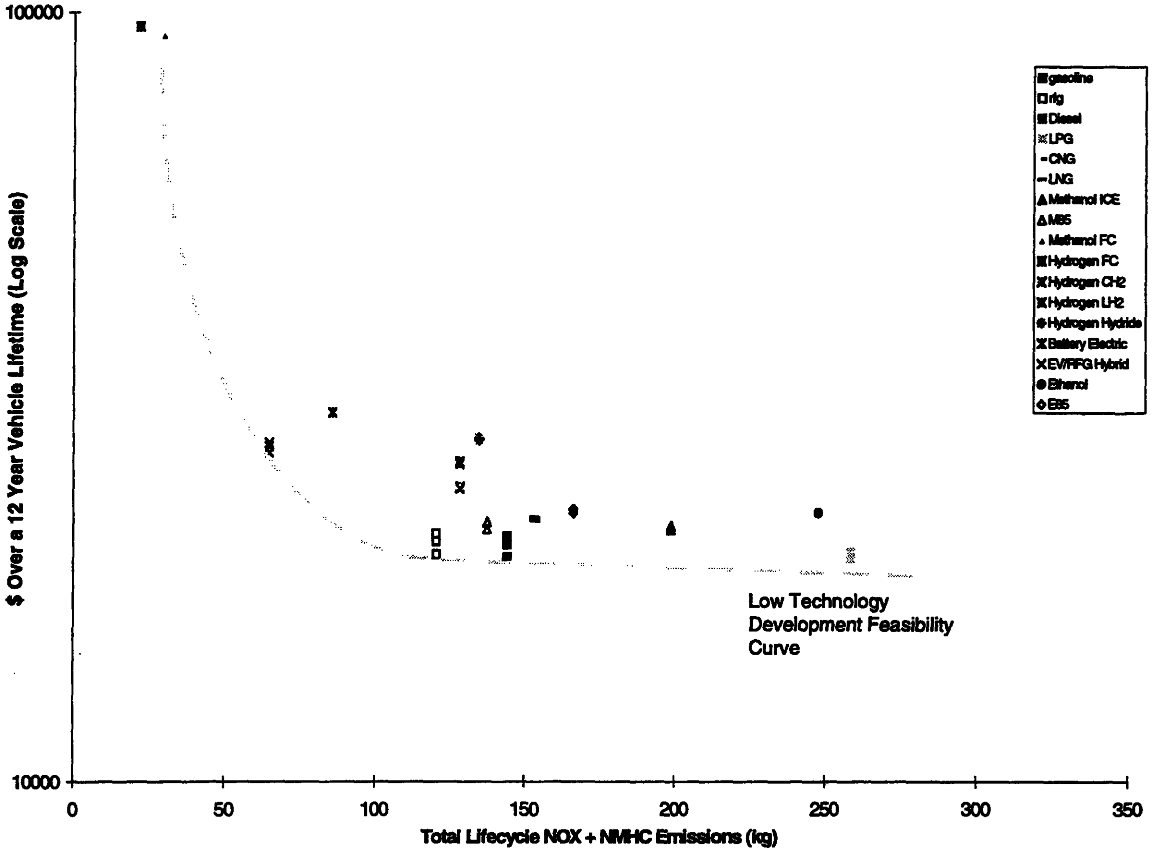

Figure 8.4: Lifecycle ozone precursor emissions tradeoff curve for three sets of resource prices in 2010, and low technological progress.

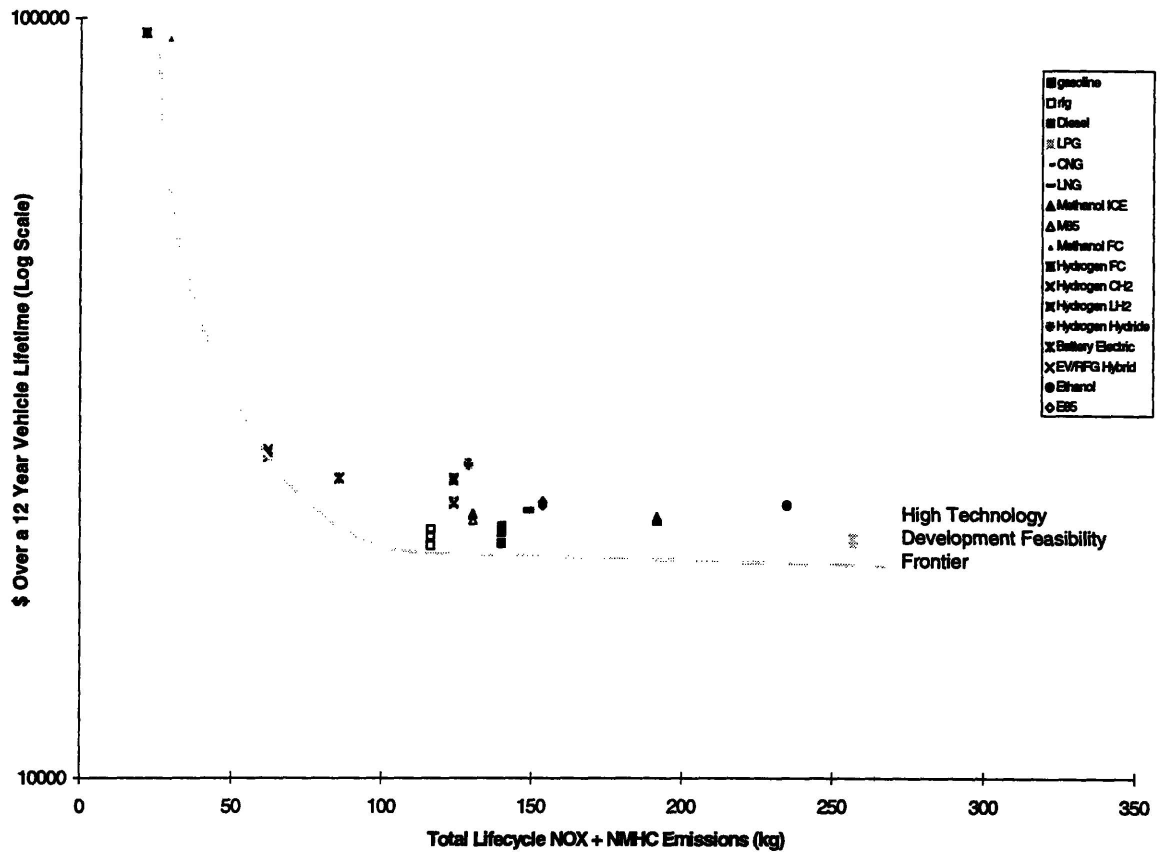

Figure 8.5: Lifecycle ozone precursor emissions tradeoff curve for three sets of resource prices in 2010, and high technological progress.

The order of the alternatives on the feasibility frontier in Figure 8.4 and Figure 8.5 stays the same, regardless of the future resource prices except that hydrogen and methanol fuel cell vehicles should be included as (the lowest emitting) alternatives. RFG and RFG hybrid electrics, even if there are no technology improvements in these vehicles, emit the next lowest total ozone precursors. Third best alternatives remain M85, gasoline, and natural gas, at emissions increases of 15% over RFG. Compressed hydrogen could be economically efficient if cost reductions are realized. Diesel remains the worst ozone precursor emitter in all scenarios because of the NOx emissions. If low sulfur fuel is used, a NOx catalytic converter could lower diesel NOx like it has been lowered for gasoline cars. This was not modeled.

8.2.4 Particulate Matter Emissions

There is no change in the dominant alternatives with respect to particulate emissions due to technology improvements or resource price changes. Even under high fuel chain emissions controls, ethanol still emits too much lifecycle particulate matter (143 and 128 kg, low and high technology) to appear on the plot scale that suits the other alternatives in Figure 8.6 and Figure 8.7. The best fuel is still LPG for low cost. The second best on the feasibility frontier is either a diesel for low cost, or liquid or compressed hydrogen for an exotic, expensive but very low emission alternative (at a cost difference of $4000 over the base case in the high technology/high resource prices case, $4700 low technology and low resource prices case). BEVs, of course, emit no PM from the vehicle, but cost an extra $3400-$4400 lifetime over average ICEVs with the USABC long-term battery ($9500-$10,600 with USABC short term battery) (see Figure 8.1), and are not economically efficient over the lifecycle for reducing PM.

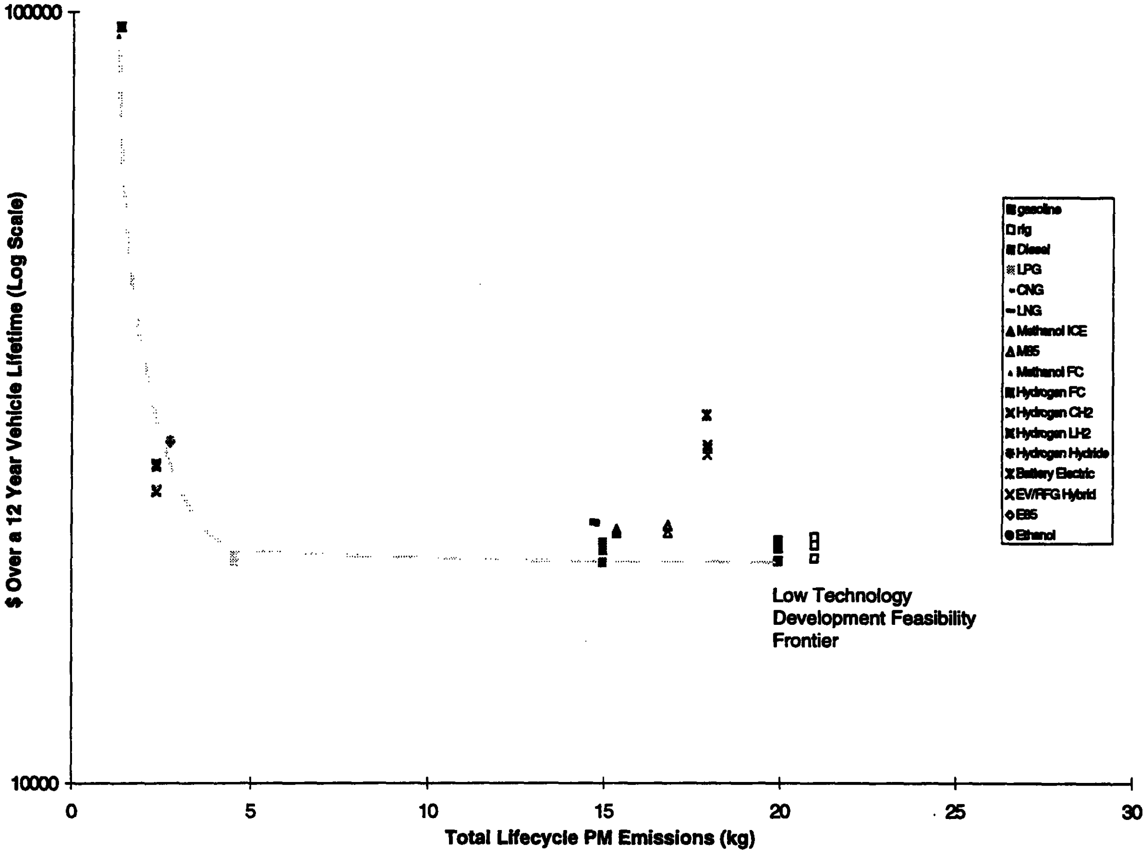

Figure 8.6: Lifecycle particulate matter emissions tradeoff curve for three sets of resource prices in 2010, and low technological progress.

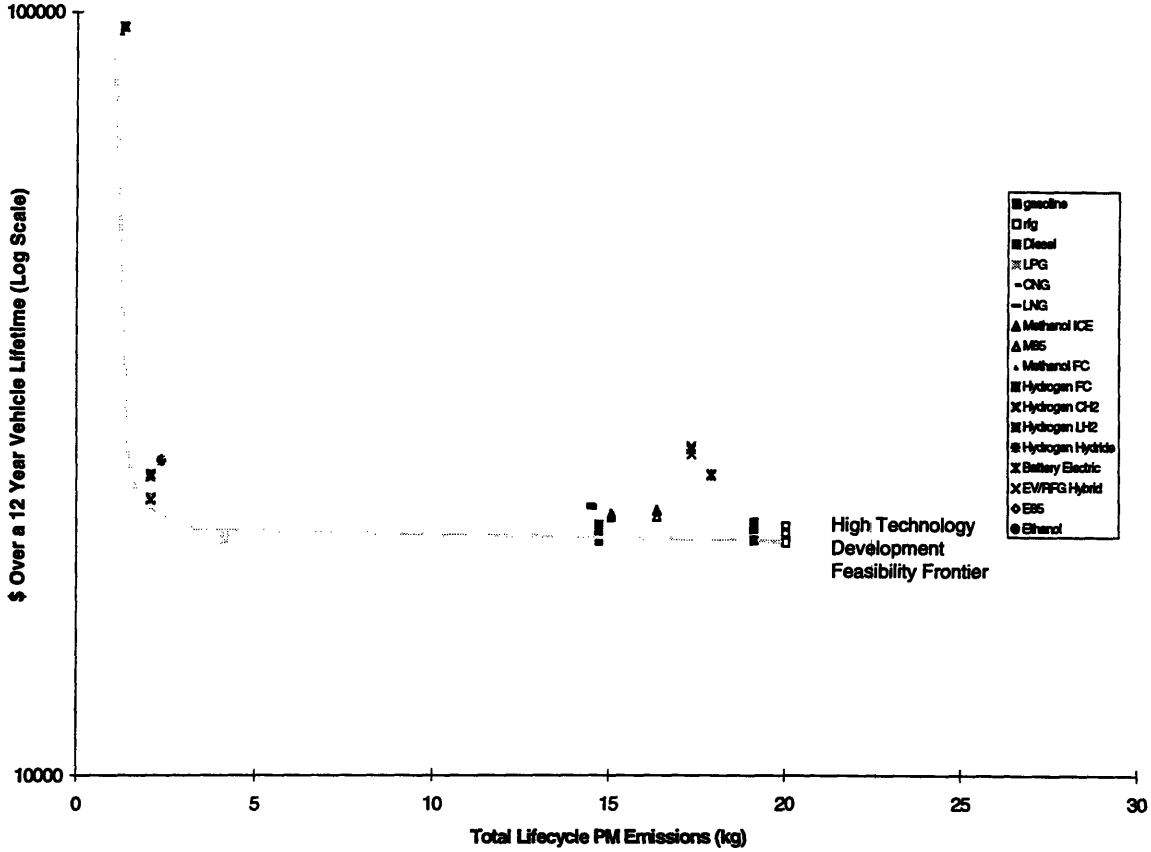

Figure 8.7: Lifecycle particulate matter emissions tradeoff curve for three sets of resource prices in 2010, and high technological progress.

8.2.5 Carbon Monoxide Emissions

As in the base case, most alternatives gather near the feasibility frontier for lifecycle carbon monoxide emissions in the low and high technology cases under all scenarios (not plotted). The highest vehicle CO emitters are liquid petroleum fuels, even the otherwise impressively clean RFG, and they are not improved enough by high technology to surpass the other alternatives. Methanol and ethanol are near the feasibility frontier, but ethanol costs more than methanol, even within the uncertainty of the model. M85 costs more than M100 in all the future scenarios because of the high oil price, and emits about 150% as much CO as M100. Still, this CO emission is 30% that of RFG. Natural gas emits less CO than M85 and more than ethanol, but has a lower cost than ethanol. Compressed hydrogen (CH2) is the least costly ZEV, with BEVs next with the high technology battery.

8.2.6 Lifecycle Energy Efficiency

High technology advances shift the energy efficiency feasibility frontier to the right. New components on ICE vehicles to reduce emissions and improve energy efficiency raise their lifecycle cost over the low technology and base cases. Figure 8.8 and Figure 8.9 show that the same alternatives for all sets of resource prices remain at the feasibility frontier as in the base case, for both high and low technology development cases.

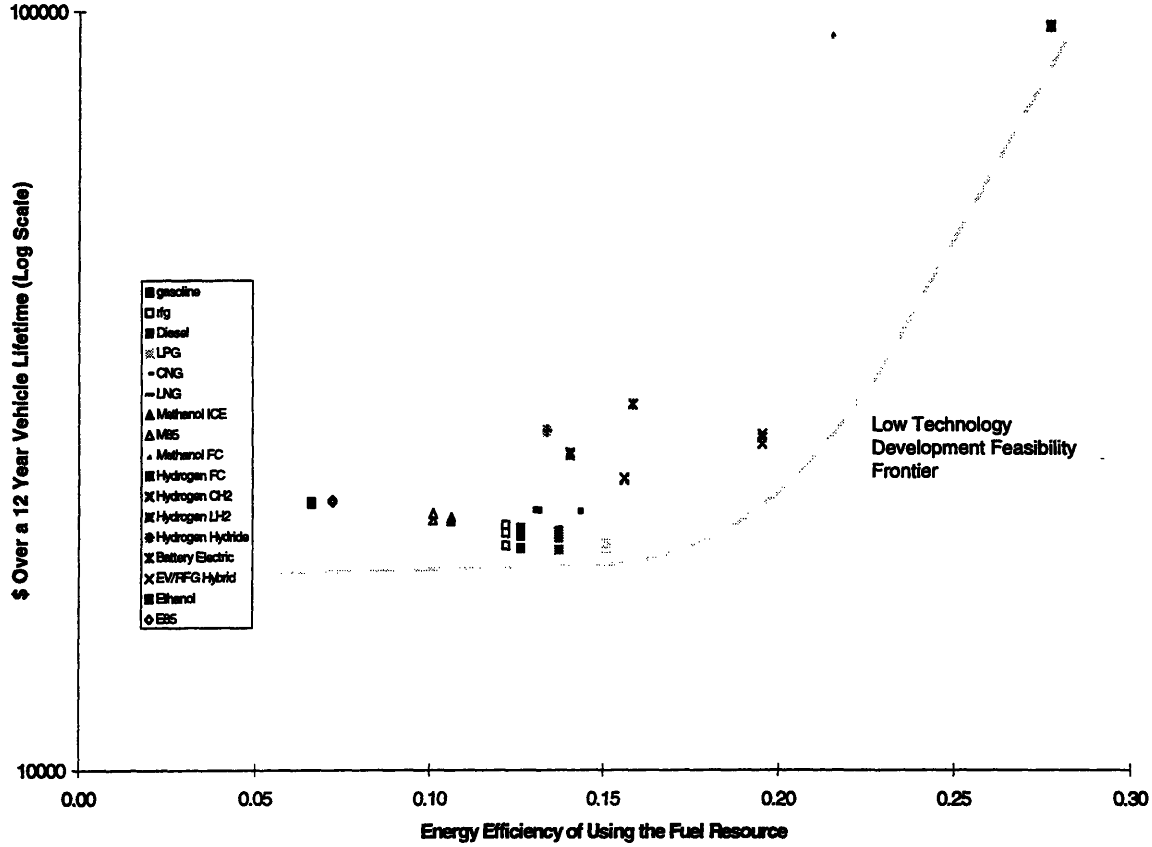

Figure 8.8: Lifecycle energy efficiency tradeoff curve for three sets of resource prices in 2010, and the case of low technological progress.

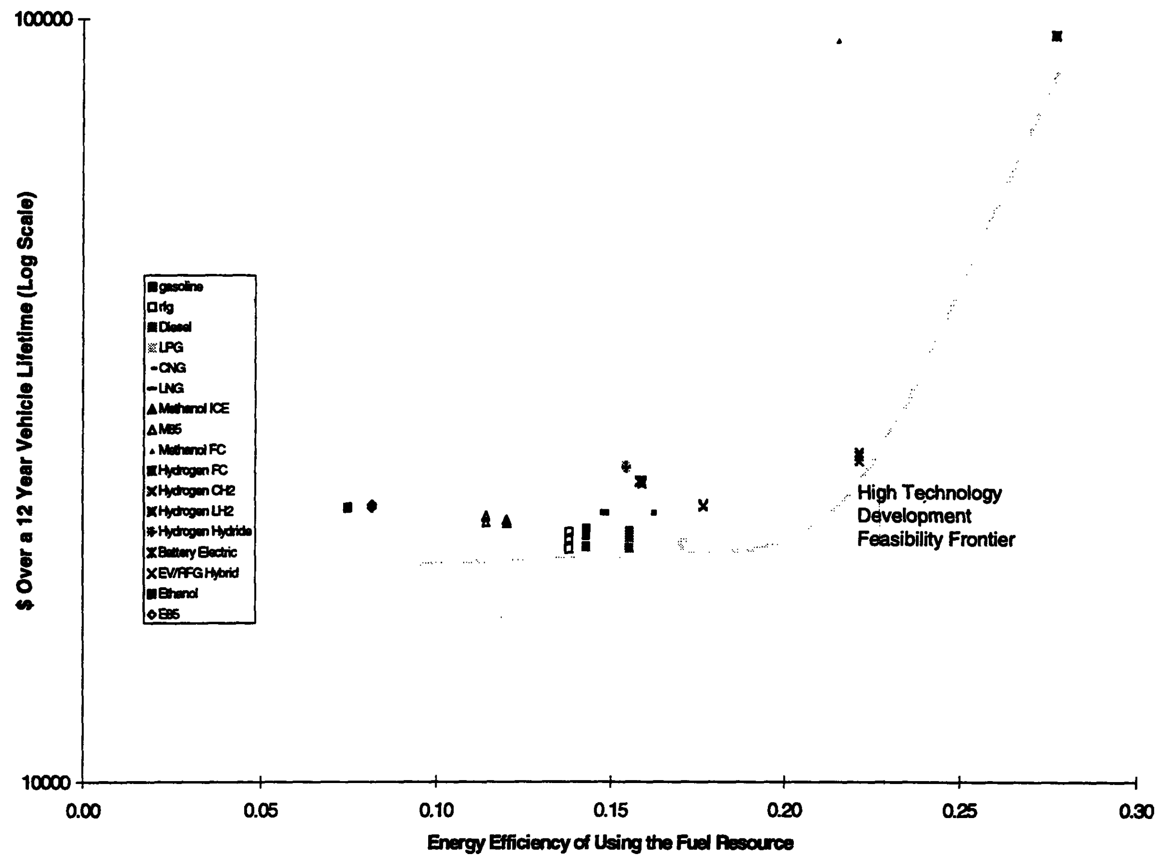

Figure 8.9: Lifecycle energy efficiency tradeoff curve for three sets of resource prices in 2010, and the case of high technological progress.

8.3 The Best Case Fuel Cell Scenario

This section presents the best case for the technology development and cost reductions of fuel cell vehicles compared to the high technology development case of all the alternatives. The differences between this scenario and those previously presented lie in two areas: first, all technologies are presented only in their high technology development case; and second, the costs of fuel cell vehicles are at their lowest possible value. Because of the small effect of the resource prices on lifecycle cost, the comparison with the best case fuel cell vehicle only considers the reference (medium) set of resource prices.

In the best case for fuel cell vehicles, their lifecycle cost competes with the "medium" cost group of vehicles identified in Chapter 6 and Figure 8.1. The technical feasibility frontier is lower as fuel cell costs come down. The hydrogen fuel cell cost tradeoffs for energy efficiency appear better than for methanol fuel cells, but the two are otherwise indistinguishable.

Figure 8.10 through Figure 8.13 show the same data discussed in the preceding sections, with two additional data points on each plot for the reduced cost fuel cells. The possible improvements in fuel cell vehicles are highlighted on each plot.

8.3.1 Lifecycle Greenhouse Emissions: Best Case Fuel Cell Development

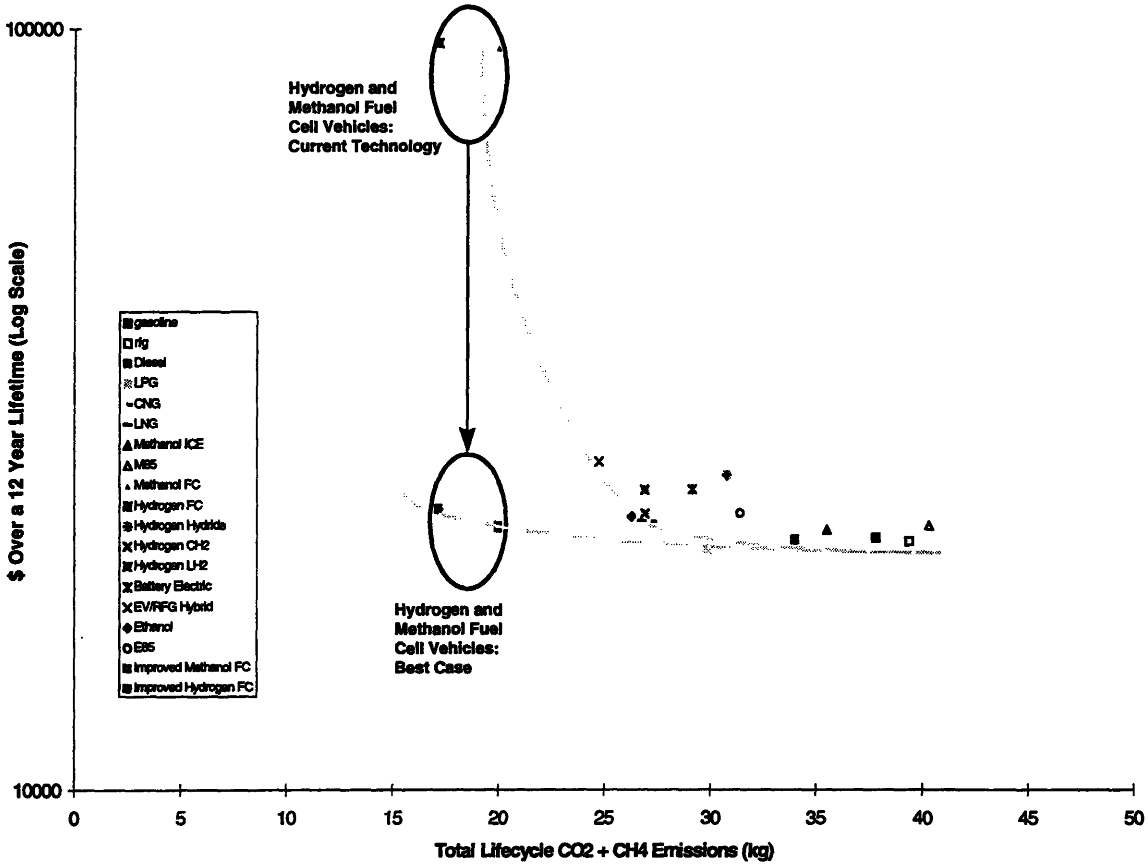

Figure 8.10: Lifecycle cost vs. greenhouse equivalent emissions for the best case fuel cell development.

A large cost reduction in fuel cells could lower the feasibility frontier for greenhouse emissions to a revolutionary extent (Figure 8.10). Fuel cell vehicles would be a clear dominant solution in this case, offering the highest greenhouse gas emissions reductions at a medium-level cost. Most other alternatives would be left well within the interior of the new feasibility frontier, at a cost disadvantage for their emissions benefits. Even at higher costs, fuel cell vehicles may be a competitive alternative if controlling greenhouse gas emissions becomes a priority. LPG and diesel fuel become the second and third best options because of their low cost.

8.3.2 Ozone Precursor Emissions: Best Case Fuel Cell Development

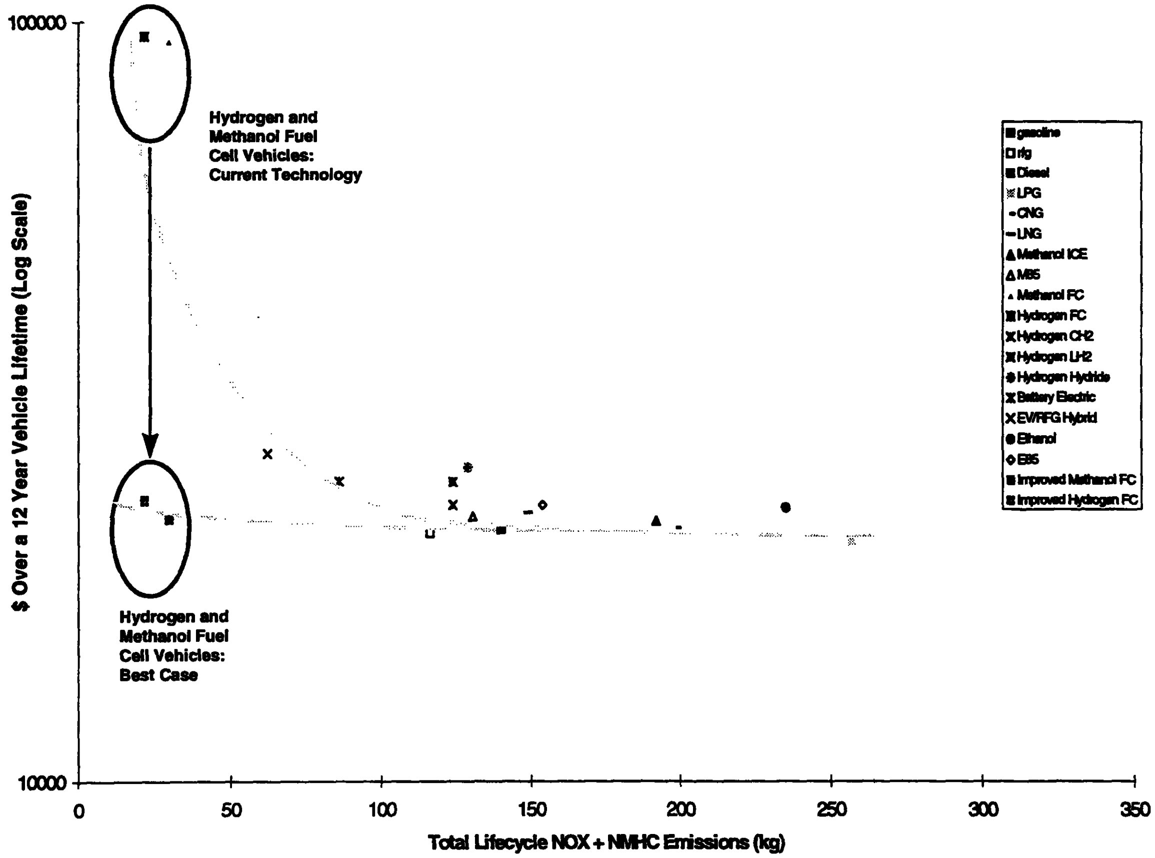

Figure 8.11: Lifecycle cost vs. ozone precursor emissions, best case fuel cell development. Reducing the cost of fuel cells would lower the feasibility frontier for lifecycle ozone precursor emissions, and would make fuel cell vehicles a competitive alternative for reducing ozone.

Figure 8.11 shows that either fuel cell vehicle could reduce ozone precursor emissions almost 90% from gasoline for the same the cost as natural gas or alcohol fuel vehicles, if fuel cells achieve their lowest predicted cost. The fuel cell vehicles would be on the feasibility frontier however, and the alcohol and natural gas vehicles would not be. The second and third best alternatives after fuel cell vehicles would be RFG and gasoline vehicles, because of their low cost. All other vehicles would be relatively costly for their potential in reducing emissions.

8.3.3 Particulate Matter Emissions: Best Case Fuel Cell Development

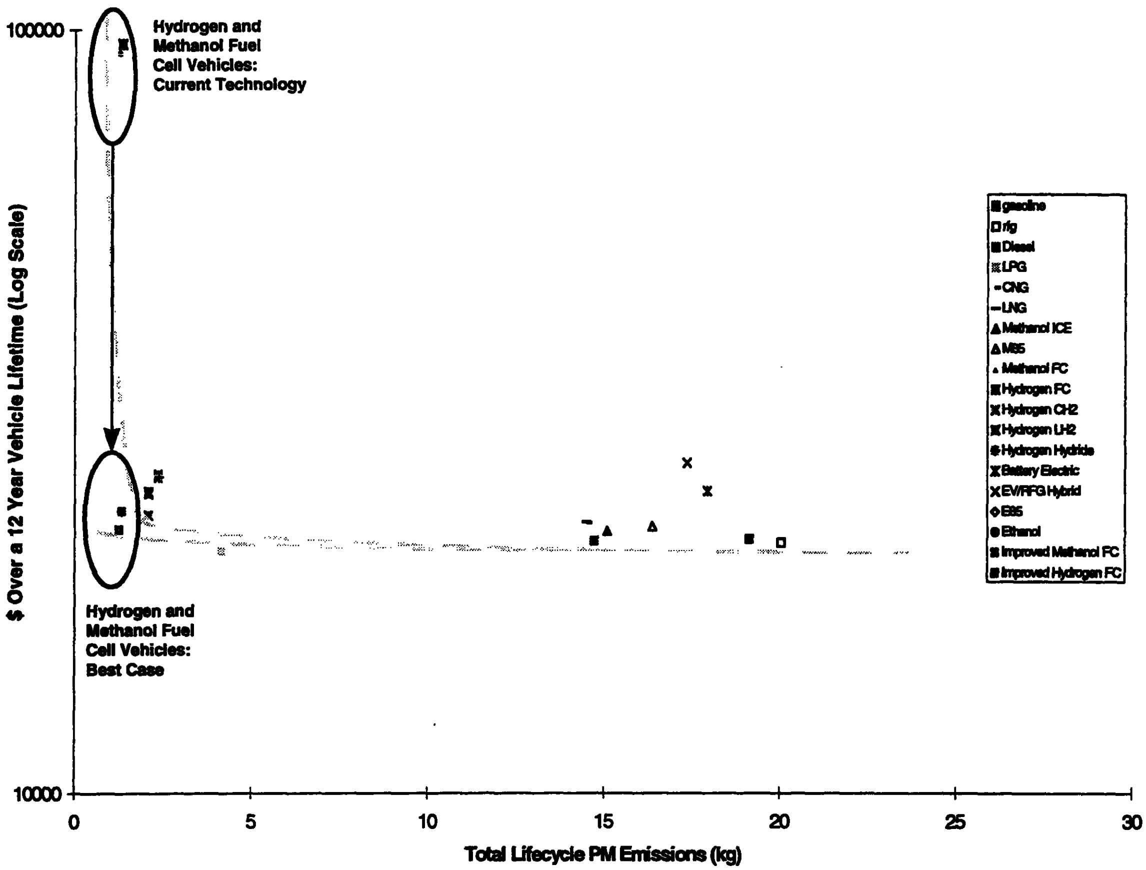

Figure 8.12: Lifecycle cost vs. particulate emissions, best case fuel cell development. The best case fuel cell vehicles would replace hydrogen combustion vehicles as the most cost-effective alternative for extremely low particulate emissions.

Because of the lower cost of fuel cell vehicles in Figure 8.12, hydrogen vehicles are no longer most cost-effective for their low emissions because fuel cells do a better job at reducing particulate emissions, for a lower cost. LPG remains a strong alternative for reducing PM, with the diesel next (again, because of the particular way in which the diesel engine was tested in the cited literature. See Sections 4.2.3 and 5.3.4).

8.3.4 Energy Efficiency: Best Case Fuel Cell Development

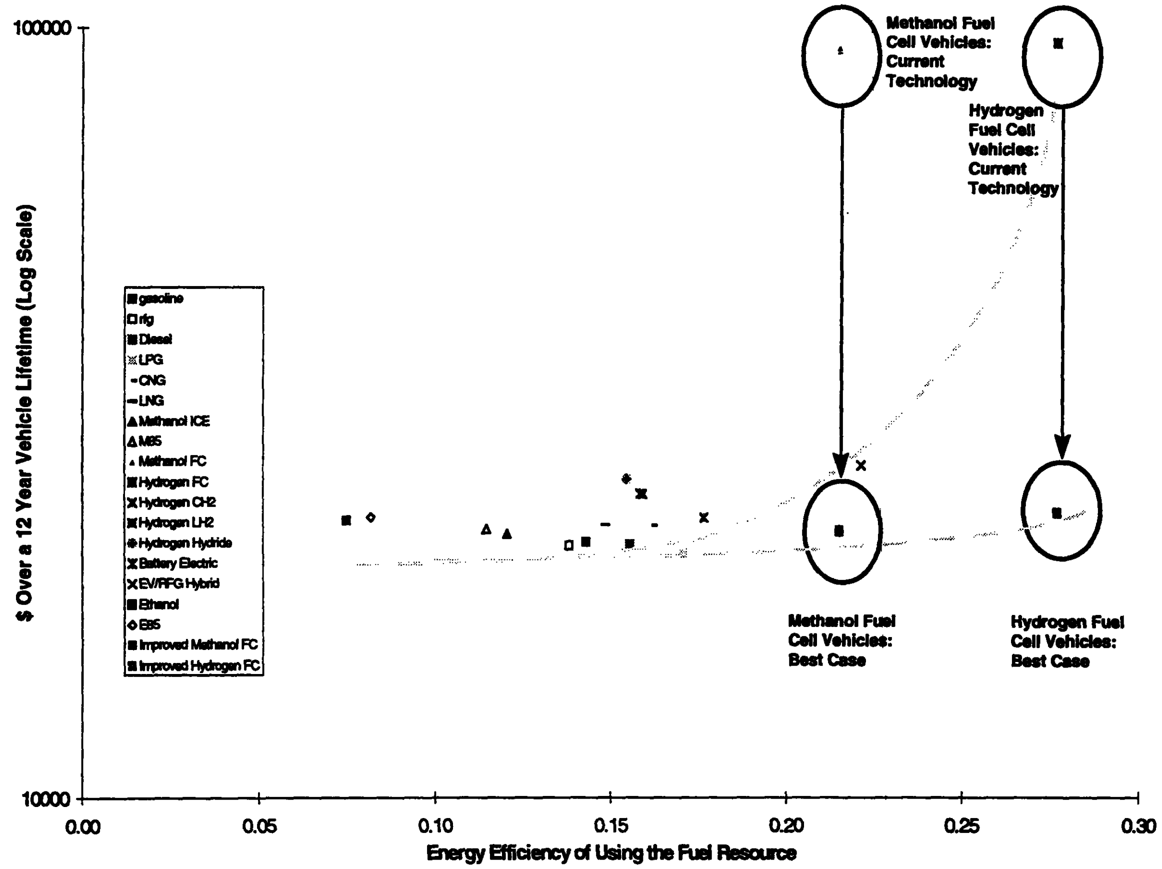

Figure 8.13: Lifecycle cost vs. energy efficiency, best case fuel cell development. Fuel cell vehicle lifecycle efficiency depends on the fuel. Hydrogen fuel is more efficient than methanol, resulting in less cost-effective efficiency improvements with the methanol FCV than with hydrogen FCVs.

The different fuel chains result in different lifecycle energy efficiencies for hydrogen and methanol fuel cell vehicles (see Figure 8.13). Only the hydrogen fuel cell vehicle lies on the feasibility frontier, because the lower efficiency of the methanol fuel cell vehicle, for roughly the same cost, causes it to be less cost-effective. However, under the best case fuel cell scenario, the methanol fuel cell vehicle is still a better alternative than either electric vehicle for its efficiency/cost tradeoff.

8.3.5 Summary of the Best Case Fuel Cell Development

A dramatic drop in fuel cell cost from the average $2600/W to the most optimistic $200/W would result in dramatic shifts in the feasibility frontiers for the cost of reducing lifecycle emissions and increasing energy efficiency. This change renders all the other technologies cost-inefficient for the improvements they offer. This may not be a realistic stable situation, considering that most of the technologies are currently grouped closer to the feasibility frontiers. It would be unlikely that advances in fuel cell vehicle technology would come unaccompanied by advances in other technologies, because if there is any benefit to be gained by reducing emissions and increasing energy efficiency, the other technologies would be competing for these same rewards alongside fuel cell vehicles.

This analysis for the best case of fuel cell development shows that, even with the dramatic environmental and fuel consumption improvements offered by the fuel cell technology, the cost of these vehicles will have to be substantially reduced, or predicted with more certainty, before they represent realistic policy alternatives.

8.4 Best Case Electric Vehicle Scenario

8.4.1 Greenhouse Emissions: Best Case Electric Vehicle

In the best case electric vehicle development, both hybrid and battery electric vehicles lie on the feasibility frontier for cost/greenhouse emissions tradeoffs, using the reference future resource prices and high technology development assumption use for the best case fuel cell development scenario (Figure 8.14).

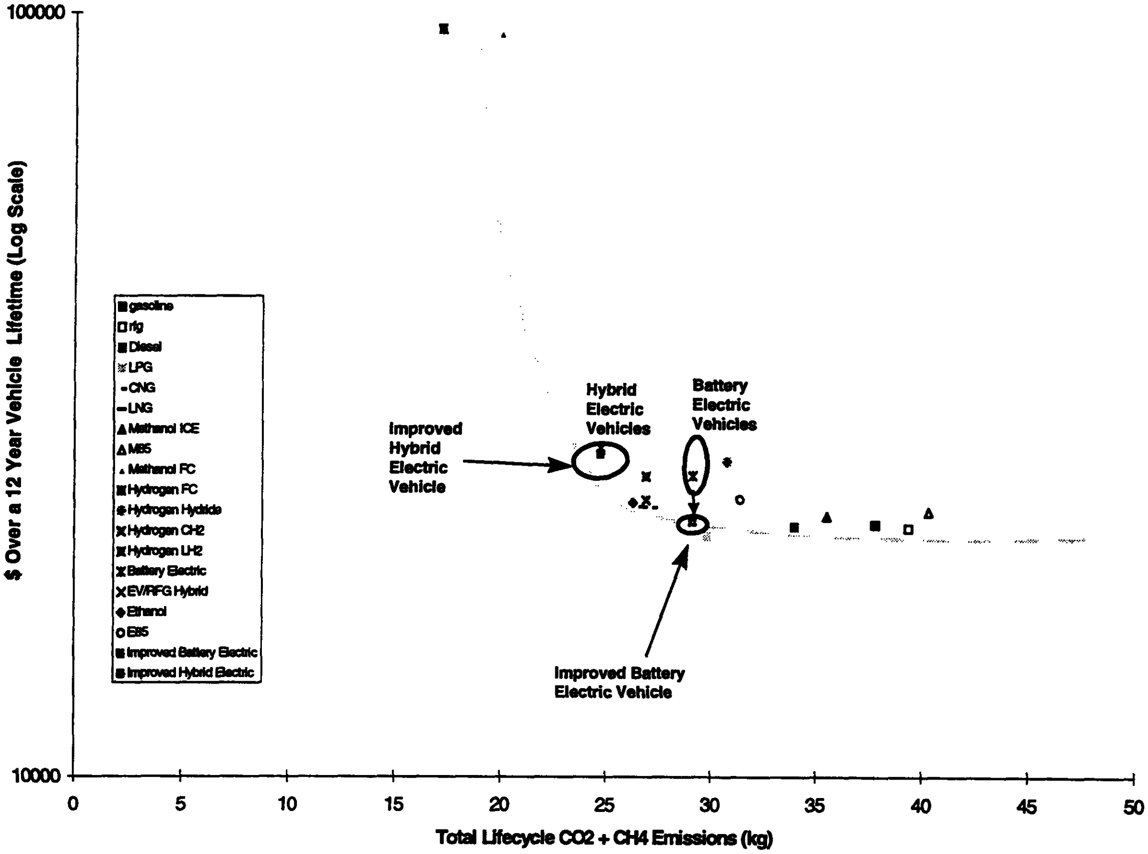

Figure 8.14: Lifecycle cost vs. greenhouse gas emissions, best case electric vehicle development. Both improved hybrid and battery electric vehicles arrive at the feasibility frontier for the three future fuel price scenarios.

8.4.2 Ozone Precursor Emissions: Best Case Electric Drive Development

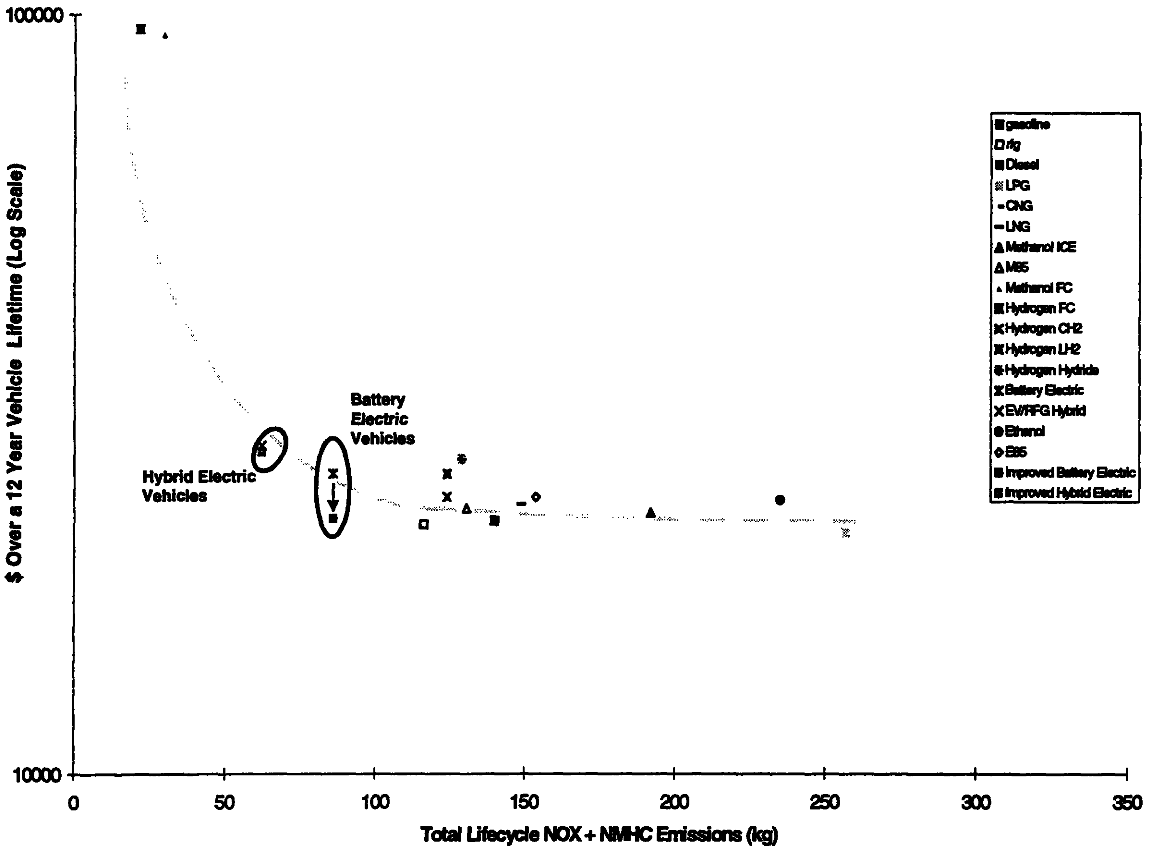

Figure 8.15: Lifecycle cost vs. ozone precursor emissions, best case electric vehicle development. Reduced EV costs improve their positions on the plot, bringing them nearer to the feasibility frontier, but they are fairly cost-effective alternatives at their average costs, anyway.

The reduced vehicle costs for hybrid and battery electric vehicles places them unquestionably on the feasibility frontier for ozone precursor emissions, making them cost-effective solutions (see Figure 8.15). But they are not far from the frontier under any future resource price scenarios in the previous case of average vehicle costs, because of their advantage in reducing ozone precursor emissions.

8.4.3 Particulate Matter Emissions: Best Case Electric Drive Development

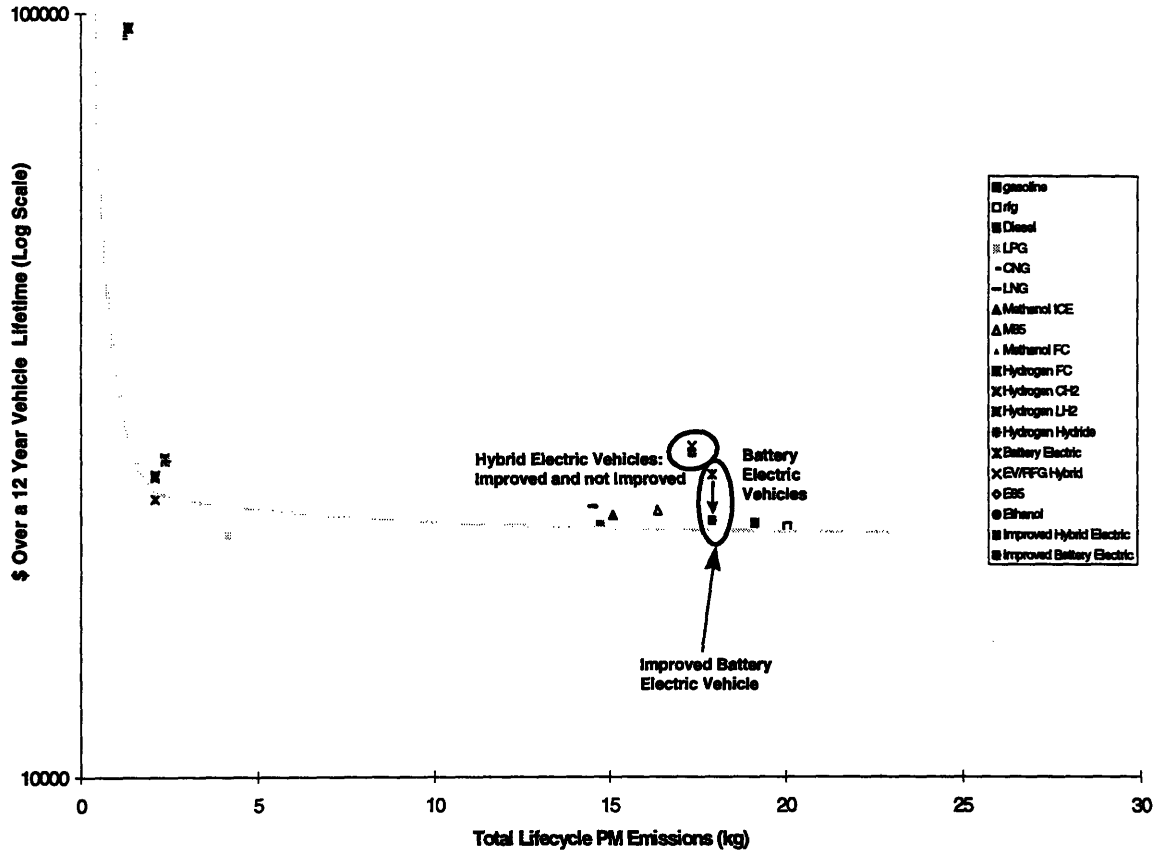

Figure 8.16: Lifecycle cost vs. particulate emissions, best case electric vehicle development. Neither type of electric vehicle lies on the feasibility frontier for cost/particulate emissions tradeoffs in this plot of their best development. The hybrid electric vehicles suffer from their carbon-rich petroleum fuel, and electric vehicles use a high proportion of coal in their electricity generation mix.

For particulate matter emissions, low-carbon fuels still determine the feasibility frontier for cost vs. particulate matter emissions (Figure 8.16). Both battery and RFG hybrid electric vehicles use high carbon fuels, ranking them as average PM emitters. However, both remain at a higher lifecycle cost than most other average PM emitters, so neither electric vehicle could be particularly cost efficient for its emissions, relative to other alternatives.

8.4.4 Energy Efficiency: Best Case Electric Drive Development

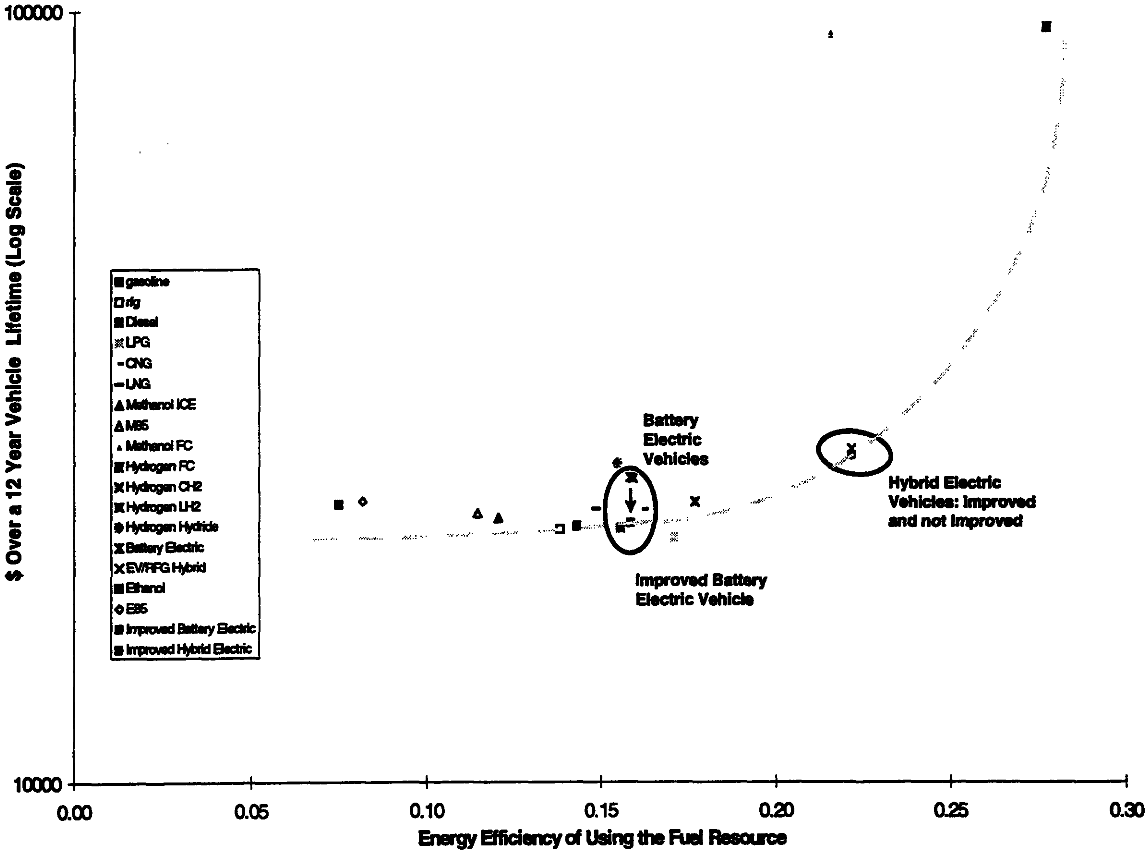

Figure 8.17: Lifecycle cost vs. energy efficiency, best case electric vehicle development. The hybrid electric with an improved energy efficiency ICE lies on the feasibility frontier, offering better lifecycle energy efficiency than a hydrogen fuel cell vehicle, at a much lower cost. The data point representing the expensive battery electric vehicle is obscured by the liquid hydrogen vehicle, but the data point for the inexpensive battery electric vehicle is visible near the feasibility frontier.

The reduced cost of the improved battery electric vehicle makes it competitive on an energy efficiency basis with conventional petroleum vehicles (see Figure 8.17). The hybrid electric vehicle's position on the feasibility frontier in has more to do with the improved energy efficiency of the internal combustion engine assumed under the high technology scenario, than with the reduced cost assumed in this section for the improved electric drive. The reduced cost makes this alternative appear a slightly more attractive way to reduce fuel consumption, however.

8.4.5 Summary: Best Case Electric Drive Development

The battery electric vehicle, because of its use of the high-capital intensive, and therefore slowly replaced, electricity generation infrastructure, will not be able to improve in lifecycle efficiency as much as an HEV with an internal combustion engine. Despite the BEV's large cost decrease under the assumptions of an improved manufacturing process, it can only manage to compete with the more efficient types of conventional petroleum vehicles on a lifecycle energy efficiency basis.

8.5 Summary of Scenario Results

The two main areas in which AFVs may have advantages over petroleum vehicles are reduced emissions from the tailpipe and fuel chain, and less reliance on imported oil for vehicle fuel. The cost tradeoffs for these benefits in the level-playing field model results do not identify a clear dominant alternative which would compel a nationwide policy to change motor fuel within the next 15 years.

The technology development of scenarios, either high or low, do not change the overall dominant alternatives from the base case, except that fuel cell vehicles become part of the cost-effective set of alternatives, despite their high forecast cost.

The lack of large change in the costs versus emissions or energy efficiency benefits between alternatives in the base case and the future scenarios is explained by the following assumptions in the model and its inputs:

- First, the rise in natural gas prices alongside crude oil prices results in small relative cost changes between fuels which derive from either resource. The cost reductions enjoyed by natural gas fuels as a result of manufacturing improvements and returns to scale are small relative to the increased costs of the natural gas feedstock. If crude oil prices were to rise while natural gas prices stayed lower, natural gas-derived fuels could have tradeoff advantages for emissions and energy efficiency.

- Second, emissions controls or energy efficiency gains achieved by one combustion engine vehicle are shared by all combustion engines where feasible. The improvements for each fuel are limited by the fuel's physical characteristics. For example, vehicles using carbon-containing fuels could not emit zero CO2, CO, or hydrocarbons. They can only reduce these emissions based on their fuel consumption or exhaust gas management.

- Finally, the uncertain future costs and performance of the experimental alternative fuel vehicles (hydrogen fuel, fuel cells, and electric drive vehicles) were represented by a wide range between high and low forecast vehicle costs. Using the average of these two costs makes for a lifecycle cost that is less responsive to inputs than that of vehicles whose cost is more precisely known. These cost results are very "blurry" between the high and low bounds of the input values. Because of a lack of available information, the possible effect of emissions controls, etc. on these vehicles also cannot be modeled precisely, so the thesis does not attempt to change the claimed performance values very much from the sparse information available in the literature. As a result, there was not much change in the performance of these vehicles from the low to the high technology scenario.

The special scenarios of low fuel cell and electric drivetrain costs show two extreme results of the uncertain cost. Comparing the average cost of alternatives to the fuel cell vehicle at its optimistic cost dramatically changes the prediction of dominant alternatives, making the fuel cell not only the lowest emitting type of vehicle, but also one of the least expensive. Performing the same type of comparison between reduced cost electric vehicles and the other alternatives at their "average" cost does not appreciably change the future outlook from the six scenarios which analyzed alternatives based on their average lifecycle costs.

In comparisons of the average lifecycle costs of every alternative, the base case results in Table 6.3 hold through the three sets of resource prices and two cases of technology development, showing that several fuel alternatives could be economically efficient ways to reduce certain emissions. In addition, compressed hydrogen combustion vehicles could become economically efficient alternatives for reducing greenhouse gases and ozone precursor emissions, and ethanol fuels could benefit from fuel chain improvements to become economically efficient at reducing greenhouse gas emissions (see Table 8.3).

Table 8.3: Vehicles with Cost Tradeoffs on the Feasibility Frontier under Future Scenarios

Fuel Group	Greenhouse Gas	Ozone Precursors	Particulate Matter	Carbon Monoxide	Energy Efficiency	Fuel Resource Extender
Liquid Petroleum	Yes	Yes	Yes	Yes	Yes	
Methanol Fuels (ICE)				Yes	Yes	Yes
Natural Gas	Yes		Yes	Yes		Yes
Ethanol Fuels	Yes			Yes		Yes
CH2, LH2 (ICE)	Yes	Yes	Yes	Yes		Yes
RFG Electric Hybrid	Yes	Yes			Yes	Yes
H2 Hydride			Yes	Yes		Yes
Battery Electric		Yes		Yes		Yes
Methanol Fuel Cell	Yes	Yes	Yes	Yes		Yes
H2 Fuel Cell	Yes	Yes	Yes	Yes	Yes	Yes

The model also shows that improvements in AFV technologies resulting from current regulatory-driven R & D could continue to fill locally sustainable AFV niche applications where air pollution laws, lower fuel costs, or consumer preference allow AFVs to be competitive.

9. Policy Recommendations

The nation's dependence on personal motor vehicles and freight trucks suggests that prudent long-term national policy should prepare strategies for two possible situations:

- The need to reduce vehicle emissions in the face of continued VMT growth
- Ways to cope with eventual constraints on oil supply.

The model results from Chapters 6 and 8 do not identify a clear dominant fuel or vehicle alternative to motivate immediate change, but these future scenarios should motivate nationwide policies that gradually lay a foundation for fuel alternatives which lower emissions and extend the oil resource. The results of the modified ADL/Ford model provide a summary of the technology alternatives that a policy approach for incremental change might consider pursuing in the next 15 years. Based on the research results presented in the preceding chapters, this chapter suggests both a national AFV role of low-tailpipe emission vehicles in a strategy which continues to use petroleum, and steps to prepare nationally for gradually introducing natural gas as a complementary alternative transportation fuel resource.

9.1 Organization of Policy Formulation Presented in this Chapter

This thesis uses the following organization in arriving at its policy recommendations:

- **A statement of the problem.** What motivates consideration of alternative fueled vehicles? A short review of the problem background (presented in Chapter 2) is summarized in Section 9.2.
- **Definition of opportunities for AFVs.** What roles can they can play in solving the problem? What goals should be set, and what results should be expected? The potential opportunities and roles of different AFV technologies are also presented in Section 9.2.

- **Comparison of alternatives for reaching the goals.** Which might actually work, and which should be avoided? This is based on model outputs drawn from summaries of Chapters 4, 6 and 8, and is presented in Section 9.3.
- **Choice of effective alternatives.** These are defined within the uncertainties of the model, the future scenarios, and the goals of using AFVs, in Section 9.3.
- **Definition of a sustainable policy strategy.** The strategy promotes the effective alternatives. Defining a policy strategy relies on technical and economic information about AFVs, consumer demand, and political concerns involved with each alternative. The policy strategy is described in Section 9.4.
- **Implementation of the policy.** By what mechanisms could the policy measures be accomplished? Section 9.5 lays out the considerations for implementing the policy strategy.

9.2 Opportunities for AFVs

The future of AFVs relies on the continued need for reduced mobile source emissions and an anticipated need to change from oil as the sole transportation fuel. These needs are not sensed by consumers of personal transportation, and are not currently internal to the cost of owning and operating a vehicle except when oil prices rise. The federal government has created a possible application for AFVs as low-emitting vehicles in the CAAA by federally regulating tailpipe and regional pollutants and by supporting, with EPACT, the conversion of fleets to AFVs, at least through 2004. Similar controls on emissions and fuel consumption will be necessary beyond 2004 for AFVs to enjoy any market in the U.S.

9.2.1 Role in Reducing Emissions

AFVs will find geographically localized roles as technologies which can help reduce mobile air emissions, when and where they cost less (to the consumer) than low-emission petroleum vehicles. This role could be threatened either by low cost modifications to petroleum vehicles that reduce tailpipe emissions to AFV levels, or transportation control measure (TCM) policies that aim at cutting VMT to reduce emissions. The lowest emission vehicles may have an advantage over like-priced, higher emitting vehicles in the future when states consider vehicles in their SIP requirements, because federal policies are likely to continue to lower maximum local air pollution standards, if not tailpipe emissions directly.

Some AFVs may reduce local emissions resulting from vehicle use, but might increase total emissions when the fuel chain is considered. Whether they do depends on the mix of resources from which their fuel is derived. These AFVs might still be able to be introduced nationally along with an emissions trading system in the context of the existing AQCR system of pollution control jurisdictions. Areas which benefit from using the vehicles could end up paying compensating money, for example, to the areas which have raised their emissions in order produce the vehicles' fuel. The fuel chain would probably be managed locally like any other stationary emitter, even though its emissions are directly tied to VMT in another (or the same) region.

9.2.2 Role in Resource Conservation/Diversification

The AFV role in reducing oil consumption could lie either in a complete change from oil, consuming only fuels from renewable sources, natural gas, or coal, or in the consumption of oil-derived fuels that have been mixed with other fuels in order to extend the life of each resource. This means that several types of AFVs could be used concurrently in the future, with fuels separated by the application niche of the vehicle, like diesel and gasoline are today between heavy trucks and cars in the U.S.

Increasing the energy efficiency of vehicles would have the doubly beneficial effect of reducing emissions and extending the fuel resource. AFVs with internal combustion engines will benefit from any technological advance that increases the energy efficiency of gasoline vehicles, so more efficient gasoline vehicles should not deter the introduction of alternative combustion fuels, but could postpone the introduction of more efficient but more expensive competing vehicle technologies like BEVs and FCVs. Whether energy efficiency policies like CAFE influence alternative fuels will depend on the specific wording of the law and its interpretation. For example, a "per gallon of gasoline" mileage standard could encourage auto manufacturers to design for fuel blends which reduce the gasoline content in the fuel, thus raising the "miles per gallon of gasoline" of the vehicle, whereas a "per gallon of fuel," or as in this thesis, a "per GJ of fuel" efficiency standard might not encourage this experimentation, and would focus their efforts instead on optimizing engine function for a specific fuel (most likely gasoline, because it is the established fuel). Any efficiency law with the aim of reducing dependence on crude oil will have the potential of benefiting AFVs.

9.2.3 Regional vs. National Role

The role that cleaner vehicles play in reducing emissions is regional, and perhaps even consuming local fuel. But the regional policies which promote AFVs affect the nation through car and fuel manufacturers and through interregional issues like vehicle and infrastructure compatibility. Vehicles have the capacity to "migrate" much farther and faster than most air pollutants, and to range beyond local fuel supply infrastructure. Because of this, their support infrastructure has to be guided under a national policy. Niche applications of AFVs will correspond more practically to different vehicle uses rather than to different geographical areas.

9.2.4 Conclusion of AFV Role

The long-term role of AFVs would be to diversify or switch the nation's fuel resources. Improved vehicle performance (including emissions) will be a secondary role unless decision makers evaluate the cost of air pollution from vehicles as being as high as the cost of depending heavily on crude oil.

In the short term however, considering the prospect of rising VMT and the low cost of crude oil, AFVs should meet or improve on the emissions benefits of using reformulated gasoline for a cost-effective policy.

9.3 Comparison and Choice of the Alternatives for Achieving a National, Low Emission AFV Policy

This section summarizes the modified ADL/Ford model outputs from Chapters 6 and 8 in a policy context.

9.3.1 Choosing an AFV on the Basis of Fuel Resource Tradeoffs

Resource reliability over the long term will be a vital component of AFV success. It has to be plentiful, accessible, low cost, easily converted to a useful mobile form of energy, and if it is not clean, it must be able to be cleaned inexpensively.

LPG

The LPG resource is very limited. Its proven reserves are only 1% of those of gasoline, when expressed in terms of potential vehicle miles (Table 6.2). LPG is also an important fuel for rural households which are not utility-connected to natural gas (DOE 1992b). As a vehicle fuel, LPG cannot be used for more than a niche role, despite its low cost and superior emissions characteristics.

Biomass

Biomass is one of the potential “zero” greenhouse gas emitting resources, but it appears to be an unreliable primary fuel resource because of its potential annual variation in supply and environmentalists’ opposition to large crops on the grounds of decreased biodiversity. Fuels from biomass, ethanol and methanol in the model, are also expensive and have high lifecycle PM emissions in the base- low technology case because of emissions during the harvest and fuel fermentation process (Figure 6.6, Figure 8.6, and Figure 8.7). In the high technology development cases modeled for 2010, ethanol would be an economically efficient way to reduce greenhouse gas emissions (Figure 8.3). As a gasoline extender and reducer of lifecycle CO2 emissions, biomass could continue in a future role as a feedstock for additives to conventional petroleum fuels, where it could enjoy a substantial market. It competes with less expensive methanol derivatives as a gasoline extender, however.

Coal

The coal resource in the U.S. is very large compared to other North American resources. However, it is a dirty fuel in terms of particulate emissions (which may be able to be filtered out), and in terms of CO2 (which cannot be avoided as coal is processed into other forms of energy). The CO2 problem makes this fuel resource an unlikely alternative for vehicle fuels other than the established electricity generation infrastructure. With respect to greenhouse gas emissions, coal's best use in a vehicle is as a resource for methanol or hydrogen for direct conversion fuel cell vehicles. But natural gas is a better resource for these fuels from an environmental and cost standpoint.

Coal conversion into the fuels modeled here is expensive. This thesis did not model coal liquefaction into heavy oils or gasoline. See, for example, National Research Council (1990) for more details on this technology. Coal will likely be only the third resource choice for transportation (except for battery electric vehicles at a niche level) behind oil and natural gas.

Natural Gas

Natural gas is a good second mainstream fossil resource for vehicle fuels.

In the terms of the resource reserves, natural gas reserves in North America could provide transportation with 150-200% of the "mileage" of its oil reserves in combustion vehicles (see Table 6.2). As a large resource component of M85, natural gas could extend gasoline miles 170% until its supplies were exhausted. This would only use 15% of the potential oil "mileage" in the form of gasoline, leaving roughly 85% for use in diesel trucks or gasoline vehicles. An alternate strategy combining these two approaches might use natural gas as combustion fuel for some vehicles, while continuing to use crude oil fuels in others. Dividing vehicle types between those which use pure natural gas and those which use crude oil resources could provide total vehicle miles of 300% of the mileage from gasoline alone.

Because of the large storage space needed for fuel in natural gas vehicles, either liquid or compressed, the use of this fuel is more suited to large vehicles or heavy duty applications in which a few cubic feet more or less of trunk space will not affect vehicle sales. Even with the compromised cargo space, the range of these vehicles would be shorter than that of conventional vehicles. The high capital cost of a natural gas filling station suggests a fleet niche to maximize the efficient use of the filling station investment.

Hydrogen from natural gas would be a very clean fuel, and its use in vehicles is an efficient application of the natural gas resource in a lifecycle sense (Table 6.2). Its widespread use in vehicles suffers from the same technical problems as natural gas, and it is expensive. Because of its economic efficiency in reducing particulate emissions and lifecycle efficiency (Table 8.3), and its low tailpipe ozone precursor emissions (Figure 6.5), it should not be discounted as a viable niche technology.

Because natural gas is used extensively in industry, and this use is growing, the EIA forecasts a rise in its prices in excess of the rise in oil prices in the next 15 years. When this forecast is used in the model, it causes the difference in cost between natural gas fueled vehicles and liquid petroleum vehicles to rise in all but the high cost 2010 scenarios, compared to this relationship today. However, the larger natural gas reserves in North America may indicate that this rate of price increase could stabilize in this country at a lower rate than that of crude oil. The cost results in Chapter 8 show that the lifecycle cost of M100 ICE vehicles could match that of conventional gasoline vehicles at a high crude price if the price of petroleum and natural gas rise at the same rate.

Crude Oil

The crude oil is the most economical resource, is plentiful and easily obtainable, and has a developed supply infrastructure. Experience with the oil-derived fuels shows that their emissions can be controlled to a low level for a reasonable cost. There is no reason to change from oil in the next 15 years on arguments of the emissions, availability, or cost of the resource or its fuels. Mixing crude-oil derived fuels with fuels from other resources could improve their emissions and extend the crude oil reserves.

9.3.2 Choosing an AFV on the Basis of Lifecycle Emissions Tradeoffs

Under all scenarios that use the average of forecast vehicle cost, no alternative except the liquid petroleum fuels is economically efficient relative to all of its emissions or lifecycle energy efficiency (Table 6.3 and Table 8.3). Some of the other fuels and vehicle types offer compromises that are compared here. Hydrogen and methanol direct fuel cell vehicles could offer economic efficiency with emissions and energy benefits if their costs decrease dramatically relative to the cost of the other vehicles (Section 8.3).

This section divides the discussion into cost groups because cost would be a central issue of political debate. The boundaries between the cost groups were not set at fixed dollar values, rather at each large "step" up in incremental cost over a conventional gasoline vehicle (see discussion of costs in Chapters 6 and 8).

Low Cost Alternatives

For "low" cost, the vehicles using conventional petroleum fuels, and especially RFG, provide the best all-round performance (see Table 6.3 and Table 8.3). All of these fuels show lifecycle costs within $150-$160 of each other over the lifecycle, within the uncertainty of the model assumptions. We have shown that LPG cannot be a mainstream fuel for supply constraints. RFG contains 11% by volume of an alternative fuel (MTBE, a methanol derivative), presenting a potential large market for this fuel, which is derived from natural gas. In areas needing low CO and ozone precursor emissions, the emphasis of the CAAA90 vehicle fuel programs, RFG vehicles with catalytic converters and evaporative fuel canisters can only be improved upon in an economically efficient way by battery electric and hydrogen or fuel cell vehicles.

New low sulfur diesel could enable the use of a catalytic converter on diesels to reduce NOx, but this alternative was not modeled for a lack of data. This promising (because of low cost and simple compatibility) alternative should be studied and compared to the potential diesel substitutes, natural gas and methanol.

Medium Cost Alternatives

The resource advantages outlined above could be realized with equal or improved emissions relative to RFG by using M85, NG, or pure alcohol fuels in their best technology case, for a medium lifecycle cost. This would involve a lifecycle cost increase over liquid petroleum vehicles of about $540-$3000, depending on the scenario (Figure 8.1). The range of lifecycle costs for fuel cell vehicles includes the possibility of great emissions reductions for a cost that falls within this range.

Natural gas vehicles are the most popular AFV in the world. NGVs suffer from either reduced range or cargo capacity because of the space needed for the pressurized or cryogenic tanks. They therefore face difficulty in becoming a complete replacement in the passenger vehicle market, but work well as fleet vehicles. Natural gas combustion vehicles could also be very clean replacements for large diesel trucks. A further study is recommended to evaluate heavy duty diesel trucks in a lifecycle analysis alongside heavy duty natural gas trucks. Methane fuel cell vehicles were not modeled in this thesis, but are a possibility that should continue to be investigated. NGVs are currently supported in federal and state policies by tax deductions for refueling stations and rebates for vehicle purchases (Chapter 3). Their break-even natural gas price, relative to the crude oil price, is only slightly lower than that for M100 ICEVs, but higher than that for M85.

Pure alcohol combustion vehicles do not appear promising. Both pure ethanol and pure methanol vehicles have cold-start problems which would limit their use without gasoline as an additive to raise their volatility. Pure ethanol may have supply problems, depending on crop yields and political pressure. Neither AFV is a likely replacement for gasoline vehicles or heavy trucks because of the cold-start problem. Research to solve this problem is progressing in the direction of engine design and fuel additives that do not raise alcohol fuel emissions (Roller 1996). Pure methanol ICEVs are one of the only alternative fuel vehicles with a reasonable break-even resource price that would enable it to compete on a level playing field with gasoline (see Section 8.2.1).

The alcohol/gasoline blends offer similar performance to each other in the high technology development case, but M85 is much cheaper than E85. In the likely future of continued combustion engine use, M85 appears to be a competitor with RFG if policies begin to stress either the use of the natural gas resource in vehicle fuels, or a reduction in lifecycle greenhouse emissions. M85 vehicles have a higher lifecycle cost than RFG vehicles under all scenarios tested in this model, but if natural gas prices do not rise as much relative to crude oil as this research assumes, then it could compete on a cost basis with RFG (see Chapter 8). It would have a disadvantage with respect to pure methanol, because of the cost added to it by its crude oil component.

High Cost

Among the expensive vehicles, battery electric and hydrogen fuel vehicles share the best emissions characteristics, with RFG HEVs emitting low per mile amounts of NOx. Of course, only BEVs have no drivetrain emissions. The high energy efficiency of hybrid and battery electric vehicles reduces their lifecycle emissions, especially of CO2, over conventional petroleum vehicles. All of them have potential niche applications due to their exceptionally low tailpipe emissions, but BEVs and HEVs have a more widespread "fuel" distribution network and "friendly" reputation than hydrogen. Though hydrogen vehicles remain high cost alternatives under future scenarios, they are the only alternative that shows potential to be as economically efficient as liquid petroleum in terms of each of its emissions.

In the best case future scenario for electric vehicles, battery electric vehicles could experience cost reductions which make them cost-competitive over the lifecycle between liquid petroleum and methanol fuels. They would be a more attractive alternative than combustion fuels in this case for applications emphasizing energy efficiency, greenhouse gas emissions, and ozone precursor emissions. Pursuing the USABC battery development goals would be a good way to encourage vehicle manufacturers to continue working on manufacturing cost reductions for electric vehicles.

Experimental Vehicles: Fuel Cells

The highest emissions reductions are available in fuel cell vehicles, which are not market ready and which have an uncertain future due to their low power density, which results in a large-sized powerplant. H-Power, Inc., a fuel cell development company, predicts that fuel cells will first be used in heavy duty trucks because of their high volume displacement (Maceda 1996).

Fuel cell vehicles have an extremely high and uncertain expected lifecycle cost, though if the lowest vehicle cost is assumed to prevail in the next 15 years, they could be an attractive alternative at the medium cost level. The very high emissions reductions and energy efficiency gains for these vehicles suggest that this technology is worth developing further in an effort to reduce its cost toward the optimistic cost used for the scenario analysis in Chapter 8, and to reduce its size for use in passenger vehicles.

9.4 Suggestions for Sustainable AFV Policy in the U.S.

The preceding sections have identified a nationwide role for low emission AFVs which utilize some combination of natural gas and crude oil for fuel. In the absence of a pressing resource or pollution need to compel a change to alternative vehicle fuels, but with the knowledge that a resource change will have to be made eventually, this study recommends some steps to take soon to prepare for supplementing crude-oil fuels with the use of natural gas-derived fuels sometime after 2010. The starting point for the recommendations are existing programs at the national level.

The concerns that guide the recommendations in this section include:

- **Best alternatives:** Choice from the previous section
- **Efficacy:** Which alternative technologies really reduce emissions? Will anyone use them enough to make a difference in emissions or oil consumption?
- **Stability of alternatives:** Will (should) there be one or many alternatives in the future for a stable transportation resource base? Will they change more than once?

Fuel resource concerns drive the choice of alternative fuel, and emissions and cost concerns drive the efficacy of the policy.

9.4.1 Summary of the Policy Recommendations

This study recommends to continue using conventional petroleum fuels in most vehicles, while insisting on low tailpipe emissions and low regional pollution levels with RFG as the first alternative fuel for cars in ozone polluted regions. Additionally, we recommend preparing for a nationwide introduction of AFVs which use the natural gas resource as an alternative to crude oil, which will run into supply constraints some day. While hoping to leave the choice of timing the introduction of alternative fuel vehicles to local market demand for low-emitting vehicles, the recommendations suggest that the country prepare its fueling infrastructure for a personal vehicle fleet which uses fuels that mix crude-oil and natural gas derived liquid fuels (RFG and M85, or possibly M100 if methanol fuel cells develop).

For heavy duty vehicles, this study recommends that low sulfur diesel be evaluated next to natural gas using this level-playing field lifecycle method, to see how cost-effective each are at reducing NOx and particulate matter emissions.

Niches where vehicles are used in conjunction with centralized refueling locations should look at natural gas as a fuel, and at battery electric and hydrogen vehicles in the next 15 years if there is pressure for very low emissions.

These suggestions recognize the superior emissions benefits offered by RFG and the availability of crude oil, and recommend continuing its use in high pollution regions as a low cost method of reducing emissions. However, they also recognize the desirability of avoiding multiple incompatible fuel systems or changes in fuel systems over time.

9.4.2 Summary of the Alternatives to Pursue

Recommendation to Prepare for Alternative Fueled Passenger Vehicles

The recommendations would modify standard gasoline refueling infrastructure or fuel storage practices across the country for alcohol compatibility, including automobile fleets. We do not expect that ethanol could be used on a widespread basis, but we cannot exclude its use from consideration due to its regional appeal in the Midwest. However, methanol is the intended "alcohol" for the majority of the country in the remaining discussion. The differences between methanol and ethanol compatible vehicles would be slight.

Certain alcohol-proofing practices, like periodically vacuuming excess water out of fuel storage tanks, are already followed in regions which use E10 (gasohol oxygenated fuel). Gasoline station modifications would require replacing certain plastic parts of tanks, pipes, and pumps with alcohol resistant parts, and either removing anti-corrosion tank liners that can dissolve in the alcohols, or replacing the tanks.

Since all tanks and pumps eventually need to be replaced, we recommend a simple regulation which mandates that replacement parts must be alcohol compatible. The cost would be borne by the gasoline stations, and passed on to consumers, at first in the form of higher gasoline or RFG prices, and later in the prices of alcohol fuels. This low cost, estimated in the model at about 11 cents per GJ of fuel (about 0.8 cents per gallon of gasoline) is included in the lifecycle cost analyses presented in Chapter 6.

This recommendation has its roots in the Clean Cities Program of the CAAA90, which states a commitment to "clean corridors" between cities along which clean burning alternatives refueling stations should be established (Chapter 3). Whether and where alcohol fuels are actually adopted will depend on emissions requirements, which is a local effect, and on relative fuel prices, which is partly a national policy decision. Continued pressure on the states to improve regional air quality will be necessary for the introduction of alcohol fuels.

Recommendation for Further Analysis of Natural Gas Fleets in Urban Environments

The recommendation is to continue the Clean Cities and the Clean Fuels Fleet Programs of the CAAA. These hope to lower urban particulate and NOx emissions either by replacing diesel buses with natural gas buses, or by introducing low-sulfur diesel and requiring catalytic NOx converters and particulate filters on buses. Natural gas can lower local NOx emissions over diesels because they can use a catalytic converter that diesels cannot use, due to the sulfur content of the diesel fuel that fouls the converter catalyst. The low sulfur diesel was not modeled here due to lack of information on new low-sulfur diesel and exhaust filtration products.

We recommend a further cost analysis of low-sulfur diesel with new information, when it becomes available, because this fuel is mandated by the CAAA, and its efficacy should be compared to that of natural gas before policies can be recommended.

Centrally refueled urban fleets other than buses should be encouraged to continue introducing natural gas vehicles, as UPS, Federal Express, and the U.S. Postal Service, among others, are doing. Fleets of smaller vehicles, like taxi cabs, could convert to natural gas, but at a loss of vehicle range. The benefits might include more public adoption of natural gas vehicles, as well as the immediate air quality benefits of the NGVs.

Heavy Duty Engines

Pure natural gas fuels have a potential excellent application in heavy duty engines, which should be pursued by local policy. National policy could set emissions standards for those vehicles which are to be used in urban regions, low enough to send a message that natural gas powerplants would be preferred, though not specifically required, and coherent financial incentive programs could be offered in the high-ozone level states to partially offset the per vehicle cost of installing the refueling stations. Farm vehicles could continue to use diesel, since farms are not generally in high ozone regions.

According to Maceda (1996), heavy duty vehicles might also be the first market applications of fuel cell vehicles, because of their low power density. They may convert diesel or gasoline to hydrogen on board the vehicle at first, but if manufacturers succeed in developing the methanol fuel cell further, it would be a small step for manufacturers of heavy duty vehicles to remove the hydrogen reformer and substitute methanol fuel cells. Fuel cell vehicles using hydrogen fuel instead of a liquid fuel face more obstacles because of the volume of the gas or cryogenic storage system in the vehicle, and the need to install high pressure or cryogenic refueling stations. Once vehicle fleets use centralized natural gas or hydrogen refueling systems however, it is a smaller change to replace combustion vehicles with fuel cell vehicles that use hydrogen or natural gas. Given the uncertainty in the development of fuel cells, their introduction should be left to their manufacturers, and helped by strict vehicle emissions or efficiency standards.

9.4.3 Efficacy of Chosen Alternatives

Considering the relative roles of individual vehicles and of VMT in contributing to pollution, we see that changing a small proportion of vehicles to very low emissions or an alternative fuel will not have the large effect that a small change over many vehicles would have. Dramatic changes risk being difficult to accept, so a conservative approach to successful alternative fuel introduction should first try to find the most acceptable alternative.

RFG can be used in any modern vehicle, and does not cost appreciably more than normal gasoline. Its emissions benefits can be realized within the time it takes to sell all the conventional gasoline at a gas station and refill its storage tanks with RFG. At 11% MTBE by volume, RFG (and oxygenated gasoline) commands almost 24% of the world methanol market already (Methanex, 1995), and if used on a widespread basis across the United States, could provide a measure of energy security by replacing roughly 11% of gasoline that would otherwise have been consumed. Its effect on reducing emissions or increasing energy security are not dramatic, but they are inexpensive and of high value for their low cost, relative to other fuel alternatives.

Conditioning all fuel stations to be alcohol compatible is another way to reach many vehicles quickly, but within the next 15 years we do not foresee that there will be many people buying these vehicles, or refueling stations offering alcohol fuel blends. However, should the nation choose to replace crude oil as its sole transportation fuel, following this path of using current gasoline infrastructure for alcohol blended fuels is a low cost, direct, and simple way to prepare for this change.

Replacing fleet vehicles with natural gas, battery electric, or hydrogen vehicles can only reach 6-8% of the nation's 134 million automobiles (Chapter 2). But all buses (671,000), and most heavy trucks (64 million) are in fleets, so addressing the heavy duty engine fleet market may be an effective place to start introducing alternative fuels. Trucks use only 16% of the total energy used in transportation in the U.S., however, so though the number of vehicles is high, the total potential market share of energy is still a small part.

From an emissions standpoint, the impact of replacing urban fleet vehicles with low emitting vehicles would depend on the relative number of vehicles in fleets on a regional basis. Most freight truck miles are driven on interstate highways, not in urban regions, so from an emissions point of view, there would not be a great impact from changing interstate trucks to a cleaner fuel than diesel. Replacing urban buses with a cleaner fuel could reduce PM emissions in cities.

The real gain of a policy which attempts this niche introduction of alternative fuels and powertrains (fuel cells, battery electric vehicles) is the public exposure of the technologies. Once people see such vehicles, they may inquire about them at car dealerships. And once a natural gas refueling station has been built, the public may have the opportunity to pay the fleet (or gas utility) operator to use it.

9.4.4 Stability of Alternatives

Our recommended policy avoids the mistake of committing early to one fuel alternative and investing heavily in its infrastructure. It recognizes the necessity of stability for planning purposes in the very large vehicle and fuel industries, and the importance of compatibility across the country to preserve the mobility that is crucial to the economy. The different refueling infrastructures recommended in this policy maintain national compatibility because they are divided between vehicle application niches whose borders are not crossed today.

It is important to let the market guide the timing of the policy while the nation works toward preparing for several compatible alternatives. A methanol or ethanol compatible refueling infrastructure can be used with internal combustion vehicles, electric hybrid vehicles, or fuel cell vehicles, depending on which emerges as the dominant alternative after 2010. The existence of the infrastructure would provide an invitation to fuel producers and vehicle manufacturers to work together to stimulate a market for their alternative products, when they are economically competitive with liquid petroleum.

9.5 Strategy for Implementing Policy

This section outlines the way in which the policy recommendations could be implemented, beginning the change to alternative fuel vehicles. It focuses on two issues:

- **Timing:** When could (should) AFVs be introduced, and where?
- **Methods:** How could an AFV policy be implemented?

9.5.1 Timing the Policy

The CAAA has already begun the introduction into fleets of heavy duty natural gas vehicles, like city buses, as part of the Clean Fuels Fleet and Clean Cities Programs. This policy should continue at a slow growth rate, depending on the performance of low-sulfur diesel. Either the low-sulfur diesel or the natural gas alternative would take the same amount of time to implement, since vehicles would have to be purchased at about the same cost for each. If low-sulfur diesel emits sufficiently low NOx to meet with national health standards, there would be no reason to continue with natural gas in urban buses except for fuel independence concerns.

RFG should remain the main fuel open to urban regions which do not attain national air quality standards for regions. Its cost and performance tradeoffs should be the standard to meet for timing the introduction of an alternative.

Converting standard gasoline refueling stations to methanol or ethanol compatibility could begin anytime, but timing should be determined by state needs, as decided upon in their SIPs, and may even be accompanied by requirements for alcohol vehicle fuels, like in the California Pilot Program (Chapter 2). Beginning earlier would make alcohol fuel alternatives attractive sooner, of course. After the infrastructure conversion, the timing for the introduction of methanol blended fuel, M85, will depend on each region's emissions levels, emissions standards, and the local demand for reduced emission vehicles.

In introducing M85 or E85, correct timing could save money in society as a whole by avoiding costs imposed by small scale manufacture of M85 vehicles and distribution of M85 fuel. Mandates to sell M85 vehicles, timed with mandates to sell M85 fuel, are an efficient way to go about reducing these costs caused by supply lags. However, sales mandate approaches have proven to be unwise for political and technical reasons. Timing introductions might better be achieved through differential taxation of fuels or the introduction of an emissions or fuel resource credit trading market.

9.5.2 Methods for Implementing AFV Policy

Government should be relied upon to strive for, if not guarantee, a degree of stability in a market opportunity it has opened by its regulations. This could be accomplished by mandates that set standards that control emissions or air quality, and incentives for pursuing alternatives which have been identified as helpful in attaining mandated standards. Sustainable incentive-based regulations should ideally work as a transistor works in solid state electronics: steering the flow rather than acting as a source of flow (of electric current, or in this case, money).

Many small, but concerted and enforced mandates can have a greater effect than one high visibility, focused mandate. Each rule directly influences a different party to act in the desired direction, but to a tolerable extent that does not provoke inaction or cries of unfairness. One of CARB's failures was the way in which it appeared to hit carmakers very hard relative to other parties involved in the fuel/vehicle emissions chain.

Freedom for the States to set their own policies has been highly valued in past air quality regulation. Regional air quality standards must be retained and enforced as they are through the effective mechanisms of the CAAA. The AQCR boundaries must be federally set to avoid free riding polluters between regions. Providing state autonomy in setting fuel policies will introduce fuel alternatives at a technically efficient pace, but federal commitment to a national methanol-compatible refueling system would be an incentive for state mandates to include alcohol fuels in their SIPs, to take advantage of the available infrastructure.

Inter-industry cooperative development of markets would be an advisable way to introduce and sustain new vehicle technologies, subject to emissions standards. Some DOE projects, like USABC, PNGV, or Clean Cities Program, have taken steps in this cooperative direction. The projects are led and coordinated by the federal government, and industry representatives take part in planning and product concept development. The goals could be set as compromise agreements between industry and government, or in a sort of competition between the best technology "offers" of individual firms.

9.6 Conclusions

These policy recommendations take more than a "wait and see" approach. They recognize that, within the uncertainty programmed in the model used for this research, conventional petroleum vehicles will remain the least costly vehicle arrangement through the next 15 years, and that these vehicles can be modified to emit low amounts of pollution relative to today's cars by changes in fuels and engine management computers.

The recommendations prepare the refueling infrastructure for a change in fuel resource, which will likely be the eventual driving force behind changing vehicle fuels rather than emissions requirements. It does not set a timetable, funding levels, or specific rules to accomplish these ends, but it does present rational and supported guidelines for specific decisions to begin a changeover to the natural gas fuel resource.

Recognizing the vast financial resources of the private marketplace, and the auto/fuel market in particular, the policy recommendations rely on approaches which attempt to define "markets" for alternative fuels and emissions that include the money spent on fuels and vehicles. The policy does not rely on continued government subsidies (an "unsustainable" policy).

The results presented here attempt to show the limits of the spectrum of possible alternatives for the future vehicle fleet in the U.S., and how this modified ADL/Ford model may be used to compare them. Many fuel/vehicle combinations were not tested . It is possible that one of these may turn out to be the future mainstream vehicle, and that none of the presented vehicles succeed at all. The model itself cannot give a reliable answer unless the information that is input into it has been thoroughly researched.

It is important that policies made on the recommendations derived from this model recognize the uncertainty not only of the model output, but of the model input, as well. The user of the model could be looking in entirely the wrong direction when entering the fuels and vehicle types to consider. This is one reason to avoid technology mandates, since they can exclude alternatives that analysts overlooked or did not consider significant.

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11. Appendix: AFV Technology

11.1 Function of an Otto Cycle Engine

In a carburetted otto cycle engine, a vacuum pulls liquid gasoline and air into the carburetor at a mechanically specified ratio, where it is mixed together as an aerosol. For complete combustion of the fuel into H2O and CO2, the air/fuel mixture should be at its stoichiometric ratio of 14.7:1 by mass. Higher air/fuel ratios are referred to as "lean." Lean burns use the fuel efficiently because most of it combusts with the excess air. But lean burns also result in higher NOx emissions because of the high temperature at which this combustion takes place. Low ratios are called "rich," and result in more power but less efficiency and higher emissions of HC and CO due to the incomplete burn. Rich mixtures burn at a lower temperature because excess fuel carries heat away from the combustion chamber and out the exhaust pipe, so NOx emissions are lower.

As the mixture proceeds from the carburetor to the cylinders, it heats up and the gasoline evaporates to the gas phase. The gaseous mixture enters the cylinder as the piston falls, and is compressed by the piston as it rises again, until just before the mixture reaches its minimum volume where the piston hits its highest point. At this point, the spark plug fires and ignites the air/gasoline mixture, which heats and expands as it burns, driving the piston back down.

11.2 Samples of Current OEM Vehicles Offered by the Big 7

General Motors, trailing the Big Three in AFV selection and sales, is currently offering 36 month leases for its much-heralded EV-1, a sporty 2-seat BEV designed from the ground up for the CARB mandates. Lead-acid versions lease for $480 per month, and NiMH versions for $640 per month , at 24 Saturn dealers in California and Arizona. 76 people leased EV-1s in 1996 when they were offered for one month, and 469 people have applied for the 36 month leases. GM will not offer the vehicles for sale. At the end of the lease period, GM will take the cars back to study their condition (GM 1997).

The move appears to be an attempt to generate public confidence in the technology and in the company as an EV leader, while gathering in-use vehicle and consumer preference data about EVs. By offering no option to buy the vehicles, GM ensures that it earns a small return on its large development investment while getting its vehicles back for study and re-release as used cars. Also, as flashy leased sports cars, EV-1s may attract curious consumers who are interested in performance and image, but not necessarily electric vehicle technology of itself. This group would be different from the typical EV enthusiast, who tends to be an energy-conscious environmentalist or a hobby mechanic who is willing to accept breakdowns and decreased performance for benefits in emissions and energy efficiency (Sperling 1995). The resulting data could be very useful to GM. EVs, after all, may end up being luxury vehicles when they are introduced in 2003.

Through Chevrolet, GM will introduce its S-10 pickup nationwide this year in a converted EV version.

Honda has introduced a four-seat, Civic-type "EV Plus" in the region, which leases for $499 a month at four California dealers. It is also not for sale. It uses NiMH batteries, and Honda claims a 100 mile range with an 8 hour recharge time at 220 volts (vs. 3-5 for GM's lead acid battery). A Honda spokesman said that the realistic range on hills and with passengers may be more like 60-80 miles. The Honda accelerates much slower than the EV-1 (0-60mph [0-100km/h] in 18 seconds, versus 8 seconds for the EV-1), but it is clearly intended for a different consumer, with its compact car configuration and four seats (GM 1997). This vehicle may be a more realistic type of EV for short-term market introduction because four seats make it more useful, and its modest performance suits the available battery technology more appropriately. Honda and Toyota, with its minivan/sport utility RAV4-EV, will be partnering with area fleets to distribute EVs to gather fleet performance and marketing data (Davis et al 1996).

Ford's newest EV is a $32,800 converted Ranger pickup truck. According to Ford, they chose to make an electric Ranger because of its image as a durable vehicle, and because of its strong sales as a gasoline truck. The sales targets are electric utility and government fleets, and Ford hopes to sell 1,000 of them in 1998. Ford claims a range of 58 (95 km) miles on the 2,000 pound (1000 kg) lead acid battery, and an acceleration of 0-50mph (0-80 km/h) in 12.5 seconds. According to the news release, Ford intends to offer the vehicle across the country. The company will sell a home recharger with the truck for $1,000 each, but will give the units away for free with the trucks until March 18, 1998. The announcement stated that Ford intends to sell the truck with more advanced NiMH batteries in October of 1998, which they claim will extend the range to 100 miles (Ford Motor Co. 1997).

Chrysler, which leads the nation's OEMs in EV sales with 43, will continue development of its EPIC (Electric Powered Interurban Commuter) minivan, with no announced date for its unveiling (Davis et al 1996).

Electric conversions from glider chassis and kits are performed by many more companies, though in very small volumes. The major advantage of glider conversions over kit conversions is that some version of the OEM vehicle warranty is usually approved by the original manufacturer to extend to the glider conversion. There is usually a supplemental warranty for the electrical and electronic components added in the conversion. An example of this is the Geo Metro sedan glider converted by Solectria Corporation into the electric Solectria Force. The vehicles cost $31,000 with a lead acid battery ($68,000 with NiMH), claim a 50 mile range (100 with NiMH) and a 70 mph (112 km/h) top speed. Solectria also converts small S-10 pickup trucks into the E-10. The company has sold only about 250 vehicles, though, but has recently put their EVs on the showroom floor at a New England Chevrolet-Geo dealership.

Conversion kits have the advantage for hobbyists that the "glider" can be a used petroleum vehicle, purchased for a potentially low bartered sum, particularly if the vehicle has engine or transmission problems. And if the used vehicle runs well, the engine and drivetrain could be sold to offset the cost of converting the vehicle. Kits cost between $2,000 and $4,000, depending on the sophistication of the energy management computers and the efficiency and type of the motor. The battery pack would be an additional $3000-$6000 purchase, again depending on its size and composition.

There are small firms around the world which manufacture small passenger electric vehicles that are intended to replace petroleum vehicles only in specific urban or suburban niches. Such vehicles are called, "station cars," or ,"neighborhood electric vehicles" (NEV) in the U.S., and "light electric vehicles (LEV)," in Europe. These vehicles cannot travel faster than 40 or 50 mph (60-80 km/h), and usually carry only 2 people and 50 or so pounds (20 kg) of cargo. Their ranges are reduced for low weight to below 40-60 miles (60-100 km), though their gasoline equivalent fuel efficiency may exceed 100 mpg. Some only have three wheels, and some have quite sophisticated chassis/body structures and safety equipment, including airbags (Muntwyler and Kleindienst 1996).

This product illustrates the close relationship between forms of AFV and socioeconomic influences. Most passenger vehicle trips in the U.S. do not require more power, range, or carrying capacity than these small vehicles can provide (U.S. DOT 1994), though a detailed California study of 50 households suggested that a minimum 80 mile vehicle range might be necessary for such a car's successful introduction in the U.S. (Sperling 1995). Most suburban households that might find a use for a vehicle like this have access to a spot for recharging it at home, but apartment dwellers may have more difficulty finding a charging outlet (Sperling 1995). However, these small electric vehicles cost as much as an inexpensive new subcompact ICEV, which has vastly superior cargo space and range. Opening this application niche to small EVs will be a matter of matching purchase prices and lifetime operating costs to the convenience of the vehicle. Current test projects in industrialized countries are investigating these niches as one method of developing an EV market.

11.3 EV and Society: European Markets

A large-scale energy efficiency demonstration project, which will eventually include 7 cities in Switzerland, France, and Germany, is currently investigating the effects of a federal government purchase subsidy of up to ½ the purchase price of the small, light electric vehicles, with other incentives like: battery leasing as opposed to purchase, free maintenance, guaranteed rides in case of a breakdown, and free parking (Muntwyler and Kleindienst 1996). The study intends to find out what kind of changes will occur at the municipal level to promote LEV use when 8% of a city's vehicles are EVs, by simulating the vehicle reliability and lower price expected in the near future. Research includes looking at changed driving habits as a result of LEV use, route choice with LEVs, safety, private investment, and joint urban transportation planning initiatives. As of mid-1996, after one and a half years, the project had added about 50 EVs in the first participating city of Mendrisio, Switzerland (10,000 population), and were adding additional vehicles at the rate of 6 per month. It expects to have a total of 300 EVs in the city by 2003. The subsidies are available only to vehicles which consume less than 20kWh/100km (better than 110 mpg equivalent) for two-seaters, and 25kWh/100km (better than 90 mpg equivalent) for four seaters. Public charging stations, including a solar-powered station, have been privately funded in at least three of the cities, where vehicles may plug in for a fee. Project leaders have calculated that the stations will never pay for themselves, however.

In a separate project titled "PRAXITELE", the city of Saint-Quentin-en-Yvelines, a Paris suburb, began an experiment this year to provide small electric vehicles as a form of public transportation in the city center. The privately managed high-tech system uses inductive vehicle chargers (chargers without an electrical contact), which charge the vehicles from underneath in special parking spaces, smart cards to bill users of the privately-operated fleet, and the global positioning system to locate unoccupied vehicles for users (Parent, et al 1996). According to engineers in PRAXITELE, the visionary goal of such a project is to offer mobility to everyone in the city center, especially the very old. The vehicles in this visionary city center would run on their own roadways with very simple operating controls, like a single joystick, and would not require a driver's license. A similar project is underway in Switzerland, in Monthey.

11.4 Batteries Currently Used in Vehicles

Batteries which are common today, lead-acid and nickel cadmium, either meet most of the above mid-term criteria or could meet them with reasonable redesign. Lead acid batteries are very powerful and very cheap. They use lead electrodes, bathed in a weak sulfuric acid electrolyte. They are heavy however, and their energy density is the lowest of the nine alternatives at 35-50 Wh/kg*. They have the great advantage of an established presence in the automotive world as starter batteries in nearly all cars produced since the 1920s. Large-scale production plants to manufacture 30-40kWh lead batteries in volumes of 10-100,000/yr could be built in a few years, given the demand for the batteries. Battery costs would be $100-150/kWh, below the mid-term criterion. Large volume deposits on the electrodes caused by charging deteriorate the batteries' ability to hold charge, and limit the number of cycles of battery usefulness. Modern, pulse recharging units can reduce deposits and increase the lifetimes of lead-acid batteries.

Nickel cadmium, or NiCd batteries, have a very long cycle life, are easily quick-charged at a high rate, and are the most common backup battery in consumer products. They are twice as expensive as lead-acid, and do not store enough energy for the USABC mid-term criterion. Cadmium is a toxic heavy metal, and large scale manufacture would not be possible without guarantees of total recycling. SAFT produces 6,500 12 kWh NiCd batteries per year for use in small Peugot 106s, Renault Clios, and Citroen AXs.

11.4.1 Prototype or Limited Production Batteries

The California panel found two types of nickel metal hydride (NiMH) batteries, AB2 and AB5, to hold promise as a mainstream EV battery. The AB2 and AB5 designations refer to the hydride, or negative, electrode composition. Both are nickel alloys, but AB2 is a

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* All energy densities are measured at the C/3, or 3-hour discharge rate.

more disordered array and can hold more hydrogen than the AB5 electrode. AB5 development is going on in Europe at DAUG/Hoppeke, SAFT, and Varta, the latter two starting up a pilot production plant in 1996. In Japan, the companies Japan Storage Battery (JSB), Matsushita/Panasonic, and Yuasa are working on the battery, and the latter two plan to open a pilot plant in 1997. In the U.S., Ovonics and GM develop the AB2 version of the batteries. The USABC supports research at Ovonics and SAFT. The AB2 version meets the minimum energy density goals of the USABC at 75-80 Wh/kg, and Ovonics expects to exceed this value with a 120 Wh/kg battery in the near future. Cycle life varies, but the AB5 version could even meet the long-term USABC goals of 1,000 charge cycles. AB5 energy and power performance is slightly less impressive, but satisfactory for the mid-term goals. With the pilot plants up and running, increased EV demand could drive production scale to higher economies. Ford and GM plan to introduce 1998 vehicles with NiMH batteries.

Sony has been manufacturing lithium ion batteries for extensive use in cellular telephones and portable computers. Small prototype vehicle batteries reach 100 Wh/kg energy density, well over the mid-term goal, and specific power is 300 W/kg, double the mid-term, but not high enough for the long-term goal. Cycle life ranges from 400-1200, could meet long-term goals because of the relatively minor electrode changes which occur in each battery charge cycle. Research goals are to reduce the cost of the battery by eliminating expensive cobalt from the electrodes, and to address safety issues in the case of overcharging. Currently, the battery has no way to absorb excess energy during recharging, and it either burns or explodes if overcharged. Lithium is flammable and potentially explosive in contact with water, and must be kept from exposure to it. In Japan, Sony and JSB are working on the battery. European developers include Varta/Duracell, and SAFT. W. Grace works on them in the U.S. The USABC supports research by Varta/Duracell, and W.Grace. The panel determined that a pilot plant could be built in 2-4 years, and that production could begin in 5-6 years, given a demand.

Lithium polymer batteries have been researched in laboratories for 25 years, as a subject of thin film applications. They feature a polymer electrolyte and a theoretically high energy density. A lithium polymer battery would only have to reach 20-25% of its theoretical energy storage capacity to exceed the long-term USABC energy density goals. Lab samples exist with energy storage capacities of 20-100Wh, barely large enough to light a bright light for a fraction of an hour. The USABC is sponsoring research on this battery at 3M and Hydro-Quebec.

Sodium nickel chloride (NaNiCl2) batteries, "ZEBRA," run at a high temperature, 270-350 degrees Centigrade (520-660F). The battery has a high potential energy density, a high tolerance for overcharging, and a very high cycle life. 70 prototype vehicles in Germany use NaNiCl2 batteries made by the Anglo American Company and Daimler Benz AEG. The batteries have an energy density of 90 Wh/kg, a rather low specific power of 130 W/kg, and potential lifetimes of over 1200 cycles. The thermal losses are limited to 102 W by the insulation layer in a 17kWh battery. As this battery is in the primary stages of development, its energy density is only 11% of the theoretical value of the reaction, but researchers think it could reach 30% of the theoretical value, which would make this battery a serious contender for mainstream EV application. The battery manufacturers will decide this year whether to open a 15-30,000 battery/year plant.

Zinc bromide (ZnBr2) batteries have been under development for 20 years and have over 60,000 miles of test driving. They are a potential low cost battery, though it is unlikely that they will reach the long-term goals of any USABC criterion. Nonetheless, a 45kWh battery may enter mass production in the next few years, according to the CARB study, to compete with lead-acid. Bromine is toxic however, and safety precautions would be in order.

Zinc/air is another promising battery type for the near and long-terms. Its current energy density meets the USABC long-term goal, and is still at only 17% of its theoretical maximum. Its power density only meets the mid-term goal however, and it has problems with a short cycle life. The zinc electrodes erode markedly with every charge. The zinc/air battery has a method to overcome this problem which requires removing the zinc electrodes from the discharged battery and reconditioning them ("mechanically" recharging the battery) in a separate apparatus which does not degrade them as much. This method of recharging has the advantage of extending the number of cycles that the batteries can be charged, but the disadvantage of labor-intensive procedure and the requirement for a large storage area for reconditioned zinc and a reconditioning facility for the electrodes from the discharged battery. Fleets seem the ideal application for this type of battery, where recharging and maintenance are localized, and the standardized electrodes can be taken from one vehicle and returned to another without concern. Currently, the German Postal Service is running 64 test vehicles with zinc/air batteries. If the tests are successful, 40,000 vehicles in the postal service and telecommunication fleets could be replaced by zinc/air vehicles.

11.4.2 Unlikely Battery Contenders

Sodium sulfur (NaS) batteries have been researched for 30 years. Both their reactive and containment components are inexpensive. The reactions run at 300-350 degrees Centigrade (575-660 deg. F), with a ceramic electrolyte separating the charges. The battery has a theoretically very high energy density like lithium polymer batteries, good cycle life of 750-1500 charges, and a specific power which could meet the long-term goals of the USABC. The high temperature have proven to be a public relations concern and a design problem, however. The high temperature requires an insulation layer to maintain battery efficiency, and the battery reactants reach a high vapor pressure at the high temperature. RWE Energie AG removed its support in 1995 from the Silent Power company, which was the last major company working on the battery. The prototype Silent Power batteries of 28kWh had a 107Wh/kg energy density and a specific power of 230 Wh/kg, both significantly exceeding the mid-term goals. Despite this advanced development however, sodium sulfur has more problems to overcome than most other batteries.

11.4.3 Recharging Infrastructure

Establishing a recharging infrastructure for AFVs will have to accompany or precede market share growth. The California Air Resources Board has conducted a study of ways in which to simplify establishing a recharging infrastructure for electric vehicles. An EV Corridor Communities Program supports the deployment of EV fast-charging infrastructure along freeway corridors and in volunteer "EV-ready" communities. Local governments will be in charge of developing charger installation standards, permitting and inspection, writing new codes for the installations, and overseeing the provision of public charging infrastructure. An outreach group coordinating the state's utility companies has identified three areas to address for introducing public charging: consistent charging rates between utility service areas; simplifying procedures for residential installation of chargers; and development of a universal billing system. The Public Utilities Commission determined in 1996 that utilities should not install charging equipment, because they are constrained to working on the "utility side of the meter."

Some people feared that this decision would potentially frustrate homeowners and builders from taking on the complicated process of contracting a designer, securing code approval, and contracting for construction of a conforming 220-volt outlet charger themselves. But Southern California Edison Corporation (SCECorp) formed a new company, Edison EV, in partnership with GM/Saturn, to take care of the burden of administration and contracting for home charger installations and encourage homeowners to consider EVs.(Davis et al 1996) New home construction in some parts of California now have to include circuitry ready for EV charger installation.

Similar partnerships will be necessary for any alternative fuel vehicle system to develop in the U.S. Interests limited to only vehicles or only fuel manufacture and distribution will have a more difficult time penetrating the mobility market with their products. Stakeholders will have to venture outside of their sphere of expertise or specialization to bargain with each other creatively. In the Southern California case, a spinoff of the electric utility joined with a major automaker and dealership to manage private construction contracts.

12. Appendix: AFV Policy

12.1 Example of AQCR

For example, Title I (Provisions for Attainment and Maintenance of NAAQS) of the 1990 amendments identify twelve eastern states from Virginia to Maine as contributing to each others' ozone pollution, and has classified each as a non-attainment area within an "ozone transport region." The Ozone Transport Commission (OTC) was established as an oversight group for attainment in these states by the CAAA. States can obtain an exemption if they can show that further emissions reductions from their own states will not improve the composite region's attainment status. These states have formed a coalition, the Northeastern States for Coordinated Air Use Management (NESCAUM) to develop a strategy for reducing ozone. Arguing that they have borne an unfair burden in reducing ozone levels in their states, NESCAUM recently published a report implicating NOx emissions from Midwestern electric power plants as the limiting reagent creating northeastern ozone (NYT 3/16/97). This claim must now either be refuted scientifically, or else the responsibility for reducing NOx in this AQCR may have to be reconsidered.

12.2 State Implementation of Oxygenated Fuels: Colorado Example

The states implement the oxygenated fuels program, usually as part of their SIP. An example of the program's implementation is the regional program in Denver, Colorado, which because of "severe" non-attainment for CO began its oxygenated fuels program in 1987, as per the CAAA77. The state's Regional Air Quality Council (RAQC) has established a system of tradable oxygen credits for the Denver-Boulder region in its oxygenated fuel program to encourage higher oxygen content fuels, which contain ethanol and are slightly more expensive. By using more expensive, but more effective fuels, the Council claims to have saved Coloradans $2 million in 1995-96 by shortening the oxygenated fuels period by two weeks, ending it on February 14th instead of the 28th.

Methanol supporters consider this tradable credit program to be a concession to the state's ethanol lobby, which succeeds by this policy to sell more of its expensive fuel than it would without the higher average oxygen content rule.

In this tradable credit market, Control Area Responsible parties (CARs) are authorized by the state to deal in oxygen credits. CARs may be oxygenated fuel blenders or simply state authorized oxygen credit agents. A system of measuring and reporting at the blending sites establishes the average percent oxygen content of the fuel sold by each fuel blender through the winter. Each gallon of fuel sold must not contain less than 2.7% oxygen by weight, nor more than 3.5%. The average for the region is set at 3.1% (one-half MTBE and one-half ethanol blends sold). Blenders exceeding 3.1% oxygen accrue credits to sell to blenders falling below that average. The ethanol additive is much more expensive than the MTBE, so the credits market provides an incentive to blend higher oxygen content using ethanol (Colorado Reg. 13 1995). Attesting to the efficacy of the oxy-fuels program in the area, Denver has had only one CO non-attainment day in the winters of 1994-7, and expects to achieve CO attainment area status in 1997/98.

13. Appendix: Resource Transport Assumptions

Table 13.1: Assumed Shipping Distance of Each Fuel or Resource by Mode

Resource/Fuel	Pipeline	Truck	Train	Tanker	Barge
Oil					
Lower 48	500	500	50	0	1000
Alaska	1200	0	0	2500	0
Imported	50	0	0	9500	0
Coal	300	60	530	0	450
Gas	1000	0	0	0	0
Gasoline*	600	100/50	0	1200	300
RFG*	600	100/50	0	1200	300
Diesel*	600	100/50	0	1200	300
LPG	600	150	600	0	1000
CNG	0	0	0	0	0
LNG	0	0	0	0	0
Methanol	800	75	800	0	800
Ethanol	500	250	600	0	600
Hydrogen	100	0	0	0	0

***The two shipment numbers for truck hauls refer to bulk plant and service station shipments**

Table 13.2: Assumed Percent of Shipments of Each Fuel or Resource by Mode

Resource/Fuel	Pipeline	Truck	Train	Tanker	Barge
Oil					
Lower 48	71	3	3	0	23
Alaska	100	0	0	100	0
Imported	100	0	0	100	0
Coal	0	16	66	0	18
Gas	100	0	0	0	0
Gasoline*	62	100/100	0	24	14
RFG*	62	100/100	0	24	14
Diesel*	62	100/100	0	24	14
LPG	95	100	4	0	5
CNG					
LNG					
Methanol	60	100	30	0	45
Ethanol	0	100	70	0	20
Hydrogen	100	0	0	0	0

***The two shipment numbers for truck hauls refer to bulk plant and service station shipments**

Table 13.3: Costs of Transporting Resources and Fuels, by Mode

Transport Mode	Transport Cost-Fixed	Var Transport Cost- $/mi	Units	Transport Cost Variable (dry goods)	Units
Diesel Train		\$0.0198	\$/gal	\$0.025	\$/ton-mile
Fuel Oil Ship		\$0.124	\$/gal		
Inland Barge		\$0.025	\$/ton-mile		
Diesel Truck	\$0.008	\$0.00022	\$/gal-mile	\$0.220	\$/ton-mile
Oil Pipeline		\$0.014	\$/ton-mile		
Gas Pipeline		\$2.543	\$/MMSCF-mile		

14. Appendix: Tailpipe Emissions

Fuel \ Vehicle Type	**RAF (MIR) (a)**
Gasoline	1.00
Reformulated Gasoline (RFG)	0.98
Diesel	1.00
Liquefied Petroleum Gas (LPG)	0.50
Compressed Natural Gas (CNG)	0.18
Liquefied Natural Gas (LNG)	0.37
Compressed Hydrogen	0.00
Compressed Hydrogen	0.18
Liquefied Hydrogen	0.00
Hydrogen Hydride	0.00
Methanol	0.00
Methanol	0.00
M85	0.63
Ethanol	1.13
E85	0.41
Battery Electric	0.63
Hybrid ICEV/Electric Vehicle	0.98

(a) Wang, 1993. RAF=Reactivity Adjustment Factor, according to the MIR (maximum incremental reactivity) scale.

Fuel/ Drivetrain	High Technology Scenario		Vehicle Emissions (g/mile)				
	CO2	**SO2**	**NOx**	**CO**	**NMHCs**	**CH4**	**PM**
Gasoline	241.39	NA	0.5	10	0.35	0.1	0.1
RFG	256.94	NA	0.4	0.1	0.125	0.1	0.1
Diesel	264.23	NA	4	0.1	0.1	0.1	0.05
LPG	207.26	NA	1.1	0.3	0.2	0.1	0.01
CNG (f)	174.52	0	0.7	0.3	0.125	0.5	0.045
Methanol ICE(otto)	200.22	0	0.6	0.1	0.125	0.25	0.1
Methanol FC	111.93	0	0	0	0	0.1	0
LNG (e)	171.40	0	0.7	0.3	0.125	0.6	0.045
Hydrogen FC (c)	0.00	0	0	0	0	0	0
Hydrogen Hydride	0.00	0	0.7	0	0	0	0
Hydrogen CH2	0.00	0	0.7	0	0	0	0
Hydrogen LH2(e)	0.00	0	0.7	0	0	0	0
Ethanol	0.00	0	0.6	0.1	0.1	0.1	0.045
Electricity(b)	0.00	0	0	0	0	0	0
M85	237.07	NA	0.2	0.1	0.125	0.25	0.1
E85	53.04	NA	0.2	0.1	0.125	0.1	0.1
EV/RFG Hybrid(g)	160.29	NA	0.2	0.05	0.05	0.05	0.1

The tailpipe emissions model from the modified ADL/Ford model in the high technology scenario.

Fuel/	Vehicle Emissions (g/mile)						
	Current, or Low Tech Scenario						
Drivetrain	CO2	SO2	NOx	CO	NMHCs	CH4	PM
Gasoline	241.39	NA	0.5	10	0.35	0.1	0.1
RFG	244.53	NA	0.4	8	0.25	0.1	0.1
Diesel	240.03	NA	4	15.5	1.3	0.1	0.1
LPG	199.88	NA	1.1	5	0.8	0.1	0.01
CNG (f)	170.75	0	0.7	2.7	0.22	0.88	0.1
Methanol ICE(otto)	197.71	0	0.61	1.7	0.47	0.25	0.1
Methanol FC	111.93	0	0	0	0	0.1	0
LNG (e)	167.63	0	0.7	2.7	0.22	0.88	0.1
Hydrogen FC (c)	0.00	0	0	0	0	0	0
Hydrogen Hydride	0.00	0	0.7	0	0	0	0
Hydrogen CH2	0.00	0	0.7	0	0	0	0
Hydrogen LH2(e)	0.00	0	0.7	0	0	0	0
Ethanol	0.00	0	0.61	1.7	0.47	0.1	0.1
Electricity(b)	0.00	0	0	0	0	0	0
M85	232.83	NA	0.2	2.8	0.4	0.25	0.1
E85	48.64	NA	0.2	2.9	0.27	0.1	0.1
EV/RFG Hybrid(g)	147.80	NA	0.2	8	0.125	0.1	0.1

The tailpipe emissions model from the modified ADL/Ford model in the low technology scenario and base case.

Table 14.1: Vehicle Tailpipe Contribution to Lifecycle Emissions, Expressed as a Percentage of Lifecycle Emissions

Fuel/ Drivetrain	Percent of Lifecycle Emissions from Vehicle Tailpipe							Total CO2 Equivalent Emissions	Total NOX + HC
	CO2	SO2	NOx	CO	NMHCs*	CH4	PM		
Gasoline	83	NA	68	99	75	69	52	83	**42**
RFG	81	NA	60	99	69	68	**48**	81	**39**
Diesel	92	NA	96	100	96	71	80	92	73
LPG	87	NA	90	99	93	73	**19**	87	67
CNG	85	**0**	68	98	**35**	68	86	84	61
Methanol ICE(Otto)	73	**0**	52	94	59	**35**	83	73	**42**
Methanol FC	73	**0**	**0**	**0**	**0**	**30**	**0**	73	**0**
LNG	85	**0**	69	98	**35**	68	87	84	62
Hydrogen FC	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Hydrogen Hydride	**0**	**0**	61	**0**	**0**	**0**	**0**	**0**	58
Hydrogen CH2	**0**	**0**	65	**0**	**0**	**0**	**0**	**0**	61
Hydrogen LH2	**0**	**0**	65	**0**	**0**	**0**	**0**	**0**	61
Ethanol	**0**	**0**	**33**	92	83	93	**4**	**0**	**28**
Batt. Elec.	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
M85	76	NA	**27**	96	56	**38**	71	75	**19**
E85	**17**	NA	**15**	95	68	86	**5**	**17**	**12**
EV/RFG Hybrid	81	NA	55	99	64	63	60	81	36

***Non-methane hydrocarbons emitted from the vehicles have been corrected for the MIR reactivity adjustment factor (RAF) for that vehicle (chapters 2 and 5).**

NA = not available.

The tailpipe contributions which are less than half of the total emissions are highlighted.

15. Appendix: Specific Model Input

15.1 Industry Emissions Controls

The model enables the user to choose the percentage of certain industries and fuel processing stages which have state of the art (SOA) emissions controls. Some of these controls have a major impact on the lifecycle emissions of certain AFVs, and some have almost no effect at all (see Chapter 7). For the base case, 10% of all the industries have state of the art emissions controls. Evaporative emissions in the fuel chain are controlled to 95% SOA, and vehicle refueling controls have reached half of the refueling stations. Both low and high AFV technology scenarios in the year 2010 have 50% controlled SOA emissions from industry and 95% controlled emissions from vehicle refueling procedures. Table 15.1 lists the industries or fuel chain stages whose emissions can be controlled by the user, as set for the base case.

Table 15.1: The Percentage of Average and State of the Art Emissions Controls for Industry

Fuel/Technology	SOA Low Tech	SOA High Tech
Diesel Train	10%	50%
Fuel Oil Ship	10%	50%
Diesel Truck	10%	50%
Coal Boiler	10%	50%
Coke Boiler	10%	50%
Residual Oil Boiler	10%	50%
Natural Gas Boiler	10%	50%
Wood Boiler	10%	50%
Diesel - IC Engine	10%	50%
Distillate Oil - Turbine	10%	50%
Natural Gas - IC Engine	10%	50%
Natural Gas - Turbine	10%	50%
HD Gasoline Vehicle	10%	50%
Evaporative Emissions	Controlled Low Tech	Controlled High Tech
Fuel Chain	95%	95%
Vehicle Refueling	50%	95%

15.2 Vehicle Cost Input

Cost of a new gasoline ICE	15000

	15000	**Incremental Cost of AF Subcompact Vehicle over Conventional Gasoline Subcompact Vehicle**					**Per Vehicle Cost of Refueling Station***
FuelVehicle	**Conversion L**	**Conversion H**	**OEM Low**	**OEM High**	**FFV Low**	**FFV High**	
Gasoline	$0	$0	$0	$0	$0	$0	0
RFG	$0	$0	$0	$0	$0	$0	0
Diesel	$0	$0	$0	$0	$0	$0	0
LPG	$1,500	$2,500	$200	$800	$800	$1,700	58
CNG	$1,200	$1,800	$400	$1,000	$2,000	$2,500	0
Methanol ICE	$200	$400	$0	$300	$400	$800	68
Methanol FC	NA	NA	$3,000	$147,000	NA	NA	68
LNG	$600	$1,200	$400	$800	$4,500	$5,200	0
Hydrogen FC	NA	NA	$3,800	$148,200	NA	NA	0
Hydrogen Hydride	$1,042	$11,091	$694	$7,394	NA	NA	0
Hydrogen CH2	$1,200	$1,800	$800	$1,200	$4,500	$5,200	0
Hydrogen LH2	$1,200	$1,800	$800	$1,200	$4,500	$5,200	0
Ethanol	$200	$400	$0	$300	$400	$800	68
Battery Electric	$2,000	$4,000	-$3,000	$3,000	NA	NA	400
M85	$0	$0	$0	$300	$200	$400	68
E85	$0	$0	$0	$300	$200	$400	68
Hybrid RFG/EV	$2,500	$8,000	$4,000	$5,000	NA	NA	0
Fuel2							

Range(mi)	300
Mi/gal gasoline	30.5
Gal gasoline tank	9.8
ICEV Fuel to Motion Efficiency	0.15

Sample input table for vehicle costs from the modified ADL/Ford model

16. Appendix: Specific Model Output

16.1 Fuel Chain Results

16.1.1 Costs by Stage

Figure 16.1 shows the components of fuel production costs, illustrating the areas in which the largest portion of costs are incurred for each version of each fuel. This helps to understand the strengths and weaknesses of each fuel in the context of future price scenarios. The following discussion of each fuel chain refers to Figure 16.1.

Allocating costs between "resource" and "production" is arbitrary in the models for some fuels, as byproducts from production could be counted either way. In the natural gas →LPG chain, for example, production costs are assumed to be entirely due to processing the resource because LPG must be dissociated from the natural gas at extraction in order for the gas to be sold (i.e. have value in the market). Meanwhile in the petroleum → LPG chain, LPG is treated as a byproduct of gasoline and diesel production, and all production costs attributable to LPG are assumed to come from the cost of the input petroleum. Natural gas shipments, when gas is used as a fuel itself, are counted as "fuel shipments", but as "resource shipments" when the gas is to be processed into another fuel. Since electricity is only modeled as a cost to the user (the electricity price), its costs are not broken down into the various components.

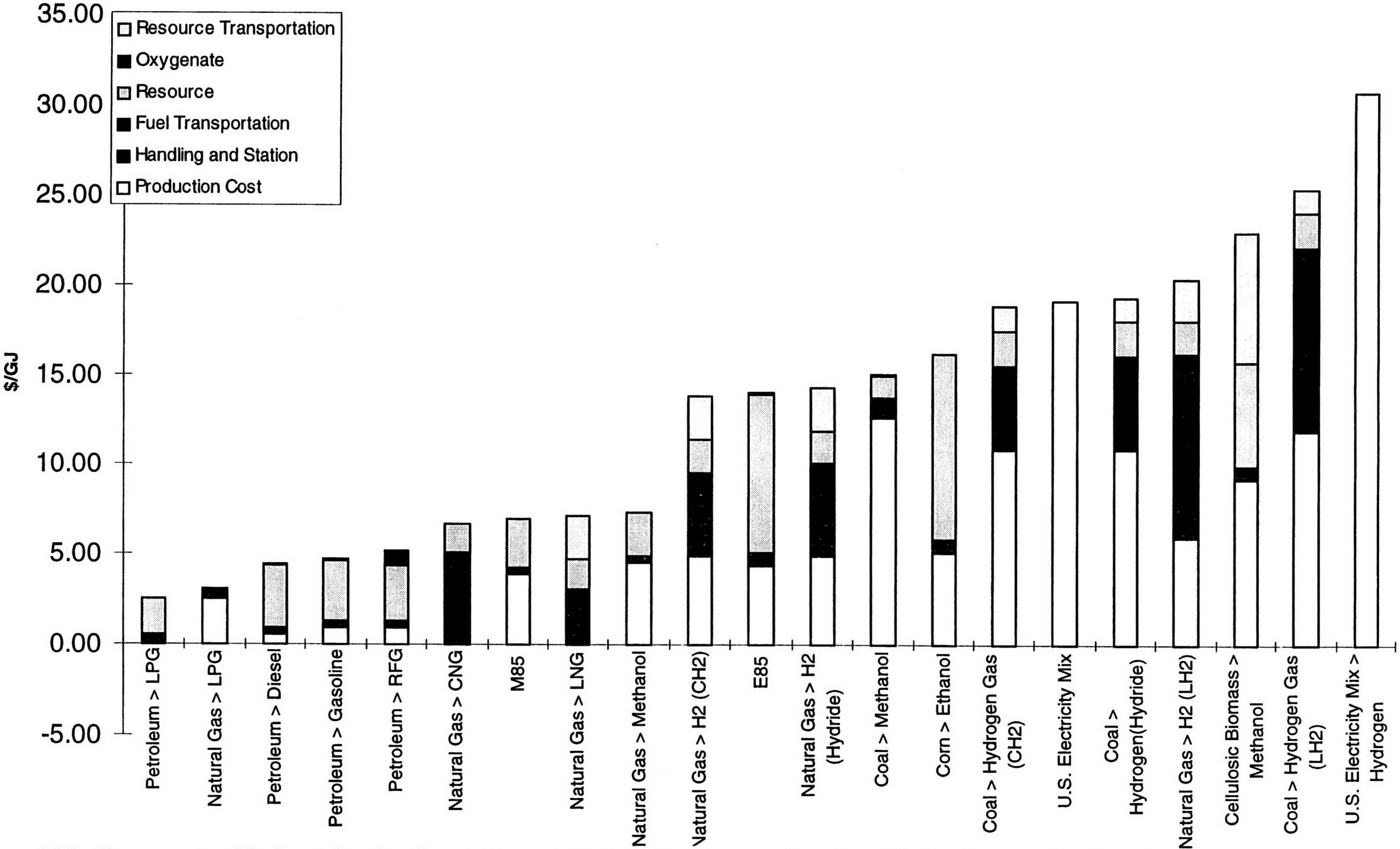

Figure 16.1: Components of fuel cost showing the relative contribution of each processing stage. Production costs dominate less mature fuel processes. Resource costs dominate mature fuel processes. Special handling costs dominate exotic gaseous fuel costs.

16.1.2 Petroleum Fuels

The cost of petroleum dominates the cost of the delivered petroleum fuels. This sensitivity to variable input costs is characteristic of mature industries with low capital and operations costs. It tends to pass the volatility of oil and natural gas prices on to the consumer, unattenuated by the high proportion of fixed costs that some other fuels incur. The incremental cost of RFG is almost entirely due to the added cost of the MTBE oxygenate additive, though the amount of oil displaced by MTBE in each gallon of RFG lowers the cost of the resource component so that the total cost increase is lower than the incremental cost of the added MTBE. In the future scenarios of high petroleum prices, RFG is actually less costly than conventional gasoline because it contains less of the expensive gasoline per gallon, containing instead MTBE, which is assumed to be relatively cheaper in the future scenarios.

Future petroleum fuel costs rise to the \$8-9/GJ range for the high petroleum price scenario, \$6-\$7 for the medium scenario, and do not change in the low price scenario.

The production and delivery cycle is 84%-91% efficient for the different petroleum fuels. This means that of all the energy originally contained in the extracted petroleum, plus the energy used in refining and delivering petroleum vehicle fuel, 84%-91% of it is still available in the fuel to be used in the vehicle.

16.2 Natural Gas Fuels: CNG and LNG

Compressed and liquid natural gas incur high fuel shipment and handling costs per unit energy. The pipeline shipment costs per unit energy are high in the model for natural gas because they assume one average cost for all pipelines over all distances (1000 miles. See Chapter 5). That cost is fixed per GJ, and makes up about 1/3 of the cost of the delivered fuel. There is no other practical mode for transporting natural gas in its gaseous state, but trucking liquefied natural gas could be cheaper than using natural gas pipelines for shipments shorter than about 300 km, including boiloff losses (DeLuchi 1989).

In the base case, natural gas compression and liquefaction occurs at retail stations, which must purchase the appropriate pumps, compressors, and storage tanks for the fuel. This rather high cost, about 1/3 of the delivered base case cost when expressed on a per GJ basis, will be an unavoidable fixed cost per unit energy in CNG and LNG stations under all scenarios.

The remainder of the cost for natural gas fuels is the variable cost of the gas itself, though there is a small production cost for LNG which involves the inefficiency of compression and cooling. In future scenarios, the natural gas price rises from $1.70/Mcf (million cubic feet) to $4-4.65/Mcf. This rough 150% increase in the variable production costs raises the cost of natural gas fuels about 40%, to $9-$10/GJ.

Extracting, purifying, and compressing natural gas is 87% efficient in the model. Liquefaction is 78% efficient because of boiloff losses during refueling. These vapors (methane) can be recaptured and compressed or reliquefied, but this technology is not modeled.

16.3 Alcohols and Alcohol Mixtures

16.3.1 Methanol

For methanol derived from either natural gas or coal, the production cost is the dominant component of the delivered fuel cost. This is because of the inefficient conversion process from either resource into the alcohol (62% for the natural gas chain and 60% for the coal chain). The fixed processing cost from the natural gas resource is more than 60% of the per unit energy cost of pure methanol. From coal, processing is more than 90% of the delivered cost. This cost is reflected in the base case resource mix as 50% of the M85 gasoline blend's delivered cost (no coal component is included because the resource "mix" is 100% natural gas).

The cost of the resource (natural gas, in the base case) in methanol manufacture is about 1/3 of the delivered fuel cost. This is a relatively high cost per unit energy of fuel delivered, again because of the inefficient conversion process.

The per unit energy transport cost of the natural gas used to make methanol is low because the methanol plants are assumed to be within 50 miles of the wellheads, so that methanol, rather than natural gas, is shipped over long distances in pipelines at a much higher energy density. This lowers the total per unit energy transportation cost for methanol. The high transport cost per unit energy of natural gas makes it more desirable to locate methanol plants nearer to wellheads and farther from methanol distribution centers, and to construct higher pressure natural gas pipelines to these plants.

16.3.2 M85

M85 costs little less than pure methanol on an energy content basis because the 15% gasoline boosts the energy content and lowers the costs which are attributable to the methanol content.

The high fixed costs for methanol manufacture mean that its cost will not be very sensitive to changes in the price of coal or natural gas. Future prices of methanol are forecast in the model to be $10-$11/GJ, only a 25%-30% increase despite more than doubling the natural gas price.

16.3.3 Ethanol

Ethanol is assumed to be derived completely from corn, though it can be made from any other starch- or sugar-containing crop. Its resource cost is about 60% of its delivered cost, including the sale of corn byproducts as animal feed at twice the price of corn. This shows a high sensitivity of the fuel cost to the price of corn and animal feed. Neither current nor future prices of ethanol in the model are competitive for the energy it contains.

The model reports the efficiency of producing ethanol from corn as 39%, meaning that only this much of the total energy that is used to produce ethanol, plus the energy that was originally in the corn, is useful in the vehicle. This efficiency figure could be misleading however, if one assumes that the remaining 61% of the energy was wasted. Indeed most of it is lost in heating the environment around the coal boilers used to break down starches in the corn, but the animal feed byproducts resulting from this process contain as much as half of the energy of the ethanol produced.

16.4 Lifecycle Costs

Figure 16.2 shows the relative cost contributions of the new vehicle, fuel used, maintenance, refueling station, and replacement batteries to the difference in lifecycle costs of each AFV.

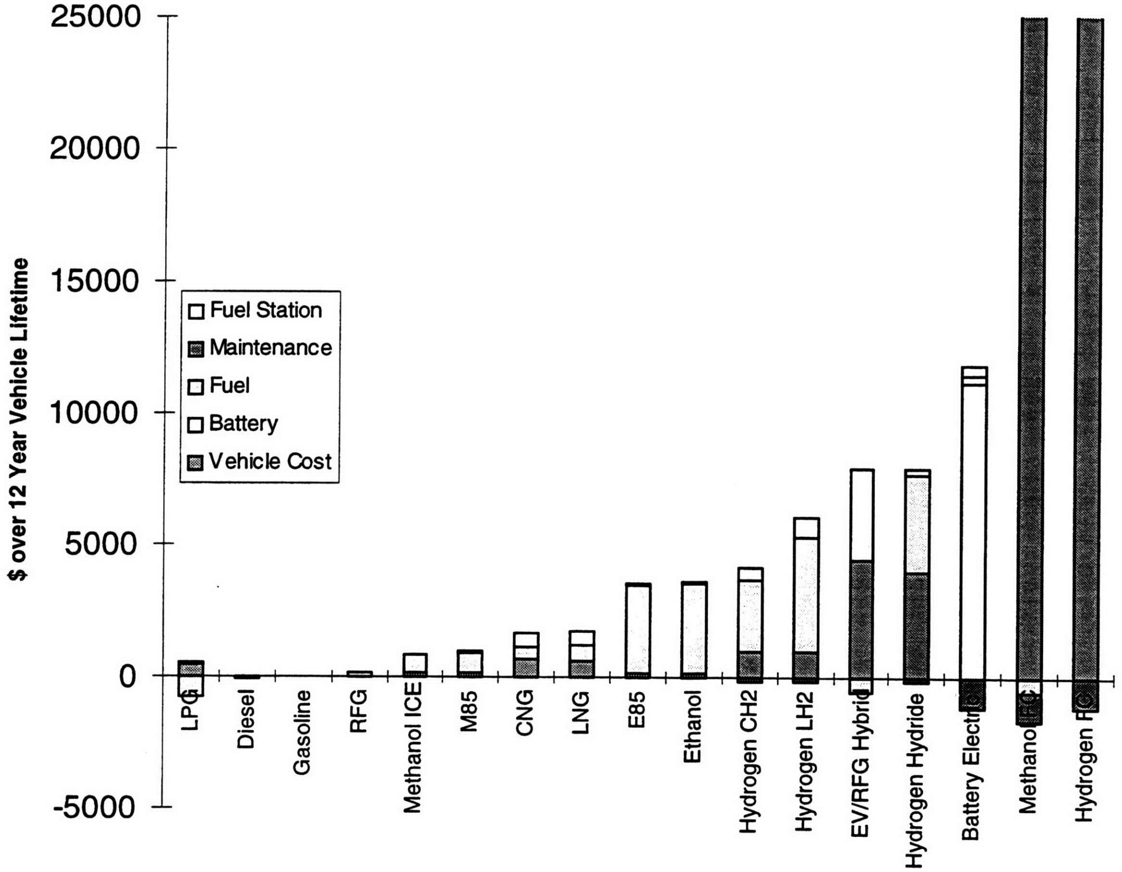

Figure 16.2: Depending on the vehicle type, the incremental lifecycle costs over a CGV would be most influenced by assumptions about the vehicle cost, the battery technology (for electric vehicles), or fuel cost. Assumptions about maintenance costs are relatively constant across AFV types.

This figure does not illustrate the fact that the base vehicle cost, which has been subtracted out of this representation, is one to twenty times larger than the bar heights (cost differences) shown here, except for fuel cell vehicles. However, this figure represents how the model works in adding a cost increment to the base CGV cost.

Assumptions about the vehicle cost carry the most influence in more experimental or complicated vehicles. The cost of replacement batteries has the most important role in determining the lifecycle cost of BEVs. Fuel costs dominate lifecycle outcomes for hydrogen and alcohol fueled vehicles. The sensitivity of natural gas vehicles' costs is divided equally between station costs, fuel costs, and the cost of the vehicle.

17. Appendix: Tables of Model Results

The following seven sections contain model output tables for fuel cost, lifecycle costs, emissions, and efficiency. There are three tables for each scenario combination of world oil prices and low or high technology improvements.

17.1 Base Case

Fuel Cost

Transportation Fuel	Total $/GJ	Total $/L	Total Cost Gasoline Equ (GJ)
Gasoline	4.74	0.17	1.00
RFG	5.18	0.18	1.09
Diesel	4.51	0.17	0.95
LPG	2.80	0.07	0.59
CNG	6.70	0.05	1.41
LNG	7.19	0.19	1.52
Methanol	7.36	0.13	1.55
Hydrogen Hydride	18.90	0.04	3.98
Hydrogen LH2	24.94	0.25	5.26
Hydrogen CH2	18.37	0.05	3.87
Ethanol	16.20	0.38	3.42
Electricity	19.17	NA	4.04
M85	6.69	0.14	1.41
E85	13.83	0.35	2.92

Emissions

Fuel/ Drivetrain	Total Emissions Resulting from Vehicle Fuel Use (g/mile equiv)							Total CO2 Equivalent Emissions	Total NOX + HC
	CO2	SO2	NOx	CO	NMHCs*	CH4	PM		
Gasoline	349.9	NA	0.7	10.1	0.5	0.1	0.2	351.2	1.2
RFG	360.2	NA	0.7	8.1	0.4	0.1	0.2	361.5	1.0
Diesel	326.1	NA	4.2	15.6	1.3	0.1	0.1	327.3	5.5
LPG	270.7	NA	1.2	5.0	0.4	0.1	0.1	271.9	1.6
CNG	232.5	0.1	1.0	2.8	0.1	1.3	0.1	244.1	1.1
Methanol ICE(otto)	309.5	0.1	1.2	1.8	0.3	0.7	0.1	315.9	1.5
Methanol FC	152.5	0.0	0.3	0.1	0.1	0.3	0.0	155.5	0.3
LNG	228.3	0.1	1.0	2.8	0.1	1.3	0.1	239.9	1.1
Hydrogen FC	131.3	0.0	0.2	0.0	0.0	0.2	0.0	133.5	0.2
Hydrogen Hydride	272.2	0.1	1.1	0.1	0.1	0.5	0.0	276.7	1.2
Hydrogen CH2	233.5	0.1	1.1	0.1	0.1	0.4	0.0	237.3	1.1
Hydrogen LH2	233.5	0.1	1.1	0.1	0.1	0.4	0.0	237.3	1.1
Ethanol	317.9	2.5	1.9	1.9	0.4	0.1	2.3	318.8	2.2
Batt. Elec.	221.4	0.9	0.8	0.1	0.0	0.6	0.2	226.8	0.8
M85	354.4	NA	0.7	2.9	0.3	0.7	0.1	360.3	1.0
E85	359.8	NA	1.4	3.1	0.3	0.1	2.1	360.8	1.6
EV/RFG Hybrid	224.6	NA	0.4	4.0	0.2	0.1	0.2	225.4	0.6

Cost

Fuel/ Drivetrain	Fuel Cost	Maint. Cost	Replacement Battery Cost	Refueling Station Cost $/vehicle	Lifecycle OEM Low	Lifecycle OEM High
Gasoline	1718	2748	0	0	0	0
RFG	1876	2748	0	0	158	158
Diesel	1633	2748	0	0	-86	-86
LPG	924	2748	0	58	-537	63
CNG	2206	2748	0	474	888	1488
Methanol ICE(otto)	2318	2748	0	68	667	967
Methanol FC	1142	1649	0	68	4393	148393
LNG	2326	2748	0	537	1007	1407
Hydrogen FC	2496	1649	0	272	6478	150878
Hydrogen Hydride	5321	2610	0	239	4160	10859
Hydrogen CH2	4437	2610	0	483	3381	3781
Hydrogen LH2	6024	2610	0	797	5228	5628
Ethanol	5149	2748	0	68	3498	3798
Batt. Elec.	1949	1649	11145	400	7677	13677
M85	2424	2748	0	68	773	1073
E85	5011	2748	0	68	3360	3660
EV/RFG Hybrid	1170	2748	3374	0	6825	7825

17.2 Scenario 2L: 2010 Reference Price: Low Technology

Fuel Cost

Transportation Fuel	Total $/GJ	Total $/L	Total Cost Gasoline Equ (GJ)
Gasoline	7.16	0.25	1.00
RFG	7.65	0.26	1.07
Diesel	6.80	0.26	0.95
LPG	4.54	0.11	0.63
CNG	9.41	0.07	1.31
LNG	9.90	0.26	1.38
Methanol	11.32	0.20	1.58
Hydrogen Hydride	21.75	0.05	3.04
Hydrogen LH2	27.87	0.28	3.89
Hydrogen CH2	21.24	0.06	2.97
Ethanol	13.96	0.33	1.95
Electricity	20.62		2.88
M85	10.37	0.21	1.45
E85	12.66	0.32	1.77

Emissions

	Total Emissions Resulting from Vehicle Fuel Use (g/mile equiv)							Total CO2	Total
Fuel/ Drivetrain	CO2	SO2	NOx	CO	NMHCs*	CH4	PM	Equivalent Emissions	NOX + HC
Gasoline	42948.0		85.2	1293.7	58.9	17.3	20.0	43103.7	144.1
RFG	44664.7		74.9	1037.5	45.6	17.5	21.0	44822.3	120.6
Diesel	38770.1		527.2	1998.3	173.5	16.9	15.0	38921.8	700.7
LPG	33771.3		151.9	646.6	106.6	16.7	4.6	33922.0	258.4
CNG	29325.4	7.7	115.5	352.7	38.1	162.0	14.8	30783.8	153.5
Methanol ICE(otto)	39421.6	9.0	123.9	230.8	75.0	85.6	15.4	40192.4	198.8
Methanol FC	19598.4	4.5	22.4	6.1	7.2	39.2	1.2	19951.5	29.6
LNG	28792.0	7.6	115.0	352.6	37.9	161.2	14.7	30242.5	152.9
Hydrogen FC	16877.5	6.0	17.6	4.1	4.1	28.5	1.3	17134.3	21.7
Hydrogen Hydride	34979.2	12.5	126.4	8.4	8.5	59.2	2.7	35511.6	134.9
Hydrogen CH2	30004.4	10.7	121.2	7.2	7.3	50.7	2.4	30461.0	128.5
Hydrogen LH2	30004.4	10.7	121.2	7.2	7.3	50.7	2.4	30461.0	128.5
Ethanol	29631.5	127.1	179.8	317.2	67.9	14.3	143.2	29760.3	247.8
Batt. Elec.	28453.3	111.3	83.1	11.6	2.8	76.0	17.9	29137.5	85.8
M85	44970.0		70.0	372.6	67.5	79.1	16.8	45682.1	137.5
E85	35509.1		121.8	463.8	44.4	15.1	132.2	35644.9	166.2
EV/RFG Hybrid	28059.6		40.4	519.9	24.5	9.3	17.9	28143.6	64.9

Cost

Fuel/ Drivetrain	Fuel Cost	Maint. Cost	Replacement Battery Cost	Refueling Station Cost $/vehicle	Lifecycle OEM Low	Lifecycle OEM High
Gasoline	2594	2748	0	0	20342	20342
RFG	2772	2748	0	0	20520	20520
Diesel	2464	2748	0	0	20212	20212
LPG	1494	2748	0	58	19500	20100
CNG	3099	2748	0	474	21721	22321
Methanol ICE(otto)	3567	2748	0	68	21383	21683
Methanol FC	1758	1649	0	68	21475	165475
LNG	3203	2748	0	537	21888	22288
Hydrogen FC	2886	1649	0	272	23607	168007
Hydrogen Hydride	6125	2610	0	239	24669	31368
Hydrogen CH2	5131	2610	0	483	24024	24424
Hydrogen LH2	6733	2610	0	797	25941	26341
Ethanol	4437	2748	0	68	22253	22553
Batt. Elec.	2097	1649	11145	400	27291	33291
M85	3759	2748	0	68	21575	21875
E85	4587	2748	0	68	22403	22703
EV/RFG Hybrid	1729	2748	3374	0	26851	27851

17.3 Scenario 2H: 2010 Reference Price: High Technology

Fuel Cost

Transportation Fuel	Total $/GJ	Total $/L	Total Cost Gasoline Equ (GJ)
Gasoline	7.16	0.25	1.00
REG	6.55	0.22	0.92
Diesel	6.80	0.26	0.95
LPG	4.55	0.11	0.64
CNG	9.41	0.07	1.31
LNG	9.90	0.26	1.38
Methanol	11.17	0.20	1.56
Hydrogen Hydride	15.02	0.04	2.10
Hydrogen LH2	21.14	0.21	2.95
Hydrogen CH2	14.51	0.04	2.03
Ethanol	13.97	0.33	1.95
Electricity	20.78		2.90
M85	10.29	0.21	1.44
E85	12.69	0.32	1.77

Emissions

Fuel/ Drivetrain	Total Emissions Resulting from Vehicl							Total CO2 Equivalent Emissions	Total NOX + HC
	CO2	SO2	NOx	CO	NMHCs*	CH4	PM		
Gasoline	37657.7		82.7	1292.6	57.3	16.8	19.1	37808.7	140.0
REG	39220.0		72.2	1036.4	44.1	17.0	20.0	39372.6	116.2
Diesel	33840.7		525.7	1997.5	172.7	16.4	14.7	33988.2	698.4
LPG	29679.5		150.6	646.1	106.1	16.3	4.2	29826.0	256.8
CNG	25811.2	6.8	112.5	352.0	36.9	156.3	14.5	27217.8	149.4
Methanol	34743.4	8.0	118.5	229.3	73.3	79.3	15.1	35457.5	191.8
Methanol FC	19598.4	4.5	22.4	6.1	7.2	39.2	1.2	19951.5	29.6
LNG	25340.6	6.7	112.1	352.0	36.8	155.5	14.5	26740.2	148.8
Hydrogen FC	16877.5	6.0	17.6	4.1	4.1	28.5	1.3	17134.3	21.7
Hydrogen Hydride	30273.5	10.8	121.5	7.3	7.3	51.2	2.4	30734.2	128.8
Hydrogen CH2	26474.5	9.5	117.5	6.4	6.4	44.8	2.1	26877.4	123.9
Hydrogen LH2	26474.5	9.5	117.5	6.4	6.4	44.8	2.1	26877.4	123.9
Ethanol	26145.5	112.1	167.9	305.6	67.0	14.1	127.9	26272.7	234.9
Batt. Elec.	28453.3	111.3	83.1	11.6	2.8	76.0	17.9	29137.5	85.8
M85	39612.9		64.8	371.1	65.6	73.6	16.4	40275.3	130.4
E85	31262.7		110.5	453.0	43.2	14.8	118.1	31396.1	153.7
EV/REG Hybrid	24663.5		38.7	519.2	23.5	9.0	17.3	24744.4	62.2

Cost

Fuel/ Drivetrain	Fuel Cost	Maint Cost	Replacement Battery Cost	Refueling Station $/vehicle	OEM Low	OEM
Gasoline	2289	2748	0	0	21037	21037
REG	2094	2748	0	0	20842	20842
Diesel	2174	2748	0	0	20922	20922
LPG	1322	2748	0	58	20328	20928
CNG	2734	2748	0	419	22301	22901
Methanol	3104	2748	0	68	21920	22220
Methanol FC	1734	1649	0	68	22251	166251
LNG	2826	2748	0	474	22448	22848
Hydrogen FC	1972	1649	0	272	23492	167892
Hydrogen Hydride	3660	2610	0	207	23079	28877
Hydrogen CH2	3093	2610	0	426	22930	23330
Hydrogen LH2	4506	2610	0	703	24620	25020
Ethanol	3919	2748	0	68	22735	23035
Batt. Elec.	2113	1649	4669	400	21631	28031
M85	3291	2748	0	68	22106	22406
E85	4056	2748	0	68	22872	23172
EV/REG Hybrid	1306	2748	2249	0	26303	27303

17.4 Scenario 3L: 2010 High Price: Low Technology

Fuel Cost

Transportation Fuel	**Total $/GJ**	**Total $/L**	**Total Cost Gasoline Equ (GJ)**
Gasoline	8.48	0.30	1.00
RFG	9.01	0.31	1.06
Diesel	8.06	0.31	0.95
LPG	4.83	0.12	0.57
CNG	9.24	0.07	1.09
LNG	9.73	0.25	1.15
Methanol	11.08	0.20	1.31
Hydrogen Hydride	21.57	0.05	2.54
Hydrogen LH2	27.72	0.28	3.27
Hydrogen CH2	21.07	0.06	2.48
Ethanol	13.97	0.33	1.65
Electricity	20.70		2.44
M85	10.53	0.21	1.24
E85	12.95	0.32	1.53

Emissions

	Total Emissions Resulting from Vehicle Fuel Use (g/mile equiv)							Total CO2	Total
Fuel/ Drivetrain	CO2	SO2	NOx	CO	NMHCs*	CH4	PM	Equivalent Emissions	NOX + HC
Gasoline	42948.0		85.2	1293.7	58.9	17.3	20.0	43103.7	144.1
RFG	44664.7		74.9	1037.5	45.6	17.5	21.0	44822.3	120.6
Diesel	38770.1		527.2	1998.3	173.5	16.9	15.0	38921.8	700.7
LPG	33771.3		151.9	646.6	106.6	16.7	4.6	33922.0	258.4
CNG	29325.4	7.7	115.5	352.7	38.1	162.0	14.8	30783.8	153.5
Methanol ICE(otto)	39421.6	9.0	123.9	230.8	75.0	85.6	15.4	40192.4	198.8
Methanol FC	19598.4	4.5	22.4	6.1	7.2	39.2	1.2	19951.5	29.6
LNG	28792.0	7.6	115.0	352.6	37.9	161.2	14.7	30242.5	152.9
Hydrogen FC	16877.5	6.0	17.6	4.1	4.1	28.5	1.3	17134.3	21.7
Hydrogen Hydride	34979.2	12.5	126.4	8.4	8.5	59.2	2.7	35511.6	134.9
Hydrogen CH2	30004.4	10.7	121.2	7.2	7.3	50.7	2.4	30461.0	128.5
Hydrogen LH2	30004.4	10.7	121.2	7.2	7.3	50.7	2.4	30461.0	128.5
Ethanol	29631.5	127.1	179.8	317.2	67.9	14.3	143.2	29760.3	247.8
Batt. Elec.	28453.3	111.3	83.1	11.6	2.8	76.0	17.9	29137.5	85.8
M85	44970.0		70.0	372.6	67.5	79.1	16.8	45682.1	137.5
E85	35509.1		121.8	463.8	44.4	15.1	132.2	35644.9	166.2
EV/RFG Hybrid	28059.6		40.4	519.9	24.5	9.3	17.9	28143.6	64.9

Cost

Fuel/ Drivetrain	Fuel Cost	Maint. Cost	Replacement Battery Cost	Refueling Station Cost $/vehicle	OEM Low	OEM High
Gasoline	3074	2748	0	0	20822	20822
RFG	3264	2748	0	0	21012	21012
Diesel	2921	2748	0	0	20668	20668
LPG	1591	2748	0	58	19597	20197
CNG	3043	2748	0	474	21665	22265
Methanol ICE(otto)	3490	2748	0	68	21306	21606
Methanol FC	1720	1649	0	68	21437	165437
LNG	3148	2748	0	537	21833	22233
Hydrogen FC	2863	1649	0	272	23583	167983
Hydrogen Hydride	6074	2610	0	239	24619	31318
Hydrogen CH2	5089	2610	0	483	23983	24383
Hydrogen LH2	6696	2610	0	797	25904	26304
Ethanol	4441	2748	0	68	22257	22557
Batt. Elec.	2105	1649	11145	400	27299	33299
M85	3816	2748	0	68	21632	21932
E85	4691	2748	0	68	22507	22807
EV/RFG Hybrid	2036	2748	3374	0	27157	28157

17.5 Scenario 3H: 2010 High Price: High Technology

Fuel Cost

Transportation Fuel	Total $/GJ	Total $/L	Total Cost Gasoline Equ (GJ)
Gasoline	8.48	0.30	1.00
RFG	7.76	0.26	0.91
Diesel	8.06	0.31	0.95
LPG	4.84	0.12	0.57
CNG	9.24	0.07	1.09
LNG	9.73	0.25	1.15
Methanol	10.92	0.20	1.29
Hydrogen Hydride	14.84	0.04	1.75
Hydrogen LH2	20.99	0.21	2.47
Hydrogen CH2	14.34	0.04	1.69
Ethanol	13.99	0.33	1.65
Electricity	20.86		2.46
M85	10.45	0.21	1.23
E85	12.97	0.32	1.53

Emissions

Fuel/ Drivetrain	Total Emissions Resulting from Vehicle Fuel Use (g/mile equiv)							Total CO2 Equivalent Emissions	Total NOX + HC
	CO2	SO2	NOx	CO	NMHCs*	CH4	PM		
Gasoline	37657.7		82.7	1292.6	57.3	16.8	19.1	37808.7	140.0
RFG	39220.0		72.2	1036.4	44.1	17.0	20.0	39372.6	116.2
Diesel	33840.7		525.7	1997.5	172.7	16.4	14.7	33988.2	698.4
LPG	29679.5		150.6	646.1	106.1	16.3	4.2	29826.0	256.8
CNG	25811.2	6.8	112.5	352.0	36.9	156.3	14.5	27217.8	149.4
Methanol ICE(otto)	34743.4	8.0	118.5	229.3	73.3	79.3	15.1	35457.5	191.8
Methanol FC	19598.4	4.5	22.4	6.1	7.2	39.2	1.2	19951.5	29.6
LNG	25340.6	6.7	112.1	352.0	36.8	155.5	14.5	26740.2	148.8
Hydrogen FC	16877.5	6.0	17.6	4.1	4.1	28.5	1.3	17134.3	21.7
Hydrogen Hydride	30273.5	10.8	121.5	7.3	7.3	51.2	2.4	30734.2	128.8
Hydrogen CH2	26474.5	9.5	117.5	6.4	6.4	44.8	2.1	26877.4	123.9
Hydrogen LH2	26474.5	9.5	117.5	6.4	6.4	44.8	2.1	26877.4	123.9
Ethanol	26145.5	112.1	167.9	305.6	67.0	14.1	127.9	26272.7	234.9
Batt. Elec.	28453.3	111.3	83.1	11.6	2.8	76.0	17.9	29137.5	85.8
M85	39612.9		64.8	371.1	65.6	73.6	16.4	40275.3	130.4
E85	31262.7		110.5	453.0	43.2	14.8	118.1	31396.1	153.7
EV/RFG Hybrid	24663.5		38.7	519.2	23.5	9.0	17.3	24744.4	62.2

Cost

Fuel/ Drivetrain	Fuel Cost	Maint. Cost	Replacement Battery Cost	Refueling Station Cost $/vehicle	OEM Low	OEM High
Gasoline	2713	2748	0	0	21460	21460
RFG	2480	2748	0	0	21228	21228
Diesel	2577	2748	0	0	21325	21325
LPG	1407	2748	0	58	20413	21013
CNG	2685	2748	0	419	22252	22852
Methanol ICE(otto)	3037	2748	0	68	21853	22153
Methanol FC	1696	1649	0	68	22213	166213
LNG	2778	2748	0	474	22400	22800
Hydrogen FC	1948	1649	0	272	23469	167869
Hydrogen Hydride	3617	2610	0	207	23036	28834
Hydrogen CH2	3056	2610	0	426	22893	23293
Hydrogen LH2	4474	2610	0	703	24588	24988
Ethanol	3923	2748	0	68	22739	23039
Batt. Elec.	2122	1649	4669	400	21639	28039
M85	3341	2748	0	68	22157	22457
E85	4147	2748	0	68	22963	23263
EV/RFG Hybrid	1547	2748	2249	0	26544	27544

17.6 Scenario 1L: 2010 Low Price: Low Technology

Fuel Cost

Transportation Fuel	**Total $/GJ**	**Total $/L**	**Total Cost Gasoline Equ (GJ)**
Gasoline	5.05	0.18	1.00
RFG	5.50	0.19	1.09
Diesel	4.80	0.19	0.95
LPG	3.75	0.09	0.74
CNG	8.76	0.07	1.73
LNG	9.25	0.24	1.83
Methanol	10.49	0.19	2.08
Hydrogen Hydride	21.14	0.05	4.18
Hydrogen LH2	27.03	0.27	5.35
Hydrogen CH2	20.57	0.06	4.07
Ethanol	13.84	0.33	2.74
Electricity	19.92		3.94
M85	9.22	0.19	1.82
E85	12.13	0.30	2.40

Emissions

	Total Emissions Resulting from Vehicle Fuel Use (g/mile equiv)							Total CO2	Total
Fuel/ Drivetrain	CO2	SO2	NOx	CO	NMHCs*	CH4	PM	Equivalent Emissions	NOX + HC
Gasoline	42948.0		85.2	1293.7	58.9	17.3	20.0	43103.7	144.1
RFG	44664.7		74.9	1037.5	45.6	17.5	21.0	44822.3	120.6
Diesel	38770.1		527.2	1998.3	173.5	16.9	15.0	38921.8	700.7
LPG	33771.3		151.9	646.6	106.6	16.7	4.6	33922.0	258.4
CNG	29325.4	7.7	115.5	352.7	38.1	162.0	14.8	30783.8	153.5
Methanol ICE(otto)	39421.6	9.0	123.9	230.8	75.0	85.6	15.4	40192.4	198.8
Methanol FC	19598.4	4.5	22.4	6.1	7.2	39.2	1.2	19951.5	29.6
LNG	28792.0	7.6	115.0	352.6	37.9	161.2	14.7	30242.5	152.9
Hydrogen FC	16877.5	6.0	17.6	4.1	4.1	28.5	1.3	17134.3	21.7
Hydrogen Hydride	34979.2	12.5	126.4	8.4	8.5	59.2	2.7	35511.6	134.9
Hydrogen CH2	30004.4	10.7	121.2	7.2	7.3	50.7	2.4	30461.0	128.5
Hydrogen LH2	30004.4	10.7	121.2	7.2	7.3	50.7	2.4	30461.0	128.5
Ethanol	29631.5	127.1	179.8	317.2	67.9	14.3	143.2	29760.3	247.8
Batt. Elec.	28453.3	111.3	83.1	11.6	2.8	76.0	17.9	29137.5	85.8
M85	44970.0		70.0	372.6	67.5	79.1	16.8	45682.1	137.5
E85	35509.1		121.8	463.8	44.4	15.1	132.2	35644.9	166.2
EV/RFG Hybrid	28059.6		40.4	519.9	24.5	9.3	17.9	28143.6	64.9

Cost

Fuel/ Drivetrain	Fuel Cost	Maint. Cost	Replacement Battery Cost	Refueling Station Cost $/vehicle	OEM Low	OEM High
Gasoline	1831	2748	0	0	19579	19579
RFG	1992	2748	0	0	19740	19740
Diesel	1740	2748	0	0	19488	19488
LPG	1235	2748	0	58	19241	19841
CNG	2887	2748	0	474	21509	22109
Methanol ICE(otto)	3305	2748	0	68	21121	21421
Methanol FC	1629	1649	0	68	21346	165346
LNG	2994	2748	0	537	21679	22079
Hydrogen FC	2796	1649	0	272	23516	167916
Hydrogen Hydride	5952	2610	0	239	24497	31196
Hydrogen CH2	4970	2610	0	483	23864	24264
Hydrogen LH2	6529	2610	0	797	25737	26137
Ethanol	4399	2748	0	68	22215	22515
Batt. Elec.	2026	1649	11145	400	27220	33220
M85	3340	2748	0	68	21156	21456
E85	4395	2748	0	68	22211	22511
EV/RFG Hybrid	1242	2748	3374	0	26364	27364

17.7 Scenario 1H: 2010 Low Price: High Technology

Fuel Cost

Transportation Fuel	Total $/GJ	Total $/L	Total Cost Gasoline Equ (GJ)
Gasoline	5.05	0.18	1.00
RFG	4.63	0.16	0.92
Diesel	4.80	0.19	0.95
LPG	3.76	0.09	0.74
CNG	8.76	0.07	1.73
LNG	9.25	0.24	1.83
Methanol	10.33	0.19	2.04
Hydrogen Hydride	14.41	0.03	2.85
Hydrogen LH2	20.30	0.20	4.02
Hydrogen CH2	13.84	0.04	2.74
Ethanol	13.85	0.33	2.74
Electricity	20.08		3.97
M85	9.14	0.18	1.81
E85	12.16	0.30	2.40

Emissions

	Total Emissions Resulting from Vehicle Fuel Use (g/mile equiv)							Total CO2	Total
Fuel/ Drivetrain	CO2	SO2	Nox	CO	NMHCs*	CH4	PM	Equivalent Emissions	NOX + HC
Gasoline	37657.7		82.7	1292.6	57.2	16.7	19.1	37808.7	140.00
RFG	39220.0		72.2	1036.4	44.1	17.0	20.0	39372.6	116.2
Diesel	33840.7		525.7	1997.5	172.7	16.4	14.7	33988.2	698.4
LPG	29679.5		150.6	646.1	106.1	16.3	4.2	29826.0	256.8
CNG	25811.2	6.8	112.5	352.0	36.9	156.3	14.5	27217.8	149.4
Methanol ICE(otto)	34743.4	8.0	118.5	229.3	73.3	79.3	15.1	35457.5	191.8
Methanol FC	19598.4	4.5	22.4	6.1	7.2	39.2	1.2	19951.5	29.6
LNG	25340.6	6.7	112.1	352.0	36.8	155.5	14.5	26740.2	148.8
Hydrogen FC	16877.5	6.0	17.6	4.1	4.1	28.5	1.3	17134.3	21.7
Hydrogen Hydride	30273.5	10.8	121.5	7.3	7.3	51.2	2.4	30734.2	128.8
Hydrogen CH2	26474.5	9.5	117.5	6.4	6.4	44.8	2.1	26877.4	123.9
Hydrogen LH2	26474.5	9.5	117.5	6.4	6.4	44.8	2.1	26877.4	123.9
Ethanol	26145.5	112.1	167.9	305.6	67.0	14.1	127.9	26272.7	234.9
Batt. Elec.	28453.3	111.3	83.1	11.6	2.8	76.0	17.9	29137.5	85.8
M85	39612.9		64.8	371.1	65.6	73.6	16.4	40275.3	130.4
E85	31262.7		110.5	453.0	43.2	14.8	118.1	31396.1	153.7
EV/RFG Hybrid	24663.5		38.7	519.2	23.5	9.0	17.3	24744.4	62.2

Cost

Fuel/ Drivetrain	Fuel Cost	Maint. Cost	Replacement Battery Cost	Refueling Station Cost $/vehicle	OEM Low	OEM High
Gasoline	1615.99	2747.89	0	0	20363.9	20363.9
RFG	1481	2748	0	0	20229	20229
Diesel	1535	2748	0	0	20283	20283
LPG	1093	2748	0	58	20099	20699
CNG	2547	2748	0	419	22114	22714
Methanol ICE(otto)	2873	2748	0	68	21689	21989
Methanol FC	1605	1649	0	68	22122	166122
LNG	2641	2748	0	474	22263	22663
Hydrogen FC	1881	1649	0	272	23402	167802
Hydrogen Hydride	3511	2610	0	207	22930	28728
Hydrogen CH2	2951	2610	0	426	22788	23188
Hydrogen LH2	4327	2610	0	703	24441	24841
Ethanol	3885	2748	0	68	22701	23001
Batt. Elec.	2043	1649	4669	400	21560	27960
M85	2921	2748	0	68	21737	22037
E85	3886	2748	0	68	22702	23002
EV/RFG Hybrid	924	2748	2249	0	25921	26921
EV/RFG Hybrid	924	2748	3374	0	27046	28046

18. Appendix: Sensitivity Tests of the Modified ADL/Ford Model

Table 18.1: Results of the Modified ADL/Ford Model Sensitivity Analysis. Costs in the Table Refer to the Cost Difference Between AFV and CGV.

Input Varied	Outputs Affected	Greatest Magnitude of Effect: % change in input / % change in output	Effect of Improvements in Input on Results
Battery Lifetime # cycles 600-1000 for BEV; 5000-10000 for HEV.	BEV, HEV cost	BEV Lifecycle cost: 1 / 0.6 HEV Lifecycle cost: 1 / 0.3	Max foreseen improvement for BEV will give 40% reduction in incremental cost. Hybrid model already uses best technology.
Battery Cost 150$/kWh-100$/kWh	BEV, HEV cost	BEV Lifecycle cost: 1 / 0.6 HEV Lifecycle cost: 1 / 0.3	Expect 50% reduction possible over base case, equals 35% and 15% reduction in incremental cost for BEV, HEV.
Discount Rate 10%-15%	Rise makes cheaper fuels seem more expensive	BEV Lifecycle cost: 1 / 3 Replacement battery purchase cost is reduced by higher D.R.	Changes in incremental costs can be significant between vehicles with different fuel costs. Comparative scenarios must use same D.R.
Methanol Production Location Mix Region I-IV	Cost of Methanol Powered Vehicles	Very Small Effect on Methanol Cost	Not a concern.
Relative Vehicle Efficiency to CGV 0.9-1.1	Emissions, Efficiency, Fuel Consumption, Fuel Costs	Emissions Change: 1/1 for petroleum fuels. Cost: < 1/1 for efficient vehicles, > 1/1 for less efficient ICEV	Makes already clean alternatives cleaner relative to CGV. Makes efficient vehicles cheaper relative to CGV.
Base (CGV) Vehicle Efficiency 15%-20%	Emissions, Cost, Efficiency of ICEVs	Emissions: 1/1 except NOx, 1/0.4; PM 1/0.5. Cost: 1/0.2 Lifecycle Efficiency: 1/1 Lifecycle	Does not affect electric powertrain vehicles, which are modeled independently of the ICE drivetrain. Improved ICE efficiency decreases attractiveness of electric alternatives very slightly. Max efficiency of ~20% gives max improvement in cost of -4%, emissions of ~-9%.
LPG Resource Mix: Petroleum vs. Natural Gas 50/50 to 30/70	LPG emissions, cost	Emissions: 1% increase toward Natural gas/0.1% emissions increase Cost: 1/0.6	No concern unless LPG costs from petroleum and natural gas resources are very different.

H2 Resource Mix: Natural Gas vs. Coal 90/10 to 70/30	H2 emissions, cost	Emissions: 1% increase toward coal/1% increase in CO2 equivalent emissions (inc. CH4) and 1.5% increase in PM. Cost: Fuel and lifecycle costs 1%/1% increase for shift toward coal.	Concern for CO2 equivalent emissions if the base case 90% NG/10% Coal resource mix is incorrect.
Coal Price $22/ton-$26/ton	Hydrogen and Methanol Cost, lifecycle costs	Hydrogen Cost: 1% rise in coal cost/1% rise in hydrogen cost	Not enough contribution to fuel manufacture to cause concern.
Corn Byproduct Price $200/ton-$0	Ethanol Cost	Complete removal of corn byproduct market, price from $200/ton-$0/ton, increases lifecycle cost of ethanol vehicles 35%.	At 1%/0.3%, not a significant impact on lifecycle cost. Much more significant is low yield of ethanol per unit corn input, which is set at the maximum yield in the base case.
Petroleum Price $21/bbl-$25/bbl	Lifecycle cost of petroleum vehicles.	1%/1% effect on Lifecycle vehicle cost.	Petrloeum vehicle incremental cost is zero except for different fuel costs. Changes in petroleum price propagate to vehicle lifecycle cost at 1:1 ratio.
Natural Gas Price $1.70/cf-$2.50/cf	Methanol, CNG, LNG cost and lifecycle cost of these vehicles	1%/0.1% Lifecycle cost effect on LNG, CNG. 1%/0.3% for ICE methanol vehicles. No effect for fuel cell.	Significant cost of fuel cell vehicle causes no lifecycle impact of changes in methanol cost. High vehicle cost increment causes low impact on lifecycle cost for CNG, LNG. Low vehicle cost increment makes methanol ICE sensitive to natural gas price.
Coal Boiler technology controls 10%controlled-50% controlled	Ethanol, electricity efficiency and emissions	Ethanol, E85: Emissions: PM 1/1 NOx 1/0.2 BEV: Emissions: NOx 1/0.3	Ethanol PM emissions are strongly influenced by the control technology on coal boilers.
Natural Gas Boiler technology controls: same as above	Methanol, hydrogen emissions and efficiency	<1/0.1 effect on all emissions	Room for improvement is small for natural gas boilers. Insignificant effect on output.

Methanol Resource Mix: Natural Gas vs. Coal 100/0-50/50	Cost of methanol Emissions of methanol Efficiency of methanol conversion	Cost: 1% more coal/1% higher incremental lifecycle cost Emissions: 1% more coal/1% higher greenhouse emissions 1% more coal/0.5% lower NMHC emissions. No change in efficiency	An unlikely scenario unless the process becomes cheaper. Effects are traceable in 1/1 incremental lifecycle cost and greenhouse gas increase.
Vehicle tailpipe emissions See Below	Emissions, Cost of Vehicle	Emissions change in proportion to ratio of tailpipe-to-fuel chain emissions.	All vehicles have similar tailpipe emissions except ZEVs. Base case vehicles have ~65% tailpipe emissions. Changes in tailpipe emissions count less as better control technology is used.
Vehicle Acquisition OEM low and OEM high predictions	Lifecycle Cost	For ICE and fuel cell vehicles, a 1% change in vehicle price gives a 1% change in lifecycle cost. For BEVs and HEVs, which have high future expenses, the ratio is < 1/0.4	OEM low and OEM high prices reflect known prices of available vehicles or projected prices of experimental vehicles. Uncertainty is so high for experimetal vehicles that no reliable prediction can be made.
Liquid Fuel Shipment Distance 50 mi to 75 mi	Petroleum and Alcohol Vehicle Lifecycle Cost	50% increase in truck transport increases lifecycle cost \$50 for ICE, \$25 FC, \$44 M85 This is 8% rise in difference cost for methanol.	Denser location of fuel plants or dist. centers (shorter trucking distance) will lower LCC only a little.
Barge Cost 2.5c/t-mi to 5c/t-mi	All fuels	100% rise, \$20 rise in petroleum and ethanol vehicles, \$13 hybrid	Inconsequential to LCC
Truck liquid transport cost	Liquid fuels carried by truck	100% rise in per mile cost raises methanol, M85 vehicle LCC 100\$, ethanol, E85 LCC rises \$125 This is 15% incremental increase for methanol, 2.5% for ethanol	Not significant enough to make methanol vehicles as inexpensive as gasoline.
Gas Pipeline	Natural Gas fuels	50% reduction reduces CNG, LNG LCC \$400, hydrogen vehicles \$250-\$300 25% reduction for LNG, CNG	Single cost could mask regional cost effectiveness of CNG, LNG vehicles.
Fuel Production Cost: NG → MeOH High → Low	Methanol Fuel	Increased number of large-scale production plants from 10% to 50%. Lowers MeOH LCC \$50, M85 \$40, MFC \$25	Not significant enough as a single variable to make methanol as inexpensive as gasoline over Lifecycle.

Fuel Production Cost: NG→H2 High→Low	Hydrogen Fuel	60% reduction in fuel production cost causes: LCC of H2 FC reduced $800, H2 Hydride $1700, CH2 and LH2 down $1440.	Could make compressed hydrogen ICEV less expensive than pure ethanol.