34

Effectiveness of Electric Vehicles Vs. Other Vehicle Technologies: A Case Study in Environmental Transportation Policy

by

Konstantinos Sgoutas

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Massachusetts Institute of Technology
September 1995

Signature of Author...

Certified by ....
Dr. Joel P. Clark
Thesis Supervisor, Professor of Materials Engineering

Certified by ....
Dr. Frank R. Field, III
Thesis Supervisor

Certified by...
Professor Peter P. Belobaba
Thesis Reader; Chairman, Transportation Education Committee

Certified by ....
Professor Richard de Neufville
Chairman, Technology and Policy Program

Accepted by ....
Professor Harold Y. Wachman
Chairman, Departmental Committee on Graduate Studies

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Abstract

This study assesses the consequences of developing and using Electric Vehicles. The technical, economic, environmental, political and industrial implications of forcing the development of Zero Emission Vehicles are analyzed. Electric Vehicles are compared to other alternative fuel technologies on a cost effectiveness basis. The sensitivity of the recommendations under different sets of assumptions is examined to account for technical, economic and market penetration uncertainties.

Results show that the present state of Electric Vehicle development is adequate for supporting only the most limited applications. Battery technology is presently the limiting technology for their successful commercialization. Moreover, the cost of producing and using Electric Vehicles exceeds the corresponding Internal Combustion Engine vehicle cost by a very large margin. Even if a technological or manufacturing breakthrough is accomplished, Electric Vehicles will not become cost competitive to conventional technologies. Environmental benefits will be small to moderate, especially if fuel cycle emissions and solid waste implications are taken into consideration.

Other alternative fuel technologies are shown to be superior to Electric Vehicles on a cost effectiveness basis. In particular, Compressed Natural Gas vehicles are shown to be orders of magnitude more cost effective. This conclusion coupled with the technological, economic, regulatory and environmental uncertainties associated with Electric Vehicle development suggest that adopting an inflexible, technology forcing approach is an unfounded and erroneous policy decision.

Thesis Supervisor: Prof. Joel P. Clark
Title: Professor of Materials Engineering

Thesis Supervisor: Dr. Frank R. Field, III
Title: Director, Materials Systems Laboratory

Thesis Reader: Prof. Peter P. Belobaba
Title: Chair, Transportation Education Committee

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Table of Contents

Appendices

List of Figures

List of Tables

1. Introduction

The concept of sustainable transportation has been increasingly receiving attention both nationwide and internationally. The notion of sustainability encompasses economic, environmental, social and energy goals. All these goals and objectives affect and are affected by transportation. Therefore, the increasing demands on the transportation system to support economic growth and competitiveness while operating in an environmentally sensitive and energy-efficient manner pose new challenges. [Sussman, 1994]

Within this context, public and private interest in the research and development of alternative fuel vehicles has been increasing considerably in the early nineties. The US government has extended its involvement in the development of such advanced automobiles in its effort to address environmental and energy consumption concerns and at the same time to facilitate and assure the competitiveness of the US industry in these advanced automotive technologies. Federal and state initiatives and regulations such as the Clean Air Act Amendments of 1990, the Energy Policy Act of 1992 and the Partnership for the Next Generation of Vehicles have all contributed towards these public policy objectives. At the same time, the established Original Equipment Manufacturers (OEMs) together with entrepreneurial in nature start-up companies have joined the race for successfully developing and commercializing such innovative technologies.

Perhaps the primary motivation for attempting to make the transition away from the Internal Combustion Engine automotive culture has been the inherent potential of alternative fuel technologies for reducing airborne emissions and therefore enhancing Air Quality. As Figure 1 portrays, motor vehicles account for a significant portion of total emissions.

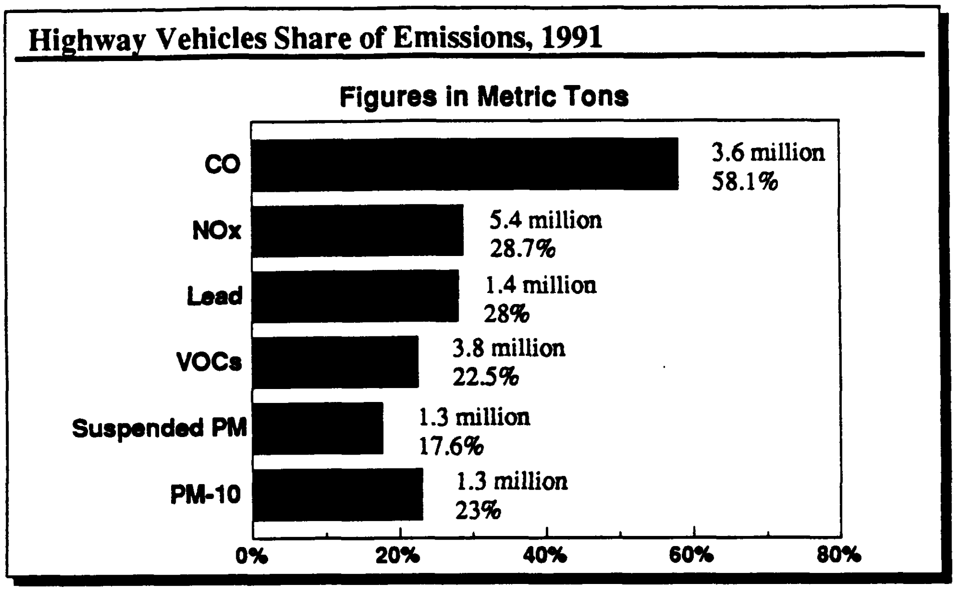

Figure 1: Highway Vehicles Share of Emissions, 1991.

Source: Office of Transportation Technologies, US DOE

The transportation sector remains a major contributor to air quality problems despite the immense reductions in emissions rates that have been accomplished since the early sixties. In principle, the average emission rate is a function of the age distribution of the vehicle fleet, the deterioration of emissions performance with age, the effects of tampering and the effectiveness of Inspection and Maintenance programs. Figure 2 shows the increasingly stringent pollution regulations for hydrocarbons, nitrogen oxides and carbon monoxide, all three pollutants being regulated by the Environmental Protection Agency. During the time period from the early sixties until 1993, hydrocarbon emissions rates have been decreased by 94%. The corresponding reductions for nitrogen oxides and carbon monoxide have been 89% and 96% respectively. Despite the major regulatory and pollution control programs which have resulted in considerably reduced emission rates, some urban areas still exceed the National Ambient Air Quality Standards.

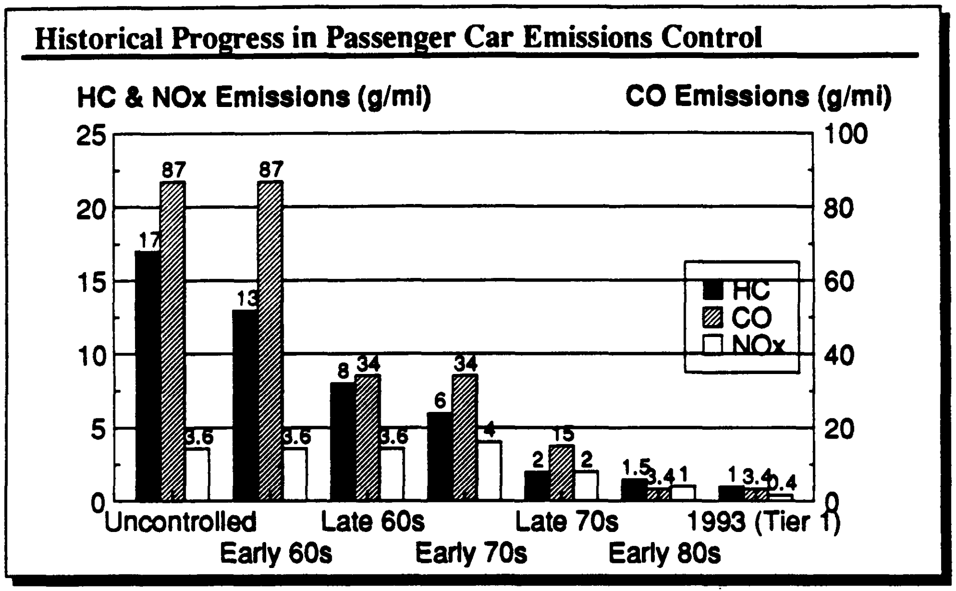

Figure 2: Historical Progress in Passenger Car Emissions Control.

Source: [Austin, 1994]

One important reason explaining the shortcomings in emissions reductions is that although regulations are effective in the sense that new production vehicles do meet the emissions requirements, through the testing and certification of prototypes over 50,000 miles and through testing at the end of the production line, performance in actual use is not as good. The observed differences are not surprising when one considers the nature and complexity of the product and the uneven commitment of vehicle owners to necessary maintenance. [Calvert, 1993]

The main reason why some areas of the country still encounter significant air quality problems is the fact the number of miles driven in major urban areas has gone up, thereby partly offsetting the emissions reductions accomplished through decreasing the grams/mile rates. In particular, as Table 1 portrays, total vehicle miles traveled have increased by 211% since 1960. Furthermore, one can also observe that the bulk of the growth in vehicle miles driven has been accounted for by urban miles. Urban miles have increased by 298% since 1960 compared to a corresponding 136% increase associated with rural miles.

Table 1: ***Total Vehicle Miles Traveled, 1960-1992 (in Billions)***

Year	Urban	Rural	Total	% Change
1960	332	387	719	n/a
1970	570	539	1109	54.2
1980	855	672	1527	37.7
1990	1277	870	2147	40.6
1992	1320	917	2237	4.2

Source: AAMA Motor Vehicle Facts & Figures

These increases in Vehicles Miles Traveled (VMT) are a result of both a larger in-use fleet and a larger number of miles driven per vehicle.

Based on the above discussion, one can group proposals for enhancing air quality into two major categories, namely technical and behavioral solutions. Technical solutions primarily include alternative fuels or advanced automobile designs such as electric vehicles, compressed natural gas vehicles and reformulated gasoline. Behavioral solutions include both regulatory policies attempting to reduce grams/mi and incentive base policies attempting to reduce the number of vehicle miles driven. Enhanced Inspection and Maintenance programs qualify in the former category while the latter category includes VMT based taxes, car-pooling incentives and congestion pricing.

There are some attributes associated with behavioral solutions that make them intrinsically less attractive. Specifically, behavioral solutions are inherently more difficult to implement. Such solutions will directly raise the cost of transportation. One could therefore argue that public opposition will be considerably larger when compared to technical solutions. Funding for the research and development of technical solutions comes primarily from non-earmarked taxation, such as income taxes. The cost for their development is therefore considerably less "visible" to the users. Secondly, technical solutions do not provide incentives to reduce VMT and can not therefore be "accused" of slowing down the economy. The above statement is based on the argument that the transportation system supports the economic activities of a region. Attempting to apply restrictions on the use of the transportation system can therefore be counter productive. Finally, some of the technology based solutions offer the potential for zero emissions at the tailpipe and therefore no deterioration in emissions performance. Battery powered electric vehicles are a good example of such a technology. For these reasons technology based solutions seem to be inherently more attractive from a public policy standpoint.

Air quality considerations are not the sole motivation behind the increased governmental and entrepreneurial interest in alternative fuel technologies. The transportation system accounts for 27% of the nation's primary energy consumption and consumes 65.7% of the petroleum supply. There are two major interrelated reasons why the US government is concerned about the information presented by the two graphs shown in Figure 3.

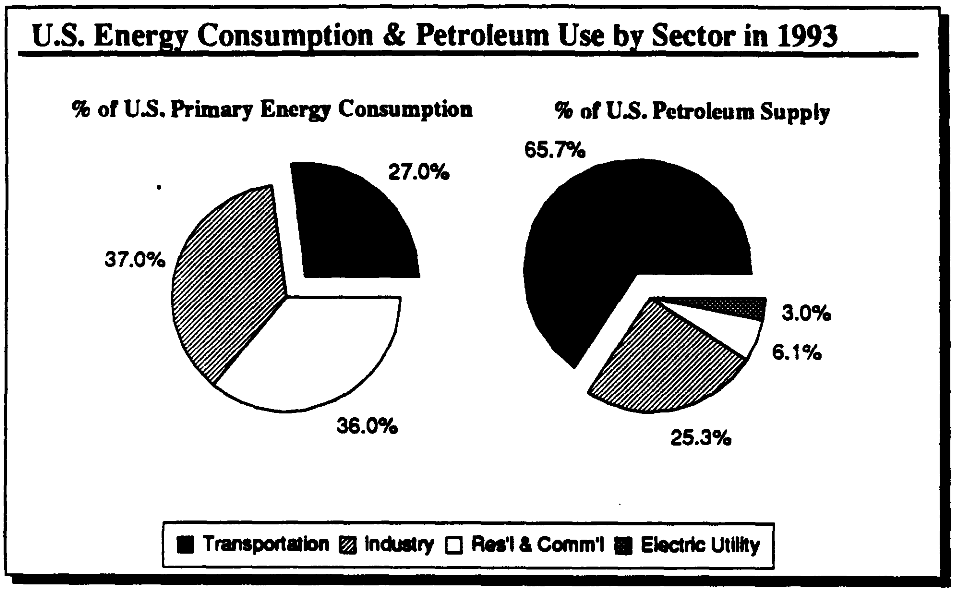

Figure 3: US. Energy Consumption & Petroleum Use by Sector in 1993.

Source: Office of Transportation Technologies, US DOE

The first reason is a pure efficiency argument, not disfavoring the status quo internal combustion engine technology. Since transportation accounts for more than 25% of the country's energy consumption, it is in the interests of society for the transportation sector to be efficient. Simply put, more fuel efficient cars consume less energy, with obvious economic implications and the associated air quality benefits[1]. The second argument which is more relevant to the discussion of alternative fuel technologies is related to the second chart in Figure 3. The transportation system accounts for two thirds of the nation's petroleum needs. In addition, as Figure 4 portrays, 46.1% of the petroleum demand is met through imports. According to DOE's Annual Energy Outlook (1994), net oil imports could rise to between 60 and 75 percent by the year 2010.

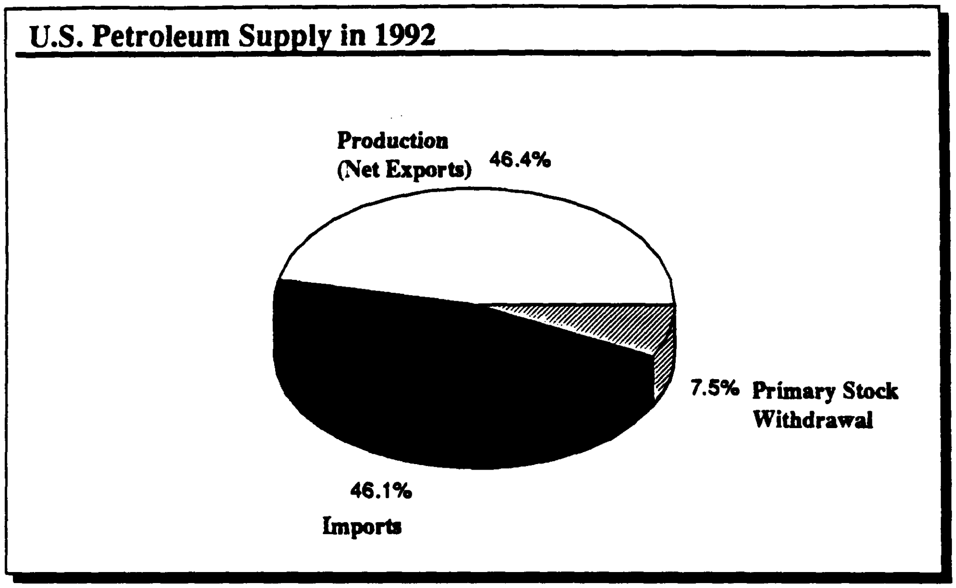

Figure 4: US. Petroleum Supply in 1992.

Source: Office of Transportation Technologies, US DOE

These observations raise important national security concerns and bring the transportation system in general and motor vehicles in particular into the spotlight. The argument in favor of alternative fuel vehicles is therefore that by developing technologies

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[1] to the extent to which pollutant releases are correlated with fuel efficiency.

whose energy requirements can be met by domestic production, the threats to US security from potential interruptions in supply will be reduced, if not eliminated. Many analysts have gone so far as to relate balance of trade concerns to the development of such technologies. Finally, alternative fuel technologies, unlike the internal combustion engine, offer the potential for radical rather than incremental fuel efficiency improvements.

Apart from air quality and energy efficiency considerations, research and development in advanced automotive technologies has also been motivated by important industrial policy concerns. In particular, public policy analysts argue that sooner or later the internal combustion engine status quo is bound to change. Hence, it is in the best interest of the United States to promote research and development in advanced automotive technologies in order to assure the competitiveness of the US industry in the twenty first century. Interestingly enough, apart from Department of Transportation and Department of Energy funds, alternative fuel vehicle research has been receiving substantial amounts of funding from traditionally defense oriented agencies. For example, in 1993 the Defense Department's Advanced Research Projects Agency awarded $25 million for the development of electric vehicle technology. [Automotive News, July 19,1993] At the same time, private companies with a strong background and tradition in defense related projects have entered the automotive supplier market. In other words, a considerable portion of previously allocated to defense dollars has been diverted to advanced automotive technologies. There is no doubt that both the federal government and the US industry realize the potential for competition in the global marketplace that these technologies might offer and therefore do not want to fall behind. Furthermore, states like California and Massachusetts believe that the development of advanced automotive designs could boost local employment through the successful emergence of new, local players in the automobile industry.

This thesis attempts to assess the economic and technical feasibility of alternative fuel vehicles. Moreover, the degree to which each alternative succeeds in addressing the issues that have been the motivation for their development will be appraised. This latter discussion will focus on the air quality and energy consumption implications of the alternatives. Finally, policy recommendations will be made based on a cost-effectiveness evaluation and comparison among the alternatives.

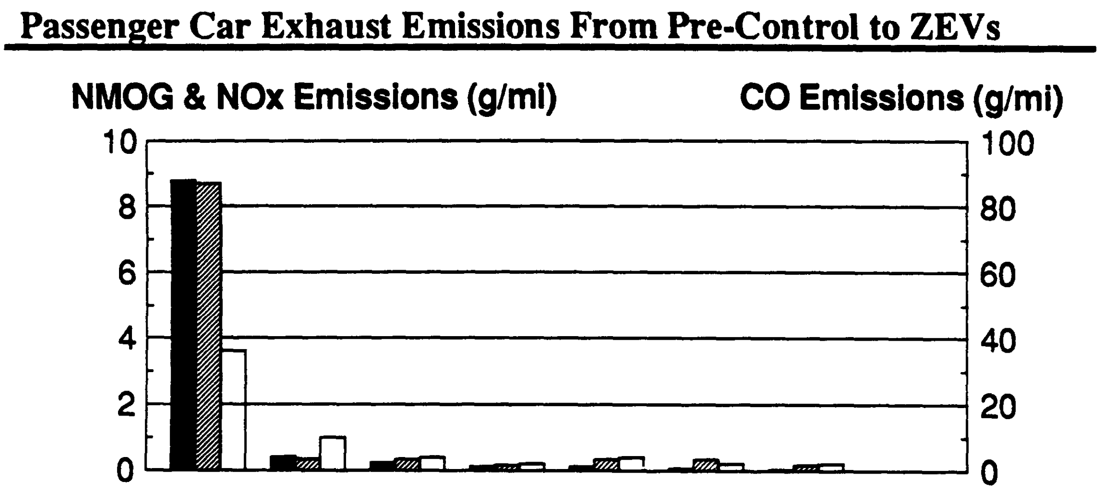
2. Background

2.1 Regulations and Initiatives for Alternative Fuel Vehicles

Initiatives and regulations in the area of advanced automotive technology and alternative fuel vehicles have contributed decidedly in accelerating the research, product development and commercialization efforts for such technologies. The US government has set the stage for dramatic changes in automobile technology through a substantial body of technology forcing regulations. In addition, federal and state governments have generously funded activities in these advanced technologies and have attempted to coordinate research by forming partnerships both at the supplier's and the manufacturer's level. In other words, the US government has assumed a major role in moving the automobile into new regimes of performance. [Field, 1995] The next section is intended to outline the major characteristics and implications of the most important of the initiatives.

Clean Air Act Amendments, 1990: California Emissions Standards

In 1990, the Congress passed the Clean Air Act Amendments (CAAA) in an attempt to accelerate the pace of emissions reductions and bring urban areas into compliance with National Ambient Air Quality Standards. The 1990 amendments, the subject of intense debate over costs, benefits, and regional differences, will continue the downward trend in standards for new car exhaust emissions; mandate fuel improvements to further reduce vehicle emissions; impose more stringent requirements on stationary sources and introduce specific controls on powerplants to reduce acid rain. [Calvert, 1993] In September 1990, the California Air Resources Board (CARB) adopted its Low Emissions Vehicle (LEV) regulations. These regulations establish four categories of increasingly more stringent emission standards, namely Transitional Low Emission Vehicle (TLEV), Low Emission Vehicle (LEV), Ultra Low Emission Vehicle (ULEV), and Zero Emission Vehicle (ZEV). Zero Emission Vehicles have been defined by CARB as vehicle associated with zero emissions at the tailpipe. Figure 5 portrays both the California and the federal exhaust emissions standards for light duty vehicles.



	Uncontrolled	1993 Federal	Tier 1	Tier 2	TLEV	LEV	ULEV	ZEV
NMOG ■	8.800	0.410	0.250	0.125	0.125	0.075	0.040	0.000
CO ▨	87.000	3.400	3.400	1.700	3.400	3.400	1.700	0.000
NOx ☐	3.600	1.000	0.400	0.200	0.400	0.200	0.200	0.000

Figure 5: Passenger Car Exhaust Emissions From Pre-Control to ZEVs.

Source: [Austin, 1994]

CARB has also specified an introduction schedule for each of these vehicle categories. The mandated penetration percentages for each vehicle category are summarized in Table 2.

Table 2: *Introduction Schedule for the Low Emissions Vehicle Program*[2]

Model Year	1991/1992	1993	TLEV	LEV	ULEV	ZEV
1991/1992	100					
1993	60	40				
1994	10	85	10			
1995		85	15			
1996		80	20			
1997		75		25	2	
1998		48		48	2	2
1999		23		73	2	2
2000				96	2	2
2001				90	5	5
2002				85	10	5
2003				75	15	10

Source: [Yaxas, 1994]

Perhaps the most important and clearly the most controversial of the above increasingly stringent standards is the requirement than in 1998 2% of new cars and light trucks will have to be Zero Emission Vehicles. Only OEMs whose annual California sales exceed 35,000 will have to comply with the regulation. This percentage increases to 5% in year 2001 and to 10% starting in year 2003. From 2003, the mandates will apply to all

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[2] Numbers are in percentages of total fleet sales.

manufacturers selling vehicles in California, irrespective of their annual sales. These percentages translate into approximately 40,000, 120,000 and 260,000 vehicles respectively assuming a 6% annual market growth. The only vehicles expected to meet the CARB mandates are battery powered electric vehicles. Hydrogen powered vehicles using fuel cells would also qualify as ZEVs, but such vehicles cannot be realistically expected to meet the 1998 deadline with current technology. Hence, the CAAA in conjunction with the CARB California requirements have led to extensive consideration of the opportunities for electric vehicles.

In February 1994, the Ozone Transport Commission States, comprising of the twelve Northeast States and Washington DC, voted to petition EPA to permit them to adopt the California LEV Program. The EPA responded in December 1994 by allowing each individual state to adopt at will parts or the whole program including the controversial ZEV mandate. Massachusetts and New York are the only states other than California that have so far mandated the sale of ZEVs. However, it should be noted here that these three states account collectively for roughly 20% of the total annual new registrations. Meanwhile, the US auto manufacturers have made a counterproposal through the American Automobile Manufacturers Association (AAMA) that, based on EPA's analysis, is equally effective but less costly than the LEV program. This proposal is called the "49 state plan" and proposes the sale of a "cleaner" automobile in all states except for California starting in 1998. The implementation of such a plan is contingent upon New York and California backing off from their ZEV mandates.

Energy Policy Act, 1992

In October 1992, the Congress passed the Energy Policy Act. This law, having as its primary objective the reduction of the nation's dependence on foreign oil imports by encouraging the use of domestically produced fuels, embodies a combination of mandates and incentives for alternative fuel vehicles. The motivation behind the Energy Policy Act has been national security concerns. This observation distinguishes this Act from the CAAA which focuses on air quality. Moreover, the Energy Policy Act is broader in scope as it affects fleets in 125 metropolitan areas[3] compared to a mere 21 affected by the Clean Air Act Amendmends. Although no fuel that could contribute significantly towards the Act's objectives is excluded, the following fuels have been selected as being the most promising ones under the Energy Policy Act:

- Methanol
- Ethanol
- Natural Gas
- Propane
- Hydrogen
- Coal Derived Liquids
- Biological Materials
- Electricity

The following table summarizes the annual purchase requirements for federal and state fleets, alternate fuel providers, and private and municipal fleets:

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[3] affected areas are those with a 1980 population of at least 250,000.

Table 3: *Annual Purchase Fleet Requirements for AFVs*

Year	**Federal Fleets**	**State Fleets**	**Fuel Providers Fleets**	**Private[1] Fleets**
1993	5000	-	-	-
1994	7500	-	-	-
1995	10000	-	-	-
1996	25%	10%	30%	-
1997	33%	15%	50%	-
1998	50%	25%	70%	-
1999	75%	50%	90%	20%
2000	75%	75%	90%	20%
2001	75%	75%	90%	20%
2002	75%	75%	90%	30%
2003	75%	75%	90%	40%
2004	75%	75%	90%	50%
2005	75%	75%	90%	60%
2006 on	75%	75%	90%	70%

[1] if DOE decides that such requirements are "necessary and practicable" to achieve the goals of the Act.

Source: [Consolidated Natural Gas Company, 1992]

It should be noted here that for non-governmental fleets, the penalties for violation start at $5,000 and increase to $50,000 for repeat violations. Furthermore, the Energy Policy Act provides tax incentives that range from $2,000 up to $50,000 per vehicle (depending on size) and up to $100,000 for businesses that install refueling stations. [Consolidated Natural Gas Company, 1992] Finally, other provisions of the Act such as low interest loans further facilitate the introduction of AFVs.

Partnership for a New Generation of Vehicles (PNGV)

In September 1993, President Clinton and the Big Three US automobile manufacturers jointly announced their intent to form a government industry partnership to revolutionize the automobile industry and strengthen US competitiveness. [Office of Transportation Technologies, 1994] In a formal Declaration of Intent, the Partnership for a New Generation of Vehicles stated three partnership goals:

(1) Develop advanced manufacturing technologies.

(2) Develop near term vehicle improvements.

(3) Develop advanced vehicles that are up to three times more fuel efficient than today's automobile.

Within this context, six primary research areas have been identified; (1) energy storage materials and processes, (2) energy conversion materials and processes, (3) lightweight materials, (4) the impact of emissions on the atmosphere, (5) emissions control and sensors for control, (5) performance and (6) emissions. [Automotive News, Feb. 20, 1995] The early research focus of PNGV has been on "hybrid" vehicles which employ a high efficiency heat engine in conjunction with an electric drivetrain. The automobile manufacturers see an opportunity to increase fuel economy substantially while continuing to satisfy the customer's ever increasing expectations of automobile value for money. The PNGV magnifies this interest, with the goal of tripling the fuel economy of existing vehicles. Along these lines, the Hybrid Propulsion Program has set goals to complete the development of a production feasible propulsion system by 1998 and to begin the production of a first generation vehicle in 2000. Market introduction of vehicles would begin in 2003.

United States Advanced Battery Consortium (USABC)

Based on the recognition of the fact that battery technology is currently the limiting technology for electric vehicles, the United States Advanced Battery Consortium was formed in 1991. The objective of the consortium is to accelerate and coordinate the development of batteries. In particular, USABC set the following goals:

- Establish a capability for a United States advanced battery manufacturing industry.
- Accelerate market potential of electric vehicles by jointly researching the most promising advanced battery alternatives.
- Develop electrical energy systems capable of providing electric vehicles with range and performance competitive to petroleum based vehicles.
- Pool funding for high risk, high cost advanced battery research and development for electric vehicles.

The USABC is a historic $262 million partnership among Chrysler, Ford, General Motors, the electric utility industry represented by the Electric Power Research Institute (EPRI), and the US Department of Energy (DOE). DOE equally shares the consortium's funding with the auto manufacturers. USABC signs contracts with battery manufacturers and has set performance targets for battery development. Table 4 summarizes the most critical targets.

Table 4: *USABC Mid Term & Long Term Goals*

	Mid Term Goals	**Long Term Goals**
Energy Density (Wh/kg)	**80-100**	**200**
Power Density (W/kg)	**150-200**	**400**
Life, cycles (80% DOD)	**600**	**1000**
Life, years	**5**	**10**
Manufacturing Cost (US$/kWh)	**150**	**100**
Commercial Availability	**2000**	**2002-2004**

Source: United States Advanced Battery Consortium

The primary USABC contracts include the following:

Table 5: *USABC Research Contracts*

Company	**Battery Type**	**Time Frame**
Ovonic Battery Corporation	*Nickel Metal Hydride*	Mid Term
Silent Power	*Sodium Sulfur*	Mid Term
Saft America	*Nickel Metal Hydride*	Mid Term
	Lithium Iron Disulfide	Long Term
W. R. Grace	*Lithium Polymer*	Long Term
3M	*Lithium Polymer*	Long Term

Source: United States Advanced Battery Consortium

2.2 The Case of Electric Vehicles

Electric vehicles clearly present a special case in the Alternative Fuel Vehicle debate. As has been already described, the CAAA call for the development and sale of "Zero Emissions Vehicles" by 1998. ZEVs have been defined as vehicles associated with zero emissions at the exhaust. The CAAA have therefore led to extensive consideration of electric vehicles, especially since states in addition to California are considering EV introduction through the adoption of the California requirements. The automakers have settled upon an all electric battery base propulsion system to meet the legislation's specific performance requirements. As has been previously stated, a hydrogen powered vehicle using fuel cells would also qualify. However, such alternatives are less feasible from a technological and economic standpoint and therefore ZEVs have come to mean EVs. The most critical barriers to the application of fuel cells for automotive vehicles is capital cost, closely followed by size. Stationary system fuel cell power plants have been under development for the past 30 years and capital costs are still above $3,000/kilowatt. DOE analysts argue that for vehicle applications, these costs will have to be reduced by at least a factor of 50. [Office of Transportation Technologies, 1994]

The primary advantage and distinguishing feature of electric vehicles is that they produce no emissions at their point of use. This feature has made this class of AFVs the centerpiece of the California Emissions Standards. Unlike any other combustion based vehicle powerplant, the electric vehicle is associated with zero carbon monoxide (CO), nitrogen oxides (NOx) and reactive organic gases releases while in use. [Field, 1995] For this reason, such vehicles have been viewed as a promising way to enhance urban air quality. Moreover, their emissions performance does not deteriorate with time. Emissions degradation has been cited as one of the most crucial reasons for the current "unsatisfactory" air quality associated with some urban areas.

These arguments in favor of electric vehicles are definitely not new. Battery powered vehicles have been developed since before the turn of the century and were at one time viewed as the favorite vehicle propulsion technology [Wakefield, 1994]. The renewed interest in electrically powered automobiles has been primarily a consequence of government initiatives directed at changing the technology of automotive propulsion. The next two sections intend to highlight the major implications associated with the development and use of EVs, identify the major stakeholders and outline their perspective on the EV debate.

2.3 Development of Electric Vehicles: Concerns & Implications

Technological & Performance Issues

Range, i.e. the distance the vehicle can be driven between successive recharges, is the most critical performance limitation for the successful commercialization of electric vehicles. The ranges claimed by EV manufacturers typically fall in the 40-120 mile bracket. On average therefore an EV's autonomy is only a sixth of that associated with a typical ICE vehicle. Moreover, the range of the vehicle is very much dependent on the speed, starts, stops and acceleration that the vehicle goes through over the "range", information that electric vehicle proponents vary rarely provide. Without this information, a simple presentation of vehicle range is essentially valueless since energy consumption is a strong function of speed and acceleration as well as weight, geometry, tire characteristics and ambient temperature. For example, General Motors tested the Impact at zero degrees Fahrenheit and found out that its range fell from 70 miles under idealized conditions to a mere 12 miles. [Ellis, 1994]

The underlying cause of this performance limitation is battery technology. Simply put, chemical storage batteries are very heavy and bulky in relation to the amount of energy they can store. In fact, the amount of energy per kilogram of battery is currently lower than the equivalent gasoline storage capacity by a factor of 342. [Lave, 1995] Furthermore batteries are difficult to handle and maintain. Recharging, is another major concern. Different battery types require different strategies to optimize performance and maximize the life of the battery. Moreover, determining the state of charge and optimally controlling the charging and discharging of batteries will require a dramatically increased use of electronics and computers in automobiles. Electric Vehicles will essentially become "computers on wheels".

In order to overcome the performance limitations of electric vehicles, efforts by manufacturers have been focused in two basic areas. Firstly, research is being carried out to improve the energy density of the battery itself. The USABC goal of improving the energy density from today's 30-50 wh/kg to 100 wh/kg in the near term and 200 wh/kg in the long term contributes towards this objective. Secondly, manufacturers have been examining the potential for reducing the weight of the vehicle through the use of ultra-lightweight materials. Simply put, a lighter vehicle body will require less energy and therefore a lighter battery to reach a given set of performance targets.

Economic Considerations

The cost of producing and using an electric vehicle is another major area of uncertainty. Estimates for the production cost of electric vehicles range from as low as $20,000 to over $100,000. Production cost depends primarily on performance targets, the materials and overall design of the body, and on the number of vehicles that are being produced. The cost of using the vehicle will largely depend on the reliability, longevity and performance of batteries. EV proponents have argued that maintenance costs for EVs could be as low as half the equivalent ICE costs due to the vastly simplified mechanical systems and smaller overall number of parts. However, should the complex electronic systems prove to be unreliable, then maintenance costs could parallel or even exceed ICE maintenance costs. Most importantly however, it is not unrealistic that due to poor battery longevity, consumers may end up replacing expensive batteries on a yearly or biennial basis. Finally, setting up a ubiquitous and dependable recharging infrastructure has uncertain economic implications especially if fast charging technologies become available.

Industrial Implications

There is no doubt that electric vehicles are overwhelmingly different than conventional ICE automobiles. Some analysts have argued that these design differences may lead to a dramatic restructuring of the automobile industry. In particular, they claim that non traditional automobile firms will capitalize on the opportunities presented by the electric vehicle mandates and therefore reconfigure the industry. The degree to which these opportunities exist and are sufficient to lead to the kind of dramatic changes described above, will be assessed in Chapter 9 of this document.

Market Penetration Concerns

The question of whether EV manufacturers will be able to reach the production volume levels necessary to realize considerable economies of scale is one of the most critical ones. Pricing policies and federal or state incentives will also be crucial. Given the performance limitations of EVs, pricing above the equivalent ICE price would not help towards making EVs attractive to the consumers. In addition, fleet turnover might be slowed down under such a pricing policy, thereby resulting in increased emissions as a result of fleet aging. Therefore, it is quite probable that EVs will be priced competitively with ICE vehicles. Prices for ICE vehicles might also increase to cross subsidize electric vehicles either on a local or a nationwide basis. "Demand" for electric vehicles will be both voluntary and a result of mandates. The consensus of market studies that have been carried out seems to be that electric vehicles of modest performance, such as could be produced very soon, are likely to have no significant market even if priced competitively to conventional technologies. [Calfee, 1985] For these reasons, most analysts believe that unless a technological breakthrough is realized, initial electric vehicle applications will be targeted at private fleet applications. Another reason for avoiding selling to the general public is that because of the low performance and sensitivity of EV technology to bad handling, many companies do not want to risk harming the reputation and perception they currently enjoy.

Environmental Issues

There is no doubt that the main reason why electric vehicles have become the centerpiece of the CAAA and the California Emissions Standards has been their inherent potential to enhance air quality. Electric vehicles produce no pollutant releases at their point of use. However, this does not imply that the total emissions associated with the use of Electric Vehicles are zero. EVs need to be charged on a daily basis using electricity. Electricity generation plants use as raw energy inputs coal, nuclear energy, gas, oil, and renewable energy sources. In other words, electricity generation is not an emissions free process, which implies that electric vehicles do not eliminate airborne emissions. Zero Emission Vehicles can therefore be more realistically be thought of as emission displacement vehicles, essentially displacing emissions from the point of vehicle use to the point where electric power is generated. Another point worth mentioning is that powerplant generation mix varies significantly by region as Table 6 portrays. This diversity implies that the airborne powerplant emissions associated with electric vehicles are not likely to be uniform. For example, one might expect significantly greater benefits from EV introduction in California than in Boston or Tennessee. France on the other hand, has a much cleaner generation mix as nuclear energy is used for more than 70% of its electricity generation.

Table 6: *Electricity Generation Mix*

	Coal	Nuclear	Natural Gas	Oil	Other
Los Angeles	16.9%	39.3%	14.5%	26.0%	3.3%
Boston	0.0%	0.0%	11.0%	89.0%	0.0%
Tennessee	88.3%	4.0%	0.1%	0.3%	7.3%
France	7.3%	70.3%	0.6%	1.5%	20.3%

Source: [DeLuchi, 1993]

Emissions within the use phase of a vehicle's life might be the most important, but certainly not the sole, environmental impact of an automobile. Environmental releases associated with the resource extraction, manufacturing, assembly, and disposal and recycling phases cannot be overlooked. Introduction of electric vehicles can alter significantly the environmental consequences of an automobile in all the above phases of the life cycle. Most battery technologies that are under consideration for EV applications contain either toxic materials (e.g. Nickel Cadmium batteries), or are polymer based and therefore are for all practical purposes non-recyclable (e.g. lithium polymer batteries). Moreover, it has been argued that, as a result of the mining, smelting and recycling processes, a lead acid powered electric vehicle will release six times more lead than an ICE vehicle burning gasoline with lead additives. [Lave, 1995]

As has been previously explained, currently available batteries are very heavy in relation to the amount of energy they can store. This technological limitation is the primary motivation for using lightweight materials such as aluminum and plastics for vehicle body designs. However, current recycling technologies for lightweight materials have not been developed nearly as much as for conventional vehicle body designs.

In other words, the environmental benefits associated with the introduction of EVs are uncertain especially if one considers the full life cycle and solid waste implications.

2.4 Major Stakeholders in the EV Debate

The California ZEV mandate and its potential adoption by other states has resulted in significant turmoil in the automobile industry. The dramatic technological shift associated with the development of electric vehicles has definitely shaken the established automobile manufacturers and fuel providers. At the same time, new stakeholders have emerged in a debate which is characterized by highly polarized opinions, and heated arguments and confrontations. More specifically:

Established Automobile Manufacturers

The automobile manufacturers main contention against the ZEV mandate has been that the automobile market has not expressed any interest in these advanced, "clean" automobile technologies. Competition in the automobile industry is not only based on "needs". Customer "wants" are equally important. A 30 mile range vehicle may be what some customers actually need, but it is definitely not what they want. The Big Three US manufacturers argue that electric vehicle technology may be an attractive and viable alternative in the future. However, the technology is not currently mature and therefore a technology forcing mandate is inappropriate. The success of electric vehicles is contingent upon an inexpensive and powerful battery. Moreover, they often cite a very legitimate timing concern. To be able to mass produce in 1998, a two year lead time for any auto product is needed. For example, nickel metal hydride batteries whose performance is considerably better than currently available lead acid batteries cannot be mass produced in 1998 even though they might at that point in time be the state of the art. They also argue that the mandate is not flexible in that it does not give the same chance to other technological options by defining ZEVs as zero emission vehicles at the point of use rather than considering the full fuel cycle. Finally, the established automobile manufacturers believe that with the ZEV mandate, financial and market risk is not equally shared among the stakeholders.

Start-Up Companies

Start-up companies are typically small scale entrepreneurial in nature manufacturers acting to capitalize upon the market niche that has been created by the mandates. These companies primarily convert ICE vehicles into electric by essentially ripping out all unneeded components. Recently, some of these companies have been developing ground-up electric vehicles by optimizing their designs for electric drive and using lightweight materials. Start-up companies are in general risk prone, lack resources for mass production, but believe that their small size and flexibility are essential for success in a technology driven industry. Their major concerns include:

- *Funding:* The Banking and Investment industry is very skeptical about investing in products that are associated with both market and technological uncertainty.

- *Safety Certification:* Full FMVSS safety certification seems to be necessary for successful market penetration, but is a process that small scale manufacturers cannot afford.
- *Gliders:* A glider is essentially a vehicle manufactured by a conventional automaker that does not include the standard powertrain and drivetrain. Converters would encourage the provision of gliders because the cost of purchasing and subsequently removing the ICE and associated parts can represent up to 30% of the total conversion cost. [US Electricar, 1994] Moreover, the EV industry can avoid the investment necessary to mass produce automobile bodies. Unfortunately, the conventional manufactures have been reluctant in providing gliders due to liability, image and public perception concerns. Recently however, conversion companies have been working with OEMs to establish quality assurance standards. [Automotive News, November 21, 1994]

Electric Utilities

The electric vehicle mandates present an enormous opportunity for electric utilities to increase revenues without substantial capital expenditures. Electric utilities believe that electric vehicles are an insurance policy for global warming, air pollution, dependence on imported oil and a prerequisite for what they call a "sustainable fuel supply". Moreover, they argue that electric generation will become cleaner over time and therefore the emissions performance of electric vehicles will improve rather than deteriorate as is the case with conventional ICE technologies.

A typical electricity demand vs. time of day diagram is shown in Figure 6. Clearly, one can observe a significant "valley" in the electricity demanded occurring between 10 pm and 7 am. Hence, if electric vehicles are to be charged overnight, there is a tremendous potential for "filling the demand valleys". This would imply that revenues for electric utilities would increase substantially. At the same time since limited powerplant additions will be required to support this increased demand, electric vehicle mandates are often being perceived by electric utility representatives as "a gift from above". The extensive promotional campaigns and demonstration programs they conduct contribute therefore towards their ultimate objective of seeing a large number of EVs on the road.

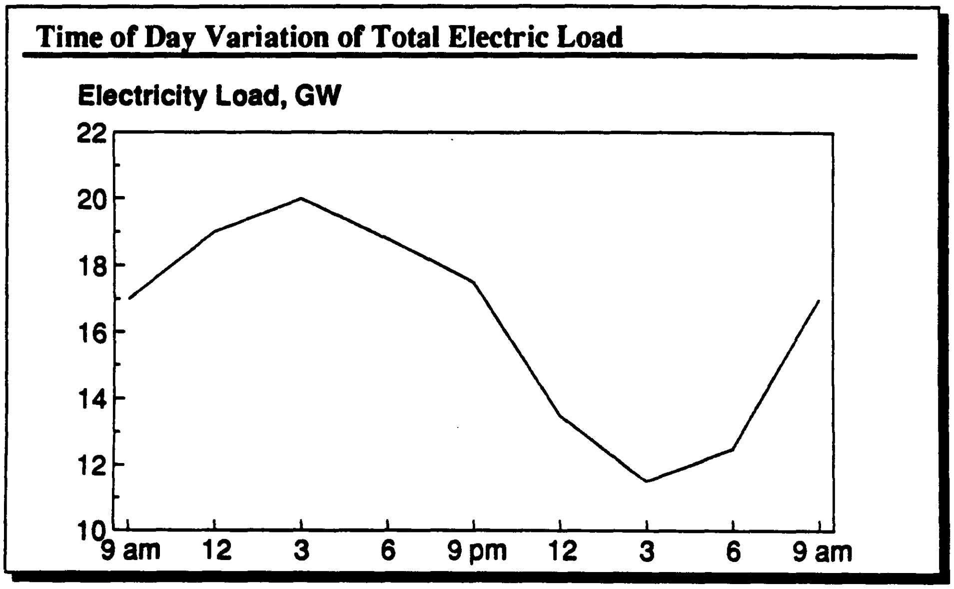

Figure 6: Time of Day Variation of Total Electric Load.

Source: [Chapman, 1994]

Battery/Propulsion Systems Manufacturers

For battery and electronic components manufacturers, the opportunity for entering the automobile industry is simply too overwhelming to be overlooked. Moreover, the larger of these companies have been on the receiving end of substantial amounts of both governmental and private sector research and development funds. This has been a result of the importance of a high performance battery and a reliable drivetrain for successful EV commercialization. Although their current research focus is on basic science and product development, they anticipate cost and mass production concerns to be the major obstacles in their future efforts.

Oil Companies

Quite naturally, oil companies have been fiercely opposing the electric vehicle and alternative fuel vehicle mandates. Although the oil industry supplies some refined product to the electric power industry, the vast majority of its revenues comes from gasoline sales to the general public. Therefore, any transition away from a petroleum based transportation sector would be catastrophic. Their public media campaigns and lobbying efforts have been focusing on the following two arguments:

- Alternatively fueled vehicles are not cost-effective; and
- Reformulated Gasoline can provide substantial benefits at small cost burdens.

Environmental Groups

The various environmental groups around the country and in particular the environmental movement in Southern California have been particularly active launching campaigns and embarking on lobbying efforts in order to promote "green" technologies. Their primary target has been the established automobile manufacturers, who in their view try to undermine the future of the EV industry by lobbying and providing misleading information about the cost and performance of Electric Vehicles.

Government/EPA

The government's role in initiating and funding the major initiatives in the area of alternative fuel vehicles has been previously described. Government officials are the targets of lobbying efforts by all interested parties. Given the considerable political implications of the debate, they therefore very often try to act as middlemen and balance the needs of the stakeholders.

3. Problem Statement

From the preceding discussions, it is clear that the consequences of developing and using electric vehicles are uncertain. As has been indicated, there exist significant uncertainties associated with the degree of environmental benefits that can be realistically achieved with the introduction of electric vehicles. When these uncertainties are coupled with the technological, economic, market and industrial uncertainties, the appropriateness of Electric Vehicle policy for meeting societal concerns becomes even more questionable. Furthermore, the abundance of highly polarized points of view does not contribute towards an unbiased assessment of the consequences of EV introduction. Environmental groups, regulatory agencies, automobile manufacturers, electric utilities; in short all stakeholders in this debate are launching campaigns and publishing studies. However, as one would expect, the vast majority of these publicly available studies are biased because of the financial or other interests that the different groups have in this debate.

The goal of this thesis is to enlighten the debate by providing unbiased answers to the most pertinent questions that are being raised by the EV mandates. In particular, the questions and issues that will be addressed in this thesis are the following:

1. What are the consequences of developing and using a "ZEV"?
    - economic
    - air quality
    - energy consumption

2. What are the factors that critically impact these consequences?

- performance targets
- battery technology
- vehicle characteristics
- demand, production volume

3. What are the potential changes in these factors and what are the associated implications for EVs?

4. How do other alternatives compare with EVs from an air quality, energy consumption and economic standpoint?

5. Based on the answers to the first four questions, what can be concluded about the implications, goals and consequences of EV policy, particularly in light of other available technologies?

6. What can be concluded about forcing technology development in the area of advanced automotive technologies?

7. Do these initiatives and regulations in the area of alternative fuel vehicles create the potential for the restructuring of the automobile industry?

In order to address these questions, this document will proceed along the following lines. First, the methodology, assumptions and framework for evaluation will be explained. Second, the economic, air quality and energy consumption results for EVs will be presented and discussed in the form of a contingency plan. These results will then be compared to those associated with other available technologies. Finally, the goals, consequences and implications of the technology forcing EV policy will be appraised.

4. Approach-Methodology

One of the leading Original Equipment Manufacturers (OEMs) provided the Materials Systems Laboratory (MSL) detailed design information about their Electric Vehicle (EV). This EV is an existing, small, two seat vehicle. Furthermore, it is a purpose built EV and therefore its systems are optimized for electric drive. Finally, it has a lightweight, aluminum intensive body structure. For reasons of confidentiality, the identity of the manufacturer and model shall remain anonymous. This design has been used as the basis for assessing the economic, performance and environmental implications of developing and using Electric Vehicles. However, in order to determine these implications and ultimately compare the electric vehicle scenario with other proposed alternative fuel technologies, a combination of modeling, analytic and other research methods had to be employed. These techniques are outlined in the following sections of this chapter. Furthermore, all the pertinent information and numerical assumptions made for the base case are summarized in Appendix 1.

4.1 Energy & Battery Requirements for EVs

The operating range of an electric vehicle is probably the major obstacle for its successful commercialization. Moreover, establishing the operating range is one of the particularly difficult aspects about electric vehicle design and testing. The range is very much dependent on the speed, starts and stops, or acceleration that the vehicle went through over that range, information that electric vehicle proponents and manufacturers very rarely provide. Without this information, a simple presentation of vehicle range is essentially valueless since energy consumption during driving is a strong function of speed and acceleration as well as weight, geometry and tire characteristics. For this reason, a model taking into account all these factors has been developed to realistically assess the performance of electric vehicles.

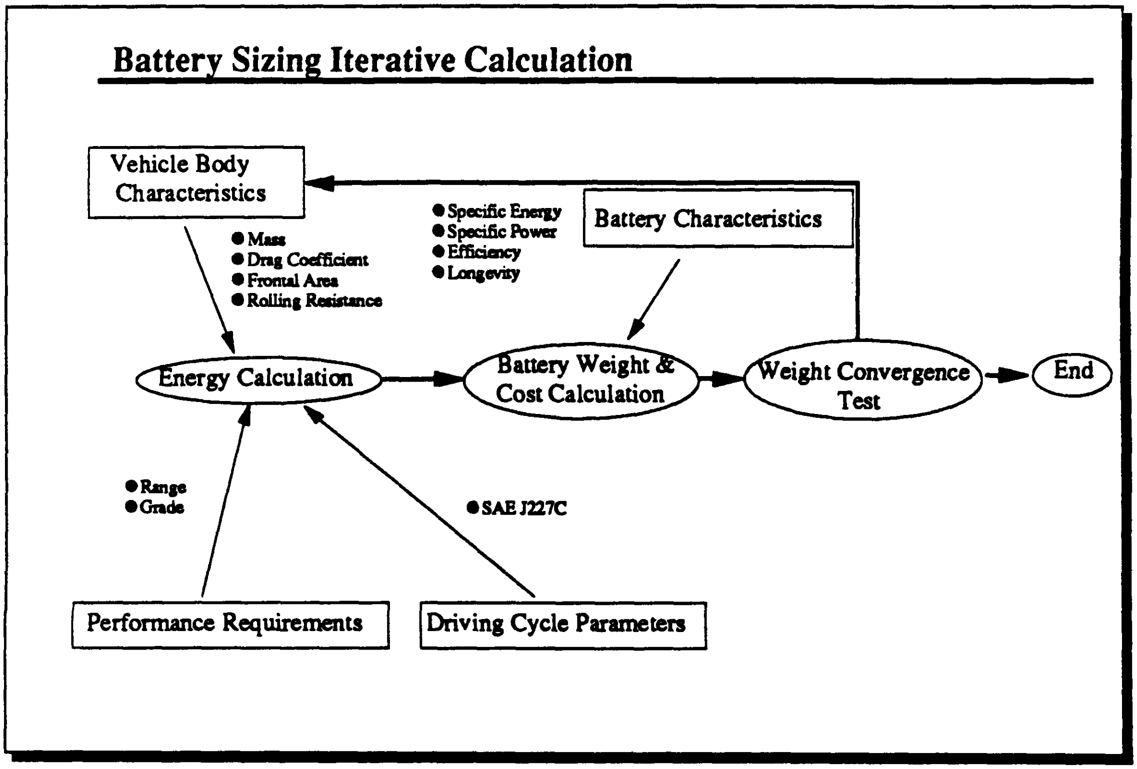

Figure 7: Battery Sizing Iterative Calculation.

The purpose of this section is to clarify the modeling approach adopted for the calculation of the battery cost and weight. The problem can be stated as follows: " What is the weight of the battery that is required for an electric vehicle to meet specified performance requirements given a set of design and driving assumptions for a chosen battery technology?" The structure of the model is portrayed in Figure 7. The inputs and outputs of the battery sizing model are shown in Figure 8.

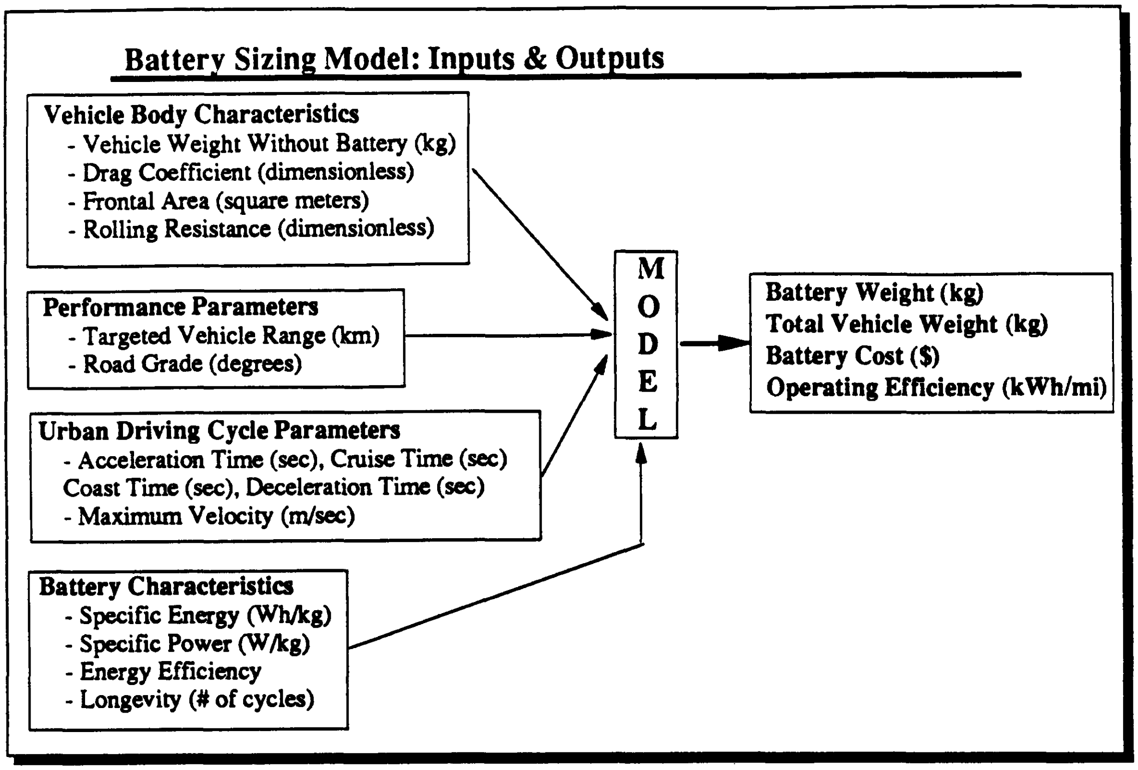

Figure 8: Battery Sizing Model: Inputs & Outputs.

Given the inputs outlined in Figure 8, the model determines the battery weight and the associated cost in three steps.

1. Energy Calculation: Based on user inputs about performance targets, driving cycle parameters and vehicle body characteristics, the model calculates the energy required for the electric vehicle to perform one driving cycle. Hence, the energy requirements[4] for the

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[4] Regenerative barking has not been included in the calculation since the reported benefits that do not exceed 15% are offset by other parasitic losses such as those from an air conditioner, heater, radio and head-lights, all of which have also been disregarded.

battery pack of the vehicle can be determined. A detailed mathematical treatment of this fundamental first step is provided in Appendix 2.

2. *Battery Weight Calculation:* The results of the energy calculation, in conjunction with inputs about battery capabilities (e.g. specific energy, specific power and energy efficiency), enable the calculation of the vehicle's battery weight.

3. *Weight Convergence Test:* It should also be noted that the energy required to drive a given range is dependent on total vehicle weight. Total vehicle weight obviously includes battery weight, the quantity this model attempts to establish. Since battery weight is not known beforehand, the calculation is inherently iterative. A weight convergence criterion is therefore applied for the termination of the calculation.

4. *Cost & Vehicle Efficiency Calculations:* Once the calculation has converged, the associated battery cost can be calculated by simply multiplying the battery energy capacity (kWh) by the cost per kWh. The latter is a characteristic of the battery technology. Moreover, crucial parameters such as vehicle efficiency (kWh/km) can be evaluated.

To summarize, this model can address critical issues such as the cost and weight implications of vehicle design, performance requirements and improvements or shortcomings in battery technology.

4.2 Technical Cost Modeling

The cost modeling of the vehicle's body has been performed using the Technical Cost Models (TCM), developed at MIT's Materials Systems Laboratory. This analytic framework has been devised in an effort to capture the most pertinent features of manufacturing operations and quantify their impacts. [Busch, 1987] Essentially, these models simulate production processes, such as stamping, extrusion and die casting, in order to determine the production economics associated with the manufacture of a particular component.

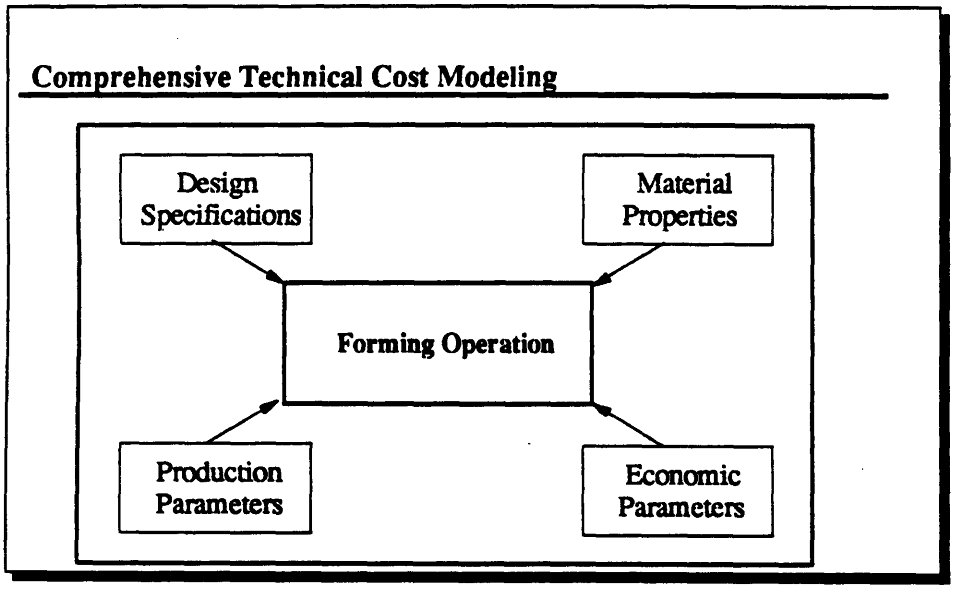


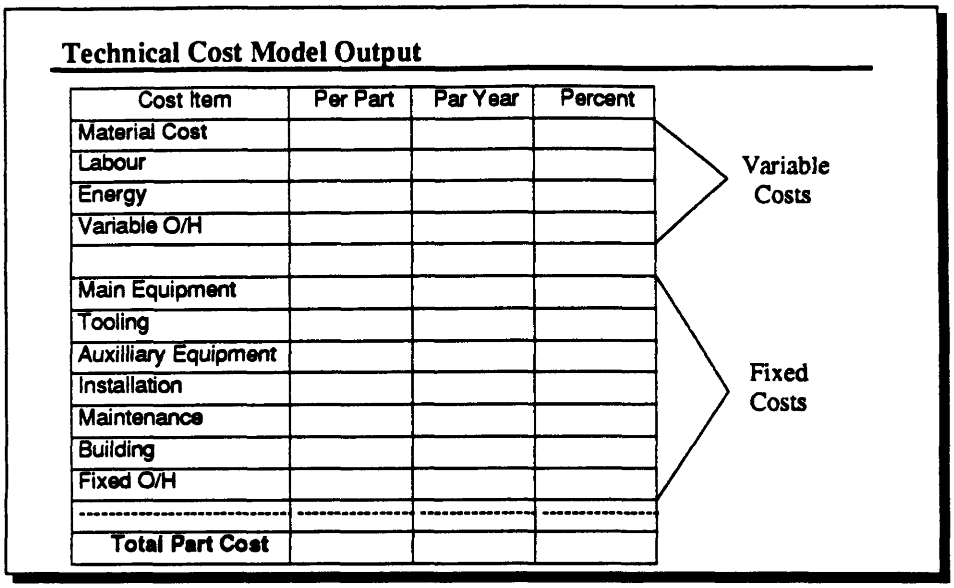
Figure 9: Comprehensive Technical Cost Modeling.

As Figure 9 portrays, the inputs required for any TCM can be grouped into four distinct categories. [Politis, 1995] In particular:

- Design Specifications, e.g. part weight and geometry.
- Material Properties, e.g. stiffness, density and material price

- Production Parameters, e.g. production volume, scrap rate, down time.
- Economic Parameters, e.g. wages, benefits, electricity cost.

Using these inputs, the model performs a series of engineering and economic calculations simulating the production process. The component cost is therefore determined in disaggregate form as portrayed in Figure 10.



Technical Cost Model Output

Cost Item	Per Part	Par Year	Percent
Material Cost			
Labour			
Energy			
Variable O/H			
Main Equipment			
Tooling			
Auxilliary Equipment			
Installation			
Maintenance			
Building			
Fixed O/H			
Total Part Cost			

Figure 10: Technical Cost Modeling Output.

This disaggregated presentation of cost information enables the user to identify the most critical parameters affecting the model's outcome. Furthermore, the structure of the model makes it relatively easy to perform extensive sensitivity analysis. The significance of input uncertainty and the potential impact of alterations in technological or economic parameters can therefore be appraised.

4.3 Emissions Modeling

Despite being classified as Zero Emission Vehicles, EVs are essentially emission displacement vehicles. For the vehicle use phase, these "displaced emissions" are primarily powerplant emissions associated with vehicle recharging. When, therefore, one Internal Combustion Engine (ICE) vehicle is replaced by an EV, the emissions benefits are equal to the ICE use emissions net the EV recharge emissions. In order to capture both these aspects of pollutant releases, the EPA Mobile 5a model has been used in conjunction with EGEAS, a powerplant simulation model. [US EPA, 1991] [Fleck, 1989] It should be noted here that the emissions analysis was conducted with MIT's Energy Laboratory's help. The two models alluded to previously can be briefly described as follows:

Mobile 5a: EPA's model is used to determine the expected yearly average emissions benefits if a given percentage of the annual fleet additions is electric rather than ICE. The model takes into account all of the following factors:

- Vehicle fleet mix.
- Annual mileage by model year and by vehicle type.
- Fuel characteristics.
- Operating conditions: temperature, average speed etc.
- Emissions performance deterioration by model year and by vehicle type.
- Emission Control Programs: Inspection & Maintenance, Evaporative Tests and Anti-Tampering Programs.

The model's output consists of the average emission rates (g/mi) by calendar year, pollutant category and vehicle category. The effectiveness of different emission reduction policies can therefore be assessed under this framework.

EGEAS Powerplant Simulation Model: The emission benefits associated with EV use are dependent on the local electricity generation mix. As has been exhibited in Chapter 2, the "cleanness" of electricity generation is highly non-uniform throughout the US. As a result, the effectiveness of EVs for reducing emissions is in turn region specific. Hence, any accurate analysis of emissions has to be local.

The New England utilities have provided the MIT Energy Laboratory with a powerplant dispatch simulation model for the New England region. Hence, although the Mobile 5a results are generic, the powerplant emissions analysis focuses on the New England region. Besides making the assessment more accurate, this analysis focus is interesting as the New England states have been considering the adoption of the ZEV mandates. [Automotive News, December 12, 1994]

The structure of the model is portrayed in Figure 11. Essentially, the user inputs the number of EVs in fleet use, the associated annual mileage and the EV's energy efficiency. The EV induced electricity demand can be therefore estimated. An assumption about the timing of EV recharging has to be made. This assumption affects both the pollutant releases and the need for additional electricity generation capacity. For the purposes of this study, primarily off-peak charging has been assumed. This assumption is realistic at least for the first years of EV introduction, where the number of vehicles in fleet use would not justify investment in additional capacity. Utilities would therefore attempt to even out their demand curve by encouraging EV recharging to take place at night. Based on these inputs, the model can estimate the emissions associated with EV recharging.

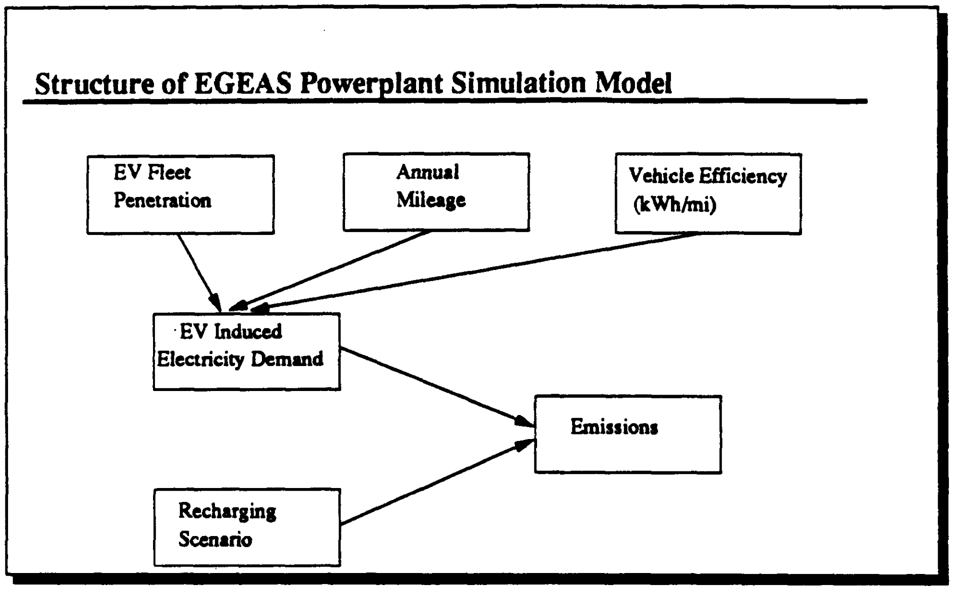


Figure 11: Structure of EGEAS Powerplant Simulation Model.

4.4 Literature Review/Survey Methods

Finally, a combination of literature review and survey methods have been employed to assess the cost and performance of the vehicle systems that have not been modeled. For this reason, representatives of the major suppliers and manufacturers have been contacted and interviewed. Drivetrain systems (e.g. motor, controller, gearbox etc.) were the most important among the systems that were not modeled.

The same type of literature review and interviewing methods were used for the assessment of the cost-effectiveness of Alternative Fuel Vehicles. The people involved with the development of these vehicles were contacted to determine the associated cost premiums and the performance and emissions implications. Publicly available studies were also used for these purposes. These combined both experimental and modeling approaches to the problem.

5. Cost Analysis for Electric Vehicles

The economic implications of producing and using electric vehicles are investigated in this chapter. Initially, the extent to which battery technology is currently the major obstacle for successful EV commercialization will be examined. Subsequently, the economics of total production cost will be assessed. Finally, by incorporating the use phase, the life cycle economic repercussions of EVs will be appraised. Tables 1-7 in Appendix 1 are intended to summarize the most important inputs to the models.

5.1 Battery Technology

Limited driving range and relatively high production costs have been cited by many analysts as the two most important obstacles for EVs. [Cimpa, 1995] Undoubtedly, cost and range are interrelated. As a manufacturer wants to increase the distance its vehicle is able to cover between successive recharges, one would expect the capacity of the required battery to increase. Intuitively therefore, the battery cost would therefore also increase with range.

As has already been discussed, a simple presentation of vehicle range is essentially valueless without specifying the speed, starts, stops and acceleration that the vehicle went through over that range. The Society of Automotive Engineers (SAE) has a standard driving schedule which can be used to evaluate the performance of a vehicle under a variety of operating conditions. The standard is specified according to a period of acceleration to a peak speed, cruising at that speed, a brief coast and then a brake to a complete stop. This standard, SAE J227, comes in four flavors: A, B, C and D. The time spent in each phase and the peak speed are the sole distinctions between the four flavors. Table 7 outlines the four cycles:

Table 7: *SAE Driving Schedules*

Schedule[1]	A	B	C	D
t_{accel}	4	19	18	28
t_{cruise}	0	19	20	50
t_{coast}	2	4	8	10
t_{brake}	3	5	9	9
t_{idle}	30	25	25	25
T (total)	39	72	80	122
V_{max}	16 km/hr	32 km/hr	48 km/hr	72 km/hr

[1] All times shown are in seconds.

Source: [SAE International, 1992]

For the results presented in this study, the SAE J227 C urban driving cycle was decided to be most representative. The cycle parameters of SAE J227 C are graphically portrayed in Figure 12. In addition, the vehicle design and battery technology inputs are included in Tables 1 & 5 of Appendix 1.

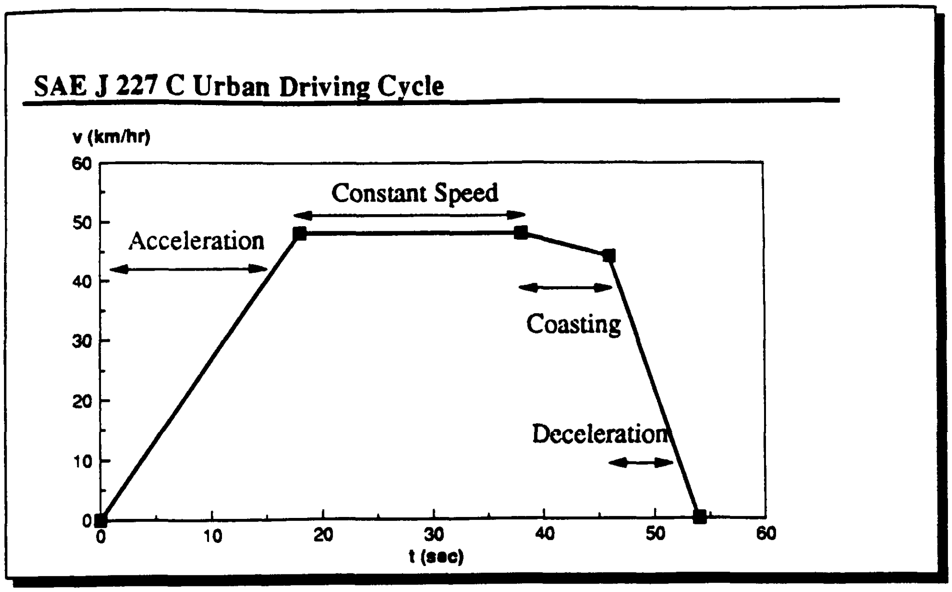


Figure 12: SAE J 227 C Urban Driving Cycle.

Figure 13 shows the cost of the initial battery pack as a function of vehicle range. The battery cost is dependent on battery technology. Figure 13 shows the costs associated with four distinct battery generations. Due to the uncertainty associated with the performance of currently available lead acid batteries, the worst case and best case scenarios were identified. The "Lead Acid" line therefore represents the worst case lead acid battery scenario, while the "Advanced Lead Acid" line represents the best case lead acid battery scenario. The shaded area therefore shows an envelope of achievable performance with currently available technology. Although, it seems that at least the first two model years of EVs will be powered with lead acid batteries, this is not to say that other currently available technologies are disregarded in this study. The area between the two extreme lines encompasses such other presently available technologies. The "USABC Mid-Term" and "USABC Long-Term" lines represent the battery costs if the mid-term and long term goals set by USABC are met. In other words, these lines are performance targets for battery capabilities and are not associated with presently available technologies.

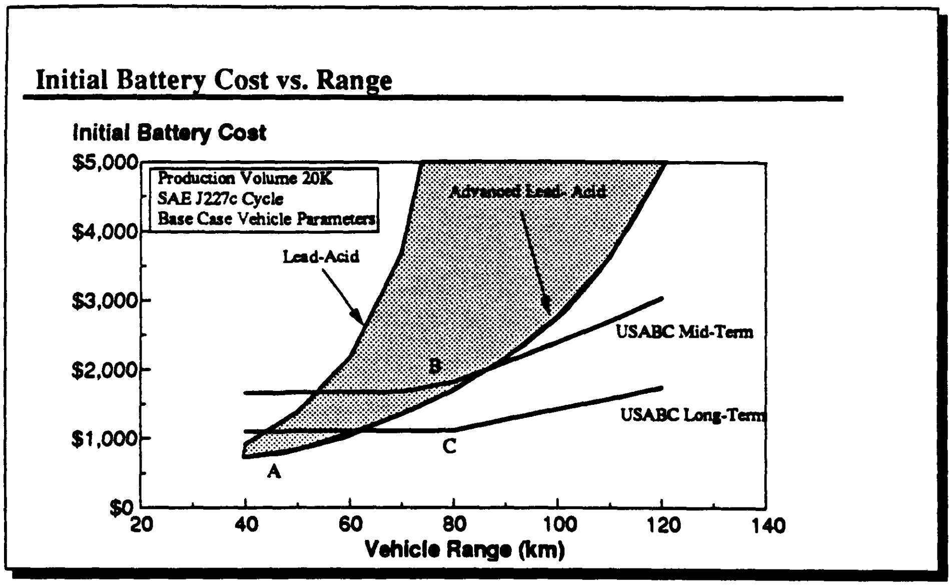


Figure 13: Initial Battery Cost vs. Range.

As one would expect, battery cost increases with vehicle range for all battery technologies. For a given battery technology, driving cycle, vehicle design and set of performance targets, the mass of the battery must be large enough to satisfy both the energy and the power constraints.

The energy requirement is related to the vehicle's targeted range. The battery's energy density, i.e. the amount of energy it can store per unit mass, is the property directly associated with the satisfaction of the energy requirement. In order to put this discussion into perspective, a kilogram of gasoline is equivalent to 13,000 watt-hours (Wh); in contrast, a typical lead-acid battery contains only 38 Wh per kilogram. [Lave, 1995]

On the other hand, the power constraint is related to the vehicle's acceleration and hill climbing ability. The battery's physical property that is directly related to the satisfaction of the power constraint is called power density and is a measure of the instantaneous power available from a unit mass of battery. The vehicle's battery weight is therefore determined by whichever of the energy or power constraints is binding.

One would expect, the energy requirement to be binding at moderate to high targeted vehicle ranges. Furthermore, vehicles powered with batteries whose energy density is low, are expected to be energy constrained. One the other hand, at low targeted vehicle ranges, one would expect the battery weight to be constrained by the power requirement which is primarily a function of the driving cycle.

As Figure 13 portrays, battery costs rise very rapidly with range for currently available technology. In essence, the battery's capabilities are so poor that the vehicle requires "more batteries to carry around batteries". The point at which this increase in cost becomes very rapid and sensitive on even very small changes in targeted vehicle range, depends largely upon the assumed status of lead acid battery technology. For the pessimistic scenario, the initial battery costs exceeds $5,000 for a range of 80 km or 50 miles. For the optimistic "Advanced Lead Acid" scenario, the targeted vehicle range for which the initial battery pack costs more than $5,000 is in excess of 120 km or 75 miles. For targeted ranges in excess of 45 km (Point A in Figure 13), the battery weight and therefore the battery cost become constrained by energy, a result of lead acid battery's low energy density.

If the goals set by USABC are met, then the considerable battery cost sensitivity experienced with lead acid technology, will no longer be observed for targeted vehicle ranges below 120 km or 75 miles. For ranges below the low 70s, the battery cost is constrained by power in the case of the mid term battery. Essentially, the battery mass required to support the driving cycle's acceleration profile is greater than the battery mass required to drive the vehicle for, say, 60 km. For ranges in excess of 74 km (Point B in Figure 13), the energy requirement takes over and the battery cost is energy constrained. In the case of the long term battery, the point at which the energy constraint becomes binding occurs at a targeted vehicle range of 79 km (Point C in Figure 13).

As one would expect, the USABC battery targets are not cost effective at really low vehicle ranges when compared to lead acid technologies. The benefit associated with their superior performance (resulting in a smaller kWh battery pack) is more than offset by the unit cost premium related to these advanced technologies (higher $/kWh unit cost). As the targeted vehicle range increases, however, a point is reached where the superior performance benefit exceeds the cost penalty associated with advanced batteries. Hence, USABC long term batteries are less expensive than advanced lead acid batteries for ranges above 61 km. Similarly, for ranges above 88 km the advanced lead battery becomes more expensive than the USABC mid term goals. The corresponding intersection points for the pessimistic lead acid battery scenario occur at much lower ranges, as one would expect. In particular, the intersection points with the USABC long term and mid term batteries occur at targeted vehicle ranges of 43 and 53 km respectively.

Clearly, batteries can become very expensive as the targeted vehicle range increases. Before presenting the total production cost results, it would be interesting to see the percentage of total vehicle production cost accounted for by batteries.

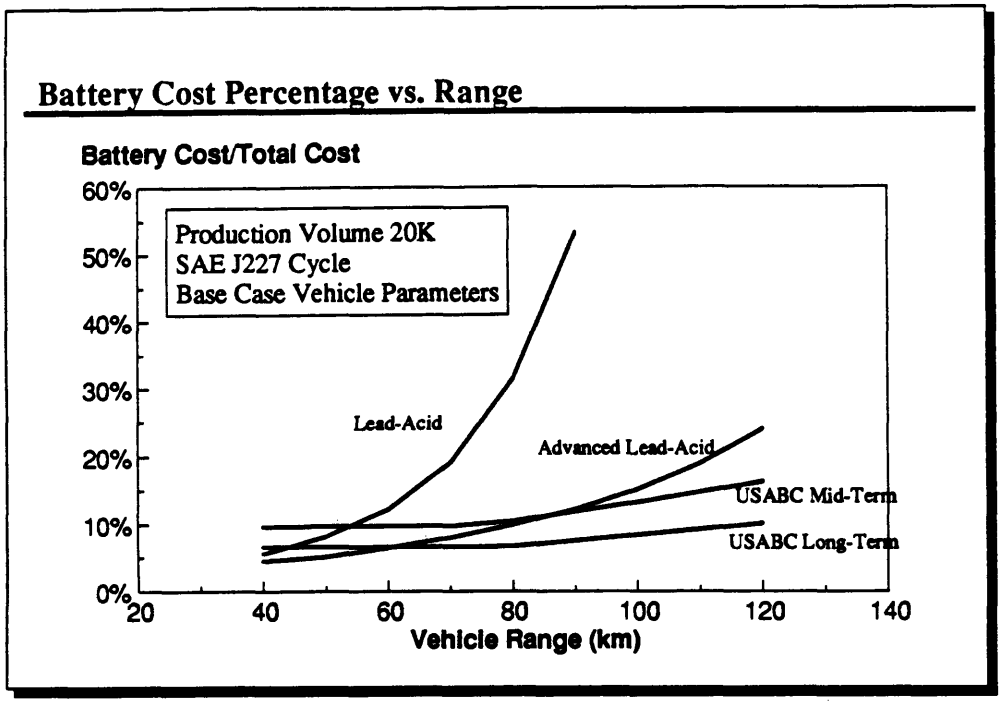


Figure 14: Battery Cost Percentage vs. Range.

Figure 14 exhibits the battery cost percentage as a function of vehicle range for the same four battery technologies that have already been discussed. Figure 14, being very similar to Figure 13, will not be analyzed in detail. However, this figure puts the battery cost issue into perspective and demonstrates why batteries are indeed the limiting technology for EVs. A lead acid battery with capabilities half way between the pessimistic and optimistic scenarios, would account for 14% of the total vehicle production cost at a targeted vehicle range of 50 miles. This percentage would increase to 53% for a vehicle range of 75 miles. If however, the mid term and long term goals set by USABC are met, then batteries can be affordable and no longer account for such a big portion of the vehicle's total cost. In fact for a targeted vehicle range of 120 km or 75 miles, the battery percentage falls to 16% and 10% for the mid term and long term USABC goals respectively.

5.2 Total Production Cost

Section 5.1 of this chapter demonstrated why batteries are presently the Achilles heel of electric vehicles and why batteries with capabilities equaling or surpassing the goals set by USABC need to be developed and become commercially available at an affordable unit cost. This section considers the total production economics associated with the base case aluminum intensive vehicle. The key inputs for the modeling of the vehicle body are presented in Tables 3 & 4 of Appendix 1. Moreover, Tables 6 & 7 of the same Appendix tabulate the results of a cost survey concerning the propulsion and secondary systems and components. Typical manufacturers of such systems were surveyed. The average of the prices obtained for each system were used in the study.

Figure 15 shows the variation of production cost with annual production volume. This figure corresponds to an electric vehicle with a range of 80 km. Furthermore, the cost variation with production volume is portrayed for three battery technologies, namely the pessimistic lead acid case and the USABC mid term and long term goals.

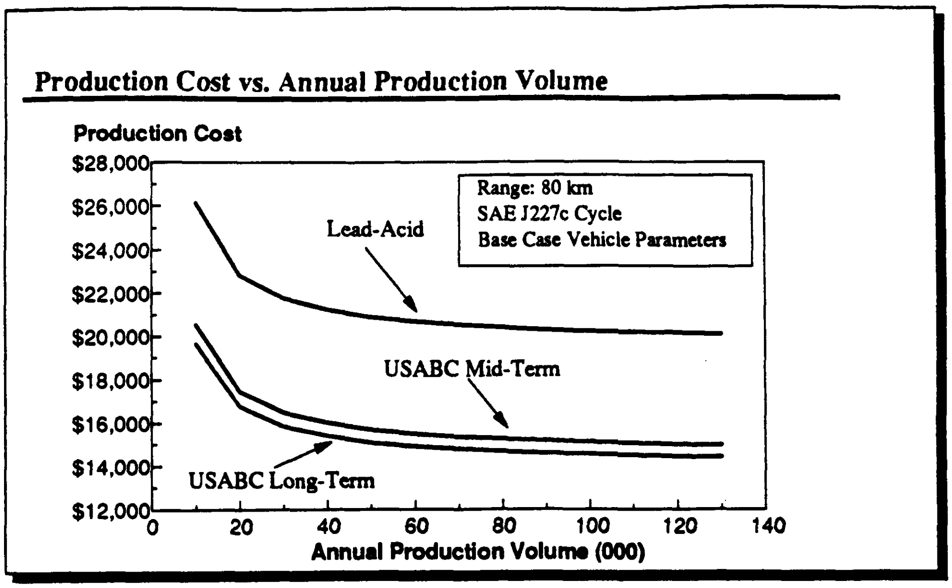


Figure 15: Production Cost vs. Annual Production Volume.

Table 8 shows the cost breakdown at an annual production volume of 20,000 vehicles for a "Lead Acid Battery".

Table 8: Typical Production Cost Breakdown

	Cost	Percentage
Battery Cost	$7,178	31.5%
Propulsion/Electronics	$3,549	15.6%
Motor/Gear Set	$3,499	15.3%
Total Body	$8,578	37.6%
Total	*$22,805*	*100%*

Clearly, one can once again observe the huge cost benefit associated with the advanced battery standards set by USABC. This benefit would become even larger if the targeted range for the vehicle was greater than 80 km. Furthermore, the minimum efficient scale for electric vehicle production is reached at an annual production volume of approximately thirty thousand. The mandated sale in California will result in annual sales of approximately 40,000 in 1998, rising to 200,000 in 2003. Assuming that the six OEMs will equally share the mandated market, then the annual production volume for a typical manufacturer will be 6,650 in 1998. The OEMs will be therefore asked to initially produce at the steep portion of their economies of scale curve, at volumes well below their minimum efficient scale. The production volume will be expected to rise to 33,000 units per year in year 2003. This is the absolute maximum, since in year 2003, all manufacturers selling vehicles in California will be required to satisfy the 10% sales mandate. Hence, it is very likely that even in 2003, automakers will be producing at volumes below their minimum efficient scale.

Related to the economies of scale issue that is being discussed is one of the biggest uncertainties in the electric vehicle debate. This uncertainty involves the possible adoption of similar ZEV legislation by some or all of the Northeast states. If all twelve Northeast states and the District of Columbia adopt the ZEV mandates, then the expected total[5] EV sales in 1998 will be 123,500 (compared to 40,000 if only California requires ZEVs), assuming a 6% annual growth in sales. In year 2003, the expected EV sales will be 826,250 (compared to 200,000 if only California requires ZEVs). Moreover, if only the states of New York and Massachusetts adopt the ZEV regulations in addition to California, then the EV sales forecast for the three states will be 66,000 and 439,000 in

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[5] including the state of California.

1998 and 2003 respectively. In conclusion, regulatory initiatives might prove to be instrumental in reducing the electric vehicle costs by guaranteeing a large enough market for the manufacturers to reach their minimum efficient scale.

However, even if batteries become affordable and economies of scale are achieved, the production cost for an electric vehicle will still be high. A production cost of $14,500 for a two seat vehicle is definitely not low. To put this cost discussion into perspective, the GEO Metro which is the type of ICE vehicle the electric vehicle that is being modeled will compete with, only costs $9,000 to purchase. This, suggests that, in addition to bulky batteries and small production volumes, there are other reasons that drive the cost of this purpose built EV, up. More specifically:

By looking at Table 9, it is clear that the amount of electronic systems that are required for reliable electric drive is unheard of in today's ICE vehicles. Many analysts in the EV debate have characterized electric vehicles as "computers on wheels". [Hogarth, 1994] These systems are presently quite expensive, as Figure 16 portrays. Moreover, even if mass production economies are achieved, the propulsion and electronic systems and components will still account for a significant portion of the total vehicle production cost.

Table 9: Propulsion Systems & Electronics Costs

Vehicle System/Component	**100 units per year** **$**	**20,000 units per year** **$**
Motor	$2,500	$1,000
Controller	$3,000	$1,000
Gearbox	$3,000	$2,500
Battery Charger	$4,000	$1,250
Maximum Power Tracker	$1,000	$500
DC-DC Converter	$800	$200
Gauges	$700	$400
Other	$500	$200

Source: Cost Survey & Literature Review

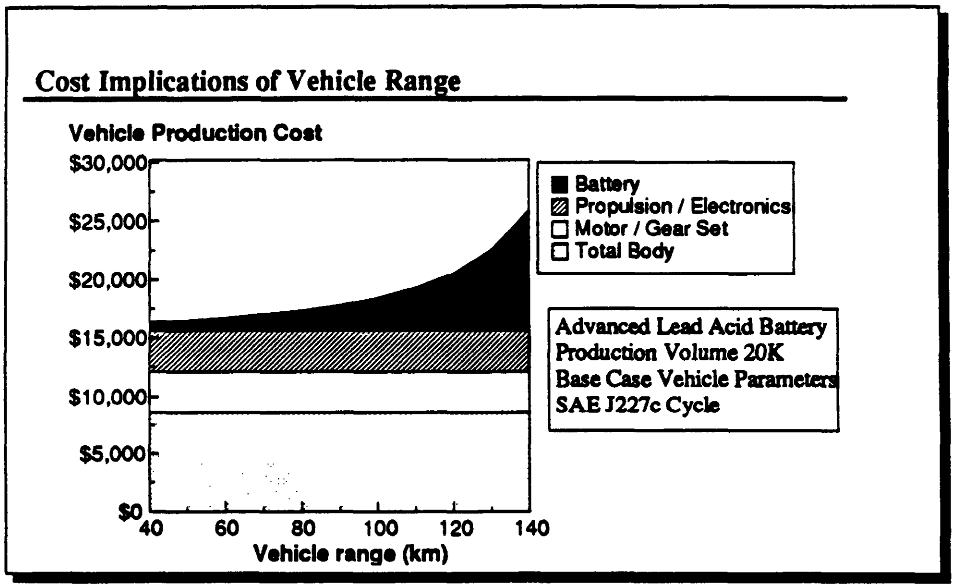

Figure 16: Cost Implications of Vehicle Range.

Furthermore, the cost associated with the body of the electric vehicle is also high. At a production volume of 20,000 units per year, the total body cost is $8,600. This cost includes both the chassis cost and the cost associated with the vehicle's secondary systems that are tabulated in Table 7 of Appendix 1. In particular, at this production volume, the total body cost is equally split between the chassis and secondary systems costs. A cost of $4,300 for the vehicle's chassis is undoubtedly not competitive. The manufacturing processes associated with lightweight materials (e.g. aluminum stamping, Sheet Molding Compound) are not competitive with conventional steel practices at an annual production volume of 20,000. As has already been discussed, such a low production volume may very well prove to be well above that associated with an electric vehicle manufacturer. Materials substitution issues for electric vehicles are discussed in Chapter 6 of this document, where the economics of purpose built vehicles are compared to those associated with conversion vehicles.

5.3 Life Cycle Cost Considerations

In order to assess the economic implications of electric vehicles accurately, the framework of analysis that has been presented so far needs to be expanded to include the use and post use phases of the life cycle. Such an expanded framework ought to include the fuel cost, battery replacement cost, maintenance cost, insurance cost and the cost associated with the disposal and recycling of the automobile. The disposal and recovery phases have not been included in the discussions due to the large uncertainties associated with the economics of disposing and recovering lightweight automobile materials, batteries, and complex electromechanical componentry. In this section, the life cycle cost results for EVs will be presented and subsequently compared to the corresponding costs associated with a comparable ICE vehicle. The following paragraphs briefly summarize the aspects of the use phase have been included in the calculations and explain why some other aspects have been disregarded.

Fuel Cost: In the case of ICE vehicles, fuel cost is simply defined as the amount of money paid over the life cycle for refueling the vehicle. In the case of EVs, the corresponding fuel cost is related to the user's electricity expenditure needed for recharging the EV. For both EVs and ICEs, fuel cost is a function of the fuel price (electricity or gasoline) and fuel efficiency (kWh/mi or mi/gal). Figure 17 demonstrates that, in the case of EVs, fuel efficiency is a strong function of battery technology. In this figure, electricity consumption is plotted as a function of battery specific energy. Battery specific energy or energy density is the battery parameter directly related to the range of the vehicle. The energy consumption curves have been plotted for three targeted vehicle ranges. Furthermore, the battery selected for the calculation performs according to the USABC mid term goals, except for the specific energy parameter, which has been treated as a variable. The three curves converge towards the same numerical value since eventually the specific energy of the battery is large enough to make power the constraining factor. Figure 17 portrays the importance of reaching the USABC mid term goal for specific energy which is 80-100 Wh/kg. For energy density values above 100 Wh/kg, the energy density curves become flat even for targeted vehicle ranges of 120 km or 75 mi. This sensitivity of energy consumption to battery capabilities will result in the consideration of different battery scenarios in the life cycle cost calculations.

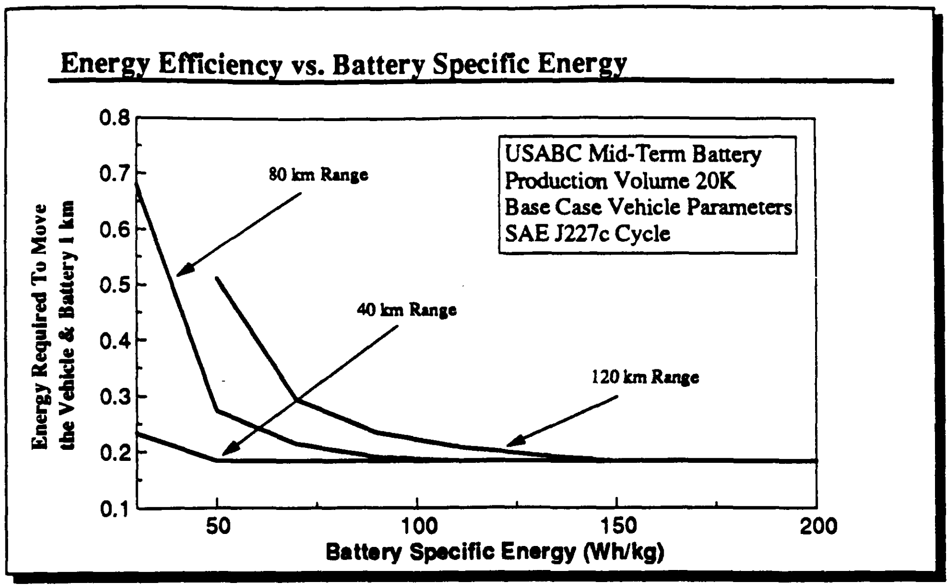

Figure 17: Energy Efficiency vs. Battery Specific Energy.

Battery Replacement Costs: The longevity (in miles) of a battery pack is a function of the number of charging cycles it can endure and the number of miles driven between recharges. The former is a battery characteristic and therefore varies with battery technology. The upper limit for the number of miles driven between recharges is the range of the vehicle. However, drivers are unlikely to risk running their batteries to exhaustion on the road. Therefore the average distance driven between recharges is expected to be lower than the vehicle's range. Furthermore, the distance might be constrained by the large recharging time[6] and low range, resulting in daily recharging irrespective of the distance that has been driven.

Maintenance Cost: Electric vehicle proponents have argued that, due to their simpler design and fewer parts, the cost associated with the maintenance of EVs can be as low as

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[6] presently 6-8 hours with lead acid batteries.

half of the corresponding ICE maintenance costs. However, during the first 5 years of EV introduction, one cannot expect EV maintenance costs to be significantly lower. Once the technology matures and electric drive systems reach their expected reliability levels, then maintenance costs for EVs may ultimately be lower than the equivalent ICE costs. Any new technology is associated with a certain learning period for both the manufacturers and its users. Furthermore, the majority of initial EV sales are likely to be fleets which are maintained very frequently anyway. In conclusion, maintenance costs have been disregarded for the comparisons that will be presented, implicitly assuming that they are equal between ICEs and EVs.

Insurance, Depreciation and Licensing & Registration Costs: All these costs have been disregarded from the comparative life cycle cost estimates since no one really knows at this stage whether these costs will be different than those associated with ICE vehicles.

Hence, life cycle cost is defined as follows for the purposes of this study:

Life Cycle Cost = Purchase Cost[7] + Discounted Fuel Cost + Discounted Battery Replacement Cost[8]

The life cycle cost comparisons between ICE vehicles and four generations of EVs will be now presented. The assumptions that are consistent for all cases are shown in Table 10.

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[7] assuming no mark-up in the case of EVs.

[8] only applicable for EVs.

Table 10: ***Assumptions & Inputs for the Use Phase of the Life Cycle Cost Models***

	ICE Vehicle	Electric Vehicle
Fuel Price	1.2 $/gal	0.042[1] $/kWh
Vehicle Life	12.5 years	12.5 years
Discount Rate	10%	10%
Vehicle Range	490 mi	50 mi
Annual VMT[2]	10,000 mi	10,000 mi
Production Volume	> 200,000	20,000

[1] off-peak rate; fuel costs corresponding to the peak rate of 0.8 $/kWh are shown in parentheses in Figure 18.

[2] Vehicle Miles Traveled.

As Table 10 shows, it has been assumed that electric vehicles will be recharged at on off-peak rate. The discount rate is calculated by subtracting the current inflation rate from the relevant interest rate. [Hausman, 1979] All four electric vehicle generations have been compared to the GEO Metro, an ICE vehicle with a 490 mi range. The targeted range for the electric vehicle has been set at 80 km or 50 mi. It has been assumed that the EV will be used for commuting purposes. With such a range therefore, EVs can meet the 10,000 annual mileage associated with the ICE vehicle, assuming they are recharged every working day. An annual mileage of 10,000 miles corresponds to 38.5 miles per working day. Figure 18 shows the results of the life cycle cost comparisons. The assumed battery capabilities for the different EV scenarios are tabulated in Table 5 of Appendix 1.

Life Cycle Cost Results

	ICE Veh.	Avg. Pb-Acid	Adv. Pb-Acid	USABC Mid Term	USABC Long Term
Purchase Cost	$9000	$18,143	$17,344	$17,452	$16,748
Fuel Efficiency	45 mi/gal	0.91 kWh/mi	0.55 kWh/mi	0.29 kWh/mi	0.25 kWh/mi
Annual VMT	10,000 mi	8,000 mi	10,000 mi	10,000 mi	10,000 mi
Discounted Fue LC Cost	$2,465	$2,842 ($5,414)	$2,136 ($4,068)	$1,131 ($2,155)	$970 ($1847)
Battery Longevity	N/A	11,600 mi	21,150 mi	23,100 mi	41,000 mi
Req'd Battery Packs	N/A	8.6	5.9	5.4	3.0
Discounted LC Battery Cost	N/A	$11,061	$4,830	$4,616	$1,293
Discounted LC Cost	$11,465	$32,046	$24,309	$23,199	$19,011

Figure 18: Life Cycle Cost Results.

ICE Vehicle: The GEO Metro is a very low purchase price, small ICE vehicle. Its small purchase cost in conjunction with its very high fuel efficiency[9] result in a very low life cycle cost of $11,645. Based on the performance of the EV, this is the type of vehicle the two seat base case EV would compete against.

"Average Lead Acid" EV: This is the worse case scenario for EVs. However, it is representative of the presently available battery technology. The battery's capabilities are relatively poor, resulting in low fuel efficiency (0.91 kWh/mi) and a relatively high fuel cost of $2842 assuming off-peak recharging ($5,414 assuming peak rate recharging).

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[9] measured by EPA.

Furthermore, the battery's poor longevity of 11,600 miles (assuming 375 cycles to 80% DOD, 31 miles per working day and recharging every working day) results in very frequent replacement. More specifically, 8.6 battery packs would be required if the vehicle were to be driven 8,000 miles per year. The 10,000 mile target was abandoned under this scenario, as it would result in annual battery replacement and therefore very high life cycle cost. Realistically, the consumer would restrict the scope of EV applications with such a battery and hence an annual mileage of 8,000 miles was assumed. The battery replacement cost of $11,061 accounts for more than a third of the total life cycle cost. In conclusion, the high production cost, the low fuel efficiency and the battery longevity problems result in a life cycle cost of $32,046, almost three times the equivalent ICE cost.

"Advanced Lead Acid" EV: This case represents the best case lead acid battery scenario. The assumption is that such batteries will be commercially available in mass production for the 1998 model year at the latest. Under this optimistic scenario, purchase cost is reduced due to the cheaper battery. Moreover, the much improved vehicle efficiency results in reduced fuel cost. The fuel cost expenditure is in this case lower than the equivalent ICE fuel expenditure for the off-peak electricity rate case. The battery's significantly improved longevity implies that 10,000 miles a year can be driven with a reasonable number of battery replacements. The battery replacement cost is reduced by $6,231 when compared to the previous scenario. The total discounted life cycle cost of $24,309 is $7,737 less than the "Average Lead Acid Battery" scenario, but still $12,645 more than the ICE vehicle's cost.

"USABC Mid Term" EV: If the USABC mid term goals are met, then one can expect some further life cycle cost reduction. In particular, the vehicle's improved efficiency of 0.29 kWh/mi would result in reduced fuel cost. In addition, the somewhat longer battery life further reduces the battery replacement cost. The total life cycle cost reduction is $1,100 compared to the "Advanced Lead Acid Battery" scenario. It should be noted here that, as exhibited in Figure 13 of this chapter, the cost difference between the "Average Lead Acid" battery and the "USABC Mid Term" goals are a function of the targeted vehicle range. Hence, as range increases above 80 km, then the USABC Mid Term battery goals become much more cost effective. Therefore, the relatively small life cycle cost difference at the 80 km targeted vehicle range, should not give the impression that the mid term goals are not that much better than the maximum that can be achieved with state of the art technology. For ranges in excess of 100 km, the mid term goals result in considerably less expensive and more efficient battery packs. For a targeted vehicle range of 120 km for example, a USABC mid term battery pack costs $3,037 and has a 0.34 kWh/mi efficiency whereas the corresponding numbers for the "Average Lead Acid" Battery are $4,904 and 1.3 kWh/mi respectively.

"USABC Long Term" EV: Finally, as one would expect, the USABC Long Term battery goals yield the lowest life cycle vehicle cost of $19,011. The vehicle's fuel efficiency is further improved resulting in a fuel expenditure which is only 40% of that associated with the GEO Metro. Furthermore, due to the improved battery longevity, only three battery packs are required during the 12.5 year vehicle life. The battery replacement cost is no longer a major factor, as the vehicle's life cycle cost is definitely dominated by the

production cost. Still the $19,011 cost is 65% more expensive than that associated with the GEO Metro. In fact, a gasoline price of 4.87 $/gal would be necessary to bring these life cycle costs into parity.

European Scenario: In Europe, where, on average, the price of gasoline is almost four times more expensive than in the US, EVs are much more cost competitive. Table 11 shows the life cycle cost calculation for an EV to be used in Europe assuming a gasoline price of 4 $/gal. Table 12 exhibits the life cycle costs for the European ICE and the four generations of EVs[10].

Table 11: ***European ICE Life Cycle Costs***

Purchase Cost	$9,000
Fuel Price	4 $/gal
Fuel Efficiency	45 mi/gal
Annual VMT	10,000 mi
Discounted Fuel LC Cost	$8,217
Discounted Total LC Cost	$17,217

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[10] EV results are identical to Figure 18.

Table 12: *Total Life Cycle Cost Comparisons*

	European ICE	**Avg. Pb-Acid**	**Avg. Pb-Acid**	**USABC Mid Term**	**USABC Long Term**
Total LC Cost	$17,217	$32,046	$24,309	$23,199	$19,011
Difference from European ICE	N/A	$14,829	$7,092	$5,982	$1,794
% Difference	N/A	+86.1%	+41.2%	+34.7%	+10.4%

Clearly, the life cycle cost differences under the European gasoline pricing scenario are considerably reduced. However, EVs are still more expensive. Only if the USABC long term goals are met can EVs become cost competitive to ICEs. Higher gasoline prices are the primary, but not the only, reason why the future of EVs looks brighter in Europe. Shorter commuting distances associated with the more dense urban development is another important difference. As a result, the range limitation in Europe is not as big a concern as it is in the US. Finally, sub-compact type, "city car" vehicles like the GEO Metro are much more prevalent in Europe. This implies lower curb weights and therefore lighter and cheaper batteries for a given set of performance standards.

5.4 Conclusions

This chapter has shown that electric vehicles are more expensive and associated with poorer performance than their ICE equivalents. In particular, battery technology has been cited as the major obstacle for the successful commercialization of EVs. Batteries are expensive to make, require frequent replacement and heavily restrict the vehicle's range and performance profile. Economies of scale and the high cost propulsion systems and power electronics are also significant factors raising the EV production cost. Furthermore, the fuel cost benefits associated with EVs do not affect the life cycle cost comparison in a dramatic way, especially in the US where taxes on gasoline are relatively low.

The production and use economics of electric vehicles raise the following questions: Are the environmental or other benefits of EVs large enough to justify the considerable cost premiums that have to be borne? Are there other alternatives that are more cost-effective in addressing the same concerns? The effect of electric vehicle introduction on air pollutant releases will be examined in Chapter 7. The cost effectiveness question will be addressed in Chapter 8 of this document. Finally, the next chapter addresses some other important economic and performance considerations for EVs.

6. Economic & Performance Considerations

In Chapter 5, the economic and performance consequences of developing and using the base case EVs were appraised. Although critical inputs such as battery technology and production volume were treated as variables, some assumptions were consistent for all the calculations. In particular, the body weight and body material choice have been treated as constants. Moreover, the base case EV scenario represents a ground-up EV. This chapter is intended to examine the implications of relaxing some of these assumptions. In particular, Section 6.1 compares the economics of purpose built vs. converted EVs, and Section 6.2 examines the implications of using lighter materials for the vehicle's chassis.

6.1 Purpose Built vs. Converted EVs

The vast majority of the EV models that are being presently offered to fleets and consumers are low production volume conversions of existing ICE steel vehicle designs. Conversion companies such as Solectria and US Electricar essentially purchase the ICE vehicle, remove the internal combustion engine and the associated parts, and subsequently install the electric drivetrain, batteries and other differentiating components. Information about the prices and characteristics of various EV conversions is given in Table 13.

Table 13: *Market for EV Conversions*

Make & Model	Price $	Battery Type	Seating	Range [miles]	*Characteristics*
Peugeot 106	16,000	Ni Cd	4	45	*Steel Conversion*
US Electricar GEO Prizm Conversion	39,000	lead-acid	5	50-80	*Steel Conversion*
Solectria Force GEO Metro Conversion	26,050	lead-acid	4	55-60	*Steel Conversion*
Solectria Force GEO Metro Conversion	28,280	lead-acid	2	70	*Steel Conversion*
Solectria Force GEO Metro Conversion	59,350	Ni Cd	2	100-110	*Steel Conversion*
Bat GEO Metro conversion	15,900	lead-acid	2	60-100	*Steel Conversion*

From a performance standpoint, a purpose built EV is preferred to a conversion vehicle. Its systems and overall vehicle design are optimized for electric drive. Furthermore, ground-up EVs are almost always associated with the use of lightweight materials. Hence, for a given battery capacity, the performance of the purpose built EV will be superior to that associated with the converted vehicle. Furthermore, if for comparison purposes, the performance of the vehicle is held constant, the ground-up vehicle would require a smaller battery pack. This reduction in battery weight, together with the efficiency improvements associated with propulsion systems optimization, are likely to lead in cost gains for a given set of performance goals.

Overall however, an efficient conversion process is likely to be the preferred option as far as cost is concerned. Under such an approach, the EV industry does not have to make the considerable financial, manufacturing and intellectual investment required for mass producing a vehicle chassis. Simply put, conversion companies will be able to take advantage of the vast experience that the established OEMs have gained in doing so. Moreover, economies of scale and manufacturing issues associated with the lighter materials used in ground-up EVs also make the cost comparison lean towards conversions. In particular, one has to balance the cost gains due to lightweighting and efficiency improvement associated with the ground up design against the cost penalty related to producing, say, an aluminum rather than steel chassis. More specifically, one has to compare the aluminum unibody design at 5,000[11] vehicles per year, to a steel unibody at more than 200,000 units per year since steel conversions come from existing designs. Studies have shown that the aluminum unibody at a production volume of 20,000 is $5,832 more expensive than the steel unibody at 300,000 units per year. [Politis, 1995] A typical low volume EV manufacturer like Solectria, producing a maximum of 100-200 vehicles a year, is therefore much more likely to opt for a conversion rather than a purpose built EV design. Finally, offering a variety of EV models to meet the diverse consumer needs and the sales mandates is much easier if a conversion strategy is adopted. The manufacturer would simply have to order more models from the OEM rather than having to go through the timely and costly process of developing a purpose built vehicle for each consumer application.

This process of removing the ICE and associated parts is presently quite inefficient and costly. The GEO Metro, an ICE vehicle frequently used for conversions, can be purchased at $8,500 to $10,000 depending on the accessories. A typical lead acid EV

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[11] typical annual production volume for a typical OEM with current EV regulations.

conversion of the GEO Metro costs anywhere from $16,000 to $28,000 as shown in Table 13[12]. In addition to the cost of alternative powerplants, drivetrains and associated components, and the low production volume concerns, the notion that the converter has to purchase and subsequently remove "unwanted" parts suggests a considerable and costly inefficiency in the conversion process. For this reason, EV conversion companies would much rather purchase vehicles from the conventional automakers that do not include the standard powerplant and drivetrain. Such "engineless" vehicles are called "gliders." The adoption of such a strategy is associated with considerable cost advantages. In particular:

- The process of purchasing and subsequently removing the ICE and associated parts can represent up to 30% of the total cost of the converted vehicle.
- The EV industry can avoid the substantial capital, manufacturing and intellectual investment necessary to mass produce automobile bodies.

The Big Three OEMs, who are likely to be the "glider" providers, have expressed some concerns regarding this strategy. [Rajan, 1994] First, the potential adoption of such a strategy raises some important public perception, liability and image questions. Who is to be held liable if for example a "poorly" converted Ford glider is involved in an accident? Most importantly however, how will such an accident hurt Ford's image and perception among the consumers? Second, OEMs and the interested conversion companies have failed to reach a consensus as to what an "optimum" glider exactly is. Finally, the manufacture of a glider may represent a significant disruption of assembly plant operations, thereby reducing the associated economic advantages.

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[12] cost varies with range, seating capacity and manufacturer.

The OEMs have therefore been quite skeptical about this strategy. However, the possibility that the sale of gliders could count toward meeting their annual mandate EV sales requirement (via a "credit" mechanism) is too overwhelming to be overlooked. [New York Times, July 25, 1995] For this reason, OEMs have been working with conversion companies in order to establish guidelines for the provision of gliders. [Automotive News, November 21, 1995] In particular, the Big Three want conversion companies to agree to a quality control process, warranty and service provisions and assure they have the right liability protection.

6.2 Lightweighting

The total vehicle weight reduction associated with reducing the vehicle chassis weight through the use of lighter than steel materials, has two components:

a. the reduction in chassis weight, e.g. if the chassis weight is reduced by 300 lbs then one can at least expect the total vehicle weight to be reduced by 300 lbs.

b. the reduction in battery weight. If the performance of the vehicle is assumed to remain constant, then a smaller battery is needed in order to move the lighter chassis.

The relative importance of these two components depends considerably on battery technology, as will be shown below. More specifically, the second component tends to be more important in light of the current, low performance battery technology. If the battery technology advances, then these synergies between chassis weight and battery requirements decline and the majority of weight savings are a result of the former component.

Tables 14, 15, & 16 portray the total vehicle weight, initial battery cost and energy efficiency as a function of battery technology for two chassis weights. The performance of the vehicle has been held constant at a 80 km range under SAE J227 C driving conditions. These tables can be used to assess the importance of lightweighting and advances in battery technology. In particular, the questions examined are the following: "What are the implications of reducing the total body[13] weight from 800 kg to 700 kg, a 12.5% decrease, as far as total vehicle weight, battery cost and vehicle efficiency are concerned?" and "How these implications are affected by advances in battery technology?" More specifically:

Table 14: ***Total Vehicle Weight Vs. Body Weight***

	Advanced Pb-Acid	**USABC Mid-Term**	**USABC Long-Term**
800 kg	1,338	941	861
700 kg	1,179	826	754
Absolute Decrease	156	116	107
Relative Decrease	11.8%	12.3%	12.4%

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[13] without the battery.

Table 15: *Initial Battery Cost Vs. Body Weight*

	Advanced Pb-Acid	USABC Mid-Term	USABC Long-Term
800 kg	$1,726	$1,845	$1,133
700 kg	$1,534	$1,636	$1,004
Absolute Decrease $	$192	$209	$129
Relative Decrease	11.1%	11.3%	12.8%

Table 16: *Vehicle Energy Efficiency [kWh/mi] Vs. Body Weight*

	Advanced Pb-Acid	USABC Mid-Term	USABC Long-Term
800 kg	0.56	0.29	0.25
700 kg	0.5	0.26	0.22
Absolute Increase	0.06	0.03	0.03
Relative Increase	10.86%	11.16%	11.24%

The conclusions that can be drawn from the above tables can be summarized as follows:

1. In absolute terms, the gains associated with advanced battery technologies are lower when compared to those associated with currently available technologies.

2. However, on a percentage basis the gains are roughly equal. If one wanted to interpret the slight increase in percentage gains as battery technology advances, one could argue that with better battery technology, batteries are to a smaller degree the critical, limiting technology and hence lightweighting produces more visible results.

3. In the beginning of this section two components were identified for total vehicle weight reductions. The following table examines the relative significance of these components for the example being considered, i.e. a 100 kg reduction in body weight, from 800 to 700 kg.

Table 17: *Components of Lightweighting*

	Advanced Pb-Acid	USABC Mid-Term	USABC Long-Term
Chassis Weight Reduction [kg]	100	100	100
Battery Weight Reduction [kg]	56	16	7
Total [kg]	156	116	107
% Comp 1	64.1%	86.2%	93.4%
% Comp 2	35.9%	13.8%	6.6%

Clearly, the second component is much more significant with the currently available battery technology. In other words, more than a third of total weight savings with today's technology stem from the fact that for given performance requirements you need less battery to move the lighter body. If the battery technology advances, then these synergies between body weight and battery requirements decline. In other words, the effect of chassis weight reduction is smaller.

4. In cost terms, the gains associated with lightweighting (initial battery cost & efficiency gains) are higher for current battery technologies in absolute terms, but are roughly equal among battery technologies in relative terms. As has already been discussed in Section

6.1, these cost gains have to be compared to the cost penalty associated with producing the lighter body. This extra cost is a function of material choice, the manufacturing processes employed and differences in production volumes. Suppose, for example, that the base case vehicle, whose body weight is 800 kg, is a steel unibody converted EV whose chassis is produced at annual production volumes in excess of 200,000 units. Then for the lighter 700 kg vehicle consider three separate cases:

- An aluminum intensive unibody, purpose built EV, similar to the GM Impact.
- A polymer intensive purpose built EV, similar to the Solectria Sunrise.
- An aluminum spaceframe design, similar to Amerigon's "running chassis" concept.

All the above purpose built designs will be produced at much lower production volumes than the base case. Moreover, since the material choice and manufacturing methods are different, the production costs are likely to vary considerably among the three alternatives. Comparing the production economics associated with the three alternatives is beyond the scope of this study. Politis [1995], for example, provides some insight into the impact of wholesale aluminum vehicle substitution. However, as has already been indicated in Section 6.1, the cost penalty over the base case steel unibody is likely to more than outweigh the cost gains due to the smaller battery and improved efficiency, at least for the kind of production volumes that will be typical for the initial EV market.

7. Emissions Results

The effectiveness of Electric Vehicles in reducing airborne emissions has been assessed using EPA's Mobile 5a model in conjunction with a powerplant simulation model for the New England Region. Section 7.1 of this chapter presents the results of the emissions modeling while Section 7.2 includes a discussion of the results. The methodology for the emissions assessment has been outlined in Chapter 4.

Organic gases in the vehicle exhaust consist of methane, non methane hydrocarbons and oxygenated compounds such as aldehydes, alcohols, ethers and ketones. Methane, having a very long half life of approximately 100 days, is the least reactive of the hydrocarbons and is hence not considered an ozone precursor. Therefore, standards for organic gases have been set for non methane organic gases (NMOGs). [Seinfeld, 1986] [Fox, 1995]

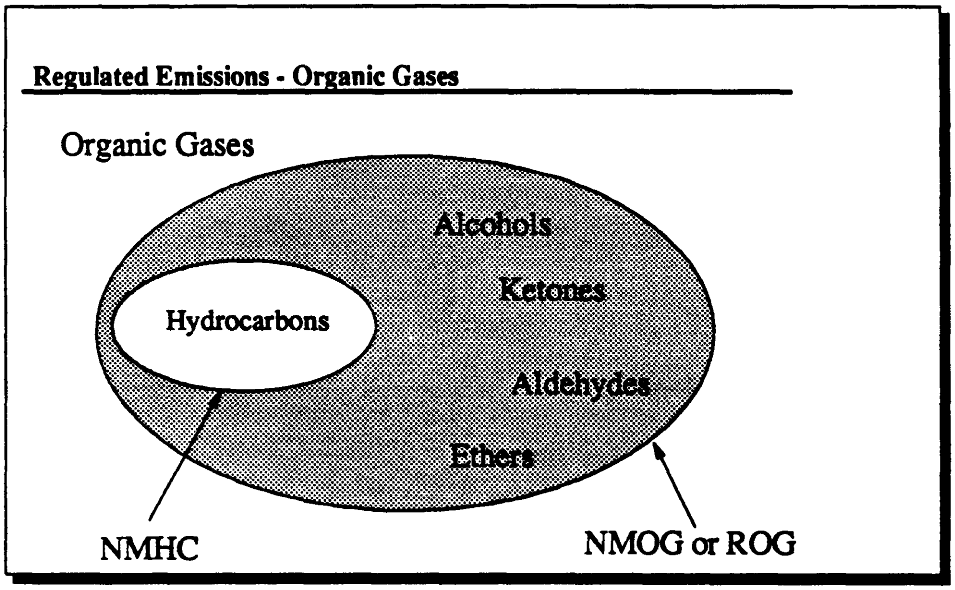

Figure 19: Regulated Emissions-Organic Gases.

Figure 19 clarifies the distinction between non methane organic gases (NMOGs) and non methane hydrocarbons (NMHCs). NMOGs include both NMHCs and oxygenated compounds such as aldehydes, ethers, alcohols and ketones. The California standards have shifted from NMHCs to NMOGs for the low emission vehicle (LEV) program beginning with the 1994 model year. [Clean Fleet Project, 1994] This change has been made so that ozone precursors such as alcohols, ketones, aldehydes and ethers are taken into consideration.

7.1 Presentation of Results

Figures 20 through 23 exhibit the effect of EV introduction by pollutant category. In each figure, three lines have been plotted. The "Powerplant Increase" line portrays the expected increases in powerplant emissions if EVs are introduced into the vehicle fleet. The "Displaced ICE" line shows the expected decreases in vehicle emissions. These decreases in emissions will occur as a result of EVs replacing ICE vehicles in the vehicle fleet mix. Finally, the "Net Change" line is simply the sum of the "Displaced ICE" and the "Powerplant Increase" line. Hence, a net change of zero implies that EV introduction will have no effect on the emissions releases associated with that particular pollutant. A negative net change would imply that EVs will result in lower emissions for the particular pollutant category. Similarly, a positive change implies that the powerplant emissions increases more than offset the displaced ICE emissions. In other words, all three lines represent changes relative to the "no EV scenario" portrayed by the zero line in the graphs. Finally, it should be noted that the California EV market penetration percentages (2% of annual sales in 1998, rising to 5% in 2001 and 10% in 2003) have been assumed for the calculations. In other words, the results presented here examine the effects of a potential adoption of the California ZEV mandates in the New England Region.

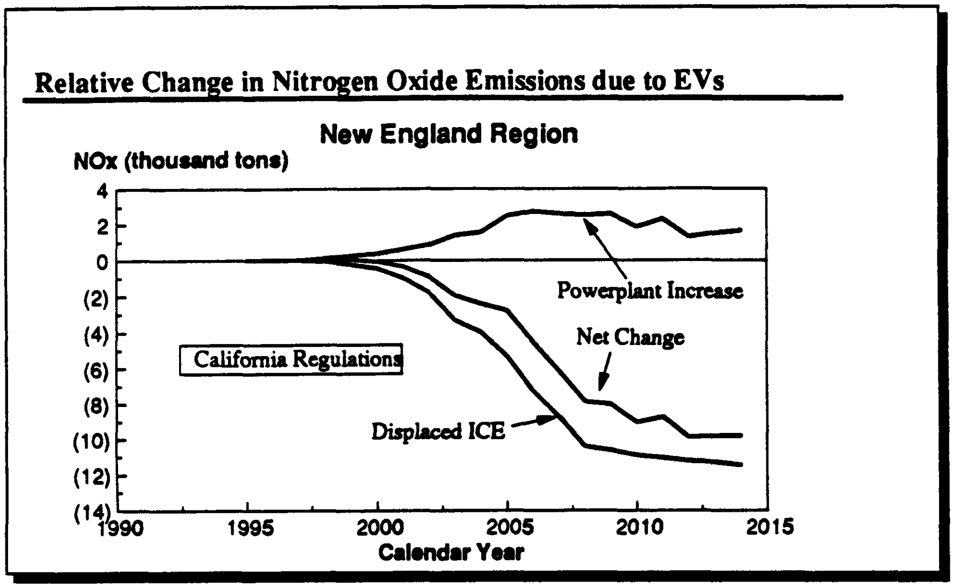

Figure 20: Relative Change in Nitrogen Oxide Emissions due to EVs.

EVs are expected to be beneficial in the case of nitrogen oxides (NOx) as Figure 20 shows. This implies that the powerplant emissions associated with vehicle recharging are lower than the expected benefits related to the replacement of ICE vehicles with battery powered EVs. The same applies for carbon monoxide (CO) and reactive organic gases (ROG) emissions. ROG emissions include tailpipe, refueling and some evaporative emissions. As Figure 21 portrays, powerplants emit negligibly small amounts of CO and ROGs. As a result, electric vehicles can be thought of as truly zero emission vehicles as far as these pollutants are concerned.

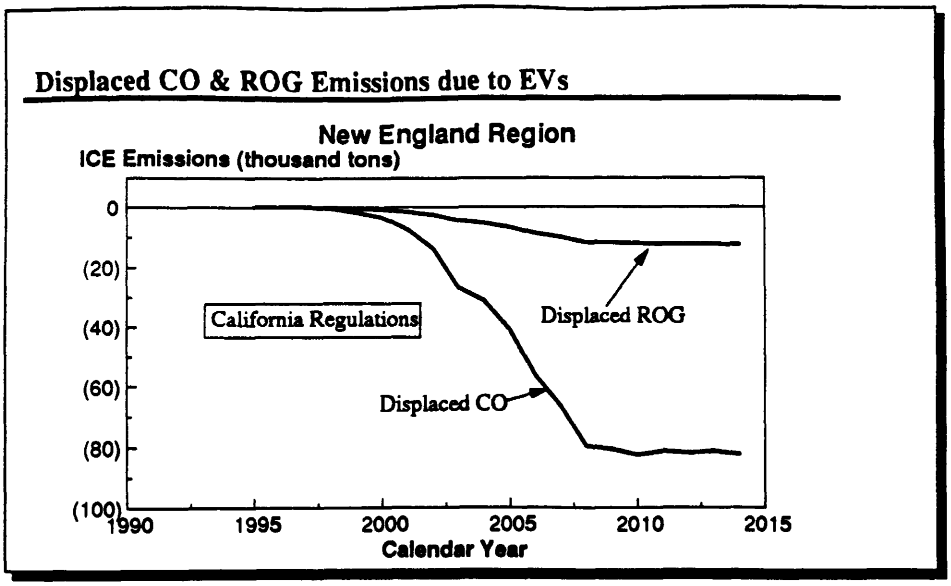

Figure 21: Displaced CO & ROG Emissions due to EVs.

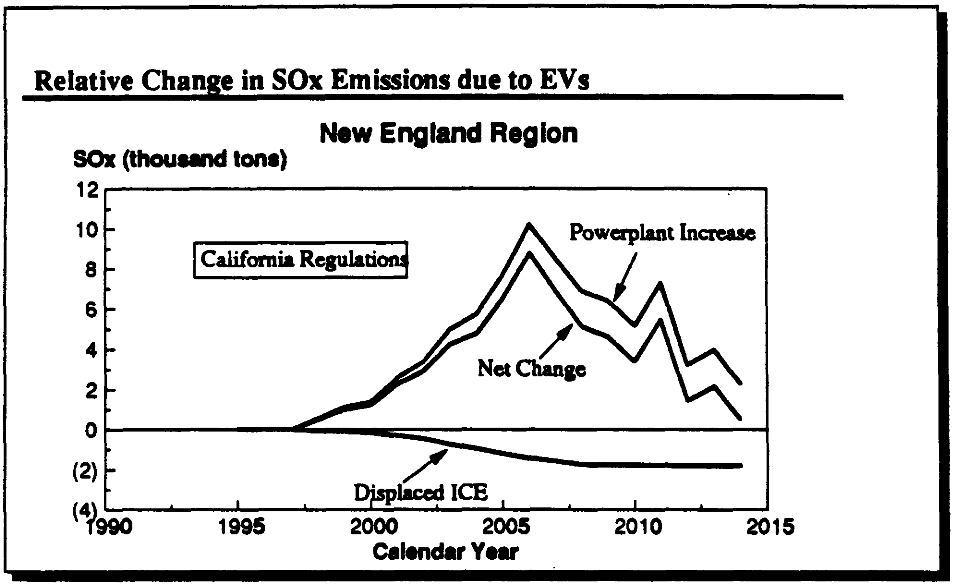

Figure 22: Relative Change in SOx Emissions due to EVs.

In the case of sulfur oxide emissions, EVs will result in net increases of the releases into the atmosphere. The very low sulfur content of gasoline is the reason behind this increase in emissions brought about by a potential adoption of EV mandates in the New England

Region. The peak in SOx emissions observed in year 2003 is associated with the retirement of oil fired units (gross polluters) combined with the effect of regulatory caps set on SO_2 powerplant emissions. Finally, the expected reductions in CO_2 emissions are portrayed in Figure 23.

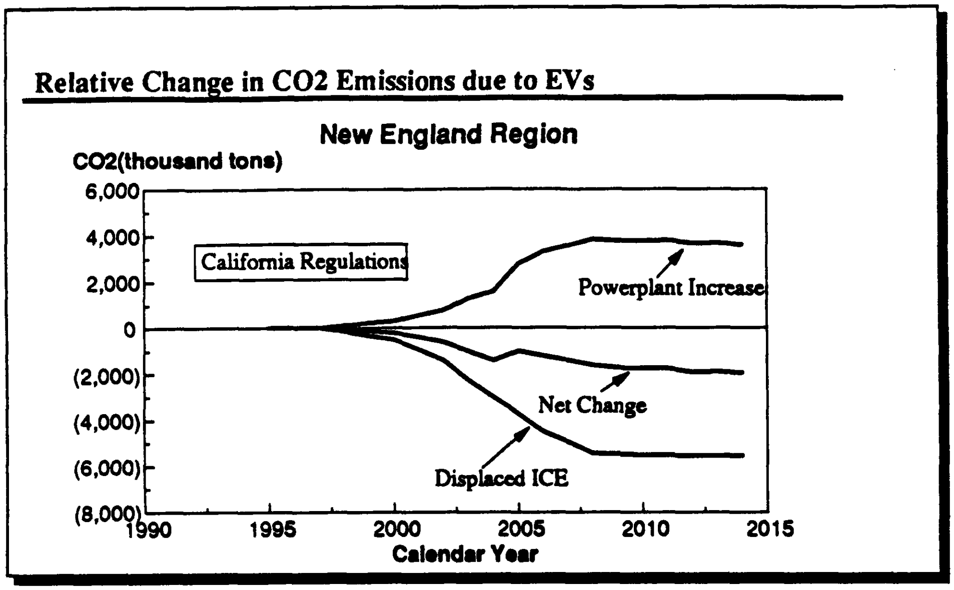

Figure 23: Relative Change in CO_2 Emissions due to EVs.

EVs are expected to reduce CO_2 emissions. However, as will be further discussed in Section 7.2, the results, especially in the case of CO_2, are quite sensitive on the assumption made about the mix of the EV fleet (passenger cars vs. fleet vehicles and trucks) and the efficiencies associated with the vehicle use and recharging. Finally, Figure 24 summarizes the "Net Change" lines for all pollutant categories. Emissions are expected to be reduced relative to the "no EV" scenario for all pollutants except sulfur oxides. The emissions reductions vary, however. Hence, determining the relative importance of the various pollutant categories becomes crucial in assessing the overall effectiveness of EV mandates.

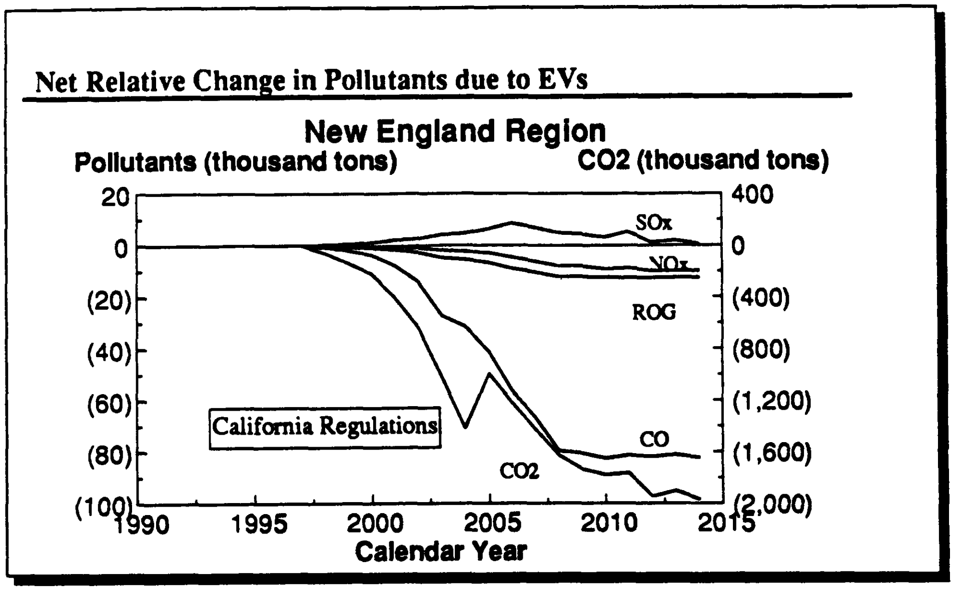

Figure 24: Net Relative Change in Pollutants due to EVs.

7.2 Discussion of Results - Conclusions

The emissions results that have been presented raise some important issues that will be addressed in this section of the study:

1. Modeling Uncertainties / Considerations:

- The make-up of the EV fleet is important (passenger cars vs. fleet & truck vehicles) as it affects the distribution and magnitude of MW and GWh impacts. For example, trucks are less energy efficient and are driven more miles than, say, a passenger car used for commuting purposes. For the results that have been presented the population breakdown is the following: 13.3% passenger cars, 26.6% fleet cars and 60% fleet trucks. This breakdown is consistent with the industry wide belief that initial sales will be largely fleet oriented.

- The severe peaks and troughs in the graphs are usually associated with fluctuations in fuel prices. Changes in fuel prices affect the dispatch of additional kWh. Emissions are therefore highly sensitive to the relative prices of various fuels, especially for the fossil intermediate units (typically, coal, gas and oil units) used to meet the additional electric vehicle demand. If, for example, the natural gas price goes up, then utilities will substitute towards using more of their coal plants, thereby increasing emissions. Moreover, retirement of "dirtier" units also accounts for some of the discontinuities in the emissions figures.
- Improvements in emissions reductions are both a result of changes on the generation side ("cleanness" of powerplants) and improvements on the vehicle's energy efficiency (electricity consumption in kWh/mi).
- The issue of whether the EPA Mobile 5a model underestimates emissions is a controversial one. [McRae, 1995] There have been many publications discussing the accuracy of the models. [Fox, 1994] [Auto/Oil Air Quality Improvement Research Program, 1995] If however, it is true that the model underestimates ICE emissions, then the emissions benefits associated with EV use would be greater as EVs would replace essentially "dirtier" vehicles than the ones the model assumes.

2. *Ozone:* Additions to the natural ozone present in the troposphere are a result of chemical processes such as those in photochemical smog, and of direct ozone transport from urban centers. Photochemical smog is the designation given to the particular mixture of reactants and products that exists when hydrocarbons and oxides of nitrogen occur together in an atmosphere in the presence of sunlight. Hydrocarbons usually occur with oxides of nitrogen in an urban atmosphere since a major fraction of each results from the same type of source, namely motor vehicles. Irradiation of air containing hydrocarbons and oxides of nitrogen leads to oxidation of NO to NO_2, oxidation of hydrocarbons, and finally formation of ozone. [Seinfeld, 1986]

The formation of ozone by its two precursors, nitrogen oxides and hydrocarbons, is non linear. [Seinfeld, 1986] Figure 25 describes qualitatively the implications of these non linearities for the effectiveness and appropriateness of EV policy.

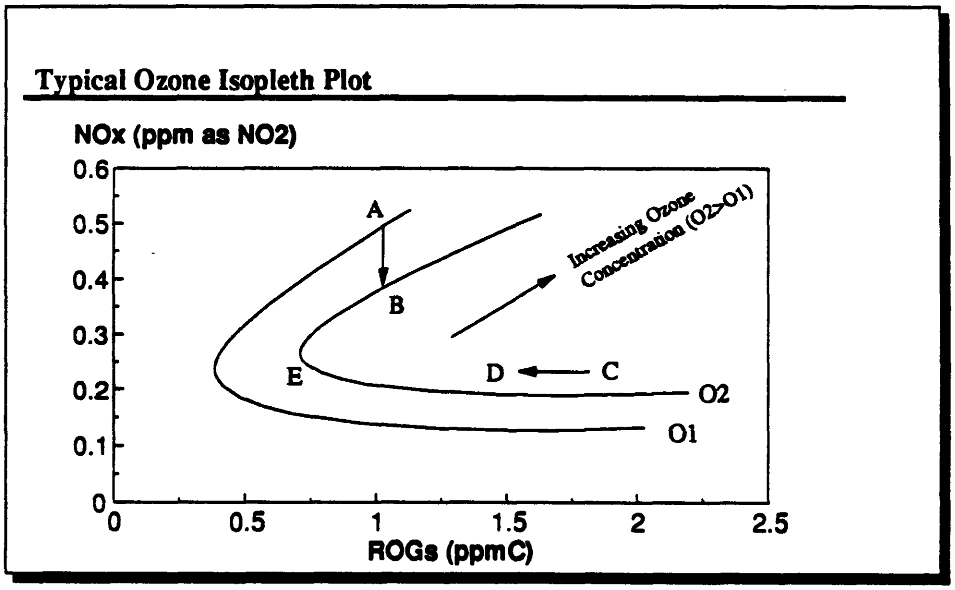

Figure 25: Typical Ozone Isopleth Plot.

Ozone concentration is plotted as a function of the concentration of ozone precursors. The two lines that have been plotted are iso-ozone lines. Hence, at any point on each line, ozone concentration is constant. Furthermore, line "O2" is associated with a higher ozone concentration than line "O1".

Figure 25 challenges the assumption that reductions in pollutants are always beneficial. Consider for example an urban community with ozone precursor concentrations A. The implementation of a NOx reduction policy would result in moving from point A to point B. Point B however is associated with a higher ozone concentration, a quite counterintuitive result. Furthermore, consider another urban region associated with ozone precursor concentrations C. The implementation of a ROG emissions control policy thereby "moving" the region from C to D would be completely ineffective in reducing ozone concentrations as points D and C belong to the same iso-ozone line.

In other words, the a priori concentrations of ozone precursors are very critical in determining the most effective policy for ozone control. Analysts have argued that the Los Angeles basin has ozone precursor concentrations very similar to point E in Figure 25. [Connors, 1995] For such a point near the knee of the iso-ozone curve, NOx and ROG reduction policies are likely to be equally effective in reducing ozone concentrations. The New England Region's a priori position on the ozone isopleth plot is similar to point D on Figure 25's plot. [Connors, 1995] As has been already indicated, a ROG control policy would not make a lot of environmental sense. Hence, policies concentrating on aggressive NOx reductions such as the NOx controls on stationary sources might be much more effective in reducing ozone than say electric vehicles that moderately reduce both precursors.

The above discussion has been made in order to illustrate the complexity of atmospheric chemistry by showing that "less is better" is not always true. Furthermore, as far as ozone reduction for the New England Region is concerned, ROGs reduction might be completely irrelevant. An assessment of the relative importance of the different pollutants is therefore necessary in order to accurately valuate the effectiveness of a particular policy. This thesis however only concentrates on inventory emissions analysis. A discussion of pollutant impacts and human health effects is beyond the scope of this study.

3. Percentage Magnitude of Emissions Reductions: Establishing the percentage magnitude of emissions reductions is not an easy task. The reason for this is that the annual releases into the atmosphere are very difficult to measure. Furthermore, accurately determining the percentage of the total emissions accounted for by the transportation system is even more difficult. For the purposes of this study, a very rough calculation was made to determine the percentage reduction in emissions caused by EVs. This calculation was made for the year 2014[14] where the EV fleet and therefore the annual emissions benefits within the modeling time frame will be at their maximum. The basic assumptions for the calculation have been the following:

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[14] last year in the modeling results that have been presented.

- In year 2014, the combined passenger car and truck registrations will be twice the equivalent 1992 number. This inherently assumes a 3.2% annual growth in passenger car and truck registrations.
- The annual mileage for both passenger cars and trucks is 10,000 miles.
- Tier I light duty car emissions rates are considered representative of the average emissions performance of a typical car in the 2014 fleet. This assumption will be revisited in the discussion that follows.

Table 18 summarizes the results of the calculations for NMOGs, CO and NOx.

Table 18: ***Percentage Reduction in Emissions due to EVs in 2014***

	Tier I Emissions Rates (g/mi)	Motor Vehicle Pollutant Releases (thousand tons)	EV Pollutant Reductions (thousand tons)	"Optimistic" Percentage Reduction (%)	"Realistic" Percentage Reduction (%)
CO	3.4	623.2	82.3	13.2	4.4
NOx	0.4	73.3	9.8	13.4	4.5
NMOG	0.25	45.8	12.6	27.5	9.1

The "optimistic" scenario presented in Table 18 is the best case scenario for EVs primarily as a result of the third basic assumption of the calculation. The actual average emission rates for a typical (not new) vehicle in the year 2014 fleet are likely to be considerably higher than the equivalent Tier I light duty car rates because of deterioration in emissions performance, tampering, and existence of gross polluters. Moreover, vans and trucks are associated with much higher emissions rates . The motor vehicle pollutant releases would therefore be higher resulting in lower percentage reductions associated with EVs. If for example, the average emissions rates are three times higher than Tier I, then the associated percentage reductions for CO, NOx and NMOG would be 4.4, 4.5 and 9.1 percent respectively. Finally, considering only the "best" year within the modeling period is also biased towards EVs.

In conclusion, even under the most favorable assumptions for EVs, the expected emissions reductions are moderate, if not small. This conclusion is very important, especially if one considers the cost premiums that have to be borne. This leads back to the central problem that this thesis tries to address: Are there other alternatives that are more cost effective in addressing the same concerns with the EVs? In other words, are the technology forcing EV mandates justifiable and appropriate?

8. Alternative Fuel Vehicles

In Chapters 5-7, the economic and environmental consequences of developing and using EVs have been assessed. However, one cannot determine whether the ZEV technology-forcing policy is justifiable without considering the other alternatives that have been proposed for addressing the same concerns. In this chapter, both economic and emissions comparisons will be presented in order to assess the cost effectiveness of the various alternatives.

This study inherently assumes that air pollution is a problem that needs to be addressed. In other words, no attempt has been made in determining whether the current state of environmental regulations is "adequate." Such an analysis would require an assessment of the human and biodiversity impacts of air pollution, and a subsequent comparison of these impacts to other risks that human beings and the environment are faced with. Such an assessment however, is beyond the scope of this thesis.

Moreover, as has already been discussed in Chapter 1, this thesis concentrates on the advanced automotive technologies and alternative fuel options. In other words, solutions such as enhanced inspection & maintenance programs and old vehicle scrappage programs are not being considered. Hence, this chapter examines the implications of switching from the current ICE technology, to an advanced, "cleaner" automotive technology.

The problem that this chapter addresses can therefore be stated as follows: "Assuming that air quality has to be enhanced and that the available societal resources for doing so are limited, how do the various technical alternatives compare on a cost-effectiveness basis?"

The analysis of the alternative fuel technologies has been based on the results of publicly available studies and on an industry survey. The published studies, which combined both experimental and modeling approaches to the problem, served to clarify the emissions impacts of the alternative fuel vehicles (AFVs). The examined studies are listed below:

- Clean Fleet Project; *Experimental* [Clean Fleet, 1994]
- Comparison of Fuel Cycle Emissions for Electric Vehicle and Ultralow Emissions Natural Gas Vehicle; *Modeling* [Darrow, 1994]
- What's the Charge? : Estimating the Emissions Benefits of Electric Vehicles in Southern California; *Modeling* [Chapman, 1994]
- Volvo; *Experimental* [Agnetun, 1993]
- SAE Study; *Experimental* [Hellman, 1994]

In order to assess the economic implications, people involved in the development of such technologies in the major OEMs have been contacted. Moreover, the Department of Energy (DOE) provided information regarding fuel prices.

Hybrid vehicle technologies have not been considered in this thesis, although they may in the medium or long run prove to be a very promising alternative in reducing emissions and improving the transportation sector's energy efficiency. Research and development in the area of hybrid vehicles has been enhanced under the Partnership for the Next Generation of Vehicles (PNGV) which has set a goal of mass producing a vehicle having a fuel efficiency of at least 80 mi/gal at an affordable price. However, such technologies are currently in their very early research and development stages under PNGV. Furthermore, some of the demonstration vehicles that have been manufactured, Volvo's Concept Car being one example, are presently at the prototype stage of development. Their manufacturers have therefore not given extensive consideration to mass production issues, nor have they conducted extensive emissions testing. Finally, a "hybrid" design can be associated with many different configurations and fuels. The heat engine can burn almost any fuel and therefore the environmental consequences of hybrids are fuel specific and therefore not generic. Also, a series configuration poses different design challenges than a parallel configuration. In a series configuration, an electric motor provides the torque to the wheels and therefore the vehicle is equipped with fully electric drive. The thermal engine powers a generator. Depending on the vehicle mission, the electric energy produced by this generator can be either used for recharging the batteries or for supplying energy directly to the motor. Alternatively, in a parallel configuration, the vehicle is equipped with two drive systems. The torque to the wheel can be supplied by either the thermal engine or the electric motor, separately or together.

For all these reasons, assessing their economic and environmental implications at this very early stage of development is very hard and would very likely be inaccurate. Hence, hybrid vehicle technologies have been disregarded for the purposes of this study.

In Sections 8.1 & 8.2 of this chapter, the major results of the first two of the studies that have been considered will be presented along with the findings of the cost survey. These studies have been selected since in the author's view, they provide interesting insight into the "clean car" debate and help illustrate most of the major issues and concerns associated with the development and use of such innovative technologies. Moreover, both studies compare the effectiveness of alternative technologies. Finally, by presenting both a modeling and an experimental approach, the conclusions that will be drawn are likely to be more robust.

8.1 Clean Fleet Project: *Cost Effectiveness Comparisons*

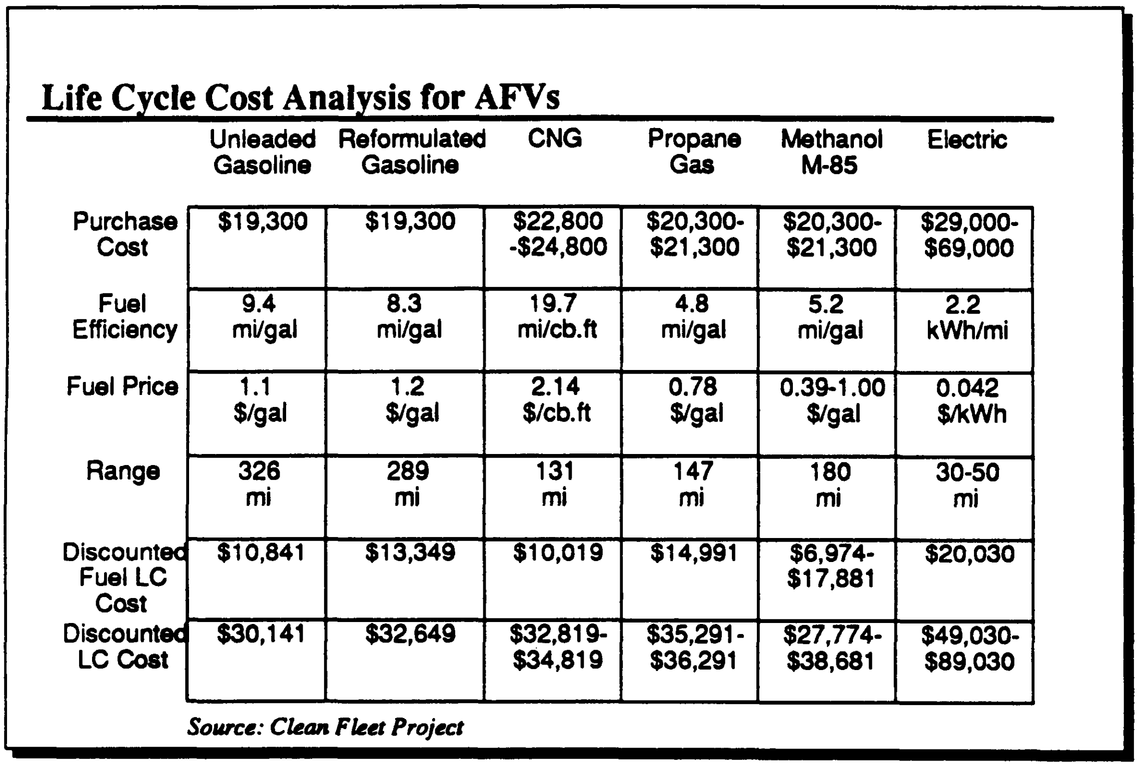
The Clean Fleet Project has been the most comprehensive side by side evaluation of alternative motor fuels that has been carried out so far. The Big Three US automobile manufacturers provided Federal Express with 111 alternatively fueled vans. The five alternative fuels tested throughout a two year long period were: California Phase 2 reformulated gasoline, methanol (M-85), compressed natural gas, propane gas and electricity. Unleaded gasoline has been the control fuel. Federal Express used these AFVs in its daily operations in the Los Angeles basin. The $16 million project was funded by a private-public consortium of 19 sponsoring agencies and companies. Data corresponding to more than three million of miles delivering packages for FedEx were collected in a two year period. Information was gathered on eight topics; (1) tailpipe and evaporative emissions, (2) fuel economy, (3) driving range, (4) performance, (5) fleet economics, (6) maintenance and durability, (7) infrastructure needs and (8) safety.

The main advantage of considering such an experimental approach to the problem of evaluating alternative fuel technologies is that a "real world" test of AFVs is likely to yield the most realistic results regarding their feasibility. The obvious drawback is that, as the vehicles become optimized for alternative fuel use, emissions and performance can be expected to improve considerably over those presented. However, since this study will be primarily used to compare the different technologies relative to each other rather than in absolute terms, a study that is representative of the current "state of the shelf" AFV technology is a choice likely to yield realistic results.

Life Cycle Cost Comparison

Figure 26 shows the life cycle cost results for the control fuel and the five alternative fuel technologies that have been evaluated. The base case van used for the cost calculations is the Ford Econline van which can be bought for $19,300 as an ICE van. Based on the results of the cost survey, the premiums associated with each technology were added to the base case price of $19,300.

The cost ranges shown for most of the alternatives reflect the cost uncertainty related to each of the alternatives. Chapters 6 & 7 indicated that the cost of developing and using EVs cannot be determined with certainty. In fact, the cost varies considerably with battery technology, performance goals, production volume and vehicle design philosophy (purpose built vs. conversions). As shown in Figure 26, both purchase cost and cost uncertainty vary significantly with technology. Compressed Natural Gas (CNG) vehicles are expected to cost $3,500 - $5,500 more than the base case van. On the other hand, vans burning Reformulated Gasoline will cost the same to purchase as the base case van. Methanol and propane vehicles are expected to cost $2,000-$3,000 more relative to the ICE van. Finally, the cost premium estimates for electric vans have ranged from $10,000-50,000 or even higher. For example, a representative of one of the leading battery manufacturers recently revealed that the cost for a fully equipped (air conditioning, power steering, audio system, etc.) 70 mile Dodge TE Van conversion exceeded $120,000, of which the Nickel Iron battery pack accounted for approximately $60,000.



Life Cycle Cost Analysis for AFVs

	Unleaded Gasoline	Reformulated Gasoline	CNG	Propane Gas	Methanol M-85	Electric
Purchase Cost	$19,300	$19,300	$22,800 -$24,800	$20,300- $21,300	$20,300- $21,300	$29,000- $69,000
Fuel Efficiency	9.4 mi/gal	8.3 mi/gal	19.7 mi/cb.ft	4.8 mi/gal	5.2 mi/gal	2.2 kWh/mi
Fuel Price	1.1 $/gal	1.2 $/gal	2.14 $/cb.ft	0.78 $/gal	0.39-1.00 $/gal	0.042 $/kWh
Range	326 mi	289 mi	131 mi	147 mi	180 mi	30-50 mi
Discounted Fuel LC Cost	$10,841	$13,349	$10,019	$14,991	$6,974- $17,881	$20,030
Discounted LC Cost	$30,141	$32,649	$32,819- $34,819	$35,291- $36,291	$27,774- $38,681	$49,030- $89,030

Source: Clean Fleet Project

Figure 26: Life Cycle Cost Analysis for AFVs.

The fuel efficiency results that are shown on the second line of the table in Figure 26 were taken directly from the fuel economy reports of the Clean Fleet Project. The fuel prices were provided by DOE. [US Energy Information Administration, 1995] In the case of CNG vehicles, the pressure of the compressed gas was assumed to be 3,000 psi. The range capabilities of the different technologies were also measured in actual FedEx routes.

Based on the fuel efficiency and fuel price information, the discounted life cycle fuel cost related to each technology was calculated. A 10% discount rate and a vehicle life of 12.5 years were assumed. The annual mileage for all technologies, except for electric, was assumed to be 10,000 miles. In the case of EVs, the annual mileage fell to 8,000 due to range limitations. Finally, the discounted life cycle cost was defined as follows:

Discounted Life Cycle Cost = Purchase Cost + Discounted Fuel Cost[15]

All other cost components of the use phase, such as maintenance, insurance and registration costs, have been disregarded for the reasons that have already been discussed in Chapter 5 of this document.

The van burning unleaded gasoline is associated with the lowest life cycle cost - $30,141. If reformulated gasoline is used instead, then the life cycle cost increases by $2,508 due

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[15] In the case of EVs the fuel cost includes both the electricity cost due to vehicle recharging and the battery replacement cost, a result of battery longevity being smaller than vehicle life.

to the fuel's higher price and the vehicle's lower fuel efficiency. CNG vehicles, on the other hand, have a lower fuel cost when compared to the base case. Hence, due to their lower than the base case fuel cost, the life cycle cost premium for CNG vehicles is reduced to $2,678-$4,678 compared to a $3,500-$5,500 cost premium related to the vehicle's purchase. Although cheaper to purchase than CNG vehicles, propane fueled vehicles are significantly more expensive to use, resulting in a total life cycle cost ranging from $35,291 to $36,291.

Methanol is a quite interesting case. Presently, the price for this fuel is 39 cents per gallon. With such a price, the life cycle cost of $27,774 is lower than the base case gasoline fueled vehicle. The reasons that M-85 is not in widespread use are twofold. First, methanol is used by both the chemical and fuel industries. Therefore, the fuel price is highly volatile as it responds to fluctuations in both the fuel and the chemical market. Second, the M-85 fueled vehicles emitted 5.5 times more formaldehyde than the base case unleaded gasoline vehicle case. Formaldehyde is an air toxic regulated by the EPA.

Finally, not surprisingly, EVs are associated with the higher life cycle cost. Equally importantly, the uncertainty related to the life cycle cost is very large. Actually, the life cycle cost for the EV van is expected to range from $49,030 -$89,030.

Tailpipe Emissions Comparison

Table 19 exhibits the applicable exhaust emissions standards for the results that will be presented.

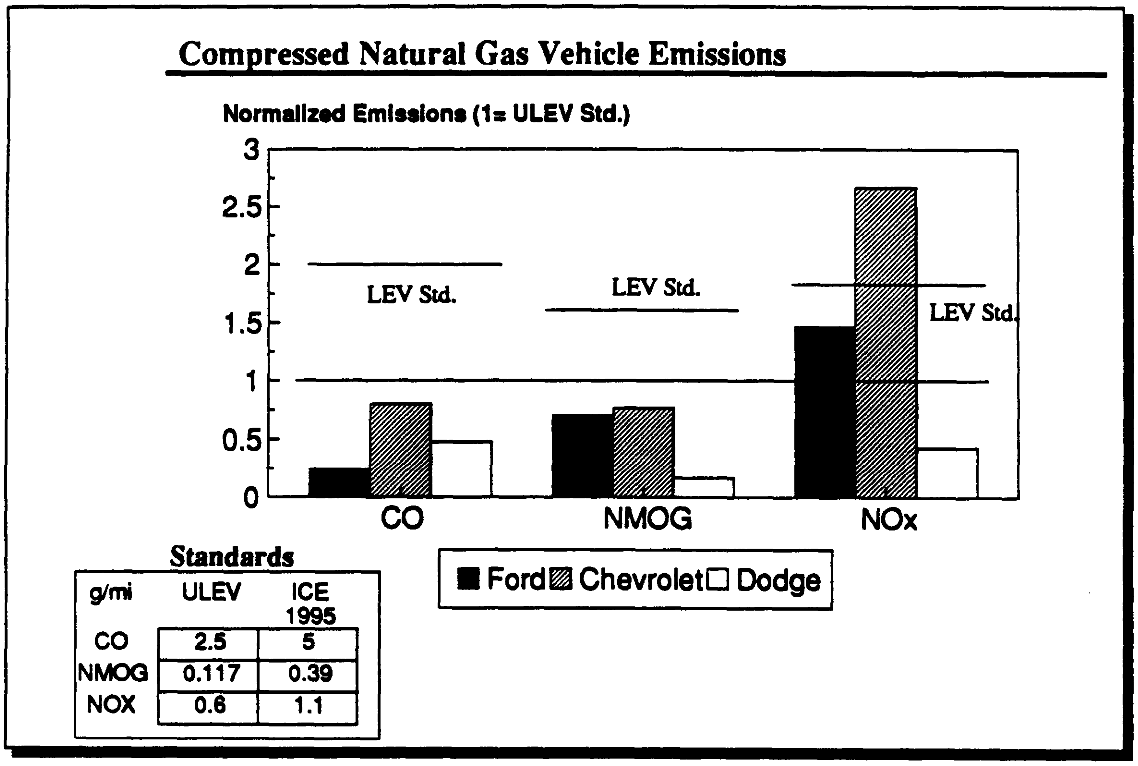
Table 19: ***California Exhaust Emissions Standards for Medium-Duty Vehicles***

Standards[1]	NMOG (g/mi)	CO (g/mi)	NOx (g/mi)
1995 + Conventional and Methanol	0.39	5	1.1
LEV	0.195	5	1.1
ULEV	0.117	2.5	0.6

[1] 50,000 mile standards for vehicle weights in the 5,751-8,500 lbs range.

Source: [Clean Fleet Project, 1994]

Figures 27-31 show the normalized exhaust emissions results for the four alternative technologies and the base case unleaded gasoline burning vehicles. The emissions results are also tabulated following Figures 27-31 in Table 20. Electric vehicles have zero emissions at the tailpipe. The impact of the powerplant emissions due to vehicle recharging will be assessed in the next section of this chapter where cost effectiveness issues will be discussed. The pollutant categories considered are Carbon Monoxide (CO), Non Methane Organic Gases (NMOG), and Nitrogen Oxides (NOx). The emissions rates are normalized with respect to the Ultra Low Emission Vehicle (ULEV) standard defined under the California Low Emission Vehicle Program. In other words, a normalized emission rate equal to 1 exactly corresponds to the ULEV standard. Similarly, a normalized emission rate equal to two implies that the emission rates for a particular vehicle were twice the ULEV standard. The box at the lower left hand corner of each Figure shows the ULEV standard in g/mi together with the corresponding conventional vehicle standards for 1995. In addition, the normalized Low Emission Vehicle (LEV) Standard for each pollutant category is also exhibited. It should finally be noted that the higher emission rates associated with the Chevrolet van are due to the fact that the provided van is certified under heavy duty standards. As Table 19 shows, the medium duty standards that apply to the Ford and Chrysler van were used as the normalizing basis for the figures.

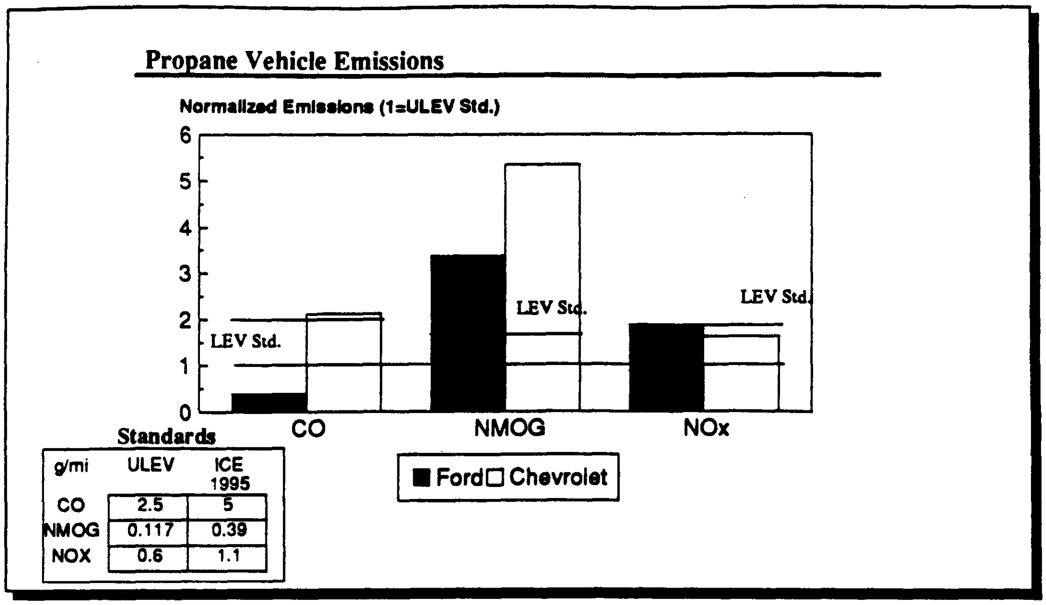


Standards

g/mi	ULEV	ICE 1995
CO	2.5	5
NMOG	0.117	0.39
NOX	0.6	1.1

Figure 27: Compressed Natural Gas Vehicle Emissions.

Source: [Clean Fleet Project, 1994]

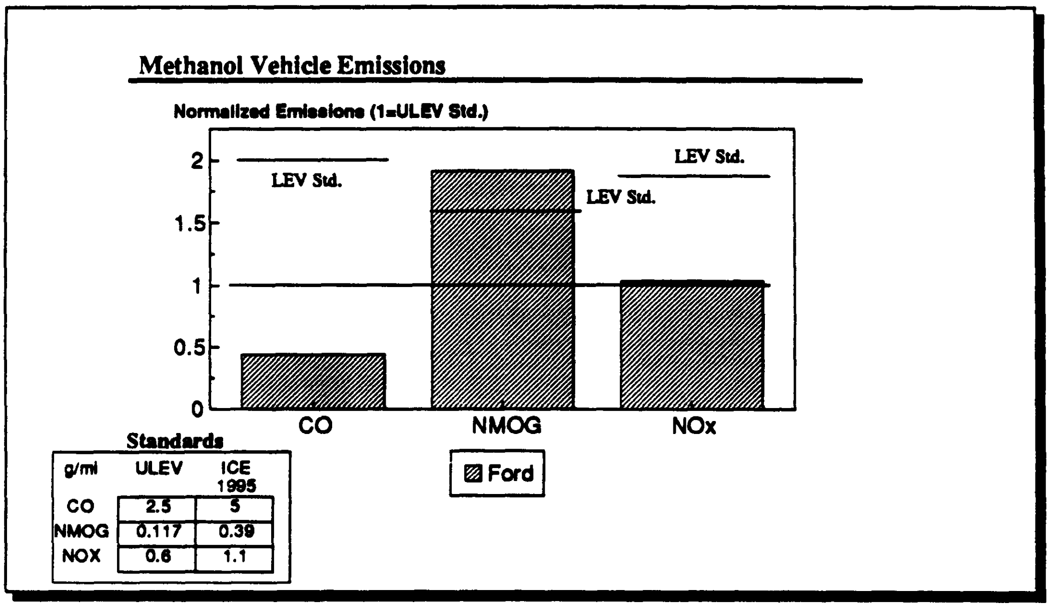


Standards

g/mi	ULEV	ICE 1995
CO	2.5	5
NMOG	0.117	0.39
NOX	0.6	1.1

Figure 28: Propane Vehicle Emissions.

Source: [Clean Fleet Project, 1994]

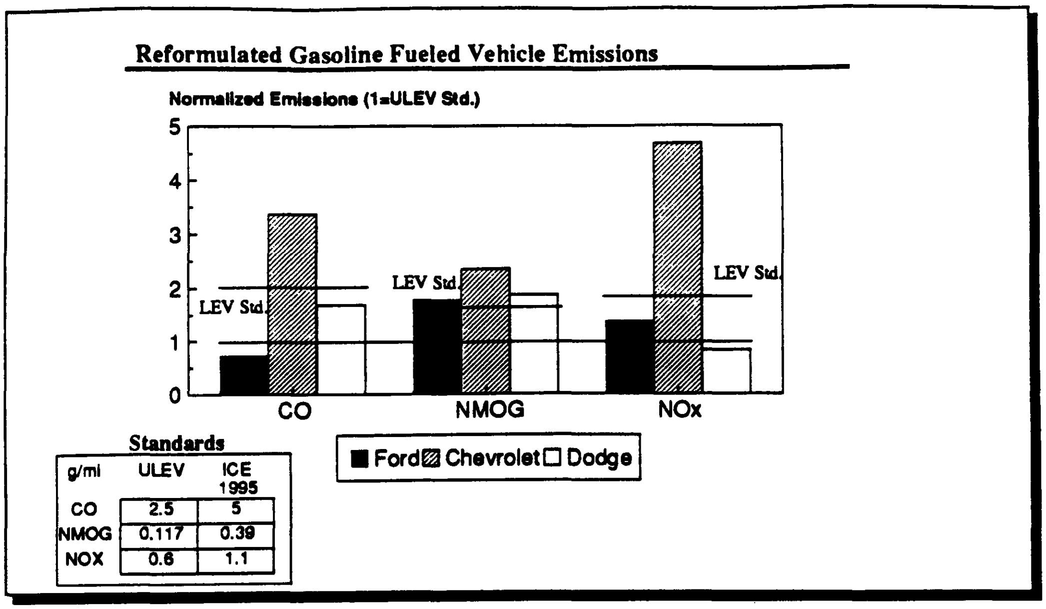


Standards

g/mi	ULEV	ICE 1995
CO	2.5	5
NMOG	0.117	0.39
NOX	0.6	1.1

Figure 29: Methanol Vehicle Emissions.

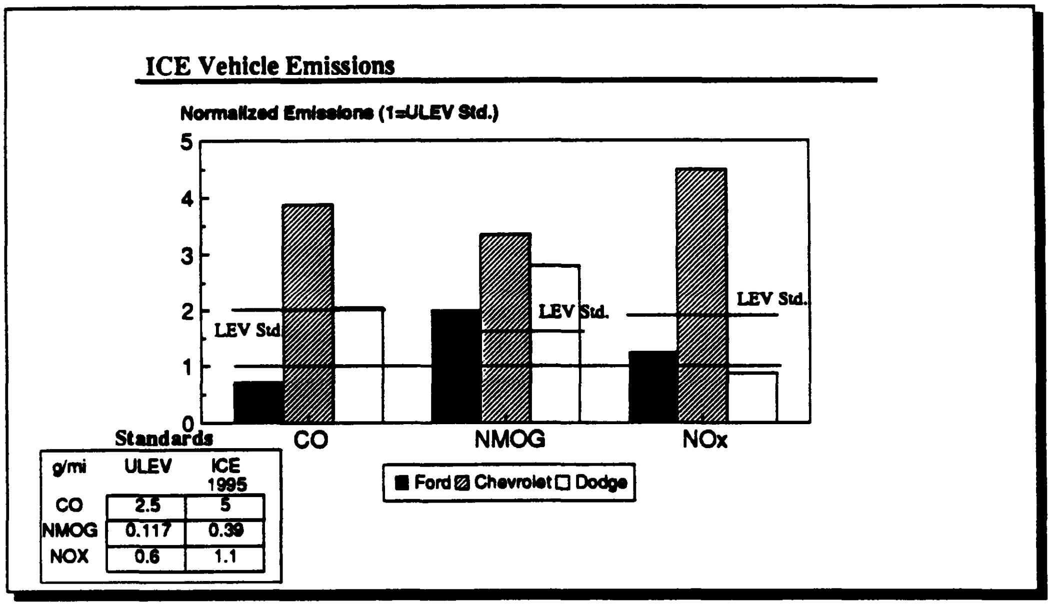
Source: [Clean Fleet Project, 1994]



g/mi	ULEV	ICE 1995
CO	2.5	5
NMOG	0.117	0.39
NOX	0.6	1.1

Figure 30: Reformulated Gasoline Fueled Vehicle Emissions.

Source: [Clean Fleet Project, 1994]



g/mi	ULEV	ICE 1995
CO	2.5	5
NMOG	0.117	0.39
NOX	0.6	1.1

Figure 31: ICE Vehicle Emissions.

Source: [Clean Fleet Project, 1994]

Table 20: *Normalized Emissions Results*[16]

OEM	Fuel	CO	NMOG	NOx
Chevrolet	CNG	0.8	0.769	2.666
	Propane Gas	2.12	5.34	1.63
	RFG	3.36	2.342	4.666
	Unleaded Gasoline	3.88	3.35	4.5
Dodge	CNG	0.48	0.171	0.433
	RFG	1.68	1.872	0.833
	Unleaded Gasoline	2.04	2.803	0.866
Ford	CNG	0.244	0.709	1.466
	M-85	0.44	1.915	1.033
	Propane Gas	0.396	3.367	1.833
	RFG	0.72	1.77	1.36
	Unleaded Gasoline	0.72	2	1.25

Source: [Clean Fleet Project, 1994].

CNG vehicles perform very satisfactorily as far all three pollutant categories are concerned. In the case of CO and NMOGs, their emissions are lower than the ULEV standard for all three vans provided by the Big Three manufacturers. For NOx however, only the Chrysler van meets the ULEV standard while the Ford van exceeds the ULEV but meets the LEV standard. The Chevrolet van has higher emissions since it is a larger van, certified under heavy duty standards.

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[16] with respect to the ULEV standards.

In the case of propane fueled vehicles, the emissions results are not as good, but still quite satisfactory. The Ford vehicle meets the CO ULEV standard, the NOx LEV standard, but exceeds both standards for NMOGs. The Chevrolet vehicle on the other hand, is very close to the LEV standard for both NOx and CO, but exceeds the NMOG LEV standard by a large margin. The Ford M-85 vehicle performs very well as far as CO and NOx are concerned. The performance for NMOGs is also reasonable since the LEV standard is only exceeded by a small margin.

Vehicles burning reformulated gasoline are also associated with good emissions performance as Figure 30 exhibits. The rates for all three pollutants are very close to the LEV standard, except for the Chevrolet van. For some combinations of pollutants and van types, even the ULEV standard is met. Finally, Figure 31 shows the performance of the base case vehicle with respect to the applicable standards.

The figures that have been presented raise some issues that will be now addressed. In particular:

- Although the results of the project are preliminary, CNG vehicles seem to outperform all alternatives, except for electric in terms of emission rates. The results for the other alternatives are mixed. The rates vary with pollutant category and manufacturer. In some cases, the alternatively fueled vehicles are associated with higher emissions rates than the base case unleaded gasoline vehicle. An example of such a case are the NOx and NMOG emissions of the propane vehicles.

- The AFVs that have been tested are not fully optimized for burning alternative fuels. Hence, one could argue that significant improvements in both fuel efficiency and emissions should be expected. In fact, R&D efforts to improve such technologies are ongoing and advances are being made at a very fast rate. Moreover, the Clean Fleet vans have different levels of optimization across fuels and models. The Clean Fleet vans therefore represent a snapshot in time of the technology that could be demonstrated in commercial applications in 1992.
- Although in this study the emphasis is given on the emitted mass of ozone precursors, what is more pertinent to ozone formation is ozone reactivity. The differences in ozone reactivity of the exhaust emissions from each alternative fuel fleet derive from differences in both the mass of compounds emitted and from their specific reactivity (i.e. ozone reactivity per gram of NMOG). For example, while propane-gas-powered vans emitted the greatest mass of NMOG, the calculated ozone reactivity of propane gas emissions is lower than that of gasoline vans. [Clean Fleet Project, 1994] This is because the reactivity of light end hydrocarbon alkanes is typically much lower than that of mid range hydrocarbons.
- Methane emissions for CNG vehicles were an order of magnitude greater than those of the control vehicle. The emission rates vary from a factor of 7 on Dodge vehicles to a factor of 36 on the Chevrolets. The only fuel for which methane emissions were significantly lower than the control vehicle was M-85. Hence, if the exhaust emissions of total[17] hydrocarbons are compared among the technologies, one would expect CNG vehicles to perform a lot worse than if only NMOGs are

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[17] including methane

considered. Table 21 emphasizes this point by presenting the total hydrocarbon and NMOG comparative results by fuel and OEM.

Table 21: *Exhaust Emissions of Total Hydrocarbons*

OEM	Fuel	Total Hydrocarbons g/mi	NMOG g/mi
Chevrolet	CNG	2.12	0.09
	Propane Gas	0.61	0.625
	RFG	0.35	0.274
	Unleaded Gasoline	0.4	0.392
Dodge	CNG	0.55	0.02
	RFG	0.29	0.219
	Unleaded Gasoline	0.44	0.328
Ford	CNG	2.12	0.083
	M-85	0.18	0.224
	Propane Gas	0.52	0.394
	RFG	0.32	0.208
	Unleaded Gasoline	0.35	0.234

Source: [Clean Fleet Project, 1994]

- Finally, it should be noted that, although the alternatives will be eventually compared against each other in terms of emissions benefits and life cycle costs, the vehicle performance is not identical across the technologies. The fourth line in Figure 26 showing the range capabilities of each technology clearly illustrates this point. The mileage autonomy of the control vehicle is 326 miles. Electric vehicles on the other hand need to be recharged every 30 to 50 miles, with all other alternatives falling in between. These differences in performance have considerable implications about the infrastructure that would be necessary to support the refueling of each of the alternatives.

Cost Effectiveness

The five alternatives can be compared on a cost effectiveness basis by combining the economic and emissions results that have been presented (Figures 26-31). The cost effectiveness measure that has been used for the comparisons is defined as follows:

Cost Effectiveness = Life cycle cost premium per kg reduction in life cycle tailpipe emissions[18]

Hence, the smaller the "cost effectiveness measure" is, the more cost effective a particular technology is. The assumptions for calculating the life cycle emissions reductions have been the following:

- The annual mileage for all technologies except for EVs has been assumed to be 10,000 mi. In the case of EVs, an annual mileage of 8,000 miles was assumed due to their performance limitations. The vehicle life has been assumed as being 12.5 years.
- The recharging emission rates for the medium duty electric vans have been generated from the EGEAS powerplant simulation model and from the results of publicly available studies. [Darrow, 1995] [Chapman, 1994]

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[18] emissions benefits and cost premiums are measured with respect to the control vehicle burning unleaded gasoline.

- One-for-one substitution between AFVs and ICEs has been assumed[19]. In other words, an AFV replaces an ICE and is used in exactly the same manner as the ICE. This assumption may be optimistic for AFVs due to their performance limitations. As has been indicated, the range capabilities of the different alternatives vary considerably. Hence, it is very likely that the scope of AFV operations will be limited, thereby resulting in fleet size increases and therefore reduced cost effectiveness. In other words, these are best case estimates of cost effectiveness.

Figure 32 exhibits the results of the cost effectiveness analysis. The emissions benefits and cost premiums vary considerably among the technologies leading to significant differences in cost effectiveness. Electric vehicles yield the highest emissions benefits. At the same time the associated life cycle cost premium is by far the highest. The resulting cost effectiveness ratios also turn out to be high, especially in the case of NOx and ROGs. This observation raises the following question: Are there other alternatives that are more cost competitive yet still yield considerable emissions reductions? Figure 32 shows that the answer to the above question is affirmative. CNG vehicles are much more cost effective, i.e. a smaller amount of money needs to be spent to reduce tailpipe emissions by a kg over the base case van. In fact, CNG vehicles are 12.5 times more cost effective in reducing NOx emissions, 4 times more cost effective in reducing NMOGs and 1.4 times more cost effective in reducing CO when compared to EVs. If total hydrocarbons are used instead, then CNG vehicles will result in increased emissions over the base case as shown in Table 21.

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[19] except in the case of EVs were 1.25 EVs are required to replace one ICE as EVs are driven 8,000 mi/year compared to the 10,000 mi/year ICE mileage.

Cost-Effectiveness

	Life Cycle Cost Premium	Reduced Emissions CO (kg)	Reduced Emissions NOx (kg)	Reduced Emissions NMOGs (kg)	Premium/ reduced kg of CO	Premium/ reduced kg of NOx	Premium/ reduced kg of NMOGs
CNG	$3,678	488	33	39	**$8**	**$111**	**$94**
Methanol M-85	$3,086	88	16	1.5	**$35**	**$193**	**$2,057**
Propane Gas	$5,650	101	Increase	Increase	**$50**	**N/A**	**N/A**
RFG	$2,508	113	3	14	**$22**	**$836**	**$179**
Electric	$48,611	4,328	35	127	**$11**	**$1,389**	**$383**

Figure 32: Cost-Effectiveness.

The results for the other alternatives are mixed. Use of propane as the transportation fuel could lead to the counterintuitive result of increasing the ozone precursor emissions. When the vans are optimized for burning propane, minor ozone precursor emissions decreases over the base case can be expected. M-85 fueled vehicles are quite cost effective for reducing CO and NOx. However, they are particularly cost ineffective in reducing NMOGs. Furthermore, their very high formaldehyde releases impose an additional problem limiting their attractiveness as a transportation fuel. Finally, reformulated gasoline performs well on a cost effectiveness basis for all pollutant categories and is probably the second best (following CNG vehicles) option.

The performance limitations of AFVs may result in lower than one-for-one substitution between AFVs and ICEs. In other words, more than one AFV will be required in order to perform the daily operations of the replaced ICE. If, for example, 2 propane gas fueled vehicles are required to replace one ICE, then the corresponding cost effectiveness metric will be doubled. Due to their low range capabilities (30-50 miles), EVs are the technology for which this assumption is weakest. Hence, the cost effectiveness metrics presented here are probably optimistic.

This preliminary comparative evaluation of the alternatives suggests that, given the current technological limitations, electric vehicle policy is not cost effective and therefore not justifiable on a cost effectiveness basis. CNG vehicles, on the other hand, appear to be much cheaper per reduced kg of tailpipe emissions for all pollutant categories. The differences in cost effectiveness ratios are so large that the results would be the same even with large errors in the measurements of emissions rates. This conclusion undoubtedly challenges the appropriateness of the ZEV mandates. The implications of the results of the cost effectiveness study will be further discussed in Chapter 10 of the thesis.

8.2 Energy International, Inc. Study: *Fuel Cycle Considerations*

One of the major limitations of the emissions results that have been presented is that only exhaust emissions are considered in the evaluation. Emissions associated with producing, refining, generating, refueling and transporting the fuels need to be considered if the environmental consequences of alternative fuel vehicles are to be appraised accurately[20]. All these stages of emissions releases comprise the fuel cycle. The Energy International, Inc. study compares the fuel cycle emissions of electric and compressed natural gas vehicles. In addition, the comparison is performed twice: once for 1993 vehicle technology and also for expected year 2000 technology.

The study was performed for the Los Angeles basin. Hence, the fuel cycle emissions were decomposed into three categories; namely: In Basin, Other California and Out of State. The Ultra Low Emission Vehicle (ULEV) standard is also shown for comparison purposes. In the case of the CNG vehicles the majority of the in basin emissions come from the vehicle's exhaust. The "Out of State" emissions are the result of production, clean-up and transmission of the fuel while the "Other California" emissions include most of the natural gas transmission line compression stations. In the case of EVs, the majority of emissions are powerplant emissions due to vehicle recharging. The electricity fuel cycle consists of the utility combustion emissions and the upstream fuel cycle emissions. Figure 33 portrays the somewhat more complicated natural gas fuel cycle.

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[20] It should be noted here that one of the drawbacks of pursuing a fuel cycle analysis is that the location of atmospheric releases is not taken into account. This drawback does not affect the ozone precursor (NOx & ROG) analysis since ozone is not a local phenomenon. The analysis of greenhouse gases is also not affected by ignoring the locality of emissions. In the case of CO however, locality is important and therefore essentially "adding up" the emissions associated with the various stages of the fuel cycle is not accurate. Urban emissions should not valued equally to, say, powerplant emissions in a non inhabited area. Such an approach however, is definitely better than completely disregarding stages of the fuel cycle.

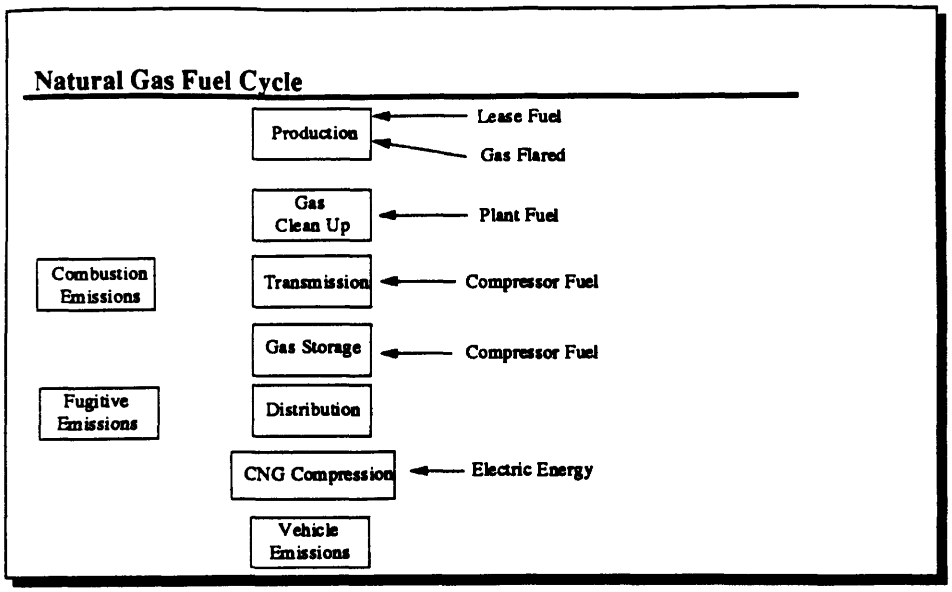

Figure 33. Natural Gas Fuel Cycle

Source: [Darrow, 1994]

Figures 34-36 graphically summarize the results of the study for nitrogen oxides (NOx), carbon monoxide (CO) and reactive organic gases (ROG). In-Basin NOx impacts are lowest for the CNG vehicle. However, for both technologies the in-basin fuel cycle emissions are well below the in-basin ULEV standard. In addition, the total NOx impacts of EVs and CNG vehicles operating in the basin are considerably higher than the in-basin impacts. The CNG vehicle emits lower amounts of NOx than EVs when the full fuel cycle is considered. For the EV, these NOx emissions are being largely produced during coal fired generation across the border.

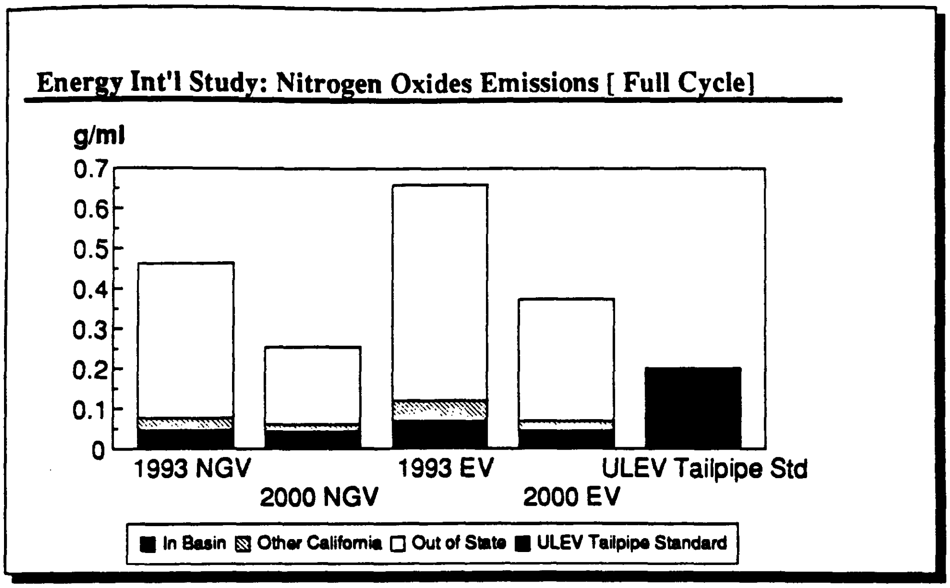

Figure 34: Energy Int'l Study: Nitrogen Oxides Emissions (Full Cycle)

Source: [Darrow, 1994]

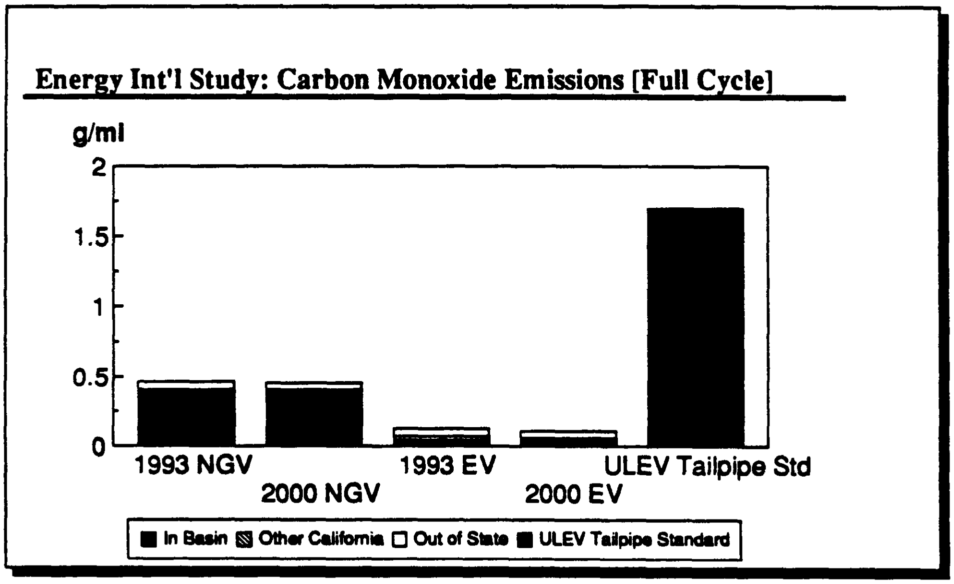

Figure 35: Energy Int'l Study: Carbon Monoxide Emissions (Full Cycle)

Source: [Darrow, 1994]

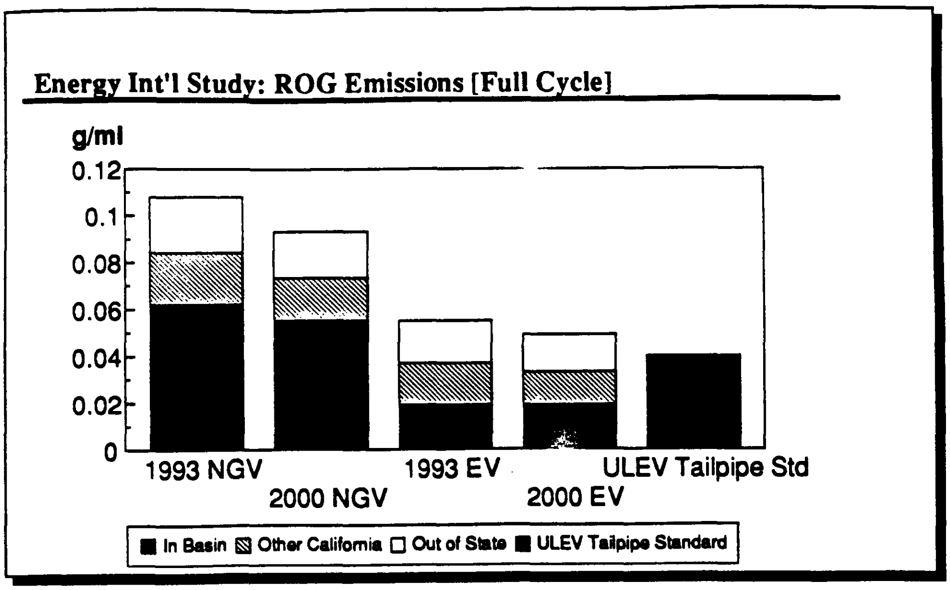

Figure 36: Energy Int'l Study: ROG Emissions (Full Cycle)

Source: [Darrow, 1994]

In the case of CNG vehicles, the "out of basin" impacts are the result of production, clean-up, and transmission outside the state. [Darrow, 1994] CO emissions are predominantly in basin. The emissions associated with EVs are extremely low. CNG vehicle emissions are higher, but still less than a quarter of the ULEV standard.

As far as ROG emissions are concerned, EVs produce lower ROG emissions than CNG vehicles both in the Los Angeles basin and if the total fuel cycle is considered. The in-basin CNG vehicle emissions exceed the ULEV tailpipe standard. However, if an estimate of the evaporative and running losses is added to the tailpipe standard, then the new standard[21] rises to 0.23 and therefore both technologies would emit only a fraction of the ROG emissions of a liquid fueled ULEV. [Darrow, 1994]

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[21] including exhaust, evaporative and running emissions.

It should also be noted here that the results are not reactivity weighed. Most of the CNG fuel cycle ROG emissions are ethane, which has a very low reactivity factor compared to the components of gasoline.

The results that have been presented raise two major interrelated issues that will be now discussed. First, the results of the study show that the emissions benefits of CNG vehicles are comparable to those associated with EVs if the complete fuel cycle is considered. This result is consistent with the findings of the previous case study that was based on the Clean Fleet project. The notion that electric vehicles have the potential of leading to dramatic emissions reductions compared to any other alternative is therefore challenged. Moreover, both technologies are associated with exhaust emission rates that are well below the ULEV tailpipe standards. From a public policy perspective, it is therefore very important to acknowledge the existence of all the alternatives that are capable of producing emission rates between the ULEV and ZEV.

Second, it is even more crucial for the regulatory framework to be flexible enough to allow the development of the most cost competitive of these comparably effective technologies. The current regulatory framework mandates the use of EVs. By defining ZEVs by only considering the vehicle exhaust emissions, more incremental and less costly technologies that are capable of producing vehicles with comparable emissions performance are ignored (e.g. CNG vehicles). Recently, CARB has been considering the possibility of redefining ZEVs so that at least hybrid vehicle technologies can qualify. [Automotive News, June 12, 1995] A broadened and more flexible definition, encouraging the development of all promising vehicle technologies, would lead to more efficient developments from both a technological and an economic standpoint.

9. Industrial Implications of Advanced Technology Vehicles

Having assessed the economic, technical and environmental consequences associated with Advanced Technology Vehicles (ATVs), this chapter examines the industrial implications of their development. Increasingly stringent emissions regulations such as the CAAA of 1990 and the California Emissions regulations have challenged the status quo internal combustion engine paradigm. With the radical changes in vehicle design, performance and function that advanced automotive technologies such as EVs are likely to bring about, some analysts have argued that initiatives such as the ZEV mandates and the PNGV could potentially lead to the emergence of new players in the automobile industry. This chapter examines the likelihood of an industry restructuring taking place.

Despite spending a considerable amount of money lobbying against technology forcing regulations such as the ZEV mandates, the Big Three automobile manufacturers have been conducting significant research and development in the area of advanced automotive technologies, both independently and cooperatively under PNGV. At the same time, entrepreneurial companies such as Solectria have entered the automotive business hoping to capitalize on the market niche created by regulations. Moreover, electronic systems suppliers such as General Electric, AC Delco and Westinghouse have been increasingly interested in the automobile industry. As a result, their automotive departments have been among the fastest growing in the early nineties. Some of the small companies have gone as far as forming partnerships with suppliers in order to take advantage of each company's strengths and expertise and therefore make their entry into the automobile market more likely to succeed. A good example of such a private sector partnership is CALSTART, a non-profit partnership bringing together 120 firms, 8 of which manufacture vehicles. Their objective is to encourage collaboration and competition among the partners in order to speed up innovation in the area of advanced technology vehicles. Besides demonstrating the technology, they have recently focused on attempting to create a full fledged advanced vehicle industry by moving away from demonstration projects and toward the development of the necessary financial and manufacturing capabilities.

Although some of the players mentioned in the previous paragraph believe that electricity based propulsion systems will very soon replace the ICE, the majority of the companies believe that the ATV market is presently regulation driven. [Cimpa, 1995] [Gifford, 1995] A technological breakthrough in battery technology and considerable cost reductions are necessary to make ATVs market driven. However, if such progress were made, the gains for the companies that would be able to capitalize on the opportunities would be overwhelming. Therefore, most of the established manufacturers and suppliers have chosen to pursue a hedging strategy and perform research and development efforts in the field of advanced automotive technologies. However, they do not plan to commit resources to mass production before a reasonable market niche is guaranteed, either through technological improvements or through regulation and considerable cost reductions.

There is no doubt that an electric or hybrid vehicle will be very different both from a design and a functional standpoint. The changes in vehicle motive power, control systems, electronic complexity, vehicle function and vehicle reliability over the ICE vehicle will be radical. These changes definitely create some opportunities for non traditional automotive companies. The critical question however is the following: Are these opportunities large enough and most importantly, can they be best exploited by non conventional manufacturers? If the answer to the above questions is affirmative, then a restructuring and reconfiguration of the automobile industry might take place. If not the experience and competitive advantages of the established OEMs will prevail over the efforts of the new entrants.

If these opportunities are going to lead to a transformation of the automobile industry, then they must be associated with three important characteristics. First, they must be opportunities which can be developed independently of the existing industry, since otherwise they will be coopted by the existing players. For example, Dr. Amory Lovins has suggested that advanced automobiles are technically and economically feasible today using off-the-shelf technologies employed in high-tech industries such as the aerospace and the micro-electronic industries. [Lovins, 1993] Second, they must be opportunities which afford advantages that can be exploited at both low and high production volumes, to enable the new entrants to transition from niche producers to major competitors. Third, they must be opportunities which can either build upon the elements of the existing automobile supplier base, or can easily be used to replace that supplier base. [Field, 1995] The third attribute is especially crucial since the role of automobile suppliers has been expanding considerably in that the industry increasingly relies upon suppliers who sell not only parts, but also design, manufacturing and systems integration capabilities which the automaker decides not to keep in house. [Lamming, 1993] Thus technological superiority has become the most critical area of competition among the suppliers to the automobile industry. OEMs have concentrated their efforts on vehicle design and product assembly and successful coordination of technological developments through the efficient management of their relationships with the suppliers. Hence, new entrants into this industry must choose to woo or supplant the current supplier base in order to compete in the industry. The rest of this chapter examines whether opportunities such as those alluded to in this paragraph do exist.

The increased reliance on suppliers for activities that had been traditionally performed in-house such as systems design, has created a status quo that new entrants will find difficult to overcome successfully. The principal reasons why the current OEM-supplier is quite robust and possesses major competitive advantages over new entrants will be now outlined.

First, the existing automobile industry has amassed considerable experience and expertise in developing and manufacturing automobiles and therefore satisfying the performance needs and economic limitations of consumers. The OEMs will most likely retain the know-how necessary to manufacture automobiles in large production volumes in the most cost effective manner.

Second, the existing automakers have invested in the current marketing and distribution channels. Hence, they will most likely enjoy an advantageous treatment over the new entrants. It would not be surprising if the current producers attempted to maintain their exclusivity on the conventional distribution channels and therefore force the new entrants to seek alternative routes for marketing and distributing their products.

Third, in the area of advanced automotive technologies such as EVs, the established OEMs have been investing significant amounts of money and have built state-of-the-art prototypes that have helped them gain experience and appreciation for the challenges that they need to overcome. Probably, the most sophisticated technology in this area is presently in Detroit, despite the fact that the Big Three have been also spending considerable funds lobbying against the mandated introduction of such technologies. The probability that a new entrant will be able to completely disprove the economic benefits of mass production is very low. Finally, the cooperative nature of the PNGV assures that any technological breakthrough will not be controlled by a single firm. Hence, in the area of advanced vehicle technologies, OEMs are very well positioned from a strategic standpoint over the small size, entrepreneurial firms.

Fourth, the potential new entrants in the supplier and propulsion systems field will have to face the competition of the existing suppliers to the OEMs (e.g. AC Delco, Energy Conversion Devices, Inc.). They must therefore develop technologies that the automakers and system integrators do not have. The suppliers' expanded role in the design, manufacturing and integration of vehicle systems has dramatically increased their technological expertise. Hence, the OEMs are unlikely to miss out on any technological innovation in the area of advanced vehicle technology. But even if they do so, the highly competitive nature of the industry will ensure that their delay in adopting such an innovation will be small unless of course a proprietary, radical breakthrough materializes.

Fifth, these suppliers have been accustomed in working with the automobile industry and recognize the technological requirements implicit in undertaking a mass production effort. Technologies that can accommodate these requirements have proven to be the most cost effective way for producing vehicles.

These advantages associated with the established OEM-supplier relationships lead to the conclusion that a major restructuring of the automobile industry is unlikely. At the same time however, they point out the area of greatest opportunity for the developers of these technologies. Given the automakers' increasing reliance upon suppliers to provide complete vehicle systems, there is no reason to expect that powerplants and powertrains would be exempted from this approach. [Field, 1995] The technological leaders among such firms may very well find that there is considerable demand for such systems. It is very likely that the OEMs will decide that it is more cost effective to purchase drivetrains and install them themselves rather than supplying gliders to the conversion companies. Such a cooperative rather than competitive arrangement would take advantage of the OEM's mass production, marketing, vehicle design and coordination expertise and the ability of advanced technology developers to be technologically flexible to new developments. Advanced technology firms could therefore concentrate their efforts upon the development of advanced powerplants rather than also attempting to learn vehicle design and manufacture. In other words, it seems that the most cost effective arrangement for the successful commercialization of advanced technology vehicles is one where the advanced technology firms would become suppliers to the OEMs which will still be on the driver's seat. Hence, although it is very likely that advanced technology firms will be a considerable part of the development process of advanced technology vehicles, it is probably highly unlikely that new major players will emerge and the industry will be restructured and reconfigured.

10. Discussion & Conclusions

This thesis has shown that the successful development and commercialization of advanced technology vehicles such as electric vehicles is associated with problems and obstacles that seem insurmountable with current technological and manufacturing capabilities. These limitations, coupled with the economic, environmental, industrial, regulatory and market uncertainties, suggest that the ZEV technology forcing sales mandates are a high cost, high risk policy associated with questionable benefits; in short an unjustified policy. While such mandates can lead to increased activity in the area of advanced technology vehicles, there is no assurance that such activity will actually lead to technologically and economically efficient developments.

Electric vehicles are undoubtedly a special case among the advanced technology vehicles due to the Clean Air Act Amendments (CAAA) of 1990 and the California Low Emission Vehicle Program (LEV) that call for their development and sale by 1998. The results presented in Chapters 5 & 6 indicate that battery powered electric vehicles are limited by the current state of technology to restricted specialty applications such as fleets. While the industry can afford to focus upon these markets in the short term, there are real dangers to relying upon these markets in the long term. The vehicle technology must develop to the point that the performance of the product, and the degree of expertise required to employ the product is indistinguishable from conventional technologies. [Field, 1995]

Presently, the major technological limitation for EVs is related to battery technology. Poor battery technology results in performance limitations for the vehicle. Furthermore, attempting to improve the vehicle's performance results in large increases in both battery weight and battery cost. In particular, the major concern is vehicle range, i.e. the distance the vehicle can be driven between recharges. It has been shown that, with presently available lead acid battery technology, battery cost can exceed $4,000-$5,000 for targeted vehicle ranges as low as 50 miles. Simply put, lead acid batteries are very bulky in relation to the amount of energy they can store. Moreover, due to their poor longevity, the batteries presently available need to be replaced as often as every one or two years, depending on the assumed vehicle utilization. If the goals set by USABC for battery capabilities are met, improved battery performance will result in affordable battery packs associated with reasonable vehicle performance.

The total production cost for a two seat, 50 mile range, aluminum intensive electric vehicle has been estimated at $18,000 with presently available technology and at an annual production volume of 20,000 units. The currently expensive drivetrain systems and electronics, together with the cost ineffectiveness of present manufacturing processes, all account for the high production cost of electric vehicles. For EVs to be successful, concomitant with the necessary technological development must be a focus upon manufacturing processes in order to scale the technology to meaningful production volumes in a cost effective manner. The current developers of purpose-built EVs are largely applying manufacturing technologies suited to low production volume applications. These choices are likely to limit these developers in the long term.

It has been argued that the superior energy efficiency of an electric drivetrain will result in lower use costs over a comparable ICE vehicle, thereby reducing the life cycle cost premium associated with EVs. Although it is true that the electricity cost for vehicle recharging might be lower than the equivalent gasoline cost, especially as battery technology advances, the necessary frequent battery replacements challenge the above statement if a comparable utilization in terms of annual mileage is assumed. As a result, the life cycle cost of a "presently available" EV can be as high as three times that of a comparable ICE. Even under the most optimistic scenario for future technology developments where the USABC Long Term goals are met, EVs will cost 65% more than the ICE equivalent. In fact, a gasoline price of 4.87 $/gal would be necessary to bring these life cycle costs into parity. Such a fuel price is currently higher than the gasoline prices prevailing in Europe.

The economic implications of developing and manufacturing EVs are particularly sensitive to the size of the regulated market. At annual production volumes of as low as 4,000-5,000 units, manufacturers will not be able to capitalize on the economic benefits associated with large scale production. Such small production volumes are likely to be typical for a manufacturer such as Ford in the first couple of years of EV introduction in California. If, however, the Northeast states adopt the ZEV California regulations, then the market for EVs will increase substantially, thereby enabling manufacturers to take advantage of economies of scale. The analysis that has been carried out showed that the minimum efficient scale for EV production is at approximately 30,000 units per year, although at this production volume the production cost is still substantially greater than the equivalent ICE alternative.

Perhaps the primary motivation for developing advanced vehicle technologies such as EVs has been their potential for dramatically reducing air pollution. However, Chapter 7 has shown that, even under the most optimistic assumptions, the expected emissions benefits are likely to be moderate. Emissions benefits are expected to lie in the range of 4-14% for most pollutant categories in year 2014, when the EV fleet will be the largest within the modeling period that has been considered. When these small to moderate emissions benefits are coupled to the uncertain environmental implications of the extraction, use, and recovery of materials used in exotic batteries, light weight automobile bodies materials, and complex electrochemical componentry, the environmental appropriateness of electric vehicles becomes questionable.

Enormous uncertainties are associated with almost every aspect of the EV debate. Perhaps the word "uncertain" is the one that best describes the current state of EV development and commercialization. From a technological standpoint, the currently available technology can only support a very limited set of applications. Furthermore, future developments are uncertain. The necessary breakthrough in battery technology may equally likely happen next year, in a decade or even in two decades. Uncertainties on the regulatory front also considerably affect the economies of scale and therefore the production economics of EVs. Finally, from an environmental standpoint, the expected benefits are not very clear, especially if the full fuel cycle and solid waste implications are taken into consideration. When these uncertainties are coupled with the economic burden that an EV mandate places upon the US economy, adopting such an inflexible, technology forcing approach becomes an ill-advised policy decision.

The above argument is further reinforced by the existence of alternative, more cost effective approaches for addressing the same concerns as Chapter 8 has shown. Some of these alternatives are much more competitive with the ICE vehicle from an economic standpoint and at the same time yield somewhat smaller, but comparable, emissions benefits. Not only are alternatives such as Compressed Natural Gas (CNG) vehicles more cost effective with presently available technology but, most importantly, the uncertainties associated with their development and environmental implications are considerably smaller. Moreover, their range capabilities and performance in general are much closer to those associated with conventional technologies.

The presently technologically inadequate and expensive state of EV development, the related present and future uncertainties, and the existence of more cost effective alternatives suggest that the inflexible regulations mandating the development and use of EVs are unreasonable from a technological or an economic standpoint. In principle, the government intervenes into the marketplace and forces the development and use of a particular technology when a considerable societal benefit will be derived from this intervention. Mandating seat belts and air bags to improve safety and requiring automobiles to be equipped with catalytic converters to reduce emissions are examples of such interventions by the government. This thesis has shown that, in the case of EVs, the degree of expected societal benefits is both questionable and uncertain. Moreover, EVs are much less cost effective when compared to other, less exotic technologies. It seems, therefore, that the ZEV regulations that essentially mandate EVs are arbitrary and not based on the results of cost effectiveness or feasibility assessments. In addition to the choice of technology, the time schedule and the choice of market penetration percentages is also unfounded. Hence, the ZEV mandates either represent a not well thought of technology policy or alternatively, they have been brought about in California for reasons not directly related to technology, environmental or transportation policy. However, promoting these other agendas without taking into consideration the huge economic and technological implications of such technology forcing mandates can be very dangerous. This arbitrariness in public policy raises many concerns, especially if one considers the amount of money that has been invested in such an unproven, problematic and high risk technology. The USABC alone will spend $262 million in order to advance battery development. The Department of Energy (DOE), the Defense Department's Advanced Research Project Agency (ARPA), the Electric Power Research Institute (EPRI), the Big Three automobile manufacturers and many other companies, agencies, utilities and laboratories, have all been spending millions in order to successfully develop EVs. The most troubling aspect of the ZEV mandates is that this huge investment has been made for an unproven, costly and risky technology, whose current or potential future superiority has not been demonstrated and whose societal benefits are questionable and uncertain. Within this context, electric vehicle mandates are misguided and erroneous.

Besides the technology choice issue, the inflexibility associated with the ZEV mandates is also ill-advised. Flexibility, which is the hallmark of effective regulation, is required if the environmental challenges are going to be met in a cost effective manner. A flexible regulatory framework encourages innovation where it is most cost-effective. In other words, the regulatory framework should be such that the industry can determine itself the most cost effective way for meeting a given set of environmental standards rather than specifying and subsequently forcing a particular technology.

The major inflexibility of the current ZEV mandates is related to the definition of Zero Emission Vehicles as being vehicles associated with zero emissions at the point of use. With such a definition, all other stages of the full fuel cycle are disregarded. Hence, battery powered electric vehicles are essentially the only technology currently qualifying for ZEV status. As a result, all the alternative technologies that are associated with some emissions at the point of use but yield comparable to EVs emissions if the full fuel cycle is considered, do not meet the ZEV standards. Less costly and more incremental technologies that are capable of producing vehicles with comparable to EV emissions performance are ignored. CNG vehicles are a good example of such a technology.

In addition to the vehicle technology, the time schedule for ZEV introduction is also inflexible. In particular, the ZEV sales mandates require the introduction of electric vehicles in 1998 at 2% of vehicle sales. This percentage increases to 5% in 2001 and 10% in 2003. This time schedule, originally set in 1990, is inflexible to the technological, economic or manufacturing status and feasibility of EVs. According therefore to the regulations, EVs will be introduced into the vehicle fleet no matter what their cost and performance is. The great danger of such an approach is the development of inefficient and ineffective products which must be sold, irrespective of market demand for such products.

From a public policy perspective, it is therefore very important to acknowledge the fact that EVs are essentially emission displacement vehicles rather than zero emission vehicles. In other words, the definition of ZEVs needs to be altered to reflect the contribution of all stages of the fuel cycle. By doing so, all the technical possibilities for vehicles to go well below the ULEV standards would be acknowledged. Such a broadened perspective would enable the manufacturers themselves to select the most cost effective option which may very well at some point in the future be electric vehicle technology despite the fact that it is currently economically and technically risky. In addition, the time schedule for the introduction of advanced technology vehicles ought to be flexible with respect to technological, economic and manufacturing shortcomings or breakthroughs. A reliance upon inflexible sales mandates has the potential to weaken advanced technology vehicles in the long term. In conclusion, a flexible regulatory approach is needed to lead to technologically and economically efficient developments and therefore assure an efficient allocation of societal resources and a cost effective transition of the transportation system to a more environmentally sensitive and energy efficient vehicle technology.

11. Future Work

This thesis has appraised the implications of developing and using electric vehicles. Moreover, the air pollution and economic consequences of electric vehicles have been compared to those associated with other alternative fuel technologies on a cost effectiveness basis. Extensive research and development efforts in the area of advanced automotive technologies result in rapid technological advances. Such advances should be taken into account in any future study to make it as representative and up to date as possible. In addition, there still remain some issues that in the author's view require further investigation.

As far as electric vehicles are concerned, the implications of alternative design strategies for the automobile body should be analyzed. In particular, the economic and vehicle performance implications of material and manufacturing process choices should be appraised. Furthermore, the trade offs involved in the purpose built vs. conversion choice should be analytically quantified. Finally, the environmental implications analysis should be expanded to include all stages of the life cycle of the vehicle. In particular, the consequences of the extraction, use, and recovery of materials used in batteries, lightweight automobile bodies materials, and complex electromechanical componentry should be quantified.

The analysis of the most promising of the alternative fuel technologies should become more detailed and be updated to acknowledge any technological advances. Hybrid vehicle technologies have been the early research focus under the PNGV. The PNGV aims to develop and mass produce vehicles with triple the efficiency of today's vehicles at an affordable cost. The technological, economic and environmental trade-offs associated with the development and use of hybrid vehicles should therefore be investigated in detail.

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Appendix I

EV Cost Modeling: *Fundamental Inputs & Assumptions*

EV Cost Modeling: *Fundamental Inputs & Assumptions*

Table 1: *Vehicle Design*

Vehicle Weight Without The Battery	790 kg
Drag Coefficient	0.19
Frontal Area	2.1 sq. meters
Rolling Resistance Constant	0.012

Source: Manufacturer & Literature Review

Table 2: *SAE J 227 C Driving Cycle Parameters*

t_{accel}	18 sec
t_{cruise}	20 sec
t_{coast}	8 sec
t_{brake}	9 sec
V_{max}	48 km/hr

A 5 degree grade at the cruise phase of the cycle was also assumed.

Table 3: *Vehicle Body Manufacturing Input Data*

Process	Material	System	Piece Count	Mass (kg)
stamping	aluminum	structure	65	59
folding	aluminum	structure	55	32
extrusion	aluminum	structure	41	26
casting	aluminum	structure	4	7
sheet molding compound (SMC)	polyester	exterior	12	54
reaction injection molding (RIM)	polyurea	exterior	8	20
injection molding	polypropylene	exterior	4	5
sheet molding compound (SMC XTC)	polyester	exterior	1	6
injection molding	high density polyethylene (HDPE)	exterior	3	17

Source: Manufacturer

Assembly Information:

- Total Number of Welds	2000
- Total Adhesive Bonding Length	270 m.

Table 4: *Detailed Chassis Cost Breakdown at 20,000 Units Per Year*

Part Name	System	Process	Weight (kg)	Part Cost ($/unit)
door inner panels (combined left & right)	exterior	compression molding	13	$67.65
door outer panels (combined left & right)	exterior	compression molding	17	$58.65

hood outer	exterior	compression molding	5.8	$23.19
deck lid outer	exterior	compression molding	3.5	$13.91
48 other SMC parts	exterior	compression molding	14.7	$61.12
rocker covers (combined left & right)	exterior	injection molding	4.2	$18.71
quarter panels (combined left & right)	exterior	injection molding	7.8	$75.88
front fascia	exterior	injection molding	5.4	$31.37
fenders (combined left & right)	exterior	injection molding	3.8	$30.69
5 other injection moldings	exterior	injection molding	26.8	$198.02
door rings (combined left & right)	structure	stamping	9.3	$390.09
dash panel	structure	stamping	4.4	$195.76
62 other stampings	structure	stamping	45.3	$1,937.17
tunnel torque boxes	structure	extrusion	3.7	$17.73
rocker inners (combined left & right)	structure	extrusion	5.1	$24.44
38 other extrusions	structure	extrusion	17.2	$82.42
front shock towers (combined left & right)	structure	casting	5.5	$235.20
2 other castings	structure	casting	1.5	$64.14
tunnel	structure	press brake	7.7	$35.28
4-bar	structure	press brake	8.1	$35.55
53 other foldings	structure	press brake	16.2	$72.63
Assembly	BIW	weld/bond	226	$608.42

Source: Manufacturer

The total chassis cost at this production volume is therefore $4,278.

Table 5: *Battery Technology Inputs & Assumptions*

	Lead Acid	Average Lead Acid	Advanced Lead Acid	USABC Mid Term	USABC Long Term
Energy Density Wh/kg	33	41	50	100	200
Power Density W/kg	80	110	140	200	400
Life, Cycles 80% DOD	149	375	550	600	1,000
Efficiency %	68	75	80	90	90
Ultimate[1] Cost $/kWh	90	90	90	150	100

[1] At an annual production volume of 20,000 units.

Source: Literature Review

Table 6: *Propulsion Systems & Electronics Costs*

Vehicle System/Component[1]	**100 units per year $**	**20,000 units per year $**
Motor	$2,500	$1,000
Controller	$3,000	$1,000
Gearbox	$3,000	$2,500
Battery Charger	$4,000	$1,250
Maximum Power Tracker	$1,000	$500
DC-DC Converter	$800	$200
Gauges	$700	$400
Other	$500	$200

[1] *Source: Cost Survey & Literature Review*

Table 7: *Secondary Systems/Components*

Climate Control System	$1,000
Wheels	$800
Tires	$400
Seats	$500
Air Bag System	$200
Paint	$400
Other	$1,000

Source: Cost Survey & Literature Review

Appendix II

Battery Sizing Iterative Calculation: *Energy Calculation*

Battery Sizing Iterative Calculation: *Energy Calculation*

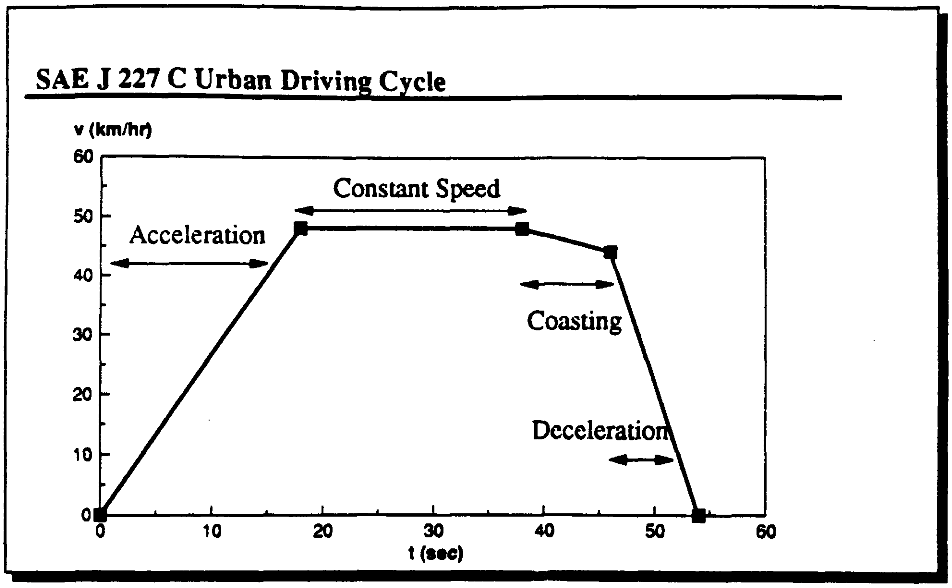
This first step in the calculation determines the distance traveled and energy required based on a driving cycle and the inputs regarding vehicle characteristics. Both these parameters are required to establish battery requirements. The mathematical treatment that follows is intended to show how the energy and distance traveled has been determined. The analysis presented here is based on the following reference: Comprehensive Treatise of Electrochemistry, Vol. 3, Chapter 15; Ed Bokris et al; Pentum Publishing Corp.; 1981.

The Society of Automotive Engineers (SAE) has a standard driving schedule which can be used to evaluate the performance of a vehicle under a variety of operating conditions. The standard is specified according to a period of acceleration to a peak speed, cruising at that speed, a brief coast and then a brake to a complete stop. This standard, SAE J227, comes in four flavors: A, B, C and D. The time spent in each phase and the peak speed are the sole distinctions between the four flavors. For the purposes of this analysis, the C standard has been chosen.

The SAE J227 C driving schedule is defined as follows:

$t_{accel} = 18$ sec $\quad t_{coast} = 8$ sec $\quad V_{max} = 48$ km/hr

$t_{cruise} = 20$ sec $\quad t_{brake} = 9$ sec



The " Power Curve" is the relationship between vehicle weight, geometry, speed and the power necessary to maintain that speed. It is essentially the product of the sum of all forces which oppose vehicle motion and the velocity at which the vehicle is traveling:

$$Power = \frac{\Delta(Energy)}{\Delta(t)} = (\Sigma F) \bullet v$$

Let us start with the most familiar of the force terms, F=ma. Researchers have suggested that, in the presence of mechanical inefficiencies, a more appropriate empirical relationship is the following:

$$F_{accel} = 1.1 \bullet m \bullet \frac{dv}{dt}$$

Our next consideration is aerodynamic resistance. The drag force is given by the following equation:

$$F_{aero} = \rho \bullet C_d \bullet A \bullet \frac{v^2}{2}$$

where

ρ: air density = 1.2255 kg/m^3

C_d : non dimensional drag coefficient

A : frontal area of the vehicle

Next we have rolling resistance. The approximate equation for this force is the following:

$$F_{rolling} = m \bullet g \bullet K \bullet [1 + 4.7 \bullet 10^{-3} \bullet v + 1.3 \bullet 10^{-4} \bullet v^2]$$

where

g: gravitational acceleration

K: rolling resistance constant (dimensionless); roughly 0.012

m: vehicle mass

Finally, there must be consideration to the fact that roads are not flat. Hence, for a given road grade:

$$F_{grade} = m \bullet g \bullet \sin(\theta)$$

Instantaneous power is just force times velocity, or:

$$Power = [F_{accel} + F_{aero} + F_{rolling} + F_{grade}] \bullet v$$

All these terms are related to one another by velocity. In the case of constant velocity (the cruising phase of SAE J227 C) or constant acceleration the equations of motion are relatively straightforward to treat. However, the acceleration during the phase from startup to cruising speed cannot be assumed constant. In fact, the typical behavior is more closely described by:

$$\frac{dv}{dt} = a_o - \frac{v}{10} \Leftrightarrow \int_0^v \frac{1}{[10 \bullet a_o - v]} dv = \int_0^t \frac{1}{10} dt$$

$$\Rightarrow v_{acc}(t) = 10 \bullet a_0 \left[1 - e^{\left(-\frac{t}{10}\right)} \right] \qquad \text{... (1)}$$

With this velocity function, the distance traveled is given by:

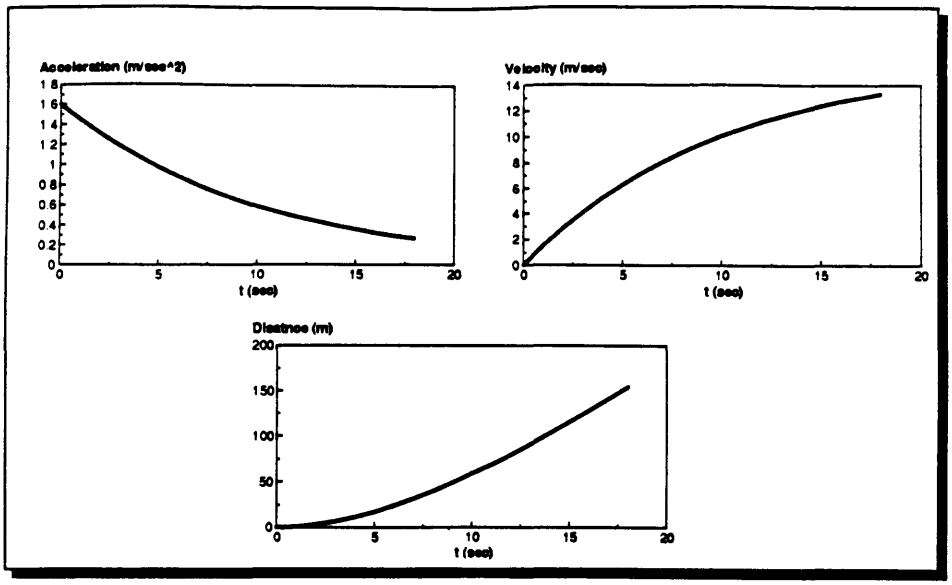
$$\int_0^t 10 \bullet a_o \bullet \left[1 - e^{-\frac{x}{10}} \right] dx = 10 \bullet \left[t + 10 \bullet e^{-\frac{t}{10}} \right] \bullet a_o - 100 \bullet a_0$$

$$\Rightarrow x_{acc}(t) = 10 \bullet a_o \bullet \left[t + 10 \bullet \left(e^{-\frac{t}{10}} - 1 \right) \right] \qquad \text{... (2)}$$

Using the SAE J227 C values for the first stage of the test cycle, we can solve for the constant a_o from equation (1):

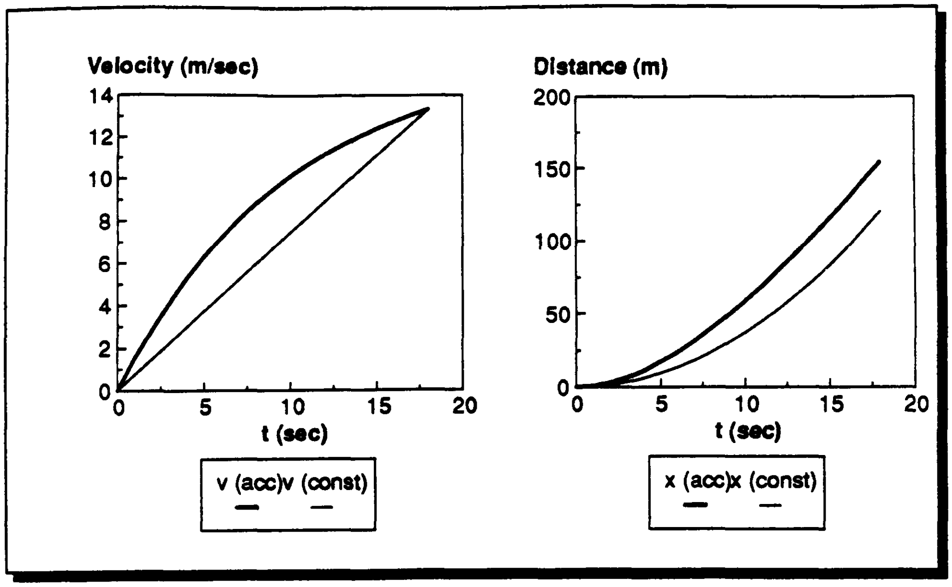
a_o= 1.597 m/sec^2

Hence, for the acceleration phase the acceleration, velocity and distance profiles can be plotted as follows:



An interesting question about the analysis that has just been carried out is whether assuming constant acceleration would have produced significantly erroneous results. Let us compare the above distance/velocity profiles with the one we would get assuming constant acceleration:

$a_{const} = (13.333/18)\mathrm{m/sec}^2$, $v_{const}(t) = a_{const}*t$, $x_{const}(t) = a_{const}*t^2/2$



$\frac{[x_{const}(18)-x_{acc}(18)]}{x_{acc}(18)} = -22.16\%$, an error which is certainly not negligible.

We are now ready to start calculating the energy required during the two main power consuming phases of the SAE J227 C cycle; accelerating to speed and cruising. At the same time the distances traveled during the cycle can also be computed. Recall from above that the terms of a power curve are of the form of constants times velocity to the first, second and third power and a constant times velocity times acceleration. Rather than solving the entire integral, the functional form of the function will be separately computed.

Let us start with the pure velocity terms:

$$v(t) = 10 \bullet a_o \bullet \left[1 - e^{-\frac{t}{10}}\right]$$

First Order Term:

$$\int_0^t 10 \bullet a_o \bullet \left[1-e^{-\frac{t}{10}}\right]dt = 10 \bullet a_o \bullet \left[t+10 \bullet e^{-\frac{t}{10}} - 10\right]$$

Second Order Term:

$$\int_0^t 100 \bullet a_o^2 \bullet \left[1-e^{-\frac{t}{10}}\right]^2 dt = 100 \bullet a_o^2 \bullet \left[-5 \bullet \left(e^{-\frac{t}{10}}\right)^2 + t + 20 \bullet e^{-\frac{t}{10}}\right] - 1500 \bullet a_o^2$$

Third Order Term:

$$\int_o^t 1000 \bullet a_o^3 \bullet \left[1-e^{-\frac{t}{10}}\right]^3 dt = \frac{1000}{3} \bullet \left[10 \bullet \left(e^{-\frac{t}{10}}\right)^3 - 45 \bullet \left(e^{-\frac{t}{10}}\right)^2 + 3t + 90 \bullet e^{-\frac{t}{10}}\right] \bullet a_o^3 - \frac{55000}{3} \bullet a_o^3$$

And finally the velocity times acceleration term:

$$\int_o^t 10 \bullet a_o \bullet \left(1-e^{-\frac{t}{10}}\right) \bullet \left[a_o - a_o\left(1-e^{-\frac{t}{10}}\right)\right]dt = a_0^2 \bullet \left[50 \bullet e^{-\frac{t}{10}} \bullet \left(-2+e^{-\frac{t}{10}}\right) + 50\right]$$

We are now in a position to calculate the energy consumed during the acceleration to speed (evaluating each of the above integrals between the two time points and multiplying by the appropriate constants) and the energy consumed during cruising (merely the product of the sum of forces at cruising speed times the cruising time). These calculations are done in the battery sizing spreadsheet and will not be reproduced here.

Let us now treat the other two parts of the cycle; coasting and braking. During the coasting phase, there is no battery drain, and the force terms will determine vehicle motion. It is reasonable to assume constant deceleration to determine the distance covered in this phase of the cycle as it can be shown that the error associated with this approach is in the order of 1% of a more accurate approach where:

$\frac{dv}{dt} = -A - B \bullet v^2$ where A, B are constants relating to vehicle design

During the braking phase, energy potentially could be generated and stored. To treat either of these cases, the force terms have to be examined a little more closely. However, regenerative braking has not been treated in this calculation since the reported benefits that do not exceed 15% are offset by other parasitic losses such as those from an air conditioner, heater, radio and head lights, all of which have also been disregarded. Again to determine the distance covered in this phase, constant deceleration was assumed for the same reasons as before.