SENSITIVITY OF UNITED STATES EMISSIONS REDUCTIONS TO MARKET PENETRATION VARIABLES OF ALTERNATIVE VEHICLES

by

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EXECUTIVE SUMMARY

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Technology is often touted as the solution to many of our environmental problems, but how much can we depend on new vehicle technologies to mitigate our impact on the atmosphere and air quality? This thesis examines a handful of the most promising vehicle technologies, specifically: hybrid electric vehicles, hydrogen fuel cell vehicles, and battery electric vehicles. The purpose is to study the technological potential of alternative vehicles to affect aggregate emissions. Although this potential could be partially dependent upon various policies, the intent is not to determine which policies would be necessary to achieve a certain level of reductions. Rather, the focus is to explore the plausible maximum effect that technology-oriented transportation policies might have on the timing and magnitude of emissions reductions. This effect is highly sensitive to the rate of market penetration, which is determined by a host of technological, social, economics, and political factors, but previous studies have not generally accounted for this uncertainty. Low-emitting technologies that penetrate at a fast rate will obviously reduce aggregate emissions more than technologies that penetrate at a slower rate. Other penetration-related factors, especially level of saturation and time of introduction, would also influence the extent of emissions reductions.

Using historical penetration rates of automotive technologies to create a set of penetration rate scenarios of alternative vehicle technologies, future emissions of greenhouse gases and air pollutants can be calculated in an age-specific model of vehicles in the United States. My findings indicate that the selection of technology will prove to be a significant factor in potential reductions. The rate of market penetration and the time technologies are introduced will also play an important role. Although transportation-related measures are unlikely to contribute to near-term emissions reductions such as those included in the Kyoto Protocol, a plausible scenario with conservative assumptions indicates that light-duty vehicle emissions could be reduced by 50% from the reference case within 40 years. Progress in emissions reductions could be further accelerated with the help of more aggressive policy to expedite introduction of alternative vehicles and encourage their adoption.

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To my family for teaching me to pursue my passions and my teachers who gave me the means to do so.

GLOSSARY

CAFE – Corporate Average Fuel Economy

CO_2 – carbon dioxide

Freedom CAR – Freedom Cooperative Automotive Research

ghg's – greenhouse gases

GREET – Greenhouse gases, Regulated Emissions, and Energy use in Transportation

HFC – hydrofluorocarbons

LDV – light duty vehicle

mMTCe – million metric tons of carbon equivalent

N_2O – nitrous oxide

NEMS – National Energy Modeling System

NO_x – nitrogen oxides

NRC – National Research Council

PNGV – Partnership for a New Generation of Vehicles

VMT – vehicle miles traveled

VOC's – volatile organic compounds

Introduction

The global environmental impact of personal transportation increases in severity as more countries adopt transportation systems similar to that of the United States. In the United States, much of the transportation sector's contribution to the problem stems from its high energy consumption and its carbon-intensive fuel source. US energy consumption by the transportation sector is second only to the industrial sector in total energy consumption and appears to be continually increasing with time [Figure 1].

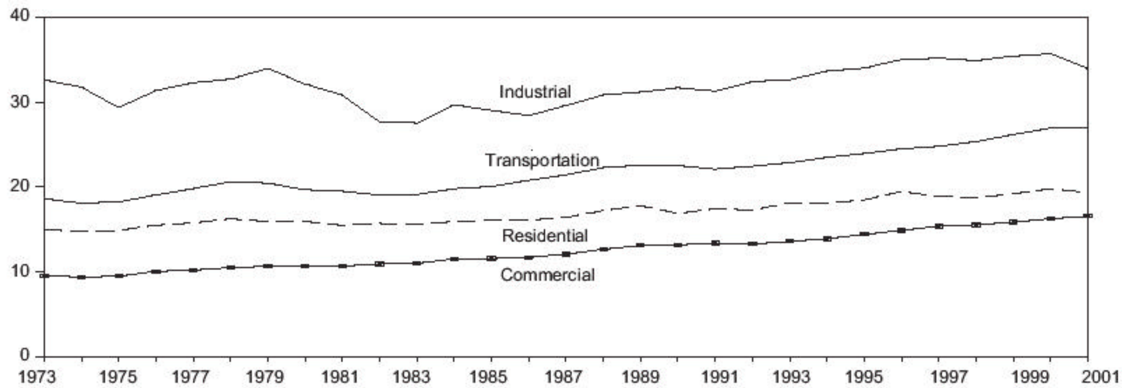

Figure 1. Total Energy Consumption by Sector (Quadrillion Btu) – By End Use, 1973-2001
Source: Energy Information Administration, Monthly Energy Review, March 2002

Almost all of this energy results from the combustion of the highly polluting fossil fuel petroleum. [Figure 2] Consequently, transportation is a significant contributor to climate change, responsible for about one-third of U.S. anthropogenic carbon dioxide (CO_2) emissions, the most abundant of greenhouse gases (ghg's). [*1*] Although the sector's contribution of other ghg's are not as substantial as its contribution of CO_2, its emissions of nitrous oxide (N_2O) and hydrofluorocarbons (HFCs) are not insignificant.

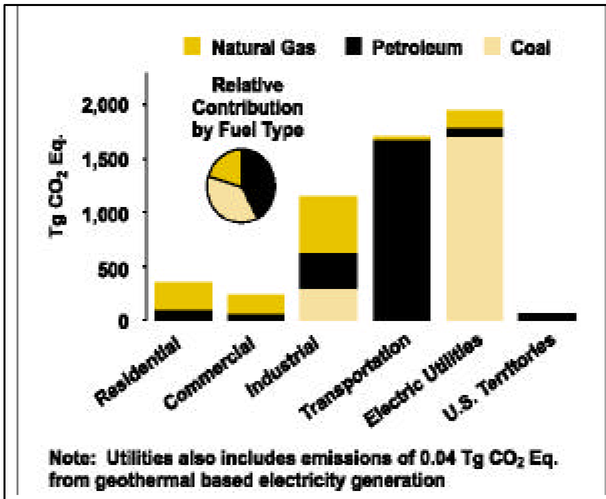

Figure 2. 1999 CO_2 Emissions from Fossil Fuel Combustion by Sector and Fuel Type
Source: U.S. Inventory of Greenhouse Gas Emissions and Sinks: 1990–1999. (EPA)

Important to note is that all modes of transportation are included in this sector. Thus, besides light duty vehicles (LDV's), this sector also includes airplanes, heavy trucks, rail, buses, and motorcycles. Still, when divided into subsectors, 59% of total transportation energy use can be attributed to passenger cars and light trucks, which comprise the light duty segment (1999). [*2*] As a result, this segment is responsible for roughly 58% of transportation-related CO_2 emissions [*3*].

In addition to greenhouse gases, light duty vehicles also contribute high levels of nitrogen oxides (NO_x) and volatile organic compounds (VOC's), with highway vehicles accounting for 35.1% of NO_x and 29.6% of VOC's in the United States [*2*]. Both chemicals are precursors to ground level ozone, the primary component of smog, which can lead to severe respiratory and pulminary conditions as well as general health effects such as eye irritation and headache. Most metropolitan areas in the country are in nonattainment for ozone under National Ambient Air Quality Standards established by the Clean Air Act. Incomplete combustion from light duty vehicles also generates 55.9% of the nation's carbon monoxide, another criteria air pollutant regulated under the Clean Air Act. Carbon monoxide is known to reduce the oxygen-carrying capacity of blood, exacerbating cardiovascular disease and impairing certain mental and physical functions in healthy individuals. [*4*]

Thus, the light duty segment's significant contribution to greenhouse gases and criteria air pollutants makes it an obvious target for reductions. Their contribution could grow in the future as more fuel inefficient light trucks gain in popularity relative to passenger cars and as the segment grows in size overall. Advances in vehicle technology could be instrumental in reducing the environmental impact of personal transportation. Technological change offers the advantage of reducing emissions without necessarily imposing on lifestyles through improvements in efficiency that reduce energy consumption or by switching to cleaner fuel sources. Light duty vehicles, which account for more than 90% of all highway vehicle miles traveled in the country [*2*], are arguably the most pervasive method of personal transportation. As such a diffuse product, sizeable niche markets are available to incubate new technologies that might eventually be adopted by the mainstream. For instance, engineers and environmentalists are often considered the demographic group most likely to purchase an alternative vehicle, even at a slight premium. With such a decentralized and widespread system, vehicle owners have the potential to influence technological change from the grassroots level.

Part of this potential lies in the fairly quick turnover of the total vehicle stock, which allows for new technologies to be incorporated at a faster rate than technologies with lower turnover. The average age of vehicles reflects the rate of turnover with a low average age generally indicating quick turnover and a high average age generally indicating slow turnover. In 1999, the average age of passenger cars was 8.9 years and light trucks 8.2 compared to 1970 when passenger cars averaged 5.6 years and light trucks 7.3. Although the potential for rapid technological change in the vehicle fleet has fallen slightly in the past thirty years as predicted by average age, it is still much greater than electric utilities, whose CO_2 emissions exceed those of the entire transportation sector (for comparison, the average age of coal-fired power plants in Pennsylvania is 31 years [*5*]).

Thus, policy makers continue to be optimistic about technological solutions. The former Partnership for a New Generation of Vehicles (PNGV) sponsored a research and development program to assist the automotive industry produce a commercially viable sedan with triple the current fuel economy. More recently in January 2002, the United States Department of Energy announced a new program, Freedom Cooperative Automotive Research (CAR), intended to replace PNGV, which will focus solely on the development of marketable hydrogen fuel cell vehicles. These vehicles are potentially emission-less, but while the merits of alternative vehicles appear fairly obvious at the vehicle level, how much and how fast these vehicles could reduce aggregate emissions from the entire vehicle fleet remains to be seen.

The purpose of this thesis is to study the technological potential of alternative vehicles to affect aggregate emissions. Although this potential could be partially dependent upon various policies, the intent is not to determine which policies would be necessary to achieve a certain level of reductions. Rather, the focus is to explore the plausible maximum effect that technology-oriented transportation policies might have on emissions reductions. In particular, reductions are highly sensitive to assumptions about market penetration rates, a factor frequently overlooked by previous studies. Low-emitting technologies that penetrate at a fast rate will obviously reduce aggregate emissions more than technologies that penetrate at a slower rate. Other penetration-related factors, especially level of saturation and time of introduction, would also influence the extent of emissions reductions. However, of greater interest is the effect of changing these variables on the levels of reductions produced as well as when possible targets could be achieved. The Kyoto Protocol calls for the United States to reduce greenhouse gas emissions to 7% below 1990 levels between 2008 and 2012. Although doubtful that technological change will occur at a fast enough pace to make a significant contribution to these reduction in the near-term, alternative vehicles could potentially contribute considerably to these efforts in the following decades.

Previous Studies

A number of previous studies have created CO_2 emissions scenarios to analyze various policy options, including improved CAFE / fuel economy standards and advanced vehicle technology. However, their estimates of CO_2 emissions vary widely. [Figure 3] DeCicco and Mark (1998) estimate a 20% reduction in CO_2 from the baseline with improvements in fuel economy alone in 2010, though reductions could reach as high as 50% by 2050. [6] The National Research Council (NRC) (1997) also assumes improvements in fuel efficiency but estimates that a 20% reduction would not occur until 2020. [7] Meanwhile, Greene and Plotkin (2001) are more optimistic about reductions

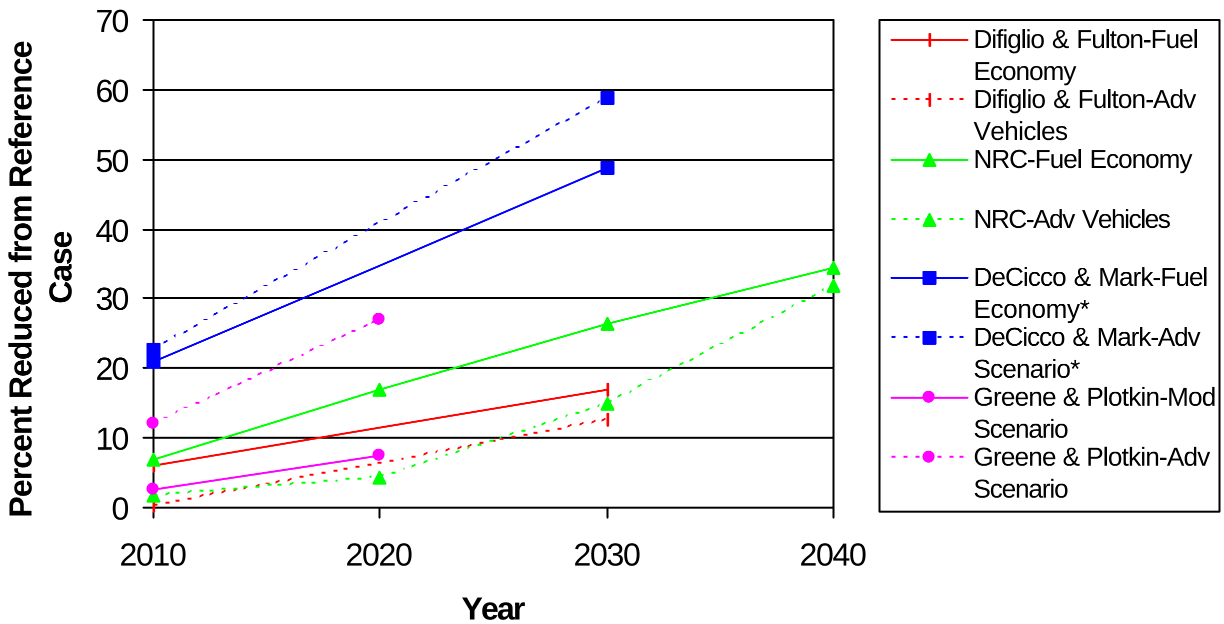

Figure 3. Emissions Reductions from Previous Studies.
Note that reference cases differ between studies and trends assumed to be linear when intermediate time points were not provided. * denotes reductions for the *entire* transportation sector.
Sources: Difiglio & Fulton (2000), NRC (1997), DeCicco & Mark (1998), Greene & Plotkin (2001)

arguing that a 27% reduction could be achieved in 2020 under their advanced policy scenario. However, their moderate policy scenario is less optimistic, producing reductions of only 8% in 2020. [*8*] Difiglio and Fulton (2000) are also less optimistic and project that, even in 2030, emissions reductions will only reach about 15% through the adoption of either advanced vehicle technologies or improved fuel economy. [*9*] Overall, reductions are fairly modest, especially when placed in the context of reductions necessary for the entire country and not just the light duty vehicle sector. Based on year 2000 data, the United States would need to reduce greenhouse gases by more than 1350 mMTCe to reach the Kyoto targets [*3*]; the amount of reductions will likely continue to increase in the future if emissions remain unchecked. Even the most optimistic results would only contribute roughly 400 mMTCe in reductions and could not be realized until 2030.

The variability in magnitude of reductions are in part due to the assumptions about penetration rates and saturation levels of each scenario. Extending the projection period by several decades would inevitably increase the maximum potential reductions as the additional time would allow for greater market penetration and/or further improvements in fuel economy or vehicle technology. Even extending all study results to the year 2040 would likely show an increase in reductions for the same reasons. However, the magnitude of reductions would still vary due to the assumptions of each scenario. First, each study makes different assumptions about what technologies are available. DeCicco and Mark, Difiglio and Fulton, and the NRC include scenarios for conventional vehicles with improved efficiency as well as alternative or advanced vehicles. The NRC assumes advanced vehicles to include hybrid electric, biofuel, and hydrogen fuel cell vehicles, while Difiglio and Fulton examine only PNGV vehicles, essentially either hybrid electric vehicles or conventional vehicles with dramatically improved fuel economy. Meanwhile, DeCicco and Mark assume only hydrogen fuel cell vehicles, but only in combination with increased efficiency, and other renewables and policy options. Similarly, Greene and Plotkin consider a range of vehicle technologies including direct injection and diesel engines, hybrid electric drivetrains, fuel cell powerplants, cellulosic ethanol, and lighter-weight materials, though again, only as part of a larger policy package.

Second, previous studies differ in how soon new technologies become available and how quickly they become adopted. Based on extrapolations from the National Energy Modeling System (NEMS) model, DeCicco and Mark assert that an annual improvement of 1.5 miles per gallon (mpg) is already technologically feasible, making a new fleet average of 45 mpg (or 27 mpg on-road stock average[1]) a realistic goal for 2010. Continued improvements in fuel economy result in an on-road stock average of 52 mpg by 2030. However, the NRC assumed a more modest improvement in fuel economy of new vehicles of 1.5%. Difiglio and Fulton used a more intermediate approach, assuming a 20% increase phased in between 2001 and 2006 which was then followed by a 1% annual increase. Such assumptions about fuel economy implicitly incorporate rates of market penetration as new vehicles with greater efficiency will only become integrated with the on-road stock gradually.

Some studies address market penetration more explicitly, though, applying specific rates of market share to alternative vehicles. Difiglio and Fulton assume market

[1] "On-road stock" refers to vehicles of all ages still in use while "new fleet" refers only to new vehicles sold during a given year.

penetration rates projected for PNGV sales of 3% in 2010, 15% in 2015, and 50% in 2030. In contrast, the NRC's advanced vehicle scenario uses a penetration rate reflected by vehicle miles traveled (VMT) rather than new sales. Calculated this way, penetration appears somewhat slower, with advanced vehicles comprising only 5% of total fleet VMT in 2020 and increasing to 20% and 45% in 2030 and 2040, respectively. Green and Plotkin use a modified NEMS Transportation Sector Model to generate a market penetration curve with 50% market share for alternative vehicles in 2020. DeCicco and Mark assume a much more optimistic penetration rate for their hydrogen fuel cell vehicle scenario; introduced only in 2010 (i.e. 0% market share in 2010), fuel cell vehicles obtain 90% of new light duty vehicle market share in a mere 20 years.

A final consideration in previous studies influencing potential reductions is the extent to which a technology can saturate the market. Saturation differs from penetration in that saturation reflects the long-term maximum penetration. Difiglio and Fulton assume that alternative vehicle sales will saturate at 50% due to consumer resistance and market niches incompatible with alternative technologies. Such an assumption markedly limits the potential emissions reductions resulting from alternative vehicles. Although the remaining studies do not explicitly cite their saturation, alternative technologies can presumably saturate the market completely.

Important to remember is that the technology scenarios in each of these previous studies was only one of a number of scenarios. The overall goal of these studies was to examine policies rather than technologies per se. Besides the technological policies that might mandate improvements in fuel economy or changes in other vehicle characteristics, these previous studies also analyzed the impact of behavioral or economic policies. Behavioral policies include incentives to increase telecommuting, carpooling, or public transit ridership that would reduce vehicle miles traveled. Economic policies include measures such as gas taxes, carbon taxes, or parking taxes that would increase the cost of driving. Of course, policy will undoubtedly overlap with one or more of these categories as economic policies are aimed at inducing behavioral change. In fact, Decicco and Mark and Greene and Plotkin's scenarios incorporate technological changes simultaneously with economic and behavioral policy, thus masking the effect of technology on emissions reductions.

A Focus on Penetration Rates

This study differs from previous scenario studies in that it estimates emissions reductions based only on technological change. These previous studies were interested in comparing the effects of policy—technological, behavioral, and economic—each assuming only a single (generally conservative) market penetration curve for alternative vehicles. However, as discussed above, considerable variation exists between previous works in their assumptions for rates of market penetration. The existence of so many simultaneous variables precludes drawing any definitive conclusions about the most significant aspects of market penetration that influence emissions reductions.

The advantage of this study it offers a consistent framework in which to systematically examine each of the market penetration variables. This study examines scenarios within the technological scenario, varying only market penetration while keeping all other factors constant; thus, measuring the sensitivity of vehicle emissions projections to technological change, assuming the appropriate policy measures that might be necessary to realize such change. Because market penetration is generally unpredictable and widely variable, these scenarios produce both upper and lower bounds for potential reductions, thereby reducing some of the uncertainty of future projections as well as revealing possible error in previous studies. Such an approach is also beneficial as it allows explicit comparison of the effects of technology at the aggregate rather than vehicular level.

DETERMINANTS OF MARKET PENETRATION. One inherent drawback of relying solely on technological solutions is the necessary time lag between when a new technology is introduced and when the market becomes saturated. In fact, of the multitude of technologies introduced, only a select few will ultimately penetrate the market at any significant rate, often abruptly rather than gradually. The rate these technologies will penetrate the market depends on a host of variables—robustness of the technology platform, strength of automaker demand, strength of consumer demand, and strength of societal requirements—all of which will vary based on both economic and societal trends. [*10*]

Robustness of the technology platform, essentially the market-readiness of the technology, includes factors that relate to production or manufacturing of a quality product as well as systematic infrastructure that will support the new technology. A company will manufacture only those products that are cost-effective to produce, thus making material performance and production costs important hurdles to overcome. For instance, anti-lock braking systems were at first not robust when initially developed in the 1960's. However, decades later they became robust when their inferior analog computer systems could be replaced with cheaper, more reliable digital computers and sensors. Often additional technologies become feasible by co-opting components of the initial technology. In the case of anti-lock brakes, the wheel speed sensors and hydraulic actuators could also be used for traction and vehicle stability control and cruise control. [*11*] Manufacturers must also be prepared to increase production to fulfill market demand. Any manufacturing limitations will inherently limit market share as well. Of course, companies will only produce those products they believe will sell. Without the necessary infrastructure that allows a product to be practical to the consumer, companies will be unlikely to invest in research and development for the technology.

Beyond producing technologies that automakers will be able to sell, the technologies also need to fit within the existing "cultural ambiance" in order to rapidly penetrate a market. Automakers will demand (and incorporate) new technologies if they provide some external value, such as appealing to a niche market, improving the company's brand image, or enhancing its ability to meet a regulatory mandate. Similarly, consumer demand plays an important role in market penetration. Technologies that are not perceptible to consumers in that they require no change in behavior and result in no depreciation of vehicle performance will likely encounter less resistance and thus be able to penetrate the market more quickly. The one exception is vehicle styling, which is in fact highly visible to consumers and intended as such. Despite an automakers best effort to promote a quality feature, without customers, the technology essentially does not exist. Consumer demand is one of the most difficult variables to predict given that attitudes and perceptions can reverse completely in a short time span. Airbags during the 1970's hardly attracted any attention, while today the federal government mandates driver-side airbags and safety-conscious consumers are willing to pay for optional, additional airbags.

Societal values, frequently shaped by marketing companies, are not the only influences on consumer demand. Economic conditions, such as consumer confidence and fuel prices, also affect product demand. The dilemma that automakers face is the disparity in time between when consumers first demand a product and when it is actually market-ready. Automakers must also comply with government mandates, which may or may not coincide with consumer demands. Both parties tend to agree on the importance of safety; however, opinions on fuel economy often differ.

Thus, the market penetration of a given technology will depend on a variety of determinants: market-readiness, "cultural ambiance", societal values, economic conditions, and government regulation. All of these factors combined will determine the rate a technology penetrates the market, if at all. With so many variables, penetration projections are both highly unpredictable and largely uncertain. Historical data therefore provide an indication of possible market penetration rates for future technologies.

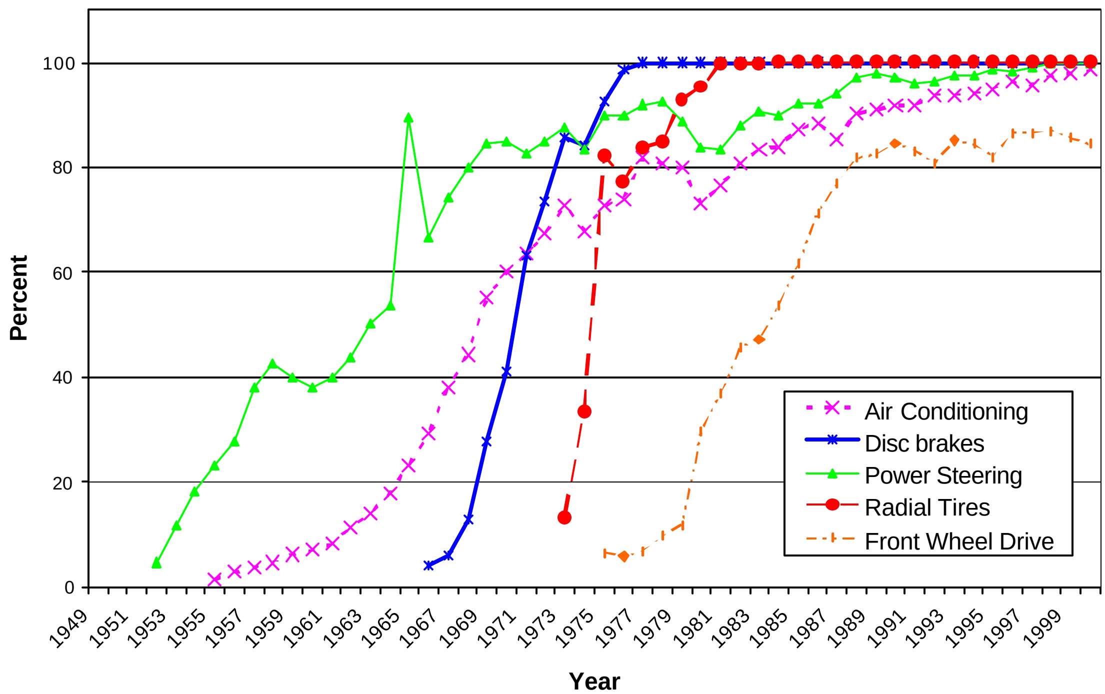

Figure 4. Factory Installed Equipment Trends on U.S. Cars 1959-2000
Source: Ward's Automotive Yearbook 2001 and Light-Duty Automotive Technology and Fuel Economy Trends 1975 through 2000 (EPA420-R-00-008, December 2000).

HISTORIC PENETRATION RATES OF FACTORY-INSTALLED EQUIPMENT. Historically, various vehicle technologies have penetrated the market at different rates as a result of the factors discussed above. Figure 4 illustrates the penetration of five factory-installed types of equipment in the domestic passenger cars market. Although these rates may vary slightly for imports and/or light trucks, they serve the purpose of providing a reasonable base from which to generate theoretical penetration curves given the dominance of domestic passenger cars in the past. Despite their higher costs, both disc braking and radial tires completely saturated the market in roughly ten years, a relatively short time for all new vehicles to be fitted with a new technology. Not only do these two features offer enhanced performance, they also improve the safety of the vehicle, thus appealing to market-readiness and societal values. The arrangement of ply cords on a radial tire produces greater resistance when cornering and improves steering, making these tires safer in bad weather. Disc brakes are fade resistant, thus improving the braking power of the vehicle over drum brakes. Such dramatic rates of market penetration are similar to rates of technology-forcing through government regulation. For example, in 1991 Congress passed the Mandatory Airbag Regulation under the Federal Motor Vehicle Safety Standard Number 208, mandating that all passengers be equipped with airbags by 1998 and all light trucks by 1999. However, these technologies had the advantage of being introduced more recently, thus able to draw upon further engineering or manufacturing research and penetrate at a faster rate.

In contrast, air conditioning and power steering have penetrated the market at a much slower rate. Initially these technologies could not have penetrated without a more cost effective method of generating power, thus hindered by economic conditions and a lack of technology robustness. Such power was not available until the advent of the high compression engine in the late 1950's, which could produce enough power to move the vehicle as well as fuel these other features. Additionally, cultural ambiance may have played a role as both power steering and air conditioning might be considered accessories rather than necessities as safety features might be categorized; consumer demand and automaker investment were thus low until these features could be added at a relatively low cost. These rates could therefore be considered to reflect market driven change rather than policy driven.

The exception to complete market saturation has been that of front-wheel drive, leveling off with roughly 85% market share. This incomplete saturation is most likely due to the presence of a niche market that will not be converted from rear-wheel drive. Automakers first introduced front-wheel drive in 1980 in response to the oil embargo of the previous decade which produced a new demand for lighter and more fuel efficient vehicles. Front-wheel drive offers the advantage of reducing weight without compromising passenger space. In addition, these vehicles perform better in inclement weather and are easier and cheaper to design and manufacture. On the other hand, luxury and sports cars are often rear-wheel drive which gives the driver better handing control and also associates an element of status to the vehicle. Luxury cars are also frequently large enough that additional passenger space is unnecessary. For these reasons, front-wheel drive may never fully penetrate the market, and may in fact experience a decline as rear-wheel drive technology improves. [*12*] Additionally, the growing popularity of light trucks with four-wheel drive may also limit the penetration of front-wheel drive.

Methods

Estimating how much and how soon emissions reductions could be attained through alternative vehicles first requires a reference emissions projection based only on conventional vehicles. Emissions in any given year are essentially a function of total number of vehicles, vehicle miles traveled, and emissions from energy use. Over time, though, emissions will vary based on the age structure of the vehicle fleet, as older vehicles tend to be driven fewer miles and are scrapped at a higher rate. The importance of market penetration rates becomes clear through the introduction of alternative vehicles based on historical rates, which effectively alters the composition of the fleet and influences emissions projections. Also influencing the magnitude of emissions reductions will be which types of alternative vehicles are introduced.

Potential Market Penetration of Alternative Vehicles

Three alternative vehicle technology types are considered here for comparison with the current internal combustion engine vehicle: hybrid electric vehicles (often referred to as simply "hybrids"), battery electric vehicles, and hydrogen fuel cell vehicles. Hybrids and battery electrics can be considered near-term technologies as both are available in the marketplace. Battery electrics are currently the only vehicles able to meet the zero tailpipe emission mandate passed in California. However, hybrids offer the promise of markedly improved fuel economy with few impositions on consumers or the energy industry. Additionally, until the recent replacement of the PNGV program, most research and development funding for alternative vehicles was invested in hybrid technology. Hybrids are not viewed as long-term technology options, though, as they can never be zero-emitting vehicles. Rather, further improved battery electrics and hydrogen fuel cell vehicles are often considered as the far-term vehicle technologies, though would not be available for at least another ten years. Both types of technologies have the potential to be completely zero emission vehicles depending on which fuel is used to generate the energy. These technologies also offer the benefit of not having to rely on foreign sources for fuel—electricity and hydrogen can be generated from a host of sources, including natural gas, coal, nuclear power, water and even solar energy. The latter three sources are additionally sustainable, i.e. non fossil, sources of energy.

With the lack of government regulation of greenhouse gases and limited restrictions on emissions of criteria air pollutants, market penetration of these alternative vehicles will depend heavily on the market-readiness of the technology, consumer acceptance, societal values, and economic conditions, though some of these factors will be related to government policy. In terms of technology robustness, both battery electrics and hydrogen fuel cell vehicles suffer from a lack of energy infrastructure. Auto manufactures often cite the nonexistent hydrogen infrastructure as a reason for not investing more in research and development of fuel cell vehicles. Vehicles will be useless without the necessary support structure; simultaneously the support structure will fail to develop without an end product in sight. However, hydrogen as an energy carrier, rather than an energy source, can be produced from a variety of fuels, both onboard the vehicle or off. Widespread success of hydrogen vehicles will invariably depend on the availability of a reliable energy infrastructure.

Battery electric vehicles also suffer from infrastructure problems; these vehicles have a limited travel range and "refueling" stations away from the home currently are not widely available. These vehicles suffer from additional technology robustness issues as well. Twice in the past battery electrics were introduced with limited success. Prior to the triumph of the gasoline vehicle and the Model T in the early 1900's, both electric and steam-powered vehicles were considered contenders in the race for personal automobility. With the discovery of inexpensive and seemingly limitless oil, though, internal combustion engine vehicles surpassed these other technologies. About ninety years later, electric vehicles were introduced again, championed for their ability to meet zero tailpipe emissions standards in California. Beyond their zero emissions, however, battery electrics could offer few comparative advantages given their prohibitive cost, limited range, the toxicity of old batteries and long recharging time. Until hydrogen vehicles become readily available, though, battery electrics are currently the only technology capable of fulfilling the zero emissions goal.

Unlike battery electric vehicles, hybrids incorporate a gasoline engine in addition to an electric motor. The battery is thus recharged by the gasoline engine, thus allowing for continued use of the current petroleum infrastructure. This also overcomes a major obstacle faced by battery electrics regarding consumer acceptance: drivers will not need to plug in their vehicles to recharge the battery. Nonetheless, three years after hybrids were first introduced production remains limited—even insignificant when compared to all remaining motor vehicles sales—with long waiting periods and only three models from which to choose, perhaps revealing a mismatch between automaker and consumer demand for the technology. Although much of a hybrid vehicle resembles a conventional gasoline vehicle, some features may require adjustment on the part of the driver, such as ignition shutoff while the vehicle is stopped. Overall, though, hybrids exhibit greater potential for significant market penetration in the near-term if their production costs can match those of conventional vehicles. For this reason, hybrids are often regarded as a transition to hydrogen vehicles, allowing the infrastructure to develop and the fuel cell technology to be better understood.

Potential market penetration of all of these alternative vehicles may also be improved with changes in societal values and economic conditions. Concerns about air pollution may begin to increase as the environmental health effects of smog become better documented. Awareness of the impacts of climate change as well as international pressure may also provoke greater concern about greenhouse gas emissions. Recent incidents of terrorism could also trigger demands for reduced dependence on foreign oil in the interest of national security. These concerns are further heightened by prospects of potential spikes in fuel prices.

Given the high level of uncertainty, historical rates provide a range of penetration rate curves that are representative of plausible penetration rates of alternative vehicle technologies. Potential market penetration curves for alternative vehicles were derived using a standard logistic curve, $P(t) = 1/[e^{-rKt}(1/P_0 - 1/K) + 1/K], t \geq 0$ [*13*], and manipulating *r*, the intrinsic rate of increase, and *K*, the saturation level, to match historical values. [Figure 5] For all three rates—high, moderate, and low—*K* was assumed to completely saturate the market, making *r* the variable of interest. In the high

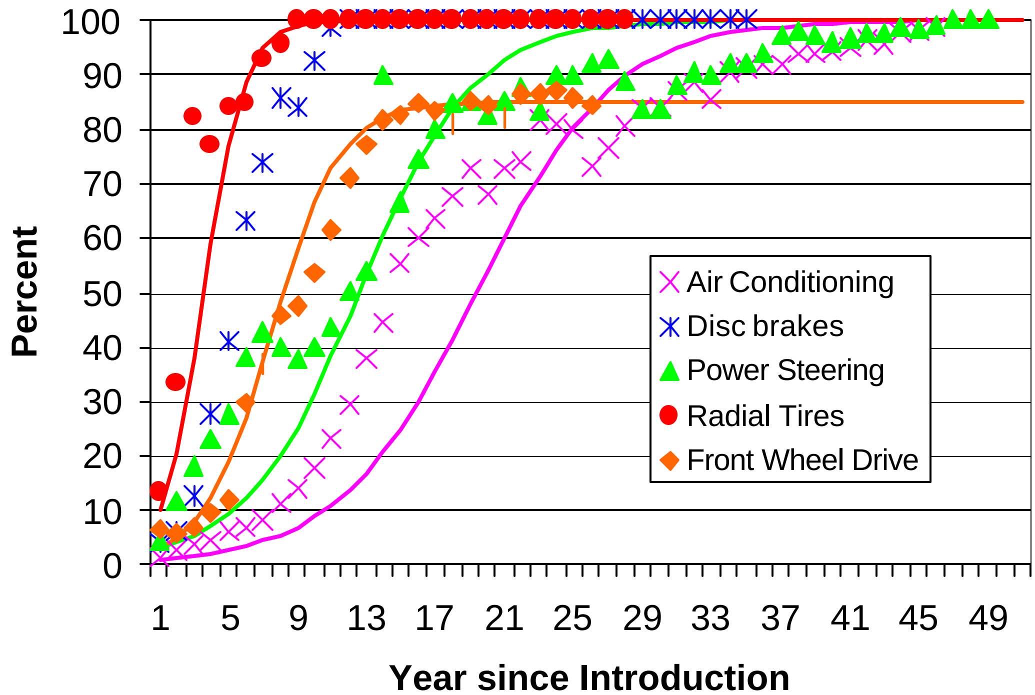

Figure 5. Historic percent of market share and matching logistic curves. Source: Ward's Automotive Yearbook 2001 and Light-Duty Automotive Technology and Fuel Economy Trends 1975 through 2000 (EPA420-R-00-008, December 2000).

scenario, *r* was adjusted so the market was saturated within ten years of introduction. Saturation did not occur until at least 25 years following introduction in the moderate case and nearly 45 years in the low case. However, a second moderate rate was generated to illustrate the effects of incomplete saturation to account for possible niche markets. Modeled after front-wheel drive trends, here the market saturated in 15 years at 85%. The use of historical values provides bounds for what might be reasonably expected in the market penetration of new vehicle technologies. The range is also broad enough to reflect a variety of policy inputs that could motivate such change.

Scenario Modeling of Emissions Reductions

The goal of this study is not to predict future transportation emissions, but to test the sensitivity of these emissions to assumptions about the rate of penetration of alternative vehicles. Assessing the potential emissions reductions from alternative vehicles is contingent upon a number of unpredictable variables, preventing any accurate or feasible prediction of future vehicle emissions. Scenario modeling, therefore, offers the advantage of comparative study rather than predictive analysis, eliminating the need to project such variables as travel demand, new vehicle sales, and vehicle scrappage that will depend greatly on fairly stochastic demographic, economic, and cultural trends. Instead, emissions from all scenarios are examined in relation to the emissions of the reference case. Only the rate of market penetration will differ between the reference case and the scenarios, with all other variables remaining the same, making the intricacies of the reference case itself less important. However, the details of the reference case are not necessarily unimportant as the sensitivity of emissions projections to the various penetration rates may depend in some way on the particulars of the reference case. Once a reference case has been developed, scenario cases incorporating different rates of market penetration can then be devised and emissions projections compared at each year and in the aggregate.

Scenarios will be created for each alternative technology using the three different penetration curves. These scenarios will allow comparison of emissions for both the differences in technology as well as the effect of higher or lower penetration rates. Additional scenarios will test the sensitivity of emissions reductions to the level of market saturation and the time of introduction for a new technology. A final set of scenarios will combine the various aspects of market penetration to determine more realistic possibilities for emissions reductions. Reductions are calculated as percentages above or below the reference case value in each year of the 50 year projection period. Comparing these reductions will reveal which factors are most important in determining aggregate emissions and how soon the light-duty vehicle segment can begin to make significant contributions to emissions reductions.

THE REFERENCE CASE.

Emissions projections for years 2000 to 2050 from the entire fleet of vehicles are derived from three major components: fleet dynamics, travel demand, and emissions factors. Thus,

Emissions = number of vehicles × miles per vehicle × grams per mile. [Figure 6]

Due to the different vehicle types currently and potentially on the market, total vehicle emissions result from the sum of emissions for *j* vehicle types, i.e.

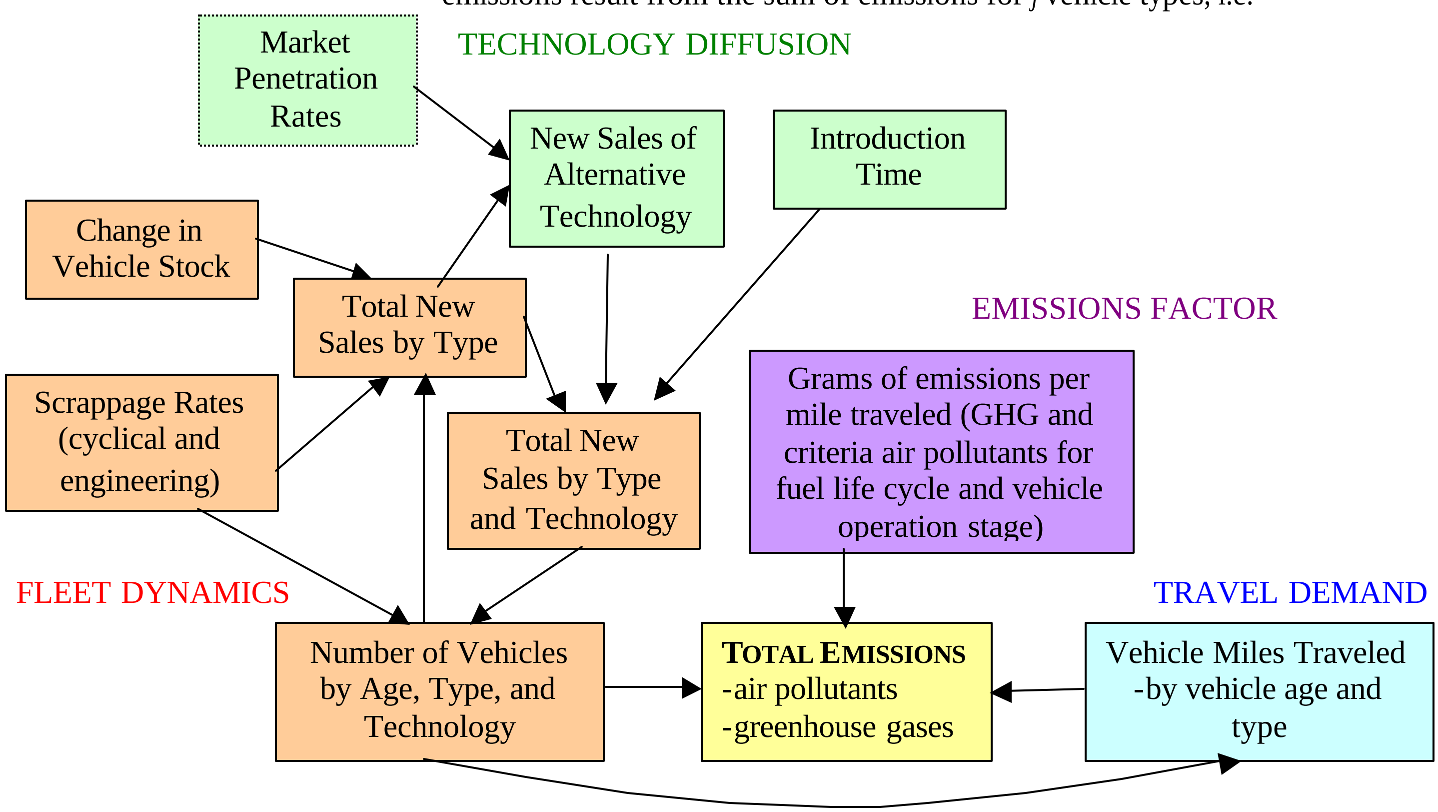

Figure 6. Sketch showing relationship between variables used to calculate total vehicle emissions.

$$\text{Emissions} = \left[\#\,\text{veh}_a \times \frac{\text{miles}}{\text{veh}_a} \times \left(\frac{\text{grams}}{\text{mile}}\right)_a\right] + \ldots + \left[\#\,\text{veh}_j \times \frac{\text{miles}}{\text{veh}_j} \times \left(\frac{\text{grams}}{\text{mile}}\right)_j\right]$$

Fleet dynamics were projected using a cohort survival method where with *j* vehicle types,

$$\text{Total LDV}(t+1) = \sum_{i=1}^{j} \text{Vehicles}(t)_i + \text{Sales}(t)_i - \text{Scrappage}(t)_i\,.$$

The total number of light duty vehicles over the next 50 years was exogenously determined using Census Bureau projections of driving-age populations and a 1:1 ratio of vehicles per person of driving age.[2] Extrapolating current trends of increasing numbers of light trucks on the road produced the proportion of passenger cars versus light trucks. [Figure 7] However, due to uncertainty about consumer preference for light trucks, the proportion of light trucks on the road was assumed to saturate at 50%.[3] Note that although sales of light trucks exceeded sales of passenger cars in 1999, the light truck

[2] Vehicles per person of driving age have been steadily increasing from a ratio of 0.93 in 1990 to a ratio of 0.99 in 2000. This ratio is assumed to saturate at 1. [Ward's Automotive Yearbook 2001 and USCB]

[3] Sensitivity analyses show that even with light trucks reaching a share of 75%, the reference case is changed by less than 10%. With light trucks remaining at 40% of the total vehicle fleet the difference in the reference case is less than 5%. Analysis of scenario results also reveal minimal changes in response to differing ratios of cars to light trucks, in part because the reference and scenario emissions are changing in similar manners.

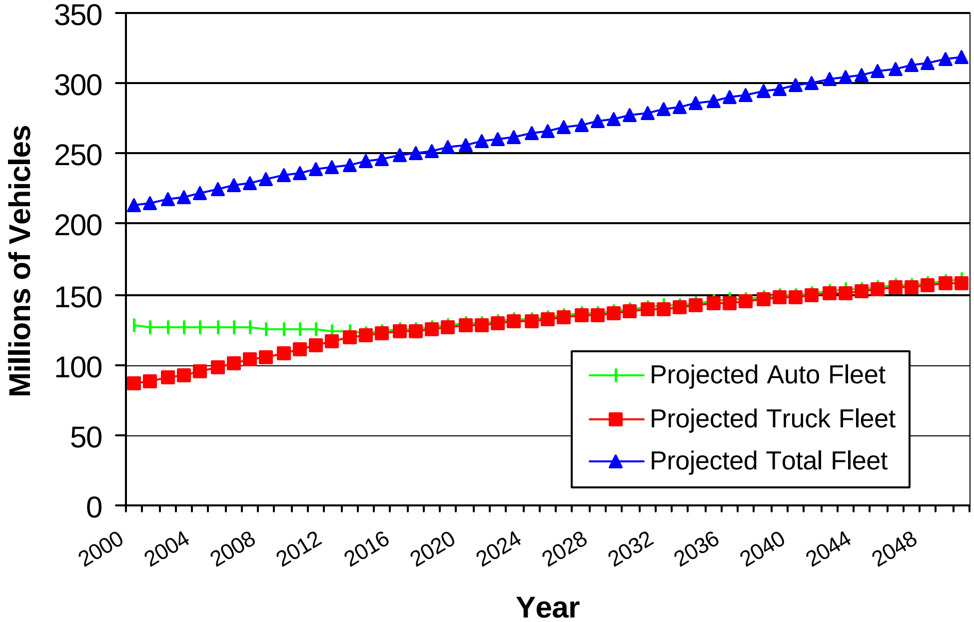

Figure 7. Projected Vehicle Stock by Vehicle Type.

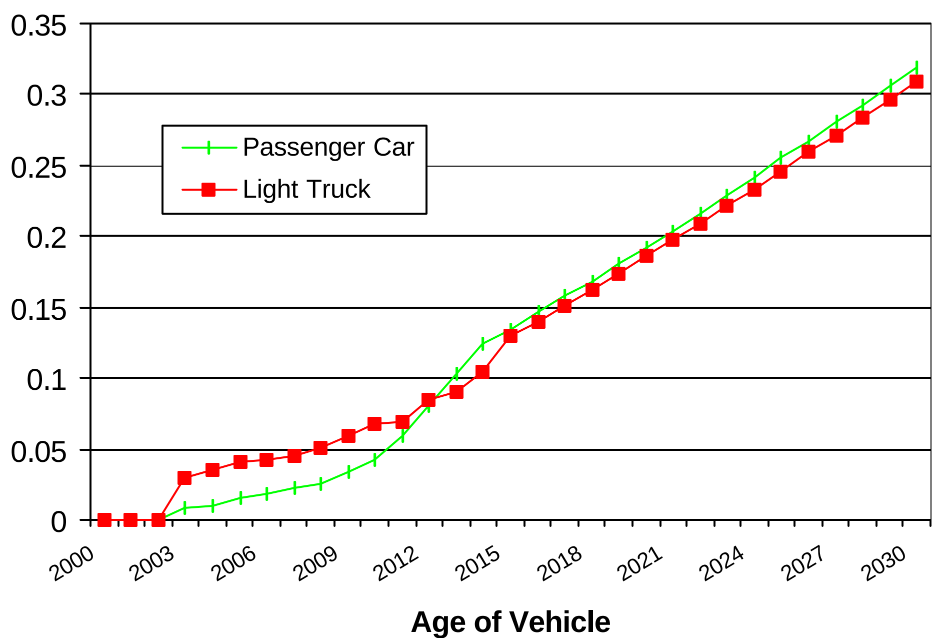

Figure 8. Scrappage Rates by Age of Vehicle
Source: Ward's Automotive Yearbook 2001, TEDB (2000)

proportion of *total* vehicles in the fleet would not reach 50% until about 15 years later due to delays from fleet turnover.

An age-specific fleet is necessary, though, as this added level of detail will provide a more accurate projection of vehicle stock. Additionally, these dynamics will be important to the introduction of new technologies. Scrappage rates for passenger cars and light trucks aged 0 to 14 were calculated using historical age distributions [*14*]; scrappage rates of vehicles 15 years or older were estimated by adjusting values cited in the Transportation Energy Data Book to match the historical figures.[4] [*2*] Vehicles younger than three years old were assumed never to be scrapped. [Figure 8] Multiplying the age-specific scrappage rates by the age distribution of vehicles produces the total number of vehicles of each type scrapped in each year. The total number of vehicles scrapped in year *t* added to the change in fleet size between year *t* and *t*+1 produces the number of sales in year *t*+1, which accounts for both sales to replace old vehicles and sales to new vehicle owners. New sales in each year were calculated by subtracting the total number of vehicles scrapped from the projected total vehicle stock.[5]

Emissions factors (grams per mile) were taken from the Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET) model developed at Argonne National Laboratory based on current fuel efficiencies. [Appendix A] One of the distinguishing features of GREET are its emissions factors based on the life-cycle of the fuel. Greenhouse gases and criteria air pollutants are released during the production and transport of the fuel source as well as from the actual vehicle operation stage, an important consideration when analyzing vehicles with zero tailpipe emissions. From a

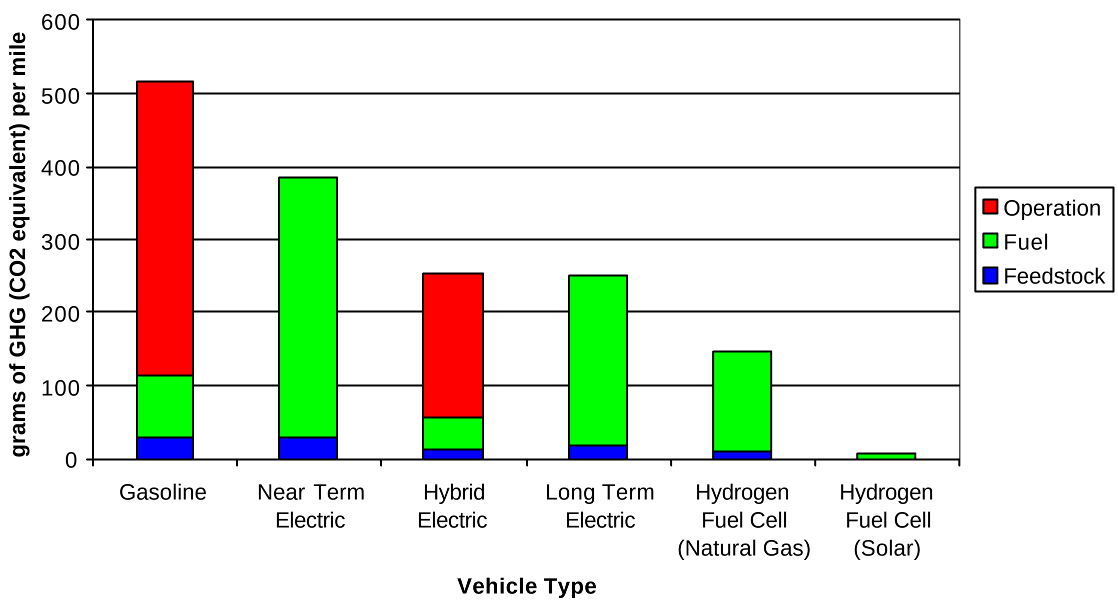

Figure 9. Comparison of fuel-cycle emissions by vehicle type.
Source: GREET Model

fuel-cycle perspective, though, the benefits of battery electric and hydrogen fuel cell vehicle are reduced when accounting for the generation of electricity or hydrogen.

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[4] Scrappage rates reported in the Transportation Energy Data Book based on Greenspan and Cohen model results were significantly lower than historical values. [*16*] To join the two sets of scrappage rates, the relative increase in model rates for vehicles ages 15 to 30 was calculated in reference to the model scrappage rate of 14 year old vehicles. These proportional increases were then applied to the historic scrappage rate of 14 year old vehicles to generate adjusted rates for the older vehicles.

[5] Some discontinuities exist in the projection of sales due to simplifications made in the model as well as assumptions about the ratio of passenger cars to light trucks.

[Figure 9] GREET readily provides the fuel-cycle grams of carbon dioxide, greenhouse gases and five criteria air pollutants per mile of vehicle travel for both passenger cars and light trucks of numerous alternative vehicle types. Light trucks were further classified into two weight categories, those with a gross weight less than 6,000 pounds and those with a gross weight between 6,001 and 8,500 pounds. As the distribution of light trucks between these two categories cannot be reliably predicted, all light trucks were assumed to fall in the heavier class, producing the worst-case emissions projection in the reference case and the most optimistic projections for alternative vehicle emissions. Such an assumption thus encompasses the full range of possible scenarios.

Because the emissions factors are in terms of grams emitted per vehicle mile of travel, creating a projection of total emissions requires projecting total vehicle mile traveled (VMT). Nationwide, VMT have been steadily increasing overall as well as on a per driver basis. [*2*] Average VMT per driver was linearly extrapolated based on historical rates of increase and then multiplied by U.S. Census Bureau projections of driving-age populations to obtain projections of total VMT. [*15*] [Figure 10] Total VMT was then adjusted to incorporate only miles traveled by light duty vehicles, rather than all highway vehicles.[6]

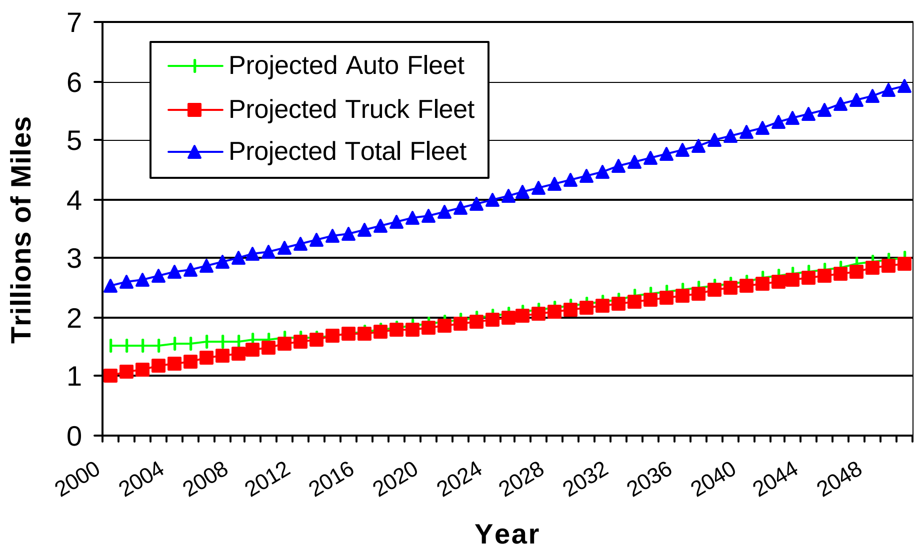

Figure 10. Projected Vehicle Miles Traveled by Vehicle Type. Based on Projections of Driving-Age Population from USCB.

Within each projection year, total vehicle miles traveled by light duty vehicles were distributed to produce average VMT per vehicle type of each age.[7] [Figure 11]

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[6] The adjustment was made by multiplying Total VMT in each year by 0.92, the ratio of VMT historically traveled by light duty vehicles.

[7] Solving for k in the equation,

$$VMT_{totalLDV}(t) = \sum_a \left[k \times \left(\% \frac{VMT}{Veh_{car}} \right)_a \times \left(\#Veh_{car}(t) \right)_a \right] + \sum_a \left[k \times \left(\% \frac{VMT}{Veh_{truck}} \right)_a \times \left(\#Veh_{truck}(t) \right)_a \right]$$

produces a scaling factor by which the age distribution of total VMT can be multiplied to generate average age-specific VMT per vehicle. The same age distribution was used for each projection year, thus, newer vehicles were assumed to be driver more intensely than older vehicles.

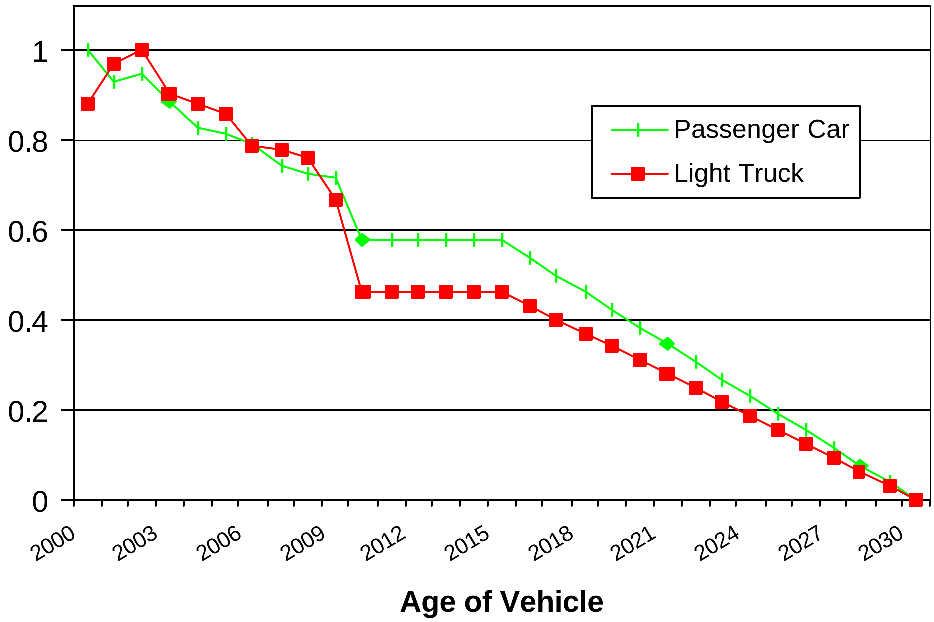

Figure 11. Normalized Distribution of Vehicle Miles Traveled by Age. Based on 1999 Estimated Travel per Vehicle (TEDB).

Age-specific distribution of VMT was normalized based on 1999 estimates of vehicle travel by age, which younger vehicles, tending to be more reliable and in better repair, driven more intensely than older vehicles.[8] [2]

Multiple factors influencing vehicle emissions were omitted from the reference case for the sake of simplicity. Economic factors such as consumer confidence and fuel prices would affect vehicle sales and travel demand. Also, fuel economy of conventional vehicles is assumed to remain constant for the 50 year projection period. Although minor improvements in efficiency could be expected, historically such improvements have been diverted to increase vehicle power or offset additional weight. The recent failure to increase Corporate Average Fuel Economy (CAFE) standards since their last revision in 1986 has left new vehicle fuel economy virtually unchanged since 1990. [Figure 12] Although a 1% annual reduction in emissions from conventional vehicles produces a 40% difference in reference case emissions by 2050, changes in fuel economy on are not incorporated into this model for three reasons. First any substantial improvements in efficiency will likely include, if not require, hybrid technologies. In addition, efficiency of alternative vehicles could also be

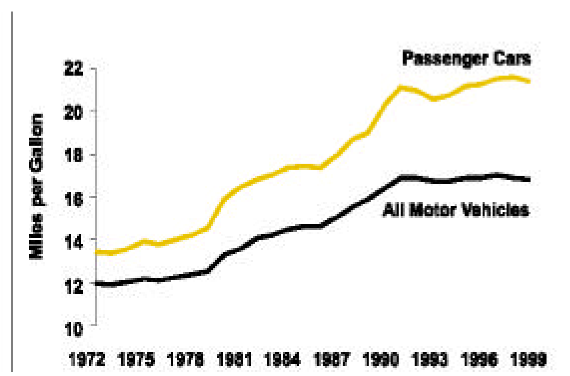

Figure 12. Trends in motor vehicle fuel efficiency. Source: U.S. Inventory of Greenhouse Gas Emissions and Sinks: 1990–1999. (EPA)

[8] Data was only provided up to vehicles aged 14 years. VMT in the final category of 15+ vehicles was thus distributed to produce a linear decline to zero at age 31.

expected to improve with time as the technology becomes better understood. Because such improvements remain unpredictable, alternative vehicle efficiency must remain constant throughout the projection period. Stagnant conventional fuel economy is therefore justified in the interest of consistency. Finally, as this model is intended to produce comparative rather than predictive results, the omission of these variables should not invalidate the projected emissions reductions.

SCENARIOS. As with the reference case, a number of omissions were made to simplify the scenarios. Economic factors were ignored that would influence whether auto manufacturers could afford to invest in research and development of new technologies. Additionally, this analysis does not make any considerations for the higher cost of alternative vehicles or the investment needed for new infrastructure. Demographic aspects such as family lifecycle, household income, and residential settlement patterns would also influence market penetration and travel demand but were not included.

As discussed previously, scenarios differ only in the penetration of alternative vehicles. In the reference case, no alternative vehicles are introduced, providing a baseline for comparison of all other scenarios. Projected sales of passenger cars and light trucks are perhaps the most important variable of the model as this is where differences between scenarios will be introduced. Market penetration is only able to influence the composition of new vehicle sales, creating a virtual bottleneck for any benefits of alternative vehicles. Multiplying market penetration by new sales will produce the total number of alternative vehicles sold in a given year; remaining sales are assumed to be conventional gasoline vehicles. [Figure 13] Alternative vehicles are assumed only to replace sales of conventional vehicles and do not create an additional market. Once alternative vehicles have been introduced into the model, they are subject to the same cohort survival patterns as conventional vehicles and the same travel demand trends.

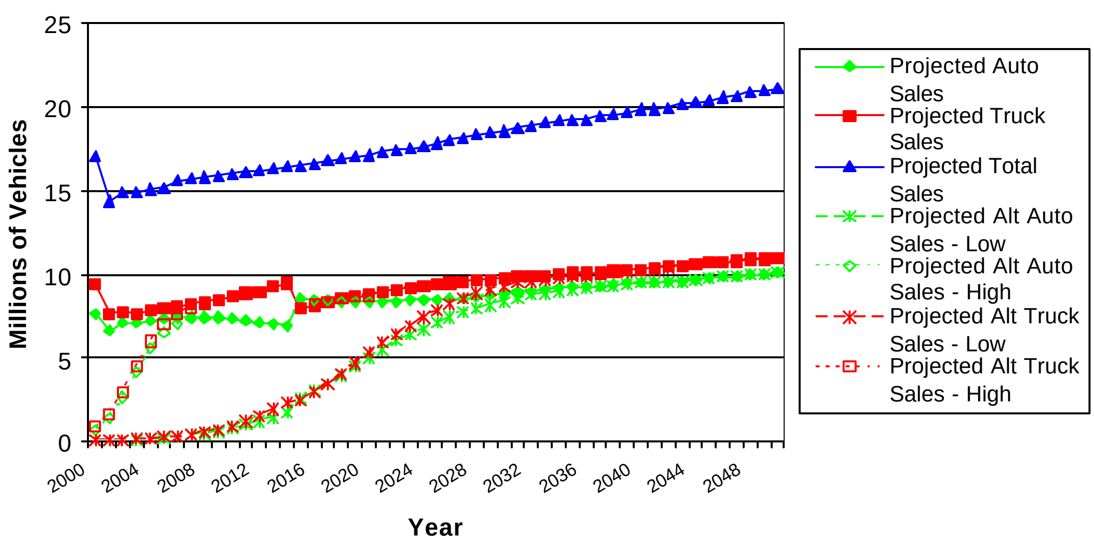

Figure 13. Projected Sales of Total and Alternative Vehicles.

Emissions projections were then generated using three different penetration rates for five alternative vehicle technologies (near-term battery electrics, hybrid electrics, long-term battery electrics, fuel cell vehicles using hydrogen produced from natural gas, and fuel cell vehicles using solar-generated hydrogen). The sensitivity of these projections to the saturation level of penetration as well as the time of introduction was also examined given that the basic penetration rate scenarios all assume 100% saturation and alternative vehicle introduction in the first year of the projection period. These penetration rates reflect potentially emissions reductions from government mandate (high) to market driven (low), as well as a combination of regulation and market incentives (moderate

Finally, while these other scenarios allow for only one alternative technology to penetrate, a transitional scenario considers the effect of sequential penetration by two different alternative technologies, simulating the prediction of hybrids serving as a transitional vehicle to hydrogen fuel cell vehicles. This scenario assumes that the total number of alternative vehicles remains fixed, but that this fleet can include two types of vehicles. Sales of the initial technology are phased out while sales of the second technology grow, though combined sales do not exceed projections for sales of any type of alternative vehicle. Such an assumption produces conservative results given that in actuality each of the alternative vehicles may appeal to different types of consumers, thus increasing the rate of market penetration for alternative vehicles.

Results

Technological Differences

Even without allowing for variations in market penetration rates, emissions projections vary widely due to the different emissions factors associated with each vehicle technology. However, in no cases did significant reductions occur prior to 2010. Assuming a moderate penetration rate for all technologies, greenhouse gases would decline over the fifty years for each of the alternative vehicles, with reductions roughly following the carbon content of each fuel source. [Figure 14] Near-term battery electric

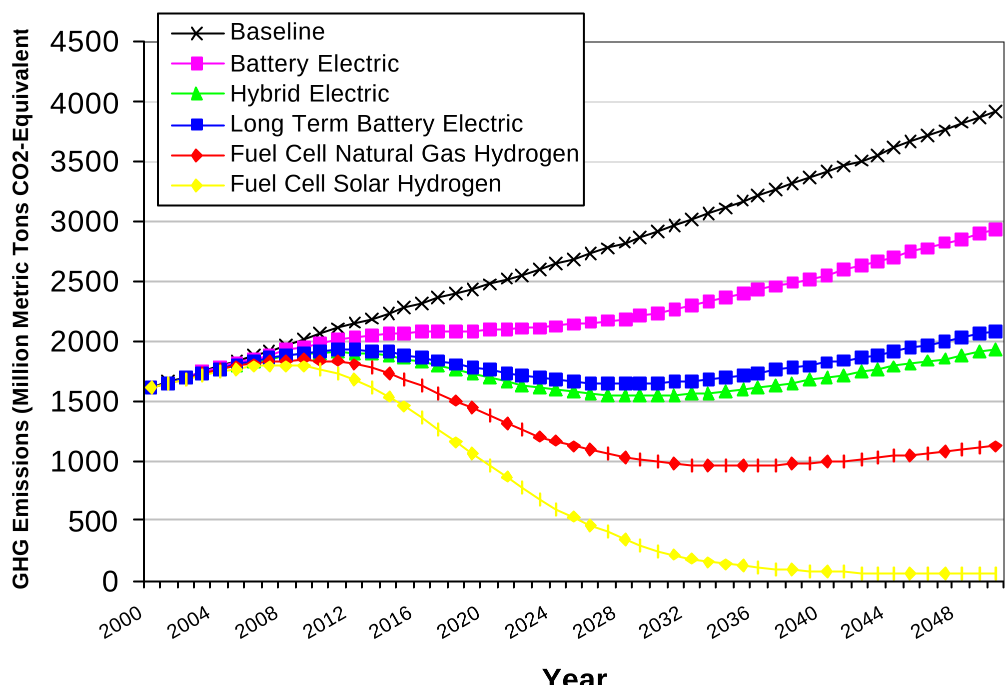

Figure 14. Technology impact on greenhouse gas emissions using moderate penetration rates.

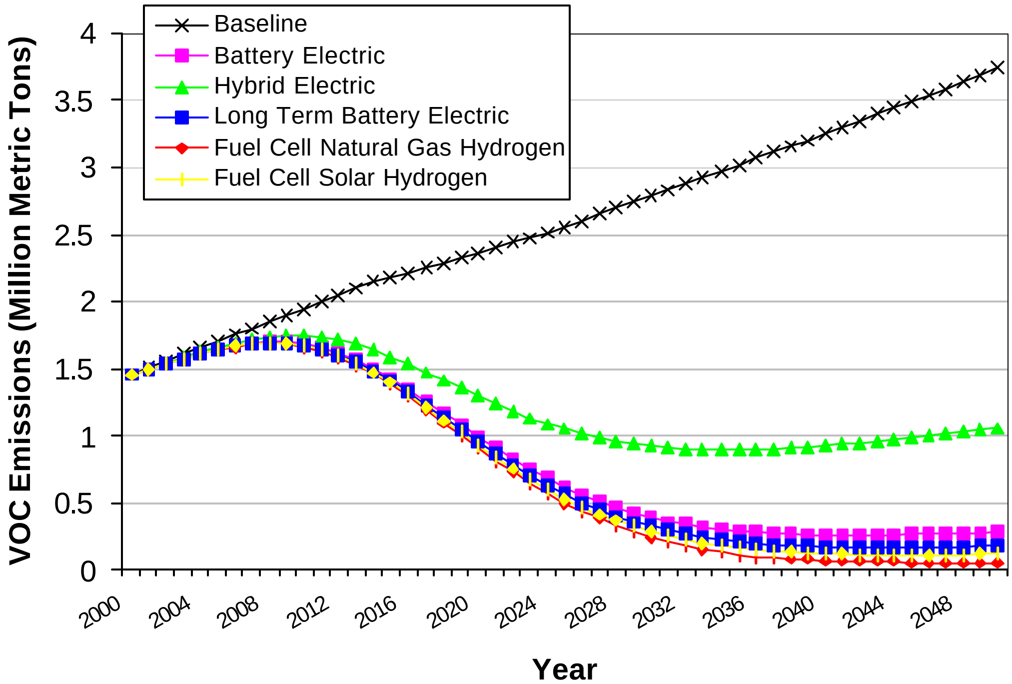

Figure 15. Technology impact on VOC emissions using moderate penetration rate.

vehicles would produce the least reduction, however, one still roughly 20% lower than the reference case at the end of the projection period. Long-term battery electrics and hybrids would reduce greenhouse gases by almost half. Hydrogen fuel cell vehicles demonstrate the greatest potential for emissions reductions, though reductions depend greatly on how the hydrogen is generated; natural gas hydrogen results in almost 75% reductions by 2050 while solar hydrogen could potentially eliminate all greenhouse gas emissions as early as 2040. Cumulative emissions reductions are not quite as dramatic, though, as delays in fleet turnover maintain higher emissions during the initial years. Thus, complete elimination (i.e. 100% reduction) of emissions by 2050 results in only a 70% reduction in cumulative emissions. [Appendix B] CO_2, as the most abundant greenhouse gas emitted by the transport sector, produces virtually identical emission reduction patterns as that of all greenhouse gases.

In all scenarios for VOC's, alternative vehicle technologies could also reduce emissions relative to the reference case. Resulting primarily from gasoline combustion, VOC's emissions are therefore almost completely eliminated with all alternative technologies except hybrid electric vehicles, which continue to use gasoline. [Figure 15] However, VOC's emissions from hybrids are still approximately 75% lower given their improved fuel economy. Emissions from the remaining alternative technologies follow almost the same pattern, though diverging slightly after 2025. Reductions in NO_x are not as promising, particularly for both types of battery electric vehicles. [Figure 16] In fact, near-term battery electrics produce equal amounts of NO_x as the reference case for the entire projection. Although long-term batter electrics eventually reduce NO_x by about 40% annually compared to the reference case, fuel cell and hybrid vehicles produce much greater reductions, though never completely resulting in zero emissions.

In contrast to the other air pollutants where all technologies were found to provide some benefits, sulfur oxide (SO_x) emissions rise three- to seven-fold under both battery electric scenarios. [Figure 17] However, total SO_x would not increase due to the

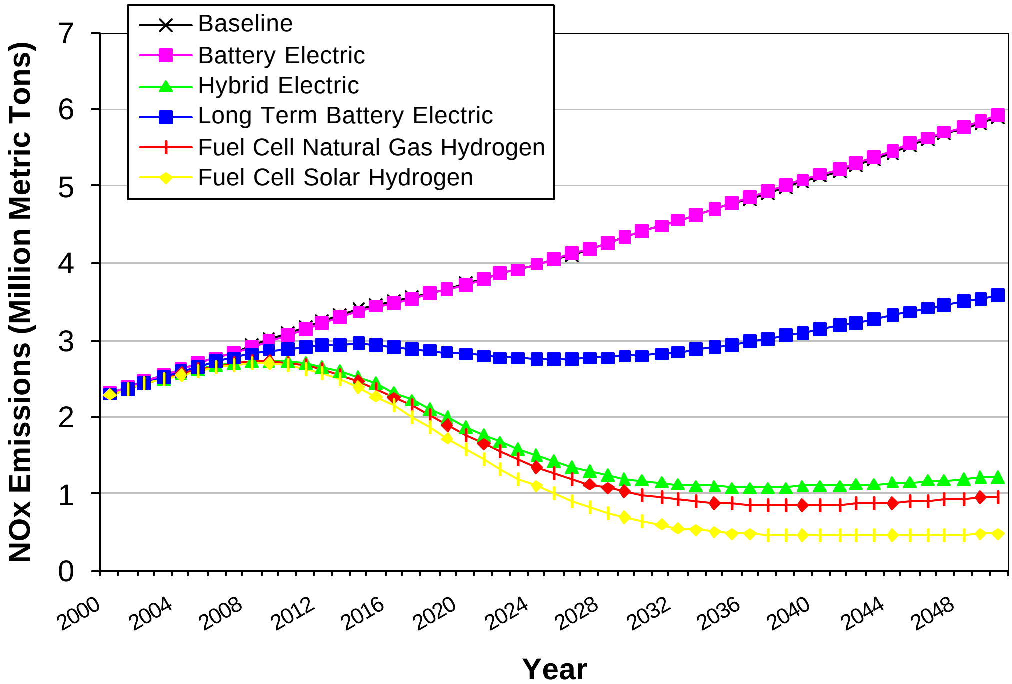

Figure 16. Technology impact on NO_x emissions using moderate penetration rate.

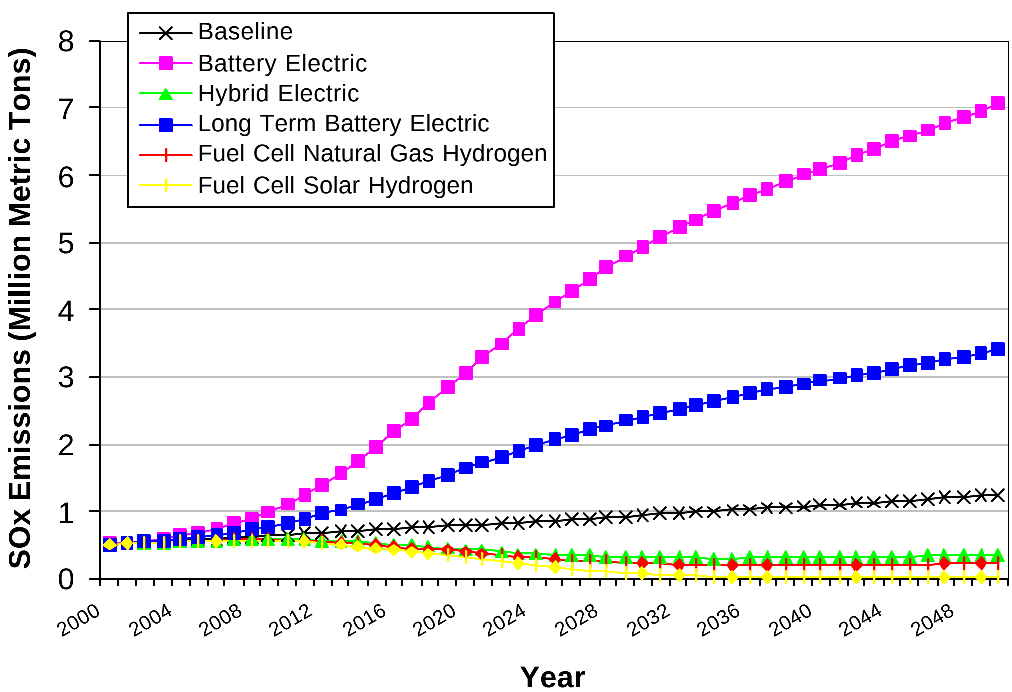

Figure 17. Technology impact on SO_x emissions using moderate penetration rate.

caps regulated by Title IV of the Clean Air Act; emissions would simply be redistributed among polluters. However, greater contributions would increase pressure for reductions and thus increase the cost of compliance. Transportation generally does not contribute to high SO_x levels, however electric vehicles would rely on highly polluting electric utilities for power. Unless the national fuel mix for electricity generation shifts away from coal to cleaner fuels such as natural gas, electric vehicles cannot be considered entirely better than conventional gasoline vehicles. The impacts to SO_x emissions illustrate the importance of analysis from a fuel life-cycle perspective for valid comparison between vehicles technologies as electric vehicles are only zero emission at the operation stage.

Battery electric vehicles, both near- and far-term, prove to be the least beneficial of all the technologies for climate change and air pollution with higher emissions of greenhouse gases, SO_x, and NO_x than the other technologies and in some cases higher than the reference case by three- to seven-fold. In contrast, hydrogen fuel cell vehicles produce reductions greater than 90% by 2050 in almost all cases. However, for all technologies, at least 20 years is required until 50% reductions from the reference case are achieved.

Penetration Scenarios

Emissions projections will also vary when using different penetration rates for each alternative technology. Nonetheless, the relative trends of emissions scenarios remain the same between the different technologies. As expected, faster penetration rates result in greater changes in emissions—both positive and negative. Likewise, slower penetration rates lead to greater overlap with the reference scenario, thus producing smaller changes. For example, looking only at hybrids—whose emissions tended to fall in the middle of the various projection ranges—the low penetration scenario reached the maximum reduction in greenhouse gases about 25 years later than the high penetration scenario. [Figure 18] Cumulative greenhouse gas emissions differ by 5-25% between the high and low penetration scenarios depending on the vehicle technology. Similarly, cumulative emissions of the air pollutants VOC, NO_x, and SO_x, are reduced by as much as 25% and SO_x emissions also increase by nearly 125% for near-term battery electric vehicles. [Appendix B]

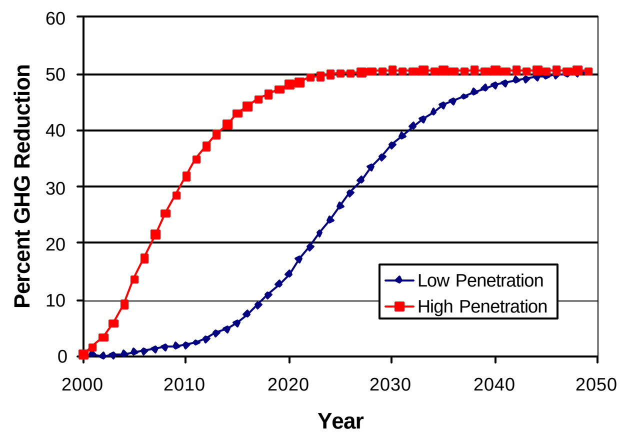

Figure 18. Difference in GHG reductions for hybrids due to different penetration rates.

These changes are significantly influenced by the assumption that alternative technologies are introduced in both passenger cars and light trucks at the beginning of the scenarios. In reality, though, new technologies tend to be introduced in passenger cars first; when and whether these technologies are introduced in light trucks remains uncertain. Previous scenario studies in fact do not explicitly distinguish whether alternative technologies are introduced only into passenger cars or all light duty vehicles. However, due to the increasing popularity of light trucks, substantial emissions reductions will depend heavily on the introduction of alternative light trucks. For instance, annual greenhouse gases will be reduced at most by 20% with only alternative passenger cars compared to 50% with alternatives for all light duty vehicles. [Figure 19] In terms of cumulative emissions, the difference between assuming only alternative passenger cars versus all light duty vehicles produces dramatic disparities in emissions reductions, particularly for some air pollutants where emissions differ by more than 50%. [Appendix B] Although these are the most extreme values given that alternative light trucks will

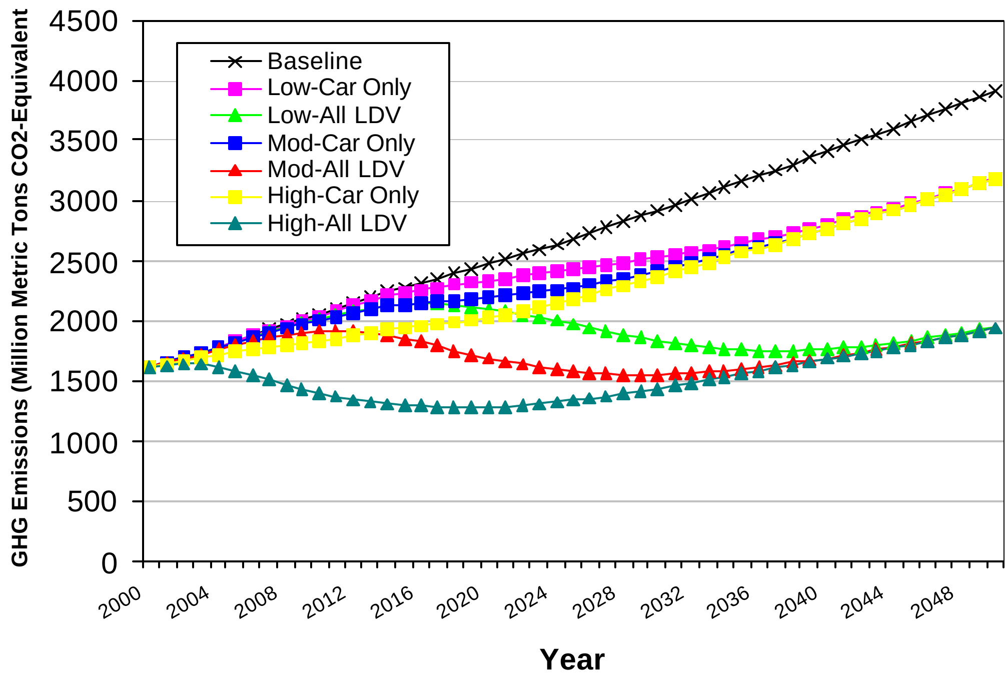

Figure 19. Differences in greenhouse gas emissions depending on penetration rate and inclusion of light trucks.

neither be introduced immediately nor not at all, the differences still illustrate the strong sensitivity of emissions to fleet composition.

The sensitivity of emissions to introduction time can be evaluated by applying the same penetration rate starting in different years. Essentially, delays in introduction cause the emissions projections to follow the reference scenario projection until alternative vehicles become "available". Thus, the longer the delay, the less beneficial the technology will be in the long run. Another possible variation on penetration rates are the market saturation levels. The three main penetration rates all assume 100% market saturation, however, as shown in the historical data for front-wheel drive, some technologies may not completely saturate. Using the 85% saturation of front-wheel drive does not produce drastically different results, though, than assuming 100% saturation. A potentially more influential effect would be to assume only 50% saturation as Difiglio and Fulton estimate. Annual reductions in the long run are essentially equivalent to saturation levels, i.e. 50% saturation produces 50% of the reductions produced with 100% saturation. Therefore, depending on the magnitude, saturation levels may or may not significantly impact potential emissions reductions.

Transitional Scenario

Introducing both hybrids and hydrogen fuel cell vehicles may not be as advantageous as expected, as fuel cell vehicles will essentially be introduced at a later time. During the interim 15 years (the time estimated until fuel cell vehicles will be commercially available on a widespread level) when only hybrids are available, penetration is still too low for emissions to differ significantly from the reference scenario. Once the fleet of alternative vehicles reaches a critical mass to impact emissions on a noticeable level, the difference between hybrids alone and hybrids with fuel cell vehicles is rather small. Whether fuel cell vehicles penetrate at a moderate or high rate changes projected greenhouse gas emissions only minimally. [Figure 20] In part, the minimal effect can be attributed to the assumption that the fuel cell vehicles will be fueled by hydrogen generated by natural gas. Such an assumption is more conservative given that infrastructure for photovoltaic hydrogen would require greater investment and more time to establish than natural gas hydrogen. However, a transition to solar-generated hydrogen would increase the benefit of fuel cell vehicles. Perhaps a more realistic transitional scenario would incorporate variations in introduction time for passenger cars and light trucks as well as add a third technology type to allow for solar hydrogen in the long term. In the short term, though, emissions reductions will be limited if a more sustainable and less carbon intensive source of hydrogen cannot be produced in a cost effective manner.

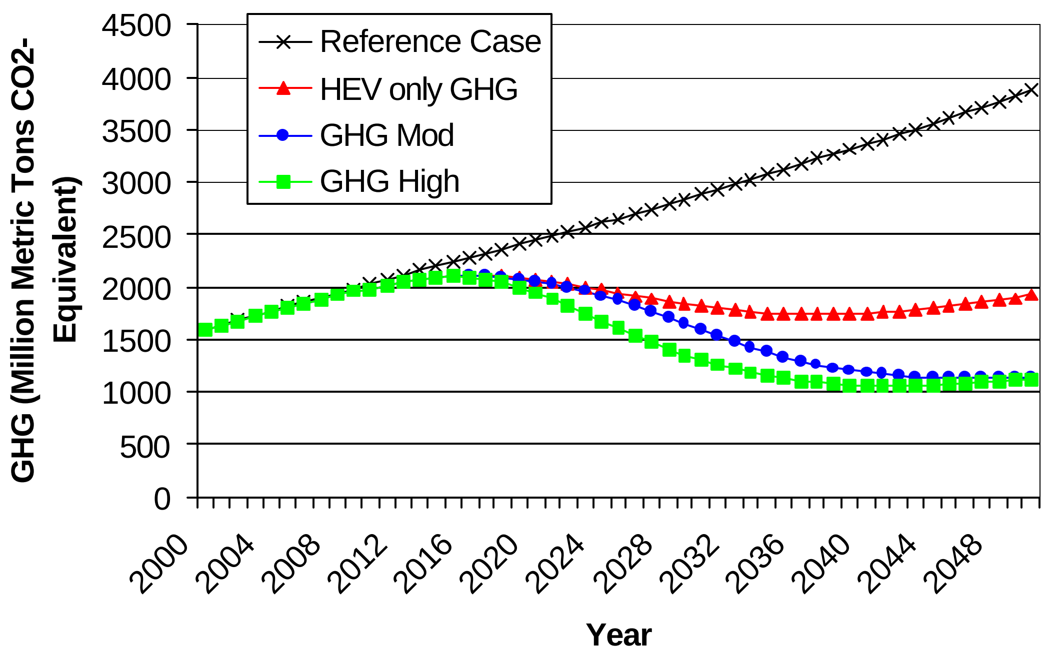

Figure 20. Transitional scenario where GHG Mod = low penetration of hybrids followed by moderate penetration of hydrogen (natural gas generated) fuel cell vehicles and GHG High = low penetration of hybrids followed by high penetration of hydrogen (natural gas generated) fuel cell vehicles. HEV only = low penetration of hybrids with no hydrogen fuel cell vehicles introduced.

Best Guess Scenario

In reality, modifying the transition scenario to account for projected delays in introduction will limit emissions reductions even further. Volume of hybrid electric passenger cars would likely not meet year one alternative sales projections until 2002 and hybrid electric light trucks are not slated for market until 2004 at the earliest. Incorporating these delays and also adjusting the introduction of fuel cell vehicles to 25 years from the start of the projection reduces cumulative emissions reductions from 40 to 30%. The delays also add an additional decade to the "no-delay" transitional scenario to reach a 50% point reduction. However, by the final year, emissions differ by only 3% from the reference case, showing promise of a nearly two-thirds reduction despite the delays. [Figure 21] For a variety of reasons previously discusses, the widespread

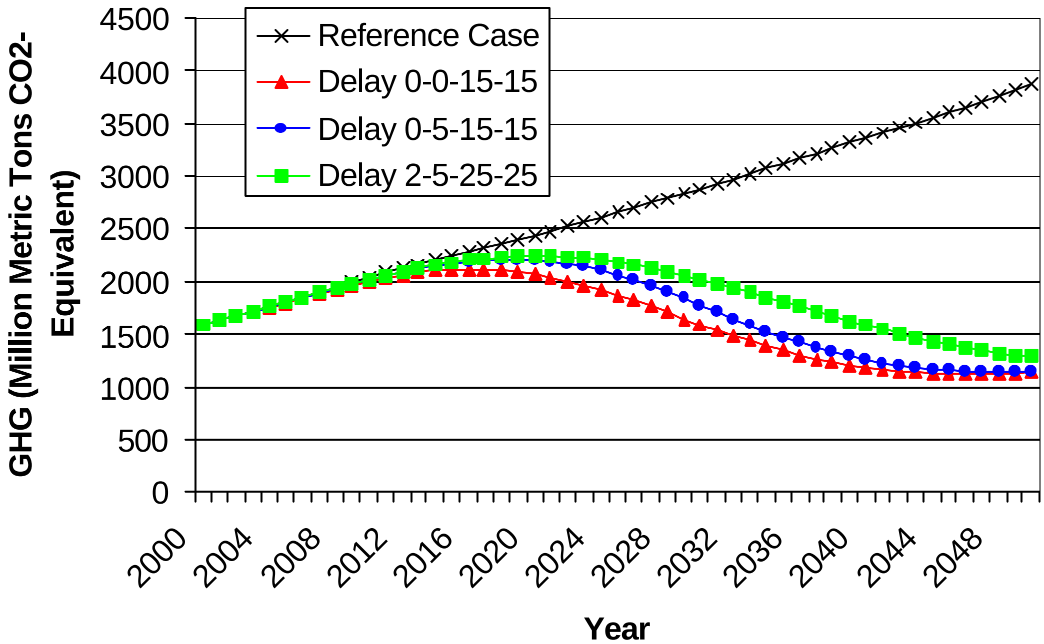

Figure 21. Results of Best Guess Scenario. Delay 0-0-15-15 = no delay in low penetration of HEV passenger cars or light trucks and 15 year delay for moderate penetration of FCV passenger cars and light trucks; Delay 0-5-15-15 = no delay in low penetration of HEV passenger cars, 5 year delay in low penetration of HEV light trucks and 15 year delay for moderate penetration of FCV passenger cars and light trucks; Delay 2-5-25-25 = 2 year delay in low penetration of HEV passenger cars, 5 year delay in low penetration of HEV light trucks and 25 year delay for moderate penetration of FCV passenger cars and light trucks;

penetration of battery electric vehicles or solar-generated hydrogen is unlikely to occur to make significant contributions to emissions reductions during this timeframe.

Discussion and Conclusion

As cautioned earlier, the results of these scenarios are intended to be comparative rather than predictive due to the number of simplifications made that render this model somewhat unrealistic. The divergence from reality is partially highlighted by the fact that a number of scenarios assumed market penetration beginning in 2000, while in the reality of 2002 these technologies have yet to be marketed. Consequently, it is difficult to conclude that any of the penetration scenarios will realistically result in achieving reductions outlined by the Kyoto Protocol or compliance with air quality standards. Estimating that a national level reduction of 30% from the reference case would be necessary to meet Kyoto targets, only hydrogen fuel cell vehicles would be able to achieve the full level of reductions within 25 years.

Nonetheless, the results of these scenarios still illustrate a few important points. First, point reductions, particularly for the final year of the projection, should not be confused with cumulative reductions. End point reductions typically reflect the improvements in vehicle efficiency, as the technology has completely saturated the market by this point and essentially permeated the entire fleet. In these scenarios, penetration rate projections all result in the same final reduction as new sales of alternative vehicles are identical by this time and enough time has passed to phase out most conventional vehicles. However, due to the varying time needed to transform the market, cumulative emissions gives a more accurate depiction of the benefits of alternative vehicles in the context of fleet dynamics. Therefore, cumulative emissions provide a better comparison for determining the effects of market penetration. Point goals will still remain important, though, for targets such as the Kyoto Protocol.

Another interesting result is the shape of the emissions projections. Scenarios may overlap with the reference case for the first one to fifteen years and even longer if there are any delays in introduction. During this period, alternative vehicle populations are too low to have any impact on total emissions. This should not be interpreted to mean that these alternative technologies should not be pursued immediately, though, as looking farther into the future reveals that emissions will eventually decline once a sufficient fleet size has been reached. Postponing or even eliminating introduction of alternative vehicles will simply increase emissions in the long term. In some cases, emissions begin increasing again during the second half of the scenario, following either a decline or plateau in emission levels. At this point, the sheer increase of vehicles overpowers any improvements in efficiency at the vehicular level.

Similar disparities between vehicular and fleet-wide effects exist with the time lag for complete fleet turnover. Thus, even though alternative vehicles completely saturate the market in less than ten years in the high scenario, maximum reductions are not achieved for another ten years, during which time conventional vehicles are replaced by alternative ones. Additionally, even with vast improvements in alternative passenger cars, fleet reductions will never reach the same levels as reductions at the vehicle level without the inclusion of alternative light trucks. Scenarios including all light duty vehicles produce reductions of most criteria air pollutants and greenhouse gases two to three times larger than scenarios with only alternative passenger cars. The disparity is even more pronounced for emissions such as CO where scenarios not included light trucks produced virtually no reductions at all, while scenarios that did include light trucks produced reductions ranging from 60 to 88%. Another disparity is the discontinuity between fuel efficiency and air pollution in hybrids. Hybrids are roughly twice as efficient as conventional gasoline vehicles, making their greenhouse gas emissions about half of the reference scenario. However, the same relationship does not hold true for VOC's, NO_x, or SO_x, where hybrids exhibit disproportionately greater benefits than perhaps expected when based on fuel economy. This effect is perhaps due to the feature in hybrids for immediate engine shutdown when the vehicle is idle or additional emission control features not present on conventional gasoline vehicles.

The main limitation of this study is the explicit omission of what policies could produce a given market penetration rate. As previously discussed, infrastructure presents a major obstacle to the adoption of battery electric and fuel cell vehicles. Another consideration is the disparity between what the scenario projects as alternative vehicle sales and what is actually available on the market. Fuel cell vehicles from any kind of hydrogen are still in the prototype stages, though some automakers are aiming for market-ready products within the next five to fifteen years. Currently, battery electric vehicles are essentially available only as fleet vehicles, as consumer models since have been discontinued. Lastly, only three hybrid vehicles are available at the moment, all of them compact passenger cars. Both the Honda Insight and Toyota Prius are produced in limited quantity with long waits for consumers. Honda also recently made the hybrid feature available on its popular Civic. However it is only now coming on the market and therefore too soon to project consumer demand and evaluate automaker supply. Performance-wise, these vehicles are not yet comparable to conventional vehicles to justify the additional cost. Eventually, though, these vehicles should become more competitive with conventional vehicles as alternative vehicles are produced using mass manufacturing techniques and the technology is improved. In the interim, tax credits have been proposed to encourage consumers to purchase alternative vehicles. However, it is unclear whether these incentives will accelerate market penetration if vehicle performance and infrastructure constraints remain an issue. Furthermore, the exclusion of economic factors such as consumer confidence and fuel prices could potentially drive sales of alternative vehicles. These considerations are all implicitly included, though, through the use of the different penetration rates.

Additionally, although this study was not explicitly examining the policy necessary to achieve the penetration rates used in each of the scenarios, some forms of policy would invariably be necessary to promote such technological change. Government mandates similar to CAFE standards or previous safety feature legislation would likely be required for any of the technologies to penetrate at the rate used in the high scenarios. Even during the oil embargo of the late 1970's, corporate average fuel economy improved only moderately, in part because of the time delay in introducing and preparing a new more fuel efficient vehicle for market as well as the time needed for vehicle stock turnover. Although the federal government subsequently began to regulate fuel economy in response to public outrage, outrage eventually diminished when fuel supplies—and prices—returned to normal and political will to improve efficiency standards could not be sustained. In the absence of the potential for a more permanent oil crisis, prospects for federal command-and-control regulation are therefore low, especially in light of the growing popularity of gas guzzling light trucks.

At the state level, though, legislatures appear somewhat more willing to regulate transportation technology itself, particularly California and the Northeast states. California has already passed stricter regulation on air pollutants, which other states are currently considering adopting. Even more radical has been the most recent passage of legislation that would place limits on tailpipe emissions of greenhouse gases in California. Though vigorously opposed by the auto industry, the bill now awaits a decision by the governor and the outcome could prove to be enormously influential in shaping market penetration of alternative vehicles.

For most states, though, more conservative policies will likely influence the rate of market penetration. Economic incentives encouraging voluntary compliance will probably be the types of policies proposed and approved, especially under the Bush administration. For example, the recent Energy Policy Act of 2002 includes $3 billion worth of tax credits for those purchase hybrids or fuel cell vehicles over the next 11 years. Such tax credits will be able to accelerate the rate of market penetration slightly over the rate from market forces alone by making conventional and alternative vehicles more comparable in price. Otherwise, at current gas prices, fuel savings over the lifetime of the vehicle would not cover the additional cost for alternative technologies.

Future scenario studies on potential emissions reductions from transportation and policy decisions should therefore account for the following influences of market penetration rates:

- Faster penetration rates increase cumulative emissions reductions by as much as two- to four-fold compared to slower penetration rates. Faster rates can also reach the same level of point reductions in half the time.
- Less than 50% saturation of the market by a new technology will likely have a minimal impact on the potential of alternative vehicles to contribute to emissions

reductions.

- Delays in introduction of new technologies will play an important role in the contribution of alternative vehicles to emissions reductions. A 25 year delay in the introduction of hydrogen vehicles, even with hybrids available in the interim, will result in a 20 year delay in achieving 50% reductions from the reference case. Despite such delays, though, alternative vehicles hold great promise for reductions in the long-term. Given realistic assumptions about introduction dates, the appropriate combination of technologies would be able to reduce emissions by roughly two-thirds below reference values by 2050.
- Market penetration rates strongly influence vehicle fleet turnover. Although fuel cell vehicles using solar-generated hydrogen are virtually emission-less, a fast or slow penetration rate will determine whether it will take 25 or 50 years for the entire fleet to become zero emission.
- Emissions reductions are highly sensitive to the composition of vehicles penetrating the market. The omission of alternative light trucks could produce emissions off by two orders of magnitude.
- Finally, the type of technology will determine how quickly an alternative vehicle can penetrate the market This selection will in turn determine the extent of emissions reductions. [Figure 22]

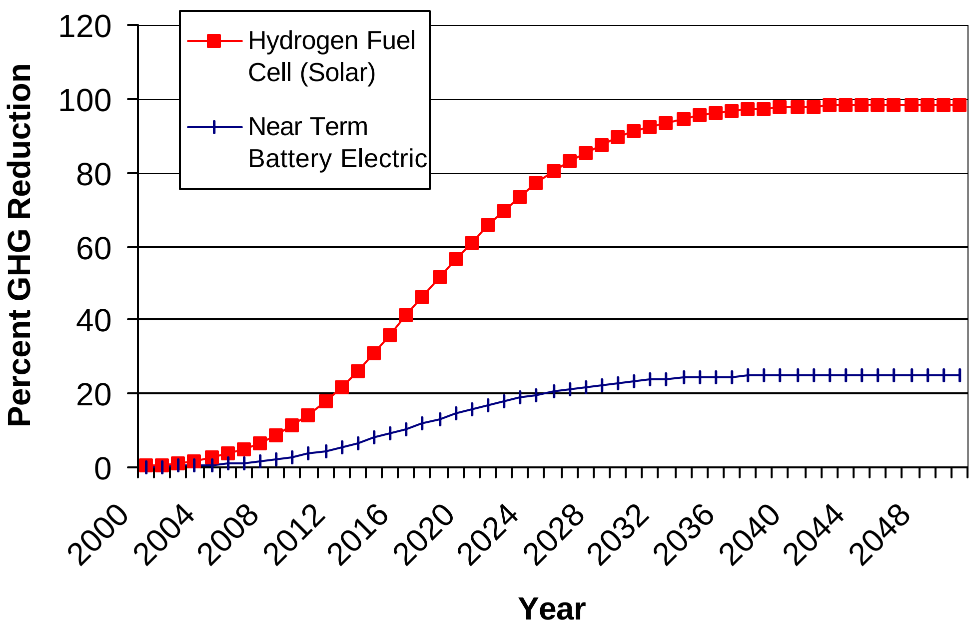

Figure 22. Difference in reductions between two technologies with identical penetration rates.

However, in no realistic cases will technology alleviate the need for the transportation sector to make emission reductions in other ways in the near term. Alternative vehicles need to account for a sizeable proportion of the total fleet before their emissions benefits will have an impact. To argue, though, that these minimal impacts warrant delayed introduction will simply postpone the benefits of emissions reductions. Instead, non-technological solutions such as curbing growth in vehicle miles traveled or vehicle ownership should be pursued in the near term to reduce the environmental impacts of personal transportation.

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Appendix A. Vehicle Emission Factors.

	PC GV CG			PC EV: US mix		
	Feedstock	Fuel	Operation	Feedstock	Fuel	Operation
Total Energy	192	1144	5156	256	5280	0
VOC: Total	0.023	0.073	0.207	0.03	0.006	0
VOC: Urban	0	0.025	0.207	0	0	0
CO: Total	0.08	0.059	5.517	0.057	0.056	0
CO: Urban	0	0.007	5.517	0.001	0.004	0
NOx:Total	0.05	0.148	0.275	0.071	0.707	0
NOx:Urban	0	0.012	0.275	0.002	0.013	0
PM10: Total	0.003	0.016	0.033	0.015	0.041	0.021
PM10: Urban	0	0.001	0.033	0	0.001	0.021
SOx:Total	0.015	0.1	0.05	0.041	0.884	0
SOx:Urban	0	0.001	0.05	0	0.002	0
CO2	18	82	390	18	353	0
GHGs	28	85	401	30	354	0

	PC GI HEV: FRFG2, MTBE			PC EV: US mix		
	Feedstock	Fuel	Operation	Feedstock	Fuel	Operation
Total Energy	90	540	2462	165	3456	0
VOC: Total	0.01	0.034	0.106	0.018	0.004	0
VOC: Urban	0	0.012	0.008	0	0	0
CO: Total	0.038	0.039	2.759	0.036	0.035	0
CO: Urban	0	0.004	2.759	0.001	0.002	0
NOx:Total	0.023	0.07	0.036	0.043	0.389	0
NOx:Urban	0	0.007	0.036	0.001	0.008	0
PM10: Total	0.001	0.007	0.033	0.01	0.025	0.021
PM10: Urban	0	0	0.033	0	0.001	0.021
SOx:Total	0.005	0.036	0.004	0.023	0.385	0
SOx:Urban	0	0	0.004	0	0.001	0
CO2	9	41	186	12	230	0
GHGs	13	44	196	19	231	0

	PC H2 FCV: NG			PC H2 FCV: solar		
	Feedstock	Fuel	Operation	Feedstock	Fuel	Operation
Total Energy	98	711	1559	0	98	1559
VOC: Total	0.001	0.007	0	0	0.016	0
VOC: Urban	0	0.003	0	0	0.003	0
CO: Total	0.02	0.065	0	0	0.036	0
CO: Urban	0	0.014	0	0	0.007	0
NOx:Total	0.016	0.108	0	0	0.061	0
NOx:Urban	0	0.037	0	0	0.012	0
PM10: Total	0.001	0.003	0.021	0	0.006	0.021
PM10: Urban	0	0.001	0.021	0	0.001	0.021
SOx:Total	0.004	0.025	0	0	0.002	0
SOx:Urban	0	0	0	0	0	0
CO2	8	133	0	0	8	0
GHGs	11	136	0	0	8	0

Appendix B. Percent Change from Reference Case of Cumulative Emissions for 2000-2050.

		VOC:	CO:	NO_x:	PM10:	SO_x:	CH_4	N_2O	CO_2	GHGs
Battery Electric (near term)	Low (Cars only)	-11.90%	-0.02%	8.60%	11.93%	100.43%	-3.48%	-20.39%	-5.28%	-5.51%
	Low (All LDV's)	-55.63%	-60.78%	0.05%	34.34%	275.16%	-7.97%	-53.74%	-14.52%	-15.00%
	Moderate (Cars only)	-14.47%	-0.02%	10.45%	14.50%	122.08%	-4.23%	-24.79%	-6.42%	-6.70%
	Moderate (All LDV's)	-67.35%	-73.50%	0.12%	41.60%	333.36%	-9.66%	-65.11%	-17.59%	-18.17%
	High (Cars only)	-17.46%	-0.03%	12.62%	17.49%	147.31%	-5.11%	-29.91%	-7.75%	-8.09%
	High (All LDV's)	-81.24%	-88.64%	0.15%	50.18%	402.14%	-11.66%	-78.54%	-21.22%	-21.92%
Hybrid Electric	Low (Cars only)	-6.82%	-0.01%	-9.70%	-5.25%	-15.86%	-8.67%	-0.00%	-11.28%	-11.07%
	Low (All LDV's)	-43.27%	-60.75%	-47.65%	-8.45%	-43.20%	-22.90%	-0.88%	-30.89%	-30.18%
	Moderate (Cars only)	-8.29%	-0.01%	-11.79%	-6.38%	-19.28%	-10.54%	-0.00%	-13.71%	-13.45%
	Moderate (All LDV's)	-52.37%	-73.46%	-57.68%	-10.25%	-52.34%	-27.74%	-1.06%	-37.43%	-36.57%
	High (Cars only)	-10.00%	-0.01%	-14.23%	-7.70%	-23.26%	-12.72%	-0.00%	-16.54%	-16.23%
	High (All LDV's)	-63.16%	-88.60%	-69.57%	-12.37%	-63.14%	-33.47%	-1.28%	-45.15%	-44.11%
Battery Electric (long term)	Low (Cars only)	-12.53%	-0.02%	-1.16%	1.91%	32.11%	-10.14%	-20.39%	-11.01%	-11.19%
	Low (All LDV's)	-57.20%	-60.78%	-23.65%	11.51%	101.59%	-23.17%	-52.86%	-27.55%	-27.94%
	Moderate (Cars only)	-15.23%	-0.02%	-1.41%	2.32%	39.03%	-12.33%	-24.79%	-13.38%	-13.61%
	Moderate (All LDV's)	-69.25%	-73.50%	-28.60%	13.93%	123.05%	-28.08%	-64.05%	-33.38%	-33.85%
	High (Cars only)	-18.37%	-0.03%	-1.70%	2.80%	47.10%	-14.88%	-29.91%	-16.15%	-16.42%
	High (All LDV's)	-83.53%	-88.64%	-34.50%	16.81%	148.43%	-33.88%	-77.26%	-40.27%	-40.84%
Fuel Cell (Natural Gas H_2)	Low (Cars only)	-13.15%	-0.02%	-9.84%	-12.88%	-17.97%	-13.46%	-22.75%	-15.49%	-15.56%
	Low (All LDV's)	-59.07%	-60.78%	-50.47%	-33.16%	-49.16%	-35.25%	-58.72%	-42.46%	-42.55%
	Moderate (Cars only)	-15.98%	-0.02%	-11.96%	-15.66%	-21.85%	-16.36%	-27.65%	-18.83%	-18.92%
	Moderate (All LDV's)	-71.52%	-73.50%	-61.09%	-40.18%	-59.56%	-42.71%	-71.15%	-51.45%	-51.55%
	High (Cars only)	-19.29%	-0.03%	-14.44%	-18.89%	-26.36%	-19.74%	-33.36%	-22.73%	-22.83%
	High (All LDV's)	-86.27%	-88.64%	-73.69%	-48.47%	-71.85%	-51.52%	-85.83%	-62.06%	-62.19%
Fuel Cell (Solar H_2)	Low (Cars only)	-12.79%	-0.02%	-11.62%	-11.93%	-21.54%	-22.02%	-22.75%	-21.40%	-21.46%
	Low (All LDV's)	-58.12%	-60.78%	-55.34%	-30.60%	-58.94%	-58.79%	-59.60%	-58.70%	-58.69%
	Moderate (Cars only)	-15.55%	-0.02%	-14.12%	-14.50%	-26.18%	-26.77%	-27.65%	-26.01%	-26.08%
	Moderate (All LDV's)	-70.36%	-73.50%	-66.99%	-37.08%	-71.41%	-71.23%	-72.21%	-71.11%	-71.11%
	High (Cars only)	-18.76%	-0.03%	-17.04%	-17.49%	-31.59%	-32.31%	-33.36%	-31.39%	-31.47%
	High (All LDV's)	-84.87%	-88.65%	-80.81%	-44.73%	-86.14%	-85.93%	-87.11%	-85.79%	-85.78%