PATHWAYS TO A U.S. HYDROGEN ECONOMY: VEHICLE FLEET DIFFUSION SCENARIOS

A Report to the BP Foundation

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A program supported by the BP Foundation and the University of Delaware

December 2006

Center for Energy and Environmental Policy

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Executive Summary

This is the second in a series of annual reports to the BP Foundation. The purpose of these reports is to examine the role that hydrogen will play in the future energy economy, focusing on the transportation industry within the United States. The first of these reports (CEEP, 2006) identified the primary role of the federal government as a source of funds for research and development rather than policy creation. The report focused on state level policies to introduce hydrogen as an energy carrier into the energy economy, since U.S. policy innovation is presently concentrated at this level of government.

In order to gain a better understanding of how energy policy is created and operates at the state level, a survey was created and sent to those states that had been identified as leaders in the promotion of alternative energy policy. Specifically, three policy areas of interest were identified: ethanol production and use in transportation; the development of renewable portfolio standards; and the development of a hydrogen based energy infrastructure. The surveys were designed to determine both the reasons for the creation of these policies as well as their effectiveness in accomplishing their goals.

A key finding of the first report (CEEP, 2006) was that fleets were expected by survey participants to play an important role in the creation of a hydrogen energy economy. Participants noted that hydrogen fuel cell vehicles in government and commercial fleets can assist in overcoming several of the barriers to the development of a hydrogen energy economy, while also providing a ‘test bed’ for solving practical problems with their market penetration. Fleets could be particularly helpful in removing those barriers created by the ‘chicken or egg’ problem in which hydrogen fuel cell vehicles are held back by high prices that will not be lowered until an economy of scale is created and by a lack of fuel availability that will not be solved until there are enough hydrogen fueled vehicles to economically justify the creation of a hydrogen fueling network. By initially introducing hydrogen fuel cell vehicles through fleets, bulk purchases may be made by corporate entities, the government, or a cooperative effort by the two parties that might circumvent the ‘chicken or egg’ problem affecting the creation of a full fledged hydrogen energy economy.

The second year report has expanded on this finding by examining the role and carbon impacts of hydrogen in fleets. Fleets have historically adopted new technology more quickly than other transportation market segments. While fleets can only modestly affect energy consumption and emissions of the U.S. vehicle transport sector, a detailed focus on diffusion of new technology by this sector enables policy-sensitive modeling which can provide reasonable estimates of parameters determining vehicle energy use and carbon impacts. To this end, the second year report centers around a model created at CEEP to examine the economic and emissions impacts of hydrogen’s introduction into U.S. fleets compared with two primary competitors, biodiesel fuel and hybrid gasoline electric vehicles. The second year report includes a detailed analysis of the economics and ‘well-to-wheels’ carbon impacts of the three technologies: hydrogen fuel cell vehicles; biodiesel fuel; and hybrid gasoline electric vehicles.

Hydrogen Fuel Cell Vehicles

Hydrogen fuel cell vehicles have, for several years, been widely promoted as a solution to many of our current environmental problems. This reputation is not without merit. However, there are several disadvantages that must be considered alongside its advantages. (e.g., Hammerschlag and Mazza, 2005; Rifkin, 2004; and Romm, 2006) The benefits of hydrogen as a fuel are significant. When utilized in a fuel cell it creates only water vapor as an emission. This would not only reduce the level of carbon emissions, which lead to climate change, but would also engender a number of other environmental and health benefits caused by the reduction of other emissions. It is also widely domestically available and from a diverse set of sources. This factor gives hydrogen substantial benefits in terms of economics and energy security, both of which would be improved by a reduced reliance on energy imports from abroad.

A final advantage of hydrogen is its nature as a versatile energy carrier. Hydrogen is not an energy source, such as fossil fuels or solar energy, because it cannot be taken directly from our environment and its production does not yield a positive energy balance. Hydrogen is not found in large quantities on the planet in its pure molecular form. Instead it is found as an element within the molecules of many other substances, most notably water and any material that is or was organic, such as biomass and fossil fuels. It can be stripped from these substances through the application of energy and stored until needed. Since hydrogen requires more energy to create than it can provide, the principal reason for this conversion is to increase energy versatility.

While today coal is largely utilized for electrical generation, it was previously a prevalent form of energy in both the transportation and heating sectors. Even though it is the largest available fossil fuel in the U.S., coal has recently been replaced by fuels that require significant imports because they are more versatile and have fewer environmental and public health problems associated with their use. For example, oil and natural gas may be recovered and transported by methods which have proved to be less hazardous than coal mining and produce fewer onsite emissions. If coal is turned into hydrogen, however, its energy can now be pumped through pipelines and no emissions will be produced on site. Of course, sources such as solar and wind energy release no onsite carbon emissions. A major technological barrier to these technologies is intermittency, the fact that the schedule on which they produce energy can only be predicted, not controlled, and this schedule may not match our energy demands. Hydrogen can solve the problem by acting as an energy carrier, storing the energy produced by intermittent sources until it is needed. Thus, hydrogen has an important advantage in bringing energy versatility to a large number of domestic energy applications and it can serve growing energy markets while resulting in potentially dramatic environmental improvements.

In addition to examining its benefits, the report outlines several disadvantages to the utilization of hydrogen. The first of these concerns emissions in a hydrogen energy economy. As outlined above, hydrogen has no emissions other than water vapor at its point of use when fed to a fuel cell. However, the entire well-to-wheels chain must be examined to determine the full level of emissions from hydrogen. Because hydrogen is an energy carrier, its emissions and almost all of its environmental impacts are determined by the energy source used to produce the hydrogen (Consonni and Vigano, 2005). Therefore, the other elements present in the source molecules for hydrogen must be considered. In the case of water, the only other element present is oxygen.

This oxygen is emitted during production and then recaptured when the hydrogen is run through a fuel cell to produce electricity and water. When fossil fuels are utilized to produce hydrogen, the other elements present in these fuels form the same pollutants that would be produced if these sources were used conventionally (Ogden, 1999). Thus, the environmental impact of a hydrogen energy economy is entirely determined by how the hydrogen is produced. There are many paths that could produce significant levels of pollutants. Currently, over 90% of hydrogen produced in the U.S. comes from natural gas (NAS, 2004; Ogden, 1999), and coal is viewed as a significant source in the future. Both sources would release carbon dioxide in order to supply hydrogen, with coal being the most carbon-intensive fossil fuel. Compared to gasoline, hydrogen harvested from natural gas may have beneficial carbon emission impacts.

There is also a problem of expense. Large amounts of infrastructure will be needed in order to sustain a substantial hydrogen energy economy. Construction of many new hydrogen production plants and a large, new distribution and transportation networks would be required at a likely cost of billions of dollars (Ogden, 1999). Additionally, a hydrogen energy economy would rely on many technologies which have yet to be developed. It is still unclear how hydrogen should be stored and transported. Because hydrogen is a diffuse gas in its molecular form, it has a low energy density and either requires a large storage volume or storage at very high pressures to meet the energy needed for U.S. transport demand. An alternative is to liquefy the hydrogen. However, this requires very low temperatures that would be costly in terms of energy and money to create, as well as making hydrogen potentially dangerous to handlers. A third option would be to absorb hydrogen within another substance in order to improve handling and energy density. A number of solids and liquids have been identified as potential storage mediums, but they are experimental and most still have several problems that would hinder their implementation (NAS, 2004). In brief, many of the technologies that would need to be utilized in the production of the new infrastructure and in the storage and handling of the hydrogen are beset by technological uncertainties. This is common with any emerging technology.

A final potential barrier facing the hydrogen energy economy is whether there will be a sufficient level of investment in hydrogen technologies sustained over several decades in order to overcome technological and market barriers. The last three decades have seen a dramatic decrease in U.S. investment in energy R&D (see Figure 6 below). This is troubling at a time when the need for energy change is significant. It is, however, difficult to say how this will affect the hydrogen energy economy because even as overall investment in energy R&D has dramatically decreased, investment into the development of fuel cell technologies has recently grown (Kammen and Nemet, 2005; Peabody and Dooley, 2004; Peabody, 2001).

Hydrogen shows significant potential in a future energy economy. Its advantages are many and it has no technological barriers that cannot eventually be overcome (NAS, 2004). However, a long-term policy commitment will be necessary if the developing hydrogen economy is to grow beyond niche status (Waegel et al, 2006). Hydrogen's negative energy balance must also be addressed if its promise is not to falter under the requirement of obtaining source fuels whose availabilities are diminishing and prices are climbing (unless, of course, the sources are renewable). And a 'well-to-wheels' solution to carbon emissions is needed for its full environmental benefits to be realized.

Biodiesel Fuels

Biodiesel is similar to diesel in most characteristics. Because of this it is able to be used in a standard compressed-ignition diesel engine with no or few modifications. As a result, it is often viewed as a low-cost method of improving the environmental impacts of the transportation industry, as well as reducing U.S. dependence on energy imports. Today, biodiesel is commonly found in blends with petroleum diesel (or petrodiesel) at levels of 2-20 %.

Biodiesel is produced by refining the oils of biomass, commonly harvested in the U.S. from soybean or rapeseed oil. This process primarily yields biodiesel and glycerin, with the latter being a valuable byproduct (National Biodiesel Board, 2002). Biodiesel can greatly reduce carbon dioxide and sulfur emissions when used to replace petrodiesel, although nitrogen emissions can be higher. It is also biodegradable and will have relatively few negative environmental impacts when spilled. Because of these factors, biodiesel offers the potential for significant improvements to the transportation sector's ecological 'footprint' (Balat, 2005; U.S. EPA, 2002; Proc et al, 2005; and Carraretto, 2004) And ince it may be produced domestically, biodiesel use can improve energy security in the same fashion as hydrogen.

Compared to hydrogen, there are fewer technological barriers to biodiesel utilization. It may be handled in the same fashion and with the same equipment as petrodiesel and little new infrastructure would need to be created for its transmission, distribution, and storage. It can run in concentrations of up to 100% in a standard diesel engine with only slight modifications and at lower percentages with no modifications (Engine Manufacturers Association, 2003). This means that little change would be needed in the infrastructure for vehicle manufacturing. Importantly, biodiesel can therefore escape the 'chicken or egg' difficulties of hydrogen.

Biodiesel is a renewable fuel that offers the potential to cut carbon emissions by as much as 78%, compared to petrodiesel, and its use would measurably lower sulfur emissions (National Biodiesel Board, 2005). It may be produced domestically thereby improving energy security. As well, biodiesel would be less expensive to introduce than hydrogen.

The technology is not without negatives, however. Of greatest concern is the ability of the country to produce sufficient crops to meet our fuel demands without impacting the ability to produce the crops needed for food. Many worry about the potential rise in prices of food products due to the increased demand of crops for fuel, and there is the possibility of an adverse impact on the U.S. balance of trade since agricultural crops are a major source of export revenue. As well, potential environmental impacts of intensified agriculture for energy supply can be counted as an important drawback. Finally, it is not clear whether would fuel a sizable share of vehicles, given that it must compete with other technologies (e.g., hybrid vehicles, which are also examined in this report) that may limit its market penetration. In that event, biodiesel's macro-level environmental, security and economic impacts may turn out to be modest.

Hybrid Gasoline Electric Vehicles

Hybrid gasoline electric vehicles are similar to conventional gasoline models in that both employ a similar engine as the basic source of power. The difference occurs primarily in the drive train and electrical systems of the vehicle, which employ advanced technologies in order to conserve and recapture the energy that would otherwise be lost in the operation of the vehicle. This is accomplished through the introduction of up to five different technologies: 1) regenerative braking; 2) idle-off technology; 3) utilization of a smaller engine size; 4) electric drive-only technology; and 5) grid-connected recharging. All of these technologies utilize a battery bank in order to store and provide power that would otherwise have been lost (Union of Concerned Scientists, 2005).

Regenerative braking is an important technology for the development of hybrid gasoline electric vehicles. It captures the kinetic energy that is normally lost to friction through braking and converts it into electrical energy. This recaptured energy is then stored in the expanded battery bank of the vehicle and used to provide power that supplements, or in some cases, serves as the principal source of energy for the vehicle's movement (see section 2.3 below for a detailed discussion).

Idle-off technology allows the gasoline powered internal combustion engine to shut off while the vehicle would normally be idling. This fuel saving is especially large in stop-and-go traffic when fuel is consumed simply to keep the engine running while the vehicle is not moving (Union of Concerned Scientists, 2005).

Utilization of a smaller engine is possible through electric assistance from a motor powered by the expanded battery bank of the hybrid vehicle. Smaller engines are often appropriate for vehicle use but are dropped in favor of large engines needed for rapid acceleration and selected driving needs. Hybrids can reduce the tendency to over-size vehicle engines and thereby increase vehicle efficiency. In those circumstances where a greater amount of power is needed, an electric motor served by the stored energy in the battery bank provides the additional motive power.

Electric drive-only technology takes a further step in making it possible to power a vehicle from a stop position for at least the initial moments of acceleration. Vehicles equipped with electric drive-only capability can significantly reduce engine use, especially during lower speeds when combustion engines are least efficient (Union of Concerned Scientists, 2005).

All of the above technologies are commonly found in hybrid vehicles today. The final technology, grid connected recharging, is not. This allows an operator to recharge the vehicle's batteries (perhaps overnight) through the electric grid. This would almost always be accompanied by a larger battery bank than is found in today's hybrids. Vehicles with grid connective capabilities can run for significant periods of time on electric power alone. The gasoline engine is only utilized when the batteries have been substantially drained, at which point the vehicle reverts to operations similar to those of a hybrid gasoline electric vehicle found in the market today (Friedman, 2003).

Hybrid technology is inexpensive to integrate into the existing transportation system because it requires no changes to be made to the fueling infrastructure. The only major changes are in vehicle manufacturing. Hybrid vehicles are also relatively close in cost to a standard vehicle, with a price premium of only a few thousand dollars. The added expense is currently being offset by federal and state tax incentives and through fuel cost savings from higher fuel economy and lower maintenance. Because of these advantages, the hybrid gasoline electric vehicle is the only technology of the three examined here that has entered the nation's vehicle pool in substantial and rapidly increasing numbers in recent years.

The environmental impact of hybrids is expected to be large. Increased fuel economy directly correlates into reduced fuel consumption and thus reduced emissions levels. TEmissions reductions vary based on the number of hybrid technologies utilized and on the weight and power of the vehicle, but modern hybrid vehicles can typically expect to increase fuel economy by 20 mpg compared to conventional vehicles with similar specifications (Friedman, 2003). Coupled with the ability to rapidly introduce these vehicles into fleets because of the lack of needed infrastructure and low cost, hybrid gasoline electric vehicles show promise for significant short- and mid- term emissions reductions (Ewing and Sarigöllü, 1998; Lave and McLean, 2002 and De Haan et al, 2006). Nonetheless, hybrids utilize gasoline (or, in the future, possibly diesel) and cannot be expected to solve long-term energy sustainability challenges.

Modeling Competing Technologies

The primary purpose of the research summarized in this report is to compare the roles of the three competing alternative vehicle technologies (hydrogen fuel cells, biodiesel, and hybrid gasoline electric vehicles) for introduction into U.S. vehicle fleets. In order to accomplish this, it was necessary to construct two models. The first of these evaluates the economics of the technologies. The model examines current costs of the different technologies, as well as their projected costs over the next 25 years. In order to determine the costs of each technology type, a number of factors were considered, including fuel costs, vehicle capital costs, and repair and maintenance.

Information from the economic model is utilized to determine the price competitiveness of the different technologies over time. While conventional gasoline and diesel fueled vehicle prices rise during the 25-year period of our analysis (due to rising fuel costs), the competing alternative technologies' prices are expected to decline as both fuel and vehicle capital cost premiums fall with each technology reaching mature status in the market. Projected price intersections for vehicle lifecycle costs are found via the model and identify benchmark years in which a given technology begins to rapidly expand due to its economic competitiveness.

This information is transferred to an emissions model, which tracks fleet composition in terms of the different technologies and then calculates the emissions from the fleet under different scenarios. The carbon dioxide emissions are calculated by using the following equation for each technology type within the fleet:

CO2 = [# of Vehicles] * [Annual Miles Driven / Vehicle] *
[Emissions Factor] / [Fuel Economy]

The [# of Vehicles] variable indicates the number of vehicles of a given technology type within the fleet and the [Annual Miles Driven / Vehicle] variable associates an average annual mileage level for the competing technologies. By multiplying these two factors the result is the annual vehicle miles driven by each pool of alternative vehicles. The [Emissions Factor] variable records the kilograms of carbon dioxide emitted per unit of fuel consumed (the unit is gallons for all technologies except hydrogen whose fuel use is expressed in kilograms). When the [Emissions Factor] variable is divided by the [Fuel Economy] variable, which is expressed as miles driven per unit of fuel, the result is the kilograms of carbon dioxide emitted per mile. When this calculation is performed for each technology type, kilograms of carbon emitted in any given year by the fleet are found in aggregate and in terms of technology shares.

Three Technology Pathways

The models were utilized to predict emission profiles for several scenarios. Each scenario was designed to reflect likely policy incentives, technology improvements, and forecasted fuel prices (based in part on the findings from our first report – CEEP, 2006; see also Waegel et al, 2006). By intent, three scenario ‘groups’ were created in which one of the alternative technologies assumed the dominant role in changing fleet vehicle composition. Within these scenario groups, technologies are introduced into the makeup of the fleet at rates and times determined to be feasible by competitiveness predictions from the economic model, by the likely policy incentives to spur use of the technologies, and by infrastructure or technological constraints. The scenario groups can thus be split into three pathways: hybrid-led; biodiesel-led; and hydrogen-led. The scenarios in each of these pathways show the carbon emissions reductions that would occur and how the barriers and limits to the different technologies would affect the emissions profiles of U.S. fleets over time.

The hybrid-led scenarios show fleet carbon dioxide emissions plateauing in 2020 and a predicted 20% reduction by 2030 (compared to the baseline). This scenario shows that hybrid gasoline electric vehicles can reduce the growth in carbon dioxide levels and, if aggressively introduced, it may cause measurable reductions in near- to mid-term fleet emissions. But unless there is a reversal in experience to date that annual vehicle miles traveled will increase, hybrids cannot cause a long-term decline in emissions. The primary strength of this technology is its ability to be introduced extensively, rapidly, and inexpensively (compared to the either biofuels or hydrogen). For this reason, hybrid technology is likely to play an important role in short- and mid-term efforts to reduce carbon dioxide emissions in the transport vehicle sector but other vehicle technologies will be required if we are to meet long-term energy sustainability goals.

The biofuels-led pathway shows many similarities to the hybrid scenarios. Since relatively few technological changes are needed to fueling, distribution, and manufacturing infrastructure, biodiesel can be rapidly introduced through fuel switching or fuel blending. Thus, there is significant potential for biofuels to reduce emissions in the near future. One scenario introduces the fuel into the sedan portion of the fleet. Due to the low level of existing diesel vehicles within the sedan pool, the level of fuel switching potential is minimal. Because of this, we see the short term rapid introduction of biodiesel from fuel switching followed by a more modest introduction of the fuel through shifts in the makeup of the vehicles within the sedan fleet, eventually achieving 20% penetration into the fleet. This is accompanied by the simultaneous introduction of hybrid vehicles in the mid-term to account for the limited penetration of biodiesels in the sedans pool. The prediction of this scenario is a near-term plateau in carbon dioxide levels at 2012 due to biodiesel use. The emissions continue to rise after this point, however, as the sedan pool reaches the saturation point for biodiesel fuel switching. The rise is minimal, however, and by 2020 emissions plateau and eventually decline again as hybrid vehicles begin to account for an increasing share of new fleet vehicle purchases. A second biodiesel-led scenario examines its use by heavy duty trucks. This is of particular interest due to the much larger portion of diesel use by trucks (compared to sedans), enabling rapid, short term fuel switching. In this scenario two-thirds of the diesel vehicles are using biodiesel and nearly all of the small number of gasoline vehicles has been replaced by hybrids by 2030. The greater level of fuel switching means that the vehicle pool does not reach a saturation point for biodiesel and, therefore, a carbon plateau is maintained to 2022, with emissions subsequently declining as hybrids become highly competitive in the scenario. Both scenarios exhibit biodiesel's strength and weakness – short-term impacts on carbon emissions but without an ability to sustain declines into the future. Compared to the hybrid pathway, fleet carbon emissions for the biodiesel-led option are higher by 2030.

In the hydrogen-led pathway, due to the extensive levels of infrastructure development and technological problem-solving necessary for the option to materialize, hydrogen-fuel cell vehicles are not expected to constitute a significant portion of fleets in the near future. As a result, it will be necessary to utilize a second technology in the near term in order to curb carbon emissions. In the scenario highlighted in this report, hybrid gasoline electric vehicles are used to perform this function. The result is a stable carbon dioxide emissions profile, maintained at 2005 levels for the majority of the time scale examined. This is primarily due to the near-term utilization of hybrid vehicles. There is a significant decrease in emissions beginning in 2027 as hydrogen fuel cell vehicles begin to represent an important share of fleet sedans. As the number of hydrogen vehicles grows, emissions continue to decline, especially as the potential increases each year for carbon sequestration or a renewable source for hydrogen with lower carbon emissions (NAS, 2004; Rand and Dell, 2005).

The pathway analysis in this report indicates that hydrogen cannot alone curb emissions over the next 25 years. However, if hydrogen is produced from fossil fuels in a transitional phase and then from renewable sources in the longer term, major decreases in carbon emissions are possible. The combination of short- to mid-term declines from hybrid technology and a longer term reduction due to the introduction of hydrogen vehicles is found to be promising for the goal energy sustainability. Hybrid gasoline electric vehicles in sectors dominated by conventional gasoline vehicles lower short-term emissions, while biodiesel accomplishes the same thing in markets dominated by conventional diesel vehicles. While hybrids and biodiesel use, when bundled together, offer the potential for important short- to mid-term reductions, we conclude that it is their combination with hydrogen fuel cell vehicles that offers the best long term hope for significant decreases in transport vehicle carbon emissions. However, this finding hinges on hydrogen being eventually produced from renewable energy sources.

1.0 Introduction

This report is the second in a series of reports to the BP Foundation on the status of hydrogen and fuel cell policy and technology in the U.S. The first report focused on state efforts to construct hydrogen economies within their borders and the challenges they have encountered. The report focused on state level policies to introduce hydrogen as an energy carrier into the energy economy, since U.S. policy innovation is presently concentrated at this level of government.

Our second report seeks to build on initial findings by examining competitive vehicle technologies in the market and how this competition might affect the introduction of hydrogen into the energy economy. The report examines the dynamics of introducing hydrogen into the most likely first point of entry into the energy economy – fleet vehicles. Extensive data exist on the composition of vehicle fleets, retirement patterns by age, fuel consumption per mile driven by vehicle type and age, etc. As well, fleets have historically adapted new technology more quickly than other transport market segments.

While fleets can only modestly affect energy consumption and air emissions of the U.S. transport vehicle sector, a detailed focus on this segment fosters the development of policy-sensitive modeling which can provide accurate estimates of parameters determining vehicle energy use and pollution.

1.1 Findings from Phase 1

Debate about transition paths for the American energy economy has grown over the past decade. Increasing concern for the environmental effects of fossil fuel combustion coupled with overseas political unrest which poses a threat to the security of fossil fuel – especially oil – supply have led to renewed interest in alternatives. In particular, the search for replacements for oil in the transportation sector has renewed with hydrogen and fuel cells gaining significant policy attention in the last 5-8 years.

Hydrogen fuel cells are attractive for a number of reasons, primarily that hydrogen may be obtained from numerous domestically available sources and when used in a fuel cell, results in water vapor emissions only. The combination of these two factors could offer important improvements to the economy, security and sustainability of the U.S. energy economy.

At the same time, the benefits of a hydrogen economy can be doubted. Currently, hydrogen and hydrogen fuel cells are substantially more expensive than gasoline, internal combustion engines (ICEs) and several other transport vehicle options. While these costs are expected to eventually decline to competitive levels as the market expands, a daunting economic problem remains in finding the capital necessary to install the costly infrastructure that will be needed to support a large scale hydrogen-based transport economy. While limited hydrogen pipeline capacity exists and a number of methane steam reformers for the production of hydrogen are available for use, significant costs will have to be incurred in the construction of a hydrogen production, transportation, storage, and distribution system.

The second question is whether a hydrogen economy can in fact lead to a sustainable energy economy. While hydrogen produces no emissions at its point of use, emissions may occur at the point of the hydrogen's production depending on the method utilized. Currently the primary method for the production of hydrogen is the steam reformation of natural gas and in the near future, some advocate the gasification and reformation of coal. Both methods produce emissions, including carbon dioxide. Hydrogen from natural gas produces less carbon dioxide than that of coal and gasoline, while coal and gasoline produce roughly equal amounts of CO_2 emissions. Although hydrogen from natural gas offers substantial reductions in carbon emissions, its use could not accomplish the deep cuts in CO_2 emissions argued by some to be necessary to avert climate change. Carbon sequestration may offer the potential for near zero carbon emissions for hydrogen harvested from both coal and natural gas, but the long-term viability of this technology has yet to be effectively demonstrated.

In an effort to gauge policy commitment for hydrogen versus other strategies to realize energy sustainability, a survey was created in Phase 1 of this project and distributed to state officials and researchers in states identified as innovators in the development of alternative energy policy. Three alternative policy choices were investigated: renewable energy portfolio standards, ethanol promotion and hydrogen development.

Those surveyed answered questions regarding the policies used to enact these energy policy choices and the expected effectiveness of such policies in producing significant change in the energy economy. Combining the survey responses allowed for the identification of policies which may be effective in the development of a hydrogen economy at the state level. Generally, survey respondents expressed optimism about hydrogen's prospects. But there was also significant interest in a multi-prong policy approach with a major commitment for aggressive development of renewable energy seen as essential.

One additional focus of the research team involved a scenario analysis of hydrogen energy economy evolution paths. Three scenarios were constructed: the Niche Hydrogen Economy Scenario, the Transitional Hydrogen Economy Scenario, and the Sustainable Hydrogen Economy Scenario. In the niche hydrogen economy, hydrogen fails to develop into a significant energy carrier and as a result achieves none of the goals of improved economy, energy security and sustainability. In the transitional hydrogen economy, hydrogen becomes commonly used in the overall energy economy and achieves improvements in the economy and energy security. The hydrogen is obtained from fossil fuel sources and thus fails to achieve dramatic improvements in sustainability due to carbon emissions and continued depletion of non-renewable resources. The sustainable hydrogen energy economy is similar to the transition scenario except in this case hydrogen is increasingly obtained from renewable energy sources rather than fossil fuels. In doing so, large improvements are achieved in long-term energy economy, energy security, and energy sustainability.

A conclusion of the Phase 1 report is that the emerging hydrogen energy economy will move from the niche scenario into a transitional role and then stall, failing to reach the goal of a sustainable hydrogen energy economy. This failure could have significant impacts on both our environment and our ability to meet our future energy needs. In order to avoid this circumstance, the Phase 1 report concluded that policy commitment to hydrogen would need to extend significantly into the future, spanning decades, in order to guide the hydrogen economy efficiently through the three stages.

1.2 Purpose of Phase 2 of the Project

The Phase 1 report identifies several factors shaping the early development of a hydrogen energy economy. The first of these factors is that for the immediate future nearly all of the hydrogen produced will come from natural gas. Hydrogen from natural gas is economically competitive with gasoline and produces a significant reduction in carbon dioxide emissions. Additionally it is currently the method that has the greatest amount of existing infrastructure, with a significant amount of hydrogen already being produced via steam reformation for industrial purposes. These factors make the reformation of natural gas the logical source for hydrogen in the near future.

Second, the report demonstrated that the likely entrance of hydrogen into the U.S. energy economy will be via vehicle applications. Hydrogen fuel cell technology, like many new technologies is having to confront a so-called ‘chicken and the egg’ problem, whereby the technology is currently too expensive to be readily adopted, but until economies of scale are achieved it is unlikely that the prices will drop rapidly. Additionally, hydrogen as a transportation fuel has the problem of requiring a large transmission and distribution network if it is to be used by the public. There will only be low public interest in purchasing hydrogen vehicles if there are few places to fuel them and fuel station owners will be hesitant to add expensive hydrogen fueling pumps to their stations when there are essentially no hydrogen powered vehicles on the road; yet another ‘chicken and egg’ problem for hydrogen.

The introduction of hydrogen into vehicle fleets has the potential to avoid both ‘chicken and egg’ problems and therefore is seen as a likely entryway into the energy economy. Fleets offer the unique situation of their operation and management requiring simultaneous decisions about fuel, vehicles and supporting fueling infrastructure. Through bulk purchases and coordinated investment across all components, fleets appear to be well-poised to build an effective infrastructure for hydrogen vehicles. If fleets were to succeed as incubators for hydrogen vehicle development, this could help alleviate entry barriers for fuel cell transport in the energy economy.

With its focus on an introduction scenario in which hydrogen is produced by natural gas reformation and hydrogen fuel cell technology is first introduced in fleets, the report compares hydrogen vehicles to its principal competitors. Currently, the primary competitors to petroleum powered vehicles are biodiesel and gasoline electric hybrids. The benefits of biodiesel, gasoline hybrid electric cars and hydrogen fuel cell vehicles are reasonably well understood which enabled our Phase 2 effort to model diffusion and policy scenarios for the three technologies.

Section 2 of this report describes in detail each of the technologies. The review considers carbon dioxide emissions, costs and technical performance. Section 3 examines the current status of the

U.S. fleets. Information in Sections 2 and 3 is then used in Section 4 to analyze the economics of each in comparison to conventional gasoline vehicles. This section considers present as well as future costs of these technologies using experience curves and projected fuel costs. Emissions data from Section 2, economic data from Section 4, and fleet data from Section 3 are then combined in Section 5 to model economic and environmental impacts of the introduction of these alternative vehicles into fleets. Selected results from this modeling process are presented in Section 5.

2.0 Literature Review

2.1 Hydrogen Vehicles

The hydrogen economy has received increasing attention in political and scientific circles over the past decade. Common reasons cited for investigating the hydrogen energy economy are improved energy security, reduced environmental impacts, and the transition to a sustainable energy future. In anticipation of these benefits, national and local initiatives have been launched in the U.S. creating pilot "roadmaps and technology partnerships to explore hydrogen economy platforms. An important question to ask is whether or not a hydrogen economy can fulfill key promises? If the answer to that question is yes, then what aspects of the current energy economy should be replaced and what are the appropriate roles for hydrogen to play in a sustainable energy economy?

The hydrogen economy is not simply a proposal for a change in fuel mix rather it entails the development and diffusion of a set of technologies that utilize hydrogen to carry the energy from conventional or alternative energy sources to its end use. Hydrogen is an energy carrier, not an energy source, which acts as a medium of storage, transmission, and end-use fuel for energy generated at power plants or harvested from fossil fuels. The energy from these sources is converted into hydrogen either by using electricity to split water into its components of oxygen and hydrogen through electrolysis or by removing the hydrogen from a feedstock energy source, usually natural gas. As a result there are different pathways that the hydrogen economy could develop along, each of which would have varying effects on the environment, economy and energy security. Currently the reformation of natural gas is considered to be the dominant pathway in the near and intermediate future for producing hydrogen gas (NAS, 2004; Ogden, 1999).

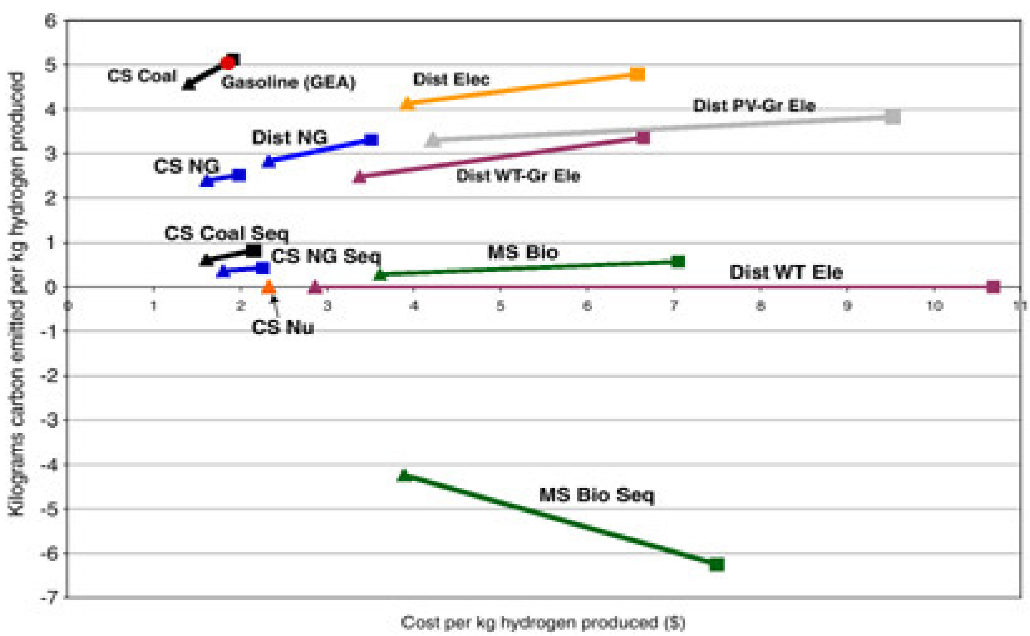
Natural gas is considered to be the dominant source for hydrogen for several reasons. Initial infrastructure improvements that would be needed to produce hydrogen from natural gas would be minimal. A large infrastructure for the distribution and extraction of natural gas already exists and more than 90% of the hydrogen produced in the U.S. for industrial purposes is derived from steam reformation of natural gas (Ogden, 1999: 239). The amount of hydrogen necessary during the early stages of the hydrogen economy could be produced relatively easily through the existing natural gas infrastructure (NAS, 2004).

Natural gas yields the greatest hydrogen to carbon dioxide ratio of all the fossil fuels. When it is reformed into hydrogen and used in a fuel cell vehicle, carbon dioxide emissions would drop by more than 60% compared to a gasoline internal combustion engine (ICE). If the natural gas is reformed in a central location, sequestration of the resulting carbon dioxide may reduce overall emissions by an additional 20% compared to gasoline (NAS, 2004).

In terms of economics, hydrogen from natural gas is 50-100% more expensive than an equivalent amount of gasoline. This difference can possibly be mitigated through efficiency increases in fuel cell vehicles. Currently this technology is considered to be too expensive for the common consumer, but there is the potential for the development of vehicle fleets that could be economical. It is expected that by 2020, the costs of hydrogen will drop below US$2.00 per gallon of gasoline equivalent. This assumes the field efficiency of fuel cells matches the theoretical calculated efficiency (NAS, 2004).

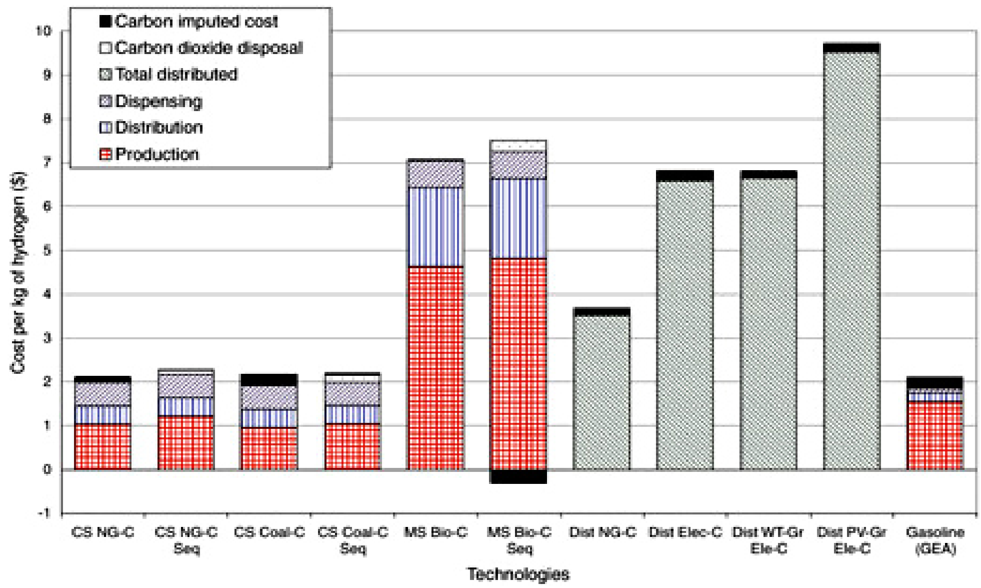
Current estimates of the cost of hydrogen vary widely from source to source and are highly dependent on the production methods used. The costs can be broken down into production, transportation and distribution. Current estimates for the transportation of hydrogen via trucks range from US$4.00 - $9.00 per gge (gallon-gasoline equivalent) but this price is considered to be significantly higher than it would be if hydrogen were shipped through pipelines (U.S. DOE, 2005).

The National Academies report (NAS, 2004) estimated the cost of production and resulting carbon emissions from hydrogen for several methods of producing the gas (Figures 1-5):



Source: NAS, 2004
Figure 1. Supply chains and estimated costs of hydrogen

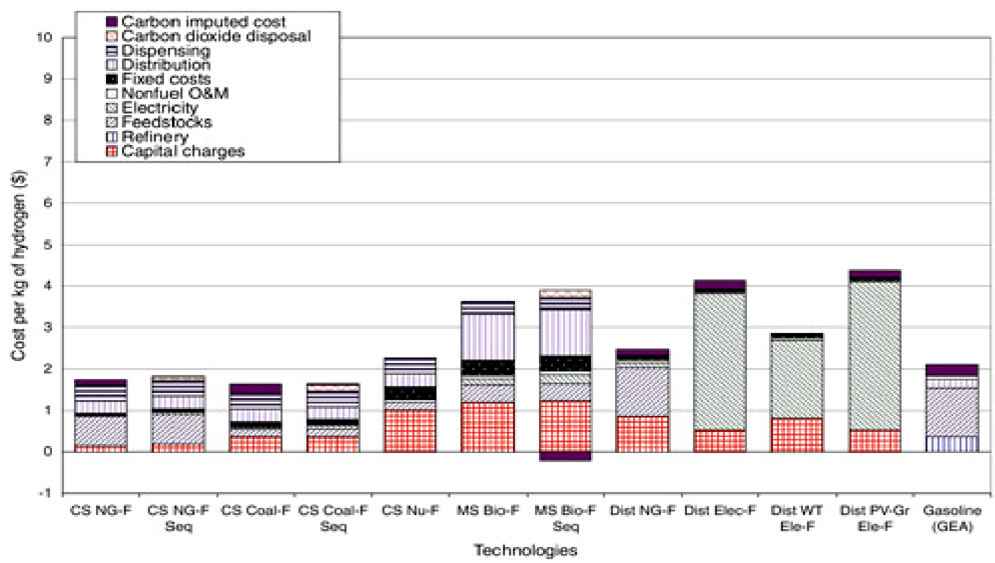
> "Unit carbon emissions (kilograms of carbon per kilogram of hydrogen) versus unit costs (dollars per kilogram of hydrogen) for various hydrogen supply technologies, in both current (■) and possible future (▲) states. NOTE: GEA = gasoline efficiency adjusted."



Source: NAS, 2004

Figure 2. Unit cost estimates (cost per kilogram of hydrogen) for the "current technologies" state of development for 10 hydrogen supply technologies

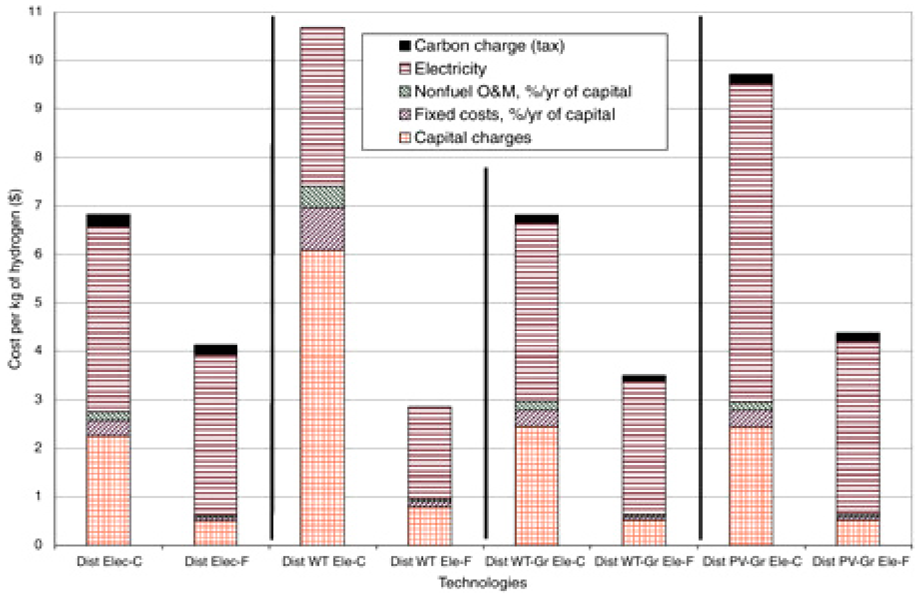
"Evaluation of a current technology case for nuclear thermal reforming of water is not included because no such technology exists at the present time. NOTE: GEA = gasoline efficiency adjusted."



Source: NAS, 2004

Figure 3. Cost details underlying estimates for 11 future hydrogen supply technologies, including generation by dedicated nuclear plants

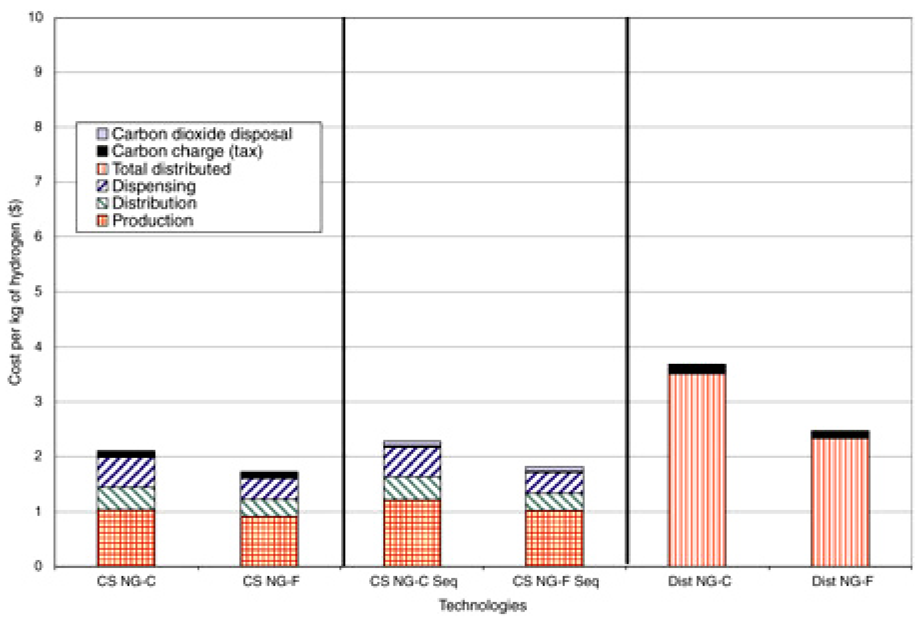
"NOTE: O&M = operation and maintenance; GEA = gasoline efficiency adjusted."



Source: NAS, 2004

Figure 4. Unit cost estimates for four current and four possible future electrolysis technologies for the generation of hydrogen

"NOTE: O&M = operation and maintenance."



Source: NAS, 2004

Figure 5. Unit cost estimates for three current and three possible future natural gas technologies for hydrogen generation

Other methods by which hydrogen may be produced include gasification and reformation of liquid and solid fossil fuels, the electrolysis of water, biomass conversion and some experimental methods involving the direct photoelectric splitting of water and production via algae or bacteria. As in natural gas, other hydrogen containing substances can be broken down and the hydrogen extracted. The process is similar but since they are either solids or liquids they must be gasified initially before being reformed. Natural gas has a lower carbon-hydrogen ratio than any of these substances, so these processes will all emit more carbon dioxide than the reformation of natural gas.

The electrolysis of water presents an alternative for low emissions in the creation of hydrogen but its effectiveness is dependent on the source of electricity used in the process. When an electrical potential is placed across a body of water, the water molecules split into their two base elements, hydrogen and oxygen. The hydrogen is then captured and used in a fuel cell, where it will recombine with ambient oxygen to reform water. This is a closed cycle with no net emissions. Carbon emissions can result from the electrolysis cycle, not from the feedstock, as they do in reformation, depending on the sources used to generate electricity to power the electrolysis. Solar, wind or similar renewable energy sources will not create carbon emissions whereas electricity from a coal power plant would produce large amounts of emissions, together with the other environmental problems associated with the operation of such a plant.

Producing hydrogen from biomass also presents interesting low carbon emission prospects. When viewed without sequestration, the use of biomass presents a carbon neutral production process, if the carbon produced during the breaking down of the biomass is excluded in the equation. The carbon that is trapped in the plant matter is taken out of the atmosphere as the plant grows and then released when the biomass is broken down to remove the hydrogen. Unlike the breaking down of fossil fuels for the extraction of hydrogen, the consumption of biomass does not release fossil carbon that had been stored in the earth long prior to its extraction. As a result, if sequestration is added to capture additional carbon, it may be possible to actually reduce the amount of carbon in the atmosphere, using the plants to extract the carbon dioxide gas and then capturing that gas as it is released along with the hydrogen and preventing it from returning to the atmosphere. The development of sequestration technologies is currently being pursued.

2.1.1 The Case for Hydrogen

There have been claims regarding the economic, social and environmental benefits of the hydrogen economy, although many of these benefits remain controversial (e.g., Hammerschlag and Mazza, 2005; Rifkin, 2004; and Romm, 2006). Certainly, hydrogen is widely considered a clean and abundant energy carrier, as it emits little or no pollution when produced from certain renewable sources and when consumed with minimal leakage and waste.

Hydrogen as a Zero Emissions Fuel

At the point of use, hydrogen can be considered a zero emissions fuel when it feeds a fuel cell. A catalyst breaks down the hydrogen, which is then combined with oxygen through an electrochemical process, resulting in the production of electricity and water vapor. When it is utilized in this fashion, the only emission from a hydrogen fuel cell is water vapor, which may either be condensed and collected or released into the atmosphere where it will eventually be returned to the earth as rain or condensation. From this perspective, hydrogen is a zero emissions fuel. This classification becomes less definite, however, when the full energy supply chain is examined to see where the hydrogen comes from and what emissions might occur to procure the hydrogen. Emissions resulting from the hydrogen supply chain are discussed in other sections of the report.

Hydrogen as a Versatile Energy Carrier

There are two primary purposes for using energy carriers rather than an energy source. They are: a) to turn a less versatile energy source, such as coal or biomass, into a more useable form; and b) to store energy from a primary energy source, such as solar or wind energy, for use at a later time. Many of the feedstocks of hydrogen are currently used to provide energy today, in one form or another, but they are restricted in the roles they might play within the energy economy due to, for example, their inability to be directly substituted for liquid fuels.

Coal is one of the most abundant fossil resources in the world and it is domestically available in large supply in the U.S. Additionally, it is relatively inexpensive to combust compared to other energy sources. At one point coal was used for transportation and home heating, but today its use in the U.S. is almost completely restricted to the role of electrical generation. Energy services for transportation and home heating have been reassigned to oil and natural gas, which increasingly are imported, causing economic outflows and raising energy security concerns.

Hydrogen extracted from coal could supply energy services for current transportation and home heating needs and would do so with no end-use pollution. Moreover, hydrogen could be derived in sufficiently large amounts to meet these demands. In this respect, hydrogen offers the potential to carry the energy from coal in a more usable and convenient form. In this manner, many of our energy needs that today rely on imported fuels could instead rely on domestically available coal.

Similar arguments can be made for hydrogen produced by extraction from natural gas, biomass, or electrolysis of water using solar or wind energy sources. In all of these cases an energy source that is currently technologically confined might play an expanded role in our energy economy, while also creating environmental and security benefits when its energy value is carried by hydrogen.

Hydrogen for Energy Storage

Hydrogen is an excellent energy carrier for energy storage purposes when compared to electrochemical means, such as batteries. Hydrogen has two features which make it well suited for energy storage. The first of these is the low level of energy degradation that occurs during the period of storage. Energy storage mediums such as deep-cycle batteries tend to leak energy over extended periods of time. If energy must be stored for a period of longer than a few days, then significant portions of the stored energy will be lost due to leakage within the battery. Hydrogen, however, can store energy with near zero leakage for months at a time.

Another benefit is that additional storage capacity is relatively cheap. If energy is being stored in deep-cycle batteries then the cost of the system will be highly correlated to the capacity of the battery bank. If capacity needs to be doubled, the cost of the system will nearly double, as well as storage volume and weight requirements. With a hydrogen energy storage system, however, storage capacity and the electrical generating unit (the fuel cell) are separate pieces of hardware and the bulk of the price of the system is the fuel cell while storage capacity is comparatively inexpensive. Using hydrogen, if the energy storage capacity of the system needs to be doubled, the price of the system only increases by a fraction of the total price.

2.1.2 The Case Against Hydrogen

Hydrogen has a number of disadvantages that may counteract the promised benefits that it may provide, especially when it is compared to alternative energy carriers that are either available on the market today or are currently being researched. The negative feature include: emissions before the point of use in the hydrogen supply chain; inefficiency compared to other carriers of electrical energy; the difficulty in developing a suitable storage medium for hydrogen to be utilized in highly mobile uses (such as cars); the high level of infrastructure construction required and its associated costs; the currently high costs of the primary technology component, the fuel cell; and also the high levels of investment that would be required to solve many of the technological problems associated with the use of hydrogen and to develop economies of scale necessary to lower critical component prices for a hydrogen economy.

Well-to-Wheels Emissions
Hydrogen's reputation as an emission-free energy system is one of the primary reasons for its promotion. When posited as a solar-hydrogen energy economy, the system offers a strategy for providing essential energy services without the high environmental and social costs of fossil fuels or uranium. Considerable research literature attests to the costs of the latter (ranging from oil spills and nuclear accidents to mineral mining, acid rain, toxic pollution on catastrophic scales, and climate change). However, the environmental benefits of a hydrogen economy hinge on factors that are often neglected when point-of-use is the basis for evaluation.

If hydrogen is to be utilized in a power plant, combustion engine or a fuel cell, the only byproduct is water. But this does not necessarily mean that hydrogen was produced in a non-polluting manner. The environmental benefits of hydrogen are determined at the very beginning of the hydrogen fuel cycle, during the production of hydrogen gas (Consonni and Vigano, 2005). Despite being the most common element in the universe, hydrogen is not commonly found as molecular hydrogen gas (H_2) on the earth. Instead, it is found as an element associated with a wide variety of other molecules and is commonly extracted from organic substances, fossil fuels or water. All of these substances have molecular structures rich with hydrogen (Ogden, 1999).

Environmental problems associated with extracting hydrogen arise from the presence of other elements within the source molecule. When water provides the source of hydrogen, few environmental problems result, as the only other element in pure water is oxygen. When hydrogen is combusted or run through a fuel cell, it recombines with ambient oxygen in the atmosphere to produce water. This means that a non-toxic gas, oxygen, is released into the atmosphere during hydrogen production through electrolysis but is reclaimed when the hydrogen is used, so that the chemistry of the atmosphere goes through no net change during the fuel cycle.

Environmental concerns arise when a source of hydrogen other than water is utilized. All biologically based sources (ethanol, methanol, and biomass) and fossil fuel sources (oil, coal, and natural gas) contain a great number of other molecules that are released when hydrogen is extracted. Usually, these elements form the same pollutants, especially carbon dioxide, that hydrogen production was supposed to reduce. For example, steam reformation of natural gas produces a unit of carbon dioxide for every four units of hydrogen produced, along with carbon monoxide and water vapor. But this equals the amount of carbon dioxide that would be produced if natural gas were combusted as a fuel. This argument holds true for any carbon-based sources of hydrogen. Some fossil fuel sources of hydrogen (e.g., natural gas) would produce less carbon dioxide then current transportation technologies fueled by gasoline, but this comparative advantage may not be sufficient if, for example, reductions on the order of 60-80% are needed to address climate change threats (Byrne et al, 2006; Mills, 2006). Therefore, hydrogen's environmental profile depends upon its source and how associated emissions are treated.

Another important difference concerns the manner in which pollution is generated and ultimately dispersed. Hydrogen production from carbon-based fuels could occur at a centralized location. Production in this manner may allow for sequestration of carbon and other pollutants, so that they are not released into the atmosphere (Rand and Dell, 2005). However, large-scale carbon sequestration technology is still in a research phase.

The pollution problem must be examined thoroughly before the hydrogen economy can advance any further. If efforts are not made to devise a reasonable control system or to mitigate negative effects, it is possible that the new hydrogen system could prove to be worse or no better for the environment than the present fossil fuel-based energy systems. In brief, a hydrogen economy could entail strong environmental benefits, or it could prove to be more polluting than the current system.

Inefficiency of the Hydrogen-Fuel Cell Energy Chain

Efficiency remains a significant obstacle to the development of a hydrogen economy. Hydrogen fuel-cell systems achieve relatively low efficiencies compared to other energy carriers and lead some to pursue alternatives (Hammerschlag and Mazza, 2005).

Low efficiency can result because hydrogen is simply an energy carrier rather than an energy source. Hydrogen energy systems differ from those requiring the user to input some level of energy in order to extract many times that amount of energy, as with coal and oil. With hydrogen, its production takes more energy, either in the form of feedstock fuels or electricity, than is retrieved in the form of usable hydrogen at the end of the production process (Dell and Rand, 2001).

Losses occur along each step of the hydrogen fuel cycle. From its production and storage to distribution and then utilization in a fuel cell, energy is lost at every stage, resulting in cumulative decreases in efficiency (Rand and Dell, 2005). Accordingly, as hydrogen passes through its numerous stages of production, energy losses accumulate even though each stage tends to have a relatively high efficiency compared to that of an internal combustion engine and other energy options. In addition to this cumulative efficiency loss are other losses associated with the production of hydrogen's initial energy source, such as solar energy and natural gas.

In effect, the user of a hydrogen energy system will realistically never receive more than 60% or so of the energy invested into the system, and currently will probably not receive more than 20%. The reason that the hydrogen cycle will never achieve efficiencies reaching even 80% has to do with thermodynamic limitations (Rand and Dell, 2005). More specifically, processes have theoretical efficiencies representing the highest possible efficiency that the process could ever achieve due to thermodynamic limits. Actual efficiencies of such processes never reach theoretical limits because forces of friction and resistance can never be completely eliminated from a system. Such relationships mean that users of hydrogen will always receive far less energy from their fuel cells than was used in production and transportation of hydrogen to the user. Accordingly, many researchers believe that, rather than focusing on the development of hydrogen systems, policy should emphasize using the initial power source more efficiently. Such a goal could be accomplished by finding ways to use electricity directly, without converting it to another form. Failing that, systems promoting energy storage should utilize fewer steps, so as not to fall victim to the cumulative nature of efficiency loss. One option commonly encouraged in this area is high-efficiency, deep-cycle batteries for mobile applications or large-scale efficient electrical storage systems for household needs and industrial electric production (Hammerschlag and Mazza, 2005).

Another response to the problem of hydrogen's efficiency difficulties involves restricting its applications to those that enjoy clear advantages over rival energy sources. For example, hydrogen is particularly good for storing large amounts of energy over long time periods, and for transferring and storing energy quickly (Rand and Dell, 2005; Suppes, 2005). In this regard hydrogen applications may be limited to certain uses in the transport sector and for seasonal needs to resolve intermittency problems in the renewable electricity sector.

Shifting the transport sector from its present reliance on fossil fuels to hydrogen presents many serious challenges, but also many unique opportunities. Various carbon-based fuels (including ethanol and other bio-fuels) emit pollution and carbon emissions on combustion. Therefore for buses, marine transport, trucking, fleet vehicles, and long distance driving, hydrogen may be a feasible fuel despite its lower efficiency. In trucking, for instance, which requires relatively quick refueling, hydrogen could play a major role. One competing alternative energy technology is batteries, but they suffer from long recharge times. However, for local driving that would not exceed the limits of a rechargeable battery, hydrogen energy systems continue to face a number of challenges in cost, efficiency and practicality.

Energy efficiency is likely to play a major role in determining when hydrogen applications are utilized. It is likely that hydrogen will be applied to those tasks where its technical advantages outweigh its comparatively low efficiency compared to other energy carriers. In practice, certain tasks may also result in the combination of a number of technologies with hydrogen energy systems, such as hydrogen-battery vehicles.

Hydrogen Storage and Distribution for Mobile Applications

Hydrogen storage for mobile applications can be a major obstacle in the transition to the hydrogen economy. Pressurized and liquefied molecular hydrogen storage could be used initially but each has shortcomings. As such, research and development efforts are now being directed toward advanced hydrogen storage technologies. Solid-state storage and nanotechnology could potentially prove to be valid options, especially as storage volumes increase, but these approaches are still highly experimental at this time (NAS, 2004).

A primary concern for the storage of hydrogen is the energy density that would be suitable for long distance transportation applications. Current storage options for hydrogen either have too low an energy density to provide adequate range for a vehicle or the method of storage is too heavy, thereby reducing the efficiency of the vehicle. There are additional concerns regarding the handling and distribution of hydrogen. In its pure form at room temperatures, hydrogen is a diffuse gas that could prove difficult to handle and distribute without high losses of the gas. While pure molecular hydrogen can be liquefied, the process involves high levels of energy loss. Moreover, hydrogen must be stored at such low temperatures in order to become a liquid that it could pose a health hazard to those handling it.

Research is underway to examine a number of novel methods for hydrogen storage that rely on the absorption of the gas within a solid or a liquid. Once absorbed by a substance, the hydrogen would be stably contained until released through heat or pressure change. However, concerns revolve around the weight of the absorbing material, the cost of the absorbing material, and how to handle, dispose of, or reuse the material once it has released all of its hydrogen (NAS, 2004). All of these efforts are presently in the research and development stage and are not ready for market integration.

Lack of Existing Infrastructure and High Cost of Construction

Traditionally, the automobile and transport fuel industries have operated largely independently, a condition that complicates economic development of the hydrogen transport economy. Expressed simply, the dilemma centers on what should come first, the hydrogen fueling stations or the hydrogen cars? The infrastructure required for energy generation, storage and distribution in a country as large as the U.S. is projected to cost many billions of dollars (Ogden, 1999). Energy infrastructure investments generally represent at least a 30-year commitment to a fixed energy system that cannot be easily modified later to meet changed market circumstances. Thus, initial investment decisions figure critically in the viability of an energy project. Given this background, investors in hydrogen supply markets may demand a market base of hydrogen-fueled cars in order to guarantee them a reasonable profit. Conversely, automakers may not be willing to build hydrogen-propelled autos unless hydrogen-fueling stations exist to serve them. It is quite difficult, as a consequence, to build a robust commercial sales platform establishing economies of scale for hydrogen technology.

Expense of Components

In addition to the high cost of needed infrastructure for a hydrogen economy, the individual components themselves are expensive compared to their conventional counterparts. Primarily this high cost is associated with the fuel cell used to convert the hydrogen to electricity (Ogden, 1999). This can cost several hundred times more than using a conventional power source. This is currently seen most strongly in the transportation sector where a fuel cell vehicle can be expected to cost approximately $1,000,000 (National Public Radio, 2005).

In addition to the high cost of the fuel cell, many of the most desirable sources of hydrogen are more expensive than an equivalent amount of hydrogen. Hydrogen from any sustainable source, such as solar, biomass, or wind is more expensive than an amount of gasoline with the same energy content. Only hydrogen from natural gas and coal are currently cost competitive with gasoline. Unfortunately these sources lack the energy security or environmental benefits that are supposed to propel interest in a hydrogen economy. As well, both have shown significant price volatility in recent years (EIA 2004).

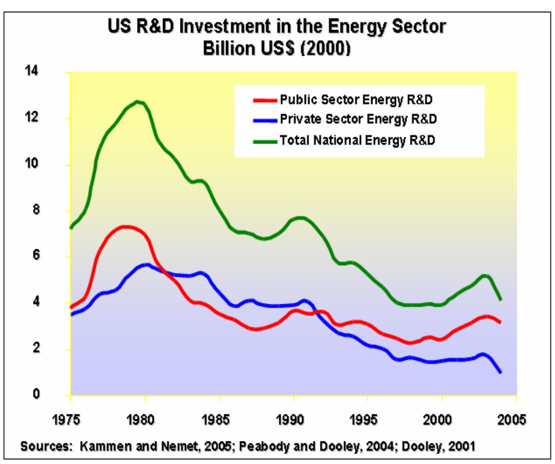
The combination of these two factors makes it unlikely that hydrogen will play a significant role in the U.S. energy system until the prices of fuel cells and sustainable hydrogen sources (i.e., renewable energy-based sources of hydrogen) become competitive.

Investment Needed

In order to lower the costs of components, create the level of infrastructure needed, and to solve the technical problems still surrounding the effective use of hydrogen as an energy carrier, substantial levels of investment are needed from both the government and the energy industry. This investment will need to underwrite research and development to solve technical problems and develop less expensive components in the hydrogen fuel cell cycle.

In this vein, significant concern exists regarding downward trends in both public and private sector energy R&D investments (see Figure 6a.). This pattern casts doubt over the likelihood that national capital commitments will be sustained for the length of time needed to fully develop the hydrogen energy economy. Declining investments in new energy technology have recently been offset by rising support for fuel cell technology (see Figure 6b.). Government investments have been robust and are rising in specific states but have not yet attracted significant private sector funding. As a result it is uncertain if a high level of support will be maintained in order to develop hydrogen fuel cell systems into a commercially viable, widely used technology.

a.



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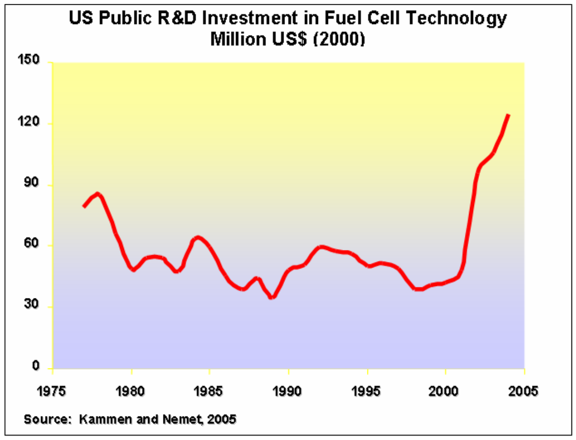


Figure 6. Investments in U.S. energy sector and fuel cell technology

In the transportation sector, hydrogen is most suited for vehicles for which low emissions are desired and would not be suited for pure electric battery systems, which would have higher efficiencies but lesser technological capabilities in regards to range and refueling capabilities. The efficiency problem is compounded beyond the efficiency of the fuel cell. There is also the efficiency of the reformation, the efficiency of distribution, and the efficiency of the compression, all of which would be processed beyond that needed for the extraction of the natural gas.

Hydrogen is not currently commonly used by any sector in particular, though there are many efforts to increase the role of hydrogen at many different levels on both the public and the private levels. While the federal government has focused on providing funds for further research into the fields of hydrogen production and storage, the individual states have taken the further step of implementing plans to create statewide hydrogen infrastructure. Most notable amongst these efforts are those of California, Texas, Florida, which have enacted legislation to construct these infrastructures and provide funding and incentives to consumers who would be willing to use the technology. California is furthest along in their attempt to create a hydrogen economy and they have already constructed a number of fueling stations throughout the state as a first step. Several different fleets, both government and corporate, use these stations.[1]

Current research in the hydrogen field can be split into two separate types, technical and policy research. The technical side of the research is focused on preparing fuel cell and hydrogen technology to a state where it can be more readily applied in real world situations. This involves finding new materials for the creation of fuel cells in order to lower their costs and creating new methods of storing hydrogen, in order to safely carry sufficient amounts to be competitive with the range achievable by conventional vehicles. Hydrogen may be stored as a gas, a liquid, or

[1] Hydrogen Fueling Stations and Vehicle Demonstration Programs. http://www.cafcp.org/fuel-vehl_map.html

stored within other substances. Storing hydrogen as a gas requires high pressure compression in order to achieve reasonable energy densities and even with this the amount that can be stored in a reasonable volume still allows for less range than would gasoline. Storing hydrogen as a liquid achieves much higher energy densities than as a compressed gas but liquefying hydrogen and storage of liquid hydrogen requires extremely low temperatures and large amounts of energy. This drastically reduces the overall efficiency of the hydrogen fuel cell cycle.

Since both compressing and liquefying hydrogen present serious problems alternative methods of hydrogen storage are being studied. Experimental materials such as metal hydrides and carbon nanotubes are capable of absorbing and releasing large amounts of hydrogen gas. Various liquids are also being examined for their ability to absorb and release hydrogen as well. These materials are all experimental, however, and have not yet proven to be suitable for application in a growing hydrogen economy. Transportation is likely to be the starting point for the hydrogen economy and it is this sector that needs the compact storage of hydrogen energy. It is for this reason that continued research into the storage of hydrogen is vital for the growth and overall success of the hydrogen economy.

The other half of the research currently being conducted in regards to the development of hydrogen involves the social and policy aspects of the implementation of a hydrogen infrastructure. This research attempts to resolve the issue of beginning and carrying through such a massive endeavor as shifting the energy system. Much of this is simply finding a way to reduce the cost of the project and raise the capital needed to construct the needed infrastructure. Additionally efforts are being made at determining how to integrate this new energy carrier into our energy system and begin having it assume a greater role in satisfying our energy demands.

Before the hydrogen economy can progress beyond the initial efforts, work must be done at the social and technical levels, primarily to make it affordable but also to increase efficiency and utility of hydrogen systems. In order for this to occur, not only must the hydrogen by affordable as a fuel, but also the infrastructure for creating and distributing the hydrogen, as well as the fuel cells required to utilize the hydrogen effectively, must be affordable. Governmental efforts at the federal level are primarily aimed at furthering hydrogen research on the technical side and efforts at the state and municipal levels are focused on the social and policy techniques that can cause the further development of the hydrogen economy. This has allowed the growth of hydrogen economies to develop in certain states, like California. Through executive support, bulk procurement, government-corporate spending matching, and incentives hydrogen infrastructure has been increased in certain areas and allowed some fleets to operate off of hydrogen. By developing these beginning levels of infrastructure it may be possible for market forces to take over and further develop the hydrogen economy in these areas.

2.2 Biodiesel Vehicles

Biodiesel is a renewable fuel made from vegetable and animal oils that can be used as a direct petroleum diesel substitute in most compression-ignition diesel engines. It is commonly blended with petroleum diesel in 5% and 20% quantities or sold in a pure form (100%). The blends are named according to the percentage of biodiesel in the fuel and listed as B5, B20 and B100.

Biodiesel can be produced from a variety of feedstocks and any number of chemical reactions, but trans-esterification of soybean or rapeseed oils is the most economically attractive process. The oils (triglycerides) are batch-reacted with an alcohol (usually methanol) in the presence of a hydroxide catalyst (KOH or NaOH) at roughly 150°F and 20psi. A high conversion of 98% of the feedstock to biodiesel is usually achieved and a considerable quantity of glycerin is produced, a profitable byproduct (National Biodiesel Board, 2002).

Biodiesel has extremely low sulfur content (0-24 ppm) and a higher lubricity than petroleum diesel, but the energy content is approximately 11% less (thereby reducing MPG fuel economy). Biodiesel is also extremely biodegradable. When petroleum diesel is substituted with biodiesel in combustion processes, significant reductions in harmful air pollutants can be achieved. Burning biodiesel (B100) creates 78% less carbon dioxide, 56% less hydrocarbons, 43% less carbon monoxide and 56% less particulate matter. However, there is a slight increase in nitrogen oxides emitted (6%) when biodiesel is burned in lieu of petroleum diesel.

The chemical properties of biodiesel are similar enough to petroleum diesel that biodiesel can be used as a direct substitute in standard compression-ignition engines. The American Society of Testing Materials has developed a uniform standard for biodiesel – D 6751 – to ensure fuel consistency among producers and consumers. This development has encouraged diesel engine manufactures to certify low percentage blends of biodiesel (B5 and B20) for use in their engines (Engine Manufacturers Association, 2003). The other advantages of biodiesel – decreased particulate, hydrocarbon, and carbon monoxide emissions, higher lubricity, lower sulfur content, and higher biodegradability – have stimulated widespread interest and demand to replace traditional petro-diesel with bio-diesel in fleets of heavy duty, diesel-powered vehicles. Additionally, biodiesel can also be used to meet up to 50% of Alternative Fuel Vehicle Fleet requirements in the U.S. (U.S. DOE, 2006). With so many distinct advantages over petro-diesel and the minor, even negligible, retrofit required to use biodiesel in a traditional engine, many fleets in the U.S. have begun to use biodiesel and demand for the fuel has exploded.

A significant advantage of biodiesel is that it can be used in diesel engines without any modification. Concern about excessive warranty claims has prevented most engine manufacturers from approving the use of biodiesel blends greater than 5% in their engines. However, numerous studies have adequately demonstrated that biodiesel blends greater than 20% do not harm the engine and, in fact, actually clean fuel lines and tanks. The largest problem with converting from petroleum diesel to biodiesel is that the biodiesel dissolves sediment in the fuel tank and clogs downstream fuel filters. The problem disappears after a few tanks of biodiesel, but nonetheless, requires the replacement of one or two fuel filters. Biodiesel fueled engines have also been shown to require less maintenance than equivalent petroleum diesel fueled engines (National Biodiesel Board, 2005).

The market for biodiesel has grown steadily in the past few years. Only 500,000 gallons were produced in the U.S. in 1999 but by 2004, production had exceeded 25 million gallons. Demand is expected to grow to over 125 million gallons of biodiesel in 2005. Beginning in 2007, the EPA will implement stricter emission standards for particulate matter and nitrogen oxide released by diesel combustion. Blending petroleum diesel with biodiesel is a simple, economic method to drastically reduce the emissions of these two air pollutants. Consequently, demand for biodiesel is expected to continue growing at a rapid pace. The USDA currently offers grants for biodiesel production through the Commodity Credit Corporation; these credits reduce the cost of soybean oil and yellow grease feedstocks for making biodiesel. Even with incentives for biodiesel production, the cost is still slightly higher than petroleum diesel. However, because biodiesel qualifies as an Alternative fuel, it has become widely used in fleets of school buses, trucks and government vehicles to qualify for Alternative Fuel Vehicle Credits. Fleet operators receive 1 credit for every 450 gallons of B100 fuel purchased, even if the fuel is blended into B20 or B5 for use in fleets. (National Biodiesel Board, 2005)

Biodiesel fuel is also widely distributed and available at many locations. Because of the proximity to the soybean feedstocks, there are a significant number of biodiesel fueling stations in the Midwest. Fleet operators have also installed their own fueling stations provide biodiesel for their vehicles. Harvard University uses biodiesel (B20) in 25 of their university vehicles which consume upwards of 60,000 gallons of fuel per year. All of the fuel comes from a new fuel station located on the campus (National Biodiesel Board, 2005). National parks have also increased their utilization of biodiesel as in the case of Mammoth Cave National Park, which runs all of their vehicles on either ethanol or biodiesel – tourist buses and even lawnmowers all use biodiesel (U.S. DOE, 2006). School districts across the nation are switching to biodiesel to reduce the exposure of children to the carcinogenic fumes associated with petroleum diesel. School district mechanics are also finding that after the initial conversion to biodiesel, they have to maintain biodiesel school buses less often than petroleum diesel fueled buses.

Biodiesel provides a number of advantages over petroleum diesel – it is renewable, emits significantly fewer harmful pollutants, combusts more completely and lubricates engine components better. On the downside, biodiesel has slightly less energy content than petroleum diesel (~11%), it is marginally worse in extremely cold weather, it costs slightly more, and using biodiesel increases nitrogen oxide emissions slightly (National Biodiesel Board, 2005). Nevertheless, the benefits of using biodiesel far outweigh the costs and demand is increasing rapidly in the U.S. Using biodiesel is unhindered by the need to introduce new engine technologies or retrofit existing diesel engines, so adoption of the new fuel and increased distribution can occur at breakneck pace. As more producers come on-line, the price of biodiesel is expected to fall, possibly below that of gasoline or standard petroleum diesel.

The major advantage of biodiesel as an alternative fuel stems from the fact that the chemical, physical, and thermodynamic properties are roughly similar to petro-diesel, thereby enabling direct substitution in compression-ignition engines. The fuels are not identical however and the slight differences can affect engine performance, emissions, and long-term fuel storage. Table 1 compares the properties of biodiesel and petro-diesel and is followed by a discussion of how the property differences affect real-world application of the fuel.

Table 1. Comparison of Properties of No. 2 Petro-diesel and Biodiesel

Fuel Property	Petro-Diesel (No. 2)	Biodiesel
Heating Value (MJ/kg)	42.6	37.2
Kinematic Viscosity @ 40°C (cs)	1.3-5.8	1.9-6.0
Specific Gravity @ 15°C	0.85	0.88
Water Content (ppm)	161	500
Molecular Composition (%) (Carbon/Hydrogen/Oxygen)	87/13/0	77/12/11
Sulfur Content (ppm)	500	0-24
Flash Point (°C)	60 to 80	100 to 170
Cloud Point (°C)	-15 to 5	-3 to 12
Cetane Number	40 to 55	48 to 60
Autoignition Temperature (°C)	316	316

Source: U.S. DOE, 2000

Biodiesel has lower energy content per kg than petro-diesel (as measured by the heating value) and it would be expected to produce slightly less energy during combustion (12.5% less). However, diesel engines meter fuel into the combustion chamber volumetrically, rather than by weight. Since biodiesel is slightly denser than petro-diesel, the energy content of biodiesel will be higher on a volumetric basis; 100% Biodiesel produces only 8-11% less energy than petro-diesel in an identical compression-ignition engine. This energy deficit should translate into reduced engine power when biodiesel is used and a lower fuel economy (miles/gal). The effect may be tempered in different diesel engine designs or by the reduced injection-plunger leakage caused by higher-viscosity biodiesel (Gerpen, N.D.)

Biodiesel has a higher cloud point, indicating that it will congeal and crystallize at higher temperatures. Operating conventional diesel engines in cold climates would be slightly more susceptible to freeze-up when using biodiesel rather than ordinary No. 2 Diesel. The problem can be rectified for both fuels by mixing with some No. 1 diesel fuel or using block heaters to prevent the fuel from freezing (Gerpen, N.D.)

The cetane number - used to measure the tendency of a fuel to auto-ignite – is generally higher in biodiesel. However, depending on the type of feedstock used to produce the biodiesel, the cetane number can vary from 48-52 for unsaturated oils to 60-65 for recycled yellow grease or animal fats. Higher cetane fuels reduce the ignition delay before auto-ignition. The truncated ignition delay can cause some minor hiccups and emissions variation in conventional diesel engines (Gerpen, N.D.)

The concentration of sulfur in No. 2 diesel fuel is particularly problematic. Even at the 500 ppm concentration currently mandated by the EPA, combustion of diesel fuel results in significant amounts of sulfur oxides (SO_x) in the exhaust (U.S. EPA, 2006a). Exposure to SO_x emissions is irritating to the respiratory system and is linked to asthma. School children across the U.S. are exposed to SO_x fumes from idling school buses each day (U.S. EPA, 2006b). The problem is accentuated by the presence of SO_x gases in the exhaust, which acts as a catalyst poison and prevents the installation of pollution control devices to reduce levels of nitrogen oxides (NO_x)

and carbon dioxide (CO). To address these problems, the EPA has mandated that petro-diesel have a maximum sulfur content no more than 15ppm starting in 2007 (U.S. EPA, 2006a).

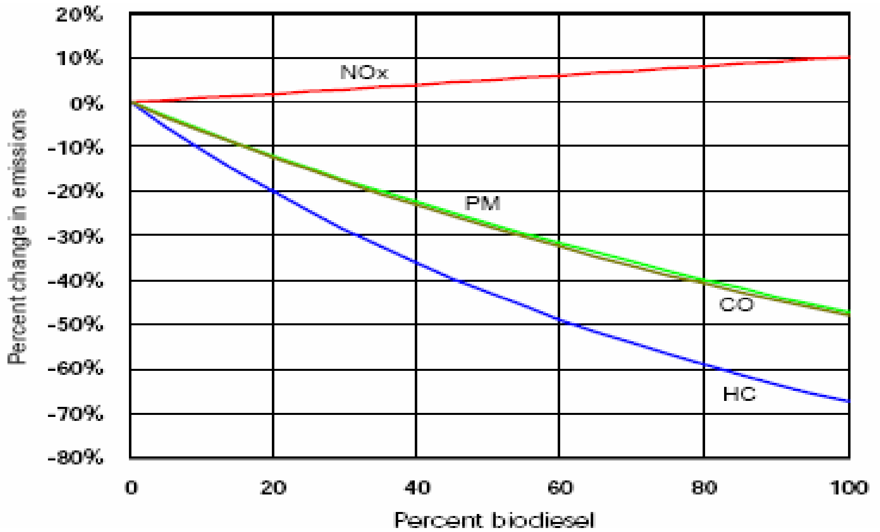
Reductions in the sulfur content in traditional diesel fuel decrease its lubricity. Since diesel engines are lubricated by the fuel, the reduction of sulfur in diesel fuel is expected to cause increased wear and tear on diesel engines. Biodiesel derived from unsaturated oils – which has no sulfur content and high lubricity – can be blended with petro-diesel in low concentrations (1-2%) to make up for this shortcoming. Biodiesel derived from yellow-grease or animal fats retains some sulfur and must be reprocessed to meet the new EPA sulfur diesel standard (Gerpen, N.D.)

Biodiesel has a different molecular composition than diesel fuel and includes oxygen atoms within the molecular structure. This is believed to contribute to more complete combustion and results in reduced soot (black smoke) and carbon monoxide but increased oxidation of nitrogen to form NO_x (Gerpen, N.D.).

Petro-diesel is normally treated as an inflammable liquid because of its high flash point (52-66°C). Biodiesel is even less of a fire hazard due to a much higher flash point (over 150°C) and can be transported with greater security (Gerpen, N.D.). Unlike No. 2 diesel, biodiesel is naturally biodegradable and will disappear from water tables or coastal areas when spilled. This is a significant benefit in farm or marine applications where fuel is spilled on a regular basis.

Biodiesel is a wholly renewable fuel that has many distinct advantages over ordinary petro-diesel. It has lower emissions, is less hazardous and safer to handle, lubricates diesel engines better, can be produced from a variety of sources, is biodegradable and easily meets the EPA requirements for sulfur content. The only detraction to this long list of advantages is that biodiesel contains slightly less energy per kg than petro-diesel fuel. The higher cloud point and small increase in NO_x emissions can be offset by the use of additives and pollution control devices respectively.

The use of biodiesel has been heralded as a way to reduce harmful emissions from cars and trucks that currently use compression-ignition engines. A number of studies have been performed to verify this assertion and have reached similar conclusions (Balat, 2005; U.S. EPA, 2002; Proc et al, 2005; and Carraretto, 2004). In general, using B100 leads to a nearly 75% reduction of life-cycle CO_2 emissions and reduced levels of carbon monoxide, sulfur oxide, unburned hydrocarbons, particulate matter and polycyclic aromatic hydrocarbons in the combustion exhaust. All studies have found that combustion of biodiesel causes increased nitrogen oxide emissions which contribute to smog and ozone formation. Figure 1 shows the commonly cited emission profile model from a 1997 EPA study for biodiesel as compared to No. 2 diesel fuel. Table 2 shows an alternative dataset derived from NREL data describing a biodiesel emission profile. It should be noted that emissions from biodiesel-fueled engines vary slightly depending on the type of biodiesel used, the particular design of the diesel engine, and whether pollution-control devices have been installed. No two tests will provide identical results and the average model generated by the EPA is probably the best source for predicting the emission characteristics of biodiesel combustion.



Source: US EPA, October 2002.

Figure 7: Average emission profile using biodiesel in heavy duty truck engine applications (EPA Report)

Table 2. Emission Effects of Replacing Petro-diesel with Biodiesel

Emission	B100	B20
Carbon Monoxide	-43.2%	-12.6%
Hydrocarbons	-56.3%	-11.0%
Particulates	-55.4%	-18.0%
Nitrous Oxides	+5.8%	+1.2%
Air Toxics	-60-90%	-12-20%
Mutagenicity	-80-90%	-20%

Source: U.S. DOE, 2000

A cradle to grave lifecycle study of biodiesel was completed by the USDA and DOE in 1998 and the results were compared to No. 2 Diesel. The benefits of substituting biodiesel fuel for petro-diesel are significant over the lifecycle of the fuel (production, transport, and consumption). Using B100 reduces net CO_2 emissions by 78% while using B20 reduces CO_2 emissions by 17%. The reduction is a direct result of the carbon recycling within the soybean plants used to produce biodiesel and not related to overall tailpipe emission of CO_2. Biodiesel has a much higher *fossil energy efficiency ratio* (total fuel energy/total fossil fuel energy used in production, transportation, etc.); biodiesel has a ratio of 3.2 while the ratio for petro-diesel is only 0.83. For every unit of finite fossil fuel consumed, using biodiesel will result in 3.2 units of available energy while using petro-diesel will only result in 0.83 units (Sheehan, 1998). Other aspects of the lifecycle study are summarized in Table 3 below.

Table 3. Lifecycle Emissions Analysis of Biodiesel vs. Petro-diesel

Overall Lifecycle and Bus Tailpipe Emissions	Biodiesel vs. Petro-diesel
Carbon Monoxide (CO)	-35%
Tailpipe CO	-46%
Particulate Matter (PM)	-32%
Tailpipe PM	-68%
Tailpipe Soot	-83.6%
Sulfur Oxides (SO_x)	-8%
Tailpipe SO_x (no sulfur in Biodiesel)	-100%
Nitrogen Oxides (NO_x)	+13%
Tailpipe NO_x	+8.9%
Hydrocarbons (HC)	+35%
Tailpipe HC	-37%
Wastewater (from Production)	-79%
Hazardous Solid Wastes Produced	-96%
Non-hazardous Solid Wastes Produced	+100%

Source: National Biodiesel Board, N.D.

In general, using biodiesel instead of No. 2 diesel has positive environmental and health effects. A large reduction of harmful emissions regulated by the Clean Air Act (CO, SO_x, and PM) occurs when diesel is replaced by 100% biodiesel. Other blends of biodiesel (B20 and B5) have a proportionately lesser, but still positive, effect on reducing harmful emissions. The more-benign emission profile of biodiesel is considered less irritating to respiratory systems and its usage can help reduce the incidence of asthma. With a lower concentration of harmful pollutants and carcinogenic compounds, biodiesel has a significantly lower mutagenicity than diesel.

Biodiesel is also a renewable fuel which can supplement and displace nonrenewable petro-diesel. A high fossil fuel efficiency ratio means that fossil fuels can be used to release more energy than they themselves contain. Additionally, the process of growing plant matter reclaims CO_2 released into the atmosphere during biodiesel combustion. While the tailpipe emissions of biodiesel and petro-diesel are virtually identical, the net CO_2 released to the atmosphere is 78% lower when biodiesel is used because of carbon recycling. The only negative environmental impact that biodiesel has when compared to petro-diesel is increased nitrogen oxide emissions. These emissions can contribute to smog and ozone formation in urban environments but present less of a problem in rural areas. Overall, biodiesel has a much less negative impact on the environment than traditional petro-diesel.

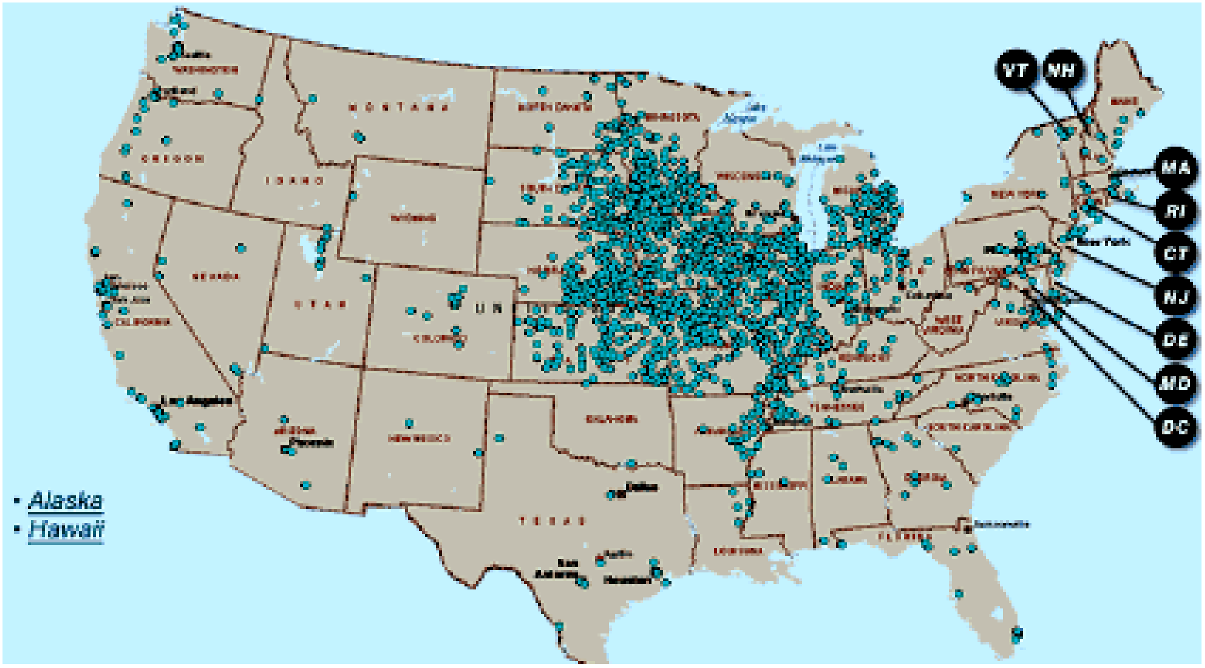
Interest in biodiesel has skyrocketed in recent years and the US market has grown to accommodate. The overall production capacity has grown from a meager 500,000 gallons in 1999 to nearly 75 million gallons in 2005 (National Biodiesel Board, 2005) A recent press release from the National Biodiesel Board states that there are 45 biodiesel production facilities in operation with another 54 planned. The average capacity of new facilities is 6.5 million gallons, although some can be as large as 30 million gallons (National Biodiesel Board, 2005).

The biodiesel is primarily being used by fleets of heavy duty vehicles like buses, garbage trucks and service vehicles (i.e., vehicles weighing more than 8500 lbs). Nationwide, more than 600 fleets have adopted biodiesel in either a blended or pure form and demand is increasing every day. In particular, biodiesel has made inroads into the US fleet of nearly 440,000 school buses which transport 24 million children (U.S. EPA, 2006b). School districts across the country have adopted biodiesel in an effort to reduce children's exposure to noxious diesel combustion fumes in accordance with the EPA Clean School Bus USA Program. Arlington County, Virginia uses B20 in 500 diesel-powered vehicles (120 school buses) while the Olympia School District in Illinois uses the B2 blend in their 33 school buses which travel a total distance of 4,000 miles per day. School districts that have switched to biodiesel blends have been overwhelming satisfied with the switch citing reduced maintenance, increased fuel economy, excellent cold weather operation and less harmful emissions. The small additional cost of biodiesel (~$0.20/gallon) is the only negative aspect, but many school districts have received grants for using biodiesel or take advantage of state programs aimed at increasing the use of alternative fuels (National Biodiesel Board, N.D.a). Warwick public schools actually found that the reduced maintenance associated with using B20 in 65 school buses saved the district $0.35/gallon compared to No. 2 diesel over the last three years. (NAFA, 2003)

Biodiesel demand has been stimulated by the Energy Policy Act of 1992 which mandated that a fraction of new vehicle purchases for qualified fleets be alternative fuel vehicles (i.e., federal/state agencies and public utilities). The rule concerning biodiesel was clarified in 1998 amid some confusion. Pure biodiesel is considered an alternative fuel and may be used at blends of 20% or higher in *existing* vehicles weighing more than 8500lbs to meet half the requirement for alternative fueled vehicles. Qualified fleets then earn one EPAct Credit for every 450 gallons of pure biodiesel used in blends of 20% or higher (U.S. DOE, 2006). There is currently no alternative fuel biodiesel requirement for light duty diesel vehicles weighing less than 8500 lbs.

The adoption of biodiesel has been rapid, in part, due to the minimal cost required to convert a standard compression-ignition engine to consume biodiesel. The engine does not have to be modified in any way since biodiesel is a solvent and has detergent-like properties, the fuel filter can become clogged when diesel sediments in the fuel tank are exposed to biodiesel and dislodged. Additionally, the effect of biodiesel on elastomers (i.e., hoses, gaskets and seals) is uncertain and may cause cracking or shortened life (Engine Manufacturers Association, 2003). Experience from fleet operators who have transitioned to biodiesel blends indicates that these problems are minor, if not negligible, and are easily rectified by replacing the fuel filter after the first one or two tanks of biodiesel and inspecting the seals during regular maintenance intervals (NAFA, 2003).

Availability of biodiesel has grown with increasing production. As the primary feedstock for producing biodiesel is soybean oils, the bulk of biodiesel production and distribution is located in the central mid-west U.S. where soybeans are grown. Individual fleets generally purchase fuel directly from a distributor or install their own centralized biodiesel storage and filling station. Consumer retail locations to purchase biodiesel mirror the locations of distributors but are less numerous. Figure 8 shows the locations of U.S. distributors.



Source: National Biodiesel Board, 2002
Figure 8: Locations of Biodiesel Distributors in the U.S.

Biodiesel is rapidly becoming an established fuel recognized by mainstream industries. Following the development of the ASTM D6751 standard for biodiesel, manufacturers of diesel engines began to support the use of B5 in their engines (Ford Motors, N.D.). The use of B20 will not void any engine warranty and both John Deere and DaimlerChrysler ship their diesel-powered vehicles from the factory with B5 fuel. Many studies have demonstrated the feasibility of using B100 in diesel engines without any adverse side effects and the fuel can be purchased at some retail locations. The U.S. Navy (the largest diesel consumer in the world) has issued a statement encouraging the use of B20 in all non-tactical vehicles with access to the fuel (National Biodiesel Board, 2005a). A biodiesel quality certification program – BQ-9000 – has also been implemented and is aimed at insuring reliable production, transportation, storage, and use of biodiesel fuel.

Demand for biodiesel is expanding rapidly. With the dedicated support of country-folk singer Willie Nelson and his network of "BioWillie" B20 fueled truck rest stops, the trucking industry has supplied unilateral support for low blends of biodiesel. The American Trucking Association announced their support for B5 in all trucks on October 20, 2005 (National Biodiesel Board, 2005a). Additionally, 5% biodiesel can be blended with home heating oil – called BioHeat™ – and used to provide heat for homes in the Northeastern U.S. Marinas and boat operators have showed a renewed interest in biodiesel since it is biodegradable and will not harm marine life when spilled. The Ft. Lauderdale Water Taxi and Channel Islands National Park have already begun using biodiesel blends. At present, biodiesel presents a number of advantages over traditional petro-diesel – reduced emissions, renewability, biodegradability – for a marginal extra cost. Biodiesel has an established fuel standard, is supported by mainstream industries, and is poised for dramatic growth.

2.3 Gasoline-Electric Hybrid Vehicles

2.3.1. Overview

In general a hybrid vehicle uses two or more energy resources to provide motive power but there is significant differentiation as to the extent that these resources provide the motive power. A hybrid electric vehicle (HEV) utilizes electricity as one of the power sources. Friedman (2003) defined four main types of hybrids, muscle, mild, full and plug-in hybrids depending on the degree of hybridization, although it is difficult to clearly define the line of demarcation between hybrid types (Table 4).

Table 4. Types of Hybrid Vehicles

Does this vehicle…	Conventional Vehicle	Muscle Hybrid	Mild Hybrid	Full Hybrid	Plug-in Hybrid
Shut off the engine at stop-lights and in stop - and - go traffic	X	X	X	X	X
Use regenerative braking and operate above 60 volts		X	X	X	X
Use a smaller engine than a conventional version with the same performance			X	X	X
Drive using only electric power				X	X
Recharge batteries from the wall plug and have a range of at least 20 miles on electricity alone					X

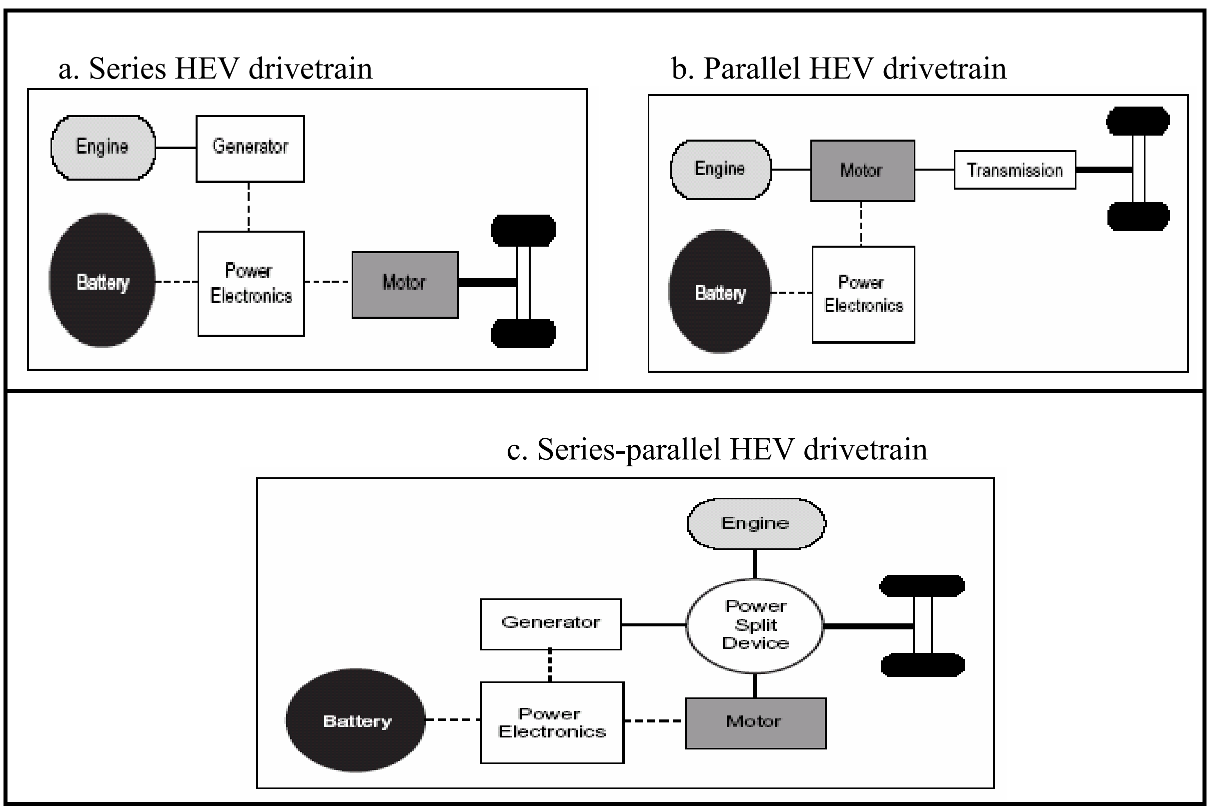
Source: Friedman, 2003

The muscle-hybrid is considered the basic form of hybridization as the technology is not used to provide additional driving power but functions as auxiliary power, and managing engine stop/ start and using regenerative braking to charge the battery.[2] The engine in a mild hybrid provides supplemental power to the conventional internal combustion engine (ICE), thereby improving the performance of the vehicle but it cannot operate the vehicle independently or start the vehicle from a standstill position – the Toyota Insight and Honda Civic are considered mild hybrids. The full hybrid technology goes one step further in that the vehicle can be independently driven by the electric hybrid motor or in association with the ICE – the Toyota Prius is considered to be a full hybrid. The plug-in hybrid encapsulates the most extensive use of hybrid technology, using a smaller ICE and its batteries can be recharged from an electricity grid, thereby extending its daily driving range.

[2] A short field guide to hybrids. http://www.greencarcongress.com/2004/08/a_short_field_g.html

The differences between the various types of hybrids is a function mainly of their drivetrain technology, which can either be series, parallel or a combination of both (Friedman, 2003). The series drivetrain configuration is the most basic of the hybrid drivetrains (Figure 9a), in that the electric motor is the only means of driving or turning the wheels. The motor receives electricity from either the battery pack or from a generator powered by the engine. The system requires a large battery pack, which tends to make series drivetrain hybrids more expensive than other options. The batteries are recharged by both the engine/generator set and by regenerative braking (storage of normally wasted energy during braking). The parallel drivetrain hybrids use both the engine and motor to drive the vehicle as they are both connected (in parallel) to a transmission system (Figure 9b). This arrangement improves the efficiency of the vehicle but also increases the complexity of the mechanics of the vehicle. They use larger engines and smaller battery packs than the series hybrids.

The series/parallel drivetrain (Figure 9c) is a combination of both configurations, in which the engine can drive the wheels directly (parallel drivetrain configuration) but it can also be disconnected from the transmission and operate similar to that of a series drivetrain's engine/generator set (Friedman, 2003). This configuration capitalizes on the efficiency benefits of both drivetrains. During lower speed driving, the vehicle uses the more efficient series drivetrain and at higher speed driving, the efficiency of a parallel drivetrain is used. The Toyota Prius is the best example of this configuration.



Source: Friedman, 2003

Figure 9. HEV drivetrain configurations

2.3.2 Hybrids Currently Available

In the market, hybrid vehicles are available in two major categories: light duty hybrid electric vehicles and heavy duty hybrid electric vehicles. The light duty HEVs are by far more popular and dominant in the market. In 2005 there were about seven different vehicle models available on the market in the US but additional models (at least eleven) have been planned for the next two years (Table 2).

Table 5. List of Light Duty Hybrid Vehicles Available on the Market – 2005

OEM	Model	Body Style	Power Type	Fuel	Date Introduced/ Announced	Production Date
Currently in Production						
DaimlerChrysler	Ram Pickup Contractor Special	Truck	Mild Hybrid	Diesel	Nov-00	2004 (Limited)
Ford	Escape	SUV	Hybrid	Gasoline	Jan-01	2004
General Motors	Silverado/Sierra	Truck	Mild Hybrid	Gasoline	Jan-01	2004 (Limited)
Honda	Accord	Sedan	IMA[1] Hybrid	Gasoline	Jan-04	2005
Honda	Insight	Coupe	IMA[1] Hybrid	Gasoline	Dec-99	2000
Honda	Civic	Sedan	IMA[1] Hybrid	Gasoline	Jan-00	2002
Lexus	RX400h	SUV	Hybrid	Gasoline	Jan-03	2005
Toyota	Prius	Sedan	Parallel Hybrid	Gasoline	Jun-00	2000
Toyota	Highlander	SUV	Hybrid	Gasoline	Jan-04	2005
Suzuki	Twin	Mini	Hybrid	Gasoline	Nov-02	2003 (Japan)
Toyota	Estima	Minivan	Parallel Hybrid	Gasoline	Jun-01	In Japan Only
Toyota	Crown	Sedan	Mild Hybrid	Gasoline	Aug-01	In Japan Only
Toyota	Alphard	Minivan	Hybrid	Gasoline	Jul-03	In Japan Only
Planned for Production						
Ford	Fusion	Sedan	Full Hybrid	Gasoline	Apr-03	2006
General Motors	Silverado/Sierra & Tahoe/Yukon	Truck & SUV	Strong Hybrid	Gasoline	Nov-03	2007
General Motors	Equinox	SUV	Hybrid	Gasoline	Jan-03	2006
General Motors	Malibu	Sedan	BAS[2] Hybrid	Gasoline	Jan-03	2007
General Motors	Graphyte	SUV	Full Hybrid	Gasoline	Jan-05	2006
Hyundai	Click	Sedan	Hybrid	Gasoline	Nov-03	2005/06 (Korea)
Mercury	Mariner	SUV	Full Hybrid	Gasoline	Apr-04	2005 (limited) 2006 (full)
Nissan	Altima	Sedan	Hybrid	Gasoline	Jun-04	2006
Saturn	Vue	SUV	BAS[2] Hybrid	Gasoline	Jan-03	2006
Toyota	Camry	Sedan	Unknown	Gasoline	Unknown	Unknown
Toyota	Sienna	Minivan	Hybrid	Gasoline	2003	2007

[1] Integrated motor assist. [2] Belt alternator starter.
Source: Barnitt and Eduy, 2005.

The market for heavy duty hybrid vehicles is also expanding particularly for transit buses and a number of cities have begun to deploy these vehicles within their fleets. New York City has been an early adopter of heavy duty hybrid technology and has about 325 hybrid buses in operation (Chandler *et al*, 2006).

Plug-in hybrids electric vehicles (PHEVs) are still being developed and there is growing interest in their use but technological challenges such as current battery technology (life, range, cost, safety etc.) and motor and power electronics costs seem to be the main market barriers (DOE, 2006).

2.3.3 Economics of Hybrid Vehicles

At present, there are a few models of hybrid vehicles present in the U.S., ranging from compacts and sedans to minivans and trucks. About 11 new models are expected to enter the market between 2006 and 2008 (Barnitt and Eduly, 2005). The increase in the number of models has resulted in a steady rise in the total amounts of vehicles sold in the U.S. (Figure 10). While in 2000 there were only 9,350 hybrids on American roads, by the end of 2005, this amount had increased to more than 200,000.

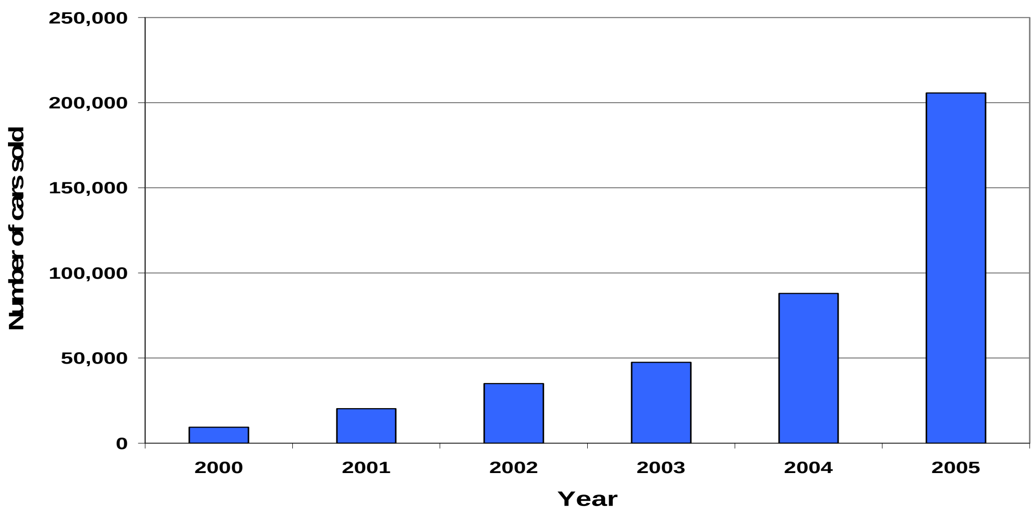


Figure 10. Sales of hybrid vehicles in the U.S. (Source: Hybridcars.com)

With the advent of commercial production of hybrid vehicles, some researchers have analyzed the potential for individuals and markets shifting towards these alternatives by means of microeconomic analysis grounded on the application of stated and revealed preference models (Ewing and Sarigöllü, 1998; Lave and McLean, 2002 and De Haan *et al*, 2006). Conclusions are diverse, with particular implication for public policy choices. Although there is some skepticism of the short-term market takeover of hybrids, a common conclusion is the decisive role played by public regulation and incentives to promote this shift. In the following section, only the conclusions of the economic analyses are presented, with the policy discussion being incorporated in a further section.

Ewing and Sarigöllü (1998), in their analysis for Montreal, built a consumer car fuel-type choice model and assessed the influence of economic incentives, with an emphasis on electric vehicles. The analysis drew some conclusions that may be applicable to the hybrid vehicle market. It was determined that there was an increased willingness to pay for less polluting vehicles, oscillating between US$872 and US$1932 in comparison to conventional vehicles of similar performance.

It was concluded that the use of price subsidies would most likely help to improve consumer choices for cleaner vehicles. Other policy alternatives were also proposed to encourage the switch to cleaner cars, including reserve lanes on major roads during high commuting periods and the application of electronic road pricing or carbon taxes that *artificially* improve the relative operating costs of cleaner vehicles. They argue that savings from the electric vehicles' lower operating costs should be triple any higher maintenance costs it may have in order for them to be advantageous. However, they do not find substantial evidence to support the effectiveness of road pricing or carbon taxes.

These are similar conclusions by Lave and McLean (2002), in their comparative cost-benefit analysis of the Toyota Prius and a conventional Corolla model. They conclude that hybrids will not have significant sales unless fuel prices rise significantly or unless regulators mandate them. Further it was argued that the price of gasoline should be more than three times greater than its 2001 price, for the Prius to be attractive in the U.S. market (this equilibrium price is about $5.10/gal). On the regulation side, it was determined that the social value of abating tailpipe emissions would have to be 14 times greater than conventional values. Given current gasoline prices, Lave and McLean's analysis offers a positive prospective for the Prius in an urban driving context, since they calculate that a gasoline price of $2.50 would be necessary to make them more attractive to customers. Finally, from a marketing perspective, the authors maintain that manufacturers should incorporate in hybrids features that are unavailable on conventional models, such as electricity-intensive electronic applications which would introduce a comparative advantage.

De Haan et al, (2006) focus their attention on determining the presence of rebound effects in the Swiss hybrid car market. A *rebound effect* appears when the demand for a product increases as the product of services becomes more efficient, for example:-

> "If the energy efficiency of a car is increased by technological innovations, 100 km can be driven with less fuel and hence at a lower cost. This lower cost could have the consequence that people drive more and longer because mobility has become cheaper."

De Haan et al, (2006) identify two potential rebound effects in the hybrid vehicle market, (i) a switch from small and/or already fuel-efficient cars to hybrid models**,** and (ii) an increase of the average household vehicle ownership if formerly-owned vehicles are not scrapped. However, after running their model, no evidence was found of the two rebound effects but their conclusions are still favorable to hybrid vehicles, as they found that hybrid cars such as the Prius may be considered fuel-efficient and effective (meaning, decreased fuel sales).

After a comparison of relevant literature, the results in different markets (Canada, U.S. and Switzerland) differ, a situation that may be explained by the different techniques used, environmental attitudes, the measurement of cost and benefits, and different regulatory frameworks. They also make dissenting points about the convenience of incentives to promote a shift to hybrid vehicles. In this respect, Ewing and Sarigöllü (1998) and De Haan et al. (2006)

are optimistic about certain instruments (price subsidies, tax rebates) while Lave and McLean call for further analysis on the area.

2.3.4 The Future of Hybrid Vehicles

Technology advancement will play a significant role in increasing the fuel economy of hybrids and reducing emissions generation. At present, a limited number of both conventional and hybrid vehicles are seen in market with "moderate" technologies. The vehicles with moderate technologies will be widely implemented across passenger fleet by 2010. Moving from technological progress of moderate to advanced technology, hybrids vehicles can achieve impressive improvements in fuel economy. Advanced technologies have not entered the market yet, but have already passed out of the research and development stage. This technology can be applied throughout the passenger fleet by 2015. For instance "Full hybrids using advanced technology and rated at 40% peak power improve 150% on the fuel economy of today's conventional vehicles, saving nearly $5,500 in gasoline and keeping 47 tons of global warming gases out of atmosphere. Mild hybrids with advanced technology show more than 100% improvement on fuel economy of today's vehicles, saving $4,700 in gasoline and reducing global energy gases by 41 tons." (Friedman, 2003)

Currently used (lead acid) batteries in hybrid vehicles are not very efficient compared to advanced battery technology and need to be replaced twice within the lifecycle of 15 years. Batteries can play a decisive factor in deciding the cost effectiveness of vehicle. There are more efficient batteries like NiMH or Li-ion batteries that are available but they are currently very expensive and the application of these sharply increases the upfront cost of hybrid electric vehicles.

Hybrid vehicles are receiving support from consumers and the future of hybrid technology in the market seems quite positive. The enhancement in the technology of hybrid vehicle can also pave the road for the development of hydrogen fuel cells. However, whether hybrids live up to their potential or not, will be a function of automakers, consumers and governments embracing them as a means of moving forward towards a lower dependence on unsecured energy sources and a cleaner and a healthier environment.

3.0 The Status of U.S. Fleets

One of the most likely paths for developing markets for alternative fuels has been through the purchase of alternative fuel vehicles (AFVs) for use in fleets by government and private industry. Traditionally, using AFVs within fleets has been considered necessary in order to develop a critical mass, which would propel new innovation in AFV technology forward (EPA, 2005). The decision framework in which AFVs are introduced into fleets requires an understanding of the traditional acquisition and retirement behavior among fleet managers and decision-makers within organizations as well as the regulatory and legislative environment, which has promoted AFVs over the last decade. Alternative fuels are increasingly fueling fleet vehicles operating in the U.S. This is due in part to federal regulations that were established in the early 1990s (EPA, 2006). This section will introduce the current state of fleets within the U.S. and will examine the main drivers that influence the fleet landscape both today and into the future.

3.1 Fleets in the U.S.

In 2003 the U.S. had just over 12 million automobiles and trucks operating within fleets (6.5 million trucks; 5.6 million automobiles). There were approximately 776,500 buses operating on U.S. roads in 2003. Of those, 470,395 were district-owned; contractor-owned and state-owned school buses and 300,000 were public transit and private touring buses (Bobit, 2005). The government and auto rental industry operated the greatest number of fleets, with businesses following closely behind. A detailed breakdown of automobiles and trucks operating within fleets is shown in Table 6. Buses are not included in the figures below (Table 6).

According to the Bureau of Transportation Statistics, 236,760,033 vehicles are registered in the U.S. (Table 7). Fewer than 5.5% of these vehicles operate within fleets. This percentage includes buses, which comprise only 0.3% of vehicles operating on U.S. roads. Today, 16% of buses use alternative power (APTA, 2005) ranging from fuel cells to clean diesel and includes all power sources except straight diesel and gasoline.

Table 6. Fleet Trends 1997-2003

U.S. Automobile and Truck Fleets by Use (Thousands of vehicles)	1997	1998	1999	2000	2001[e]	2002[e]	2003[e]
TOTAL automobiles and trucks in fleets	**15,869**	**16,879**	**15,530**	**15,196**	**13,642**	**11,985**	**12,128**
Automobiles in fleets, total	**9,225**	**9,550**	**7,742**	**7,346**	**6,640**	**5,600**	**5,647**
Automobiles in fleets of 25 or more (10 or more cars for 1999-2001 and 15 or more cars for 2002-03)[a]							
Business[b]	1,188	1,159	3,195	2,950	2,620	930	929
Government[c]	1,218	1,030	885	883	734	1,360	1,420
Utilities	377	359	320	317	U [f]	U [f]	U [f]
Police	280	289	302	306	312	317	317
Taxi (includes vans)	181	190	135	136	142	148	148
Rental (includes vans and SUVs)	1,608	1,602	1,733	1,581	1,542	1,555	1,520
Automobiles in fleets of 4 to 24 (4 to 9 cars for 1999-2001 and 5 to 14 cars for 2002-03)[a]	**4,373**	**4,921**	**1,172**	**1,173**	**1,290**	**1,290**	**1,313**
Trucks in fleets, total	**6,644**	**7,329**	**7,788**	**7,850**	**7,002**	**6,385**	**6,481**
Trucks in fleets of 25 or more (10 or more trucks for 1999-2001 and 15 or more cars for 2002-03)[a]							
Business[d]	1,332	1,360	3,016	3,026	2,820	2,180	2,181
Government[c]	2,223	2,010	2,400	2,408	2,052	2,070	2,102
Utilities	483	459	499	498	U[f]	U[f]	U[f]
Other (police, taxi, etc.)	7	8	8	8	9	9	9
Rental trucks (not including vans and SUVs)	179	181	213	248	246	251	289
Trucks in fleets of 4 to 24 (4 to 9 trucks for 1999-2001 and 5 to 14 cars from 2002-03)[a]	**2,420**	**3,311**	**1,652**	**1,662**	**1,875**	**1,875**	**1,900**

Source: Bureau of Transportation Statistics, U.S. DOT
KEY: SUV = sport utility vehicle; U = data are not available.
[a] The data source, Bobit Publishing, changed data collection categories in 1999 and again in 2002.
[b] Includes driver schools.
[c] Includes military vehicles and federal, state, county, and local government vehicles.
[d] Businesses with Class 1-5 trucks may include leasing, construction, plumbing, heating, food distribution, pest control, cable TV, etc.
[e] 2001-2003 data do not include employee-owned fleet information as the source has stopped publishing the data. [f] Business and utility data have been combined in the 2002, 2003, and 2004 *Automotive Fleet Fact Book*. **Source:** Bobit Publishing Co., *Automotive Fleet Fact Book,* Annual issues.

Table 7. Number of Vehicles in the U.S. (2003)

Number of Vehicles in the U.S. (2003)	
Type	**Number**
Passenger cars	135,669,897
Motorcycles	5,370,035
Other 2-axle 4-tire vehicles	87,031,553
Trucks, single-unit 2-axle 6-tire or more	5,666,933
Trucks, combination	2,245,085
Buses	776,550
Total Registered Vehicles	**236,760,033**

Source: Bureau of Transportation Statistics, U.S. Department of Transportation (2005)

3.2 Fleet Acquisition and Retirement

Historically, the acquisition of new AFVs into fleets, within government and private industry, has been closely linked with federal directives and incentives. Both private industry and government have adjusted their inventory, mix and type of AFVs within their fleets based on economic conditions and tax code revisions. In addition, the mix and type of AFVs from year to year has been strongly correlated to both accessibility and price of alternative fuels (Chaudier, 1989; Runzheimer, 1993).

Fleet administrators and organizational heads significantly influence the purchasing and retirement decisions of AFVs. Successful experiences with AFVs positively influence future purchasing decisions and in most cases lead to future acquisitions. Likewise, unsuccessful or marginal experiences with AFVs negatively influence future purchasing decisions and likely result in reduced AFV purchases (NYSERDA, 2005).

A study done by the University of California at Davis found that the type, quantity and frequency of AFV purchases by both government and private industry depended on the decision making structure of the organization (Nesbitt, 2001). While this might seem obvious, the underlying premise puts forth the notion that depending on the organizational structure, each fleet will treat government regulations and incentives differently. Those organizations which are most inclined to keep ahead of the technology curve, who have had past successes and who remain well-informed on the costs and benefits will likely embrace future AFV fleet acquisitions in the future. Most fleet administrators note that besides responding to economic conditions and mandates set by government, AFVs are acquired in part to reduce emissions. However, most admit this factor is not the driving force. One of the biggest challenges is "familiarizing fleet managers with the range of vehicles and alternative fuel options available to them and getting drivers to actually believe the data — and change their buying habits" (Nesbitt, 2001).

Other reasons cited by fleet administrators for acquiring AFVs included being able to evaluate the ability of AFVs to meet the needs of their organization cost-effectively, improved public relations and willingness of outside agencies to fund some of the incremental costs. The study found that most fleet administrators believed the main advantage of AFVs over conventional-fuel vehicles operating within their fleets was in reduced emissions (Nesbitt, 2001). Most research analysts have noted that increasing the replacement interval of AFVs by fleets can slow the rate of introduction of more efficient technologies, which generally possess improved emission controls.

3.3 Government Fleets

Under the 1992 Energy Policy Act (EP Act), the federal government was required by FY 2000 and beyond to acquire 75% of their light duty vehicles in "covered fleets" as AFVs. The Act also required the federal government to reduce petroleum consumption 20% by 2005 from 1999 levels, use alternative fuels in AFVs 51% of the time by FY2005, and acquire AFVs as they replace vehicles. In addition, states and alternative fuel providers were mandated to obtain AFVs. The mandates were designed to establish a critical mass within the market to propel future technological innovations in AFV car efficiency, performance, alternative fuel storage and infrastructure forward.

In general, government organizations have more guidelines to follow compared to private industry when acquiring and disposing of fleet vehicles. The federal government requires federal fleet managers to manage their assets and account for them over their lifetime ensuring that the government is receiving best value. Using lifecycle costing techniques fleet managers evaluate purchase, lease and rental options. Generally, a common asset management approach is employed where, assets are separated into vehicle classes, and the ratio of vehicles is determined based on performance measures and specialized needs of the organization.

3.4 Procurement of New Vehicles

Many government fleet programs rely on revolving funds established by the governing authority, to make new purchases and replace damaged vehicles. Government organizations are more likely to consider rehabilitating specialized equipment rather than procuring new vehicles to extend the useful life of costly equipment and reduce or delay large vehicle procurement outlays. General guidelines have been set up where rehabilitation costs should not exceed 50% of the cost of replacement. The government also has seasonal guidelines, which recommend replacing vehicles in early fall when an optimum trade-in price can be received and an optimum purchase price can be received before the new model year vehicles are introduced (Federal Fleet Management Desk Reference, 2005).

Agencies within the federal government are required to provide certification before purchasing a new vehicle through the open market or other available means that their request has not been denied by Congress, the Office of Management and Budget or Agency headquarters, and that public or private means of transportation are unsuitable or unavailable.

3.5 Replacement Guidelines

The federal government has established minimum replacement standards for agencies to abide by. According to Federal Management Regulation 102-34.265-280 agencies “may retain motor vehicles that are in usable and workable condition even though the standard permits replacement, provided that the vehicle can be used or operated an additional period without excessive maintenance cost or substantial reduction in resale value. A Government-owned motor vehicle may be replaced if it needs a body or mechanical repair that exceeds the fair market value of the motor vehicle. Fuel economy criteria must be followed in acquiring replacement vehicles” (Federal Fleet Management Desk Reference, 2005). Federal entities are required to keep fleet vehicles for at least the years or miles shown in Table 8.

Table 8. Minimum Replacement Standards

Motor Vehicle Types	Years	Miles
Sedans/Station Wagons	3	60,000
Ambulances	7	60,000
Buses		
Intercity	N/A	280,000
City	N/A	150,000
School	N/A	80,000
Trucks		
Less than 12,500 lbs GVWR	6	50,000
12,500 – 23,999 lbs GVWR	7	60,000
24,000 lbs GVWR and over	9	80,000
4- or 6-wheel drive motor vehicles	6	40,000

Source: U.S. CFR § 101–38.402

3.6 Corporate Fleets

Private industry, in an attempt to offset their exposure to higher petroleum costs and in an attempt to present a green image to the public, has incorporated AFVs into their fleets. This trend, which began in the 1980s and which has grown substantially throughout the 1990s and early part of the 21st century is proving cost-effective for many corporations who are highly dependent on fossil fuel for their operations. In the last three years, several private organizations such as UPS and Federal Express have explored the use of hydrogen in fuel cell powered vehicles. In general, implementation of alternative fuel technologies such as hybrid or hydrogen fuel vehicles into fleets usually take place after organizations receive grants and or partial funding from governing authorities. Table 9 lists the Top 20 Commercial Fleets in the U.S.

Table 9. Top 20 Commercial Fleets in the U.S.

Organization	Cars	Trucks	Vans	SUVS	Total
United Parcel Service	0	68,213	1,242	0	69,455
Verizon	5,920	21,401	26,238	0	53,559
SBC Corp	6,099	22,495	19,227	312	48,133
Federal Express	0	28,071	2,969	64	31,104
Coca-Cola Enterprises	6,109	16,369	7,799	0	30,277
Bell South	2,400	13,100	12,500	0	28,000
Service Master	1,052	21,164	3,614	240	26,070
Tyco	8,602	3,446	10,000	50	22,098
Comcast Corp	300	10,300	10,525	375	21,500
DHL Worldwide Express, Inc.	361	18,093	0	0	18,454
Pepsico, Inc.	1,237	16,638	257	160	18,292
Cox Enterprises, Inc.	1,154	6,431	6,339	1,346	15,270
Salvation Army	400	5,000	9,600	0	15,000
State Farm Insurance Co.	12,027	171	2,663	33	14,894
Interstate Brands Corp.	830	13,138	300	1	14,269
Quest Communications	200	5,200	8,500	0	13,900
Pfizer, Inc., NY	10,109	384	815	2,046	13,354
Sears, Roebuck and Co.	15	720	12,500	1	13,236
Siemens Shared Services	4,322	2,473	5,028	540	12,363
Aramark Services, Inc.	3,179	7,705	1,089	262	12,235

Source: Automotive Fleet 2005

The phasing in of new fleet vehicles and the phasing out of old fleet vehicles in the private sector is influenced by a myriad of factors. Feedback from stakeholders, including fleet management, corporate management, maintenance staff, fleet drivers, public interest groups and transportation boards influence future purchasing and retirement decisions.

Typically, fleet vehicles in private organizations are selected based on their ability to fulfill the needs of the organization in the most cost-effective manner. From a financial standpoint, gross and net capital costs, replacement costs, replacement cost intervals, maintenance costs, insurance costs and fuel costs all play a role in the type and mix of vehicles that make up a fleet. From a vehicular perspective, maneuverability, ease of access, user-friendly controls, travel-range, storage and fuel economy, play a role in the selection of vehicles. Vehicles, which offer the lowest capital costs and lifecycle costs, tend to be the most appealing choices to organizations. Sometimes, however decision-makers must choose between vehicles that have low initial capital costs but high lifecycle costs and vehicles that have high initial capital costs but low lifecycle costs.

4.0 Economics Model

4.1 Methods to Determine Costs

4.1.1 Assumptions Made

The assumptions made in this paper for the economic analyses performed reflect the current thoughts on the future prices of two factors: fuel costs and capital costs. Traditionally making any sort of price projections are likely doomed to failure due to the numerous factors involved in determining price and the uncertain manner in which world events are capable of disrupting what might at first seem to be a steady trend (Smil, 2003). The assumptions made for this paper, however, follow the best reasonable projections that can be made and are likely to remain valid for the scope of this study.

The costs of fuel were determined separately from each other as it was not possible to find a reference source that contained the required projections of diesel, gasoline, biodiesel, and hydrogen together. The price of diesel and gasoline were both taken from the Annual Energy Outlook 2006, published by the U.S. Department of Energy (U.S. DOE, 2006). These prices were then utilized as the mid-range scenario for the future costs of these fuels. The high and low price scenarios were calculated by taking 120% and 80% of this cost respectively. This calculation was performed on all of the fuels in order to determine the high and low price scenarios.

The cost of hydrogen was determined to have a starting point of $3.6/gge. This was obtained by taking the National Academy of Science's price for hydrogen from the reformation of natural gas in distributed plants (NAS, 2004). The future costs of hydrogen were determined by utilizing the Department of Energy goal for the price of hydrogen, which is $2.5/gge by 2015 (U.S. DOE, 2006). Annual prices between these two points are determined by a linear function. Due to a lack of information on the price of hydrogen fuel, beyond this point its cost is held constant from 2015 onward.

In terms of the capital costs of these vehicles, the average cost of each vehicle subtype was calculated based on commonly used fleet vehicles and this cost was projected into the future. The projections were taken from a study by Abeles (2004) and the results applied to each conventional vehicle type. In this regard, gasoline hybrid electric vehicles and hydrogen fuel cell vehicles were priced based on their premium cost over that of a conventional vehicle. For hybrid models, it was assumed that by 2030, they would have a premium of 5% over the cheapest conventional technology (NREL, 2005). To account for improved manufacturing, a decreasing exponential function was assumed. For hydrogen vehicles, it was assumed that by 2030, they would have a premium of 10% over the cheapest conventional technology. To account for improved manufacturing, a decreasing exponential function was assumed.

4.2 Determination and Summary of Life Cycle Costs

4.2.1 Small, Medium, Large Sedans

The economic analysis of vehicles considers an evaluation of five basic types of fuel technologies: conventional gasoline, petro-diesel, biodiesel, hybrid and hydrogen. This economic evaluation provides a sneak preview of which alternative fuel vehicle technologies show cost competitiveness with conventional vehicle technology. All the assumptions and factors considered for this economic analysis have been described in section 4.1. The economic analysis accounts for the life cycle cost at present time and the projected cost until 2030. This section of the paper is dedicated to the current life cycle cost of different vehicle technologies and the following section (4.3) of the economic model describes the future cost projections of all available technologies and its impact on the fleet system.

The calculation of life cycle cost considers capital cost, fuel cost and operational and maintenance cost of vehicle during its lifetime. With an aim towards comprehensive economic analysis, the sedans are further divided into three categories: Small, Medium and Large Sedans. The lifetime for all sedans in a fleet is 3 years or 60,000 miles, whichever comes first. At present, small sedans are available with all five types of vehicle technology and life cycle cost of all technologies has been performed. Similarly, in medium sedans, life cycle costs for four technologies (gasoline, petro-diesel, biodiesel and hybrid) have been evaluated. As a result of an insignificant presence of commercially available vehicles, an economic analysis of hydrogen fueled medium sedans was not performed. In the case of large sedans, an economic evaluation of only gasoline-fueled vehicles has been considered. Other forms of vehicle technology in large sedans have yet to become commercially available or are only in the demonstration phase. The summary of the life cycle cost for all sedan types is illustrated in Table 10.

Table 10. Summary of the Life Cycle Cost for Sedans in 2006

Sedans	Capital Cost	Fuel Cost*	O&M Cost*	Life Cycle Cost
Small Sedan				
Gasoline	$16,500	$4,457	$911	$21,868
Diesel	$ 20,000	$3,371	$911	$24,282
Biodiesel**	$20,000	$3,503	$911	$24,414
Hybrid	$22,000	$2,411	$911	$25,322
Hydrogen	$100,000	$1,933	$820	$102,753
Medium Sedan				
Gasoline	$20,000	$ 5,363	$582	$25,945
Diesel	$24,000	$ 4,034	$582	$28,616
Biodiesel**	$24,000	$4,192	$582	$28,775
Hybrid	$32,000	$2,844	$582	$35,426
Large Sedan				
Gasoline	$26,000	$6,392	$582	$32,974

* The cost include the life time fuel and O&M Cost

** Biodiesel stands for B20 blend.

The life cost evaluation indicates that gasoline is still the least expensive vehicle technology. On the contrary, if we consider environmental externality and oil security then alternative fuel system outweighs the conventional gasoline and diesel fuel system. The biodiesel appears cost competitive with diesel. There is 130 to160 dollars difference between life cycle cost between diesel-fueled vehicle and biodiesel fueled vehicle. If environmental and security factors are considered, biodiesel is far more economic than diesel. However, there is some hesitancy by drivers to use biodiesel in their vehicles. Lack of customer awareness and less availability of fueling stations are a few of the reasons that make customers reluctant to utilize biodiesel.

Hybrids are also an economic competitor for gasoline and diesel fueled vehicles. However, in part due to its high upfront capital cost, gasoline-electric hybrid technology has not been able to completely displace conventional vehicles in the marketplace. Nevertheless, the current skyrocketing price trend of gasoline is making hybrids more appealing and enticing to customers. Hydrogen fueled vehicles are not yet economically viable, primarily due to their high capital costs, though these are expected to go decrease significantly in the next 10 to 15 years. Many researchers and policy makers believe that hydrogen is the "fuel of the future" and its price will eventually plunge as the technology goes into commercial or mass production. Similarly, there is the growing belief that gasoline-electric hybrid vehicles will play a bridging role between gasoline and hydrogen fuel.

The life cycle cost of sedans suggests that a biodiesel-fueled system will be the most effective and economic fuel system for diesel-run vehicles. Biodiesel has economic competitiveness and is environmental friendly and reduces dependence on foreign oil. Similarly, hybrids can be economically competitive with the gasoline run vehicles. The life cycle cost analysis concludes that alternative fuel systems are becoming more cost competitive with conventional fuel systems and if environmental factors are considered, they already out-compete conventional fuel systems.

4.2.2 Buses

The determination of life cycle costs for buses was made using a 12-year lifespan and annual mileage of 20,700, the average for most fleet buses. Diesel and biodiesel (B20) buses had the lowest lifecycle costs of all technologies considered (Table 11). Using biodiesel (B20) increased lifecycle costs by just less than 1%, attributed mainly to a modest premium paid ($0.10/gallon) for B20 biodiesel. Lifecycle costs increased 5% for buses designed to combust pure biodiesel (B100) again attributed mainly to the $0.70/gallon premium paid for B100 biodiesel. Hybrid technology increased lifecycle costs by 50% with a $200,000 initial capital cost premium over diesel and biodiesel technology. Lifecycle costs increased 160% for hydrogen fuel cell buses and this was mainly attributed to the $1 million price tag associated with buying a hydrogen fuel cell bus. While fuel costs were 65-70% lower over the life of the bus, the initial capital cost was over 200% higher than conventional diesel buses. The analysis indicates that the two blends of biodiesel (B20 and B100) provided the most economical alternative to conventional diesel engines. Several transportation authorities have reported that hybrid and diesel buses have similar fuel economies averaging 4 mpg. As a consequence, fuel costs for both hybrid and diesel buses are the same, negating the benefit of using a hybrid system in their current state for buses. Fuel costs and O&M costs for hydrogen fuel cell buses were the lowest, however the extremely high initial capital costs makes this technology uncompetitive with other technologies at this time.

Table 11. Bus Lifecycle Cost

Buses				
Technology	**Capital Cost**	**Fuel Cost***	**O&M Cost***	**Life Cycle Cost**
Diesel	$290,000	$94,495	$10,741	$395,236
Biodiesel (B20)	$290,000	$98,200	$10,741	$398,941
Biodiesel (B100)	$290,000	$120,434	$10,741	$421,176
Hybrid	$490,000	$94,495	$10,741	$595,236
Hydrogen	$1,000,000	$28,298	$9,667	$1,037,965

* The cost include the life time fuel and O&M Cost

4.2.3 Light Duty Trucks

Hybrid light duty trucks provided the lowest life cycle costs in our analysis. While capital costs averaged $2000 more than conventional gasoline, diesel and biodiesel engines, lifecycle fuel costs were 35% lower (Table 12). Initial capital costs for diesel, biodiesel (B20 and B100) and hybrid light duty trucks were the same ($30,000). However, fuel costs were significantly lower for diesel and biodiesel (B20) technologies. Operations and maintenance (O&M) costs were the same for all technologies except for hydrogen fuel cell light duty trucks where O&M costs were assumed to be 10% lower. Hydrogen light duty trucks had the highest lifecycle costs with initial capital costs 230% higher than gasoline and diesel trucks

Table 12. Light Duty Truck Lifecycle Cost

Light duty Trucks				
Technology	**Capital Cost**	**Fuel Cost***	**O&M Cost***	**Life Cycle Cost**
Gasoline	$28,000	$16,758	$1,660	$46,418
Diesel	$30,000	$12,656	$1,660	$44,316
Biodiesel (B20)	$30,000	$13,152	$1,660	$44,812
Biodiesel (B100)	$30,000	$16,998	$1,660	$48,658
Hybrid	$30,000	$11,003	$1,660	$42,663
Hydrogen	$100,000	$10,205	$1,494	$111,699

4.2.4 Heavy Duty Trucks

In the heavy duty trucks category, only diesel and biodiesel trucks were analyzed as hybrid and hydrogen heavy duty trucks are not commercially viable or available at this time. From our lifecycle cost analysis, diesel heavy duty trucks had the lowest lifecycle cost, with biodiesel (B20) following closely behind Table 13. Initial capital costs were the same for all three technologies. The only variable that changed was fuel costs depending on the type of biodiesel used. Biodiesel (B20) and biodiesel (B100) increased lifecycle costs from conventional diesel technology 0.5% and 3.5% respectively.

Table 13. Heavy Duty Truck Lifecycle Cost

Heavy duty Trucks				
Technology	Capital Cost	Fuel Cost*	O&M Cost*	Life Cycle Cost
Diesel	$125,000	$20,621	$11,990	$157,611
Biodiesel (B20)	$125,000	$21,430	$11,990	$158,420
Biodiesel (B100)	$125,000	$26,281	$11,990	$163,272

4.3 Future Cost Projections for Vehicles

4.3.1 Small, Medium, Large Sedans

Small sedans represent an attractive segment of the fleet for the introduction of breakthrough technologies. In fact, diesel and hybrid technologies are already cheaper than ICE cars in terms or cost per mile on a lifetime basis. With reduced capital costs and relatively high fuel economy, capital cost is easily amortized over time and fuel cost progressively accounts for a larger proportion of total costs. Among technologies, diesel is the most advantageous option, given a considerably high fuel economy (38 mpg) and a smaller capital premium in comparison with hybrid vehicles (Figure 11). The next option in terms of cost is hybrids. They have the advantage of being fueled with conventional gasoline, and the extra capital premium paid is smoothly amortized in the lifetime. However, in other than fleets (passenger cars), small hybrids are still a more expensive option, given a lower mileage per year. Hydrogen-run small sedans hold a considerable premium nowadays, and still are in an experimental phase. However, with progressively lower capital costs, the cost per mile may actually be lower than traditional technologies by 2014, further pushing costs per mile down given an excellent fuel economy and a price of hydrogen below gasoline and diesel. The dotted lines show that with a capital costs around $60,000, small sedans utilizing hydrogen fuel cell technology would be competitive with all of the other technologies in terms of cost per mile. Decreasing capital costs at that point would not make them any more competitive, but would rather reduce profits for manufacturers.

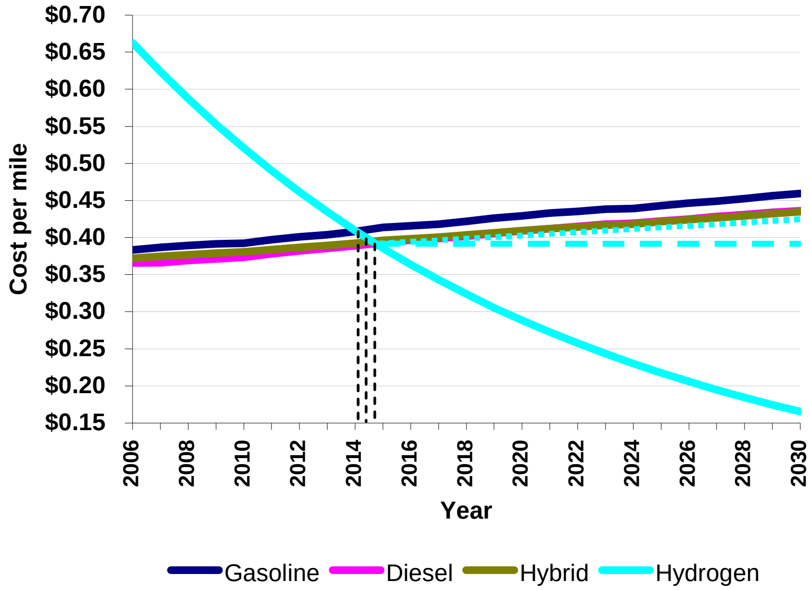


Figure 11. Future lifecycle costs of small sedans

In the category of medium sedans, in which hybrids today hold a significant premium, it is expected that their capital cost decrease over time. Again, gasoline and diesel models are vulnerable to variations of fuel prices, affecting its cost per mile considerably (Figure 12). Driven by a superior fuel economy and decreasing capital costs, hybrids would be competitive in comparison with diesel models by 2022. In relation to gasoline models, convergence would be achieved by 2029. Hydrogen medium sedans were not considered in the analysis since there is an insignificant number of reference prototypes in the market on which to draw reference data.

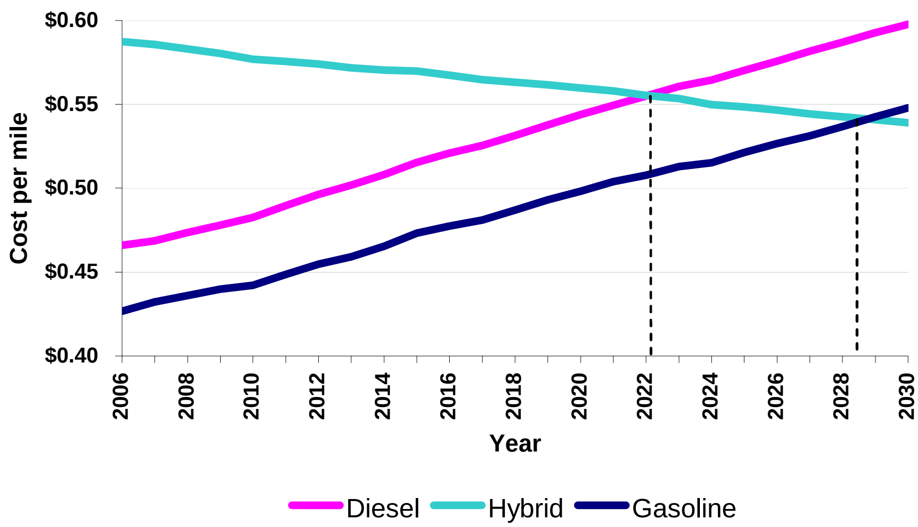


Figure 12. Future lifecycle costs of medium sedans

4.3.2 Buses

With a significant, initial capital premium, it takes a considerable time for both hybrids (premium of $200,000) and hydrogen buses (premium of $710,000) to be competitive with diesel buses. With our assumptions, hydrogen buses' capital costs would progressively decrease due to an experience curve. The convergence is driven by two salient factors: the lower fuel economy of diesel buses which makes them more vulnerable to peaking diesel prices and the lower cost of hydrogen if government goals are achieved coupled with a better fuel economy. Under these circumstances, hydrogen buses would be competitive with hybrids by 2017 and with diesel buses by 2025 (Figure 13). Under these circumstances, hybrid buses would be at a disadvantage and their progressive share in the fleet would be expected to decrease. The role of hybrid buses as an intermediate technology would have to be verified (NAS, 2004).

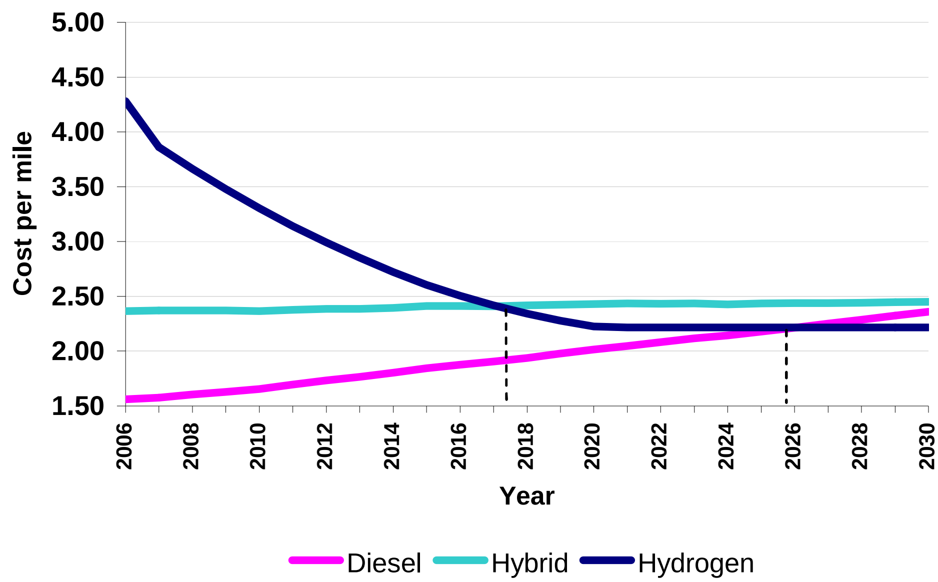


Figure 13. Future lifecycle costs of buses

4.3.3 Light Duty Trucks

Due to a low capital premium, reasonably good fuel economy and large mileage, gasoline hybrids are the most competitive alternative in the light duty truck segment at present. Diesel and gasoline have a similar behavior at the beginning of the period but gasoline has a lower slope than diesel models in the long-term (Figure 14). Hybrid diesel trucks have larger costs and hydrogen light duty trucks, presently in experimental phase, will progressively decrease their overall per mile cost. They are followed by gasoline models, which is again due to gains in terms of scale economies and technical know-how. They would be competitive with hybrid diesels by 2027 and then would be slightly more costly than the diesel option. Their competitiveness would increase as their costs per mile decline, reaching a similar cost to that of gasoline hybrids by 2030.

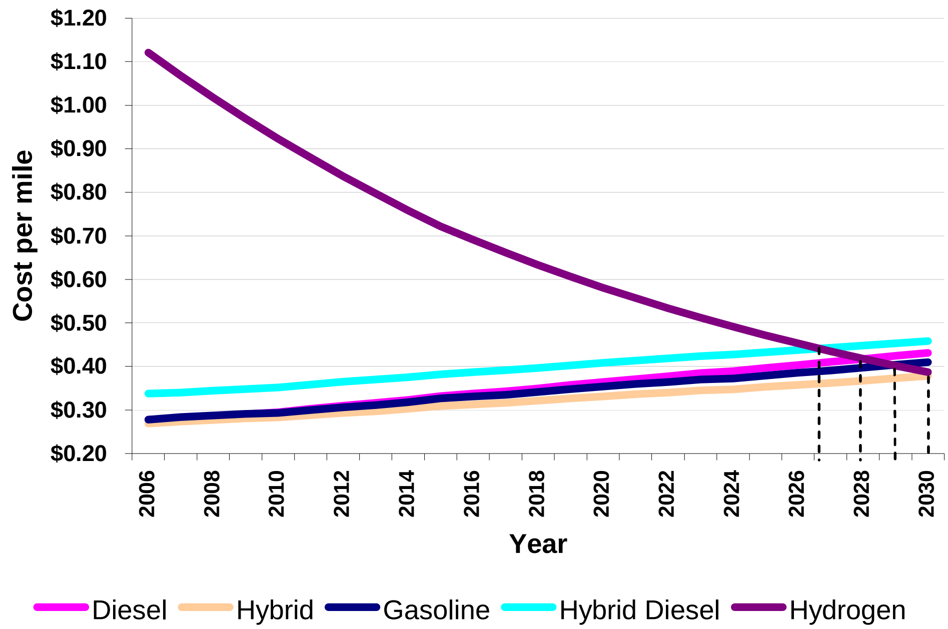


Figure 14. Future lifecycle cost of light duty trucks

4.3.4 Heavy Duty Trucks

The conventional diesel and hybrid diesel heavy trucks have a similar behavior throughout the analysis period (Figure 15). This is due to the use of the same fuel and only a small capital premium (8%) and a fuel economy that is high enough to compensate the additional cost. It is expected that the premium diminish progressively, increasing the competitiveness of hybrid models. This group did not find applications presently available to assess hydrogen-fueled heavy trucks.

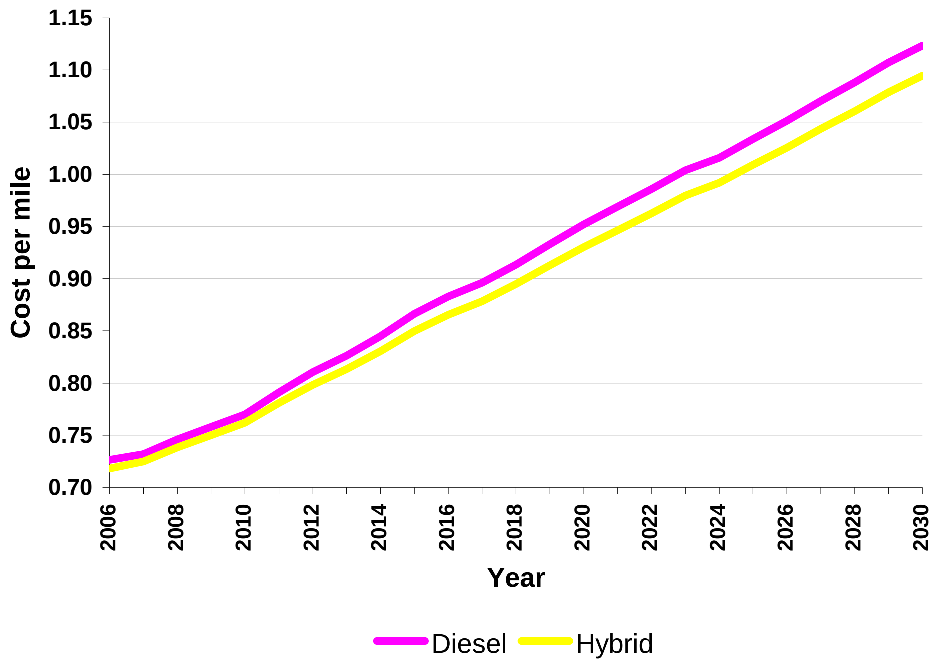


Figure 15. Future lifecycle cost of heavy duty trucks

4.4 Conclusions

4.4.1 Current Situation

An economic comparison of gasoline, diesel, biodiesel, hybrid and hydrogen powered vehicles today reveals a variety of results depending on the vehicle category that is being examined. The only constant in this analysis is that hydrogen powered vehicles are currently far more expensive than their conventional counterparts or the other alternative technologies. This is primarily accounted for by the capital costs of the fuel cell powered vehicles, which currently cost 2 to 4 times the amount of a conventional counterpart.

Amongst the other technologies, however, the economic choice is less clear. In the sedans category conventional gasoline vehicles were the best economic choice, followed closely by diesel and biodiesel. A premium of several thousand dollars is still paid for hybrid vehicles, although in the private sector much of this could be recovered through tax incentives. This is a trend that continues throughout the other categories of buses, light trucks and heavy trucks. The conventional technology types maintain an economic advantage over the alternatives available at this point in time. The advantage is slim, however, and could be readily overcome in many cases through the use of incentives and tax benefits. This is especially true in the case of biodiesel as a replacement for diesel fuels and in the use of gasoline-electric hybrid sedans, where the premiums paid for the technology are relatively small.

4.4.2 Future Scenarios and Outcomes

The future of these economic scenarios proves to be largely dependant on two factors, capital cost and fuel cost. Both of these factors favor the alternative technologies in the long run as the fuel costs for conventional vehicles is expected to rise while the capital cost of alternative technologies is expected to decrease. This is especially true in the case of hydrogen, in which the fuel cost is expected to drop moderately accompanied by an extreme decrease in the capital costs associated with the production of hydrogen fuel-cell vehicles. These factors combine to make the question not "will hydrogen powered vehicles ever be economically competitive with conventional vehicles" but rather "when?"

This question is highly variable across the vehicle types and is expected to occur earliest in sedans between 2015 and 2022, depending on the model of sedan. This change is expected to occur later in all other categories (except for in heavy trucks where it was not evaluated as an option). In the light trucks category, hydrogen vehicles are not projected to achieve competitiveness with conventional vehicles until nearly the end of the studies limits and are not expected to outperform the other alternatives until nearly 2030. In the category of buses there is a large span of time in which hydrogen vehicles are expected to be less expensive than hybrid technology (2017) but will not outperform diesel or biodiesel until 2026.

For the most part, the costs of the other technologies parallel each other much more closely than hydrogen fuel cells do. This is due to several factors but is primarily due to the fact that the alternative technologies of hybrid vehicles and biodiesel are not so extremely different from their conventional counterparts. Gasoline electric hybrids are a variation on existing gasoline internal combustion engines and are still linked in cost to the price of gasoline.

Biodiesel is commonly found in blends with diesel and so in many cases is still linked to the price of oil and since the basic engine technology used in biodiesel is the same as the technology used in any diesel engine there is not a large difference in capital costs. This leads these alternative technologies to have prices that only deviate slowly away from the costs of conventional technologies as the price of oil rises. Thus the economic competitiveness of these alternative technologies is largely dependant on the rise in price of oil and an equal rise in the cost of the conventional technologies. Should the price of oil spike rapidly then the comparative value of these alternative technologies will similarly increase. As it stands now, these technologies are roughly economically equivalent to conventional technologies and rising oil prices will ensure that they become economically competitive in the near future.

4.4.3 Benchmarks

One of the primary applications of this economic analysis is to determine timeframes in which a given technological option will become economically superior to that technology currently being used. The technology for which this is particularly important is the utilization of hydrogen to power fuel cell vehicles. As can be seen in the preceding pages the hydrogen fuel cell vehicle is still economically unrealistic as an option for transportation, primarily due to a high capital cost. This cost, however, is expected to drop drastically and relatively quickly. The important benchmarks in this study, then, are those timeframes when the cost of a hydrogen powered vehicle becomes economically competitive with hybrids and conventional gasoline powered vehicles.

This change occurs at varying times over the next 25 years for the various vehicle categories. In none, however, does the change occur during the next decade, and for both buses and light duty trucks this change is not expected to occur for nearly two decades. Based on an economic analysis it would seem as though a shift in fleet composition from conventional technologies such as gasoline and diesel internal combustion engines to alternative technologies cannot be a shift to hydrogen fuel cell vehicles if it is to occur in the next 10 to 20 years. Instead the shift must be lead by the increasing utilization of biodiesel in diesel engines and greater hybridization of gasoline powered vehicles. Both of these steps are unlikely to lead to a complete shift away from petroleum based fuels but will decrease dependence on them in the short run. It is also likely that the increased electrification of vehicles through hybridization will pave the way for the introduction of hydrogen vehicles as many of the components will be technologically similar or even identical.

4.4.4 Policy Recommendations

There are many considerations to make when deciding on a policy course to encourage the shift towards alternative vehicles in the fleet. Due to the economics of the vehicles themselves, policy should not encourage an immediate shift towards hydrogen fuel cell vehicles, but rather should seek that as a long term goal while pursuing hybridization and biodiesel in the short term. This can be accomplished in several ways. Already many states and government agencies are requiring that a certain percentage of their fleets be alternative fuel vehicles. As these are governmental agencies this is best accomplished through mandate rather than tax incentives. For private fleets the mandate is an unlikely option to encourage the shift to alternatively fueled vehicles. The private sector should have incentives for the purchase of biodiesel and tax breaks for the purchase of hybrid vehicles. There is already federal legislation encouraging purchase of hybrid vehicles through significant tax breaks but these breaks do not always cover the full amount of the premium being paid for these vehicles and are currently only available for a limited period of time. These tax incentives should be expanded to cover the full amount of the premium and be extended for at least a decade before being phased out.

Hydrogen policy, on the other hand, should be focused on research and development. This is the direction of current efforts, aimed at making the technology more reliable and bringing costs of production down but the level of effort should be extended and expanded in order to lower the costs of hydrogen based transportation to competitive levels more quickly. Little attention has been given to the question of infrastructure in the hydrogen economy thus far in this report. The costs of a massive conversion of the energy economy to hydrogen are incredibly high and cannot be ignored or borne by the government alone. Instead the government's job should be to help support the market for hydrogen until it is successfully established at which point natural market forces should be able to continue the expansion of the hydrogen energy economy. The primary way in which this will be done is by establishing a base market for the technology including vehicles, fuel production, and fuel distribution. Once a critical mass is reached then private ventures will be able to utilize slight expansion of this existing infrastructure rather than build their own. The ideal way in which this could be accomplished is through the introduction of hydrogen fuel cell vehicles into government owned and operated fleets, potentially as a cost share venture with progressive private industry.

5.0 Emissions Model

5.1 Methods to Determine Emissions

Since this report examines scenarios of technology diffusion it was vital to construct a model that would be capable of including the emissions of all three alternative vehicle technologies in the fleet, along with conventional vehicles, at the same time. Additionally, the model had to be capable of measuring the changes in the emissions profile of the fleet on a year-by-year basis as the composition of the fleet changed. This presented a unique problem where numerous factors had to be considered, some assumptions about the fleet made, calculations performed based on the numbers for a given year, and then performed for the next 25 years as the composition of the fleet changed.

Below is a breakdown of the factors taken into account, the calculation that is performed by the model, the assumptions that were made in creating the scenarios, and finally an explanation of the overall operation of the model.

5.1.1 Factors Considered

The primary factor to be considered was the carbon content of each different fuel type that could be utilized in any of the vehicle technologies being considered. Since different technologies often consume the same fuel the characteristics of the fuels were considered before any of the characteristics of the technologies were examined. The carbon content of the fuels was also viewed to be immutable, and thus was a good starting point for the study.

Also of concern were the carbon emissions resulting from the production of each fuel. None of the fuels considered is produced without some form of energy input; therefore emissions resulting from well-to-pump production of the fuels had to be considered in addition to the pump-to-wheel emissions that can be determined by looking at the carbon content of the fuels themselves. Combining these two factors provides a number for the well-to-wheel emissions associated with each fuel. These factors are displayed in Table 14 below.

Table 14. CO_2 Emissions per Unit of Fuel

Fuel Type	Well-to-Pump	Pump-to-Wheel	Total
Gasoline	2.179 kg/gal	8.533 kg/gal	10.702 kg/gal
Petrol Diesel	1.910 kg/gal	9.081 kg/gal	10.991 kg/gal
Biodiesel	-4.511 kg/gal	9.197 kg/gal	4.686 kg/gal
Hydrogen	12.619 kg/ kil	0 kg/ kil	12.619 kg/ kil

Source: Greet Model, v. 1.7[3]

The next factor considered was the fuel economies associated with the different technologies. This presented some difficulty since they could be used in a wide range of vehicle makes and

[3] http://www.transportation.anl.gov/software/GREET/index.html

models. Thus, the fuel economy is not based on the technology utilized in the vehicle alone but also by the vehicles type. We devised four types of vehicles (sedans, light duty trucks, buses, and heavy trucks) and determined what their fuel economies would be utilizing different technologies (gasoline ICE, diesel ICE, gasoline-electric hybrid (GHEV), diesel-electric hybrid (DHEV), biodiesel ICE, and hydrogen fuel cell). The results from this determination can be viewed in Table 15 below.

Table 15. Fuel Economy of Vehicle Types Based on Technology

Fuel Economy	Sedans	L-D Trucks	H-D Trucks	Buses
Gasoline ICE (mi/gal)	23.6[6]	17.4[5]	7.3[9]	n/a
Petrol Diesel (mi/gal)	32.0[6]	23.5[7]	7.8[9,10]	4.0[1,2]
GHEV (mi/gal)	44.5[11]	28.0[6]	10.0	4.0[1]
Biodiesel ICE (mi/gal)	32.0[4]	23.5[4]	7.8[4]	4.0[4]
Hydrogen (mi/kg)	55.0[6]	34.8[8]	n/a	11.0[3]

Sources: [1]Wayne et al., 2004; [2]Bureau of Transportation Statistics; [3]NREL, 2003; [4]Assumed to be the same as diesel; [5]VIUS, 2002; [6]2006 Fuel Economy Guide, 2006; [7]Calculated, diesel achieves a 35% increase in fuel economy; [8]Calculated, assumed a doubling of fuel economy over gasoline; [9]U.S. DOE, 2005; [10]VIUS, 1997; [11]Union of Concerned Scientists

With the combination of the fuel economy of all of the different vehicles and the carbon emissions per unit of fuel, it is possible to determine the level of carbon emissions per mile for any vehicle type using any technology. The next factor to consider is the number of miles an individual vehicle would drive in a given year. For this report, our concern is with the annual miles driven by fleet vehicles specifically. Once again there is a difference between the different vehicle types. The Table 16 below lists the average annual miles that were used for all four different vehicle types.

Table 16. Annual Miles Driven

Vehicle Type	Sedans	L-D Trucks	H-D Trucks	Buses
Ave. Annual Miles	20,000 mi	26,000 mi	29,245 mi	20,698 mi

Sources: U.S. DOE, 2005

The final factor to be considered to develop an annual emissions profile, now that the annual carbon dioxide emissions for each individual vehicle can be established is to determine the aggregate number of each vehicle type which is present in the fleet and using which technology. Given those numbers it is possible to develop the total emissions from the U.S. fleet. In Table 17 below are the aggregate numbers for each vehicle type currently in U.S. fleets. A description of the breakdown within those vehicle types by technology will come later in this report.

Table 17. Number of Vehicles in U.S. Fleet

Vehicle Type	Sedans	L-D Trucks	H-D Trucks	Buses
# of Vehicles	4,090,337[1]	3,760,000[2]	2,590,000[2]	737,675[1]

Sources: [1]Bureau of Transportation Statistics, 2005; [2]VIUS, 2002

The breakdown within the vehicle type is further broken down by the technology utilized (gasoline ICE, petrol diesel, biodiesel, GHEV, and hydrogen fuel cell) within each vehicle type.

Now that the emission profile for the entire fleet can be constructed for a single year it is possible to create emissions profiles for other years by changing the numbers of vehicles of each technology in each vehicle type category. In order to determine how the makeup of each vehicle type category changes, there are several factors to consider. The first factor is that the total number of vehicles within each vehicle type will not remain constant, but will instead follow the basic growth pattern which can be determined using historical data. A second factor is that some of the vehicles will be retired each year and the final factor is that a certain number of vehicles will be purchased each year. The number of vehicles purchased will be based on the increased number of vehicles in the fleet due to the growth rate of the vehicle and on the replacement of those vehicles that were retired and will need to be replaced. Thus within each vehicle type a percentage of the vehicles of each technology will be retired and new vehicles will be purchased. The percentages of each technology being purchased will vary from year to year. Thus in the early years a very low percentage of the new vehicles purchased will use hydrogen fuel cell technologies but in future years that percentage may be higher, depending on the scenario. This will allow the proportion of the technologies within each vehicle type to alter over time based on the retirement rates, the annual growth of the fleet and the varying purchasing proportions of each technology.

5.1.2 Calculations

The following calculations determine the emissions profile in a given year for a given vehicle type category:

$$\text{Emissions}_{\text{type, tech}} = [\#\text{ of Vehicles}_{\text{type, tech}}] * [\text{Annual Miles}_{\text{type}}] / [\text{Fuel Economy}_{\text{type, tech}}] * [\text{Carbon Content}_{\text{tech}}]$$

The above equation will produce the annual emissions resulting from a given technology being used within a given vehicle type (e.g., the emissions coming from all of the GHEVs within the sedans category). Adding the result of this equation across all the technologies but keeping the vehicle type constant will produce the total emissions for a vehicle type (e.g., the emissions coming from all sedans or all L-D trucks). Adding the result of this equation across all the vehicle types but keeping the technologies constant will produce the total emissions coming from a given technology type (e.g., from all hydrogen fuel cell vehicles). Finally summing across all vehicle types and technology types will produce the annual emissions being produced by the entire fleet.

In order to produce an emissions profile that varies over time due to the introduction of new vehicles of different technologies it is necessary to use the following equation.

$$\#\text{ of Vehicles}_{\text{type, tech}} = [\#\text{ Vehicles Previous Year}_{\text{type, tech}}] - [\#\text{ Retired}_{\text{type, tech}}] + [\#\text{ Purchased}_{\text{type, tech}}]$$

$$\#\text{ Retired}_{\text{type, tech}} = [\#\text{ Vehicles Previous Year}_{\text{type, tech}}] * [\text{Retirement Rate}_{\text{type, tech}}]$$

$$\# \text{ Purchased}_{\text{type, tech}} = [\text{Purchase Rate}_{\text{type, tech}}] * [\#\text{Retired}_{\text{type}}] + [\text{Purchase Rate}_{\text{type, tech}}] * [\text{Growth}]$$

$$\text{Growth}_{\text{type}} = [\text{Growth Rate}] * [\# \text{ Vehicles Previous Year}_{\text{type}}]$$

All of the variables are specific to both the vehicle type and the technology used, except for the [Growth Rate] variable which is based off of the entire fleet, [Growth $_{type}$], [# Vehicles Previous Year $_{type}$], and [# Retired $_{type, tech}$], which are based on the number of vehicles within the entire vehicle type category (e.g., all sedans). Using this set of equations the technological composition of each vehicle type category can be varied by assigning a purchase rate and retirement rate to each technology type within a vehicle type category. The retirement rate is based on how long a vehicle is expected to remain in the fleet. The purchase rate is based on the proportion of the total number of vehicles purchased within a category that are going to be a given technology. Each technology type within the vehicle type category is assigned a percentage and the sum of the percentages will equal 100% (e.g., gasoline ICE 75%, diesel ICE 5%, GHEV 10%, biodiesel 7%, hydrogen fuel cells 3%). Thus, based on the retirement rate and the growth rate it has been estimated how many vehicles will be purchased within a vehicle type category and based on the purchase rate, the proportion of the new purchases that will be of each technology type is known.

5.1.3 Assumptions

Natural Gas as Primary Source of Hydrogen

An interesting observation is that the amount of CO_2 per kilogram of hydrogen is actually higher on a well-to-wheel basis than any of the other fuel types, including gasoline. This is based on the assumption that the vast majority of the hydrogen produced in the U.S. will come from the steam reformation of natural gas at centralized plants. Numerous authors believe that hydrogen for the near future will primarily come from natural gas. Currently more than 90% of hydrogen in the U.S. comes from the steam reformation of natural gas (Ogden, 1999). Given the extensive natural gas infrastructure that is already in existence, natural gas is an obvious choice for the initial production of hydrogen as relatively little infrastructure will need to be constructed. Natural gas has been assumed to be the primary source of hydrogen for the entire time of the model. This assumption may lose some validity near the end of the scenarios when other sources of hydrogen may enter. Of particular interest, for the future, will be the introduction of clean coal technologies to produce hydrogen and the use of solar energy to produce hydrogen.

Diesel vs. Biodiesel Fuel Economy

We have assumed the diesel and biodiesel fuel economies to be equal. For B20 blends this is assuredly true but for B100 blends there may be some slight variation due to slightly different energy content, although there does not appear to be a consensus in the literature as to whether there is one or not.

Diesel-Hybrid Fuel Economy

There is limited information regarding the use of hybrid-diesel engines in heavy duty trucks in the U.S. This is primarily because the technology is relatively new, but also because very few units have been manufactured (as opposed to diesel-hybrid transit buses where there are 3 major manufacturers). Below is the logic and justification for an estimate of the fuel economy of heavy duty diesel-hybrid engines.

On March 30, 2006 the Volvo Group announced that they had developed a diesel-hybrid parallel drive system for use in buses and trucks. According to their press release, the starter motor, drive motor and generator are combined into one unit called the I-SAM which starts and accelerates the vehicle without using the full diesel engine. According to Volvo, such a system can achieve fuel savings *up to 35%* compared to a conventional diesel truck. Maximum fuel savings occurs on routes with frequent braking and acceleration.

Azure Dynamics produces diesel-hybrid heavy duty delivery and short-haul trucks. According to their product listings for the G1 Series Delivery Truck, fuel economy improves by 35-50%. Azure also produces a Class 7 Diesel-Hybrid Truck called the 2005 Super 7, which achieves a 54% boost in fuel economy over a similar conventional diesel truck. The Super 7 uses a parallel hybrid-ICE drivetrain while the delivery truck uses a series system.

Enova Systems is working with International Truck and Engine to design diesel-hybrid drivetrains. They have built a prototype school bus and a Post Transmission 120kW Hybrid Drive 4200 Series Truck that are currently in testing. According to a press release from the company, the hybrid truck provides an average fuel consumption savings of 31% and a "miles per gallon" increase in excess of 48%. It is not clear why fuel consumption savings should be so different from miles per gallon savings, as they seem the two terms seem to mean identical things.

None of these trucks have been rigorously tested for fuel economy savings by a party other than the manufacturers, so some healthy skepticism is prudent. A comparison to similarly sized transit buses (which are well-researched) shows that the fuel savings reported by manufacturers for heavy duty truck diesel-hybrids is similar to that of buses. According to an NREL report examining diesel-hybrid buses in NYC in 2005, a fuel savings of 32-52% was achieved over a conventional diesel bus.

Thus, a fuel economy savings of ~35% for using a diesel-hybrid engine in a heavy duty truck instead of a conventional diesel will balance the optimistic outlook of manufactures with reported fuel savings from actual use of the engines in real-world scenarios. Since there are no published studies of diesel-hybrid engines used in trucks, this number can at best be considered an estimate and could fluctuate significantly.

5.2 Determination and Summary WPW emissions for all technologies

To accurately characterize the impact of the various fuels and vehicle technologies on the emission of carbon dioxide into the atmosphere, a basic lifecycle analysis was utilized. The

Greenhouse Gases, Regulated Emissions and Energy Use in Transportation Model (GREET v. 1.7) developed by Argonne National Laboratory provided estimates of CO_2 emissions per gal or kg of fuel for each of the fuels analyzed. The net CO_2 emission is broken down into two parts – well-to-pump (WTP) and pump-to-wheel (PTW) – to separately show the portion of CO_2 emissions associated with the collection, refining, and transport of the fuel (WTP) and the portion of emissions tied to the operation of the vehicle (PTW). The GREET model utilizes a rigorous analysis which accounts for efficiency losses at each stage of the fuel cycle, the distance and type of transport, the use of fertilizer for soybean and corn farming, and the CO_2 reclamation attributed to the growth of corn and soybeans for biofuels. For a complete description of the inputs and assumptions used in the GREET model, please see the Appendix.

Table 18 lists the WTP emissions per unit of fuel for each of the fuel types studied using the GREET model. Neither Ethanol nor Electric Vehicles were selected for this study, but their CO_2 emissions are provided for reference in the table.

Table 18. WTP Emissions per Unit of Fuel

Fuel Type	Abbreviation	Unit	CO_2 Emissions (kg)
Conventional/Reformulated Gasoline	CG/RFG	gal	2.179
No. 2 Petroleum Diesel	PD	gal	1.910
Biodiesel (20% Blend)	B20	gal	0.706
Biodiesel (100% Blend)	B100	gal	-4.511
85% Ethanol Blend	EtOH-85	gal	-1.000
Hydrogen Gas	H_2	kg	12.619
Electric Vehicle	ELEC	GGE	25.235

CO_2 tailpipe emissions (PTW) are dependent on the type of fuel, the configuration of the vehicle (i.e., engine type, mileage) and the distance the vehicle travels. Details about the vehicle configurations, mileage and estimated annual mileage can be found in Section 5.1.2. For practical purposes, it was assumed that every unit of fuel combusts identically and that CO_2 is generated in stoichiometric quantities according to the original carbon content of the fuel. Therefore, each gallon of diesel will yield the same amount of carbon dioxide as every other gallon of diesel, regardless of whether the diesel was combusted in a small sedan, a light duty pickup or a bus. Table 19 lists the PTW CO_2 emissions resulting from the combustion of a gallon of fuel regardless of vehicle configuration. Please note, hydrogen powered fuel-cell vehicles and electric cars do not generate CO_2 during operation because a carbon-based fuel is not being combusted. Also, No. 2 petrodiesel, B20 and B100 all yield roughly equivalent amounts of CO_2 and were all approximated using the emissions value for No. 2 petrodiesel.

Table 19. Tailpipe CO_2 (PTW) Emissions per Unit of Fuel

Fuel Type	Abbreviation	Unit	CO_2 Emissions (kg)
Conventional/Reformulated Gasoline	CG/RFG	gal	8.820
No. 2 Petroleum Diesel	PD	gal	9.610
Biodiesel (20% Blend)	B20	gal	9.610
Biodiesel (100% Blend)	B100	gal	9.610
Hydrogen Gas	H_2	kg	0.000
Electric Vehicle	ELEC	GGE	0.000

Coupling the WTP and PTW emission factors will yield an overall lifecycle estimate of the net CO_2 emissions associated with a unit of each type of fuel. The Well-to-Wheel (WTW) emissions factors for each fuel type are listed in Table 20. Ethanol has been neglected because it was not a subject of this study.

Table 20. Lifecycle (WTW) CO_2 Emission per Unit of Fuel

Fuel Type	Abbreviation	Unit	CO_2 Emissions (kg)
Conventional/Reformulated Gasoline	CG/RFG	gal	10.999
No. 2 Petroleum Diesel	PD	gal	11.520
Biodiesel (20% Blend)	B20	gal	10.316
Biodiesel (100% Blend)	B100	gal	5.099
Hydrogen Gas	H_2	kg	12.619
Electric Vehicle	ELEC	GGE	25.235

5.2.1. Lifecycle (WTW) CO_2 Emissions for Each Vehicle Configuration

The WTW CO_2 Emissions factors were coupled with details about the annual mileage and vehicle characteristics to generate estimates of the CO_2 emissions for each class of vehicles. The results are reported in both kg CO_2/unit of fuel and g CO_2/mile for each type of vehicle to allow easy comparisons and analysis. The various types of vehicles examined were the Hydrogen Fuel Cell Vehicle (H2 FCV), the Hybrid Electric Vehicle (HEV), the standard Spark-Ignition Vehicle fueled by Conventional or Reformulated Gasoline (SI CG/RFG), and the standard Compression-Ignition, Direct-Injection engine fueled by No. 2 Diesel (CIDI), 20% Biodiesel (CIDI-B20), or 100% Biodiesel (CIDI-B100). Not all vehicle configurations are applicable within each of the following classes of vehicles.

a. Small, Medium, Large Sedans

Sedans are small, low-weight and relatively inexpensive to purchase and operate compared to other vehicle classes. Mileages can range from below 20 mpg to above 50 mpg depending on the design of the vehicle and can be fueled by any of the five technologies examined in this report. Table 21 shows that the lowest CO_2 emissions per mile are achieved using a diesel-engine fueled with 100% biodiesel, while the highest emissions are attributed to standard SI gasoline engines.

Emissions associated with the use of biodiesel are low because of the higher efficiency of diesel engines (relative to standard SI engines) and the fact that the fuel is renewable, thereby reclaiming CO_2 from the atmosphere. HEVs consistently show the highest mileage of all the alternative-fueled vehicles.

Table 21. CO_2 Emissions per Mile for Sedans

			CO_2 Emissions	
Vehicle Configuration	**Mileage**	**Unit**	**(kg/unit of fuel)**	**(g/mile)**
Sm. Sedan – SI CG/RFG	28.4	gal	10.999	387
Sm. Sedan – CIDI	38.3	gal	11.520	301
Sm. Sedan – CIDI-B20	38.3	gal	10.316	269
Sm. Sedan – CIDI-B100	36.4	gal	5.099	140
Sm. Sedan – SI CG/RFG HEV	52.5	gal	10.999	210
Sm. Sedan – H_2 FCV	55.0	kg	12.619	229
Med. Sedan – SI CG/RFG	23.6	gal	10.999	466
Med. Sedan – CIDI	32.0	gal	11.520	360
Med. Sedan – CIDI-B20	32.0	gal	10.316	322
Med. Sedan – CIDI-B100	30.4	gal	5.099	168
Med. Sedan – SI CG/RFG HEV	44.5	gal	10.999	247
Lg. Sedan – SI CG/RFG	19.8	gal	10.999	556

b. Light Duty Trucks

Light duty trucks and SUV's have wide application and utility and are extremely common fleet vehicles. There are large percentages of diesel and gasoline powered pick-up trucks in service throughout the U.S. The purpose, application and cost of the vehicle are generally more important to fleet operators than the fuel type when considering which vehicles to purchase. Mileages can range from below 20 mpg to nearly 35 mpg depending on the engine configuration and fuel type. Table 22 shows that the lowest CO_2 emissions per mile are, again, achieved using a diesel engine fueled by 100% biodiesel (229 g/mile). A gasoline hybrid electric vehicle is a distant second-best at 393 g/mile.

Table 22. CO_2 Emissions per Mile for Light Duty Trucks/SUVs

			CO_2 Emissions	
Vehicle Configuration	**Mileage**	**Unit**	**(kg/unit of fuel)**	**(g/mile)**
Lt. Truck – SI CG/RFG	17.4	gal	10.999	632
Lt. Truck – CIDI	23.5	gal	11.520	490
Lt. Truck – CIDI-B20	23.5	gal	10.316	439
Lt. Truck – CIDI-B100	22.3	gal	5.099	229
Lt. Truck – SI CG/RFG HEV	28.0	gal	10.999	393
Lt. Truck – H2 FCV	34.8	kg	12.619	363

c. Heavy Duty Trucks

Heavy duty trucks are typically used for hauling cargo over long or short distances. Diesel engines dominate the long-haul fleets while a mix of gasoline and diesel is used for local short-haul, delivery and towing fleets. Mileages vary little, ranging from 7.3 mpg for gasoline engines to 10.1 mpg for an advanced diesel hybrid electric (Table 23). Again, a standard diesel engine fueled with 100% biodiesel releases the lowest amount of CO_2 (689 g/mile) while gasoline releases the highest amount (1507 g/mile). A hybrid electric vehicle achieves the highest mileage over short, stop-and-go delivery routes, but will be roughly on par with other diesel engines for long-haul routes.

Table 23. CO_2 Emissions for Heavy Duty Trucks

			CO_2 Emissions	
Vehicle Configuration	**Mileage**	**Unit**	**(kg/unit of fuel)**	**(g/mile)**
Hvy. Truck – SI CG/RFG	7.3	gal	10.999	1507
Hvy. Truck – CIDI	7.8	gal	11.520	1477
Hvy. Truck – CIDI-B20	7.8	gal	10.316	1323
Hvy. Truck – CIDI-B100	7.4	gal	5.099	689
Hvy. Truck – CIDI CG/RFG HEV	10.1	gal	11.520	1141

d. Buses

Buses are commonly used in municipal fleets for public transportation or ferrying children back and forth to school. They are primarily designed to carry large numbers of people as cheaply as possible and, like heavy duty trucks, are predominately powered by large diesel engines. Mileages are exceptionally low – only 4.0 mpg – for any engine configuration using diesel (Table 24). A hydrogen fueled bus has achieved upwards of 11.0 mpg, but hydrogen buses only represent a fraction of 1% of the nearly ¾ million buses in the U.S. The high mileage and fairly low carbon emissions associated with steam-reforming methane to produce hydrogen result in the lowest CO_2 emissions of any bus (1147 g/mile). Using 100% biodiesel releases only slightly more CO_2 (1275 g/mile) but has the significant benefit that it can be used in existing buses with little to no additional cost. Hydrogen buses remain extremely expensive.

Table 24. CO_2 Emissions for Buses

			CO_2 Emissions	
Vehicle Configuration	**Mileage**	**Unit**	**(kg/unit of fuel)**	**(g/mile)**
Bus - CIDI	4.0	gal	11.520	2880
Bus - CIDI-B20	4.0	gal	10.316	2579
Bus - CIDI-B100	4.0	gal	5.099	1275
Bus - CIDI CG/RFG HEV	4.0	gal	11.520	2880
Bus - H_2 FCV	11.0	Kg	12.619	1147

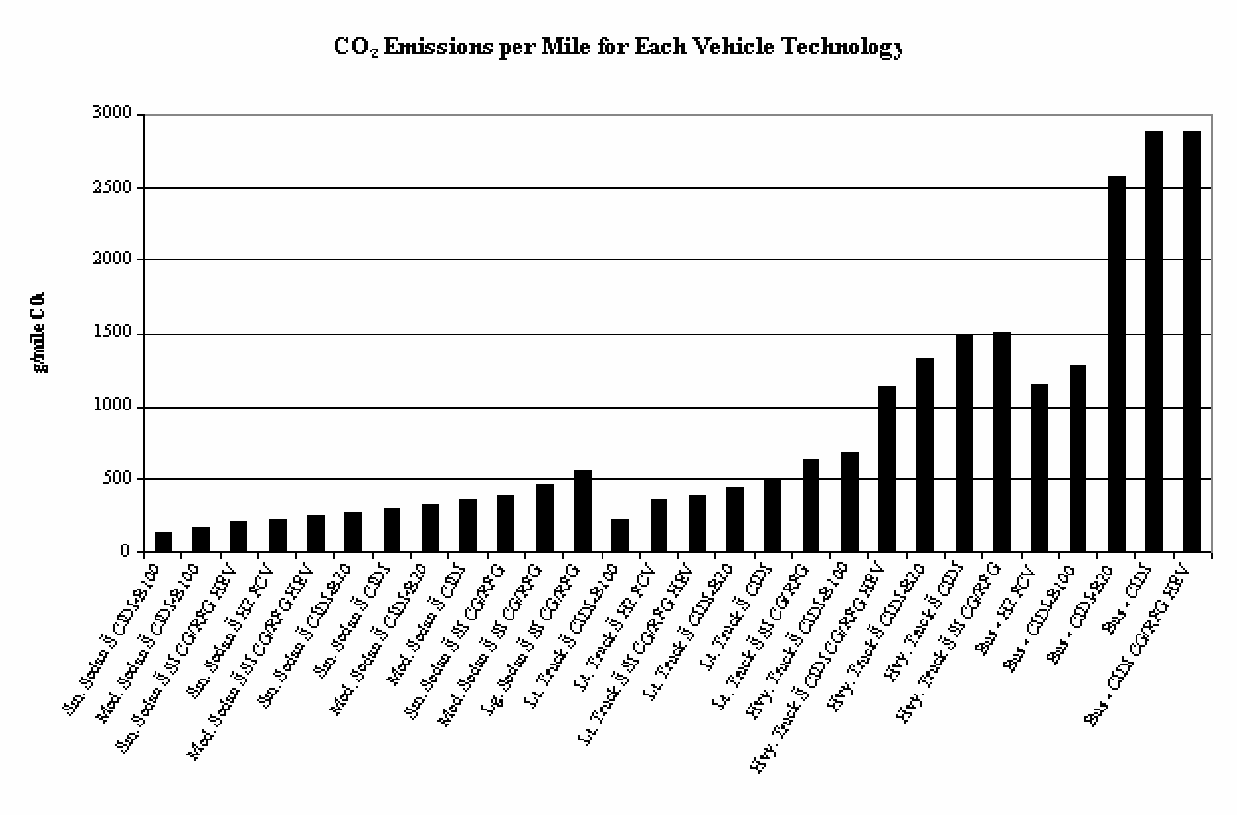


Figure 16: Comparison of all vehicle technologies with emphasis on lowest CO2 emissions in each class

Figure 16 summarizes the CO_2 emissions per mile for each of the vehicle configurations considered. The option that achieved the lowest CO_2 emissions per mile for each vehicle type is the B100 blend. Hybrids and fuel cell vehicles follow in that order, with the differences among them being modest. All outperform conventional diesel and gasoline vehicles by a large measure. For heavy duty trucks, those using B100 blends have the lowest CO_2 emissions; while for buses, hydrogen fuel cell technology is the best performer.

5.3 Conclusions

Several findings regarding emissions deserve attention. First, biodiesel is found to present the largest carbon dioxide emissions reductions per vehicle compared to other technologies, followed closely by hybrids and fuel cell vehicles. This result is only for vehicles which utilize B100 blends of biodiesel; the effect is much smaller for B20 blends. While this result indicates a carbon advantage for B100 blends, there are several factors that must be considered.

For example, a reduction in carbon dioxide does not address other environmental threats. In the case of biodiesel, NO_x emissions, a primary emission causing acid rain, are increased over gasoline, hydrogen and hybrid vehicles. Thus, a significant shift to biodiesel could lead to other ecological problems due to acidification of the environment, even as greenhouse gases are reduced. Fuel cell vehicles would not present this problem and hybrids would measureably reduce this risk (depending upon the extent of electric motor use).

The cause for the large reduction in carbon dioxide emissions through the utilization of B100 is found in the production, or well-to-pump stage, in which the growth of plant matter used to produce biodiesel removes carbon dioxide from the atmosphere and sequesters it in plants. This carbon dioxide is then partially released during combustion of the fuel.

By contrast, carbon dioxide emissions for hydrogen fuel cell vehicles are entirely within the production phase, with the usage phase releasing only water vapor. Because of this, carbon sequestration offers the potential to reduce carbon dioxide emissions from hydrogen during production.

Additional concerns include the impact that the production of plant matter for fuels will have on the availability of land for food production. If biofuels are to make up a significant portion of our energy economy, land requirements would be substantial, certainly enough to potentially affect the land available for food production. The sheer volume of biomass that would be needed suggests that this impact be significant. If more land needs to be cultivated in order to meet both energy and food production demands, the environmental damage caused by agriculture can increase as well.

In sum, biodiesel may present an advantage in terms of carbon dioxide emissions per vehicle, but other environmental impacts must be considered in a comprehensive evaluation of alternative transport technologies. Additionally, the analysis reported in this section only examined natural gas as a source for hydrogen fuel. Alternatives, particularly electrolysis using renewable energy, offer substantially reduced carbon dioxide levels. While natural gas reformation is currently the dominant path for hydrogen production, there is the potential for alternative methods to begin to account for a larger portion of hydrogen supply. Because hybrid gasoline-electric vehicles and hydrogen fuel cell cars offer significant emissions reductions as well (compared to conventional technologies), and because they compare favorably with B100 fueled sedans and light duty trucks, all three alternatives are likely to play a significant role in efforts to reduce carbon dioxide emissions levels.

6.0 Scenarios for the Introduction of Alternative Technologies into Fleets

We now turn our attention to the question of aggregate future emissions from U.S. government vehicle fleets. Dozens of scenarios were developed for this purpose and from them the research team gleaned three sets that can broadly represent likely low-carbon transport vehicle pathways (based on current knowledge). These three sets of scenarios are: a hybrid vehicle-prominent pathway, a biodiesel-prominent pathway, and a pathway in which hydrogen is prominent. Each of these scenarios describes a future in which a given technology is utilized more intensively than the others. But in all three scenarios, a diversity of fuels and technologies are present. A baseline scenario is first presented in which emissions of gasoline-only sedans are projected to 2030. While new technology use for truck and bus segments of government fleets were also considered, we concentrate here on sedan fleet comparisons. (For the B100 case, we additionally report a heavy duty truck scenario, since diesels are already prominent in this segment making it relatively easy to introduce biodiesel blends.)

6.1 Baseline Scenario – Gasoline Sedans Only

The baseline scenario concentrates on the current pricing of fuel and technology for the most numerous vehicle type in government fleets – sedans (small and medium) powered by gasoline internal combustion engines.

Table 25. Baseline Scenario Initial Conditions

Initial Fleet Conditions:

Annual Miles Traveled per Vehicle: 20,000

# of Vehicles in Fleet: 4,090,337

Technology	% of Fleet	Fuel Economy
Gasoline	100.0	23.6 mpg
GHEV	0.0	44.5 mpg
Hydrogen	0.0	55.0 mpk
Diesel	0.0	32.0 mpg
Biodiesel	0.0	32.0 mpg

Technology	Description of Scenario Purchase Rates
Gasoline	Begins at 95% of the fleet, comprises 80% of vehicles by 2030
GHEV	Begins with a purchase rate of 3% in the first year and this amount increases by 1.7% each year. This results in a purchase rate of 5% by 2030
Hydrogen	Remains constant at 0%
Diesel	Begins at 1%, increases to 2% in 2010, and increases to 5% in 2015
Biodiesel	Begins at 1% and this amount increases by 10% a year, comprising 10% of the purchase rate in 2030.

The amounts listed in the table directly above describe the “purchase rates” for new vehicles rather than actual fleet composition. It takes several years for fleet composition to match purchase rates, the exact length of time depending on the lifetimes of the vehicles in question. While the initial condition of 100% gasoline-powered sedans slightly exaggerates their presence in the existing fleet, it allows a clear comparison of aggregate and cumulative CO_2 emission effects of other technologies to a standard based on the most numerous fuel-vehicle combination today.

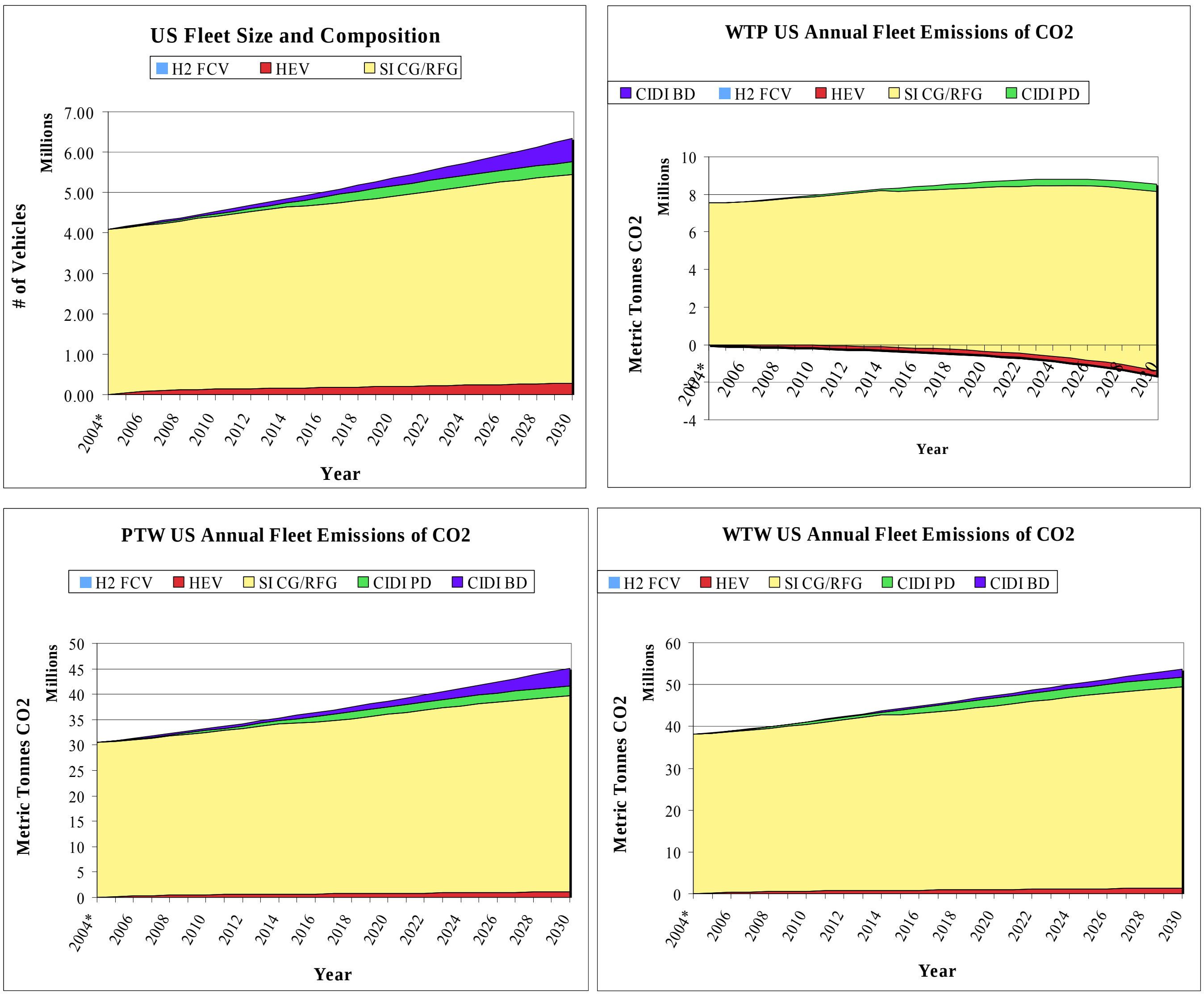


Figure 17. Baseline Sedan Pathway: CO_2 Emissions by Fuel and Vehicle Type

Overall carbon dioxide emissions grow steadily over time, closely matching increases in projected fleet size (based upon an extrapolation of recent U.S. experience). This is mitigated somewhat by a modest introduction of alternative technologies, but continues to rise. There is no peak in emissions as they do not stabilize or decline in the range of this model. At the end of the projected timeline, emissions from the fleet of sedans are 54 metric tones of CO_2 per year.

6.2 A Gasoline-Electric Hybrid-led Pathway

In this pathway, an emissions future is examined where biodiesel and hydrogen vehicles diffuse less fully than hybrid vehicles. Only sedan vehicles are modelled in this scenario as this vehicle type is the most likely candidate for hybridization (see Sections 4 and 5 of this report for detailed reasons. This scenario seems feasible given current trends in automotive purchasing and the rapidly growing importance of hybrids in the sedan market.

Currently the market penetration of hybrid vehicles within U.S. government fleets is nearly zero. Our scenario begins with a purchase rate of 3% in the first year and this amount increases by 13% each year. This diffusion rate was chosen to reflect recent fleet interest in hybrids. This results in a purchase rate of 64% by 2030. Hydrogen is assumed to account for 3% of the purchase rate by 2030, biodiesel 3%, and diesel 1%. Gasoline is assumed to account for the remainder, or 29% of vehicle fuel.

Given recent market trends it seems likely that hybrid gasoline-electric vehicles will comprise an increasing portion of sedans market share. The impact of this introduction on carbon dioxide emissions is apparent beginning in 2024 when a downward trend in emissions is found in the scenario analysis.

Table 26. Hybrid Scenario Initial Conditions

Initial Fleet Conditions:

Annual Miles Traveled per Vehicle: 20,000

# of Vehicles in Fleet: 4,090,337

Technology	% of Fleet	Fuel Economy
Gasoline	100.0	23.6 mpg
GHEV	0.0	44.5 mpg
Hydrogen	0.0	55.0 mpg
Diesel	0.0	32.0 mpg
Biodiesel	0.0	32.0 mpg

Technology	Description of Scenario Purchase Rates
Gasoline	Begins at 100% of the fleet, comprises 29% of vehicles by 2030
GHEV	Begins with a purchase rate of 4% in the first year and this amount increases by 13% each year. This results in a purchase rate of 64% by 2030
Hydrogen	Begins at 0%, accounts for 3% of the purchase rate by 2030
Diesel	Begins at 0%, accounts for 1% of the purchase rate by 2030
Biodiesel	Begins at 0%, accounts for 3% of the purchase rate by 2030

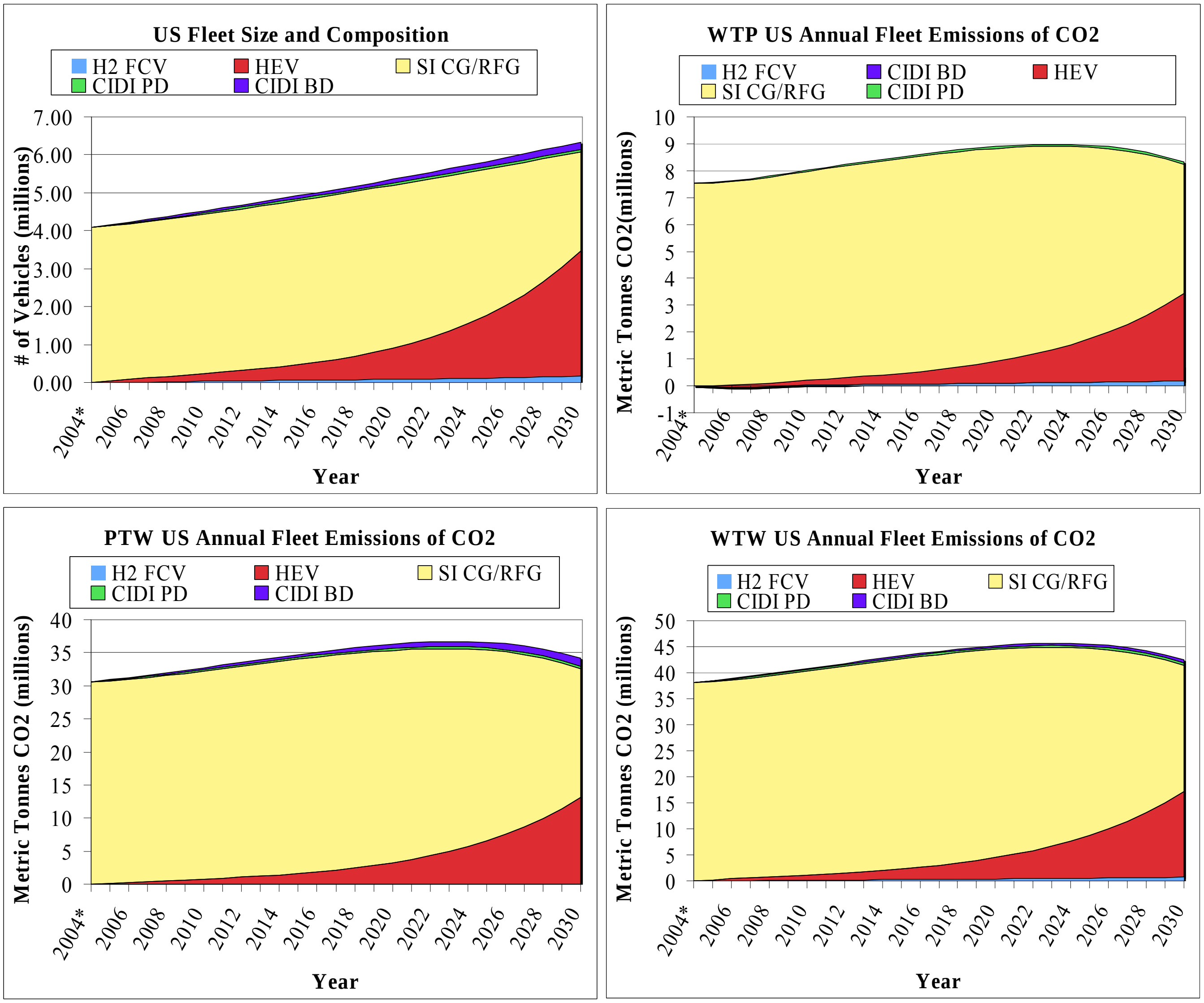


Figure 18. Hybrid-Prominent Sedan Pathway: CO_2 Emissions by Fuel and Vehicle Type

The scenario indicates a 20% reduction in carbon dioxide emissions compared to the baseline despite an overall increase in the number of fleet vehicles. While the introduction of GHEVs does not cause a decrease in year 2030 emissions compared to the starting value in 2004, the resulting level of carbon dioxide is significantly lower than it would be if GHEVs were not substantially introduced.

A second finding is the plateau in carbon dioxide emissions from GHEVs beginning around 2020 and the reduction in emissions from 2028. Although the rapid introduction of GHEVs produces significantly lower levels of carbon dioxide emissions, if the overall number of vehicle miles continues to rise, the technology cannot trigger deep emission cuts. Once the majority of conventional vehicles have been replaced by GHEVs, which given the rate of replacement in this scenario would occur approximately in 2040, aggregate emissions will cease to decline. Overall, our scenario suggests that sedan fleet emissions are likely to modestly decrease by 2030 under an aggressive policy to promote hybrids.

The results of this pathway show that the introduction of hybrid vehicles can slow the growth of carbon dioxide emissions and even has the potential to moderately reduce the overall levels of carbon dioxide emissions if they are introduced aggressively. However, GHEVs can produce only a percentage decrease in emissions per vehicle and as long as vehicle miles continue to increase, eventually carbon dioxide levels will be determined by this factor. In sum, over the next 25 years gasoline-electric hybrid vehicles offer an end to the growth in carbon dioxide emissions and potentially a future decrease, but vehicle miles will be the decisive factor in long-term emission impacts.

6.3 A Biodiesel-led Pathway

A second set of scenarios evaluate a biofuels-based transition where petroleum fuels are diminished in the transport sector by rising use of ethanol or other biomass-derived fuels. In this pathway, two factors drive expanded biofuel consumption: the positive energy output to input ratio during its creation; and the ability to utilize biodiesel in existing conventional diesel engines in blends up to 20% biodiesel with no need for any engine modifications and in blends of up to 100% biodiesel with only a few inexpensive modifications. In this respect, utilization of biodiesel can be viewed as a fuel switching program so long as vehicles previously running on diesel switch to biodiesel. Only when gasoline powered vehicles are switched for biodiesel vehicles is there a requirement to change the basic technological makeup of the fleet.

For this reason, biodiesel is already being promoted in fleets, usually in percentage blends of 20% or lower, particularly in the Midwest. We begin with a scenario that concentrates on biodiesel use by sedans in the U.S. government fleets.

In the case of sedans in fleets it is unlikely that biodiesel will ever constitute a majority share of vehicles (based on historical trends and technological factors relating to the operation of diesels). For that reason, while biodiesel may be able to be rapidly introduced, it will fill a niche market, first displacing conventional diesel (likely through fuel switching) and then through a modest adoption of new biodiesel capable vehicles. In this scenario 20% of the sedan fleet is projected to utilize biodiesel fuels. This scenario suggests an early and rapid introduction of biodiesel into the sedan fleet followed by an extensive introduction of hybrid gasoline-electric vehicles.

Table 27. Biodiesel and Hybrid Sedan Pathway Initial Conditions

Initial Fleet Conditions:

Annual Miles Traveled per Vehicle: 20,000

# of Vehicles in Fleet: 4,090,337

Technology	% of Fleet	Fuel Economy
Gasoline	100.0	23.6 mpg
GHEV	0.0	44.5 mpg
Hydrogen	0.0	55.0 mpk
Diesel	0.0	32.0 mpg
Biodiesel	0.0	32.0 mpg

Table 27. Biodiesel and Hybrid Sedan Pathway Initial Conditions (continued)

Initial Fleet Conditions:

Annual Miles Traveled per Vehicle: 20,000

# of Vehicles in Fleet: 4,090,337

Technology	Description of Scenario Purchase Rates
Gasoline	Begins at 95% and comprises 16% by 2030
GHEV	Starts at 3% and increases by 5% a year until 2013 when it increases by 13% a year until 2017 when it increases by 20% a year. Comprises 61% by 2030.
Hydrogen	Begins at 0% and comprises 3% by 2030
Diesel	Remains at 0% throughout scenario
Biodiesel	Starts at 0% and increases by 2.5% each year until reaching 20% in 2012. Then is held constant

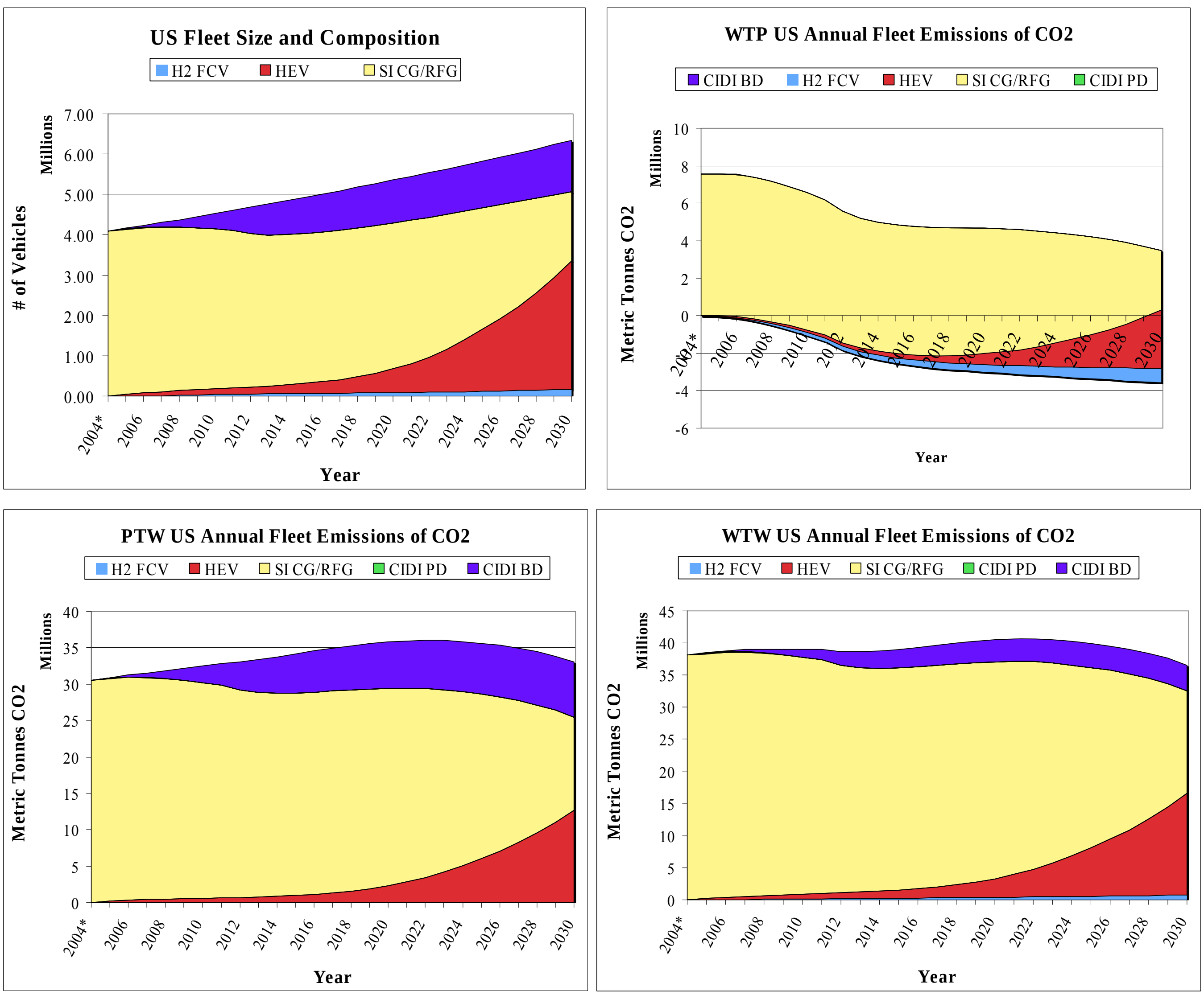


Figure 19. Biodiesel and Hybrid Sedan Pathway: CO_2 Emissions by Fuel and Vehicle Type

The addition of biodiesel, with hybrids as well, results in a significant difference in the emissions profile of the sedan fleet. Unlike in the GHEV emphasis scenario where emissions rise through 2024 before beginning a decline, this scenario allows for a more level progression of emissions. This shifts the peak of sedan fleet emissions earlier to 2022 and limits this peak to an amount of 40 metric tones of CO_2 instead of 45 metric tons. Overall, the scenario in which hybrids are combined with biodiesel vehicles results in a nearly 30% reductions in emissions over the BAU case. Thus the importance of biodiesel and biofuels in general can be seen as a technology that may be adopted quickly to produce immediate results with long term consequences, especially when it is considered in combination with an aggressive promotion of hybrids.

While the above analysis shows the impact of biodiesel introduction into the sedans fleet so that a comparison may be made between GHEV technology and biodiesel), a potentially more important area of introduction would be into the heavy trucks fleet. Due to the already high prevalence of diesel vehicles within this segment of the U.S. government fleet, biodiesel could be rapidly introduced through fuel switching without the limits imposed on sedans. This would result in a large portion of vehicles utilizing biodiesel in a relatively short period of time. The introduction would at first occur as diesel/biodiesel blends that would require little to no modification of the vehicle and would be followed by the introduction of trucks that were B100 capable, and/or the retrofitting of existing vehicles to become B100 capable. This scenario shows a deep penetration by biodiesel into the overall market in heavy duty trucks but also includes some level of hybridization as an alternative to the utilization of biodiesel.

Table 28. Biodiesel and Hybrid Heavy Truck Pathway Initial Conditions

Initial Fleet Conditions:

Annual Miles Traveled per Vehicle: 29,245

# of Vehicles in Fleet: 2,590,000

Technology	% of Fleet	Fuel Economy
Gasoline	30.0	7.3 mpg
DHEV	0.0	10.1 mpg
Hydrogen	n/a	n/a
Diesel	70.0	7.8 mpg
Biodiesel	0.0	7.8 mpg

Technology	Description of Scenario Purchase Rates
Gasoline	Remains at 0% throughout scenario.
DHEV	Starts at 0.5%, is grows each year by a factor of 1.3 until 2013; then it grows by a factor of 1.1 until the end of the scenario, and results in 29% of heavy duty trucks using DHEV.
Hydrogen	Remains at 0% throughout scenario.
Diesel	Begins at 97%. Calculated as the remainder of the other vehicles, ends at 4%.
Biodiesel	Starts at 2.5% and increases by 2.5%% each year until reaching 10% in 2008. Then it grows by a factor of 1.3 each year until 2015, then by 1.01 until the end of the scenario, and results in 67% of U.S. government heavy duty trucks in 2030 utilizing B100.

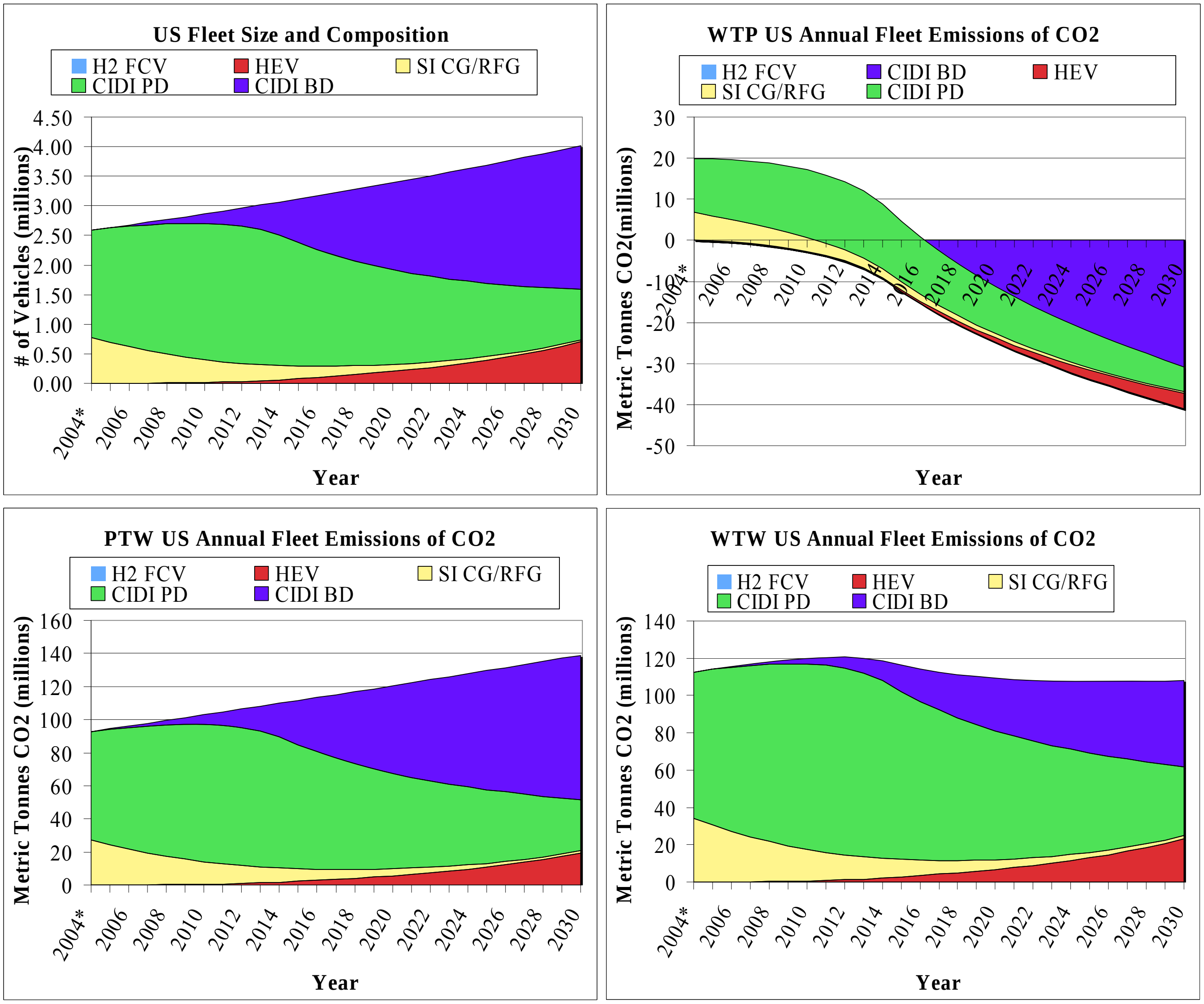


Figure 20. Biodiesel and Hybrid Heavy Duty Truck Pathway: CO_2 Emissions by Fuel and Vehicle Type

This scenario, as with all scenarios involving the introduction of biodiesel, is interesting in that it achieves large reductions in the well-to-pump emissions of carbon dioxide. This effect is so large that it even achieves a net reduction of atmospheric carbon dioxide during the well-to-pump phase of the fueling cycle. During the pump-to-wheels portion of the fuel cycle, however, emissions climb as the number of vehicle miles in the fleet increases. The combined effect of this is a slight increase in emissions of carbon dioxide as biodiesel is beginning to be introduced, followed by a decrease and a leveling off at approximately 2005 levels of emissions.

6.4 Hydrogen Fuel Cell-led Pathway

The third pathway introduces hydrogen fuel cell vehicles at a rapid rate into U.S. government fleets. This transition could be spurred through aggressive policies designed to promote the purchase of these vehicles and a government emphasis on the creation of needed infrastructure, such as fueling stations and hydrogen production plants. As this process would be extremely expensive, it is likely to be slow at first until market size is sufficient to attract private investment. It is important that the government begin the process of infrastructure development and hydrogen fuel cell vehicle utilization in order to increase the rate at which the hydrogen energy economy can develop. Examples of this approach can be seen in states such as California and their Hydrogen Highways program.

It is unlikely that hydrogen will be able to enter the market as rapidly as gasoline-electric hybrids and biodiesel. Nonetheless, hydrogen offers the potential for long-term impacts on vehicular carbon dioxide emissions. Since all of the carbon dioxide emissions stemming from hydrogen fuel cells comes from the production phase of the technology, it may be possible to sequester the carbon dioxide produced during production or to change the means of hydrogen production to less carbon-intensive methods.

Our hydrogen-led pathway begins similarly to the hybrid scenario with GHEV vehicles comprising a growing portion of the sedan market share. But in 2020 hydrogen fuel cell vehicles enter the market and capture more than one-third of the fleet by 2030. While the centrally reformed hydrogen from natural gas actually causes a sharp increase in well-to-pump emissions, a large decrease can be seen in pump-to-wheel emissions.

Overall this scenario causes emissions to remain relatively level through increased introduction of hybrid gasoline-electric vehicles until 2020 when the introduction of hydrogen vehicles causes a decrease in emissions below current levels by 2030. It is interesting to note how pump-to-wheel carbon dioxide emissions can overtake well-to-pump releases.

Table 29. Hydrogen Fuel Cell-led Pathway Initial Conditions

Initial Fleet Conditions:

Annual Miles Traveled per Vehicle: 20,000

# of Vehicles in Fleet: 4,090,337

Technology	% of Fleet	Fuel Economy
Gasoline	100.0	23.6 mpg
GHEV	0.0	44.5 mpg
Hydrogen	0.0	55.0 mpk
Diesel	0.0	32.0 mpg
Biodiesel	0.0	32.0 mpg

Table 29. Hydrogen Fuel Cell-led Pathway Initial Conditions (continued)

Initial Fleet Conditions:

Annual Miles Traveled per Vehicle: 20,000

# of Vehicles in Fleet: 4,090,337

Technology	Description of Scenario Purchase Rates
Gasoline	Starts at 95%, is calculated as the remainder, and ends at 14%.
GHEV	Starts at 3% and is multiplied by 1.4 until 2009, then it is multiplied by 1.25 until 2014, then it is multiplied by 1.03 until 2019, then it is multiplied by 1.01 until 2027 at which point it reaches 44%.
Hydrogen	Starts at 0%. In 2013 begins at 0.01% This is multiplied by 3 each year until 2018, then it is multiplied by 1.25 each year and accounts for 36% of the fleet in 2030.
Diesel	Remains at approximately 1% throughout the scenario.
Biodiesel	Starts at 1% and is multiplied by 1.067 each year, reaching 5% in 2030.

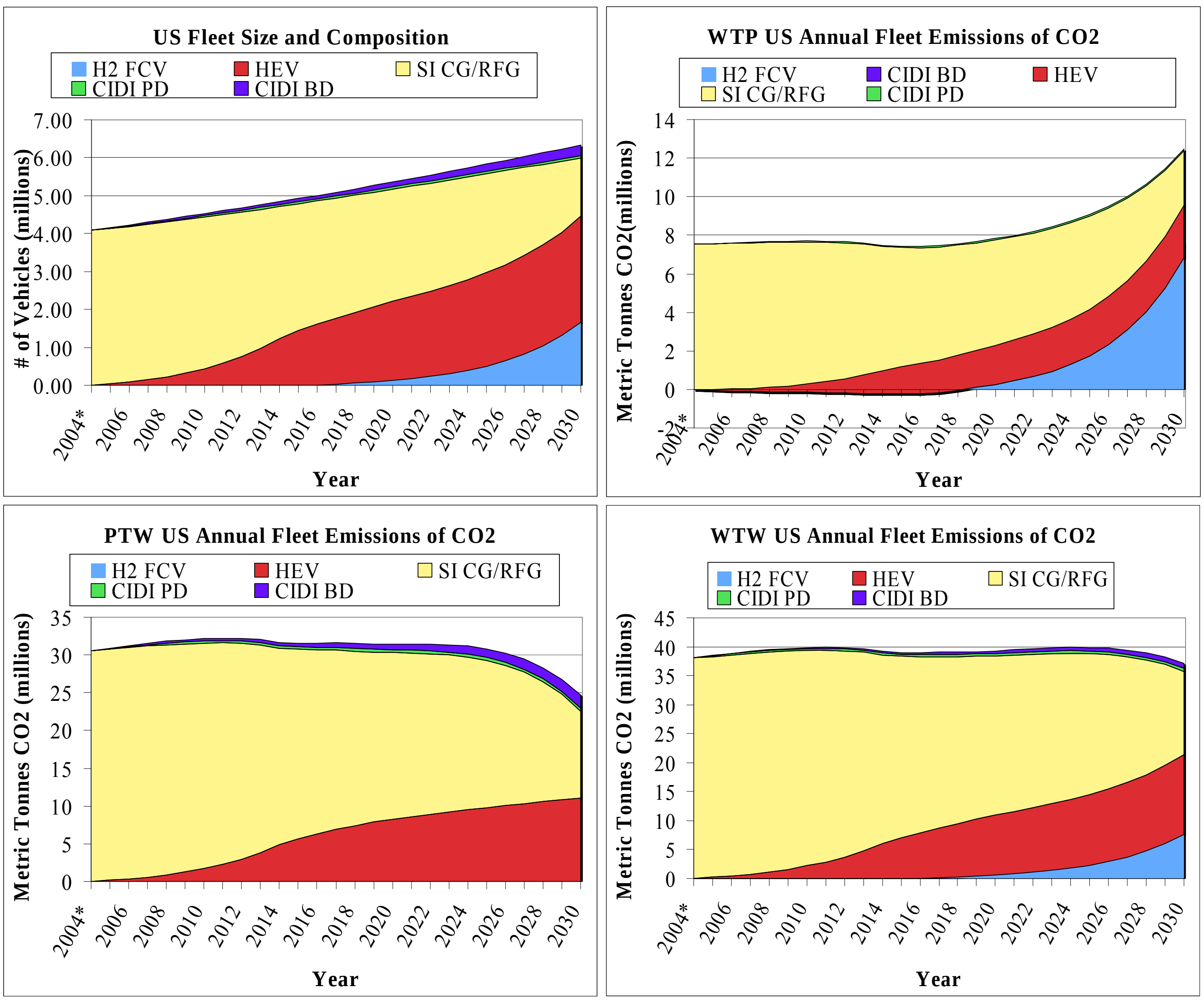


Figure 21. Hydrogen Fuel Cell-led Pathway CO_2 Emissions by Fuel and Vehicle Type

This transition from gasoline-electric hybrid to hydrogen fuel cell vehicles illuminates an important pathway towards the overall reduction of carbon dioxide emissions. Because hydrogen will require a high level of infrastructure construction and market development and because it is unlikely to be economically viable in the near future, it is important that other actions be taken over the next 10-20 years in order to help keep emissions in check. This scenario closely follows one suggested by the National Academy of Science (NAS, 2004). As hydrogen fuel cell vehicles make up an ever increasing portion of the fleets, emissions levels should remain steady at slightly below 40 metric tones of carbon dioxide and eventually begin to decrease around 2026. This will create the potential for greater changes in emissions levels in the future if hydrogen production techniques change to more sustainable methods. In sum, a hydrogen-led fleet transformation is likely to achieve approximately the same emission impacts through 2030 as a hybrid- or biodiesel + hybrid-led transformation. The key concern is whether the economics of hydrogen can be cut to a level that would justify a high level of fleet use of the technology.

6.5 Conclusion

These scenarios show that all three of the new vehicle technologies examined in this report offer the potential for carbon dioxide emissions reductions. There are several points that may be drawn from these findings. The first is that none of the technologies has the potential to cause deep cuts in carbon dioxide emissions levels from fleet transportation in the next ten years. Among the three alternatives, hybrids and biodiesels show the greatest potential for near term reductions in carbon dioxide emissions; hydrogen vehicles are not likely to reduce emissions before 2024. All three technologies show the potential for long term reduction of carbon dioxide levels compared to current amounts.

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