Technical and Financial Evaluation of Vehicle Types in the United States

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Abstract

The project objective was to research and analyze different types of alternative energy vehicles from both technical and financial perspectives. Gasoline, diesel, biodiesel, fully-electric, hybrid-electric, and hydrogen fuel cell vehicles were identified as the major vehicle types currently available. Each vehicle type was researched to gain knowledge of its powering systems, consumed fuel, energy deficiencies, and environmental impacts. Relevant financial data was gathered on each vehicle type and a cost analysis over the lifetime of each vehicle type was performed. Finally, the technical knowledge of the different vehicles was combined with the financial analysis. Using the technical and financial characteristics of each vehicle type, conclusions were formed. Small gasoline and hybrid-electric vehicles were found to be the best present-day economic choices for consumers. Additionally, an electric configuration is recommended selection for future use based on economic and technical predictions.

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Executive Summary

Introduction

We all have grown up immersed in a world where having access to a vehicle is considered commonplace, and have developed interests in many different aspects of automobile technology and development. As United States consumers prepare for the next wave of automobile technology and advancements, they need to be aware of the different vehicle options that will become available to them, and understand the ramifications of each. Our group's goal for this project was to produce a thorough analysis of the vehicles that are currently available or nearing availability in the United States. We researched each of the unique technologies and compiled the important technical, mechanical, and environmental characteristics of each to provide the consumer with the facts about each vehicle type. We also completed a cost analysis of vehicles of each type to provide an important financial perspective. We hope that our work will provide consumers with working knowledge of the available technologies so they can make informed decisions about their vehicle purchases and the impacts their cars will have on the world. We also hope that our work will encourage consumers to take a different perspective on their vehicle spending by considering the lifetime costs of a vehicle, and not just the retail price.

Vehicle Types

There are many different alternative vehicle types available in the United States that rely on a variety of different energy and fuel technologies. These vehicle types are often very similar to their gasoline counterparts in many ways; their body styles, structural materials, and aesthetic options may be the same for any type of vehicle fueling system. However, the fueling system itself greatly affects the environmental impact and mechanical design of the vehicle. Before considering the financial implications of any particular vehicle, we thoroughly investigated the differences between many of the popular vehicle types currently available or being developed in the United States. We focused our research on gasoline, diesel, biodiesel, hybrid-electric, fully-electric, and hydrogen fuel cell vehicles.

Gasoline vehicles are the best selling and most popular vehicle type in the United States. The gasoline used to power the vehicle's internal combustion engine is derived from non-renewable petroleum reserves beneath the surface of the Earth. Gasoline vehicles are only 20% thermodynamically efficient as a result of the losses associated with the internal combustion engine. In addition, the process of combusting gasoline produces large amounts of greenhouse gases like carbon dioxide. These emissions have been widely linked to climate change and greenhouse effects in the atmosphere around the world. On the positive side, gasoline vehicles are widely available in many models and styles, and are supported with an ample amount of servicing locations and refueling stations.

Diesel vehicles are typically limited to heavy trucking and industrial use in the United States, though diesel commuter cars are widely available in Europe. Like gasoline, diesel fuel is derived from petroleum reserves, and is a non-renewable energy source. Diesel vehicles are operated using a special diesel internal combustion engine that operates without spark-igniting the injected fuel. The chemical qualities of diesel fuel allow it to be compressed at higher ratios within the engine than gasoline. As a result, diesel vehicles often have higher torque outputs and efficiencies that make them ideal for use in heavy trucking. In the United States, diesel fuel undergoes less refining than gasoline, which for years allowed diesel to be sold at a lower price than gasoline. However, the reduction in mandatory refining leads to diesel being viewed as a "dirty" fuel due to the high amounts of soot particle emissions associated with their use. Even though diesel vehicles emit large amounts of hazardous soot and nitrous oxides, they produce fewer total greenhouse gas emissions than comparable gasoline vehicles.

In recent years, biodiesel fuel has gained support as a possible successor to diesel fuel. Biodiesel powers an internal combustion engine in the same fashion as diesel fuel. Unlike diesel, biodiesel is produced from plant oils and animal fats, making it the only renewable fuel used in automobile internal combustion engines. The term biodiesel can be used to refer to a wide range of blends of fuel. Though biodiesel can be produced using only renewable plant and animal byproducts, typical biodiesel being sold currently in the United States is a mixture of petroleum-based diesel and plant-based biodiesel. A typical biodiesel blend reduces emissions of many greenhouse gases associated with internal combustion engines. Moreover, these blended fuels are fully compatible with most existing diesel vehicles and engines, making a biodiesel initiative even more attractive. However, pure biodiesel is relatively expensive compared to diesel, and vehicles that operate using pure biodiesel are fairly uncommon as a result.

As electric technology has improved in recent years, many in the automotive industry have suggested switching to electric vehicle configurations. Hybrid-electric vehicles are currently being offered as the environmentally-friendly alternative to gasoline or diesel vehicles. Hybrids combine the familiar reliability of gasoline vehicles with the clean-running efficiency of electric motors and components. There are a few configurations of hybrid-electric vehicles that offer subtle differences in energy-generating and propulsion techniques, and each style has its own benefits and limitations. All of these hybrid configurations offer great reductions in greenhouse gas emissions due to their limited, efficient use of the vehicle’s internal combustion engine. Many United States automotive companies offer hybrid-electric vehicles or are currently developing models for future release. Though hybrids initially cost significantly more than a basic gasoline vehicle, retail costs have generally dropped in recent years as they become mainstream consumer favorites around the United States.

In principle, fully-electric vehicles are the idealization of the electric vehicle. Unlike hybrids, fully-electric vehicles operate without the use of an internal combustion engine, relying solely on electric motors and battery packs for operation. As a result, fully-electric vehicles produce zero emissions during operation, making them the ideal prototype for clean-running automobiles in the future. Advances in battery technology have increased the possible range of fully-electric vehicles and made them more desirable to consumers. Despite the great upside of fully-electric vehicles, there are a few downsides. Most of the electricity in the United States is generated using fossil fuels, so reliance on fully-electric vehicles necessitates a reliance on non-renewable, environmentally harmful fuel sources. There have been many clean energy initiatives in recent years to push the United States to adopt renewable energy sources, and the adoption of solar, wind, and hydroelectric power would greatly reduce the indirect environmental negatives associated with fully electric vehicles. Currently, fully-electric vehicles are being developed by many automotive companies, but none are widely available for purchase.

Hydrogen fuel cell technology has received large amounts of funding and attention from many alternative energy backers in the past few years. Despite the large following hydrogen fuel cells have gained, they are currently the most underdeveloped vehicle type of those studied. Hydrogen fuel cells offer many benefits in theory. They rely on hydrogen gas for power, and are clean running, emitting only water vapor during operation. They are also incredibly energy efficient for use in automobiles due to their high energy densities and low weights. However, the hydrogen gas needed to power the fuel cells cannot be obtained without breaking down other chemical compounds. In most cases today, the compounds used to provide hydrogen gas are fossil fuel derivatives, leading to indirect emissions caused by hydrogen fuel cell vehicles. They are also incredibly expensive to produce for use in vehicles, and therefore have not yet been introduced for mainstream purchase.

Financial Analysis

After familiarizing ourselves with the advantages and disadvantages of each vehicle type, we developed a method of calculating the estimated cost of ownership of a vehicle over the lifetime of use. Though the up-front retail price of a vehicle may be what drives consumers to purchase their vehicle of choice, focusing solely on the immediate costs of a vehicle may be misleading when considering the amount of money invested in operating a vehicle for years. Our calculations take all of the direct and indirect costs associated with vehicle ownership and combine them to provide a total ownership cost for each vehicle. We believe that this total cost should be the biggest financial factor when investing large amounts of money into a new vehicle.

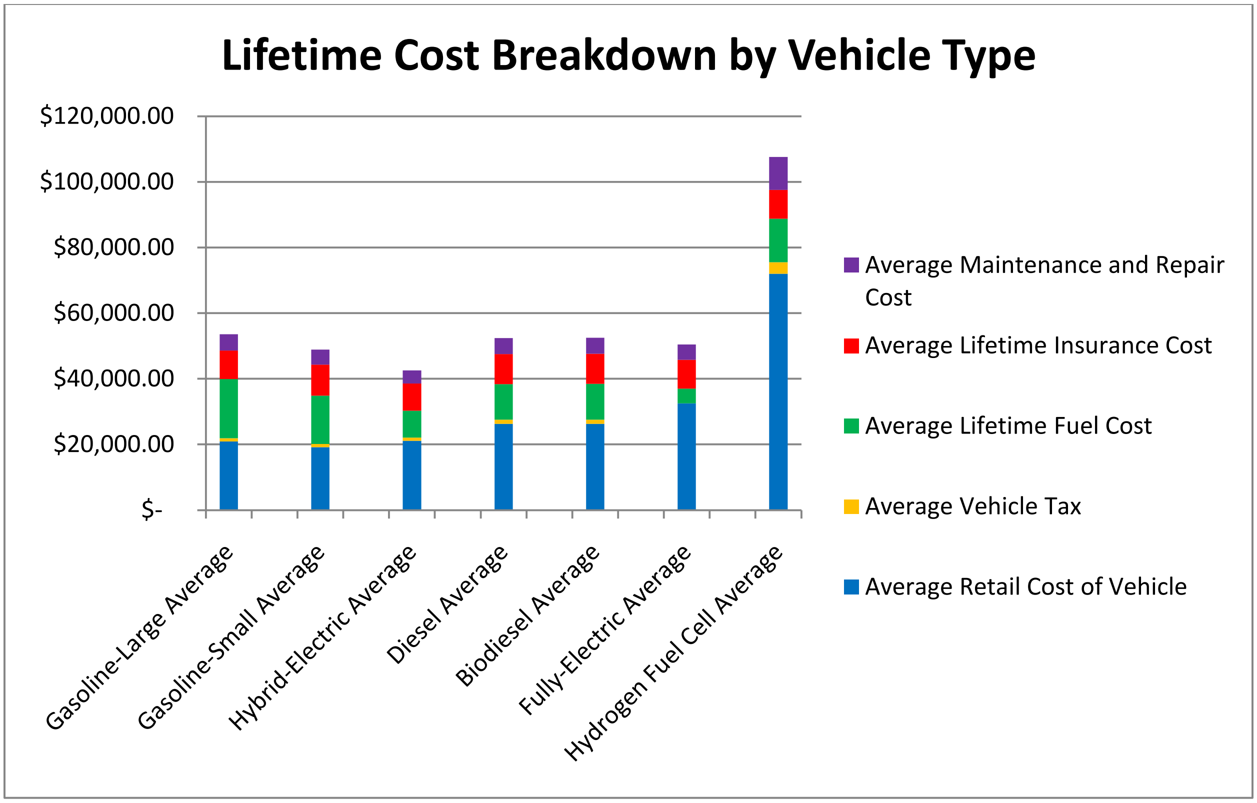
Using available data on the average driver in the United States, we calculated the average life expectancy of a vehicle to be about 150,000 miles over 10 years of operation. We used this life expectancy as the baseline for all of our lifetime cost calculations. We also compiled a list of the most common vehicles in the United States. We chose the most popular vehicles for our analysis to provide the most accurate reflection of the average cost to consumers possible.

After identifying the most popular vehicles for each fuel type, we calculated the total costs of ownership for each. First, we found the manufacturer's suggested retail price for each vehicle. We then calculated the related tax cost for each vehicle using the retail price and the national tax rate average of 4.90%. Though these costs might vary slightly across the country due to different dealership offerings and state-specific tax rates, the retail and tax costs will remain fairly static for vehicles nationwide.

Apart from retail cost, the largest variable cost associated with each vehicle is fuel expenses. We found the national averages for the costs of each fuel type in a United States Department of Energy publication from July 2009. The Department of Energy also publishes lists of fuel economy data for vehicle types available in the United States every year. Using this data, we calculated the fuel cost over the lifetime of each vehicle for highway, city, and combined driving conditions.

We also calculated the anticipated costs of insurance, maintenance, and other related secondary vehicle needs. In order to standardize our insurance premiums, we requested insurance quotes for a model person with what we considered average features. Though maintenance and servicing may vary slightly between vehicle types, we used a standard fraction of total ownership costs to calculate these costs.

After calculating all of the related costs associated with vehicle ownership, we totaled our values to arrive at the estimated total cost of ownership of each vehicle. The complete breakdowns of the total calculated lifetime costs of each vehicle are listed in the appendix at the back of this report. The graph below compares the average lifetime costs of each vehicle type we examined. The height of each bar represents the total cost of ownership, while the sections within each bar indicate the relative portion of the lifetime cost associated with the given cost area.



Lifetime Costs of Vehicles by Cost Area

Conclusions

Our financial analysis shows that hybrid-electric cars are the best financial option based on the lifetime cost of owning the vehicle. Hydrogen fuel cell vehicles are prohibitively expensive at this point in time due to their extremely high purchasing costs. Generally, the two best vehicle alternatives from a financial perspective are hybrid-electric and small gasoline vehicles. Hybrid-electric vehicles have become widely available in the last few years, and the average purchase price of a hybrid has dropped in conjunction with their availability. Small gasoline cars have lower retail prices than hybrids, but on average require more spending to fuel the vehicle than hybrids.

When considering the long-term viability of different vehicle types due to financial and technical differences, we found that a plug-in range extended hybrid-electric configuration would be the preferred dominant vehicle type of the near future. The electric design of this vehicle would minimize the negative environmental impacts associated with automobile operation. Plug-in charging would allow the vehicle to store power in battery packs instead of generating electricity onboard using a gasoline engine. The plug-in compatibility would also encourage the use of renewable energy technologies to provide electricity in the near future, further increasing the environmental friendliness of the vehicle and its infrastructure. We recommend that the vehicle contain a small auxiliary gasoline engine for use during emergencies. We believe that the inclusion would not cause any significant environmental damage due to the rarity of its use, and that the emergency engine would be an effective and familiar reserve powering system. Additionally, electric vehicle technology would likely involve many different sectors of business and technology development to collaborate and develop energy technologies that benefit many areas of life.

1. Introduction

Since the beginnings of civilization, humans have always strived to develop better ways of traveling from place to place. From horses and oxen to carriages and bicycles, the most basic forms of transportation have evolved over time into automobiles; complex contraptions of metal, rubber, and grease that whiz along highways at dizzying speeds. In many ways automobiles have become almost larger than life; cars have infiltrated our mainstream music, movies, literature, athletics, social structures, language, and businesses. From the Great American Streetcar Scandal of the 1930s and 1940s to the 1970s Oil Crisis and constant Middle East political struggles to the Bailout Bill and the Big Three in 2008, automobiles and the social structures surrounding them have been critical to the shaping of the United States and the other first world countries that employ them. Entire industries have risen and fallen in the wake of the automobile, and there is seemingly no limit to the progress to be made and achievement to be had when dealing with these exciting machines.

Recently, America, and the world as a whole, has come to a fork in the road of the evolution of the automobile. For almost a century, American cars have become larger and more powerful as technology has evolved to support these monstrous machines. The automobile has become such a demanding piece of technology that it currently threatens to obsolete itself if it remains in its current condition. Gasoline cars have dominated the market since Henry Ford perfected the assembly line and began to mass produce his Model T. However, consumers and manufacturers alike are beginning to realize the impact that millions of gasoline-powered cars can have on the Earth. Researchers have implicated automobile exhausts as major contributors to global warming, and exhausted greenhouse gases have been repeatedly linked to climate changes and altered natural environments around the globe. Additionally, an increased awareness of the finite limit of the planet's petroleum resources has heightened concerns about the longevity of gasoline vehicles. The idea of the gasoline car as the modern standard automobile constantly weakens as concerns surrounding mount. Alternative vehicle types are being developed to ease America's dependence on natural resources and eliminate the dangerous environmental side effects of gasoline-powered cars.

Our group's interest in these developing vehicle technologies is twofold. Firstly, the developments and revolutions in energy technology over the past 25 years have impacted nearly all aspects of American life. As students preparing to enter the workforce in scientific disciplines, we recognize the importance of energy technology and embrace the challenge of developing more efficient and more environmentally friendly alternatives. We are living in a time of increased awareness about the effect human beings and their actions have on the planet, and we are extremely interested in learning more about the ways engineers and scientists are improving our energy production and usage. Secondly, though energy technologies have been constantly evolving over the past 100 years, fossil fuels continue to be the leading source of energy production in the world. There have been many factors that together have perpetuated the use fossil fuels, but maybe the most important contributing factor has been cost. Apart from a few outlying periods, fossil fuels have been less expensive to harvest, refine, transport, and use. As a result, niche technologies like wind power, solar power, and nuclear power have been suppressed because of the enormous costs associated with developing and implementing them at a wide-spread consumer level. However, in recent years, the price of fossil fuels has continued to rise, while other technologies like solar and electric power have become more economical for consumer use in a variety of contexts. The world is quickly approaching a critical point where fossil fuels will no longer be the best economic option. As consumers ourselves, we know that the relative cost of a product to a consumer greatly determines his likelihood of purchasing it, and we are interested in discovering if the notion of fossil fuel power being consumer friendly still applies.

For our project, we decided to combine these interests and investigate the future of automobiles. There have been many predictions about the successor to the gasoline car, from the extremely practical battery operated car to the ludicrous ideas of personal hovercrafts or teleportation pods. Our group's goal for this project is to develop a modern understanding of the major competitors in the race for automobile dominance. Each suggested successor has its own advantages and disadvantages, and each has its own practicality both in the present and in the future. We hope to arrive at a well-informed conclusion about the best candidate for automobile supremacy going forward.

First, we will introduce the technologies that are currently being developed for use in automobiles. We will provide detailed background information on the different vehicle types by explaining the mechanics and science behind each fuel type and powering system. We will provide insight on the procurement and production of the raw fuels themselves and explanations of the processes that turn chemical and electrical energy into mechanical power. We will also highlight the mechanical advantages and deficiencies of each technology to allow comparisons to be drawn between fuel types. Additionally, we will explain the possible environmental implications of each technology to allow the advantages and disadvantages of the mechanical aspects of each to be weighed against the resultant effects of use.

Second, we will analyze each vehicle type from a consumer's financial viewpoint. The technical and environmental characteristics of an energy system are important, but we believe that an energy system will only experience widespread consumer use if the financial aspect does not inordinately burden the consumer. We will compute an estimated total cost to the consumer based on various vehicle expenses over the lifetime of the car. We will begin by providing the direct retail and tax costs paid up front by the consumer when he purchases the automobile. We will also calculate the estimated costs of fuel, insurance, maintenance and other secondary expenses that add to the consumer's financial burden. At the end of the analysis, we will bring all of these primary and secondary costs together and compute the total cost of a vehicle over its average lifetime.

Finally, we will state our conclusions, based on our research and analysis, regarding the possible future of the American consumer automotive industry. We will examine the vehicle types that are financially beneficial to consumers looking to purchase a vehicle in the near future by highlighting the cost differences and variables associated with each vehicle type. We will also discuss the future of automobile technology in the United States using our technical and environmental knowledge.

2. Types of Vehicles

In 2005, the United States Census Bureau tabulated over 243 million vehicles registered in the United States.[1] From tanker trucks to small sedans, the roadways of the country are constantly flooded with traffic made up of all types of vehicles. Though vehicles come in many sizes and designs and have many different functions, over 98% of the vehicles currently in use are powered by either gasoline or diesel fuels.[2] Even when factoring in public transportation systems that run on electricity and other fuels, gasoline provides more than 62% of the energy used to transport Americans from place to place.[3] Recently, due to a variety of economic, political, and environmental factors, United States automobile companies and consumer have started to embrace alternative energy vehicles as the average person's exposure to and education about alternative vehicles has increased. However, many Americans lack working knowledge of the emerging technologies that will shape the future of the automotive landscape. In this section, we will provide detailed breakdowns of the different vehicle types that may command wide spread market attention and commercial usage. The characteristics of automobiles that do not involve the powering systems will not be factored into our discussion. All of the vehicle types described can be used in similar, small car applications, so factors like car size, shape, aerodynamics, or common parts will not be examined.

2.1. Internal Combustion Engine Vehicles

An internal combustion engine (ICE) generates mechanical power by burning fuel inside of the engine via a combustion reaction. Generally, an ICE can burn a variety of different

[1] Statistical Abstract: 2007 Edition, section 23, table 1042.
[2] Statistical Abstract: 2007 Edition, section 23, table 1076.
[3] "Use of Gasoline."

combustible fuels, including many different types of fossil fuel derivatives and hydrocarbons. However, nearly all commercially available ICEs burn gasoline or diesel fuels to generate power.

2.1.1 Gasoline Vehicles

- Gasoline is a non-renewable fuel derived from petroleum
- Gasoline ICEs are only 20% thermodynamically efficient
- Infrastructure and servicing stations for gasoline vehicles are already in place around the country
- Gasoline ICEs emit several greenhouse gases during operation
- The United States is the world's largest producer of gasoline vehicle emissions

Gasoline, or petrol, is a non-renewable fossil fuel refined from crude oil deposits located beneath the surface of the Earth. Though gasoline is often chemically described as C_8H_{18} (octane), gasoline used in consumer automobiles is actually a heterogeneous aliphatic hydrocarbon. This means that the actual chemical composition of a large volume of gasoline actually contains many different chemical combinations of carbon and hydrogen atoms arranged in different ways.[4] In practice, molecules of gasoline may contain anywhere from seven (heptanes) to ten (decane) or more carbon atoms, but the different molecular structures add a negligible amount of uncertainty and deviation from the expected combustion of pure octane. Octane is the most commonly used hydrocarbon chain in gasoline mixtures because octane's chemical structure allows it to withstand fairly high compression within the ICE pistons. A higher compression ratio within an ICE yields higher horsepower outputs at a given engine weight; hence, the automobile industry has continually designed automobile engines for octane

[4] Brain, "How Gasoline Works," page 2.

gasoline.[5] When ideally combusted within an ICE, one gallon of gasoline releases over 125,000 BTU of energy in a chemical reaction shown in the unbalanced chemical equation below.[6]

$$C_8H_{18} + O_2 \rightarrow CO_2 + H_2O$$

Gasoline-powered ICEs generally use a four-stroke combustion cycle consisting of intake, compression, combustion, and exhaust strokes.[7] During the intake stroke, the ICE's intake valve opens and the piston moves down into the cylinder. The vacuum created by the piston's movement causes a mixture of ambient air and gasoline to rush into the cylinder. In the compression stroke, the piston pushes back into the cylinder as the intake valve closes, trapping and compressing the fuel-air mixture inside the cylinder. When the piston reaches the top of the cylinder, the combustion (or power) stroke begins as the spark plug creates a spark that ignites the compressed, highly energetic mixture. This ignition causes the combustion reaction described above to occur incredibly quickly, generating a large amount of energetic gas that expands and pushes the piston back down into the cylinder. As the gases cool, the piston moves back up into the cylinder, and the exhaust valve opens to allow the cooled gases to be ejected into the atmosphere. As the piston begins to move down again, the intake valve opens and the four-stroke process begins again.[8] Crankshafts attached to the pistons convey the energy generated by the oscillations in the cylinder to the axels and wheels, propelling the car forward with each stroke. The four-stroke ICE process is shown below in Figure 1.

[5] Brain, "How Gasoline Works," page 4.
[6] Brain, "How Gasoline Works," page 2.
[7] Brain, "How Car Engines Work," page 2.

[8] Schappell

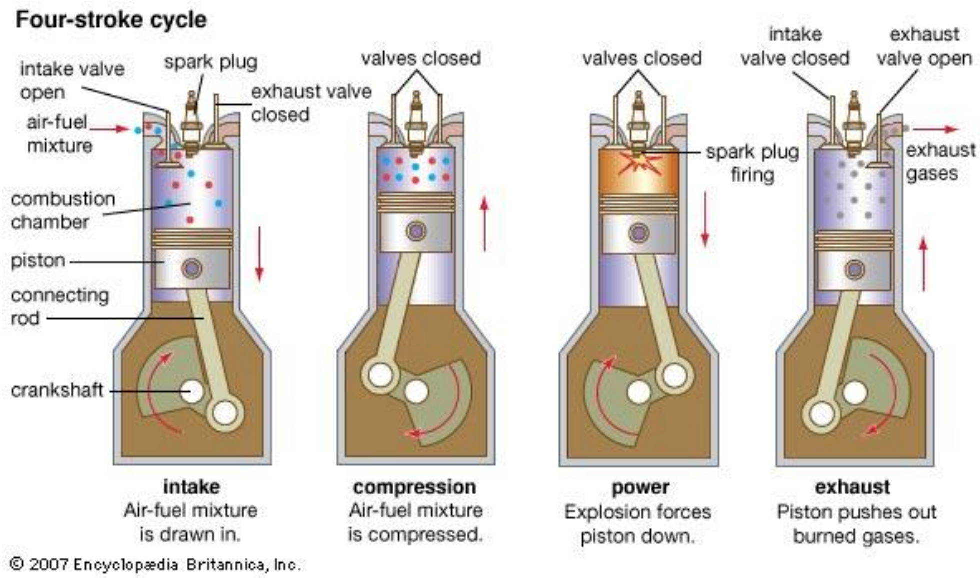


Figure 1: The Gasoline ICE Four-Stroke Combustion Cycle

Source: http://filmat11inc.com/images/ICE%20engine.jpg

For most of the 20th century, gasoline ICEs dominated the automobile engine marketplace because of their relative simplicity and ease of fuel procurement. For years, automobile-grade gasoline has been consistently priced well within the average consumer's budget, even during shortages and political embargos. For years, crude oil and the fossil fuels derived from it were seen as limitless resources due to the immense flows found beneath the Earth, and the United States auto industry evolved to rely heavily on the continued availability of gasoline. Today, the United States population consumes about 380 million gallons of gasoline every day.[9] Though the United States is one of the largest crude oil exporters in the world, it still relies on many other countries to supply the gasoline and other crude oil products needed to sustain the American way of life. About 57% of United States petroleum is imported from other countries. The statistics regarding American use of petroleum and the largest suppliers of United States oil are shown below in Figure 2, Figure 3, and Table 1.

[9] "Use of Gasoline"

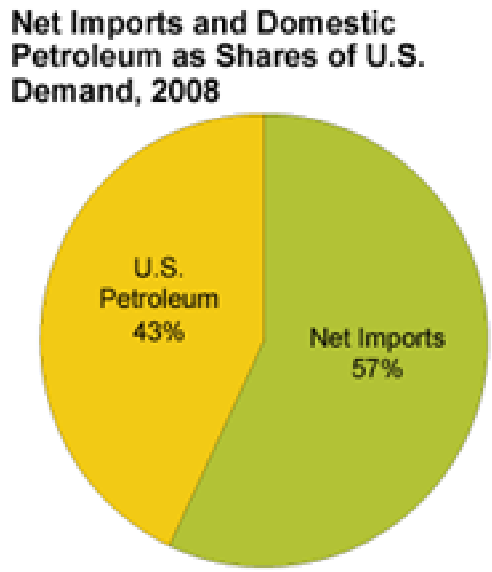


Figure 2: United States 2008 Petroleum Imports and Exports
Source: http://tonto.eia.doe.gov/energyexplained/index.cfm?page=oil_imports

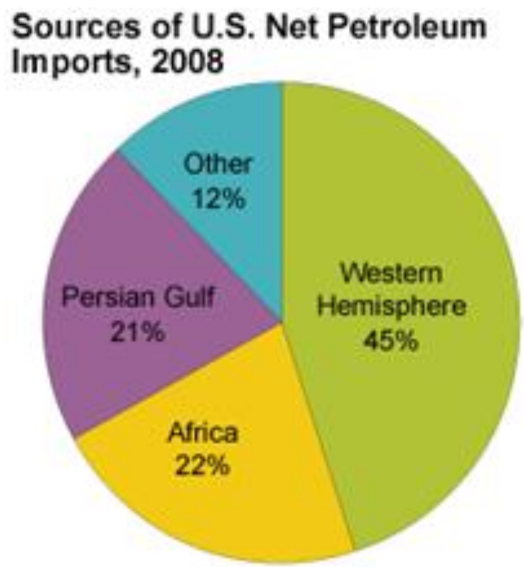


Figure 3: Sources of United States 2008 Petroleum Imports

Source: http://tonto.eia.doe.gov/energyexplained/index.cfm?page=oil_imports

Country	Percentage of US Imported Petroleum Supplied (in 2008)
Canada	19.3%
Saudi Arabia	11.8%
Mexico	10.1%
Venezuela	9.2%
Nigeria	7.7%

Table 1: Leading Supplying Countries of United States 2008 Petroleum Imports Source: http://tonto.eia.doe.gov/energyexplained/index.cfm?page=oil_imports

Because gasoline automobiles have been the dominant vehicle in the United States marketplace, the infrastructure needed to support gasoline cars already exists. There are currently over 117,000 gasoline service and fueling stations in the United States (or about 1 gas service station for every 2,500 people).[10] Additionally, the United States has developed and funded a massive network of roads and interstates called the National Highway System (NHS) that provides the United States' 243 million registered vehicles and their owners ample opportunity to explore the country with their vehicles. Though the road networks themselves would likely remain unchanged for any vehicle type that may use them, everything from pavement types to roadside rest areas to speed limits have been tailored to meet the needs of the standard gasoline automobile.

However, gasoline engines also have their downsides. Like most internal (and external) combustion engines, gasoline ICEs generate power by converting chemical and thermal energy into mechanical energy. However, the chemical processes themselves that create this mechanical energy are bound to a maximum efficiency according to Carnot's Theorem and the second law of

[10] "U.S. Census Press Release."

thermodynamics.[11] Additionally, Carnot's cycle assumes nearly ideal conditions and places restrictions of the different reversible and irreversible processes involved in the energy conversion, and in reality no combustion engine is as efficient as the one imagined by Carnot. A typical combustion engine used to power an automobile runs at a maximum efficiency of 20%. In other words, only 20 percent of the thermal energy released by the gasoline is converted into mechanical work to drive the pistons and power the car.[12] This efficiency problem presents a major flaw in ICE design that can never be designed out of an engine. As car manufacturers and consumers aim to maximize the efficiency of their products, the huge amounts of waste energy created by gasoline engines will continue to be a major limiting factor in the staying power of gasoline vehicles. A graphic illustration of energy losses in a gasoline ICE is shown in Figure 4 below.

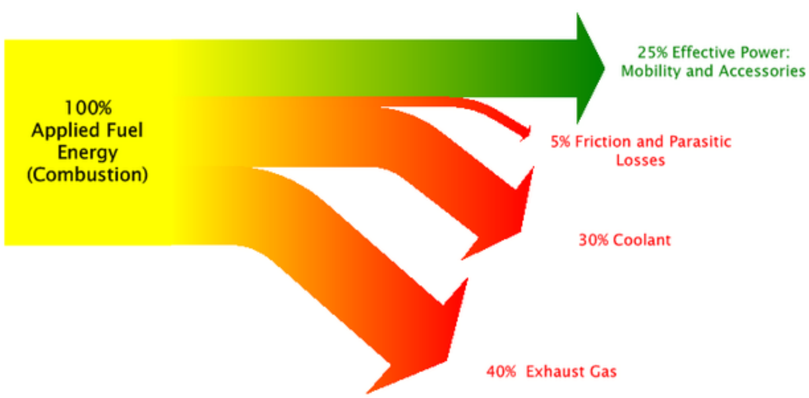


Figure 4: Losses and Inefficiencies of a Gasoline ICE

Source: http://bioage.typepad.com/photos/uncategorized/energy_path_gasoline_ice.png

Additionally, gasoline ICEs and gasoline vehicles are major sources of pollutant exhausts and greenhouse gases, including carbon dioxide (CO_2), methane (CH_4), and nitrous oxide

[11] Moran, pages 213-229. Carnot's ideal engine and work with irreversible processes were stepping stones to the eventual formulation of the 2nd law. The percentage of the energy converted is called "work".

[12] Nice, page 5.

(NO_2).[13] In recent years, environmentalists and other scientists studying weather patterns and global climate changes have identified a controversial subject known as 'global warming'. Though there are many different, complicated aspects of global warming and climate change, on a basic level, global warming refers to the increase in average surface temperature on planet Earth over the past few hundred years due to human activity (such as industrialization).[14] The human activity most commonly associated with global warming is the production of greenhouse gases by burning fossil fuels like gasoline, oil, and coal. A 2002 study found that the United States was responsible for over 1.6 billion metric tons of carbon emissions every year, accounting for around 25% of the world total.[15] As a result, gasoline vehicles have become lightning rods for criticism and have been identified as needing major technological overhauls to become more environmentally friendly.

2.1.2 Diesel Vehicles

- Diesel fuel is a non-renewable fuel derived from petroleum
- Diesel ICEs operate without sparking the fuel, allowing higher compression and higher torque outputs than gasoline ICEs
- Often used to power commercial or industrial vehicles
- Emit a variety of greenhouse gases during operation
- Soot emissions have been linked to health problems in high density areas

Like gasoline vehicles, diesel vehicles are also powered by an ICE that combines fuel and air within the piston. However, there are two major differences between gasoline vehicles and diesel vehicles: the fuel itself, and the method of injecting and igniting the fuel-air mixture.

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[13] Kiehl, page 203.
[14] Revkin
[15] "Clearing the Air on Climate Change."

Like gasoline, diesel fuel is also produced from crude oil harvested from beneath the Earth's crust. Diesel fuel is also comprised of chains of hydrocarbons refined from the heterogeneous petroleum mixture drilled from the Earth, and similarly to gasoline, the hydrocarbon chains that make up a sample of diesel fuel can range from seven to twenty carbon atoms long and react in a very similar chemical reaction. However, the average hydrocarbon chain in diesel fuel is much larger than that in gasoline: diesel fuel is often represented as $C_{14}H_{30}$.[16] The chemical equation for a diesel combustion reaction is given below.

$$C_{14}H_{30} + O_2 \rightarrow CO_2 + H_2O$$

One gallon of diesel fuel contains approximately 147,000 BTU of stored chemical energy that is released in the above chemical reaction.[17] The 18% increase in energy density for diesel fuel over gasoline can be attributed to the larger hydrocarbons of diesel fuel and the increased amount of high energy hydrogen bonds that are broken during combustion. A chemical comparison of diesel and gasoline is shown in Table 2 below.

	Gasoline	**Diesel**
Chemical Formula (Average)	C_8H_{14}	$C_{14}H_{30}$
Average Molar Mass	62 g/mol	114 g/mol
Energy per Gallon Combusted	125,000 BTU	147,000 BTU

Table 2: Chemical Comparison of Gasoline and Diesel Fuel

There are also significant differences between the gasoline ICE and the diesel ICE. Though both ICEs are typically manufactured in four-stroke configurations, the processes

[16] Brain, "How Diesel Engines Work," page 4.
[17] Brain, "How Diesel Engines Work," page 4.

defined by each stroke are different for a diesel ICE. During the intake stroke, the intake valve opens and the moving piston sucks air into the cylinder. However, unlike the gasoline ICE, no fuel is drawn through the intake valve. During the compression stroke, the intake valve closes and the piston is pushed upwards to compress the air inside the cylinder. When the piston reaches the top of the cylinder and the air is fully compressed, the diesel fuel is injected into the compressed air through an injection valve. The high pressure within the chamber causes the diesel-air mixture to self-ignite and begin the combustion reaction without the aid of an external spark plug. After the fuel combusts, the piston is pushed down and the fuel is exhausted similar to the gasoline ICE.[18] The diesel engine cycle is shown below in Figure 5. Note the absence of a spark plug.

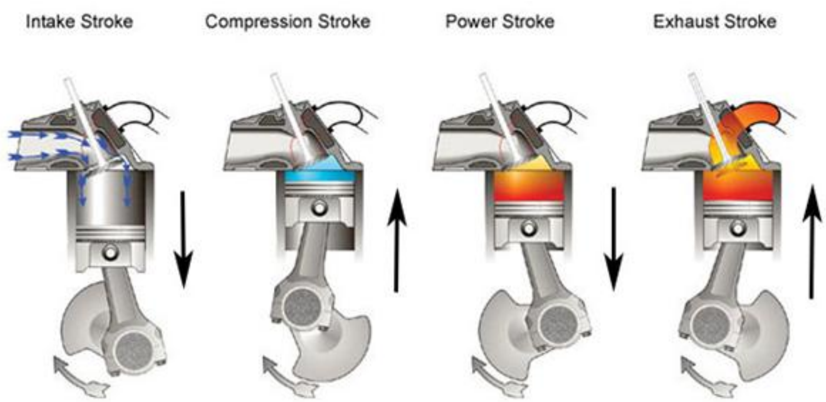

Figure 5: The Diesel ICE Four Stroke Combustion Cycle

Source: http://image.stockcarracing.com/f/9445762/scrp_0801_02_z+twelve_budget_output+four_stroke_diagram.jpg

When Rudolf Diesel began designing a more efficient internal combustion engine in the late 1800s, he believed that the key to an energy efficient engine would be the temperature and pressure of the fuel being combusted within the cylinders. Thermodynamically, the static

[18] Brain, "How Diesel Engines Work," page 2.

pressure of a gas is proportional to its static temperature according to the Ideal Gas Law as shown below.

$$PV = nRT \qquad \rightarrow \qquad P \propto T$$

Additionally, Diesel found that using fuel comprised of larger hydrocarbon molecules enabled a comparable internal combustion engine to reach much higher fuel compression ratios within the cylinders. As the Ideal Gas Law predicts, the higher pressures within the cylinders allowed the fuel to reach much higher temperatures before self-igniting. Instead of implementing a spark plug to ignite the fuel at lower temperatures like in a gasoline engine, Diesel designed his engine to compress the fuel until self-ignition occurred at high temperatures. He found that the higher pressures within the engine cylinders and higher temperature of the compressed fuel-air mixture led to higher fuel efficiency during output[19] and patented his new engine to make use of his finding. Today, diesel engines still operate with higher compression ratios than gasoline engines, and remain more thermally efficient than their gasoline counterparts. The average compression ratios of gasoline and diesel engines are shown below in Table 3.[20]

	Gasoline	**Diesel**
Average Engine Compression Ratio	8:1 to 12:1	14:1 to 25:1

Table 3: Average Compression Ratios of Gasoline and Diesel ICEs

Between the higher combustion temperatures and thermal efficiency within a diesel ICE and the high energy density of diesel fuel, diesel automobiles have better energy efficiency

[19] Brain, "How Diesel Engines Work," page 4.
[20] Brain, "How Diesel Engines Work," page 2.

ratings and are estimated to be 30-to-35% more fuel efficient than comparable gasoline vehicles.[21]

The high compression ratios of diesel engines also affects the power of the engine, which we can again explain using a Thermodynamic relationship. When a gas is compressed, its internal potential energy increases and, as a result, its ability to do work also increases according to the equation below.

$$W = -\int_{Vi}^{Vf} PdV = -P\Delta V$$

For internal combustion engines, higher compression ratios and internal pressures increase the change in pressure during the compression stroke, which in turn increases the mechanical work that will be released during the down stroke of the piston. The amount of work (or energy) the pistons convey to the crankshafts and wheels is referred to as the torque created by the engine. As a result, diesel engines have higher torque outputs than gasoline engines. The torque of a vehicle is often advertised as a selling point of large trucks containing diesel engines, but its meaning is often misunderstood. In practice, the greater torque output of a diesel engine allow it to start moving and reach higher speeds while under greater loading.[22] As a result, diesel engines are most commonly used in large commercial vehicles like delivery trucks and construction vehicles. In fact, over 94% of the world's freight is transported by diesel-fueled boats, trucks, or trains.[23]

Diesel fuel requires less refining than gasoline to meet engine specifications because diesel standards allow it to contain a wider range of hydrocarbon lengths than gasoline. Until

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[21] "Diesel Vehicles."
[22] Wickell
[23] Brain "How Diesel Engines Work," page 4.

recently, diesel fuel cost less than gasoline in the United States on a per gallon basis. Because diesel fuel undergoes less refining than gasoline, the supplier's relative savings on procuring and processing are often passed on to the consumer by way of a lower price per gallon. However, demand for diesel fuel has risen dramatically in developing countries in recent years because of the ability to procure it cheaply for large generators and machinery. This sudden increase in customer demand has allowed diesel suppliers to increase diesel fuel prices worldwide, to the extent that diesel fuel has become more expensive than gasoline in the United States.[24] A comparison of United States diesel and gasoline prices over the last 15 years is shown in Figure 6 below.

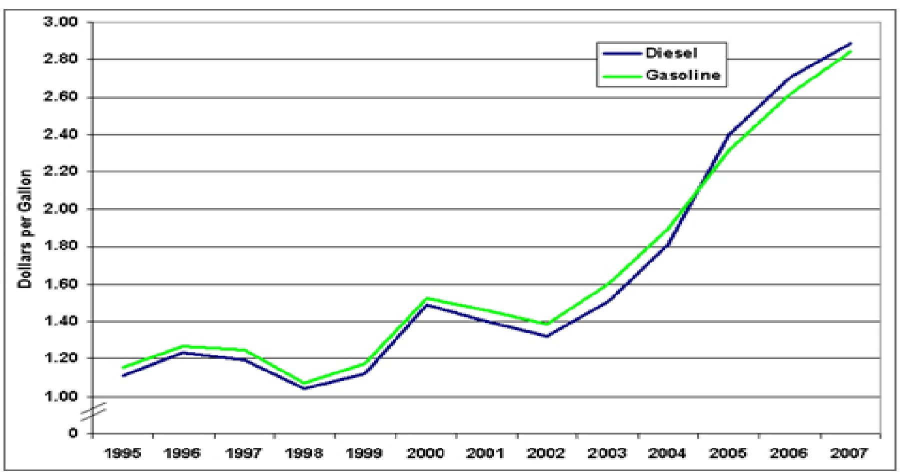

Figure 6: Diesel and Gasoline Price per Gallon in the United States

Source: http://www1.eere.energy.gov/vehiclesandfuels/facts/2008_fotw512.html

Though diesel costs per gallon have risen in recent years to be on par with gasoline costs, diesel fuel still provides the consumer more bang for the buck than gasoline because of its high energy density. When comparing diesel and gasoline costs on a cost-per-unit-energy basis, diesel fuel actually costs up to 50% less than gasoline per kilowatt of energy produced.[25]

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[24] Brain "How Diesel Engines Work," page 4.
[25] "Why Use Diesel? Advantages and Benefits."

However, the mechanical efficiencies of diesel engines are often overlooked due to the negative perceptions of diesel fuel and its environmental impact. Most Americans have found themselves behind a diesel-fueled truck on the road at some point, and most can therefore recall the smelly, dark clouds of exhaust expelled by the trucks at regular intervals. Because diesel hydrocarbons are larger than gasoline hydrocarbons, there is a higher likelihood of the molecules only partially combusting within the ICE during operation. As a result, diesel engines exhaust much higher amounts of partially combusted impure hydrocarbon particles known as soot.[26] Soot particles exhausted from diesel engines typically are classified into three categories: large, coarse, and fine.[27] Large soot particles and coarse soot particles vary in size, but are typically classified as such only if they're about ten microns in diameter.[28] Large and coarse soot particles are the most benign of the three sizes; they can be inhaled by humans and can cause coughing, throat and nose irritation, and allergic reactions until expelled from the body. In rare cases, coarse soot particles collect in the throat and cause increased irritation. However, fine soot particles of about 2.5 microns in diameter pose the biggest health risks to humans. Particles that size are small enough to be inhaled directly into the lungs and settle in the lungs alveoli (air sacs).[29] Once lodged in the alveoli, soot particles can inhibit the oxygen exchange function of the lungs and cause increased strain on the heart and lungs. Medical studies have shown that inhalation of soot particles can increase one's risk of chronic bronchitis, asthma, and respiratory infections. Additionally, diesel soot is a major contributor to atmospheric smog, or air pollution, in urban and developing areas. In 2000, the California Air Resources Board estimated that about 70% of the state's risk of cancer from airborne particulate matter and toxins could be attributed

[26] Monahan
[27] Monahan
[28] Monahan
[29] Monahan

to diesel soot and smog.[30] Table 4 below shows the Clean Air Task Force's estimated health problems attributable to diesel soot inhalation.

Adults		Children	
21,000	Premature Deaths	15,000	Asthma ER Visits
27,000	Non-Fatal Heart Attacks	29,000	Acute Bronchitis
410,000	Asthma Attacks	330,000	Lower Respiratory Symptoms
12,000	Chronic Bronchitis	270,000	Upper Respiratory Symptoms
2,400,000	Work Loss Days (WLD)		
14,000,000	Minor Restricted Activity Days (MRAD)		

Table 4: 2010 Projected Diesel Soot Impact on Health

Source: http://www.catf.us/projects/diesel/dieselhealth/national.php?site=0

Figure 7 below shows the areas of the United States deemed "high-risk" areas of diesel pollution by the Clean Air Task Force.

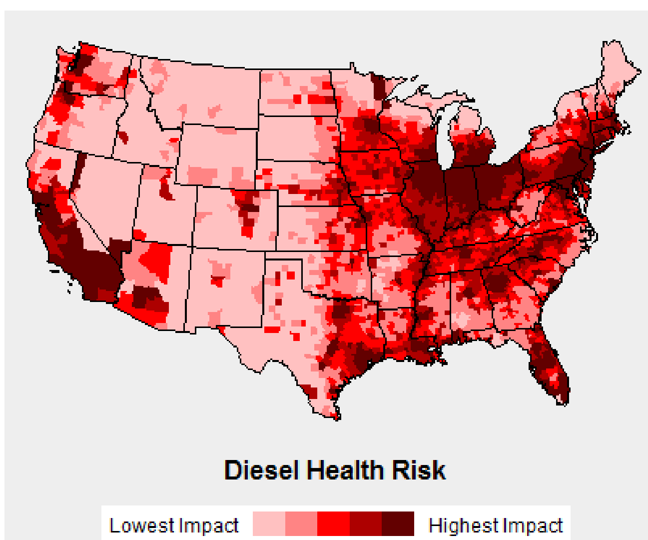

Figure 7: Diesel Pollution in High-Risk Areas

Source: http://www.catf.us/projects/diesel/dieselhealth/

30 Monahan

Figure 8 compares the number of annual deaths in the United States that are deemed premature as compiled by the Clean Air Task Force.

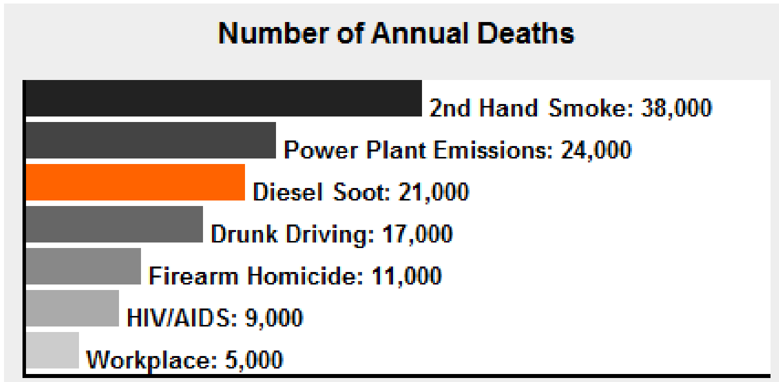

Figure 8: Annual Premature Deaths in the United States, By Cause

Source: http://www.catf.us/projects/diesel/dieselhealth/national.php?site=0

In addition to soot particles, diesel engines also emit high amounts of nitrous oxides and sulfur dioxide. Though sulfur dioxide and some types of nitrous oxides are not major contributors to the greenhouse effect, they are two of the major man-made chemical contributors to increasing acid rain levels worldwide.[31] Though not as mainstream as global warming and the greenhouse effect, acid rain continues to pose environmental problems all over the globe. Typically, acid rain causes damage to man-made structures and plant life by constantly bombarding them with corrosive compounds that are typically not found in the atmosphere. Though pure water has a neutral pH of 7.0, natural rain often has a pH of about 5.6 due to small amounts of mild carbon-based acids that naturally occur in the atmosphere.[32] However, when man-made sulfur dioxide and nitrous oxides are exhausted into the atmosphere, they react with water vapor as shown in the chemical equations below.

[31] Dowdey, page 1.
[32] Dowdey, page 2.

$$H_2O + SO_2 \rightarrow H_2SO_4 \quad \text{(Sulfuric acid)}$$

$$H_2O + NO_x \rightarrow HNO_3 \quad \text{(Nitric acid)}$$

The resulting sulfuric and nitric acids are very strong, highly corrosive acids that can significantly lower the pH levels of the rain in the atmosphere. Acid rain, defined by pH levels of 5.0 of lower, has been attributed to many different ecological and environmental problems since being identified.[33] Acid rain causes the most harm in aquatic ecosystems, as it can effectively wipe out large populations of important plant-life and eggs. Additionally, large nitrogen deposits from acid rain aid the growth of large algae colonies that often consume much of the water's consumable oxygen.[34] On the positive side, diesel fuels actually emit less carbon dioxide and carbon monoxide than their gasoline counterparts.[35] Below, Table 5 shows the annual emissions of various chemical compounds by diesel engines, including nitrous oxides (NO_X), soot particles (PM2.5 (fine) and PM10 (large/coarse)), carbon monoxide (CO) and sulfur dioxide (SO_2).

Pollutant	Annual Tons per Year	Highway (on road)	Heavy Equipment (non road)
NOx	4,513,102	2,872,333	1,640,769
PM2.5	231,634	88,306	143,328
PM10	250,687	102,383	148,304
CO	1,747,701	915,523	832,178
VOC	363,555	176,806	186,749
SO2	268,372	74,424	193,948

Table 5: Annual Diesel Emissions of Various Chemical Compounds

Source: http://www.catf.us/projects/diesel/dieselhealth/national.php?site=0

[33] Dowdey, page 2.
[34] Dowdey, page 2.
[35] Brain, "How Diesel Engines Work," page 4.

2.1.3 Biodiesel Vehicles

- Biodiesel is produced from renewable sources such as plant oils and animal fats
- Most blends work with existing diesel ICEs
- Emits fewer greenhouse gases than diesel fuel during operation
- More expensive than diesel and gasoline
- Pure biodiesel vehicles are available in limited quantities and models

As the environmental concerns surrounding diesel fuels and diesel ICEs have mounted, scientists and engineers have developed an alternative, cleaner form of diesel fuel known as biodiesel. Biodiesel is typically made from different types of plant oils, though animal fats can also be used.[36] In a transesterification process, the glycerin groups of the oil (chemically, a triacylglycerol) are separated from the rest of the molecule, leaving behind what is known as methyl esters. The glycerin groups can be salvaged and sold for use in other manufactured products like soap, while the methyl esters are collected for use as biodiesel.[37] There are literally hundreds of natural sources for tricylglycerols, and many of them are renewable and non-toxic. Commonly, biodiesel is created using soybean, cottonseed, or canola oils grown specifically for biodiesel production. However, some of the other possible sources for methyl esters include mustard seed oil, sunflower seed oil, rapeseed oil, chicken fat, fish oil, waste vegetable oil, and certain types of algae.[38]

In addition to its ability to be created from a variety of different sources, biodiesel also can be blended with standard diesel fuel without a loss of effectiveness. Industry standard dictates that any biodiesel blend be designated with a ‘Bxx’ classification; accordingly, B100

[36] Hess, page 1.
[37] "Biodiesel 101."
[38] Hess, page 2.

refers to 100% pure biodiesel made from natural oils, while B40 refers to a blend of 40% biodiesel and 60% standard diesel fuel.[39] One of the major advantages of biodiesel is its ability to be used instead of standard diesel in modern diesel ICEs. Today, the most modern diesel engines can run any type of biodiesel-blended fuel, all the way up to B100. Older diesel ICEs often require blended biodiesel because of possible fuel filter issues and clogging problems; however, studies have shown that any biodiesel blend up to B20 can be used in any existing diesel engine in proper working condition.[40]

Because procurement methods for biodiesel fuels can be fairly expensive, blending biodiesel with standard diesel yields a cleaner fuel than typical diesel with a lower cost-per-gallon than a B100 biodiesel. As of early 2010, a B20 blend is commonly offered as the best compromise of efficiency, environmental benefits, and cost to the consumer.[41] However, many have pointed out biodiesel's potential for reducing (or even eliminating) the United States' dependence on foreign oil. The United States currently imports close to 60% of its petroleum, and a major switch to biodiesel fuels would greatly reduce the country's spending on imported oil and increase domestic employment opportunities in the biodiesel sector. Currently companies and agencies within the United States employ 51,893 people involved in the biodiesel industry, and some estimate that the number of jobs could rise to over 78,000 by 2012 with appropriate emphasis and growth. All told, these jobs and industries have added more than $4.287 billion dollars to the country's Gross Domestic Product.[42] However, many of these biodiesel-induced jobs are in the research and development sectors. The fueling and servicing infrastructures

[39] Hess, page 2.
[40] *Biodiesel Commonly Asked Questions*
[41] *Biodiesel Commonly Asked Questions*
[42] "Benefits of Biodiesel"

needed to sustain large quantities of biodiesel vehicles is simply not available yet. In all of the United States, only North Carolina has more than 100 biodiesel fueling stations.[43]

Not every monetary aspect of biodiesel is a positive for the consumer. Biodiesel is more expensive than other ICE fuel types. Below, Table 6 compares the prices of the different types of ICE fuel.

	Gasoline	**Diesel**	**B2/B5 Blend**	**B20 Blend**	**B100**
Cost per Gallon (as of 10/2009)	\$2.44	\$2.54	\$2.55	\$2.69	\$3.08

Table 6: Comparison of Fuel Costs for ICE Vehicles

Source: http://tonto.eia.doe.gov/oog/info/wohdp/diesel.asp

Another major benefit of biodiesel is its reduced negative impact on the environment. Because biodiesel is created using plant and animal byproducts and not petroleum, biodiesel is a fully renewable energy source. Additionally, biodiesel-powered engines typically run cleaner than standard diesel-burning engines. Unlike standard diesel, biodiesel contains only trace amounts of sulfur, which limits the subsequent formation of sulfuric acid in the atmosphere.[44] Additionally, the use of biodiesel results in a significant reduction of unburned hydrocarbons, carbon monoxide and particulate matter (soot) when compared to standard diesel.[45] Figure 9 and Table 7 below show the impact biodiesel blends can have on the emission of a variety of harmful chemical compounds.

[43] "Alternative and Advanced Fuels"
[44] "Benefits of Biodiesel"
[45] "Benefits of Biodiesel"

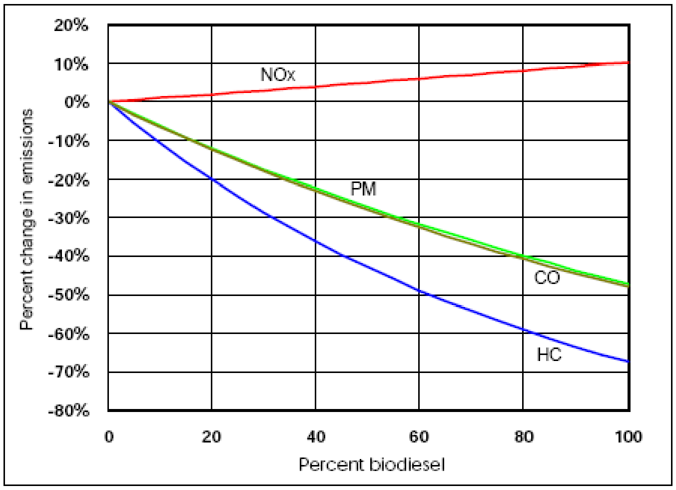

Figure 9: Average Emission Impacts of Biodiesel versus Diesel for Heavy-Duty Highway Vehicles

Source: http://dumpongbiofuels.org/biodie2.gif

Emitted Particles	*Change in Emissions versus Standard Diesel Fuel*	
	B20	**B100**
Nitrous Oxides (NO_X)	+2%	+10%
Particulate Matter (Soot)	-12%	-47%
Carbon Monoxide (CO)	-12%	-48%
Hydrocarbons (HC)	-20%	-67%
Sulfates (SO_X)	-20%	-100%

Table 7: Change in Emissions for Biodiesel versus Standard Diesel Fuel

Source: http://auto.howstuffworks.com/fuel-efficiency/alternative-fuels/biodiesel3.htm

Additionally, biodiesel has many smaller environmental positives. As its name suggests, biodiesel is biodegradable, and degrades at a rate of four times as fast as conventional diesel fuel.[46] Also, biodiesel is non-toxic to human beings and other plant and animal life. These two factors combined make biodiesel much less harmful in the event of a tanker spill or massive fueling station leak. In fact, during a 2000 EPA test, biodiesel was the only alternative fuel to

[46] Hess, page 4.

complete the Clean Air Act and EPA required health effects. The results of these tests showed that biodiesel greatly reduced all types of emission-related illness and health problems in humans.[47] It also has a higher flashpoint than conventional diesel fuel, so it is even more unlikely that a biodiesel reserve will accidentally combust during transport or in storage.[48]

However, for all of the positive aspects of biodiesel from an environmental standpoint, it fails to measure up to standard diesel in terms of energy content. Table 8 below compares the energy contents of the different ICE fuel types.

	Gasoline	**Diesel**	**B2 Blend**	**B20 Blend**	**B100**
Energy per Gallon Combusted	125,000 BTU	147,000 BTU	129,276 BTU	127,259 BTU	118,296 BTU

Table 8: Energy Content for Different ICE Fuels

Source: http://auto.howstuffworks.com/fuel-efficiency/alternative-fuels/biodiesel3.htm

As a result of the reduced energy content of biodiesel, there is a reduction in miles per gallon associated with higher percentages of biodiesel blend. Table 9 below gives the average reduction in miles per gallon for biodiesel users.

	% reduction in miles/gallon
20% biodiesel	0.9 - 2.1
100% biodiesel	4.6 - 10.6

Table 9: Fuel Economy Impacts of Biodiesel Use over Diesel Use

Source: http://www.afdc.energy.gov/afdc/vehicles/emissions_biodiesel.html

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[47] "Benefits of Biodiesel."
[48] Hess, page 4.

2.2. Electric Vehicles

Instead of relying on an ICE to power the vehicle solely with mechanical energy, electric vehicles run on electrical energy using battery packs, electric motors, and some unique charging and storing technologies that have evolved greatly over the last ten years. There are two basic types of electric vehicles currently being designed and produced by the United States automotive industry companies; hybrid-electric vehicles (HEVs) and fully-electric vehicles (FEVs).

2.2.1 Hybrid-Electric Vehicles

- Hybrid-electric vehicles combine internal combustion engine and electric components
- Hybrids are produced in different configurations to fulfill different specifications
- Plug-in models allow battery charging with limited ICE use
- Produce fewer greenhouse gas emissions than comparable ICE vehicles
- Currently available for sale in United States and increasing in popularity

Though sometimes assumed to be fully-electric vehicles, hybrid-electric vehicles are powered by a combination of an electric motor and an internal combustion engine. In practice, hybrid-electric vehicles are meant to bridge the gap between standard combustion engine vehicles and fully-electric vehicles; hybrid-electric vehicles offer more range than fully-electric vehicles by supplementing the battery power with an ICE, but typically produce less pollution and are more environmentally friendly than ICE vehicles.[49]

Hybrid-electric vehicles are classified into one of two categories based on their usage of their partnered power systems. In a series hybrid-electric vehicle (SHEV), the electric motor supplies power to the drive train to propel the vehicle forward. An ICE provides mechanical and

[49] Sperling, page 100.

thermal energy that is transferred into the electric motor. The electric motor and other systems then transform the mechanical and thermal energy into electromagnetic potential energy, or electricity. This electricity is either sent directly to the electric motor for immediate use, or diverted to a battery pack and stored for later use.[50] A SHEV configuration allows the ICE to run at a constant speed and power to generate electricity until the vehicle's battery is fully charged, at which point the ICE turns off.[51] In a parallel hybrid-electric vehicle (PHEV), both the ICE and the electric motor are connected independently to the drive train of the vehicle. This design allows the electric motor to supply additional power to the drive train and assist the ICE in propelling the vehicle.[52] As the electric motor does not provide the only source of power to the drive train, the electric components play a significantly smaller role in the vehicles operation than they do in a SHEV. This reduced role of the electrical components allows them to be scaled down in size, reducing manufacturing costs and freeing up space for other car systems.[53] Schematics of SHEV and PHEV configurations are shown in Figure 10 below.

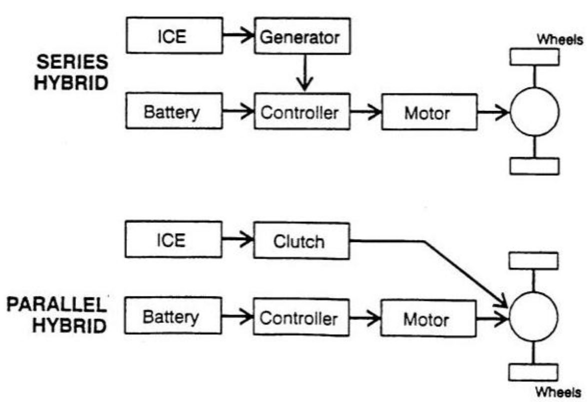

Figure 10: Schematics of Series and Parallel Hybrid-Electric Vehicle Configurations

Source: Sperling, page 103.

[50] Sperling, page 104.
[51] Sperling, page 104.
[52] Sperling, page 103.
[53] Sperling, page 103.

In addition to the different configurations of the ICE and electric motors, hybrid-electric vehicles are also classified into three additional categories based on the relative power of their electrical components. Range-extended battery hybrids have the largest electric motors of any HEV, with a typical 100 kilowatt motor and multiple battery packs. This range-extended configuration allows the vehicle to travel a maximum of about 50 zero-emissions highway miles before engaging the auxiliary ICE.[54] Range-extended battery hybrids also carry an auxiliary 10 kilowatt engine that can add an additional 50 miles of zero-emissions travel; however, it cannot be used to sustain highway speeds.[55] Dual-mode hybrids, like range-extended battery hybrids, have a maximum zero-emissions range of about 50 highway miles. However, dual-mode hybrids are equipped with a larger 40 kilowatt auxiliary engine to allow the vehicle to travel at higher speeds than a comparable range-extended hybrid.[56] When the electrical power stored in the batteries runs out, the dual-mode hybrid also contains a larger ICE to extend vehicle travel (although it no longer operates with zero emissions). Finally, fueled engine-electric hybrids are designed to utilize an ICE to generate all of the electricity used on board the vehicle.[57] Fueled-engine electric hybrids cannot operate in fully-electric mode for extended periods of time, and as a result, they do not qualify as zero-emissions vehicles because the ICE is constantly running to generate electricity.[58]

Though most hybrid-electric vehicles generate electricity onboard, a new hybrid type called the plug-in hybrid-electric vehicle has been developed in recent years using technologies originally intended for fully-electric vehicles. Plug-in hybrids are fully capable of generating electricity onboard like other types of hybrids, but they are also configured to charge their battery

[54] Sperling, page 102.
[55] Sperling, page 102.
[56] Sperling, page 102.
[57] Sperling, page 102.
[58] Sperling, page 102.

packs by plugging into an electric grid using a regular wall outlet.[59] Plug-in hybrid-electric vehicle batteries are currently being designed to be charged by a minimum potential of 120 volts, or the voltage typically running through the wall outlets in a house or office building. Most homes have outlets with larger voltage drops (such as 240 volts) to run large appliances like washers and dryers. Similarly, large office buildings use high-voltage outlets to provide the necessary electricity for their information technology systems. This means that, ideally, a typical plug-in hybrid owner would be able to plug in his vehicle and charge it fully in the comfort of his own garage while he sleeps. Such a charging system would limit lengthy fueling times associated with charging large battery packs at refueling stations and increase the user-friendliness of plug-in hybrids. Additionally, some alternative energy companies have claimed that they have the ability to construct and operate 480 volt charging stations that would be open for public use similar to today's gas stations. These specialized charging stations would reduce the charge time for a typical battery pack from up to 12 hours on 120 volts to around 20 minutes on a 480 volt grid.[60] As a result of their unique charging methods, plug-in hybrid-electric vehicles do not consume as much gasoline during normal operation as other types of hybrid-electric vehicles, making them a very popular, environmentally friendly option. A diagram of a PHEV and its components is show below in Figure 11.

[59] "Plug-In Hybrids."
[60] Lange

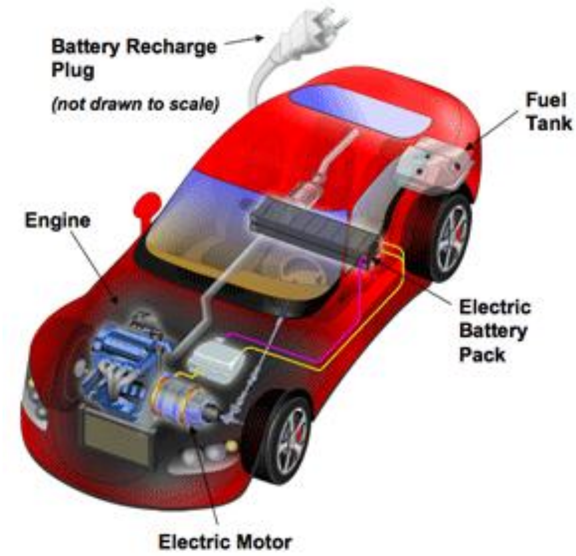

Figure 11: A Diagram of a Plug-in Hybrid-Electric Vehicle

Source: http://www.peopleandplanet.net/doc.php?id=3468

Due to the reliance on electrical components and battery packs to store energy, most modern hybrid-electric vehicles now contain a revolutionary energy-saving system called a regenerative braking system. During regular operation of a vehicle, almost 80% of the energy generated by the fueling system is dissipated during braking due to friction losses between mechanical components, tires, and the road surface.[61] Regenerative braking systems allow the wheels of the HEV to recapture up to half of the heat lost during braking and use it to generate electricity. This electricity is then stored in the vehicle's battery packs to be used to power the car later. During typical use, the addition of regenerative braking systems to HEVs has been shown to result in a reduced fuel consumption of up to 25%.[62] A schematic of a regenerative braking system is shown below in Figures 12 and 13.

[61] Lampton, page 6.
[62] Lampton, page 6.

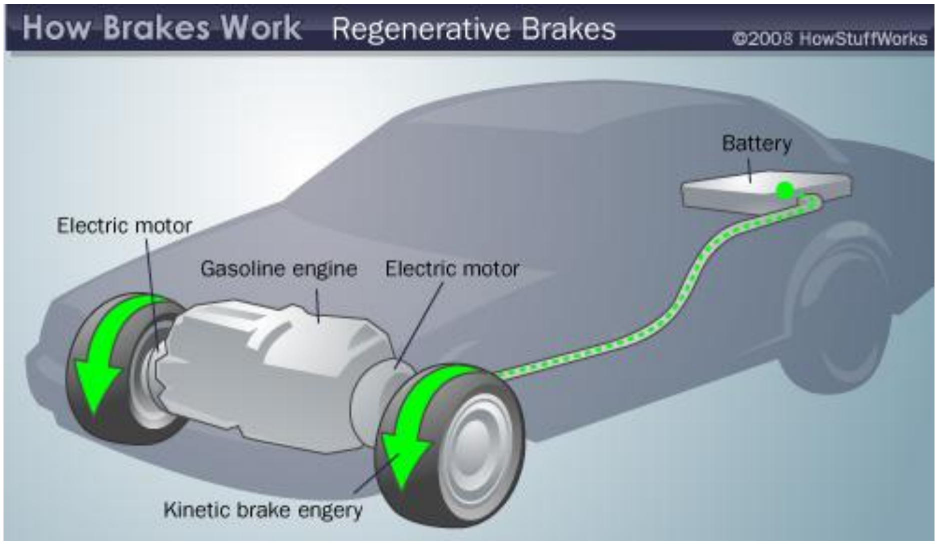

Figure 12: Diagram of a Regenerative Braking System

Source: http://auto.howstuffworks.com/auto-parts/brakes/brake-types/regenerative-braking6.htm

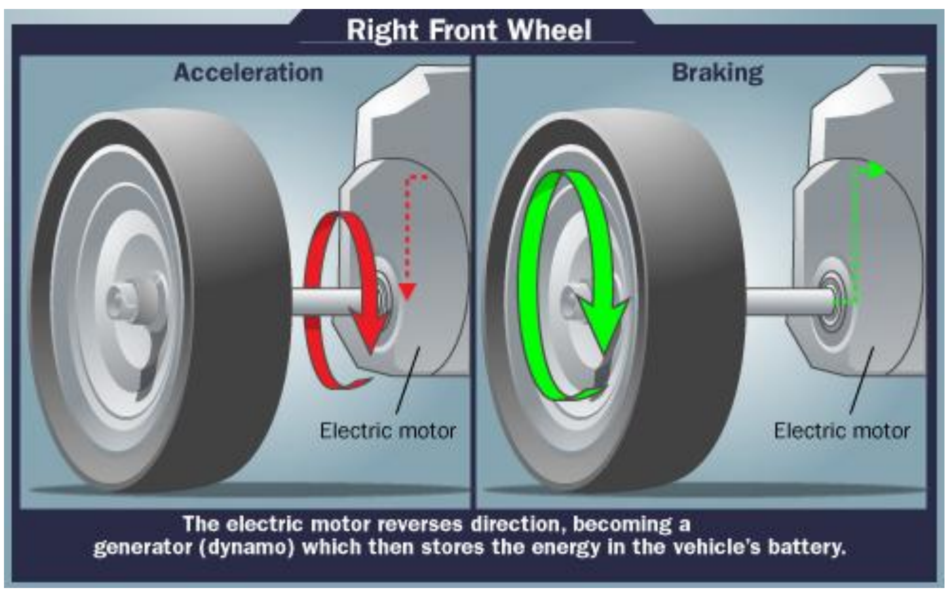

Figure 13: Wheel Action during Regenerative Braking

Source: http://auto.howstuffworks.com/auto-parts/brakes/brake-types/regenerative-braking6.htm

Because hybrid-electric vehicles do not rely on an ICE for the entirety of their power deliverance, the ICE can be downsized accordingly. In a typical car powered solely by an ICE, the engine must be large enough to provide the maximum power needed to accelerate the car at its highest rate. When an electric motor supplements the power supplied by the ICE in today's

HEVs, the more energy efficient electric motor can be used to provide the additional power during vehicle acceleration, and the ICE can be designed to handle the vehicle's average required power. This in turn makes the hybrid's ICE more energy efficient as it runs at lower speeds and wastes less energy increasing and decreasing its power outputs.[63] As a result, the constant use of an ICE within a limited range of speeds allows HEVs to drastically reduce their greenhouse gas emissions.[64]

2.2.2 Fully-Electric Vehicles

- Fully-electric vehicles are powered by electric components only
- Produce zero emissions during operation
- Charged using standard electric wall socket from home or office
- Offer possibility of entirely renewable, green energy using renewable electricity generated by solar, wind, geothermal or hydro power
- Multiple designs currently being developed for widespread release

Like hybrid-electric vehicles, fully-electric vehicles rely on a steady flow of electrical energy to power the car. However, fully-electric vehicles have a major environmental advantage over hybrid-electric vehicles in terms of exhaust and emissions. Though most fully-electric vehicle prototypes contain a small, emergency ICE that can be engaged during a battery failure, prototypical fully-electric vehicles do not generate electricity with their ICEs during normal operation. All of the energy needed for the vehicle's typical operation cycle is stored in the

[63] Sperling, page 107.
[64] Sperling, page 107.

battery packs by hooking the car up to a 240 or 480 volt outlet.[65] As a result, a typical fully-electric vehicle emits zero greenhouse gases as exhaust.[66]

For years, the concept of a fully-electric vehicle has been circulating around the automotive industry. However, since the introduction and subsequent discontinuation of General Motors' EV1 in the 1990s, a major limiting factor on the usability of fully-electric vehicles has been the battery packs. General Motors developed the EV1 to be powered using lead-acid battery packs. Lead acid batteries, though relatively inexpensive to produce, have a low energy density compared with other comparable battery options.[67] They can also be environmentally hazardous due to their reliance on lead and must be disposed of in hazardous waste management sites. The EV1 was also configured to operate using optional nickel-metal hydride (NiMH) battery packs. Though nickel-metal hydride batteries are more efficient and safer than lead-acid batteries, they are also more expensive.[68] During the 1990s, the cost of nickel-metal hydride batteries was considered too high to realistically include in electric vehicles. In recent years, many different technological innovations have required intense research into the area of battery technology. As a result, efficient and environmentally friendly battery packs that are suitable for use in electric vehicles are finally becoming affordable enough to warrant their inclusion in the next generation of electric vehicles.

Currently, the standard for efficient, safe, and reliable battery packs is being set by various types of lithium-ion (Li-ion) batteries. Lithium-ion batteries offer a few advantages over lead-acid and nickel-metal hydride batteries. Lithium-ion batteries lose their stored charge at a slower rate than nickel-metal hydride and lead-acid batteries, and do not need to be fully

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[65] Lange
[66] Brain, "How Electric Cars Work," page 1.
[67] "EV1 Specs"
[68] "EV1 Specs"

discharged to allow maximum charging efficiency. However, lithium-ion battery packs can be ruined if they are completely discharged.[69] Additionally, the low mass of the lithium and carbon atoms used to construct the battery electrodes allows the lithium-ion battery packs to retain high energy densities while remaining light-weight. They can store up to typical maximum of 150 watt-hours of electrical energy per kilogram of battery, compared to 70 watt-hours per kilogram for nickel-metal hydride batteries, and a lowly 25 watt-hours per kilogram for lead-acid batteries.[70] A graphical comparison of the energy densities of these battery types is shown below in Figure 14.

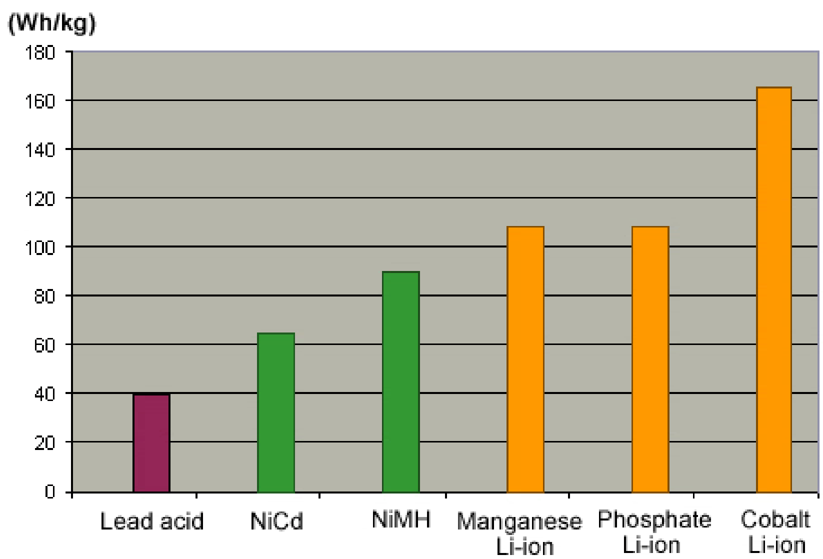

Figure 14: Average Energy Density of Different Electric Vehicle Battery Types

Source: http://www.metaefficient.com/wp-content/uploads/lifepo4-energy-weight-comparison-of-different-battery-types.gif

As battery technology increases and efficient batteries like lithium-ion battery packs become more affordable, electric vehicles will become more affordable as well, and likely increase their market share accordingly. This fact would seem to immediately signal the potential

[69] Brain. "How Lithium-Ion Batteries Work," page 1.
[70] Brain. "How Lithium-Ion Batteries Work," page 1.

dominance of fully-electric vehicles in the automotive market. However, there are a few major disadvantages to fully-electric vehicles that stunt their growth today. Currently there is a serious lack of infrastructure in place for the servicing and maintenance of fully-electric vehicles. Though many fully-electric vehicle proponents tout the ease of charging a fully-electric by connecting it to one's home power supply, little action has been taken to provide drivers with the appropriate public charging stations. In the United States, there are fewer than 500 charging stations for fully-electric vehicles, compared to over 117,000 gas stations. Additionally, many of these charging stations are closed to public use, leaving drivers of fully-electric vehicles stranded when their batteries run dry in the middle of a road trip.[71] The automobile's incredible popularity growth during the early-to-mid 20th century occurred in part as a result of the driver's freedom to travel to any corner of the United States and not be left stranded without a gas station nearby. It seems unlikely that fully-electric vehicles will begin to rise in popularity until a sufficient infrastructure is in place to provide consumers with maintenance, repairs, and precious electricity.

Unfortunately, the source of this precious electricity is another large flaw in the plan of transitioning to fully-electric vehicles. Though the fully-electric vehicles themselves would run without emissions, the electricity generated to charge the vehicles would, in most cases, still be generated using fossil fuels. Over 66% of the world's electricity is produced using the same fossil fuels that fully-electric vehicles avoid, including 68% of the United States' yearly electricity.[72] These non-renewable, greenhouse-gas-emitting generating processes partially negate the "green" aspect of fully-electric vehicles. The percentages of electricity derived from various fuel types are shown below in Figure 15.

[71] Lange
[72] Davis

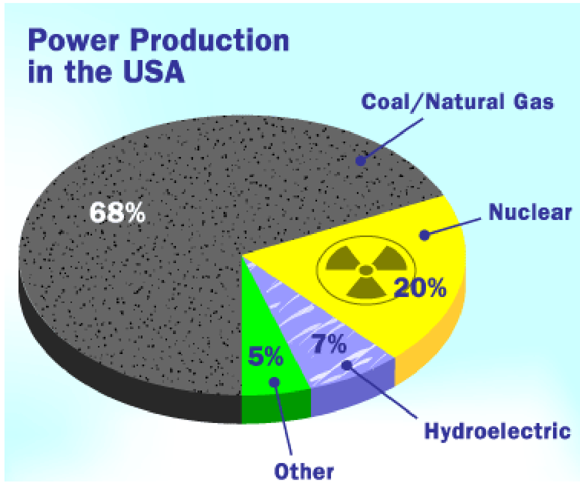

Figure 15: United States Electricity Generation by Source

Source: http://auto.howstuffworks.com/fuel-efficiency/fuel-economy/hydrogen-economy1.htm

The use of fully-electric vehicles would still have positive environmental impacts, regardless of the processes used to generate their electricity. Most power plants and other massive electrical generators in the United States are located outside of urban centers and cities. The air pollution in these high-population areas results more from automobile exhausts than from waste created by generators. The transition to fully-electric vehicles would greatly reduce air pollution in these cities by dramatically cutting emissions of reactive organic compounds such as carbon dioxide and nitrogen oxide.[73] Of course, there are many alternate ways to generate electricity without the use of fossil fuels: hydro-power, wind power, geothermal power and solar power have all experienced rises in popularity over the past decade, and their continued development provides hope for the supporters of clean fully-electric vehicles. The elimination of fossil fuel electrical power plants would also eliminate any discussion of indirect pollution caused by fully-electric vehicles. For every mile of use, gasoline vehicles emit an average of one pound of carbon

[73] Sperling, page 44.

dioxide gas. In comparison, a fully-electric vehicle would be able to drive a mile on electricity produced by coal that produces 0.8 pounds of carbon dioxide gas, a 20% reduction.[74] Using renewable sources, the carbon dioxide emissions of fully-electric vehicles would be entirely eliminated. However, regardless of the energy sources, wide use of fully-electric vehicles will certainly reduce the impact of automobile pollution in critical, high-population areas across the United States.

2.3 Hydrogen Fuel Cells Vehicles

- Powered using hydrogen gas, which must be derived from fossil fuels or other hydrocarbon or chemical compound
- Hydrogen fuel cells emit water vapor during operation, and do not emit any greenhouse gases
- Prototypical designs are currently being developed; at present, extremely limited availability and extremely high retail price

Hydrogen fuel cell vehicles are the newest and most novel technology poised to make a push for consumer applications in the automotive industry. A fuel cell is an electrochemical energy conversion device that generates electricity via a chemical reaction (often aided by a catalyst) that takes place within electrodes.[75] It is important to note that there are many different types of fuel cell technologies, and subsequently many different types of hydrogen fuel cells. Typically, though the specifics of the parts may differ, hydrogen fuel cells contain the same important parts. The catalyst is a substance that causes or speeds up a chemical reaction without

[74] Lange
[75] "A Basic Overview of Fuel Cell Technology."

itself being affected.[76] In a hydrogen fuel cell, the catalyst is located between the two segments of the electrode, and facilitates the oxidation-reduction reactions[77] of the hydrogen and oxygen gases within the electrodes. An electrode conducts an electric current into or out of the fuel cell.[78] All electrodes are made up of two distinct components; the anode and the cathode. In a hydrogen fuel cell, the anode contains injected hydrogen gas which is forced into contact with the catalyst (usually platinum).[79] Contact with the catalyst causes the H_2 molecules to oxidize and split into H^+ ions (essentially a free proton) and free electrons. These free electrons are conducted into an electrical circuit running from the anode to the cathode. This movement of electrons creates electrical energy that is then used to power an engine or generator. At the same time, a similar process occurs at the cathode on the other side of the fuel cell. The cathode contains oxygen gas, and like the hydrogen gas, the oxygen is pressurized and forced into contact with the catalyst. This contact reduces the O_2 gas and creates O^{2-} ions, which are strongly electronegative and attract the positively charged protons created in the anode. The H^+ ions pass through the electrolyte and, combined with free electrons conducted through the circuit, bond with the O^{2-} ions to create water molecules. This water is then exhausted from the electrode, and the process continues.[80]

An electrolyte is a chemical compound that conducts ions from one electrode to the other inside a fuel cell.[81] In chemistry, an electrolyte can be used to conduct positive or negative ions, depending on the chemical composition of the electrolyte. All modern hydrogen fuel cells that

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[76] "Fuel Cells: Glossary of Terms."
[77] "Oxidation and Reduction."
[78] "Fuel Cells: Glossary of Terms."
[79] “A Basic Overview of Fuel Cell Technology.”
[80] Nice, page 3.
[81] "Fuel Cells: Glossary of Terms."

are widely used contain electrolyte that will only conduct positively charged ions.[82] This ensures that only the positive H^+ ions freed within the anode will pass through the electrode, while the negative O^{2-} will remain within the cathode. Thus, the electrolyte ensures that the driving chemical reactions that generate power within the fuel cell will occur in the correct locations.

There are many different styles of hydrogen fuel cells used in commercial applications. The type of fuel cell being used in most current prototypes and the most well suited fuel cell for small consumer uses (like automobiles)[83] is the polymer electrolyte membrane fuel cell, or PEMFC.[84] PEMFCs are also sometimes referred to as proton exchange fuel cells or polymer exchange fuel cells; these names are purely aesthetic differences, as all refer to the same type of fuel cell.[85] Like all of the previously mentioned fuel cell types, PEMFCs generate electricity by chemically reacting hydrogen and oxygen gases together with the aid of a catalyst and an electrolyte. Pressurized hydrogen gas is forced through the platinum-plated catalyst, which causes the two electrons to separate from the hydrogen gas molecule, resulting in two H^+ ions (protons) and two free electrons. The free electrons are conducted through the anode; the process of conducting electrons through an anode and into a circuit creates the electrical current and allows useful electrical work. In the cathode, oxygen gas is forced through another platinum catalyst, which causes the diatomic molecule to break into two O^{2-} ions. These highly negative ions attract the free protons, which pass through the solid polymer electrolyte. The circuit with electrons flowing from the anode passes through the cathode, and two electrons join with the O^{2-}

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[82] Nice, page 3.
[83] Lee, page 175.
[84] Nice, page 2.
[85] "Collecting the History of Proton Exchange Membrane Fuel Cells."

and H^+ to form a complete water molecule. The water is then exhausted, and the process continues.[86] A diagram of a PEMFC is shown below in Figure 16.

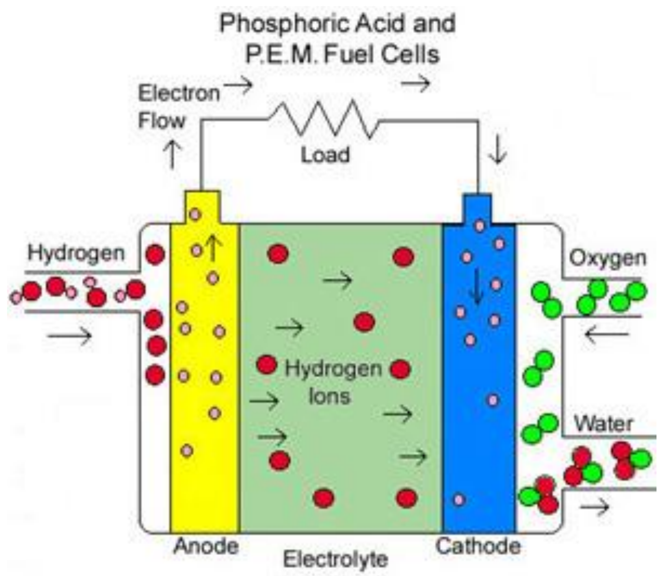

Figure 16: Diagram of a Proton Exchange Membrane Fuel Cell

Source: http://americanhistory.si.edu/fuelcells/basics.htm#q1

At peak performance, a PEMFC can produce between 50 and 250 kilowatts of power at 50 percent efficiency.[87] The major advantages of the PEMFC are twofold. First, the typical operating temperature of a PEMFC is about 175 degrees Fahrenheit[88], which is actually slightly lower than the average car combustion engine temperature of 200 degrees Fahrenheit.[89] Secondly, the PEMFC uses a solid electrolyte, which cannot leak like the liquid electrolytes used in AFCs, MCFCs, and PAFCs. Additionally, the special polymer electrolyte is extremely flexible and resists warping at the relatively low temperature at which the PEMFC operates.[90] These factors combine to make the PEMFC the premier fuel cell solution for consumer automobiles.

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[86] Nice, page 3.
[87] "A Basic Overview of Fuel Cell Technology."
[88] "A Basic Overview of Fuel Cell Technology."
[89] "How does the thermostat in a car's cooling system work?"
[90] "A Basic Overview of Fuel Cell Technology."

Like all energy producing methods, hydrogen fuel cells have their own unique advantages and disadvantages. The most widely publicized advantage of hydrogen fuel cell technology is the lack of harmful pollutants created as exhaust, and this is certainly true of most fuel cell designs.[91] Consumer and industrial hydrogen fuel cells rely on oxygen and hydrogen gases as the chemical fuels that drive the generation of power, and as described above, these reactions create water as their only product. This gives hydrogen fuel cells a large advantage over conventional fossil fuel combustion engines, coal plants, or any other process that generates greenhouse gases. However, the belief that the water produced by hydrogen fuel cells is truly harmless to the environment is incorrect. Though water is non-toxic to humans and commonly viewed as innocuous, water vapor is actually the largest contributing gas to the greenhouse effect in Earth’s atmosphere.[92] On the positive side, water vapor is less toxic to plant and animal life than the other main contributors produced by fossil fuels.[93] Additionally, the water created by a hydrogen fuel cell can be recovered and used for a variety of applications whereas the more harmful products of fossil fuels are less useful (and therefore less likely to be recovered before entering the atmosphere). During the Gemini and Apollo programs, NASA engineers developed a method to recover the water produced by the chemical reaction and use it as drinking water for the astronauts within the spacecraft.

A typical hydrogen fuel cell is more mechanically and thermodynamically efficient than a comparable combustion engine or nuclear power system. Unlike gasoline and diesel ICEs, hydrogen fuel cells are not restricted to a maximum efficiency by the previously mentioned Carnot’s Theorem because hydrogen fuel cells do not generate mechanical power using a

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[91] "Advantages & Benefits of Hydrogen and Fuel Cell Technologies."
[92] Kiehl, page 203.
[93] Kiehl, page 203.

thermal energy process. Hydrogen fuel cells use chemical reactions to generate an electrical current, which an electric motor converts into mechanical energy. This electrical-mechanical conversion still experiences some thermal losses due to resistance in the circuit, but their overall efficiency greatly exceeds that of a combustion or nuclear process. In fact, the least efficient hydrogen fuel cell models run at close to 50 percent efficiency, or more than twice that of a combustion engine. In addition to these two major reasons, there are a variety of other advantages to hydrogen fuel cells; they run quietly and vibration-free, are extremely reliable and responsive to variable electric loads, and are easily modified to adapt to different applications and specifications.[94]

However, there are three major obstacles standing between hydrogen fuel cells and the majority of the market share. The first is the extremely high cost of manufacturing and maintaining a hydrogen fuel cell. In a standard PEMFC, about 70 percent of the cost of manufacturing is divided among the proton exchange membranes (electrolytes), platinum catalyst, gas diffusion layers, and electrode plates.[95] Unfortunately, the cost of these 4 components currently exceeds the projected (and desired) costs of a PEMFC suitable for a mass-manufactured consumer vehicle.[96] Independent studies have found that hydrogen fuel cell systems must cost around $35 per kilowatt to be competitive with the costs of a comparable gasoline engine. As of early 2010, the projected high-volume production price for a PEMFC suitable for use in an automobile is $73 per kilowatt, or more than twice the desired price.[97] Research is ongoing for ways to reduce the cost of the fuel cells; finding an alternative for the

[94] "Advantages & Benefits of Hydrogen and Fuel Cell Technologies."
[95] Dresselhaus, page 56.
[96] Dresselhaus, page 56.
[97] Nice, page 6.

platinum used as a catalyst continues to be the most likely area for cost-cutting changes.[98] Obviously, it will be difficult for a hydrogen fuel cell powered vehicle to be competitive on the automobile market if the price is considerably higher than that of a comparable gasoline powered vehicle.

Another major obstacle for hydrogen fuel cell vehicles to overcome is the problem of creating a stable, permanent and sustainable infrastructure to service and power hydrogen fuel cell vehicles. Just as gasoline vehicles would be useless without the more than 115,000 gas stations in the United States[99], hydrogen fuel cell vehicles need a solid refueling and servicing infrastructure to become a popular vehicle choice. Currently, there are fewer than 100 hydrogen fueling stations in the United States, and many of them are not open for public use; additionally, many of the currently operating stations cannot pressurize the hydrogen gases to levels needed for more than about 70 miles of continuous travel.[100] In a way, this issue is almost a chicken-and-egg quandary. Hydrogen fueling stations are unlikely to be opened by businessmen due to a lack of cars to support and provide services for. However, hydrogen fuel cell vehicles are unlikely to catch on until the consumer believes there will be an adequate support infrastructure for his new automobile. Many methods have been suggested for encouraging the introduction of the needed infrastructure, but for now it still remains underdeveloped.

Lastly, though hydrogen is the most abundant element in the universe, it does not exist in its elemental form on Earth.[101] As a result, the hydrogen gas needed to power a hydrogen fuel cell must be produced from another compound containing hydrogen. In one process, called fossil fuel reforming, a fuel processor (or reformer) chemically splits the fossil fuel hydrocarbon

[98] Nice, page 6.
[99] United States Census Bureau. *A Gas Station for Every 2,500 People*
[100] Priddle.
[101] Arnett.

(natural gas or gasoline) to produce hydrogen gas (H_2) and carbon dioxide (CO_2).[102] The hydrogen gas is recovered and stored for use in a fuel cell, and the carbon dioxide is often released into the atmosphere as waste. The waste carbon dioxide sticks out as the major problem of fossil fuel reforming; producing an extremely common greenhouse gas in an effort to create "clean" hydrogen fuel contradicts the mission statement of many green energy proponents and consumers. Another major downside of fossil fuel reforming is its production of hydrogen gas does not decrease our dependence on non-renewable fossil fuels. Electrolysis of water can also be used to create hydrogen and oxygen gases out of water by running an electric current through it.[103] Electrolysis remains a major area of study in hydrogen production, but the process is not very efficient for producing hydrogen gas. Many critics of hydrogen fuel cell technologies point out that using energy to produce hydrogen to be used as fuel somewhere else seems convoluted. Still, electrolysis backers claim that the process will become an important stepping stone to developing efficient, clean and sustainable methods for producing hydrogen gas needed to power hydrogen fuel cells.

[102] Brain, page 5.
[103] Brain, page 5.

Summary Table

Type	Power Type	Advantages	Disadvantages	Picture
Gasoline	ICE	-Widely available -Cheapest retail prices -Infrastructure in place	-Not environmentally friendly -Petroleum will eventually run out	
Diesel	ICE	-Widely available -Relatively inexpensive -Infrastructure in place	-Harmful to the environment -Potentially dangerous health effects	
Biodiesel	ICE	-Environmentally friendly -Used with diesel infrastructure -Renewable	-Relatively expensive -Lack of current fueling stations	
Fully-electric	Electric Motor	-Possibly fully clean/renewable energy -Battery technologies quickly improving	-Not currently mass-produced -Expensive -Possibly difficult to refuel	
Hybrid-electric	Electric Motor and ICE	-Relatively cheap -Environmentally friendly -Currently available	-Not as many model options as gasoline -Retail prices slightly higher than gasoline	
Hydrogen Fuel Cell	Fuel Cell	-Clean running -Possible renewable energy sources	-Expensive -Must manufacture fuel -Not currently mass-produced	

Table 10: A Brief Summary of Each Vehicle Type

3. Financial Analysis

When determining what car to purchase for financial reason, the consumer must weigh the up-front retail cost of the car itself, and the future costs of ownership of the car. The data presented in this section and in the appendix reflects these costs based on the automobile market in the United States in 2009.

When determining the cost of ownership of a vehicle, the most crucial criterion to be accounted for is the life expectancy of the vehicle. The life expectancy of the vehicle is directly involved in determining the costs that constantly accumulate over the lifetime of the vehicle. Life expectancy of a vehicle is commonly expressed in terms of miles driven so that it can be easily used to determine the amount of fuel consumed by the vehicle. A vehicle's life expectancy is often used to calculate the cost of insuring the vehicle over the period of use and estimate the amount of money that will be spent on maintenance and repairs. In this report, the life expectancy of an average vehicle driven in the United States used to calculate costs is 150,000 miles.[104] Additionally, according to the EPA's Fuel Economy Guide, the average driver in the United States travels about 15,000 miles per year in his primary vehicle.[105] Therefore, the life expectancy in years of the same average vehicle driven in the United States is ten years. These numbers are summarized below in Table 11 below.

Average Vehicle Ownership Time	Average Miles Driven Annually	Average Vehicle Life Expectancy
10 years	15,000 miles	150,000 miles

Table 11: Average Vehicle Ownership Time, Miles Driven Annually and Life Expectancy

[104] Weisbaum
[105] "Fuel Economy Guide" U.S. Department of Energy. 2009.

Though every unique vehicle model and design has its own maintenance, repair and energy-use trends, we obviously could not compare the costs of ownership of every single car sold in the United States in a reasonable manner. To simplify the analysis, we calculated these costs for the highest selling vehicle models in the United States during the fiscal year of 2009 for each vehicle type.[106] In addition to the types already described, gasoline vehicles were further broken into two classes: large gasoline vehicles such as SUVs and pick-up trucks, and small gasoline vehicles such as sedans. However, the current consumer demand for gasoline vehicles in the United States greatly exceeds demand for, diesel, biodiesel, and hybrid cars. Additionally, there are very few hydrogen fuel cell vehicles and fully-electric vehicles available for wide consumer purchase because of their more recent development and lack of fully available infrastructure. As a result, after researching sales trends and press releases regarding upcoming vehicle prototypes, we added vehicles from these types at our own discretion. The vehicles analyzed in our report are listed in Table 12 below.

Most Popular Vehicles by Fuel Type	
Gasoline (Large)	***Hybrid-Electric***
Ford F-Series	Toyota Prius
Chevrolet Silverado	Honda Insight
Ford Escape	***Diesel/ Biodiesel***
Honda CR-V	Volkswagen Jetta/Golf TDI
Toyota RAV4	Audi A3 TDI
Gasoline (Small)	***Fully-Electric***
Toyota Camry / Solara	Chevrolet Volt
Toyota Corolla / Matrix	***Hydrogen Fuel Cell***
Honda Accord	Honda FCX Clarity
Nissan Altima	
Ford Fusion	

Table 12: Most Popular Vehicles by Fuel Type

[106] "Auto Sales - Markets Data Center"

3.1 Purchase and Tax Costs

- Suggested retail prices were obtained from manufacturer websites
- Estimated purchase tax costs were calculated using average national tax rate

To begin our financial analysis on the costs of ownership, we obtained the manufacturer's suggested retail price for each vehicle.[107] In most cases, the suggested retail prices are listed for the standard base model of each car with no feature packages or additional upgrades. The diesel and biodiesel vehicles are lumped together because the manufacturers do not distinguish between the fuel types when pricing diesel vehicles to be used with B5 or B20 blends. In two instances we had to define a unique retail price value. Firstly, as of the beginning of our analysis, the Honda FCX Clarity was only available for lease from the manufacturer, and not for outright purchase. As a result, we took the listed lease price per month for the Clarity and extrapolated the total cost for a consumer leasing the vehicle for the average life expectancy of ten years. Though the average gasoline vehicle lease would not last the entire lifetime of the vehicle, the FCX Clarity's lease must be continually renewed for each period of ownership. Thus, to operate the same vehicle for ten years, the lease must be paid in full for the entire period of use. Secondly, as of the beginning of our analysis, the manufacturer's suggested retail price of a Chevrolet Volt has not been announced. As a result, an estimated figure from for the possible

[107] Ford Motor Company. 2 December 2009 <http://www.ford.com/>.
Chevrolet. 2 December 2009 <http://www.chevrolet.com/>.
Honda Motor Company Inc. 2 December 2009 <http://www.honda.com/>.
Toyota. 2 December 2009 <http://www.toyota.com/>.
Nissan. 2 December 2009 <http://www.nissanusa.com/>.
Volkswagen. 2 December 2009 <http://www.vw.com/home.html>.
Audi. 2 December 2009 <http://www.audiusa.com/us/brand/en.html>.

cost of the Chevrolet Volt was used.[108] The average retail prices for the different vehicles analyzed are listed in Table 13 below.

Most Popular Vehicles By Fuel Type	Manufacturer's Suggested Retail Price
Gasoline (Large)	
Ford F – Series	$21,380.00
Chevrolet Silverado	$19,375.00
Ford Escape	$20,550.00
Honda CR-V	$21,545.00
Toyota RAV4	$21,500.00
Gasoline (Small)	
Toyota Camry / Solara	$19,395.00
Toyota Corolla / Matrix	$15,950.00
Honda Accord	$21,055.00
Nissan Altima	$19,900.00
Ford Fusion	$19,620.00
Hybrid-Electric	
Toyota Prius	$22,400.00
Honda Insight	$19,800.00
Diesel/ Biodiesel	
Volkswagen Jetta/Golf TDI	$ 22,660.00
Audi A3 TDI	$29,950.00
Fully-Electric	
Chevrolet Volt	$40,000.00
Hydrogen Fuel Cell	
Honda FCX Clarity	$72,000.00

Table 13: Manufacturer's Suggested Retail Prices of Most Popular Vehicles

[108] Valdes-Dapena

In most States in the United States, purchasing a vehicle incurs a sales tax that must be paid by the consumer.[109] The national sales tax average in the United States is 4.9%,[110] so each vehicle has an additional cost associated with it that is proportional to the suggested retail price of the vehicle. However, there is one exception; the United States government has declared that purchasing a Chevrolet Volt will enable the first 250,000 purchasers to redeem a $7,500 tax credit.[111] We included this in the final price as a negative number, as the tax cost would be effectively subtracted from the total lifetime cost. As of the writing of this report, the Volt is the only vehicle analyzed list to qualify for any purchase or tax credits from the United States government. The amount of tax to be paid by purchasers for each vehicle is listed in Table 14 below.

Most Popular Vehicles By Fuel Type	**Average Sales Tax**
Gasoline (Large)	*Dollars*
Ford F – Series	$1,047.62
Chevrolet Silverado	$949.38
Ford Escape	$1,006.95
Honda CR-V	$1,055.71
Toyota RAV4	$1,053.50
Gasoline (Small)	
Toyota Camry / Solara	$950.36
Toyota Corolla / Matrix	$781.55
Honda Accord	$1,031.70
Nissan Altima	$975.10
Ford Fusion	$961.38
Hybrid-Electric	
Toyota Prius	$1,097.60
Honda Insight	$970.20

Continued on next page…

[109] Valdes-Dapena
[110] Valdes-Dapena
[111] "Chevy Volt FAQs."

Diesel/ Biodiesel	
Volkswagen Jetta/Golf TDI	$1,110.34
Audi A3 TDI	$1,467.55
Fully-Electric	
Chevrolet Volt	$ -7,500.00
Hydrogen Fuel Cell	
Honda FCX Clarity	$3,528.00

Table 14: Average Sales Tax for Most Popular Vehicles

3.2 Fuel Costs

- Average cost of fuels based on national averages as of July 2009
- Separate fuel efficiencies were calculated for highway and city driving conditions and combined for an average fuel efficiency
- Fuel efficiencies were used to calculate total lifetime fuel usage and total fuel cost

The largest cost of ownership apart from the purchase costs of the vehicle is the cost of fuel over the lifetime of the vehicle. The prices of gasoline, diesel, and biodiesel per gallon were taken from July 2009 energy and fuel report published by the United States Department of Energy.[112] However, the prices of electricity and hydrogen were not listed in the report (likely due to the lack of mass-produced vehicles that utilize these types of energy). The price of electricity used in our analysis was obtained from a National Grid quote in Worcester, MA during January 2010. The cost of hydrogen fuel was taken from a hydrogen fueling station price listing from March 2006 and adjusted accordingly for inflation. The average cost of each type of fuel per unit is listed in Table 15 below.

[112] "Clean Cities Alternative Fuel Prices Report."

Fuel Type	Fuel Unit	Average Cost of Fuel per Unit
Gasoline	Gallon	$2.44
Diesel	Gallon	$2.54
Biodiesel (B2-B5)	Gallon	$2.55
Electricity	Kilowatt Hour	$0.08
Hydrogen	Kilogram	$5.30

Table 15: Average Cost of Fuel per Unit in the United States

The cost of fuel works in combination with the fuel economy of a vehicle to determine the total amount of fuel consumed during operation. The fuel economies for our selected vehicles were published in a report by the United States Department of Energy.[113] For each vehicle, the report listed two figures for mileage per gallon; city travel mileage (the lower value) and highway travel mileage (the higher value). In addition, the Department of Energy report stated that the percentage ratio of city driving to highway driving is 55% city to 45% highway.[114]

Fuel mileage figures for the Chevrolet Volt were not listed in the Department of Energy report because it will not be available until the 2011 model year. However, we determined the fuel economy of the Volt analytically. Chevrolet has announced that the Volt’s battery packs will allow the driver to drive up to 40 highway miles before the batteries are exhausted and the emergency ICE would be engaged.[115] If the driver drives fewer than 40 miles between recharges, he would theoretically never use his emergency ICE. As a result, he would never pay for gasoline, and the total cost of fuel over the lifetime of his vehicle would be purely a function of the price of electricity. Once a driver travels over 40 miles and passes the critical point, he would trigger the use of the Volt’s gasoline ICE, and Chevrolet has not announced how fuel efficient this component of the car will be. We assumed that the Volt’s ICE would be similar to auxiliary

[113] “Fuel Economy Guide.”
[114] “Fuel Economy Guide.”
[115] Valdes-Dapena

ICEs used in today's hybrid-electric vehicles. For the purpose of fully analyzing the Volt's fuel economy, we allowed for an ICE-aided efficiency estimate of 50 miles-per-gallon, and assumed that the driver would travel around 60 miles round trip in their daily commute to work (an average daily commute in the United States).[116] As a result, we arrived at a final estimated Volt fuel efficiency of 125 miles-per-gallon.

However, each unique vehicle that we analyzed can be equipped with various different engine types which each operate at different power and efficiency levels, which in turn produce different fuel efficiencies. To account for this possible discrepancy, the various engine fuel efficiencies were averaged together to form one final fuel economy for each of the vehicles analyzed. Our justification for allowing the use of different model engines while previously assuming the purchase of only the base model is twofold. Firstly, while there are only a few types of engine configurations for each vehicle, the other accessory packages that can be included vary greatly and could have a great impact on the pricing of the car. Secondly, the manufacturer's suggested retail price for each vehicle is a fixed value. However, the amount of fuel consumed by each engine varies according to the engine powering the vehicle. Finally, we calculated two values for the fuel economy of an individual vehicle: one for city driving, and one for highway driving. We also took the average economy of the car by averaging the city and highway efficiencies. The fuel economies used in our analysis for each vehicle are listed in Table 16 below.

[116] "Fuel Economy Guide."

Most Popular Vehicles by Fuel Type	**Fuel Efficiency**		
Gasoline (Large)	*City*	*Highway*	*Combined*
Ford F – Series	14.50	19.50	16.75
Chevrolet Silverado	14.50	19.00	16.53
Ford Escape	21.00	27.33	23.85
Honda CR-V	21.00	27.50	23.93
Toyota RAV4	20.25	27.00	23.29
Gasoline (Small)			
Toyota Camry / Solara	21.00	31.00	25.50
Toyota Corolla / Matrix	23.22	30.56	26.52
Honda Accord	20.14	29.43	24.32
Nissan Altima	20.13	28.00	23.67
Ford Fusion	20.67	29.33	24.57
Hybrid-Electric			
Toyota Prius	51.00	48.00	49.65
Honda Insight	40.00	43.00	41.35
Diesel/ Biodiesel			
Volkswagen Jetta/Golf TDI	30.00	41.50	35.18
Audi A3 TDI	30.00	42.00	35.40
Fully-Electric			
Chevrolet Volt	125.00	125.00	125.00
Hydrogen Fuel Cell			
Honda FCX Clarity	60.00	60.00	60.00

Table 16: Fuel Efficiencies for Highest Selling Vehicles

3.3 Insurance and Maintenance Costs

- Sample standardized insurance costs were illustrated using quotes for a model person
- Maintenance costs were calculated based on average maintenance and servicing spending over vehicle lifetime

Another crucial cost of ownership of a vehicle is the cost of automobile insurance. We calculated insurance costs for each individual vehicle using direct quotes from Geico, a popular national automobile insurance provider. In order to obtain quotes from Geico, we created a hypothetical model person with the following criteria, which remained the same for every quote. The hypothetical person was a 30 year old male named John Doe living at 100 Institute Road in Worcester, MA. The main use of his vehicle was stated to be commuting to work five days a week, with each one way trip being 30 miles long (which averages averaging to approximately 15,000 miles a year). We stated that John Doe started driving at age 16, and that he was neither a full-time student nor affiliated with the United States military and therefore did not qualify for the appropriate discounts. We stated that John Doe had been living in his current residence for five years, and that John Doe is married to Jane Doe, who in turn the only other driver of his vehicle. Like John Doe, Jane Doe was 30 years old, and had similarly been driving since age 16 and still had a valid license. Like her fictional husband, Jane was not a student or affiliated with the United States military. Neither John nor Jane had committed crimes before requesting the quotes. We stated that John had less than two weeks remaining with his current insurer on his current policy, and that he had been with his current insurer for less than a year with $50,000/$100,000 current bodily injury limits. Using this model person, we requested quotes for each vehicle as 2010 models with 0-99 miles on the odometer.

Geico did not have every vehicle we analyzed listed as quotable for insurance. The Chevrolet Volt and Honda FCX Clarity could not be quoted by Geico because of their rarity. We estimated that these cars would be quoted similarly to a Prius based on their relative present-day rarity and similar structures, so we accordingly substituted the Prius quote price for their insurance values. In reality, the insurance premiums for these vehicle types would likely be slightly higher than our estimates. The insurance premiums we calculated are listed in Table 17 below.

Most Popular Cars By Fuel Type	**Insurance Premium**
Gasoline (Large)	*Dollars Monthly*
Ford F - Series	$69.34
Chevrolet Silverado	$72.67
Ford Escape	$65.17
Honda CR-V	$75.67
Toyota RAV4	$77.42
Gasoline (Small)	
Toyota Camry / Solara	$72.09
Toyota Corolla / Matrix	$71.01
Honda Accord	$80.25
Nissan Altima	$89.00
Ford Fusion	$83.17
Hybrid-Electric	
Toyota Prius	$73.09
Honda Insight	$65.92
Diesel/ Biodiesel	
Volkswagen Jetta/Golf TDI	$73.00
Audi A3 TDI	$79.50
Fully-Electric	
Chevrolet Volt	$73.09
Hydrogen Fuel Cell	
Honda FCX Clarity	$73.09

Table 17: Average Insurance Premiums by Vehicle

The last major contributing factor for determining cost of ownership of a vehicle is the cost of maintenance and repair over the lifetime of the vehicle. The cost of maintenance over the lifetime of the car is approximately 9.3% of total cost of ownership.[117] The calculated costs of maintenance for each individual vehicle are listed in Table 18 below.

Most Popular Cars By Fuel Type	**Cost of Maintenance and Repair**
Gasoline (Large)	*Dollars*
Ford F - Series	$ 5393.30
Chevrolet Silverado	$ 5249.12
Ford Escape	$ 4585.75
Honda CR-V	$ 4817.02
Toyota RAV4	$ 4876.65
Gasoline (Small)	
Toyota Camry / Solara	$4444.84
Toyota Corolla / Matrix	$4004.28
Honda Accord	$4795.09
Nissan Altima	$4821.08
Ford Fusion	$4661.28
Hybrid-Electric	
Toyota Prius	$4064.52
Honda Insight	$3848.36
Diesel	
Volkswagen Jetta/Golf TDI	$4446.15
Audi A3 TDI	$5303.18
Biodiesel	
Volkswagen Jetta/Golf TDI	$4450.52
Audi A3 TDI	$5307.52
Fully-Electric	
Chevrolet Volt	$4696.02
Hydrogen Fuel Cell	
Honda FCX Clarity	$10002.25

Table 18: Maintenance and Repair Costs per Vehicle

[117] "What that car really costs to own."

3.4 Total Lifetime Costs

After calculating the costs for each individual spending area, we compiled a list of final cost of ownership over the lifetime of the vehicle by adding up the total costs for each vehicle. The final cost estimates for each vehicle are given below in Table 19.

Most Popular Cars By Fuel Type	Total Cost
Gasoline-Large	*Dollars*
Ford F - Series	$57,992.47
Chevrolet Silverado	$56,442.16
Ford Escape	$49,309.11
Honda CR-V	$51,795.93
Toyota RAV4	$52,437.14
Gasoline-Small	
Toyota Camry / Solara	$47,793.93
Toyota Corolla / Matrix	$43,056.73
Honda Accord	$51,560.07
Nissan Altima	$51,839.61
Ford Fusion	$50,121.27
Hybrid-Electric	
Toyota Prius	$43,704.52
Honda Insight	$41,380.23
Diesel	
Volkswagen Jetta/Golf TDI	$47,808.04
Audi A3 TDI	$57,023.44
Biodiesel	
Volkswagen Jetta/Golf TDI	$47,855.06
Audi A3 TDI	$57,070.16
Fully-Electric	
Chevrolet Volt	$50,494.82
Hydrogen Fuel Cell	
Honda FCX Clarity	$107,551.05

Table 19: Total Costs per Vehicle

Complete breakdowns of the costs for each vehicle are given in the appendix at the end of this report.

A graphical breakdown of the costs for each vehicle type is shown below in Figure 17. For this graph, we took the average costs of each vehicle type to make comparisons between vehicle types easier. The height of each bar gives the total lifetime cost of the average vehicle from that fuel type, and the separate sections of each bar indicate the relative portion of total cost devoted to each cost area.

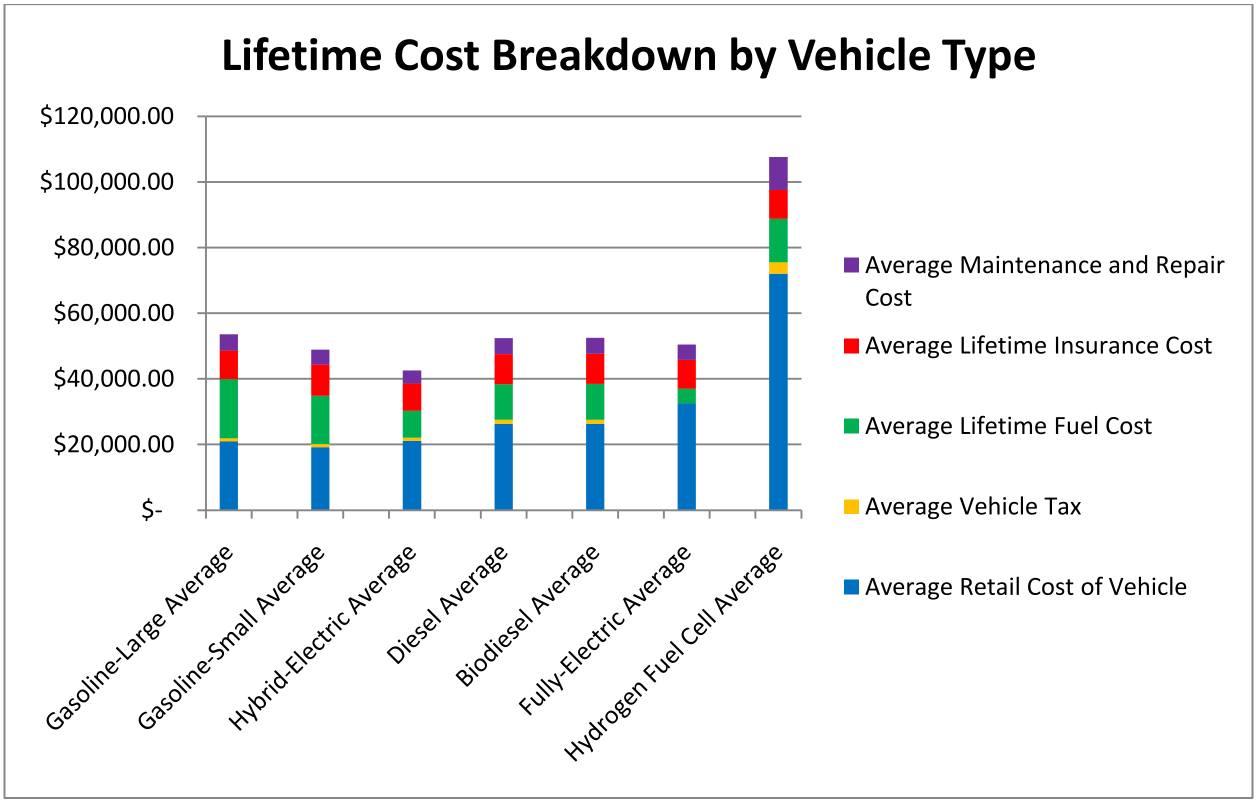

Figure 17: Lifetime Costs of Vehicles by Cost Area

4. Discussions and Conclusions

By combining our technical know-how with the financial constraints and limitations found during our analysis, we strove to develop meaningful conclusions that could be used for real life decision making and analysis. We believe that our findings can be used by consumers to help them determine the best vehicle purchase options for their unique situations.

4.1 Vehicle Choices for the Immediate Future

- Hydrogen vehicles are not an economically viable choice at this time
- Purchasing diesel fuel does not offer significant savings over purchasing biodiesel fuel
- Fully-electric vehicles cost more initially, but recover invested money by reducing lifetime fuel spending
- Hybrid-electric and gasoline vehicles are comparably priced over the average vehicle lifetimes
- Hybrid-electric vehicles will be more favorable if gasoline prices continue to increase

The analysis we carried out verifies the assumption that the retail and tax costs of a vehicle are definitely the largest contributors to the total lifetime cost of owning a vehicle. In all cases, the retail and tax costs make up at least 40% of the total costs. The lifetime cost of fuel is the next largest contributor to the total cost of a vehicle. For gasoline vehicles, the proportion of cost attributed to the fuel is higher than for any other vehicle type, especially for the case of large gasoline vehicles. We can attribute this to the poor energy efficiencies of internal combustion engines, as well as to the fairly high cost of gasoline and diesel at the present time. Though the insurance and maintenance costs are definitely significant investments when totaled over the lifetime of the car, our analysis shows that the consumer can expect to spend less in these areas than in the fuel and retail areas. We believe that the consumer should definitely consider the total cost of a vehicle prior to purchasing one, but the fact that the up-front costs of a vehicle are major portions of the total investment lends some support to the notion of buying a vehicle based purely on the price tag.

Our analysis shows that hydrogen fuel cell vehicles are not a financially sound purchasing option for typical consumers at this time. Hydrogen fuel cell vehicles are significantly more expensive over their lifetimes than comparable models from other vehicle categories. The hydrogen fuel cell car we analyzed, the Honda FCX Clarity, projects to cost up to twice as much as the average gasoline or hybrid car over the lifetime of the vehicle. The majority of the cost difference between Clarity and its competitors is the retail price. The Honda FCX Clarity costs nearly four times as much as an inexpensive gasoline sedan based on retail price alone. Even when we add up the total lifetime cost of the other vehicle types, the Honda FCX Clarity's total lease cost exceeds the lifetime costs of any other vehicle type. Of course, the high retail price of the Clarity is partially a function of the lack of current demand for it and the relatively small production lot sizes in which they are produced, and we expect the price of hydrogen fuel cell cars to drop in the future. However, they are simply not smart investments at this time due to the excessive costs associated with them.

Our analysis shows very small differences in total lifetime costs between diesel and biodiesel vehicles. Since most modern diesel ICEs can also run on biodiesel blends, most vehicle manufacturers do not make a distinction between diesel vehicles and biodiesel vehicles. As a result, there is no difference in the suggested retail price of a diesel and biodiesel vehicle when comparing popular models. Similarly, the costs associated with maintenance, repair, and insurance are nearly identical due to the lack of unique components. When calculating the fuel cost of biodiesel, we assumed that the average biodiesel consumer would purchase the cheapest form of biodiesel available to them, similar to how most gasoline-vehicle drivers use regular grade gasoline. As a result, even the fuel costs between diesel and biodiesel users were nearly identical based on current diesel and B5 prices. We can conclude that there is virtually no downside to purchasing biodiesel for one's diesel vehicle, as the total amount of money saved over the lifetime of the car is less than $100 if diesel is purchased instead of biodiesel at the current price. When considered with respect to the overall investment in the vehicle made by the consumer, a $100 dollar savings is relatively small, to the point where we cannot deem it statistically significant due to our assumptions. Combined with the positive environmental ramifications of biodiesel use over diesel use, biodiesel is definitely the better option.

The fully-electric Chevrolet Volt is definitely an interesting financial option for consumers. If Chevrolet stands by its word and prices the Volt around the reported $40,000 figure, the Volt will definitely be financially competitive in the automobile market. Many critics of Chevrolet have pointed out that the low-end retail prices suggested by their press releases are still much higher than comparable gasoline and hybrid-electric vehicles. However, we again would encourage critics to examine the bigger picture and consider the total ownership cost of the Volt. The United States government's tax credit for purchasers of the Chevrolet Volt effectively reduces the cost of purchasing a Volt by $7,500. Though the purchase cost would definitely be higher than a comparable gasoline vehicle, the cost of electricity needed to power the Volt for a typical commuter is a third of the cost of gasoline for comparable driving, and less than half of the cost of fuel for comparable hybrids. Consumers who are not financially constrained should consider purchasing a fully-electric car in the near future, as the difference in the initial investment will definitely be recovered in fuel savings over the vehicle's lifetime.

However, the concern over fully-electric infrastructure and servicing support takes away from the allure of a Volt. The lack of electric charging stations severely hinders the consumer friendliness of fully-electric vehicles for the near future.

Maybe the most important conclusion that can be drawn from our analysis is the financial implications of the gasoline and hybrid-electric competition. In the competition between the old stalwart gasoline vehicles and the up-and-coming alternative hybrids, each side continues to push for financial superiority for the consumer. Arguments persist over the costs associated with each car, so our comprehensive analysis of the costs of each will surely be helpful to those deciding between the two options. Our data shows that the difference in total cost over the lifetime of a typical commuter sedan (a small gasoline car, or typical modern hybrid) is relatively small. Though the average lifetime cost of the hybrids we analyzed is less than the average lifetime cost of the gasoline vehicles we analyzed, we found that at least one gasoline vehicle (the Toyota Corolla) that is effectively equal in cost to the hybrid competitor (the Toyota Prius). Our calculated difference in cost between these two vehicles is about $650 dollars, which we cannot consider a significant difference based on the estimates involved in our calculations. For the most part, our analysis shows that hybrid-electric and gasoline vehicles are effectively even in the cost department based on present data.

The major financial concern for gasoline vehicle owners going forward is the fluctuation in the cost of gasoline. In recent years, the price of gasoline has risen from under $2 per gallon to over $4 per gallon, and dropped back down again. Interestingly, the fact that our analysis shows that hybrids and gasoline vehicles cost nearly the same amount of money on average is a result of the current state of the cost of gasoline. Using the fuel economy numbers and fuel costs we found, we calculated what we call the critical cost of gasoline. If gasoline is very inexpensive, gasoline vehicles clearly have the financial advantage over hybrids because of the low cost for fuel being paid by the consumers. However, as gasoline prices rise, the difference in costs gets smaller and smaller. At a certain critical point, when gasoline becomes too expensive, the hybrid car begins to cost less over the lifetime of the vehicle than the comparable gasoline car due to the high amount of money being paid by the driver to fill his tank. This critical cost of gasoline, where the costs of both vehicle types intersect, was calculated to be between $2.40 and $2.70 per gallon, depending on the vehicles compared. So, if the price of gasoline dropped significantly below this critical cost, the fuel costs of gasoline vehicles would drop significantly as well, and push gasoline cars ahead in the total cost department. If gasoline prices increase significantly and greatly exceed this critical cost, the total cost of fueling a gasoline vehicle would skyrocket, and severely impact the financially appeal of gasoline vehicles. This critical cost of gasoline is very close to the current cost of gasoline, which explains why our cost analysis for hybrid and gasoline vehicles yielded such similar results. Based on the current trends in gasoline pricing and the world economy surrounding the petroleum business, we believe that we can safely assume that the cost of gasoline will not fall much below its current level in the coming years. As a result of this, it seems that the cost of gasoline will never fall far enough below this critical cost to make gasoline vehicles truly the cheaper option. Conversely, as the cost of gasoline rises, hybrid-electric vehicles will continue to become more cost-effective than their gasoline counterparts. We conclude that hybrid-electric vehicles will be the wisest vehicle purchase for the average consumer over the next few years based on the financial benefits of these vehicles.

4.2 Possible Future Considerations

- Petroleum-based vehicles will likely become obsolete due to dwindling oil reserves and reduced consumer support due to environmental impacts
- Biodiesel vehicles will likely supplant diesel vehicles for commercial and industrial applications
- Electric vehicles offer the best combination of low ownership costs and environmental friendliness
- A plug-in, range extended hybrid-electric vehicle would fill the travel needs of most drivers, limit the environmental impact of vehicle use, and be financially reasonable for most consumers

Unfortunately, not all consumer decisions can be made without future considerations. As mentioned earlier, a typical automobile sold and operated in the United States remains in use for about ten years. Consumers who are taking steps to ensure the proper vehicle choice for them would be remiss if they merely shopped based on the vehicle's present financial advantages. To truly be able to grasp the entire scope of an automobile choice and purchase, the future viability and probability of continuation of use must also be considered. The financial implications of each must be weighed against the environmental concerns and the technical possibilities of safe, efficient travel associated with each vehicle type. After considering all of these factors, we have found that the best choice for the continued development and support of the United States automobile industry is the electric vehicle. The electric vehicle has very few downsides if developed and implemented correctly, whereas there are definite problems or uncertainties associated with each other vehicle type.

The largest obstacle for gasoline-powered vehicles to overcome in the future is dwindling petroleum reserves. World petroleum consumption has increased exponentially over the past century due to booming populations and increased world industrialization. As a result, petroleum reserves that were once thought of as unlimited supplies have begun to dry up due to increased demand for extraction and production. Accurately estimating the amount of oil left to be extracted is an incredibly difficult task, but the fact that petroleum is a non-renewable resource and will eventually run out is unavoidable. Many technologies that rely on petroleum based fuels for power face uncertain futures that will hinge on the amount of petroleum remaining to be extracted. For gasoline powered vehicles, the finite limit to the amount of petroleum we can harvest from the Earth certainly indicates that gasoline cars will eventually become obsolete as petroleum becomes scarce. The uncertainty associated with the limit of usable petroleum should greatly reduce the demand for gasoline vehicles in the future, as consumers would be wise to avoid investing in a technology that could soon be obsolete. The scarcity of gasoline in the future will also continue to increase the price of gasoline, and this expected increase in cost will lessen the financial advantages of gasoline vehicles. Additionally, the increasing world-wide interest in and pursuit of clean energy and renewable resources will continue to reduce the support for gasoline vehicles. Hybrid-electric vehicles have already started to chip away at the foundation of gasoline vehicle dominance, and the rise of alternative fuels will continue to hurt the success of gasoline cars.

Like gasoline vehicles, diesel vehicles also face the problem of limited petroleum reserves. However, diesel-powered vehicles fill a niche in the automobile marketplace that gasoline vehicles cannot. As described previously, diesel fuel contains more energy per unit volume than gasoline, and diesel engines have higher compression ratios than gasoline engines.

The resulting increases in mechanical power and torque for diesel-powered vehicles make diesel vehicles ideal for high-weight commercial transportation. None of the considered vehicle types have greater torque outputs than diesel-powered vehicles, which will likely cause diesel vehicles to remain viable even longer than their gasoline counterparts. As petroleum begins to become a rare commodity and the automobile industry shifts away from petroleum-based technologies, it is likely that diesel trucks and heavy vehicles will remain operable due to their efficiency at transporting goods. Still, the environmental problems associated with diesel fuels would need to be addressed. It is likely that the United States would need to adopt stricter policies regarding the refinement and purity of diesel fuels similar to those enforced in Europe to lessen the impact of continued diesel usage. Though the price of diesel may increase as a result, the cost of fuel would likely pale in comparison to the cost associated with abandoning diesel vehicles for commercial use. Of course, perhaps the best way to eliminate most of the environmental hazards of diesel fuel and still employ them for commercial use would be to switch to biodiesel fueled vehicles. As mentioned previously, most diesel ICEs can operate using diesel-biodiesel blends, which would eliminate many possible issues with upgrading existing diesel vehicles. Though biodiesel blends do not contain as much energy per unit volume as typical diesel fuel, the high compression engines and existing infrastructure would help to promote biodiesel as a viable successor to the less environmentally friendly diesel fuel.

Hydrogen fuel cell vehicles are the vehicle type with the most uncertain future prospects. The environmental friendliness of hydrogen fuel cell vehicles is certainly an upside of their possible mainstream usage. However, there are two major issues yet to be resolved that will hinder the popularity of hydrogen fuel cell cars. First, the lack of suitable infrastructure for simply cannot be understated as an issue. Unlike the other vehicles examined, hydrogen fuel cell vehicles would require a nearly complete overhaul of the existing vehicle infrastructures in place. Unlike diesel and gasoline vehicles, which have large oil corporations and even entire countries backing them, there are no multi-billion dollar industries eager to support the fueling stations and delivery systems for hydrogen cars at this time. Secondly, the production of hydrogen would require huge investments of both time and money to solve the problem of providing enough fuel to power a massive fleet of hydrogen vehicles. The inefficient production methods themselves also limit the feasibility of hydrogen usage. However, in recent years companies and research laboratories that work on developing hydrogen fuel cell technology have received large grants from many governmental and non-profit organizations, including the United States government. It's possible that the large public backing of hydrogen fuel cell technology will continue to slowly but surely push hydrogen vehicles into the public's hands.

With all of these uncertainties surrounding other technology types, the electric car stands out as the one stable possibility for vehicle technology in the future. Electric vehicles are clean-running, energy efficient, environmentally friendly, and are on the cusp of being widely available to consumers at reasonable prices. The advantages of electric vehicles have already been discussed; however, there are many types of electric vehicles and many possible ways for them to become main stream. We believe that there are steps that should be taken to ensure that the implementation of electric vehicles and everything they require will be as cost-friendly, environmentally-friendly, and smooth as possible.

First, we believe that the ideal electric vehicle configuration should be similar in design to a range-extended, plug-in hybrid-electric vehicle. Though first instinct might suggest that fully-electric vehicles would be the best choice because they do not rely at all on petroleum products, we believe that the above configuration would make the transition away from gasoline-powered vehicles as smooth as possible. In a perfect world, there would be no resistance to the switch to electric vehicles by gasoline vehicle owners. However, with 243 million vehicles on the road, it is unlikely that every car owner would be willing to give up their current vehicle. Additionally, we find it unlikely that diesel or biodiesel vehicles will be eliminated because of the commercial and industrial reliance on these powerful vehicles. These two complications imply that the need for some sort of liquid fuel (likely petroleum based) will never truly be eliminated. There will always be demand for some sort of minor petroleum-based infrastructure and support in the United States, and the range-extended hybrid configuration would allow the electric vehicles of the future to capitalize on this fact and utilize an ICE as an emergency power system. Vehicle owners would retain the peace of mind that they have come to associate with their gasoline powered cars, but the environmental damage done by each car would be nearly eliminated. Ideally, the auxiliary ICE would be powered with pure biodiesel to completely eliminate the automobile industry’s reliance on petroleum and make the vehicle as environmentally friendly as possible.

Of course, the main draw of this suggested configuration is the plug-in electric aspect. Plug-in electric vehicles produce no emissions of any kind during operation, which cannot be said for even the cleanest running gasoline or diesel car. However, in order for fully-electric vehicles to be truly environmentally friendly, the electricity used to charge them must come from clean, renewable sources. Though much of the world’s electricity is currently generated using fossil fuel products, green energy technologies that harness solar, wind, geothermal, and water power are constantly being developed and improved. We believe that investments into these clean energy technologies would be more beneficial to the environment than investments in hydrogen technologies because they could be applied to many aspects of life. Manufacturers of electric vehicles would be able to pool resources with other businesses interested in energy generation and technology, which would likely increase the investment in clean, affordable technologies like electric vehicles. Electric vehicles offer the best synergy between all types of technological developments and their applications to the automobile sector, and we believe they will become the dominant vehicle type in the United States in the future.

Appendix

Average Life Expectancy of a Vehicle in Miles
150,000.00
Driving Distance Per Year
15,000.00
National Tax Rate
4.90%

Fuel Type	Average Cost of Fuel/Unit
Gasoline (per gallon)	$2.44
Diesel (per gallon)	$2.54
Biodiesel (B2-B5) (per gallon)	$2.55
Electricity (per kilowatt-hour)	$0.08
Hydrogen (per kilogram)	$5.30

Individual Vehicle Lifetime Cost Breakdowns

Key:

<table>
<tr><th rowspan="2">Vehicle</th><th>Manufacturer Retail Price of Vehicle</th><th>Average Tax</th><th colspan="3">Vehicle Fuel Efficiency</th><th>Total Fuel Consumed</th></tr>
<tr><td>Dollars</td><td>Dollars</td><td>City</td><td>Highway</td><td>Combined</td><td>Per Unit</td></tr>
<tr><th>Total Fuel Cost</th><th colspan="3">Insurance Premium</th><th>Cost of Maintenance and Repair</th><th>Total Cost of Vehicle</th><th>Cost Per Mile Driven</th></tr>
<tr><td>Dollars</td><td>Dollars Monthly</td><td>Dollars Yearly</td><td>Dollars Total</td><td>Dollars</td><td>Dollars</td><td>Dollars</td></tr>
</table>

Gasoline – Large

Ford F-Series	**Manufacturer Retail Price of Vehicle**	**Average Tax**	**Vehicle Fuel Efficiency**			**Total Fuel Consumed**
	$21,380	*$1,047.62*	*14.50*	*19.50*	*16.75*	*8955.22*
Total Fuel Cost	**Insurance Premium**			**Cost of Maintenance and Repair**	**Total Cost of Vehicle**	**Cost Per Mile Driven**
$21,850.75	*$69.34*	*$832.08*	*$8,320.80*	*$5,393.30*	*$57,992.47*	*$0.3866*

Chevrolet Silverado	**Manufacturer Retail Price of Vehicle**	**Average Tax**	**Vehicle Fuel Efficiency**			**Total Fuel Consumed**
	$19,375.00	*$949.38*	*14.50*	*19.00*	*16.53*	*9077.16*
Total Fuel Cost	**Insurance Premium**			**Cost of Maintenance and Repair**	**Total Cost of Vehicle**	**Cost Per Mile Driven**
$22,148.26	*$72.67*	*$872.04*	*$8,720.40*	*$5,249.12*	*$56,442.16*	*$0.3763*

Ford Escape	**Manufacturer Retail Price of Vehicle**	**Average Tax**	**Vehicle Fuel Efficiency**			**Total Fuel Consumed**
	$20,550.00	*$1,006.95*	*21.00*	*27.33*	*23.85*	*6289.35*
Total Fuel Cost	**Insurance Premium**			**Cost of Maintenance and Repair**	**Total Cost of Vehicle**	**Cost Per Mile Driven**
$15,346.01	*$65.17*	*$782.04*	*$7,820.40*	*$4,585.75*	*$49,309.11*	*$0.3287*

Honda CR-V	**Manufacturer Retail Price of Vehicle**	**Average Tax**	**Vehicle Fuel Efficiency**			**Total Fuel Consumed**
	$21,545.00	*$1,055.71*	*21.00*	*27.50*	*23.93*	*6269.59*
Total Fuel Cost	**Insurance Premium**			**Cost of Maintenance and Repair**	**Total Cost of Vehicle**	**Cost Per Mile Driven**
$15,297.81	*$75.67*	*$908.04*	*$9,080.40*	*$4,817.02*	*$51,795.93*	*$0.3453*

Toyota RAV4	**Manufacturer Retail Price of Vehicle**	**Average Tax**	**Vehicle Fuel Efficiency**			**Total Fuel Consumed**
	$21,500.00	*$1,053.50*	*20.25*	*27.00*	*23.29*	*6441.22*
Total Fuel Cost	**Insurance Premium**			**Cost of Maintenance and Repair**	**Total Cost of Vehicle**	**Cost Per Mile Driven**
$15,716.59	*$77.42*	*$929.04*	*$9,290.40*	*$4,876.65*	*$52,437.14*	*$0.3496*

Gasoline – Small

Toyota Camry / Solara	**Manufacturer Retail Price of Vehicle**	**Average Tax**	**Vehicle Fuel Efficiency**			**Total Fuel Consumed**
	$19,395.00	*$950.36*	*21.00*	*31.00*	*25.50*	*5882.35*
Total Fuel Cost	**Insurance Premium**			**Cost of Maintenance and Repair**	**Total Cost of Vehicle**	**Cost Per Mile Driven**
$14,352.94	*$72.09*	*$865.08*	*$8,650.80*	*$4,444.84*	*$47,793.93*	*$0.3186*

Toyota Corolla / Matrix	**Manufacturer's Retail Price of Vehicle**	**Average Tax**	**Vehicle Fuel Efficiency**			**Total Fuel Consumed**
	$15,950.00	*$781.55*	*23.22*	*30.56*	*26.52*	*5655.62*
Total Fuel Cost	**Insurance Premium**			**Cost of Maintenance and Repair**	**Total Cost of Vehicle**	**Cost Per Mile Driven**
$13,799.71	*$71.01*	*$852.12*	*$8,521.20*	*$4,004.28*	*$43,056.73*	*$0.2870*

Honda Accord	**Manufacturer Retail Price of Vehicle**	**Average Tax**	**Vehicle Fuel Efficiency**			**Total Fuel Consumed**
	$21,055.00	*$1,031.70*	*20.14*	*29.43*	*24.32*	*6167.33*
Total Fuel Cost	**Insurance Premium**			**Cost of Maintenance and Repair**	**Total Cost of Vehicle**	**Cost Per Mile Driven**
$15,048.29	*$80.25*	*$963.00*	*$9,630.00*	*$4,795.09*	*$51,560.07*	*$0.3437*

Nissan Altima	**Manufacturer Retail Price of Vehicle**	**Average Tax**	**Vehicle Fuel Efficiency**			**Total Fuel Consumed**
	$19,900.00	$975.10	20.13	28.00	23.67	6337.47
Total Fuel Cost	**Insurance Premium**			**Cost of Maintenance and Repair**	**Total Cost of Vehicle**	**Cost Per Mile Driven**
$15,463.43	$89.00	$1,068.00	$10,680.00	$4,821.08	$51,839.61	$0.3456

Ford Fusion	**Manufacturer Retail Price of Vehicle**	**Average Tax**	**Vehicle Fuel Efficiency**			**Total Fuel Consumed**
	$19,620.00	$961.38	20.67	29.33	24.57	6105.83
Total Fuel Cost	**Insurance Premium**			**Cost of Maintenance and Repair**	**Total Cost of Vehicle**	**Cost Per Mile Driven**
$14,898.22	$83.17	$998.04	$9,980.40	$4,661.28	$50,121.27	$0.3341

Hybrid-Electric

Toyota Prius	**Manufacturer Retail Price of Vehicle**	**Average Tax**	**Vehicle Fuel Efficiency**			**Total Fuel Consumed**
	$22,400.00	$1,097.60	51.00	48.00	49.65	3021.15
Total Fuel Cost	**Insurance Premium**			**Cost of Maintenance and Repair**	**Total Cost of Vehicle**	**Cost Per Mile Driven**
$7,371.60	$73.09	$877.08	$8,770.80	$4,064.52	$43,704.52	$0.2914

Honda Insight	**Manufacturer Retail Price of Vehicle**	**Average Tax**	**Vehicle Fuel Efficiency**			**Total Fuel Consumed**
	$19,800.00	$970.20	40.00	43.00	41.35	3627.57
Total Fuel Cost	**Insurance Premium**			**Cost of Maintenance and Repair**	**Total Cost of Vehicle**	**Cost Per Mile Driven**
$8,851.27	$65.92	$791.04	$7,910.40	$3,848.36	$41,380.23	$0.2759

Diesel

Volkswagen Jetta/Golf TDI	**Manufacturer Retail Price of Vehicle**	**Average Tax**	**Vehicle Fuel Efficiency**			**Total Fuel Consumed**
	$22,660.00	*$1,110.34*	*30.00*	*41.50*	*35.18*	*4264.39*
Total Fuel Cost	**Insurance Premium**			**Cost of Maintenance and Repair**	**Total Cost of Vehicle**	**Cost Per Mile Driven**
$10,831.56	*$73.00*	*$876.00*	*$8,760.00*	*$4,446.15*	*$47,808.04*	*$0.3187*

Audi A3 TDI	**Manufacturer Retail Price of Vehicle**	**Average Tax**	**Vehicle Fuel Efficiency**			**Total Fuel Consumed**
	$29,950.00	*$1,467.55*	*30.00*	*42.00*	*35.40*	*4237.29*
Total Fuel Cost	**Insurance Premium**			**Cost of Maintenance and Repair**	**Total Cost of Vehicle**	**Cost Per Mile Driven**
$10,762.71	*$79.50*	*$954.00*	*$9,540.00*	*$5,303.18*	*$57,023.44*	*$0.3802*

Biodiesel

Volkswagen Jetta/Golf TDI	**Manufacturer Retail Price of Vehicle**	**Average Tax**	**Vehicle Fuel Efficiency**			**Total Fuel Consumed**
	$22,660.00	*$1,110.34*	*30.00*	*41.50*	*35.18*	*4264.39*
Total Fuel Cost	**Insurance Premium**			**Cost of Maintenance and Repair**	**Total Cost of Vehicle**	**Cost Per Mile Driven**
$10,874.20	*$73.00*	*$876.00*	*$8,760.00*	*$4,450.52*	*$47,855.06*	*$0.3190*

Audi A3 TDI	**Manufacturer Retail Price of Vehicle**	**Average Tax**	**Vehicle Fuel Efficiency**			**Total Fuel Consumed**
	$29,950.00	*$1,467.55*	*30.00*	*42.00*	*35.40*	*4237.29*
Total Fuel Cost	**Insurance Premium**			**Cost of Maintenance and Repair**	**Total Cost of Vehicle**	**Cost Per Mile Driven**
$10,805.08	*$79.50*	*$954.00*	*$9,540.00*	*$5,307.52*	*$57,070.16*	*$0.3805*

Fully-Electric

Chevrolet Volt	**Manufacturer Retail Price of Vehicle**	**Average Tax**	**Vehicle Fuel Efficiency**			**Total Fuel Consumed**
	$40,000.00	*$(-7,500.00)*	*125.00*	*125.00*	*125.00*	*1200.00*
Total Fuel Cost	**Insurance Premium**			**Cost of Maintenance and Repair**	**Total Cost of Vehicle**	**Cost Per Mile Driven**
$4,528.00	*$73.09*	*$877.08*	*$8,770.80*	*$4,696.02*	*$50,494.82*	*$0.3366*

Hydrogen Fuel Cell

Honda FCX Clarity	**Manufacturer Retail Price of Vehicle**	**Average Tax**	**Vehicle Fuel Efficiency**			**Total Fuel Consumed**
	$72,000.00	*$3,528.00*	*60.00*	*60.00*	*60.00*	*2500.00*
Total Fuel Cost	**Insurance Premium**			**Cost of Maintenance and Repair**	**Total Cost of Vehicle**	**Cost Per Mile Driven**
$13,250.00	*$73.09*	*$877.08*	*$8,770.80*	*$10,002.25*	*$107,551.05*	*$0.7170*

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