Study of Factors around Automotive Fuel Cell Implementation and Market Acceptance

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Abstract

There are data that suggest that the earth's surface temperature has increased over the past century. Many scientists believe that this rise is due to the emissions of greenhouse gases by anthropogenic sources, while others believe it is due primarily to natural phenomena, such as solar cycles. Regardless of the actual cause, we should be motivated to drastically reduce emissions of these gases, improve fuel efficiency, and reduce other type of air pollution. This will also reduce the country's reliance on potentially unstable foreign sources of these fuels. There are many technologies currently being developed which promise to reduce our consumption of fossil fuels in automotive applications, including direct injection internal combustion engines, hybrid engines, battery-powered cars, fuel cells, 42-volt electrical systems, and lightweight bodies. When considered on total lifecycle and infrastructure bases, there can be significant downsides associated with any of these technological improvements, but each also offers a potential contribution to lowering fuel consumption. This thesis proposes that there are steps that can be taken to enhance the mainstream acceptance and benefits of these technologies, including early electrification of loads onboard vehicles, incremental reductions in consumption, and use of fleets to implement technologies requiring new infrastructure buildouts. However, automotive emissions are a small part of the overall emission problem, and we should also be concentrating efforts in other areas as well.

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Table of Contents

Index of Exhibits

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Chapter 1: Introduction

The purpose of this thesis is to explore the myriad of issues surrounding the implementation of alternative power sources for automobiles to replace internal combustion engines (ICE's), with a specific effort in the area of using fuel cell technology as the ultimate solution. Currently, the ICE is the dominant design in automotive power production, but this was not always so. Before the ICE became the dominant design, there were a wide variety of technologies from which to choose. The various car builders used such widely diverse technologies as electric batteries, gasoline, diesel, and steam. However, around the turn of the century, the ICE emerged as the technology of choice for vehicular propulsion.

However we are now faced with some significant problems that have arisen from a century of ICE use. These problems come at us from many fronts, the most pronounced of which are environmental and political. Many would propose that there is no way that the ICE will ever be economically and practicably replaced, but this view is very short-sighted and ignores technological history. Examples of complete technology displacement surround us. Witness the number of vinyl LP's, black and white televisions, and 5 ¼ inch floppy disks on store shelves today. How many carbureted ICE's are sold by local new car dealers these days? New technologies have always had detractors, and not just from the technologically impaired:

"I must confess that my imagination, in spite even of spurring, refuses to see any sort of submarine doing anything but suffocating its crew and floundering at sea."—H.G. Wells, 1901

"While theoretically and technically television may be feasible, commercially and financially, I consider it an impossibility, a development of which we need waste little time dreaming."—Lee DeForest (American inventor and pioneer in radio and TV), 1926

"There is not the slightest indication that (nuclear) energy will ever be obtainable. It would mean that the atom would have to be shattered at will."—Albert Einstein, 1932

"This is the biggest fool thing we have ever done....The bomb will never go off, and I speak as an expert in explosives."—Admiral William Leahy, advising President Harry Truman, 1945[1]

1.1: Evolution and Revolution

Though the concept of evolutionary and revolutionary change has been specifically applied to innovation in the information industry, these concepts also lend significant insight to the automotive world. Evolutionary change typically revolves around compatibility with previous versions of the technology, while revolutionary change focuses on raw performance.[2]

Compatibility refers to how well the technology will incorporate past versions of itself. In our context, it is an issue of how well the new technology will be able to use the installed infrastructure, including the roads, fueling regime, technical support, and all the other less tangible factors that go into making the new technology relatively transparent on a practical scale. For example, if we propose to move directly to a fuel-cell-powered vehicle (FCV) fueled with pure gaseous hydrogen, then this technology could not be considered backward compatible with the existing fuel distribution infrastructure, unless there is a technological breakthrough which enables such a hydrogen powered car to also run as well on gasoline. Compatibility requirements typically lead to incremental, or evolutionary change.

The other side of compatibility is performance, which is a circumstance where the new technology offers such a strong performance advantage over the old, that consumers are willing to forgo backward compatibility with the old technology to have the higher performance design, even at higher cost.[2] A good recent example of this is the audio CD. The CD offered an overwhelming suite of improvements over the old vinyl record technology, including better sound quality, service life, and size. These were so significant that consumers were willing to forgo the ability to play their vinyl LP's on the new players to enjoy the benefits offered by CD's. This is an example of revolutionary change. When recording and rerecording capabilities become economically available in DVD technology, we will see the same effect repeating itself as DVD's completely replace videotapes in the mainstream marketplace. In our discussion of fuel efficient vehicles, the argument will revolve around just how much improvement over the old technology is offered by the new one. This is important because some technologies, like fuel cells, are best implemented with fuels that do not currently have adequate infrastructure installed to be viable in the marketplace, as in the cases of methanol and hydrogen. Switching to a new fuel paradigm will be expensive, as was voluntarily obsolescing vinyl LP's. The benefits of the new technology will have to be so overwhelming that our incurring of this cost can be justified by the benefits that will be enjoyed by doing so.

So what is the best path to pursue in our case? Unfortunately, as of 2001, we have not discovered a practical technology to offer the significant benefits that would be required to overcome the significant switching costs (fuel infrastructure, manufacturing facilities, training of service technicians, etc.) that would be incurred in abandoning ICE-powered cars. However, there are technologies that can ease the problems we currently face with ICE's and pave the way toward the Holy Grail of clean hydrogen-powered transportation. I believe that due to the high switching costs associated with making a drastic jump to a radical new technology, we will be forced to take the transition in smaller steps.

The issues surrounding continued unabated use of ICE's are many and complex, but a brief discussion of the major issues is instructive in understanding the motivations behind new technologies.

1.2: Global Warming

While it seems that there is general consensus surrounding the issue of global warming, it is not totally clear cut. Data show that the world has been warming over the last century. The environmental activists are convinced that this effect is the result of greenhouse gas emissions from human activity. However, there are still vigorous debates regarding the actual source of the problem. You can get a pretty convincing story on either side of the environmental fence depending on whom you talk to. Anyone who studies natural history can tell you that the world endured periods of drastic climatic change before man ever emerged on the scene. For instance, it would be hard to blame the Ice Ages on anything done by civilization.

However, there are data to suggest that in the last hundred years, coincident with the Industrial Revolution, we have seen a very real rise in the earth's surface temperature. According to the U. S. Environmental Protection Agency (EPA) the earth's temperature has risen approximately 0.5C in the last century. This has resulted in rising rainfall amounts in higher latitude areas (about 1" extra per year). EPA data also suggest that mean sea level has risen around 15-20 cm in the same timeframe, with 2-5 cm of that effect from the melting of mountain glaciers and 2-7 cm from the expansion of warmer water in the oceans themselves.[3]

EPA data from 1998 shows that 86% of CO2 emissions in the US are the result of the burning of fossil fuels for energy production. The burning of petroleum fuels accounts for approximately 42% of energy-related CO2 emissions (the other 58% is from natural gas and coal), while the burning of petroleum specifically for the purpose of transportation was responsible for 30% of total CO2 emissions. Of the emissions from transportation, around 70% is specifically from automobiles and other highway transportation equipment. Combining these figures results in highway vehicles emitting around 20% of all CO2 emissions. In the years between 1991 and 1998, these transportation-source emissions rose by 33% as a result of the booming American economy.[3][4] As for other anthropogenic sources of CO2, residential and commercial fuel consumption accounted for 6% and 4% of emissions, respectively, electricity generation accounted for 37%, and industrial processes gave off 22%.[4]

Are these emissions resulting directly in the elevation of the earth's surface temperature? Some scientists say absolutely not. They believe that the warming effect is due to natural forces, such as minor alterations in ocean currents which are in turn driven by small changes in ocean salinity patterns. As temperature changes very slightly, the amount of water vapor in the atmosphere, itself a greenhouse gas, will cause a positive feedback effect and cause temperatures to rise even higher.[5] Other scientists are convinced that the fluctuations are the result of solar activity.[3] There are many other explanations proposed by those who believe that warming is the result of natural processes.

On the other side of the coin, a recent United Nations-sponsored study proposes that the earth's temperature could rise by anywhere from 1.5C to 6C between the years of 1990 and 2100. The report concludes that there is a substantial link between anthropogenic CO2 production and this warming effect. This study is the result of research by hundreds of scientists from all over the world.[6]

The bottom line is that while the scientific community may be somewhat divided, there currently appears to be a global consensus that there could be a definite link between man's activities and his global environment. By the time the issue is definitively resolved the detrimental effects could be irreversible. For this reason, we must pursue alternative energy sources as soon as they are technologically feasible.

1.3: Politics

Another significant driving force for finding alternatives to ICE's has been politics. The United States imports petroleum from the countries/organizations shown in Exhibit 1. The consumption of petroleum by sector is shown in the table in Exhibit 2. These data show that we imported over 54% of our total petroleum usage in 1999. One surprising result of these numbers is that we import only 23% of our total imports from the Persian Gulf region, or about 12% of our total consumption. OPEC, which includes not only Persian Gulf countries but also others such as Nigeria, Indonesia, Venezuela, supplies 24% of our oil.[7]

While we typically think that our reliance on the relatively unstable Persian Gulf region is the Achilles Heel of our energy policy, we could eliminate our reliance on this region by cutting back on our consumption by 12%. "In 1994, automobiles used 39 percent of transportation energy, light trucks (including minivans and sport utility vehicles) used 20 percent, and heavier trucks used 16 percent."[8]

In 1998, there were 131.8 million cars and 71.8 million light trucks registered in the U.S. In that same year, the cars were driven 1,546 billion miles, and burned 72.2 billion gallons of gasoline in the process. Improving the average efficiency of these cars by 1 mile per gallon would have saved 3.2 billion gallons of gasoline in 1998. For another 4 miles per gallon, we could have saved 11.4 billion gallons.[9] The average barrel of oil yields 19.5 gallons of gasoline, so 11.4 billion gallons equates to around 585 million barrels of oil.[10]

1.4: Methodology

In this paper, I will examine several technologies which have the potential to substantially reduce our automotive petroleum consumption and curb the environmental damage done by ICE's, and a couple that may not. Among other technologies, I will discuss electric vehicles, hybrid engines, 42-volt electrical systems, lightweight construction, and fuel cells. In the end I will propose how these technologies could be used in the next 20 years to reduce environmental impacts of driving ICE-powered automobiles and lead the way to implementing fuel cells as a final solution. In order to determine which of the proposed engine technologies currently may be the most suited to replace the ICE in the mainstream market, I will use a relatively simple framework proposed by White (1978) in order to evaluate the technical and business merits of each and propose some steps to take to assist in mass market implementation of fuel cell technology.

Chapter 2: Currently Proposed Technologies

In this chapter, I will discuss several technologies that have been recently proposed as promising developments in the effort to reduce petroleum consumption and greenhouse gas emissions. While obviously not all technologies can be discussed here, I have attempted to cover the major influences we may see in the next twenty years.

2.1: Battery Powered Vehicles

The electric vehicle has been an icon of environmentally friendly travel for decades. Their primary appeal has been that they have no tailpipes, and generate no pollution, at least locally for the user. The problem with this general thinking is that the electricity must come from somewhere. According to the U.S. Department of Energy, in 1999 73% of our electrical generation capacity was based in fossil fueled facilities (40% of the 73% is from coal), 12% was from nuclear plants, and 15% was from hydroelectric and other generation facilities.[11] So electric vehicles are great for the environment, as long as you do not live near a conventional power plant. In terms of actual consumption (as compared to generation capacity), the fractions from the different sources are a little different than those for generation capacity, with coal at 51%, nuclear at 19.7%, gas at 15.3%, oil at 3.2%, and hydroelectric and others providing the remaining 10.8%. The U.S. consumed 3691 billion kW-hrs of electricity in 1999.[11]

There are many ways to model the relative costs and savings from using different technologies. According to one model from VTPI in Canada which accounts for expected mileage traveled, fuel, purchase, and other ownership costs, an electric vehicle with performance comparable to that of an intermediate size ICE vehicle costs an extra $0.22/mile to own compared to an average-polluting ICE vehicle (an intermediate size, 21 mpg car). However, this type of analysis depends heavily upon the assumptions made regarding average mileage and location.[12]

Another issue with electric vehicles is the lead required to produce the batteries. Assuming a fleet of 500,000 battery-powered vehicles in Southern California, this would result in the raising the level of lead in the environment per mile driven by 80 times compared to using ICE's with unleaded gasoline. These emissions arise from the mining, smelting, and recycling operations required to manufacture and process the 500 kg (the General Motors EV1 has 595 kgs)[13] of batteries in each vehicle. Reported cases of violations of air quality standards around lead smelters are already fairly common. In areas like California, where the environmental standards for ICE's are the most stringent, we actually find the least benefit from the deployment of electric cars, since the relative benefit per vehicle is already reduced by the ICE emissions standards already in place. Currently, car starter batteries consume about 85% of the lead produced each year.[14] While the use of nickel hydride batteries could be a way of getting around the lead problem, this adds even more cost to the vehicle. For example, the GM EV1 has a list price of $33,995 with lead batteries, while the same vehicle with a nickel-metal hydride battery costs $10,000 more. These cars have operating ranges of 55-95 miles and 75-130 miles, respectively.[13]

While most people cite operating range as a major concern around electric vehicles, one point to keep in mind is that the average annual mileage for cars in the U.S. is around 12000 miles. Assuming this mileage occurs over 365 days, this works out to about 33 miles per day. If you assume that the car sits idle for 1 day on an average weekend, then the mileage occurs over about 310 days, and the average daily mileage is less than 40 miles. So as long as there is another conventional vehicle available for longer trips, the EV1 is not totally impractical on a range basis for everyday driving for the average person.

The public perception of the reduced performance of electric vehicles is a significant obstacle in the American market. One study on the topic of consumer resistance to electric vehicles concluded that the average consumer would only buy an electric car if it were priced about $28,000 less than a comparable internal combustion powered vehicle.[15] This is a significant hurdle to overcome. Much of the problem is weight. Even the advanced nickel-metal hydride battery in the EV1 weighs 521 kgs. If you have not charged the battery and need to go somewhere quickly, you have a real problem. The recharging times for the EV1 are around 6 hours on the 220V charger and 23 hours with the 110V "convenience" charger.[13]

2.2: SIDI and CIDI Engines

Obviously, the fuel-air ratio in the mixture burned in an ICE is a prime determinant of the engine's fuel economy. In order to be compatible with current catalytic converter technology, engines today run with stoichiometric ratios. Running with a lower fuel-air ratio (excess air) will improve fuel economy. Spark ignition and compression ignition direct injection engines (SIDI and CIDI) are the gasoline and diesel fueled versions of a new generation of lean burning ICE's which promise to improve fuel economy and reduce CO2 emissions by 15 to 35%. They are still in the experimental stage and there are some significant barriers to overcome before they can be used in the mass market. Lean burning engines have high NOx emissions that require lean burning catalysts to clean up. The problem arises in the response of the catalysts to sulfur in the fuel. The performance of these catalysts is severely degraded by sulfur content levels of over 5 ppm.[16] California currently limits sulfur in gasoline to less than 40 ppm, and other states have higher limits, so this is going to be a nationwide problem in implementing this technology in the U.S.[17] So like gasoline fuel cell systems discussed below, desulfurization of gasoline is currently a major limitation of this technology. Also, while 15 to 35% improvement will help, this will still not be adequate to solve our CO2 emission problem.

2.3: Hybrid Electric Vehicles

A significant fuel-efficient technology that we can buy today is the gasoline/electric hybrid vehicle. Currently available examples, like the Honda Insight and the Toyota Prius show that this technology is technologically feasible. Each can be purchased for around $21,000. However, these cost figures can be misleading. For example, though the actual number is not available, Japanese automotive industry analysts have estimated that the Toyota Prius costs Toyota around $41,000 per car to build. While this cost can be expected to come down as production progresses due to scale and learning curve effects, it is primarily a public relations exercise and not a viable commercial product as it stands right now.[18] Honda has also stated that they are losing money on sales of their Insight hybrid vehicle, but have not specified how much. They are confident that they will make a profit on the Insight within a couple of years.[19]

A couple of different schemes can be employed using hybrid technology. In a series hybrid vehicle, the engine is not directly connected to the drive train. It is simply used to generate electricity for the electrical drive system that is supplied by the battery, like an onboard charging system for an electric vehicle. One of the significant advantages of this system arises from the fact that an ICE's fuel efficiency varies widely with its operating speed. If the engine is not directly connected to the drivetrain, it can be run at its most fuel-efficient and emission minimizing speed in its function as an electrical power generator. This scheme is particularly useful if the engine design makes it impractical to connect mechanically to the drivetrain, as is the case with gas turbines which will be discussed later. Disadvantages of this scheme are that it requires a large generator and there are efficiency losses in the electrical conversion process.[20]

Another hybrid scheme is the parallel hybrid layout, where the engine is mechanically connected to the drive train with a supplemental electrical drive system attached in parallel to the drive train, between the flywheel and the transmission for example. In this system, the engine can be sized to provide the power needed for steady state operation, while the electric motor connected in parallel with the engine is used to supplement engine power under higher power demand situations such as acceleration and hill climbing. An advantage of this system is that there are not nearly the same levels of electrical conversion losses and no separate generator is required. However, this system does require a mechanical transmission with its attendant weight and mechanical friction losses. Also, since the engine is mechanically linked to the drive wheels, its speed must vary with vehicle speed within the limits of the transmission design, so the engine does not always run at its most efficient speed.[20] A continuously variable transmission (CVT) can alleviate this shortcoming, but CVT design is still in the development stage. The Toyota Prius is the only production vehicle currently available with a CVT, though the Insight may soon be available with one as well.[18][19]

There are also hybrids of these hybrid systems, called series-parallel combined systems. These systems combine the best of both worlds. There are two types. The switching system uses a clutch between the engine/generator unit and the electric motor, which is on the driveshaft between the clutch and the drive wheels. For parallel operation, the clutch is engaged between the engine and the driveshaft, and the engine/generator drives the car mechanically with electric assist. In series operation, the clutch is disengaged and the engine/generator unit simply generates electrical power to drive the motor through the battery. The series arrangement could be used in city driving where low loads are required, and the parallel arrangement could be used for highway or more power-demanding conditions. This design still incorporates transmission equipment and therefore incurs a weight penalty.[20]

The second type of combined system is the split system, where the engine output is connected to a generator through a planetary gear to the drive train and the generator unit. With this system engine speed can be controlled by the generator while the engine is still mechanically linked to the wheels through the planetary gear.[20]

The key advantage to these systems is that energy stored in the battery during normal operation can be used to supplement a smaller, more fuel efficient engine to provide peak power required for acceleration and grade climbing. In addition, in the series configuration the engine speed is independent of vehicle speed, so the engine can run at its most optimum fuel-efficient speed and load under almost all conditions. The advantage of the parallel configuration is the extra power that can be provided directly from the engine itself when required. All of these vehicles run on currently available fuel with no modifications. Still, there are CO2 emissions associated with these vehicles, and while the significant increases in fuel economy will help, they will still not completely solve our emissions problems altogether.

Fuel cell vehicles can also be considered hybrids when a storage battery is used to help the fuel cell meet peak demands in vehicle operation.

2.4: Gas Turbines

One relatively obscure alternative for the ICE is the gas turbine. The airline industry has been using this technology reliably for over 40 years, and the Navy has been using the gas turbine to power its surface combatants for the last few of decades. Recent advances in materials and design have enabled engineers to reduce the size and increase the power density of these power plants.

Gas turbines have several advantages over ICE's. They are lighter per unit of power generated, more durable, and more reliable than ICE's. Currently the maximum efficiency we can expect to squeeze from the ICE is less than 30%, while a gas turbine can obtain efficiencies in the low-40% range. Their emissions, without any exhaust gas treatment, are lower than those of ICE's with exhaust gas treatment. Turbines are also much more fuel agnostic than their ICE counterparts, and can run on almost any liquid or gaseous fuel.[21]

Even compared to fuel cells, gas turbines have some practical advantages, especially in the area of power/weight ratio. A gas turbine can produce 3-4 kW per kg of engine weight, while fuel cells are currently in the range of 1.5 kW per kg and batteries are in the range of 0.5-1.0 kW per kg. The gas turbine could be used with available technology to build a mid-sized family car capable of 80 miles per gallon, the current PNGV mileage goal.[21]

One example of the industry's recent interest in this technology can be found at Volvo. In 1986 Volvo, ABB, Swedish power company Vattenfall A.B., and the Swedish government began the development of a high-speed 20kW electrical generator which could run at 100,000 RPM. In 1990, Volvo, ABB, and Vattenfall began a project aimed at designing a hybrid electric car, the Environmental Concept Car (ECC), to take advantage of the compact, high-speed generator. The Volvo design was a series hybrid design, where the single three-phase synchronous electric motor could be operated in two modes, hybrid-electric and electric. The turbine was used to charge the nickel-cadmium battery and well as provide electrical power to the motor. In electric mode, the turbine did not run and the car operated solely on battery power. It had a range of about 53 miles in electric mode. In hybrid electric mode, the car was able to achieve about 45 miles per gallon on the highway, and 39 miles per gallon in the city.[22]

There was a potentially serious limiting factor in this car's design. The car was built with a 2-speed transmission to feed power from the main motor to the rear wheels. The use of a transmission adds significant weight to the car, and sending power to the rear wheels makes this effect worse. The car could very easily have been lighter with independent electric drives on the wheels. This could have added materially to the car's mileage performance. This car was the size of a standard Volvo sedan, and already could achieve 45 miles per gallon with the existing experimental design. Lightening the car and eliminating the parasitic power losses in the transmission could have increased this performance by several percent.[23]

There were other drawbacks to this design. There were significant problems related to high temperatures generated by the turbine in the relatively small engine compartment of the automobile. There were also problems related to gyroscopic effects of the high-speed turbine on the handling characteristics of the car. There are serious doubts at Volvo as to in our cars, except for some very extreme cases. However, if the performance metric is greenhouse gas emission reduction or elimination, then they come up way short compared to the ideal state of zero emissions. We could choose from a long list of others, like torque, noise, excess heat, convenience of use, effects on handling, cost per mile, ease of recycling spent components, energy expended in creating/fabricating the technology, safety, product life, odor, etc. Even one performance metric, emissions, can be broken down into several relevant components, whether it is CO2, NOx, particulate, or others. Each special interest will have its own performance metric against which to measure any existing and proposed technology.

For the purposes of this paper, I am concerned with emissions, cost, and convenience (infrastructure), subject to other major concerns surrounding the technologies. I am also concerned about whether the technology is disruptive to the consumer, assuming that the car manufacturers do not produce the vehicle until the underlying technology gives the vehicle mechanical performance equivalent to that of an ICE vehicle. Here is where the standard disruptive technology discussion and this discussion diverge. A disruptive technology is an inferior technology will find a niche where its weaknesses are strengths, probably not the one initially envisioned by the technology implementers, and will gradually improve in performance until it overtakes the incumbents in the industry. I feel that this is an improbable scenario in the case of automobile propulsion for a couple of reasons.

against limitations. First, it is now common for electrical loads on cars to exceed 2 kW, and the current trend is that this will grow at about 4% per year due to ever-increasing amenities and electrical functions. The belt-driven alternator is limited to about 3 kW due to high noise levels and extra cooling that must be implemented. Also, with the increasing lengths of wiring going into cars every year, heavier wiring is required to carry the extra currents being demanded by the heavier electrical loads, resulting in more weight.[27]

The new 42-volt design will be capable of generating up to 8 kW of electrical power that will allow further electrification of various loads on the car. As will be noted later, this could be a significant factor in driving toward fuel cell implementation in automobiles.

For example, the belt drive systems used to power many engine auxiliaries parasitically drain valuable power from the engine, even when the load itself is not being used, converting engine power to wasted heat. If these loads could all be driven electrically, these belt drive losses could be eliminated.[26] Also, the engine's operating efficiency is intimately linked to the amount of control which can be exercised over several of its operating parameters, valve timing in particular. Currently, valve timing is a purely mechanical function, with the valves being operated either by a camshaft driven by a chain or belt off the engine crankshaft, or by pushrods driven off the crankshaft. There have been various attempts to design around this limitation, notably in the Porsche 968 and the Acura NSX, but these schemes are limited in the amount of adjustment allowed the engine management electronics due to the basic mechanical design of the systems.

This mechanical linkage severely limits the degree to which valve timing can be varied relative to crankshaft position over the wide range of engine loads and speeds, and in turn limits efficiency gains that could be achieved by optimizing the timing for engine operating conditions. All of the mechanical parts in this scheme, from heavy valve springs, chains, belts, and the contact surfaces, also rob power from the engine.[27] The extra power afforded by the 42-volt electrical system would enable electrically driven valve actuators, which in turn would enable the engine control computer to have total control of valve timing. This measure alone is expected to increase fuel economy by 15%. Electrification of the power steering pump will add another 2 to 5%. Brakes can also be electrified for faster response time (twice as fast). These new electric loads will need about 2 kW for valves, 4 kW for brakes, and 0.5 kW for power steering. Another electrification benefit will be to install heaters in the catalytic converter (another 2kW), which will permit rapid heat up upon starting and reduce startup emissions by 60-80%. It is easy to see why the extra power capability of the 42-volt system is needed.[28]

This system will have a single alternator/starter unit, most likely mounted directly on the drive shaft between the engine and the transmission. From this position, it will also allow the engine to be turned off when the vehicle is stopped. This way there is no fuel consumption from idling in stop-and-go traffic. The higher voltage allows quicker and more reliable starts when the throttle is depressed, with start times of about 0.2 seconds.[26]

Of course, this will be more complicated than it seems. First of all, all current car accessories run on 14-volt power. Running them on 42 volts would have a generally negative impact on their operation. There are two solutions to this problem. First, we can use 42 volts to run certain engine related components and auxiliaries, then step down the voltage to run other items like car radios, navigation systems, lights, etc. This would result in having two different electrical systems on the car, and would also require the extra weight and power consumption of voltage conversion equipment. A second solution would be to convert all electrical loads over to the 42-volt standard in one shot. What we will probably see is a slow progression from the first solution to the second.[26] A second major issue will arise when someone's battery goes dead. While trying to jump start a 42-volt vehicle off of a 14-volt system probably will not give a satisfactory result, jumping a 14-volt vehicle from a 42-volt system will most likely provide more excitement than bargained for unless safeguards are put in place to prevent this from occurring.[26] Remember that when jump starting the car, it is not just the starter that is exposed to the incoming voltage.

The 42-volt system is closer to implementation than most realize. They are currently expected to be on the road by 2004 in luxury cars, and then trickle down to most other cars shortly afterward.[26]

2.6: Lightweight Car Bodies

While not directly linked to propulsion technology innovation, vehicle weight is a major consideration in fuel economy, and is mentioned here to illustrate that while there are benefits, even this is still not free. There has been a big push to reduce the weight of cars in the last couple of decades. Vehicle weights in that timeframe have dropped nearly 25%.[29] An important factor to remember is that this includes the effects of adding amenities to the vehicle at the same time. When removing weight from a car, we realize two immediate benefits. First, the fuel economy of the vehicle will rise about 3% due having to overcome less inertia and rolling resistance with a 10% reduction in weight for the same overall vehicle performance. A second effect is that we can use a smaller engine and lighter power train to power the vehicle, which in turn provides another 4% increase in fuel economy for a 10% weight reduction, for a total of 7% per reference [27]. Reference [29] puts this estimate at 6%, and reference [30] puts this estimate at closer to 14% when combined with other advanced body design features. Much of the reduction in weight over the years has been through the use of aluminum in frames, bodies, engines, and other parts as a replacement for steel. This replacement does not come without a cost.

One of the major problems with use of aluminum is that, compared to steel, it takes substantially more input energy to produce 1 ton of aluminum than 1 ton of steel. Producing one ton of virgin aluminum parts requires thermal energy input of 166 GJ, assuming a standard electrical consumption and a thermal conversion efficiency of 2.9:1. By contrast, production of 1 ton of steel requires only 6.7 GJ of energy, with the same assumptions. Recycled parts from each material require 14.4 GJ per ton for steel and

14.3 GJ per ton for aluminum. Therefore, in terms of energy consumption over the lifecycle of the vehicle, the aluminum car starts out from an economically disadvantaged position compared to the steel car.[30] When we evaluate the payback period in terms of overall CO2 emissions considering the short and long term effects of electrical generation sources for the extra aluminum production and fleet introduction schedule effects, the benefits of using aluminum are questionable. An MIT study concluded that while just one vehicle will pay back the initial energy investment in 6 to 8 years, it will actually take 15 to 17 years for the whole fleet. This payback period increases to 32 to 38 years when compared to the Ultra Light Steel Auto Body (ULSAB).[31]

Another important aspect of lightweight body technology is safety. As so many consumers move toward heavy luxury cars and SUV's, consumers contemplating buying light, fuel efficient vehicles cannot help but imagine in the backs of their minds what the outcome of a collision between the lightweight car and a Lincoln Navigator would look like, and what their odds of survival would be. This is a very real and valid concern for environmentally conscious drivers, especially those with families.

2.7: Issues of Fuel Cells and Fuels

Of the obstacles standing in the way of mass acceptance of fuel cell vehicles, probably the biggest issue is the selection of the best fuel. The current practical choices are among several hydrocarbons and pure hydrogen. The best source of fuel from the standpoint of efficient fuel cell operation is pure hydrogen. The problem with this fuel is that storing it on board the vehicle is problematic. The three most commonly proposed methods of on board storage are compressed gas, liquid hydrogen, and metal hydrides or carbon nanotube materials.

To achieve a range comparable to gasoline engines, the compressed gas solution will require the hydrogen to be initially stored in a tank at over 3600 psi.[32] Ballard Power Systems estimates that the pressure required in the automotive application will be closer to 5000 psi.[33] This scheme faces a few major hurdles. First, even the most rational scientific consumer will have some serious reservations about hurling down the freeway, along with other hurlers, in a car carrying a highly pressurized flask of hydrogen. Even ignoring the combustibility issues, just suffering a casualty which ruptures the tank will have severe consequences. Secondly, how will a new, inexperienced 16-year old driver fill the car with fuel when it takes the form of such a highly pressurized gas? The pressurized gas scheme will require a fully automated refueling system to be considered even marginally non-hazardous. This will add burdensome cost and complexity to the implementation of this scheme. Third, even at 5000 psi, to have roughly the same range as a 13 gallon tank of gasoline or methanol, the hydrogen tank will have to have a volume of 150 liters, or close to 40 gallons, which is a significantly larger tank to try to wedge into the car's structure.[34]

The liquefied hydrogen scheme requires the hydrogen to be stored and dispensed at –253^0C. This scheme would also require a fully automated refueling system. Another problem with using this scheme for everyday use in passenger cars is boil-off of the fuel over time. The average driver does not immediately use all of the fuel once the vehicle is filled up. The car will typically be required to use a charge of fuel over a period of several days, or even weeks. Keeping the fuel tank below hydrogen's liquefaction temperature in Houston during July will be a very challenging problem indeed.[32]

The use of hydrides or carbon adsorbents like carbon nanotubes to store hydrogen is still not a viable technology for common hydrogen storage, and will not be for some time to come.[32]

As a result, we are forced to face the reality that pure hydrogen will not be a viable mass-market fuel any time soon. "Recently, a panel of fuel cell experts reported to the California Air Resources Board that, 'hydrogen is not considered a technically and economially[sic] feasible fuel for private automobiles now or in the foreseeable future.' The panel found that fueling infrastructure problems and the storage of an extremely cold liquified fuel or highly compressed gas on board a vehicle would not be 'practical'. The panel concluded that fuel cell vehicles must get their hydrogen through the on-board processing of a hydrogen-rich fuel."[35]

There is another surprising problem with hydrogen fuel. While the use of pure hydrogen in a fuel cell results in the lowest local emissions at the point of consumption, the picture is a little less rosy when the overall picture is considered. Hydrogen is commonly produced by two different methods today, electrolysis of water and processing of natural gas. Assuming the electrolysis process is powered from the electrical grid of today, there is more CO2 produced in the production of the electricity required to produce the hydrogen than is precluded by elimination of the gasoline combustion process in the ICE for the same miles traveled. Hydrogen production from processing natural gas does reduce these emissions by about 75% to be the lowest CO2 emitter overall, but this process results in the release of NOx at a level around 60% of that of gasoline in an ICE and about 81% of that of a hybrid system, well to wheels.[36]

With all of these considerations in mind, we are forced to consider hydrocarbon fuels. If hydrocarbons are dispensed directly into the vehicle's fuel tank, then the use of an on board reformer will be required to process the raw fuel, in the form of gasoline, methanol (with a possible exception of direct methanol fuel cells, discussed later), or any other liquid hydrocarbon fuel into a hydrogen rich mixture that can be effectively utilized by the fuel cell stack. When considered on a heating value basis for comparison between the fuels, and considering the inefficiencies encountered when using reformer systems, we can optimistically expect the hydrogen fuel cell car to get about 106 miles per equivalent gallon of gasoline, with methanol and gasoline fuel cell vehicles getting around 70 miles per gallon each. The higher heating value for gasoline is about twice that of methanol on a volume basis, but the hydrogen concentration in the reformed methanol fuel stream has twice the concentration of that in the reformed gasoline fuel stream.[34]

While the reformer system adds complexity to the on board system as a whole, liquid hydrocarbon fuels do have one significant advantage over hydrogen that makes them attractive. The average consumer is already accustomed to pulling up to a fuel station and filling up his/her tank with liquid fuel. Also, the already installed infrastructure is already set up for and proficient at distributing liquid fuel to a wide variety of customers and fuel burning equipment. As we move toward implementation of fuel cells as a significant factor in vehicle propulsion, we will be asking average citizens to accept a radical new, relatively unknown technology in the most critical piece of equipment in their daily lives. This task will be a challenging enough without also requiring them to deal with a radical new refueling mechanism like that required to refuel with gaseous fuel. There is still a large fraction of our society that refuses to have anything to do with computers because they fear technology.

Using a liquid fuel to power fuel cell vehicles will also be a major benefit in the fuel distribution infrastructure as well. We have an extensive network of refineries, tanker transports, and fuel stations which are optimized for liquid fuels. However, even if gasoline is used as fuel, there will be some obstacles to overcome. First, today's gasoline has many additives which would make it very difficult to reform into a clean, hydrogen-rich fuel cell fuel.[35] Also, gasoline tends to have an appreciable sulfur content. Sulfur will poison any currently viable fuel cell design. California has a gasoline sulfur limit of 40 ppm, while other states permit higher levels. The sulfur will need to be removed either by the refiners or on board the vehicle. However, putting the desulfurization equipment on the vehicle adds weight. One team at MeDermott Technology, Inc. in collaboration with a team at Catalytica Advanced Technologies is developing an on board desulfurization process which will reduce sulfur to less than 2 ppm. Current desulfurization equipment is expected to add 463 kg to the vehicle weight, which is over half of their total reformer system weight of 863 kg, but the experimental system could reduce desulfurizer weight to around 6 kgs.[17] The specially refined "clean" gasoline would require separate transport and storage facilities throughout the supply chain. Gasoline will require higher reformer temperatures than some other fuel alternatives, and will result in more CO and lower hydrogen concentration than another fuel like methanol. CO is a fuel cell poison, so current formulation gasoline as a fuel is unhealthy for fuel cells due to both sulfur and CO.[35]

Another promising fuel is methanol. Methanol is a man-made liquid fuel that is formulated from natural gas or renewable biomass sources. It has several advantages over gasoline as a fuel. First, its molecular structure makes separation of the hydrogen from the carbon and oxygen much easier than for other hydrocarbon fuels. This will lower the temperature required for the reformation process, which in turn leads to cheaper, lighter design and quicker startups. Methanol contains no sulfur, so it requires no desulfurization equipment at the refinery or on board the vehicle. It also has a higher ratio of hydrogen to carbon in the molecular structure, so we get more hydrogen for each unit of CO2 emission. Another benefit is that adding a methanol capability to an existing service station will cost in the neighborhood of $50,000 per station. Researchers at the American Methanol Institute (AMI) propose that introduction of methanol infrastructure should be started in the states and countries with the worst pollution problems and/or the most stringent air quality regulations. In the United States these states would be California, New York, and Massachusetts. As of 1998 these states had around 20,800 service stations, so converting 25% of them to a methanol capability would cost around $260 million. Also, assuming an expected fleet of 35 million vehicles by the year 2020 consuming 15.4 billion gallons of methanol annually, the consumption of methanol would be equivalent to 135% of our current production capacity. Since major methanol plants can be built in less than 2.5 years, meeting this demand should not be a major problem. 15.4 billion gallons of methanol would require the production of 1.4 TCF of natural gas, about 2% of our current production capacity. Almost 3 times this amount is flared and vented each year in the production of petroleum and natural gas, so production of the required natural gas should not be a problem either.[35] The use of methanol produced from natural gas, well to wheels, produces CO2 in quantities roughly equivalent to the CO2 emissions from the use of hydrocarbon-sourced hydrogen.[37]

There is some concern over the detrimental effects of using methanol. However, in some ways, methanol is safer than gasoline. Methanol has been used in Indy car racing since the 1960's because of its reduced fire risk. It is harder to ignite than gasoline, burns 60% slower, and releases energy at 20% of the rate of gasoline when it does burn. However, when it does ignite it burns clear, so detection of a fire may depend upon visibility of other materials burning with the fuel. Gasoline is listed as a carcinogen, while methanol is not. Methanol is more toxic than gasoline, with a lethal liquid ingestion dose of 25-90 ml, compared with that of gasoline of around 120-300 ml. The body actually generates methanol after consuming beverages sweetened with aspartame. It is highly soluble in water and quickly biodegradable by aerobic and anaerobic microorganisms. Exposure to methanol vapors during a four-minute refueling stop will result in methanol exposure equivalent to ingesting 3 ml of liquid methanol. Consuming one diet soda with aspartame will result in the body's generating the equivalent of 20 ml of methanol over time. So while methanol is toxic, its use should not incur any significant limitations in excess of those on gasoline.[37]

Regardless of the fuel that wins out, this is a market that will substantially "tip" in the long run, so we want to minimize the number of significant shifts over time. Fuel is not an area where incremental change will win the race. There is too much infrastructure investment required at each stage to support an incremental approach. I believe that using the methanol infrastructure as a sole stepping stone to hydrogen is the best way to proceed, since it has significant advantages over gasoline in the fuel cell application, can be relatively easily implemented when compared to gaseous fuels or cryogenic liquids, and will support the shift to hydrogen fuel directly.

Chapter 3: Dominant Design and Technology Diffusion

3.1: Dominant Design

Fuel cells and gas turbines are a radical departure from the internal combustion engine, while the hybrid gasoline-electric is less so. As the ultimate goal is to get fuel cells into cars, the following discussion will concentrate on that technology.

An important consideration in any strategy of technology diffusion is the concept of the "dominant design", and its effects on markets for new technologies. Typically, when a new technology presents itself, there is an era of ferment when several firms work on several different versions of how the technology should be embodied in marketable products. Then one design layout emerges which essentially becomes the standard for the technology, and then firms either get onboard or get acquired/exit the market. This is usually the point at which the technology gains widespread acceptance.[38]

For example, at one point around 1923 there were almost 75 companies producing cars in the United States alone, and this only includes the firms that actually produced cars for more than 5 years. Over 100 such firms entered the U.S. business between 1894 and 1980. These firms were all producing different styles of cars, as none had emerged as the dominant design. However, in 1923 Dodge introduced an enclosed, all steel body design that strengthened the body and simplified the manufacturing process. In the next 2 years one-third of the companies exited the market. By 1926 80% of all cars produced were of this design. It is typically upon the emergence of the dominant design and the establishment of this standard that firms that were betting on the losing designs tend to go out of business or be acquired by the winners and the diffusion of the technology really takes off.[38] A popular fuel cell website lists 17 public companies that are working on proton exchange membrane (PEM) fuel cells alone. This does not even include the private companies and the ones working on other types of fuel cells. The development of the dominant design should be the primary goal of any firm that wishes to see a new propulsion technology take off. Before fuel cells take off and become a major factor in the automotive industry, the companies involved in the research and development of this technology must come to some agreement on the standard configurations of such features as the fuel cell itself and the standard type of fuel, and use them to create a reliable, user friendly, complete vehicular package. The average consumer does not understand the technology and if forced to choose between different technology options, the consumer will not feel that the technology is ready for "prime time", and will just wait until the industry makes up its mind on the standard product it will offer. No one wants to be stuck with the "Betamax" of the fuel cell vehicle world.

Ballard apparently has this motivation in mind with its Mark 900 fuel cell system. They have announced that the Mark 900 is the "final, frozen design for future series production."[39] Unfortunately, just because a manufacturer freezes development efforts on a certain product to get it into production, this does not necessarily mean that the market will accept it as the dominant design, but it is a step in the right direction to at least go to production with a standard product. They may be able to find great success in being the "first mover" with regard to getting a standard product to the market.

For the last century, internal combustion engines have been the dominant design in any application involving the local generation of power in equipment such as lawnmowers, household generators, chainsaws, motorcycles, cars, trucks, and anywhere else sub-megawatt levels of local or mobile power have been required. In automotive applications, it supplanted previous ferment-era experiments with electric, steam, and other propulsion systems. The automotive industry is fairly well entrenched in this technology, preferring to make incremental (evolutionary) improvements in the performance of the existing technology rather than jump ship and implement completely different types of power generation. Quite frankly, consumers would be uncomfortable with discontinuous, revolutionary technological change in such an important part of their lives, especially if it rendered previous significant investments worthless and had no previously established performance track record. They have grown accustomed to incremental change.

In their defense, there has not really been a viable substitute for the internal combustion engine up until now, especially in the automotive application, and there have been significant but incremental improvements in the efficiencies of these machines. 50 years ago the fuel economy numbers for the average American car were in the area of 15 mpg. These economy numbers remained relatively stable from 1950 until 1975, when the United States government instituted CAFÉ regulations in response to the energy crisis of the 1970's.[40] As a result, average fuel economy for cars has risen from 16 mpg in 1975 to around 28 mpg in 2000, while the average light vehicle's fuel economy (includes light trucks) has risen from 15 mpg to 24 mpg.[41] Also, in the last 25 years we have reduced the emissions of other pollutants, such as NOx, hydrocarbons, and CO by over 90%.[27] In the realm of cars designed specifically for fuel economy, we can now choose from normally powered sub-compact cars that get mileage of over 40 miles per gallon, and from hybrid gasoline/electric cars like the Honda Insight that can achieve upwards of 70 miles per gallon.

As discussed before, there have been a couple of assaults on the ICE as the dominant design in automotive propulsion. These include gas turbines, various configurations of hybrids, solar, electric, and other more esoteric designs. However, none have made any great inroads, though the hybrid design is just getting started. If we assume that direct solar power (solar cells directly on the vehicle) will never be practical for a family car, and that the electrical infrastructure will not shift totally over to a non-fossil fueled paradigm, then the only currently technically feasible (if not commercially), completely clean technology will be to burn or electrolytically utilize hydrogen in our cars, where the hydrogen is produced by a non-polluting technology, such as electrolysis of water using solar or wind power. The problem is that it is hard to picture this happening in our lifetimes by pure market factors alone, if for no other reason than the "chicken or the egg" problem between the hydrogen cars themselves and the required infrastructure to support them. The hydrogen industry will not make the huge investment in the required infrastructure without an existing market to pay for it, and no one will buy a car that they cannot conveniently refuel when they buy it. It is also hard to imagine a country generally hooked on gasoline guzzling performance just voluntarily adopting a much lower performance technology.

There are significant organizational issues surrounding the implementation of radical technologies which are displacing incumbents. We must consider that the fuel cell, regardless of its application, will be displacing an existing technology, whether in the generation of electrical power for standard electrical loads or as a replacement of the internal combustion engine. An existing organization which was built around the old technology and lacking true entrepreneurial thinking probably will not be able to successfully develop this technology into a mass marketable success.[42] In our discussion, the established organizations would be represented either by the major automotive manufacturers or to a lesser extent by the oil companies. The best ways for the motivated organization to develop this new technology would be to either spin off a completely separate company of entrepreneurially motivated managers and technicians or to partner with an outside firm that possesses these characteristics.[42] We can see this in practice through the partnerships formed between independent fuel cell companies and the major automotive manufacturers. For example, the leading PEM fuel cell company, Ballard Power Systems, of Vancouver, has strong partnerships with Ford and Daimler, and serves as their research and development arms in the fuel cell field.

Chapter 4: Economic Forces

4.1: Consumer Sentiment

A basic question we must answer regards how we will motivate the average consumer to purchase this new technology. Can it be done based upon fuel efficiency arguments alone? Recent research shows that the answer is "probably not". The graph in Exhibit 3 shows that since the energy crisis in the late 1970's until 1996, the interest in fuel economy has dropped significantly compared to other factors such as dependability, quality, and safety. In fact, while the original J.D. Power and Associates survey showed that in 1980, fuel economy was the most important factor in new car selection, a more recent survey shows fuel economy to be the 15th most important factor, behind such factors as seating and hauling and towing capacity. Jane Beseda, manager of marketing strategies at Toyota Motor Sales USA, states "What surprised us in our research was that, in just the past two years, consumers' willingness to pay more for an environmentally friendly vehicle has actually declined by 7 percent in California and by 6 points across the United States." This sentiment is backed up by our car purchasing habits. While from 1976 to 1983, our purchases of large cars dropped from 23% to a low of 13%, they have crept back up from 13% in 1987 to 15% in 1996. This rise probably was only mitigated by the shift to light trucks. Light truck sales (which include minivans, pickups, and SUV's such as the Lincoln Navigator) have climbed from just over 2 million units in 1982 to over 6 million units in 1995.[43] It gets worse. An Associated Press report from November 1998 stated that for the first time in history, light truck sales surpassed car sales in the United States. The report also stated that among truck buyers, fuel economy ranked 35th among factors influencing the sale.[44] When we factor in the fact that fuel efficient technologies do not generally perform as well as ICE's as far as vehicle performance, it gets even worse. As mentioned before, one study concluded that consumers in general would only buy an electric car if it was priced about $28,000 less than a comparable internal combustion powered vehicle.[45] This would be a significant obstacle to overcome in the marketplace.

Economically, it is difficult to fault the U.S. consumer for this attitude toward fuel efficiency. How much does fuel economy mean to the average U.S. consumer? For illustration, assume the average consumer drives 20,000 miles a year. This is my typical mileage, but the actual average mileage is in the range of 12,000 miles per year, so these savings will be roughly cut in half on average. Also assume that gasoline prices are in the $2/gallon range. Under these conditions, increasing gasoline mileage from 35 to 70 miles per gallon will save this consumer less than $600 per year in gasoline costs. Tripling the mileage to 105 miles per gallon saves less than $800 per year. If the price of gasoline were doubled to $4/gallon, as it is in other parts of the world, these savings are doubled. It would seem that raising the price of gasoline would be a powerful lever in driving economic incentives to pay more for fuel efficient cars, though this is certainly a politically repugnant option. It would be hard to imagine average politicians, for whom reelection typically seems more important than the common good, passing laws to raise gasoline taxes to a point where there are sufficient economic incentives to spend thousands of dollars extra for fuel efficient cars.

So what is an environmentally conscious car manufacturer to do? One possible solution is to pursue a strategy aimed at "chasm crossing". This term refers to helping a new product make the transition from being a neat technical gadget for early adopter, "techie" types of customers to being a mass-marketable "whole product" solution for the "early majority" average consumer, the soccer mom who just wants a trouble-free way to get the kids to and from the game without worrying about the technology that gets them there. Early majority, or mainstream, consumers for any new technology need to be able to reference the experiences of other early majority consumers, which sounds a lot like another "chicken or the egg" problem. The early majority consumers are not interested in helping to debug an incomplete product. They want a complete solution that has been successfully implemented by others already. One way to do this is to find a neglected niche of consumers who are not being adequately served by the current technology, and devote a great deal of effort to completely satisfying that niche with a whole product solution. Once you have successfully satisfied this group, they can serve as references for the rest of the early majority, which should result in a snowballing effect supporting widespread public acceptance of the new technology.[46] A possible set of early adopters is proposed in the next chapter.

However, this probably will not be enough. The bottom line is that fuel cell technology at this point in automotive history is probably not quite ready for the mass market for a couple of reasons. First, the best fuel for fuel cells is hydrogen, and the infrastructure for getting it into the tanks of the average citizen's car is just not there, nor will it be there any time soon. If we use fossil fuels, then a fuel reformer will have to be used unless the direct methanol fuel cell can be commercialized rapidly, and reformer technology is just not yet ready for the mass market. Reformers add weight, add extra transient response time that makes larger batteries to satisfy power transients a near necessity, and add additional startup time for the system. It is not a robust, reliable technology that the average consumer will be comfortable with in such a critical application, at least not with the value that a typical consumer would perceive in the technology's current portfolio of benefits.

BP Amoco is investing in direct hydrogen technology. Their management does not believe that the proposition that each vehicle will roll around with its own hydrogen-generating reformer system is practical. Though they feel that widespread implementation of hydrogen-fueled engines (more specifically their distribution infrastructure) is still decades off, it is promising enough that BP Amoco does not want to forgo strong investment in the field.[47]

Another reason that reformers may not find widespread commercial success is that a reformer system will add over $500 to the cost of the methanol fuel cell system, and over $850 for the gasoline system.[34] The standard designs for partial oxidation reformers and their auxiliaries for gasoline can weigh over 600 kgs. The gasoline desulfurizer alone can weigh almost 500 kgs, though there is currently work on new designs weighing as little as 6 kgs. This would leave the rest of the reformer system weighing nearly 100 kgs.[17]

However, there are at least two ways of getting fuel cell designs into automotive applications. First, and unfortunately most likely, the government can step in and require a shift to this technology, regardless of cost. California has tried to implement this type of solution, by passing clean air laws requiring that 10% of all cars sold there by 2003 be zero emission vehicles. This requirement keeps getting pushed back due to technological arguments from auto manufacturers. If these are electrics, then they just shift the pollution elsewhere, as the power to charge the batteries will be generally produced by burning fossil fuels. Also, as the citizens of California have discovered, in some areas at certain times there is inadequate electrical capacity in the electrical power grid to charge thousands of electric vehicles every day.

Another answer is to gradually change the dominant design. This is a popular theme in the automotive industry. For the last 100 years, the basic ICE technology has not changed that much. The changes have been in how its operation has been managed. We have gone from carburetors to fuel injection, points to electronic ignition, mechanical or electric fuel injection and mechanical timing to digital engine control. We need to progress through the incremental technologies and move from direct mechanical drives to more electrically-oriented drive systems, which will shift consumer expectations toward those consistent with fuel cell propulsion. This incremental approach will also provide us enough time to perfect the fuel cell "whole product" to be a more acceptable and robust system for the average consumer.

4.2: Disruption

An important consideration in commercializing new technologies is whether the technology is disruptive to the current technologically paradigm or merely sustaining. This distinction can be made by several criteria, none absolute in their powers of differentiation.[42]

The emergence of a disruptive technology is heralded by, among others, the following characteristics: 1. There is an oversupply of performance from the existing technology, 2. The attributes of the disruptive technology that reduce its value in mainstream markets are its strengths in an emerging market, 3. The disruptive technology tends to be cheaper, simpler, and more reliable than the existing technology, and 4. The performance of the disruptive technology is increasing faster than that required by the consumers from the existing technology, allowing the disruptive technology to attack from below and eventually (and sometimes unexpectedly) exceed the performance of the existing standard.

Of course, one of the most important determinants in these discussions is that of which performance metric to use. Disruption usually occurs in a condition of oversupply of performance by the existing technology. If the metric is power output, or power density, then we can conclude that in the ICE realm there is a condition of oversupply of performance. The current ICE technology can provide us with all the power we demand the prospect of correcting these issues with materials innovations, though they believe that the technology is very well suited to applications in larger vehicles, such as buses and trucks.[24] Even so, other manufacturers are still considering the gas turbine as a possible ICE replacement. Ford's Synergy 2010 concept car, built in 1996, featured a hybrid power scheme which could be powered from an ICE, a gas turbine, or a fuel cell.[25]

2.5: 42-volt Electrical Systems

One serious limitation on the current automobile engine is auxiliary power drain from loads like air conditioners, water pumps, power steering pumps, electrical loads, valve timing chains and belts, and the auxiliary belts themselves. The next step in addressing this issue will probably be shifting the electrical system from the familiar 12-volt (actually 14-volt) system to what will be known as the 42-volt system. This system will have a 36-volt battery which will operate at 42 volts during vehicle operation, analogous to the current 12-volt system which operates at 14 volts during operation.[26] The 42-volt system will incur voltage peaks limited to 58 volts, which is less than the accepted industry standard of 60 volts in automotive applications.[27]

Currently, the typical car has a separate alternator and starter. The starter is a heavy electrical device that is used only while starting the car, then disengaged and carried around during operation. The alternator is a belt driven device that is capable of generating up to about 3 kW of power.[26] The current alternator design is coming up

First, we have to rule out that a fuel cell company could compete successfully as an automobile producer, at least initially. The automotive industry is a capital-intensive industry. The cars themselves will most likely continue to be manufactured and marketed by the incumbents who have the required complementary assets, such as the manufacturing facilities, developed supply chains, distribution systems, etc. These incumbents will not substitute an inferiorly performing technology and potentially lose market share unless they are forced to by regulation. If the auto were a simple device made up primarily of just a few simple components, then the standard arguments surrounding disruptive technologies would be more valid in this case. But the automobile is a complex system in a very competitive market, and the odds of getting the established manufacturers to jeopardize their market positions with a new, underperforming technology, are slim. It would only happen if the mechanical underperformance of the new technology were outweighed by the cost performance sufficiently to justify its purchase anyway. In the U.S. with our current low gasoline prices, it will be very difficult to do that without a much lower sticker price. Assuming that the new technologies will be more expensive for some time to come, the new "engine" will have to have equal or superior performance compared to the ICE, or it will not be used without regulatory motivation.

Secondly, automobile design is very heavily influenced by state and federal regulation in the U.S. Getting a car into production for the mass market requires millions of dollars in testing and red tape. One of the reasons that the Porsche 959 was never sold here because they could not justify crash testing 4 cars to meet safety regulations when each car could be sold for over a million dollars.

Current automotive fuel cell work by Ballard, International Fuel Cells, and others is being carried out in partnership with the major auto manufacturers. While fuel cells may find uses in new applications that their developers did not predict, as most disruptive technologies do, the specific application into which they are going to be forced into service, and with which we are concerned, is in automotive propulsion. Fuel cells may be a disruptive technology in powering other devices, like laptops, cell phones, and PDA's, where they will replace the battery power supplies in these devices through disruptive market forces. However, in cars, they will become dominant over ICE's in large part through government intervention before they would do so by normal market means.

Since the fuel cell will not be introduced into the mainstream market until its mechanical performance is comparable with that of the ICE or the government mandates it, and for the other reasons above that tend to invalidate the disruptive technology treatment, then I do not believe that analyzing fuel cell implementation in the sense of a purely disruptive technology is very useful. We should therefore treat fuel cells as another sustaining technology from the viewpoint of the consumer, as technology that will be best commercialized (to the consumer) by the incumbent car manufacturers. The same is true for the other technologies discussed so far. Chances are that none of these technologies would be implemented commercially in the U.S. without some type of regulatory interference in the market. The reason that we are even seeing them in the U.S. at all is as a result of the California Air Resources Board's laws regarding cars sold in that state from the year 2003 onward. These rules are being adopted by other states, like Massachusetts and New York, over time. Carmakers are going to be forced to get to the market with low or zero emissions vehicles or they will not be allowed to sell any vehicles in those states.

4.3: Analysis Framework

So, since the standard disruptive technology framework will not adequately describe the complex factors surrounding these technologies, another more generic framework may be more appropriate in this context. White (1978) provides a simple framework for evaluating the commercialization potential of a new technology. Of course, no framework can be 100% accurate in predicting how the market will respond to a new idea, but it helps to have an organized process through which an informed decision can be made.

In this framework, the innovation is evaluated on 4 fronts: Inventive Merit, Embodiment Merit, Operational Merit, and Market Merit. The first two factors determine the innovation's technology potency, how overwhelming the technology is compared to those it may be replacing. The second two describe the business advantage the implementer of the technology should enjoy.

The inventive merit specifically addresses how the new technology relieves the constraints of the old technology, also considering the constraints implicit in the new technology. Embodiment merit describes how much additional engineering is required in other parts of a product to fully realize the benefit from the new technology. It is evaluated on the type and number of additional component enhancements that are required to gain the full advantage of the new technology, and whether the new components dilute or enhance the benefits from the new technology. Finally, the additional embodiment is evaluated on whether it offers further opportunity for inventive enhancement. These two considerations make up the technology's technology potency.

Operational merit tries to capture whether the new technology will simplify or complicate business practices. It asks whether the firm's current business operations are suited to implement the new technology, or will be displaced or weakened by it. Does the business need to put new operations in place to support the new innovation and how hard will that be? Will this change be beneficial to the organization as a whole or not? Finally, market merit encompasses the effect of the technology on the final market size for the whole product. Does the final product significantly enhance the end user's experience and potentially expand the market, or will it just substitute for current product? Are there significant cost advantages in delivery of the product with the new technology? Are the benefits of the new technology relevant to the market? These two factors make up the business advantage provided by the new technology.[48][49]

A technology does not need to receive high ratings in every aspect to have a good chance of success. No one measure is necessarily more important than the others. However, by getting an overall picture using this method, we can get a better grasp of whether the technology has a good chance of success or does not, and why.[48][49]

I have attempted to evaluate the engine and fuel technologies in question in Exhibits 4 through 8. Each measure of merit was given a score between 1 (worst) and 5 (best) from the automobile manufacturers' points of view. I will use the sum of the scores to determine the technology and business advantage and then overall potency of the technologies. The scores are subjective based upon evidence provided on each. They are presented only as one opinion, and are subject to individual interpretation of the qualitative and quantitative data available. In the fuel discussions, the factors are evaluated only as they affect that fuel's implementation in fuel cells, and as such they should be evaluated against each other and not against engine technologies.

The final scorecard looks like this:

Electric: Technology potency: 3 Business advantage: 2 Total merit: 5
SI/CIDI: Technology potency: 5 Business advantage: 6 Total merit: 11
Hybrid: Technology potency: 7 Business advantage: 5 Total merit: 12
FC gen: Technology potency: 7 Business advantage: 3 Total merit: 10
H2 fuel: Technology potency: 2 Business advantage: 3 Total merit: 5
Methanol: Technology potency: 7 Business advantage: 7 Total merit: 14
Gasoline: Technology potency: 4 Business advantage: 7 Total merit: 11

While these results are fairly subjective, I believe that they do reflect the current relative market feasibility of the different technologies. They show that currently the hybrid technology is the most feasible, but fuel cell technology has significant promise. The best fuel in the is methanol, due primarily to the relatively benign reformer technology required compared to gasoline and the potential of designing a fuel cell that will run directly on methanol without a reformer. Obviously, gasoline's primary advantage is that its infrastructure is already well established, but its inefficiency in the reformation process and sulfur restrictions limit its appropriateness for fuel cell applications. Hydrogen suffers from its storage and infrastructure challenges, though it is the best fuel from a fuel cell design and operation standpoint.

A limitation of this model is that the embodiment factor is supposed to deal with only with the devices on the device itself that enhance or dilute the technology, but this ignores critical infrastructure issues. I have also included fuel infrastructure and other fuel issues. The same effect occurs in the operational factor and market factor, where I had to blur the line between the effects on the automobile manufacturers and the oil companies. This is a simple model which is being applied to a complicated problem and some shortcomings are inevitable, but it is a valid framework for basic analysis.

Chapter 5: Approaching the Market

5.1 Possible Introduction Schemes

Based on my personal experience and the limited market data presented previously, I believe that while the average American consumer is somewhat concerned about the environment and the impact of the internal combustion car engines upon it, he/she is not going to make any significant personal sacrifice, either in terms of convenience or finance, to do what will be required to make any significant headway in correcting the situation. That is not to say that no one will. There is a niche of individuals for whom fuel economy is a real concern, either for environmental or financial reasons. For example, there were 3250 electrical vehicles in use by the end of 1999.[50] Honda's original sales projections for its new Insight hybrid vehicle came up short by 50%, and they have upped their target to 6500 units per year.[19]

I believe that the average American will only accept the fuel cell powered car if the shift is made gradually. The problem is that we must take immediate action to curb our greenhouse gas emissions. Our current consumption habits indicate that the masses do not believe that we may have a crisis looming on the very near horizon. The only solution that currently appears feasible is to charge people for their emissions, through higher gasoline prices or significant taxes on sales of high consumption vehicles that give consumers a real incentive to buy fuel efficient cars. In the meantime, we must continue to encourage the development and production of fuel efficient vehicles like the currently available hybrid vehicles, hopefully driving their production costs down in the process so that they will be profitable endeavors for the manufacturers. Our immediate concern should be to squeeze every bit of efficiency out of our current technology, and use incremental changes to pave the way for eventual fuel cell power. One of our goals in this program will be to drive electrification of loads like air conditioners, power steering pumps, and intake and exhaust valves to familiarize consumers and service organizations with this scheme and improve fuel economy at the same time. The 42-volt program will be a critical part of this effort. The earlier we maximally electrify our cars, the earlier they become commonplace, the earlier we work the unforeseen bugs out of the complicated control equipment required to make it work, and the earlier we drive down their cost before the more expensive power generation changes are made.

It is my strong belief that the "chicken and egg" problem inherent in any discussion of new automotive technology, and especially here, will be best solved by starting out with local fleet operators, like government or utility vehicles. A fleet car's use is generally constrained to a local area travel, and can therefore be fueled at a central location without worrying about developing fuel distribution facilities in less populated areas. Many fleets have central gasoline fueling facilities already. In 1996, there were over 9 million cars in the U.S. in fleet applications. The government alone operated over 1.2 million, not including military vehicles, while utilities operated over 300,000.[51] Ballard would need annual production of 300,000 fuel cell power units per year to be cost competitive with ICE's.[33] The government could accomplish this all by itself if it replaced its government cars on a 4-year lifetime basis. There are 2 obvious problems with this plan.

One is that these vehicles would hopefully have a much longer lifetime than ICE vehicles due to their reduced susceptibility to mechanical wear, so after initial deployment, demand will have to shift elsewhere to sustain production levels. There are other fleet applications, like taxis (130,000 in U.S.) or other business fleets. Other businesses operate 1.3 million cars in the U.S.[51] Tax incentives could be used to encourage alternative vehicle use by commercial fleets. Secondly, the fleet operator would have to have a plan for the disposition of the vehicles once the operator is ready to replace the vehicle. For operators who currently sell the vehicles as used to the public, they will have significant difficulty doing so if during the interim, no public infrastructure has been developed. They will be forced to keep them until they are ready to be scrapped. Third, one has to realize that the CEO of a fuel cell company may be optimistic in his estimation of requirements for profitability of his firm, so estimates of breakeven production levels would have to be considered best case and subject to change.

As fleet use builds, reliability is improved, production costs come down, the public gets more exposure to the technology, and the fleet operators become reference points for the mass market. If this experience is a positive one, then the public fuel distribution companies will begin to see an economic driver for developing infrastructure for the general public, and the technology hopefully will gain a substantial toehold in the mass market while minimizing government mandates that adversely disrupt mass market forces. If the market tips to a certain fuel, the government may have to step in initially to regulate fuel pricing until the market stabilizes.

Obviously, in targeting specific implementation fleets, severity of use should be considered. These vehicles would be inappropriate as police cars, for example, where high performance is frequently required. However, for a driving school operator, or the parents of teenagers, these cars would be a Godsend.

Local municipalities and states can also give incentives for adopting fuel efficient technologies. They can give excise, income, and property tax breaks to individuals who invest in fuel efficient cars. Having ample, low cost, designated parking areas for these cars in congested areas would be a huge incentive for buying one.[52] Giving them HOV access regardless of number of occupants would help.

The bottom line of any scheme of introducing new technologies to the automotive market is to try to start with a small niche that can be well served by the new technology and then drive the technologies toward wider acceptance through positive feedback effects. The best niches would be characterized as those where people do not drive long distances from a central location and do not need high performance. There are fairly strong network effects at play here, just as in the information industry, due to the massive infrastructure requirements of any new fuel paradigm. This goes back to the chicken and egg problem discussed before. Without an installed base of new technology cars requiring the new fuel, it will be hard to convince anyone to make large capital investments in the new fuel infrastructure. The whole problem will be driven by the installed base of vehicles. As the installed base gets larger, several effects occur. The perceived risk of owning the new vehicle goes down. The fuel infrastructure becomes more ubiquitous as it becomes more profitable to service the larger installed base, which in turn makes the vehicle more convenient to own. Also, as the number of vehicles produced rises, the cost to the manufacturers and consumers will drop. All of these effects will make consumers more willing to change to the new technology, which will be a positive feedback effect to the growth of the installed base. The added experience gained with cumulative production and usage will allow faster learning and rapid improvement of the technology's performance and reliability to better serve mainstream consumers without the niches' limitations. As the potential user pool drops, these effects, especially the cost reductions and technology improvements, will grow the potential user pool, which will again increase the adoption rate and grow the installed base. By planting the initial installed base in the beginning with niche users, we can "prime the pump" of technology adoption and hopefully guide the new technology with added initiatives and benefits to widespread acceptance through these positive feedback effects. This model is shown graphically in Exhibit 9.[53]

5.2: Current Experiments

Fuel cells are being evaluated in operating city bus fleets. The cities of Chicago, Illinois and Vancouver, B.C. each tested 3 Ballard hydrogen-powered fuel cell buses 1998 from 1998 to 2000. This is a perfect application for this technology as city buses are found in high pollution areas, they do not have severe space constraints onboard the vehicle, they can easily be centrally fueled, and their operators do not require rapid power transient handling capabilities in their operation. Therefore buses are excellent test and development platforms for new technologies. Trials like these allow the manufacturers to get real world information on the reliability and practicality of their systems and permit meaningful improvements to be made prior to implementing mass market applications of the technology. The bus test programs were concluded in year 2000 and were regarded as successes by Ballard and its industrial partners as well as the transit systems involved. These Phase 3 tests will be followed by Phase 4 tests with improved designs based upon the results of the Phase 3 tests.[54] Transit bus designs have also been developed by International Fuel Cells, a subsidiary of United Technologies, as well as other fuel cell manufacturers.[55]

There are also many concept car projects which are currently underway or already completed. DaimlerChrysler has recently introduced a concept Jeep Commander SUV which runs on reformed methanol using a battery to assist in handling power transients and also using regenerative braking. Daimler-Benz has also produced the Necar 5, which runs on a methanol-fuelled fuel cell. General Motors has developed its Precept concept car which they believe will achieve 108 miles per gallon. They are developing reformer technologies which will allow the use of gasoline in PEM fuel cells, and have announced their intention to have a fuel cell car on the market by 2004. Ford is working with Ballard and DaimlerChrysler to have a hydrogen-fuelled vehicle available in California soon. Ford has unveiled its TH!NK FC5, which is a methanol-fuelled family sedan Ballard has also been working on the direct methanol fuel cell which needs no reformer system onboard. They are currently accepting orders from automobile manufacturers for the 75 kW Mark 900 fuel cell. International Fuel Cells (IFC) is working on unpressurized fuel cells designs, and has demonstrated a 50 kW unit which can be coupled to a gasoline reformer to power a passenger car. They are currently looking to form a partnership with a car manufacturer to commercialize this technology. BMW has developed a 7-series car that will use a hydrogen combustion engine to move the car, but use a fuel cell for all electrical loads. All of the major Japanese manufacturers are also producing fuel cell prototypes.[55] While it is obvious that much work is being done, it is still a major challenge to commercialize these designs, especially with the wide variety of approaches. The effort will be greatly facilitated by settling on a standard design.

Chapter 6: Conclusions

The movement toward electrification of automobiles will give us opportunities that we currently do not enjoy in terms of safety, design, and functionality. With the current state of power plant design, we are forced to have a bulky ICE unit with auxiliaries like air conditioners and alternators mechanically driven by belts, adding to the bulkiness of the power unit. The ICE design itself is constrained by the mechanical systems which operate critical subsystems like the intake and exhaust valves.

Electrification will alleviate these design constraints. Designers will be allowed to put auxiliaries wherever they best fit in the car. The power plant size will be reduced due to the removal of the mechanical drives on the auxiliaries. Also, the higher useful power output afforded by the more efficient auxiliary power generation and greater control flexibility gained over valve timing will allow smaller engines. The reduced power requirements from body design improvements allowed by the smaller power plant will further improve engine sizing. Maintenance on the new designs should also be easier with fewer interfering parts, like belts, to get in the way.

Once the leap is made to fuel cells, or at least series hybrid designs, then constraints of mechanical linkages between the power plant and the drive wheels also disappear. The plate stack of the fuel cell power plant can be designed to be placed anywhere the designer wants to put it, allowing further flexibility in the overall vehicle design. This will permit a stronger influence from other factors like safety to dominate the design features of the vehicle instead of mechanical system layout. The designs will be more aerodynamic, safer, and efficient than currently allowed.

While it was stated earlier that the in the near future the established automobile manufacturers would be the only firms with the ability to build cars with the new technologies, these same new technologies could one day allow the vehicle design to be so modularized that car manufacturing could indeed become similar to computer manufacturing, where a new firm just buys the components from suppliers and builds cars in smaller but still efficient plants.

All of these benefits are added on top of the benefits of reduced emissions, reduced fuel cost, and reduced energy waste, which in themselves would be more than adequate justifications for pursuing these more fuel efficient technologies. However, one of the most important and, up until this point, neglected points that needs to be made in any study such as this one or any other on this topic is one of perspective. While automobile emissions are a concern for greenhouse emissions as well as other pollutants that directly affect our health, they still only account for 20% of the overall anthropogenic greenhouse gas emissions. So even if we are able to run our cars on hydrogen produced by a solar or wind powered electrolytic process, we only reduce our overall CO2 emissions by 20%. We will still be conducting industrial operations, operating electrical loads that get power from fossil fueled power plants, and conducting other activities in our everyday lives that emit CO2. In 1998, the transportation sector, including not just cars, but also trucks, airplanes, and other modes, accounted for 31% of total CO2 emissions, and two-thirds of this amount was from gasoline combustion in motor vehicles. The electric utilities accounted for 37%, while residential and commercial activities produced 6% and 4% of emissions, respectively, and industrial fuel consumption accounted for 22%.[4] So while highway transportation receives considerable attention in the global warming debate, we must also be concentrating on what we will do in other areas, especially our growing appetite for electrical power.

As mentioned earlier, we are forcing fuel cells into an application for which they are not particularly well suited in an attempt to partially preempt a potential environmental crisis. In the automotive application their benefits are significantly diluted by the weight and complexity added by reformers and gaseous storage schemes as well as infrastructure issues. While this is a noble goal, there are still significant problems to be overcome. For the sake of acceptance of the fuel cell itself, we should also just as vigorously be pursuing uses where it is more naturally suited for use and more likely to find commercial success. A great application would be as a backup power supply in residential and business structures. In this type of application, no one will care how much the whole system weighs and space is not nearly as limiting a factor. A large, low pressure hydrogen flask sitting in the corner of the room is more likely to be accepted than a high pressure flask going 70 mph on the interstate. They could run off of natural gas piped into the system from normal lines, obviating the requirement for onsite storage altogether. As data centers, hospitals, and other businesses become more reliant on stable, uninterruptible power, this application becomes more appropriate.

In areas where declining reserve electrical power supplies are a major issue, this technology could have a major impact. If a reversible fuel cell design could be developed which could produce hydrogen from water using grid power during off peak hours, then generate power through normal operation by using the stored hydrogen during the peak hours, we could move toward more self sufficient homes and businesses. Producing hydrogen from solar or wind power for use during peak hours would allow even greater self-sufficiency and reduce required investments in new power generation and transmission infrastructure.

Overall, I feel that we should pursue this technology for automotive applications, but there are also other applications for which it will be viable and these should also be pursued with as much interest and urgency. Doing this would also expose the general public to the technology in a better light, and make them more likely to accept fuel cells in cars in the future.

Time will tell whether fuel cells are a disruptive technology. If we believe that their adoption will be critical to our survival in the long run, then hopefully they are not. We are taking these technologies and forcing their employment in the automotive propulsion application. Study of disruptive technology reveals repeatedly that the early attempts to pinpoint the most viable application for the technology by the developers will invariably be wrong. It is quite possible that we cannot afford to be wrong.

Exhibit 1: United States Oil Imports (1999)

(thousands of barrels)

Petroleum Imports from Persian Gulf Nations	884486
Petroleum Imports from Algeria	93192
Petroleum Imports from Nigeria	238081
Petroleum Imports from Saudi Arabia	531362
Petroleum Imports from Venezuela	528220
Petroleum Imports from OPEC	1771180
Petroleum Imports from Canada	550065
Petroleum Imports from Mexico	474490
Petroleum Imports from United Kingdom	128278
Petroleum Imports from Virgin Islands and Puerto Rico	103786
Petroleum Imports from Total Non-OPEC	2080053
Petroleum Imports	3851233
Petroleum Imports from Persian Gulf Nations as Share of Total Imports	22966
Petroleum Imports from OPEC as Share of Total Imports	45990

Source: United States Environmental Protection Agency [7]

Exhibit 2: United States Petroleum Consumption by Sector (1999)

(thousands of barrels)

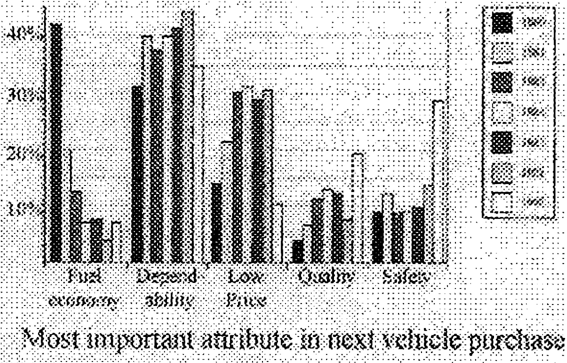
Aviation Gasoline Consumed by the Transportation Sector	7784
Distillate Fuel Consumed by the Transportation Sector	862636
Jet Fuel Consumed by the Transportation Sector	608322
LPG Consumed by the Transportation Sector	4362
Lubricants Consumed by the Transportation Sector	30301
Motor Gasoline Consumed by the Transportation Sector	3010451
Residual Fuel Consumed by the Transportation Sector	128223
Petroleum Consumed by the Transportation Sector	4652080
Residual Fuel Consumed by Electric Utilities	126117191
Distillate Fuel and Kerosene (Light Oil) Consumed by Electric Utilities	22750966
Petroleum Coke Consumed by Electric Utilities	8038
Petroleum Consumed by Electric Utilities	156906
Petroleum Consumption	7076895

Source: United States Environmental Protection Agency [7]

Exhibit 3: Consumer Preferences in Automotive Features over Time

Figure 9

Expressed demand for fuel efficiency has declined



Source: DOE, 1997. Based on J.D. Power data for 1980s and Opinion Research Corporation survey in 1996 performed for NREL, with data normalized to sum to 100% [43]

Exhibit 4: Merit Analysis of Battery-Electric Drive

Inventive merit: Score....2
Constraints removed:
1. Removes most "regular" and "irregular" maintenance associated with ICE's (oil changes, tune-ups, belts, spark plugs, head gaskets, etc.).
2. No noise,
3. No transmission weight or other associated losses.
4. No belt drive and mechanical-electrical conversion losses.
Constraints added:
1. Adds the constraints of limited range (requires another vehicle for trips longer than 50 miles away)
2. Battery charge time can be excessive.
3. Vehicle size must be reduced while batteries take up significant interior space.
4. Battery weight.
5. Battery cost.
Embodiment merit: Score...2
Additional components:
1. Electronic controls.
2. Battery storage compartment
Dilution or enhancement:
1. Requires a lightweight body with most limited extra room taken up by batteries.
2. Requires recharging equipment.
3. Widespread use will require more electrical power generation capacity in certain areas of country, especially in California where earliest implementation is mandated.
Additional opportunity:
1. Higher capacity batteries will aid in their success.
Operational merit: Score....1
Displaced business operations:
1. Engine and transmission manufacturing.
2. Hopefully will require less maintenance support, but this will reduce maintenance revenues.
New business operations:
1. Service organizations will have to support more types of technologies.
2. The new vehicle will require new manufacturing infrastructure to produce
3. New battery manufacturing/lead smelting facilities.
Market merit: Score....2
Enhanced effectiveness to final user:
1. Low noise.
2. Refueling can be done at home.
Reduced cost:
1. Lower maintenance to user, but higher manufacturing cost.
Expansion or substitution market:
1. Can be envisioned radically affecting long term automotive market, since mechanical wear of ICE's and mechanical auxiliaries is currently a major determinant of vehicle life.
2. Will replace, not expand, current market

Exhibit 5: Merit Analysis of SIDI/CIDI Engines

Inventive Merit: Score....2
Constraints removed:
1. Increases fuel economy.
Constraints added:
1. Requires sulfur elimination from fuel.
Embodiment merit: Score....3
Additional components:
1. High pressure fuel systems.
Dilution or enhancement:
1. Dilution due to increased weight of fuel delivery system.
2. Requires desulfurized gasoline in current configuration.
3. Requires lean catalyst system.
Operational merit: Score....4
Displaced business operations:
1. None.
New business operations:
1. New groups to implement and manage the technology, e.g. emissions systems.
Market merit: Score....2
Enhanced effectiveness to final user:
1. Better fuel economy.
Reduced cost:
1. None to manufacturers, better fuel economy to final users.
Expansion or substitution market:
1. Substitution.

Exhibit 6: Merit Analysis of Hybrid Gasoline/Electric Drive

Inventive merit: Score....4
Constraints removed:
1. Removes constraints of high local emissions.
2. Current designs can eliminate all idle emissions and fuel consumption.
3. High fuel economy
4. Reduces engine size for given peak power requirement.

Constraints added:
1. Relatively anemic mechanical performance. Embodiment merit: Adds constraint of space taken up by batteries and battery weight, constraint of more electrical/electronic controls. Enhanced by lightweight body, regenerative braking capability, higher capacity batteries.

Embodiment merit: Score....3
Additional components:
1. Starter/alternator combined unit.
2. Electronic controls.
3. Larger battery.
4. Regenerative brakes.

Dilution or enhancement:
1. Extra battery weight.
2. Enhanced electrical power generation capability.
3. Smaller engine gives design flexibility.

Operational merit: Score....4
Displaced business operations:
1. Can eliminate transmission manufacture and design with series design.

New business operations:
1. Requires new expertise in manufacture and service.
2. Alliances with battery and motor manufacturers.

Market merit: Score....1
Enhanced effectiveness to final user:
1. Higher range, fewer refueling stops.

Reduced cost:
1. Fuel cost.
2. Currently being sold at a significant loss.

Expansion or substitution market:
1. Will replace compact cars, no significant market expansion.

Exhibit 7: Merit Analysis of Fuel Cells (General)

Inventive merit: Score....3
Constraints removed:
1. Removes constraint of high local emissions (not all unless hydrogen powered) and emissions-related regulatory constraints,
2. Allows greater vehicle design flexibility
3. Eliminates noise.
4. Removes transmission weight and associated losses
5. Eliminates belt drive and mechanical-electrical conversion losses.
6. Provides mobile power station capability without running mechanical generator.

Constraints added:
1. Increased startup time
2. Currently inferior power output compared to ICE
3. Slower transient response.
4. Requires very clean fuel

Embodiment merit: Score....4
Additional components:
1. Electronic controls.
2. Drive motors.
3. Regenerative brakes can be used with larger battery capacity.
4. Switch to electric auxiliaries

Dilution or enhancement:
1. Adds convenient mobile power generation capability
2. Allows for simpler, more modular power supply arrangement and facilitates more flexible vehicle layout.
3. Elimination of transmission and starter/alternator reduces weight
4. Electrical auxiliaries enable flexibility in their design and design of vehicle.
5. If larger battery required for transient response, adds constraint of larger battery.
6. Extra electronic control equipment uses power and adds weight.

Operational merit: Score....2
Displaced business operations:
1. If outsourced, no motor, transmission manufacturing capability required.
2. Much of current service organization displaced.

New business operations:
1. Fuel cell sourcing organization, unless brought in house, then need new manufacturing organization to manufacture fuel cells.
2. New type of service organization.
3. Should be able to sell through existing channels.

Market merit:
Enhanced effectiveness to final user:
1. Removes all "regular" and much "irregular" maintenance associated with ICE's (oil changes, tune-ups, belts, spark plugs, head gaskets, etc.).
2. Mobile power station capability.

Reduced cost:
1. Higher cost now, though eventually can see reduced cost for fuel cell over ICE.

2. Reduced vehicle manufacturing cost due to higher design flexibility.
3. Fuel economy.

Expansion or substitution market:

1. Will replace existing market, should not expand market significantly in short term.
2. Can be envisioned radically affecting long term automotive market, since mechanical wear of ICE's and mechanical auxiliaries is currently a major determinant of vehicle life. Fuel cell vehicles will not have this constraint. Score....1

Exhibit 8: Merit Analysis of Fuel Cell Fuels

Hydrogen Fuel

Inventive merit: Score....2
Constraints removed:
1. Eliminates local emissions
2. Greatly simplifies fuel cell system design.
3. Production from hydrocarbons more than halves CO2 emissions in production of H2.

Constraints added:
1. Electrolytic production adds greater CO2 emissions overall in the hydrogen production process given current electrical power generation scheme.
2. Production from hydrocarbons releases NOx.
3. Requires exotic fuel storage schemes.

Embodiment merit: Score....2
Additional components:
1. Greatly simplifies fuel cell system design compared to hydrocarbon fuel-fewer components.
2. Eliminates emission controls equipment on vehicle.
3. Requires exotic fuel storage schemes.
4. High pressure systems will require fully automated refueling system.

Dilution or enhancement:
1. Exotic storage schemes will add more weight.
2. Storage schemes will take up more space and constrain interior space.

Operational merit: Score....2
Displaced business operations:
1. Fuel groups at manufacturers will be displaced.

New business operations:
1. Requires new type of service organization and equipment.
2. Requires entirely new fuel manufacturing and distribution infrastructure be deployed.

Market merit: Score....1
Enhanced effectiveness to final user:
1. None.

Reduced cost:
1. Reduced cost for reformer/fuel cell system.

Expansion or substitution market:
1. Automotive market affected as described in general discussion.
2. Will significantly reduce gasoline production and retail business.
3. Will create whole new markets for hydrogen producers, hydrogen distribution equipment firms, and hydrogen retailers.

Methanol Fuel

Inventive merit: Score....4
Constraints removed:
1. Allows conventional fuel storage scheme.

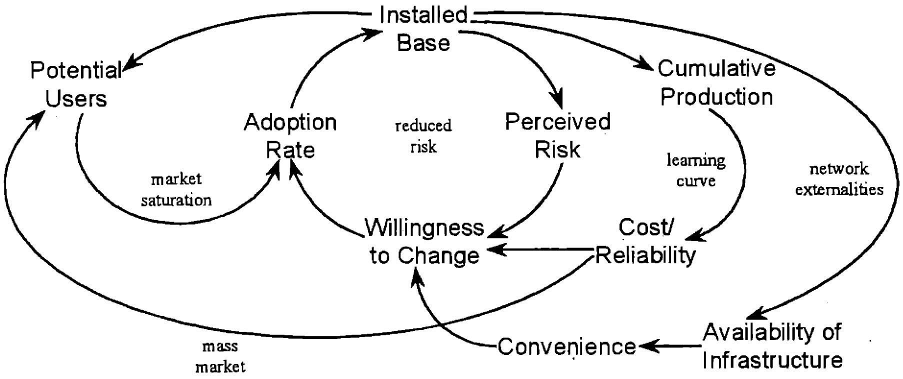
2. Can be used without reformer system in new direct methanol fuel cells under development.
Constraints added:
1. Adds constraint of material selection in fuel systems (corrosive to aluminum, for example).
2. Slightly more poisonous than gasoline.
3. Must put reliable systems in place to keep gasoline and methanol systems and parts segregated.
<u>Embodiment merit</u>: Score....3
Additional components:
1. Initially will require reformer onboard.
Dilution or enhancement:
1. Dilutes advantage through reduced efficiency, space requirements, and added weight.
<u>Operational merit</u>: Score....4
Displaced business operations:
1. Allows use of current skill sets in fuel system design.
2. Allows existing distribution system with affordable modifications.
New business operations:
1. Will require modification of existing refueling infrastructure.
<u>Market merit</u>: Score....3
Enhanced effectiveness to final user:
1. Automotive market affected as described in general discussion.
Reduced cost:
1. Cost to manufacturers nominal, market cost will probably be roughly same overall.
Expansion or substitution market:
1. Will significantly reduce gasoline production and retail business.
2. Will create whole new markets for methanol producers and methanol distribution equipment firms.
3. Will substitute for gasoline at service stations.

Gasoline Fuel

<u>Inventive merit</u>: Score....2
Constraints removed:
1. No new fuel system technology required on board.
Constraints added:
1. Sulfur content must be eliminated before use in fuel cells.
2. POX reformer systems running on gasoline produce CO (a fuel cell poison) which will reduce performance of the fuel cell.
<u>Embodiment merit</u>: Score....2
Additional components:
1. Requires reformer.
2. Requires desulfurization equipment on board if gasoline is not desulfurized.
Dilution or enhancement:
1. Reformer system adds weight and reduces efficiency.
2. Desulfurization equipment adds weight and maintenance.

Operational merit: Score....4
Displaced business operations:
1. None.
New business operations added:
1. Will require either sulfur removal at the refinery (and subsequent segregation from regular fuels) or onboard desulfurization equipment, requiring business units to deal with the added equipment.
Market merit: Score....3
1. Use in fuel cell cars will reduce gasoline demand now enjoyed by industry.

Exhibit 9: Technology Diffusion Model



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