American Energy Policy and Alternatives to the Internal Combustion Engine

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Introduction

With gasoline at a record $2.50 a gallon in the United States, and with the passage of the Energy Policy Act of 2005, now is a good time to see where the United States has been and where it might be heading in the near future, in regard to automobiles and government policies to regulate their efficiency. In this paper, I will first look at the recent history of American energy policy as applied to the transportation sector. Particular focus will be on the Energy Policy and Conservation Act of 1975 and the automobile industry's response to this legislation. Second, two new automobile engine technologies—the hybrid and the hydrogen fuel cell automobile—will be briefly described and then analyzed in terms of their technological, economic, environmental, and energy efficiency potentials. Finally, I will speculate on the automobile and American energy policy of 2025.

American Energy Policy and the Automobile from 1970 – 2005

Unlike Europe, this country had no explicit energy policy until 1975. However, there was an implicit one, namely the right of all Americans to buy inexpensive gasoline. Consequently, unlike Europe where the federal government imposed significant taxes to discourage gasoline usage, there was only a modest federal tax on gasoline in the United States to support the building of more and wider highways. The implications of cheap gasoline on America were profound. It meant that Americans could afford to travel long distances from their homes to their places of work—in other words, the creation of the suburban lifestyle and the abandonment of the American cities; the creation of a massive highway system and the abandonment or neglect of most forms of public transportation; the necessity of almost everyone over the age of fifteen to own their own car; and the marketing of cars with an emphasis on power and performance, and a de-emphasis on energy efficiency. Equally significant is the American culture that grew up along side the automobile, a culture that equates large, powerful automobiles with sexual prowess for men, safety and security for women, a culture that is still very prominent to this date. For example, analyzing present-day automobile advertisements on television or in magazines provides ample proof that appealing to these cultural ideas is still the standard method of selling cars.

The Arab oil embargo of 1973-74 changed the relationship between the federal government and the automobile industry.[1] For the first time, the federal government recognized the need to reduce America's consumption of oil and in particular her dependence on foreign oil. It became federal government policy to encourage energy efficiency in the automobile industry. In particular, the Energy Policy and Conservation Act of 1975 mandated significantly greater fuel efficiency of automobiles in its Corporate Average Fuel Efficiency (CAFE) standards. The CAFE standards required that a manufacturer's entire fleet of passenger cars achieve an average of 27.5 miles per gallon (mpg) and its light trucks (8,500 lbs or less and with two axles), an average of 20.7 mpg by 1985.

These CAFE standards were a major technological challenge for the automobile industry, but they were further complicated by new environmental standards from the Clean Air Act of 1970. This act mandated dramatic reductions (approximately a 90% reduction) in emissions of carbon monoxide, nitrogen oxides, and unburned hydrocarbons. The technological fix to achieve these lower emission levels was the catalytic converter. Since the catalytic converter was poisoned by leaded gasoline, cars had to run on unleaded gasoline. And because lead was needed to prevent pre-ignition during engine operation at high compression ratios (typical ratios were around 14 in 1975), new automobile engines had to run at much lower compression ratios (typical ratios were around 7 in 1985). Unfortunately, the efficiency of an automobile engine is directly related to its compression ratio, such that the reduction in compression ratios from 14 to 7 leads to a 17% reduction in engine efficiency (in other words, if no other changes were made in an automobile, a reduction in its compression ratio from 14 to 7 would reduce its miles per gallon by 17%).

As an historical aside, it is interesting to note that the Clean Air Act of 1970 did not require any reduction in the amount of lead in gasoline, even though all the lead in gasoline was emitted out the exhaust and into the air where it was inhaled by the public. It was well known in 1975 that lead was a serious health problem, causing neurological problems and brain damage. However, in 1975, it was believed that leaded gasoline was essential for a viable automobile. The elimination of leaded gasoline was an unintended, but extremely important, consequence of the Clean Air Act of 1970.

Remarkably, between 1975 and 1985 the automobile industry raised its fleet average passenger cars efficiency from about 14 mpg to 27.5 mpg and its light truck efficiency from about 10 to 20.5 mpg while also meeting the new pollution standards. The higher efficiency was accomplished by making cars significantly smaller, lighter (the weight was approximately reduced by a third), and more aerodynamic (soap-bar shaped cars replaced sharp-edged fins). Plastics replaced steel. Front-wheel drive cars with their lock-up torque converter and automatic overdrive transaxles replaced rear-wheel-drive cars with their lengthy, heavy and inefficient transmission systems.

Unfortunately, the automobile of 1985 was not well received by the buying public, because the low compression ratio meant a car with poor acceleration. In response, a second technological revolution of the automobile came in 1985 with the advent of the fuel-injected engine. The basic idea of the fuel injected engine is that the gasoline is injected into the cylinder (combustion chamber) under computer control, so the fuel/air ratio can be very accurately controlled. There is an oxygen sensor in the exhaust pipe that monitors the fuel/air ratio, and provides the input to the computer that controls the injectors. Previously, automobiles had carburetors where fuel and air were mixed in approximately the right ratio before being drawn into the cylinders. This fuel-injector technology achieved two goals. First, by the careful control of the fuel/air mixture, the catalytic converter will eliminate 99% of the emissions. (At present, Honda Motor Company has developed a exhaust system with two catalytic converters in a row, which eliminates 99.9% of the emissions; Honda claims that when a Honda automobile with the two catalytic converters is driven in Los Angeles, the air from the exhaust is cleaner than the air it takes in. Namely, that Honda is not only an automobile, it is a traveling air cleaner.[2]) Second, the fuel injector technology increases the engine's efficiency in two ways: first, by injecting the fuel in the center of the cylinder and away from the wall, it insures that more of the fuel is burned during combustion (the cooler walls of the cylinder cool the gasoline vapors and lead to incomplete combustion). Second, by carefully adjusting the fuel/air ratio, it permits the automobile to operate at a higher compression ratio, and consequently, greater efficiency. With the development of new hydrocarbon additives that suppress pre-ignition and with fuel injection, today's automobile typically operates at a compression ratio around 10, achieving good acceleration and improved efficiency.

Table 1 lists the number and average efficiency (miles per gallon) of licensed automobiles and light trucks on the road in the United States as a function of time.[3] Also included is a weighted average of the efficiency of both automobiles and light trucks. It is important to remember that the average automobile or light truck is on the road for 15 years, so the numbers in Table 1 include cars that were manufactured over 15 years before the year listed. Notice that since 1990, a disturbing trend is emerging—namely, the dramatic growth in light trucks. This is in reality a growth in minivans and SUVs (sport utility vehicles) that are in practice automobiles, but under pressure from the automobile industry, are categorized as light trucks so they fall under the lower CAFE standards. The consequences of this trend can be seen more dramatically in the average efficiency of all automobiles and light trucks manufactured in a given year. The fleet fuel economy for all automobiles and light trucks manufactured in a given year peaked in 1987 at 26.2 mpg when light trucks made up 28.1% of the market; by 2001, with light trucks making up 46.7% of the market, the total 2001 fleet economy fell to 24.4 mpg.[4] In recognition of the growing impact light trucks have on America's oil usage, in

April of 2003 the National Highway Traffic Safety Administration set new fuel economy standards for light trucks of 21.0 mpg for 2005, 21.6 mpg for 2006 and 22.2 mpg for 2007. Standards for years beyond 2007 are presently under serious debate by the Bush administration.

It is worth editorializing about the decision to categorize SUVs and minivans as light trucks in regard to the CAFE standards. It came at a time of low oil prices and when the memory of the 1973 Arab oil embargo had faded. I believe we will look back at this decision--which was largely unnoticed and not debated at the time it was made--as one whose disastrous consequences will cost this country dearly for many years to come. This decision permitted the purchase of millions of inefficient automobiles that will be with us for at least the next twenty years and permitted the American automobile industry to avoid the painful corporate changes needed to design and develop competitive efficient automobiles. .

Hybrid Automobiles

In the last few years, two new automobile engine technologies have emerged as possible replacements for the standard automobile engine. One is the hybrid automobile engine, and a schematic of the Honda Hybrid is shown in Figure 1. The key new elements in the hybrid are an electric motor/generator (#1 in Figure 1), that is between the gasoline engine (#2) and the transmission (#3); a battery pack (#4) in the rear of the car that provides the electricity to power the electric motor; and a very efficient small gasoline engine (#2) that is either on or off and both powers the car and charges up the battery.[5] It is important to emphasize that all the energy that drives a hybrid comes from gasoline; the hybrid just more efficiently uses that gasoline.

A sample trip will illustrate the operation of a hybrid. When the automobile accelerates from start, both the gasoline engine and the electric motor provide the needed power. When the automobile reaches cruising speed, either the gasoline engine powers the car and charges up the battery, or when the battery is charged up, the gasoline engine turns off and the electric motor powers the car. During cruising, the gasoline engine and the electric motor alternate, a process controlled by a computer to assure a smooth drive. During braking, the gasoline motor is shut off, and the electric motor becomes an electric generator, both breaking the car and converting some of the car's energy of motion into electrical energy stored in the battery. This is called regenerative braking. Finally, when the car is at rest, for example at a stop sign, the gasoline engine is off and the electric motor is not drawing current from the battery.

The Toyota Prius and the Honda Civic Hybrid are rated at about 50 mpg. The most significant energy savings are during city driving, where the regenerative braking contributes and where no energy is lost during idling. During highway driving, the smaller energy savings comes from the use of a small, very efficient gasoline engine. For example, the Toyota Prius reports 60 mpg for city driving, 51 for highway; it achieves this outstanding fuel efficiency with an internal combustion engine operating at a compression ratio of 13.[6]

There are a number of significant questions about this technology. First, there is the question of the reliability of this technology. In particular, there is a concern about the life expectancy of the battery packs; if they have to be replaced every few years, it will add significantly to the overall cost of operation. Second, there is a concern about electrical shocks during or after automobile collisions. In 2004, about 30,000 hybrids were sold in the United States; in 2005, the number has been estimated at 200,000. Given the large number of hybrids on the road, these reliability and safety questions will be resolved shortly.

Finally, the Energy Policy Act of 2005, that just passed Congress and was signed by President Bush, included a tax incentive for the purchase of hybrids. Individuals can earn a tax credit of up to $3,400, depending on the size of the vehicle and the number of hybrids an automaker sells.[7]

Hydrogen Fuel Cell Automobiles

The hydrogen fuel cell automobile is the major candidate for the automobile of the future, in the opinion of both the Bush administration and many major automobile manufacturers. This opinion is reflected in the large amount of research and development dollars spent developing this technology, both by the federal government's Department of Energy and the major automobile companies. Strong supporters of the hydrogen fuel cell include Amory Lovins[8] and Joan Ogden.[9] A more balanced approach comes from Mathew Wald[10] and the American Physical Society.[11] Robert Service[12] and Steven Ashley[13] take a more skeptical position.

The hydrogen fuel cell is fundamentally a battery that operates with hydrogen gas and air (oxygen gas) as its fuel, electricity as its output, and water and heat as its exhaust. For comparison, the lead battery in your present automobile oxidizes lead to generate electrical energy; the fuel cell oxides hydrogen to generate electricity. The physics of these two devices are identical. This article will focus on the proton-exchange membrane (PEM) fuel cell, which is the type most readily usable and currently being road tested in automobiles. Each PEM fuel cell has a sandwich structure with five layers, as seen is Figure 2.[14] The two outer layers are the backing layers. They are both porous to gases and electrically conducting, and are usually made out of carbon paper or carbon cloth. The anode-backing layer allows hydrogen gas to reach the anode and collects electrons from the anode. The cathode-backing layer allows air (oxygen) to reach the cathode, water vapor to leave the cathode, and electrons to flow to the cathode. Layers two and four are the anode and cathode, which usually consist of platinum nanoparticles embedded in a carbon substrate. On the platinum surfaces in the anode, the hydrogen molecules are split into two protons and two electrons. On the platinum surfaces of the cathode, the oxygen molecules, protons and electrons combine to from water molecules. The middle layer is a thin polymer electrolytic membrane, similar to Teflon, that allows protons to diffuse from the anode to the cathode, but is electrically insulating and also impermeable to hydrogen gas and air. The cell also generates heat, which must be removed to keep the cell at a temperature of about 80 C.

Hydrogen fuel cell automobiles are cars powered by electric motors that get their electrical energy from hydrogen fuel cells, as shown in Figure 3.[5] They clearly have a number of important advantages. First, it is an automobile that does not run on gasoline; this technology would dramatically reduce the amount of oil consumed by this country, which in turn, would also reduce our dependence on foreign oil. Second, the technology exists and is presently being field-tested.[13,15] Third, the conversion of hydrogen potential energy to kinetic energy of the automobile is very efficient, around 37%; in contrast, for the gasoline powered internal combustion engine, it is about 15%.[10] Fourth, the only waste product from the hydrogen fuel cell is water; it does not pollute.

However, there are a number of disadvantages. First, there is the question, where does all this hydrogen come from? There are no significant underground sources of hydrogen gas. Presently, over 90% of the hydrogen gas used in this country is produced by reforming methane gas. This is done by heating methane and water to very high temperatures, generating hydrogen gas and the waste products of carbon dioxide and carbon monoxide. In Norway, where they have a surplus of electricity generated from hydroelectric plants, they use that excess electricity to hydrolyze water into hydrogen gas and oxygen gas.

In this country, we do not have a surplus of electric power, and natural gas, which is primarily methane, is also in short supply. Consequently, there are at present no viable means to produce large quantities of hydrogen gas. The one fossil fuel that is plentiful in this country is coal, so it has been suggested that a new technology be developed that generates hydrogen gas from coal. The use of coal creates another serious environmental problem. Given that coal is primarily carbon, any process that generates hydrogen from coal will also generate large amounts of carbon dioxide—the major green house gas. So this new technology must also capture this carbon dioxide and store it some place—a process called sequestration. Simply put, this coal gasification and sequestration technology does not exist and faces huge technical problems.

Second, presently the cost to manufacture a hydrogen fuel cell to power an automobile is about $50,000.[11] The major reason for the high cost is the need for large quantities of platinum, a material presently more expensive than gold. Unfortunately, mass production of fuel cells will not bring down the price of platinum; most likely, the increased demand for this rare metal will drive the price up. So until there is a major technological breakthrough in finding an alternative catalytic material or in using much less platinum, the cost of the hydrogen fuel cell is prohibitive.

Third, there is the question of the safety of this technology. Unlike gasoline, which is a flammable liquid, hydrogen is an explosive gas, which can be ignited easily by a spark. How willing will the public be to housing a potential bomb in their garage? And what about the possibility of a major hydrogen explosion during an automobile crash? These risks are at present unknown.

Fourth, the range of a hydrogen fuel cell automobile is limited by the amount of hydrogen that can be stored in a cylinder in the rear of the car. With present technology, that range is now about 100 miles. Again, a significant technological improvement in hydrogen storage is needed before this car is marketable.[11]

Fifth, there is the problem of developing a hydrogen infrastructure. Simply put, the consumer will not purchase a hydrogen fuel cell automobile until there are hydrogen gas stations around the country, and the energy companies will not erect these hydrogen gas stations around the country until there is a sizeable fleet of hydrogen powered cars on the road. This is probably the least serious problem facing the hydrogen fuel cell technology. One possible approach is to start with fleets of taxis or government cars in a few cities and build hydrogen gas stations in those few cities. Then expand this approach to more cities, and eventually to more suburban and rural locations.

The Automobile Engine of 2025

Clearly, what follows is just speculation, and most likely it will be proven wrong by future events. However, embarrassment has never stopped anyone from predicting the future, and that list now includes me. Let me start with my evaluation of the hydrogen fuel cell automobile technology. In my opinion, it faces a number of major technological problems before it is ready for "prime time." My expectation is that even by 2025 hydrogen fuel cells will not be a major factor in the automobile industry. This means that gasoline powered automobiles will be with us for another generation of automobiles. In the next twenty years, I don't see a viable alternative to the gasoline powered internal combustion engine.

However, the automobiles of 2025 will be significantly different than those of today. My expectation is that very high efficiency automobiles will standard, and very possibly required. I am high on the hybrid automobile technology. The 2005 Toyota Prius is rated at 55 mpg. I expect this technology to improve and become very common in the near future. Another related and promising new technology is the electric hybrid, which is basically a hybrid automobile with a much larger battery pack that can be charged from an electric outlet. There are other engine technologies that provide high efficiency, like the diesel. The major drawback with the diesel is its exhaust of high levels of nitrogen oxides. It is very possible that pollution laws will be modified to accommodate the diesel engine, as they have in Europe, where diesels already are a significant fraction of the automobile market.

There are very serious consequences of relying on oil to fuel the automobiles of 2025. There are two trends in oil consumption that will most likely continue for the next twenty years. First, the consumption of oil by the United States will continue to grow at roughly one or two percent a year, due to an increasing population, continuing trend towards suburban and even exurban living, and greater usage of automobiles. For example, it is now becoming common for residential college students to bring their cars with them to college, leading to increased usage. Also, the average lifetime of an automobile is 15 years, so some of those inefficient SUVs and minivans sold in 2005 will be with us even in 2025. Finally, a 1 or 2% increase in oil consumption for a country that already consumes 25% of the world's oil is a large increase.

Second, the dramatic growth in Asia, and in particular in China, is already having a major impact on the oil market. To give you some numbers, in 2004, China bought 4.4 million automobiles; in 2001, the number was 2.2 million. For comparison, in the United States, the number for 2004 is about

17 million. China is now the third largest automobile market in the world, behind Japan, but ahead of Germany. It is expected that by 2020, China will be the world's largest automobile market. Furthermore, China has embarked upon a major highway building effort, to accommodate all those cars, and this is also will lead to more miles driven per car.

These two trends will create a greater and greater demand for oil during the next twenty years. Clearly from my previous discussion, I don't see any new automobile technologies that will significantly modify this trend. So the big question is, can the supply of oil keep up with this increasing demand? Notice that for supply to keep up, new sources of oil must be found not only for the increasing demand, but also for the exhaustion of present oil fields. For example, in the continental United States (excluding Alaska), oil production peaked in 1970 and has been steadily declining since then, despite new oil extracting technologies and increasing prices for oil. Of course, no one knows the answer to this supply question, but the recent dramatic increase in the price of oil reflects a judgment among oil traders that the supply will not keep up with demand. My prediction is that not only will oil prices trend higher during the next twenty years, but that there will major fluctuations in this generally upward trend in oil prices. And the consequences of a severe fluctuation are deeply disturbing.

Following the ideas of Charles Maxwell, one of two scenarios is predicted to occur in the next twenty years: an optimistic one and a pessimistic one.[16] The optimistic scenario predicts that a minor shortage of oil will cause a significant increase in the price of gasoline, such that the American automobile culture is dramatically changed. More efficient automobiles will be embraced by the public. Energy conservation will become the norm. People will move close to their work, or start car pooling. Cities will revive as the exurbs are returned to farm land. In other words, the United States will look more like Europe or Japan, in regard to life styles and automobile usage.

The pessimistic scenario envisions a major shortage of oil, a sharp increase in the price of gasoline, and consequently a major world-wide economic depression. With a sudden drop of economic activity comes a dramatic rise in unemployment and a dramatic rise in public and political discontent. It is useful to remember the consequences of the last major world-wide depression during the 1930s. The world saw the rise of Fascism in Germany and Italy, and the rise of demagoguery in the United States. There were individuals like Father Caughlin, who gained large public followings preaching a mixture of anti-Semitism and totalitarianism. A major economic depression is more than just an economic catastrophe, it can be a political catastrophe for democracy and liberty as well. How the United States and the world respond to this upcoming energy crisis will have a profound impact on those values we hold so dear—liberty, freedom, and democracy. The stakes could not higher.

Notes

1. Most of the technical material in this section was taken from F. Schafer and R. van Basshuysen, Reduced Emissions and Fuel Consumption in Automobile Engines, Springer-Verlag, Wein, 1995, and Bernard J. Feldman, "A Physicist's View of the Automobile," The Physics Teacher, 42, 543-547 (December, 2004)..
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4. Office of Aerospace and Automotive Industries' automotive Team, http://www.ita.doc.gov/td/auto/cafe/html.
5. American Honda Motors, 700 Van Ness Ave., Torrance, CA, 90501.
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11. "The Hydrogen Initiative," American Physical Society; http://www.aps.popa.hydrogen.
12. Robert F. Service, "The hydrogen backlash," Science 305, 958-961 (2004).
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14. S. Thomas and M. Zalbowitz, Los Alamos National Laboratory, see http://www.education.lanl.gov/resource/fuelcells.
15. F. Markus, "Driving impressions:GM hy-wire," Car and Drivr. 48, 77 (March, 2003) and J. Dunne, "Fuel cells from sea to shining sea," Pop. Mech. 180, 78 (Jan. 2003).
16. Charles Maxwell, "Caught in the energy vise," Chautauqua Institute talk, 23-141, 2003.

Figure and Table Captions

Table 1: Number and efficiency of licensed automobiles and light trucks in the United States.[3]

Figure 1. Schematic drawing of the Honda Civic Hybrid.[5]

Figure 2. Schematic drawing of the PEM hydrogen fuel cell.[14]

Figure 3. Schematic drawing of the Honda hydrogen fuel cell automobile.[5]

Table 1

Year	# of Cars (10^6)	MPG	# of Light Trucks (10^6)	MPG	Ave. MPG
1960	61.7	14.3			
1965	75.3	14.5			
1970	89.2	13.5			
1975	106.7	13.9	14.2	10.0	13.0
1980	121.6	13.9	20.4	10.5	13.6
1985	127.5	17.4	37.2	14.3	16.7
1990	133.7	20.2	48.3	16.1	19.1
1995`	128.4	21.1	65.7	17.3	19.8
2000	133.6	22.0	79.1	17.5	20.3