CENTER FOR AUTOMOTIVE RESEARCH

The Advanced Power Technology Dilemma: From Hydrocarbons to Hydrogen

by:

Center for Automotive Research (CAR)
1000 Victors Way, Ste. 200
Ann Arbor, MI 48108
T: 734.662.1287
F: 734.662.5736

March, 2004

ACKNOWLEDGEMENTS

We wish to acknowledge the contribution of various individuals and organizations in the development and preparation of this document. Dave Cole (CAR), Dave Merrion (Consultant), and Richard Wallace (Consultant) provided invaluable writing and editing assistance. There were many peer reviewers that offered comments and feedback, but we are especially thankful for the time and attention given by John German (Honda), Dave Hermance (Toyota), Hazem Ezzat (General Motors), and Bernard Robertson (DaimlerChrysler). Also, a grateful acknowledgement to Johannes Schwank (University of Michigan) for his background information and contributing knowledge on hydrogen fuel cell technology. Finally, a special thank you to Tina Jimenez (CAR administrator) for her consistent assistance in coordination and production efforts to keep the project successfully moving forward.

We would also like to thank the Michigan Economic Development Corporation, and the Robert Bosch Corporation, without whose generous support this project would not have been possible.

Jerry Mader, Advanced Energy Technology Consultant
Dr. Richard J. Gerth, Asst. Director, Manufacturing Systems Group
Center for Automotive Research

TABLE OF CONTENTS

EXECUTIVE SUMMARY

BACKGROUND

The Center for Automotive Research (CAR) is an independent, non-profit, policy research organization with over 25 years of experience working in collaboration with the automotive industry's manufacturers and suppliers, as well as with government organizations. Up until 2000, this work was performed as a research department in the University of Michigan's (UM) Transportation Research Institute. CAR has undertaken an "Advanced Power Technology Project" to develop an independent, third party position discussing and comparing various technology options available to automotive manufacturers for improving fuel economy and vehicular emissions. Advances in gasoline internal combustion engines, today's clean diesels, hybrid vehicles, and fuel cell technology are foremost among these options.

We have created a multi-step process for developing the independent, third party position, including: 1) a literature review, 2) discussions with automotive executives and government officials, 3) the creation of a white paper, 4) a peer review of the white paper, 5) a one-day Advanced Power Technology Forum, and 6) periodic updates based on technology advances.

THE SETTING

Imagine that you're an average consumer with limited knowledge of automotive technology, and you're concerned about reports of global warming and America's overdependence on foreign oil. You've probably read stories that car manufacturers could use alternate technologies to improve fuel economy by producing hybrid-electric vehicles or making fuel cell powered cars that use hydrogen, not petroleum, and emit only water from their tailpipes. What's your reaction? You'd probably be very excited that there are ways to make cars that will "save the planet" or give the U.S. energy independence. As you read farther down in these stories, however, you notice that numerous improvements are needed in terms of the cost and performance of these vehicles, especially with the fuel cell powered vehicles. You're left with many doubts and perhaps distrust of what "Detroit" or "big oil" is telling you about the challenges they face to comply with the ever-increasing environmental and fuel mileage standards.

Against this backdrop, CAR has developed this white paper to provide an independent, unbiased position regarding the status of advanced power technologies—looking at what's "under the hood," not the transmission. CAR has gained the participation of the U.S. Council for Automotive Research (USCAR), the U.S. Department of Energy's (DOE) FreedomCAR project, and the U.S. Environmental Protection Agency (EPA), as well as participation from many of the major auto manufacturers and suppliers, the California Air Resources Board (CARB), and the University of Michigan (UM).

AIM OF THE PAPER

The white paper is aimed at policy makers and organizational decision makers. It is not an academic journal article. Instead, it attempts to explain, in laymen terms, the basic concepts that underlie the various advanced power technology options. It presents a snapshot of where we are today with power technologies by seeking a consensus of the participants from the automotive industry, energy suppliers, government and academia, and forecasts where we may be tomorrow. CAR has studied the cost differences between the various technologies to see if the price of advanced power technologies is coming down to the point that the technologies can be commercially viable, and when.

Many believe that fuel cell technology is the ultimate choice for improving energy efficiency while reducing pollution, but this technology may not be ready until well into the next decade. Other advocates are pushing for the widespread adoption of hybrid-electric vehicles to make a more immediate impact. However, with additional improvements, gasoline and diesel engine technologies have the potential to achieve nearly the same improvements promised by the nascent hybrid and fuel cell technologies. Advanced gasoline engines, for example, still have the potential of achieving a 20 percent improvement in fuel economy and emissions reductions, but this will be very near to the upper limit of ICE technology performance.

This white paper compares various power technology options versus current gasoline engine alternatives. Each of these options is aimed at improvements in fuel economy and emissions. Notably, fuel economy and emission improvements come with a high price tag; advanced gasoline, hydrogen IC engines, and clean diesels are predicted to be $1,000 to $3,000 more expensive than current gasoline technologies. Hybrid-electric technologies may cost $5,000 to $10,000 above the baseline. The true production costs of fuel cells are not known—but they will be very expensive. Added to this stark reality, the capital cost of building a new engine plant is in the one billion dollar range.

AUTOMAKER INVESTMENT DECISIONS

There are many uncertainties and unanswered questions that the auto companies have to answer before making a decision about investments in advanced power technologies.

All of these technology options require considerable investment, technical development, the elimination of market barriers, and possible government action. The risks of developing new automotive engines come with a high price tag, and uncertainty and history have shown that many millions of dollars can be spent researching technologies that are dead ends. Automotive manufacturers that are able to meet consumer demands at the right time with the right products will be the ones that dominate the future vehicle market in the United States and abroad. Today, decision makers do not know enough about the benefits and costs of the various power alternatives to pick winners and losers. No one automaker can predict today the mix of technologies that will appear in tomorrow's market.

WHITE PAPER CONCLUSIONS

1. Too Many Unknowns to Decide

   At this time, there is insufficient knowledge for anyone to recommend one power technology over another. There are just too many unknowns to exclude any option or to declare that one will survive over another. Advanced gasoline, hydrogen ICE, clean diesel, hybrids, and fuel cells are all potentially viable options that must be considered with an eye toward their marketability.

   Today, it appears that the gasoline engine will be here for the long-term future, as long as petroleum availability and price remain relatively stable. But, clean diesel could gain a significant market share here in the United States (as it has in Europe) if the nitric oxide and particulate problems can be solved without a significant price premium. Diesel engine plant capacity is very low in the United States, and many billions of investment dollars will be required to expand plant capacity.

   The questions facing the auto manufacturers include:

   - Is investing in clean diesel technology worth the time and money involved?

   - Is this a risk worth taking given the progress with hybrid technology?

- Is a low-cost, long-life battery on the horizon that will significantly change the cost feasibility for hybrids?

- Are fuel cells really 15 to 20 years away from being commercially available?

- What if key discoveries are made in the next two or three years that lead to an inexpensive hydrogen-based fuel that could easily be converted on-board to hydrogen and an inexpensive and durable catalyst found to improve fuel cell cost and reliability?

Counterbalancing the risks are the promises that hydrogen ICE, clean diesel, and parallel (non-grid) hybrids will cut greenhouse gas emissions by about 30 percent versus today's gasoline engines. Meanwhile, parallel (grid) hybrids and fuel cells may cut emissions by as much as 50 percent.

2. Auto Manufacturers Pursue Different Solutions

Although the gasoline ICE has been the mainstay of the auto industry for a century, the doubts about which advanced power technology will win in the future is the reason why manufacturers need to pursue different solutions. There is not a uniform strategy going forward. Each automaker has different knowledge and experience with the technologies mentioned in this paper.

European manufacturers have invested heavily in diesel engines for cars, especially for high-end models like the Mercedes and BMW. Japanese manufacturers have been aggressively pursuing hybrid options. Toyota, for example, expects to sell several hundred thousand Prius models in the next couple of years. Here in the United States, manufacturers like General Motors are taking a broader view and planning hybrid introduction within the next several years, as well as investing heavily in fuel cells. Different manufacturers will pursue different paths for advanced power technologies.

3. Alliances Necessary to Surmount Obstacles

Investment in advanced power technologies is very expensive. No automotive manufacturer can afford to pursue these various options on its own. Alliances will have to be formed with other auto manufacturers, supplier companies, research firms, power and fuel companies, academia and the government at both the research and product development stages. The risks involved are:

- New automotive engine plants costing upwards of one billion dollars each.

- Battery development being costly and often fraught with dead ends.

- History showing that many hundreds of millions of dollars in research can be spent without a successful outcome.

- Fuel cell development and infrastructure being easily measured in the hundreds of billions of dollars before commercialization is realized.

4. Consumers Decide, Other Issues Influence Choices

The ultimate decision maker for choosing winners and losers in the advanced power field are the consumers. The automotive manufacturers that are better able to meet their demands are the ones that will dominate the advanced power technology future.

None of the proposed advanced power technologies are likely to be cost competitive with current technology unless tax credits or other incentives stimulate demand. If the cost gap cannot be closed, short-term incentives might not prompt investment, as costs may be too high to ensure success.

As time progresses, research will stimulate new ideas, and feasibility will become more certain. Petroleum availability and price will either remain stable or fluctuate, causing consumer preference to change, and the regulatory climate will become more or less restrictive. All these factors will affect the viability of various advanced power technology options. In the end, however, consumers will decide which technologies will make it in the marketplace.

As vehicle power technology progresses, the Center for Automotive Research will continue to track it, creating a future report looking into the questions that remain unanswered

INTRODUCTION

Imagine that you're an average consumer with limited knowledge of automotive technology, and you're concerned about reports of global warming and America's over dependence on foreign oil. You've probably read stories that the car manufacturers could use different technologies to improve fuel economy by producing hybrid-electric vehicles or making fuel cell powered cars that use hydrogen, not petroleum, and emit only water from their tailpipes. What's your reaction? You'd probably be very excited that there are ways to make cars that will "save the planet" or give the United States energy independence. As you read farther down in these stories, however, you notice that numerous improvements are needed in terms of the cost and performance of these vehicles, especially with the fuel cell powered vehicles. You're left with many doubts and perhaps distrust of what "Detroit" or "big oil" is telling you about the challenges they face to comply with the ever increasing environmental and fuel mileage standards.

Against this backdrop, the Center for Automotive Research (CAR) Advanced Power Technology (APT) project team has developed this white paper to provide an independent, unbiased position regarding the status of advanced power technologies—looking at what's "under the hood." The APT project has gained the participation of the U.S. Council for Automotive Research (USCAR), the U.S. Department of Energy's (DOE) FreedomCAR project, and the U.S. Environmental Protection Agency (EPA), as well as the participation of many of the major auto manufacturers and suppliers, the California Air Resources Board (CARB), and the University of Michigan (UM).

This project is an ongoing, living project that takes a snapshot of where we are today with power technologies by seeking a consensus of the participants from the automotive industry, energy suppliers, government and academia, and forecasts where we may be tomorrow. CAR has studied the cost differences between the various technologies, looking to see if the price of advanced power technologies is decreasing to the point that the technologies are commercially viable, and when. The project also examines government versus industry forecasts, the critical issues of fuel economy, the environment, and cost, or in other words: energy, emissions, and economics.

Figure 1 shows a typical technology development cost curve. The technology cost is reduced over time. The dotted line indicates the cost of current technology (i.e., the gasoline engine) and, if the new technology cost is projected to be more than the current technology, it will be economically infeasible.

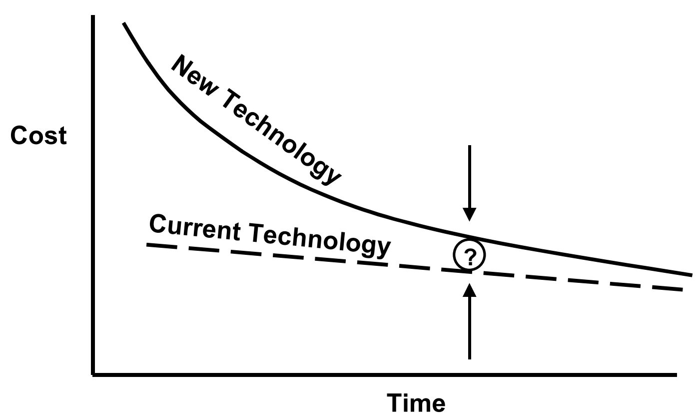

Figure 1
Typical technology development curve.

As this paper is intended for a wide-ranging audience with varying levels of knowledge, it is important to begin with the gasoline internal combustion engine (ICE) as a baseline for comparison. (The ICE section will also provide information on diesel engines.) Although diesel engine technology dates back to 1882 — making it nearly as old as the Otto-cycle gasoline engine — and it has high acceptance in Europe, it is a relatively unknown technology for use in light-duty vehicles in North America.

Many believe that fuel cell technology is the ultimate choice for improving energy efficiency while reducing pollution, but this technology may not be ready until well into the next decade. Others advocate the widespread adoption of hybrid-electric vehicles to make a more immediate impact. However, ICE technology has continued to show dramatic improvement (see Figure 2). With additional improvements, gasoline and diesel engine technologies have the potential to achieve nearly the same improvements promised by the nascent hybrid and fuel cell technologies. Advanced gasoline engines, for example, might still have the potential of achieving a 20 percent improvement in fuel economy and emissions reductions for only a 20 percent increase in cost, but this will bring us near the upper limit of ICE technology performance.

It is important to realize that fuel economy improvements are highly dependent on the driving cycle that is being considered. For example, an improvement measured at a constant speed will be very different from an improvement measured on the Federal Test Cycle used to evaluate emissions and compliance with Corporate Average Fuel Economy (CAFE) requirements. Therefore, this paper makes no attempts to quantify the exact improvements that are possible with each of the technologies, but rather estimates a percentage range to capture the differences that may be possible due to different driving cycles.

Figure 2.
Frank Klegon, Vice President of Truck Engineering for the Chrysler Group, unveils the latest iteration of the HEMI Engine for the Dodge Ram 1500 at the 2002 SEMA Show in Las Vegas. The modern HEMI has vastly superior gas mileage and emissions when compared to the 1960s HEMI engines. –Photo courtesy of Daimler-Chrysler Corporation

There are many uncertainties and unanswered questions that both government regulators and the auto companies have to answer before making a decision about investments in advanced power technologies. The different car companies have pursued different strategies, due (in part) to their particular strengths as well as to local government incentives. European manufacturers have invested heavily in diesel engines; Japanese manufacturers have been aggressively pursuing hybrid options, such as the Toyota Prius; and American companies like General Motors are planning hybrid introduction within the next several years and are investing heavily in fuel cells.

All of the advanced automotive power technologies require considerable investment, technical development, the elimination of market barriers, and possible government action. In many cases, significant discovery is required before mass commercialization can occur with any of the advanced power technologies discussed; it's just not possible to forecast the pace of invention. The risks of developing new automotive engines come with a high price tag and uncertainty. The cost of introducing (or developing) a single new ICE, for instance, is in the one billion dollar range, and history has shown that many millions of dollars can be spent researching technologies that are dead ends. Alliances will have to be formed between manufacturers, academia, power technology companies, and the government at both the research and product development stages to overcome the financial and technological obstacles ahead. Even with these alliances, the ultimate decision makers who are picking the winners and losers in the advanced power field are the consumers. The automotive manufacturers that are able to meet consumer demand at the right time with the right product and at acceptable prices will be the ones to dominate the future vehicle market in the United States and abroad. Simply put, these manufacturers do not currently know enough about the benefits and costs of the various power alternatives to pick winners and losers. No one automaker can predict today the mix of technologies that will appear in tomorrow's market.

Rather than presenting a single solution, this paper will discuss the various power technologies—from advanced gasoline and diesel engines, to hybrid-electric and fuel cell powered vehicles—and compare their strengths and weaknesses. The next section presents a brief history of the roots of the power debate, followed by an introduction into the ICE and some of the new developments in that area. Hybrid and fuel cell technologies are discussed next, followed by a conclusions section which includes a summary table displaying some of the relevant advantages and disadvantages of the major technologies.

ROOTS OF THE POWER TECHNOLOGY DEBATE

By 1990, new vehicle emissions had been significantly cut from their 1970 level thanks to environmental regulations, but these improvements would not be enough for California to meet federal air quality standards. With the State's population booming, and an increasing number of vehicles on the road, the California Air Resources Board (CARB) enacted the Zero Emissions Vehicle mandate (ZEV) as a radical solution—a quota on the types of vehicles that a manufacturer had to sell in California to avoid penalties.

Figure 3.
California's stringent air pollution rules were aimed at jumpstarting the electric car market, but battery-powered vehicles like this 1999 Ford Ranger EV proved to be useful as utility and delivery vehicles, not as passenger cars. - Photo courtesy of Ford Motor Company

According to the original 1990 ZEV mandate, two percent of cars sold in California in 1998 had to produce no tailpipe or evaporative emissions: hydrocarbons released during refueling, gases released from the foam of the interior trim and seats and from the rubber tires and hoses, emissions caused from opening the gas cap to refuel the car, or from gas tank leaks. CARB's rules also included increasing the ZEV requirement to 5 percent in 2001 and 10 percent in 2003.

The ZEV mandate was meant to promote the development of battery-powered vehicles, but despite offerings from the major automakers (see Figure 3), the general public rejected these cars which had ranges of less than 100 miles and required a significant amount of time to recharge batteries. The CARB slowly backed down from its 1990 ZEV mandate when it became clear that no one could meet its initial requirements. Then, in 1998, the Board created a category called PZEV (Partial Zero Emissions Vehicle), where internal combustion powered cars could qualify if they had nearly no tailpipe and evaporative emissions. In 2003, six percent of all new cars sold in the State had to be PZEVs and four percent had to be ZEVs.

In 2001, the CARB amended the ZEV mandate by introducing a new category, the Advanced Technology PZEVs (AT-PZEVs), which was designed to encompass those vehicles that have technologies that potentially lead to ZEVs, such as electric drive and hydrogen powered vehicles.

While the 2001 amendments maintained the ZEV and PZEV requirements, the CARB added a phase-in schedule and increased future ZEV requirements.

In 2001 there was also a lawsuit filed challenging California's right to preempt federal law regarding emissions control. This resulted in an injunction prohibiting the enforcement of the ZEV regulation for the 2003 and 2004 model years. In 2003, a settlement agreement was reached among all parties, and the ZEV mandate will be enforced starting with the 2005 model year.

STARTING AT THE BASELINE

The internal combustion engine (ICE) has been the heart of the automobile for more than a century, so much so that it is either taken for granted by the general public or viewed as old fashioned technology. Yet in the past three decades, arguably driven by fuel economy and emissions regulations, modern gasoline and diesel engines have evolved into highly sophisticated machines for converting chemical energy into mechanical energy for movement.

While this white paper is focused primarily on the engine, or power plant, it is important to note that the total drivetrain, including the engine transmission and final drive mechanisms, are important factors in fuel economy performance (see Figure 4). Also, the vehicle design is important due to factors of aerodynamic losses, tire rolling resistance, and vehicle mass. A detailed discussion of these factors is not a part of this paper, other than to mention that all internal combustion (IC) engines require a transmission to multiply engine torque and match vehicle requirements with engine performance. The final drive enables the engine/transmission power to turn a corner with a differential to allow wheels to rotate at different speeds. A number of new transmission technologies are beginning to appear, such as the six-speed automatic and continuously variable transmissions that promise to bring fuel economy improvements.

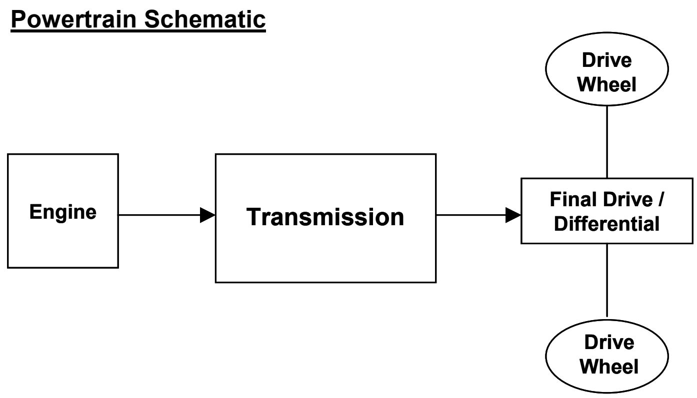

Figure 4
This illustration shows the powertrain layout of a typical ICE powered vehicle. All internal combustion engines require a transmission to multiply engine torque to match vehicle requirements with engine performance. When turning a corner, the final drive helps provide power plus the differential action needed so the wheels can rotate at different speeds—the inside wheel rotates slower than the outside wheel, for example.

The entire spark-ignited internal combustion engine (also called an Otto-cycle engine) has been under intense development for 100 years. Further improvements are reasonably limited and may be relatively expensive, but are still possible. At the risk of becoming overly technical, it is useful to review some of the basic fundamentals regarding IC engines.

EXAMINING THE WORKINGS OF GASOLINE ENGINES

All IC engines follow the laws of thermodynamics (the science of energy conversion). Here, thermal efficiency is defined as the output work or power divided by the chemical energy available in the fuel multiplied by the mass of the fuel. Real engines always exhibit thermal efficiencies below the theoretical maximum for a number of reasons, including mechanical and flow losses, heat losses, time losses (because of the inability to do things instantly), and losses in the drivetrain, which reduce the power available to turn the vehicle's wheels.

Most engines use a simple slider crank mechanism where a piston moves up and down in a cylinder and through a connecting rod to deliver power to the crankshaft (Figure 5). The Otto-cycle engine (spark-ignited, gasoline fueled) operates on the principal of drawing a mixture of fuel and air into the cylinder. This combustible mixture is then ignited by a spark plug at just the right time to create a miniature explosion that releases the chemical energy, thereby raising the temperature and gas pressure in the cylinder. This pressure pushes the piston down which, in turn, rotates the crankshaft and delivers power to the drivetrain (i.e., the transmission and then the wheels).

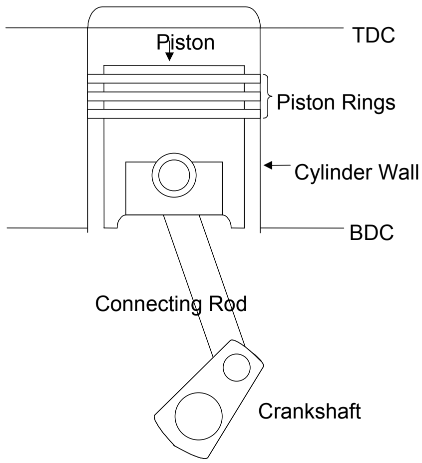

Figure 5
Slider Crank Mechanism - This illustration shows the inside of a gasoline ICE cylinder that uses a simple slider crank mechanism in which a piston moves up and down and delivers power to the crankshaft through a connecting rod.

Alternative fuels can be used for spark-ignited IC engines, such as compressed natural gas (CNG), liquid propane gas, a flexible fuel ethanol (E85), and even hydrogen. Modifications (including changes to the sealing and fuel injection technologies, as well as different hoses and connectors) are needed to handle gaseous fuel instead of liquid.

Figure 6 shows the effect of the engine's compression ratio on the thermal efficiency for both pure air (top line) and the chemically correct mixture of fuel and air (lower line) which is typical of spark-ignited IC engines. These curves illustrate the maximum thermal efficiency potential of an engine to convert energy in the fuel into useful work. For a given compression ratio and fuel-air ratio, a thermal efficiency above the curve represents a violation of the laws of thermodynamics and is, therefore, impossible. Compression ratio is defined as the volume in the cylinder with the piston at bottom dead center (BDC) divided by the volume with the piston at top dead center (TDC).

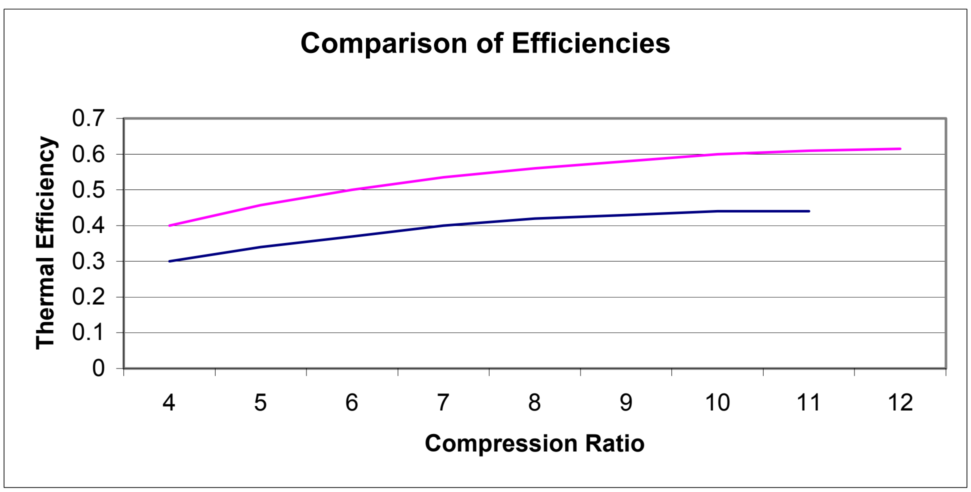

Figure 6
Comparison of Thermal Efficiency versus Compression Ratio for Air and a Chemically Correct Fuel/Air Mixture.

While current engines do not perform at their theoretical potential, it is difficult to make significant improvements. These engines have been undergoing development for over 100 years, and the relatively easy and inexpensive improvements have already been made. Some additional improvements are available through such factors as reduced engine friction, variable valve lift and timing, and cutting throttling losses. Throttling is a loss associated with drawing a fluid through a restriction (e.g., the throttle in a spark-ignited engine).

The spark-ignited ICE can be broken down into several subsystems, with some level of interaction between these subsystems:

- The thermal/fluid systems: These are related to the fluid flows (fuel and air), combustion process, exhaust, and intake processes.

- Mechanical systems: These include all moving components, such as the pistons, camshafts, connecting rods, valve train, oil pump, fuel pump, and (of course) the basic structural components of the engine, such as the block and head.

- Accessory drive systems: A modest quantity of energy is required to drive various ancillary devices. These include an air-conditioning compressor, power steering, oil and water pumps, and possibly other components.

If we examine the thermal/fluid issues associated with the operating cycle, there are several losses that degrade efficiency or fuel economy, such as:

- Time losses: These losses reflect the inability to do things instantly, i.e., releasing all of the chemical energy at the top position of the piston (top dead center) Once the spark ignites the air/fuel mixture, it takes a finite amount of time for the flame to fully propagate through the combustion chamber. Spark or ignition timing is generally controlled electronically to optimize fuel economy or performance. It would be difficult to significantly increase fuel economy further by increasing combustion chamber turbulence, since the higher gas flows increase other losses.

- Heat losses: Once combustion occurs, the temperatures of the gases increase dramatically and are significantly above those of the combustion chamber, cylinder walls, and engine coolant. Consequently, some heat is lost, reducing efficiency; it would be difficult to cut this heat transfer, because this area has already been reasonably optimized. High gas temperatures in the chamber increase the tendency of knock, requiring fuel with high resistance to auto ignition (high octane number) to rectify this problem. Knock tendency can be reduced by increasing turbulence which increases flame speed, but this also increases heat losses.

- Blow down losses: Gases and liquids have mass. Because of this, gases do not accelerate or decelerate instantly as they flow in and out of the engine. To optimize evacuation of exhaust products from the engine, the exhaust valve is opened during the latter part of the expansion stroke of the engine, resulting in a slight decrease in fuel economy. This is also a very difficult loss to prevent, even though variable valve timing can optimize gas flows in and out of the engine.

- Throttling: When fluid is passed through a restriction, such as the throttle that controls the load or power in a spark-ignited engine or over any surface, the resulting friction losses reduce fuel economy. The throttle in the spark-ignited engine is a very important source of efficiency loss, particularly at light loads (an example of light load would be "around town" driving). This is an important area for potential fuel economy improvement, and a number of technologies are being explored, including cylinder disabling (sometimes called displacement on demand), stratified charge combustion, inlet valve throttling, and variable valve timing and lift.

In summary, there are a number of factors that degrade fuel economy of IC engines, and many have been applied during the past 100 years. Still, some potential for further improvement is possible, particularly with new technology. Obviously, such tools as modern electronics have enabled a higher level of optimization than we have seen in the past, but further opportunities remain. Little improvement can be expected without added cost. In our judgment, an approximately 20 percent fuel economy improvement is available at a roughly 20 percent increase in cost.

ADVANCED TECHNOLOGIES OFFER OPPORTUNITIES

Arguably, the most important IC engine improvement was the development of electronic engine controls. This has allowed manufacturers to monitor and control engine functions, thereby significantly increasing fuel economy and performance, while reducing emissions. Today's engines, with relatively low displacement, can nearly rival the horsepower and torque produced by the big block engines of the late 1960s that were made obsolete by mileage and emissions regulations. As electronic controls continue to improve, even more benefits are expected.

Other individual engine technologies can impact fuel economy, but it is important to note that these changes are not always additive. For instance, a five percent improvement in two different areas may not yield a ten percent gain. A brief description of these technologies and their potential benefits is provided below.

- Consideration is being given to gasoline direct injection (GDI) engines, where fuel is injected directly into the combustion chamber, instead of the inlet manifold, to create a region of combustible fuel/air mixture surrounded by air. This concept may allow for a ten percent fuel economy improvement, but hydrocarbon and nitric oxide emissions are difficult to control with this technology.

- Another key to reducing emissions and increasing gas mileage is reducing friction in the engine. Friction, which produces heat and resistance, robs an engine of its performance and has been under attack since the earliest days of engine development. Friction can be reduced with improved lubricants and changes in mechanical components. Lubricants have improved dramatically during the years, with 5W-30 multi-viscosity oils now an industry standard. Low-viscosity oils, high performance additives and more carefully refined lubricants have developed through joint efforts of the oil and auto industries, resulting in remarkable gains in oil life and reduced friction.

  A lubricant film always separates the mechanical parts inside the engine, such as the pistons sliding up and down in the cylinder or the rotating parts in the cam and crankshafts. So the mechanical parts and lubricants must be considered as one system. Improvements continue to be made with roller valve lifters and lower tension piston rings. New low friction lubricants and mechanical changes could reduce mechanical losses even more, but it seems likely that these thermal efficiency gains will be minimal, in the one to three percent range.

- Cylinder deactivation (also known as displacement on demand) for six-cylinder and larger gasoline-powered engines is yet another strategy to improve fuel economy (see Figure 7). The idea is that all the engine's cylinders would be activated during acceleration periods and when pulling heavy loads. At cruising speeds, however, the flow of fuel to several of the engine's cylinders would be shut off. The National Research Council estimates the mileage gains would be in the three to six percent range.

- The ICE will also benefit from the use of 42-volt electrical systems. While the 42-volt system will add cost to the vehicle, it will allow electric motors to run more efficiently and make electric power steering and braking more viable. This increased electrical efficiency will in turn reduce fuel consumption requirements.

- Variable valve lift and timing (VVL/T) technology is currently used on some engines to improve fuel economy upwards of five percent. This system facilitates gas flows into and

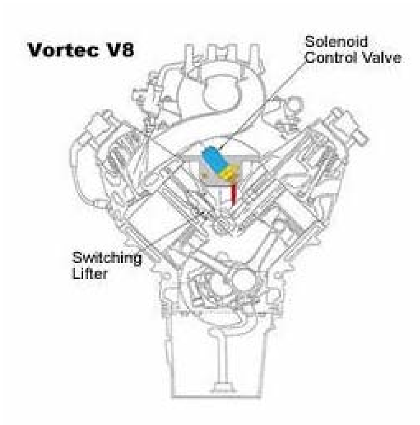

Figure 7
The 2004 General Motors Vortec V8 family will feature “Displacement-on-Demand" technology to boost the fuel economy by about 8 percent, based on an EPA testing procedure, and up to 25 percent in certain real-world driving conditions. -Photo courtesy of General Motors Corporation

out of the engine while reducing throttling losses. However, VVL/T technology is complex and costly.

- Replacing the mechanical camshaft with electromagnetic or electro-hydraulic valve actuators will permit independent valve timing and lift. This technology would offer greater control of the intake and exhaust gas process and increase efficiency by five to seven percent, or even as high as ten to thirteen percent. These camless systems are costly and are far from being ready for commercialization.
- Variable compression ratios could offer efficiency gains of ten percent, depending on driving conditions. This technology allows engine operation at higher compression ratios under light loads, where fuel octane requirements are low. At higher loads, when accelerating or pulling a trailer, the engine would revert back to a lower compression ratio. However, this system is complex, costly, and sluggish when switching from high to low compression.
- Turbocharging and supercharging technologies enable a smaller engine to operate like a larger one. Note that an engine’s power/torque potential is a function of the mass of air drawn into the engine. An exhaust gas-powered turbocharger or a mechanically driven supercharger can increase inlet gas pressure above the atmospheric pressure. Both technologies are in limited use and offer a slight reduction in fuel consumption, primarily due to lower friction and throttling losses in smaller engines. Efficiency improvements of about five percent are possible when compared to a larger displacement engine of similar power, but again, at higher cost and complexity.

THE PROMISE OF USING HYDROGEN AS A FUEL FOR SPARK-IGNITED ICES

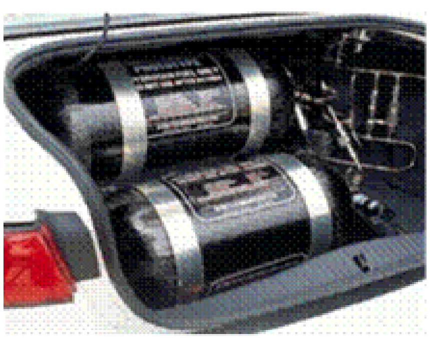

Figure 8
The prototype Ford Focus powered by a hydrogen ICE currently faces a fuel storage problem. As pictured, hydrogen storage tanks take up most of the car’s trunk space. -Photo courtesy of Ford Motor Company

As mentioned in the introduction, one of the obstacles in creating cost-effective fuel cells is the challenge to develop a hydrogen refueling infrastructure, because the fuel is not readily available at the corner gas station. Therefore, several auto manufacturers, including Ford with its P2000 program and BMW, are experimenting with a spark-ignition internal combustion engine that can run on hydrogen (H2ICE).

The H2ICE offers near-zero emissions, using nearly conventional engine technology and creating a bridge to the hydrogen fuel economy. Current near-zero emission H2ICEs have limited performance and, increasing the level of performance with today’s gasoline ICE, could result in a NO_x emission problem. Furthermore, the primary drawback with hydrogen fuel is insufficient storage and, currently, there is no adequate solution to this problem (see Figure 8). This is a very significant issue because it affects range, and an inadequate range is a definite “show stopper.” Acceleration performance is also an issue, because hydrogen is a very light gas, and it’s difficult to achieve high volumetric efficiencies with it. Some other technical challenges include a need for significant sealing and tubing upgrades to prevent leaks, upgrading fuel injectors, improving cylinder head cooling and oil management (lubricants are still needed), and a special ventilation system.

Still, H2ICE might be used to help create demand for hydrogen, allowing a nascent, yet cost-effective hydrogen fuel infrastructure to develop before fuel cell power plants become commercially viable. A further look at the daunting challenges to create a hydrogen-based economy is in the fuel cell section.

LOOKING AT THE FUNDAMENTALS OF DIESEL ENGINES

In 1882, a German engineer named Rudolf Diesel obtained patents on a reciprocating engine that was significantly different from steam engines or spark-ignited Otto-cycle engines. Diesel realized that if the air could be significantly compressed in an engine’s cylinder, then temperatures would reach the point where the fuel would spontaneously combust. Injecting fuel directly into the cylinder at this stage would eliminate the need for electric ignition. This process extracts more energy from the fuel than the Otto-cycle engine does, allowing diesel engines to operate more efficiently.

The diesel cycle is a high compression ratio with excess air cycle and with little time for the injected fuel to mix with the swirling air. Not only are diesel engines more efficient than gasoline engines, they also have lower carbon monoxide and carbon dioxide emissions, although they do have higher NO_x emissions. As a result of the incomplete mixing of fuel and air, diesels have had higher emissions of smoke, particulates, and hydrocarbons, as well as a distinct odor. Many of these disadvantages are being overcome with today’s technology (see Figure 9). Also, diesel fuel has a lower flammability limit than gasoline (meaning that it is safer) and a heating value that is twelve percent higher than gasoline (meaning that it results in better fuel efficiency).

Figure 9
In Europe, diesel-powered passenger cars like the Volkswagen Lupo TDI have won awards for their innovative designs and performance. Diesel engines are capturing a large percentage of the European car market. -Photo courtesy of Volkswagen

A significant drawback of the diesel engine is cost. The diesel is an inherently more expensive design. The engine block assembly has to be able to handle the stresses of compression ignition, and the fuel must be injected under very high pressure. A V6 diesel costs $2000-$2500 more than its gasoline equivalent. However, a recent study prepared by FEV for the U.S. EPA indicates diesel could be only $745 more expensive than gasoline for medium duty cars, not including after-treatment.

Diesel engines have used various technologies over the years to improve horsepower output, reduce smoke, and improve fuel economy. The most significant changes involved going from indirect fuel injection to direct fuel injection and the use of turbocharging. These changes in the 1980s and 1990s resulted in significant fuel economy improvements, but they also increased engine clatter; indirect injection engines were relatively quiet compared to direct injection. Emission requirements in the late 1990s and early 2000s resulted in more improvements from:

- Electronic control of fuel quantity, fuel injection timing, and speed;

- Turbochargers that use wastegating or with variable geometry turbines;

- Turbocharger compressor air discharge cooling to reduce NO_x by intercooling, or after cooling with vehicle coolant, or using air-air charge cooling with an additional radiator;

- Using uncooled exhaust gas recirculation, either with an external pipe or internally using the intake/exhaust valve element timing (see Figure 10); and

- More sophisticated, high pressure fuel injection systems including unit injectors, common rail fuel systems (see Figure 11) or hydraulic enhanced units.

Figure 10
The new Detroit Diesel Series 60 engine is equipped with an exhaust gas recirculation system. It offers the same fuel economy as similar non-EGR engines. –Photo courtesy of Detroit Diesel

Figure 11
The Detroit Diesel DELTA (Diesel Engine for Light Truck Applications) is a demonstration engine that has been installed on several sport utility vehicles on a prototype basis. It is a common rail, 4-liter, V6 engine with EGR (exhaust gas recirculation) technology. -Photo courtesy of Detroit Diesel

The U.S. EPA Tier II requirement for 2007 and the California LEV II standard represent a significant challenge to diesel engine manufacturers. The NO_x requirement of 0.07 g/mile and a particulate matter (PM) requirement of 0.01 g/mile will require even more technology and new after-treatment systems. One method to improve diesel engine emissions is to develop better fuels.

NEW FUELS AND ADDITIVES HELP DIESELS

A significant change that will aid the development of clean diesel engine technology is cutting the sulfur content in fuel as required by U.S. federal regulations. In 2006, the sulfur content for the fuels of on-highway vehicles will be cut from 500 parts per million (ppm) to 15 ppm. The following year, the diesel fuel for off-highway vehicles also dramatically drops, from 5,000 ppm to 500 ppm. This single change will greatly reduce toxic emissions and will permit diesel engines to have after-treatment systems (similar to how unleaded gasoline allowed for catalytic converters in Otto-cycle engines).

Lubricant reformulations and fuel additives for diesel engines can help avoid excessive soot in the oil, thereby reducing ash and extending oil change intervals, while making emissions after-treatment systems viable. Recent health concerns about the toxicity of ultrafine particulate matter (PM) emissions from diesel engines (particles less than 150 nanometers) has prompted studies into their cause and possible solutions. Current thinking is that the “ultrafines” are related to unburned lube oil and sulfuric acid. Modified oils combined with low sulfur fuel and catalytic filter systems should address this issue.

Alternative diesel fuels, such as water emulsions, ethanol, bio-diesel and even synthetic fuel (converted from natural gas or coal) are getting spotty support, though they are technically possible. The U.S. DOE has also funded efforts to make liquid diesel fuel from natural gas with an eye toward reducing NO_x, carbon monoxide and hydrocarbon emissions, as well as lower “nano-particles.” There are financial pitfalls with developing a natural gas-to-liquid (GTL) fuel as demonstrated by the recent Chapter 7 bankruptcy of Emex’s GTL subsidiary.

DIESEL EMISSION CONTROL SYSTEMS

Diesel engines in passenger cars and light trucks still have a poor reputation in the United States from the ill-conceived attempt in the 1980s to retrofit gasoline engines to run on diesel fuel. However, in Europe, diesel engines have overcome their lackluster reputation because of emissions and performance improvements and a high fuel economy, rivaling the mileage of many hybrids in similar class cars. However, diesels have always claimed a significant part of the European passenger car market. In the past, the European public and governments have been willing to tolerate their noise and "diesel smell" because of their better fuel economy. Europeans gave vehicle manufacturers a break, both in less environmental regulation and in tax subsidies, to promote the development of diesels until a market developed. As such, diesels have now captured over fifty percent of the high-end vehicle market. Even Jaguar will offer diesel-powered cars in Europe. In addition, most European countries do not tax diesel fuel as heavily as gasoline.

Still, stricter U.S. EPA and CARB regulations that will take effect by 2007 and beyond stand in the way of bringing more diesel-powered cars to the United States unless better emissions control systems come online. There are a number of experimental exhaust after-treatment systems under consideration. PM filters and several NO_x after-treatment systems, such as selective catalytic reduction (SCR), lean NO_x traps (LNT) and a lean NO_x catalyst (LNC) are being developed. There are also options that combine PM and NO_x filters.

PM filters have been tested on diesel engines over the last ten years using wire mesh, a ceramic wall flow monolith, or metal mesh and metal zeolite. The ceramic wall flow monolith design made out of silicon carbine along with a catalyst has shown to be more than 99 percent effective in filtering particulates. One drawback, however, is ash build up on the filter. There are ways to clean (or regenerate) the filter using high exhaust temperatures, exceeding 500°C, but many diesel engine cycles do not operate in a high temperature range.

Other methods of regenerating PM filters include increasing the level of nitrous dioxide (NO_2), putting a NO_x reduction catalyst on the filter surface, or using a fuel burner. PM filters can also be regenerated by using fuel additives to lower the carbon ignition temperature or by placing a catalyst on the soot filter.

The Selective Catalytic Reduction (SCR) system is being developed in Europe using liquid urea, which could cut NO_x emissions by 85-90 percent with only a one percent fuel penalty (SCR requires additional fuel to operate). Liquid urea is a fuel-born catalyst that will help lower particulates as well as temperature. But the U.S. EPA is not supporting this technology because it thinks the urea infrastructure cannot be made tamper-proof. Europe is developing a two-tank fuel system—one for the diesel fuel, the other for the urea. The U.S. EPA believes the European system will permit the vehicle operator to skip refueling the urea tank. And, SCR's biggest problem is the ammonia slip issue ("slip" is a term that refers to any gases coming out of the tailpipe that slip by the catalyst). For example, with 93 percent NO_x efficiency, there is three percent ammonia slip, whereas with 85 percent NO_x efficiency, there is only 0.5 percent ammonia slip.

Another emissions control technology is the Lean Nitric Oxide Trap (LNT), which could reduce NO_x emissions by 80-95 percent. But there are challenges with this technology, including: 1) it can only be used with low sulfur fuels, 2) there are questions about the high temperature durability of the filters, and 3) the boost in hydrocarbon emissions and associated five percent fuel penalty, short of the two percent benchmark set by the EPA.

Despite the significant technical challenges, these devices may be available in the 2007-2010 timeframe, according to the EPA Clean Diesel Independent Review Panel.

There is also the Lean Nitric Oxide Catalyst System, otherwise known as the De NO_x catalyst that offers a 50 percent improvement in efficiency using a silver catalyst. Yet, the De NO_x catalyst has a significant hydrocarbon slip resulting from the hydrocarbon reactant.

An emerging technology is to integrate NO_x and PM systems for both light- and heavy-duty diesel engines. Johnson-Matthew showed such a unique nested concept in January 2003. The EPA recently tested a Toyota system, but it barely met the Bin 5 FTP75 50,000 mile requirements, and it missed the US06 cycle requirements. Also, durability has not been demonstrated.

The costs of the various after-treatment systems are not readily available (at production volumes) nor are all the operating costs (fuel efficiency loss) defined at this time.

OTHER DIESEL ENGINE TECHNOLOGIES

Potential future diesel engines could use a technology known as Homogeneous Charge Compression Ignition (HCCI). There are also concept diesel engines that have been produced by FEV, the German research organization, and designs from Toyota, Cummins, and DaimlerChrysler AG that show promise.

HCCI engines, which may also be suitable for gasoline, were first proposed 20 years ago. They seem to offer high efficiency along with very low NO_x and particulate emissions. An HCCI diesel engine premixes fuel and air and injects them into the engine's cylinder simultaneously. The piston then compresses the fuel/air mixture until it ignites.

There are major drawbacks to the HCCI approach. Hydrocarbon and carbon monoxide emissions are greatly increased, and the engine's operating range is reduced. For a full HCCI the timing of the fuel ignition is not controlled, leading to problems under high loads and high peak pressures that increase mechanical stress. As a result researchers are investigating a hybrid engine where the engine is not operated as an HCCI under high load conditions.

Caterpillar is looking into a type of HCCI engine as part of its emission control technology. Also, the FEV has developed a 1.9 liter four-cylinder engine under contract with EPA which meets the federal government's 2010 NO_x requirements by a considerable margin without requiring after-treatment systems or special diesel combustion controls. This engine included a two-stage turbocharger. However, this early prototype needs to be considered carefully until more is understood regarding its cost and performance.

The Toyota Avensis engine with its Diesel Particulate NOx Reduction (DPNR) system (a combination of a diesel particulate filter with a NOx adsorber-catalyst) and after-treatment gets close to EPA Tier 2/Bin 5.

Using diesel fuel as a reductant (an agent that reduces oxidation thereby reducing NOx) in the after-treatment system also shows promise. While it reduces emissions, it requires more diesel fuel as the reductant. An EPA demonstration with a twin bypass system (two systems in parallel alternately charging and absorbing NOx) on a Cummins 5.9L and a Mercedes A170 using a diesel fuel reductant showed 84 percent reduction in NO_x and 95 percent reduction in particulate matter emissions, with a seven percent fuel penalty. But, in over-the-road testing, the NO_x conversion was 89 percent and the fuel penalty was 11.6 percent.

THE STIRLING ENGINE OPTION

Another alternative to the internal combustion engine is the Stirling engine, which is an external combustion engine that is very fuel efficient, but with complicated and costly technology. With this design, one piston compresses the fuel/air mixture which passes it to an external combustion chamber where there is an open flame. Then that gas is passed on to another chamber to expand the gas. The Stirling engine works by using a captive working fluid (the best is hydrogen) that is transferred from the hot to the cold sections of the engine, thus, creating a pressure differential across a piston.

Stirling engines can use any fuel or source of heat (gaseous, liquid or solid) and have the lowest inherent emissions of any thermal engine. External combustion engines may provide the highest energy efficiency of any thermal power technology (including existing fuel cells) well-to-wheels. Other potential advantages of Stirling engines are that they have exceptionally low noise levels, less than half the parts of an ICE, and can be made with known automotive manufacturing techniques.

The drawbacks of the Stirling engine are its design, manufacturability costs and complexity. However, STM Power of Ann Arbor, Michigan, recently started producing a new version of the Stirling engine that has overcome the problems that limited the use of earlier (rhombic drive) designs. The STM Power engine uses a double acting piston (instead of two pistons in a cylinder) and a swash plate drive. Hydrogen leakage is resolved by use of a hydrogen replenishing system. (They require very little make up hydrogen).

The company has sold beta test engines (25 kW) that are being used to produce electrical power from landfill gas. The first production engines will be rated at 45 kW; larger sizes are planned for distributed power and, ultimately, vehicle propulsion.

CONCLUDING THOUGHTS ON INTERNAL COMBUSTION ENGINES

Thus far we have used the current gasoline spark-ignition engine as the baseline to compare it to advanced gasoline engine and clean diesel technology and for the hydrogen IC and Stirling engines. As mentioned earlier, while current IC engines do not perform at their theoretical potential, it is difficult to make significant improvements. These engines have been undergoing development for over 100 years, and the relatively easy and inexpensive improvements have already been made.

Yet, by adding advanced technology to gasoline IC engines, we may see a 20 percent improvement in fuel economy with a modest increase in cost. These innovations on IC engines include reducing engine friction, advanced variable valve lift and timing technology, and displacement on demand spark-ignition. These factors can influence throttling losses which are due to the dynamics of drawing a compressible fluid (air) through a restriction, like the engine throttle. Note: since by their nature, diesel engines are unthrottled, displacement-on-demand technology would have limited value in diesel engines.

Meanwhile, the diesel engine is overcoming its image of the 1970s and 1980s with quiet, fun-to-drive vehicles with significant improvements in fuel economy. In Europe, where there is a favorable tax policy and greater acceptance of diesels for light-duty vehicles, they are rapidly displacing the gasoline engine as the preferred automotive power technology. On the other hand, NO_x and particulate emissions have not been reduced enough to meet the U.S. EPA 2007 Tier II/Bin 5 level or the California LEV II level with a sufficient margin. As a result, U.S. vehicle manufacturers are reluctant to include a large number of diesels in their product plans until these improvements are made. Furthermore, the inherent higher cost of diesels will continue to be an issue.

The combustion technology to reduce in-cylinder emissions is proceeding rapidly and is starting to appear in today's production diesel engines. The EPA regulation to reduce the sulfur content in diesel fuel to less than 15 ppm in 2006 will enable after-treatment systems for diesels, in much the same way as the introduction of unleaded gasoline helped the development of such systems for gasoline engines.

The production cost of diesel after-treatment systems is unknown, and all of the operating costs (fuel efficiency losses) are unknown at this time. The development of clean diesel systems by European, Japanese, and Korean automakers is progressing rapidly, and some U.S. and European manufacturers are bringing diesel-powered cars to North America. However, questions remain on when and if clean diesels will capture a significant market share in the United States.

The next section will deal with the development and potential of hybrid-electric vehicles which use either gasoline or diesel engines as part of their repertoire. Following the hybrid section we'll look at the potential of fuel cell vehicles, a technology that is radically different from the internal combustion engine.

H Y B R I D - E L E C T R I C   V E H I C L E S

A TECHNOLOGY THAT HAS ARRIVED

In recent years, hybrid-electric vehicles (HEV) have attracted a great deal of attention from the media and public. In only three years, since the introduction of the Toyota Prius (see Figure 12) and Honda Insight, thousands of hybrids have been sold, and Toyota alone is planning to sell 300,000 HEVs worldwide in the coming year. Honda, meanwhile, has introduced a hybrid version of its popular Civic. By late 2004, more models will be coming from General Motors in the form of light-trucks, sport utility vehicles, and sedans. Ford will offer a hybrid Escape SUV and Focus for fleet sales only.

Essentially, the term hybrid-electric vehicle covers a wide range of vehicles that have at least two energy sources to power their drivetrains. Unlike the pure-battery powered cars, which had an effective range of less than 100 miles before needing a recharge, hybrids have a great deal more flexibility—similar to that of conventional vehicles. Hybrids also do not rely solely on their internal combustion engines for all the power they need to move; so they have improved fuel economy and lower greenhouse gas emissions when compared to comparable conventional vehicles.

Figure 12
Toyota's Prius hybrid electric vehicle design has proven popular enough that the automaker has upgraded its 2004 model, pictured above, with more stylish exterior and interior features. -Photo courtesy of Toyota Motor Sales USA

In general, hybrid vehicles improve fuel economy in four different ways. First, with the existence of the secondary power source (the battery pack and electric motor), hybrid vehicles require a substantially smaller ICE than do conventional vehicles, and they can reduce reliance on the ICE when it is least efficient (e.g., in low-speed, stop-and-go traffic). Second, because battery power is available, ICE engines can be turned off at idle, offering a 5-10 percent improvement in fuel economy. Third, hybrids employ regenerative braking to capture much of the energy otherwise lost in braking. With a larger battery pack and motor, more energy can be recaptured, but increasing the size adds weight. Existing systems, such as the one used on the Civic Hybrid (about a 10kW capacity), can recapture most of the braking energy, which results in greater fuel economy gains. Fourth, most hybrids use more efficient electric pumps, which adds to a significant reduction in accessory loads.

HEVs also offer many of the same features as conventional vehicles, such as interior trim levels, roominess, heating and air conditioning systems, stereo/CD players, cruise control, etc. While the early Toyota and Honda hybrids are all small cars (the Prius and Insight sacrificed cargo capacity because of weight and equipment packaging requirements), newer hybrid models like the Civic and Ford's Escape sport utility vehicle are larger. There is no technical reason why hybrids cannot be offered for all vehicle categories.

Yet in exchange for their benefits, current hybrids have considerably greater cost and complexity, less acceleration if the IC engine is downsized, greater weight, and questions about their long-term reliability. Their higher cost may prevent HEVs from eventually dominating the new car market. And hybrids do not necessarily outperform conventionally powered cars. There are examples where conventional cars can achieve the same or better gas mileage and/or emissions ratings as hybrids, raising questions over whether the benefits of hybrids are really worth the cost. Yet, the relative benefits of improved gas mileage versus costs could be greater on larger, gas-guzzling vehicles, like SUVs and large pickup trucks. Finally, some consider HEVs to be stepping-stones from today's gasoline-powered cars to fuel cells and a hydrogen economy.

HOW HYBRIDS OPERATE

Typically, hybrid-electric vehicles have either a gasoline or diesel internal combustion engine that is mated to an electric motor and a battery pack (although other variations are possible and will be discussed further below). These vehicles are not completely reliant on their IC engines for all the power they need to move (see Figure 13). That's the simplest definition of an HEV, but the picture gets murkier when you realize that car manufacturers are developing hybrid vehicles with a wide range of design options, and these options affect the attributes of the resulting vehicles.

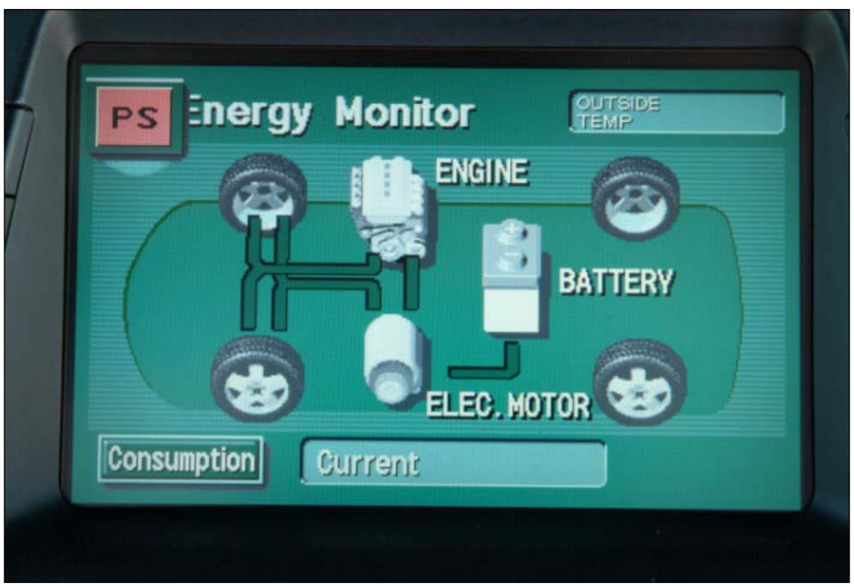

Figure 13
The driver of the Toyota Prius can watch the energy monitor screen located in the center of the dashboard to observe how the car's powertrain operates. -Photo courtesy of Toyota Motor Sales USA

Since most HEVs use an ICE, they can benefit from many of the advances being made with gasoline and diesel engine technology. Or, HEVs can be equipped with a compressed natural gas, methanol, or hydrogen IC engine.

There are three main categories of HEVs, known as "mild," "parallel," and "series" hybrids, although the Toyota Prius is a combination of parallel and series configurations. Table 1 shows the major categories of hybrid electric vehicles currently on the market or under development. Two of the public-offered HEVs—the Honda Insight and Civic Hybrid—are mild hybrids, while the Toyota Prius uses a combination of parallel and series configurations.

Table 1.
CATEGORIES OF HYBRID ELECTRIC VEHICLES AND THEIR ALTERNATIVE NAMES

HEV Type	Alternative Names	Identifying Features
Mild hybrid	Power-assist hybrid, HEV0, engine dominant hybrid	• Drivetrain powered only by conventional engine; battery provides power boost only • Approach used by Honda Insight and Civic Hybrid
Parallel Non-Plug-in hybrid	HEV0	• Both the conventional engine and electric motor can power the drivetrain • ICE engine not always on when vehicle is moving
Parallel Plug-in hybrid	Grid hybrid, HEVGRID, GCHEV, HEV20, HEV60, battery-dominant hybrid	• Battery rechargeable from electric outlet • Can operate as pure electric vehicle for extended periods of time
Series hybrid	HEV0	• Only the electric motor can power the drivetrain directly; ICE engine powers generator connected to electric motor

Mild hybrids, such as the Honda Insight and Civic, are mainly powered by their internal combustion engines, but use their battery pack to provide a power boost during acceleration. Mild hybrids (as well as the other versions of HEVs) use regenerative braking to capture some of the energy and store it in the battery when the vehicle slows down (see Figure 14). It is important to note that any car with an electric motor and battery could use regenerative braking, but electric vehicles are especially equipped to take advantage of this technology.

Parallel hybrids are so named because both the IC engine and an electric motor can provide power to the powertrain (see Figure 15). The IC engine can be shut off and restarted instantly, using an enlarged combination starter/alternator to provide power. This feature saves fuel and reduces emissions. They can also use regenerative braking. To complicate matters, parallel hybrids are subdivided into "plug-in" (a.k.a. "grid") versions, which require additional recharging, and the "non-plug-ins."

Figure 14
This illustration shows the powertrain innards of the 2004 Ford Escape Hybrid, the first HEV aimed at the popular sport utility vehicle segment. It will deliver nearly 40 mpg in city driving without sacrificing acceleration performance or cargo capacity. - Photo courtesy of Ford Motor Company

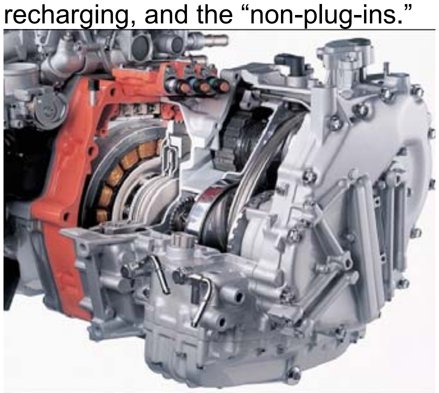

Figure 15
This picture shows a cutaway of the Honda hybrid electric vehicle engine. - Photo courtesy of Honda

A plug-in hybrid can travel about 20-60 miles on battery power alone before the battery needs to be recharged. Although the recharging requirement is an inconvenience, plug-ins can operate for long stretches of time as pure EVs, thereby offering better fuel economy and reduced emissions than non-plug-ins. On the other hand, the electrical power must be produced somewhere. Then the power has to be transmitted to the plug point and transferred to the vehicle's power storage system. Plug-in hybrids are more expensive than other HEVs largely because they require very large and expensive battery packs compared to those required for non-plug-in parallel hybrids. As implied previously, plug-in hybrids can also exist in series configuration.

Parallel non-plug-in HEVs, as their name implies, do not require an external power source. Their IC engines recharge the battery pack, so one could almost think of them as behaving like conventional cars. A series hybrid, on the other hand, uses its electric motor to turn its wheels while its IC engine and batteries connect to the electric motor. (Note, there can be different versions of series HEVs, as well).

EXAMINING BATTERIES AND ENERGY STORAGE TECHNOLOGY

Batteries and battery developments are a driving force behind the performance and cost of HEVs; the desire is to have high power and long life. However, the unknown long-term reliability of proposed battery configurations, such as nickel-metal-hydride (NiMH), lithium ion, and lead acid is a significant unknown. Thus, improvements in battery technology are essential.

The Toyota and Honda hybrids use NiMH batteries, but they cannot operate for extended periods of time on battery power. General Motors plans to offer lead-acid batteries (a larger, more specialized design than conventional batteries) on most of its forthcoming hybrids. These batteries are large, heavy packages (battery packs) that take up an enormous amount of space in the car. Generally, the additional battery weight makes HEVs more sluggish than their conventional ICE counterparts.

Although currently far more expensive than lead-acid batteries, NiMH batteries are desirable, because they are relatively environmentally friendly, recyclable, reliable, and easy to maintain. Furthermore, compared to lead-acid batteries, NiMHs provide a relatively high specific energy (Wh/kg), meaning that a smaller battery mass can deliver the same energy as a heavier mass. Indeed, an NiMH battery can be about half the weight of a lead-acid battery (and the overall weight of the HEV) and store the same amount of energy. In addition, the specific power (W/kg) – a measure of a battery's acceleration performance – of NiMH batteries has improved greatly over the past several years (i.e., 600 W/kg to over 1200 W/kg). Down the road, it appears the cost of NiMH batteries will decline.

For the future, the U.S. DOE Office of Transportation Technologies believes that lithium batteries — either lithium ion or lithium polymer — may be the best solution. Lithium ion batteries possess nearly twice the specific energy of NiMH batteries but require significant circuitry to prevent overcharging and undercharging. They also require thermal management and are considered to have safety problems.

Although batteries currently are the dominant source of electrical power in HEVs, other hybrid configurations are possible. Hybrid vehicles could use super capacitors or flywheels to supplement an internal combustion engine. Super capacitors are devices that store large amounts of electrical power; a flywheel, on the other hand, is a device that stores kinetic energy. In general, batteries offer superior specific energy (kWh/kg) but possess less specific power (kW/kg) than do flywheels or super capacitors. Another intriguing hybrid concept is the hydraulic hybrid being developed by EPA. EPA states,

> *"hydraulics have potential benefits in terms of higher power density, higher regenerative braking recovery, and lower cost, and potential drawbacks in terms of lower energy density, higher noise, and packaging issues."*

Until more development occurs with these alternative technologies, they appear to be longer-term, low probability replacements for batteries.

REMAINING CHALLENGES AND THE CASE FOR HYBRIDS

Hybrids have captured a small, but significant, segment of the market in the United States. For example, since its introduction in March 2002 to July 2003, Honda says it sold over 26,000 Civic Hybrids (see Figure 16). Toyota has sold over 51,000 Prius hybrids since their introduction in July 2000 to July 2003. Demand was especially high in February and March 2003, coinciding with the conflict in Iraq and worries over higher fuel prices. Other HEVs have sold in modest numbers. According to *Ward's Automotive*, from October 2002 to the end of April 2003, Honda sold 1,056 Insights and Toyota sold 13,084 Prius. Still, there are questions about whether or not the hybrid segment has "staying power" in the 16 million-plus new car market in the United States.

Current HEVs are decidedly more expensive to make and sell than conventional vehicles. A Toyota Prius, for example, is priced about $3,500 more than the comparable Corolla, while the Civic Hybrid is priced about $4,600 higher than a Civic LX sedan. There is little evidence to suggest that the increased purchase price can be made up from gas savings alone without some combination of tax incentives and/or manufacturer subsidies. In fact, the 30,000 hybrids sold in the last year received only tax incentives and not manufacturer incentives (other than what conventional models enjoyed for the period in question). Toyota has never offered an incentive on the Prius. If the tax incentives go away due to changes in federal and state policies, HEV sales could plummet.

Figure 16
The 2003 Honda Civic Hybrid has proven to be one the best-selling HEV since its introduction in April 2002, averaging sales of more than 1,665 per month (April 2002 to July 2003). It represents an evolutionary step away from pure internal combustion engine powered cars. –Photo courtesy of Honda

On the positive side of the ledger, HEVs offer improved fuel economy and reduced greenhouse emissions when compared to their conventional equivalents, but these improvements are not always considerable. For example, the Honda Civic Hybrid has an EPA-rated fuel economy of about 50 MPG, but the staff at *Ward's* only obtained about 40 MPG during a two-week test drive – not significantly different from a conventional Civic. Also, the Toyota Yaris offered in Europe (built on the Prius platform but with a conventional turbo diesel engine) provides better fuel economy than its better-known hybrid brethren.

On the emissions side, although HEVs perform very well, none qualifies as a ZEV, because all use an ICE engine at least part of the time. Only pure electric vehicles, such as the Toyota RAV4 electric, are awarded ZEV status. Of the three hybrid models currently available, the Prius qualifies as a super ultra-low emission vehicle (SULEV), as does the Insight when equipped with a continuously variable transmission; the 5-speed transmission Insight version and the Civic Hybrid are ultra low emission vehicles (ULEVs). Yet, there are conventional vehicles that can achieve good emissions ratings, such as the Nissan Sentra that is rated as a SULEV. Plus, the Dodge Ram Van 2500 and the Ford Econoline 250 have IC engines that run on compressed natural gas (CNG) and have achieved SULEV and ULEV status.

Hybrids have made great progress, but their future as a competitive alternative power technology depends on overcoming several remaining challenges including:

- Improving battery technology by reducing cost and increasing power density and durability,
- Lowering the cost of electric motors and motor controllers,
- Using advanced gasoline and diesel engine technology,
- Cutting the weight and improving performance,
- Reducing the complexity, and
- Cutting the overall price.

But, efforts to increase the acceleration of HEVs will reduce their fuel economy benefits. Still, increasing fuel economy requirements, emissions regulations and fuel taxes could make hybrids more attractive to manufacturers and car buyers. Likewise, corporate investment and research and development of HEVs could hasten the development of key enabling technologies, such as advanced batteries, that could cut their costs. Global events (e.g. a protracted war in the Middle East) could also dramatically raise petroleum prices, bringing hybrids into the automobile mainstream.

NOT A COMPLETE BREAK FROM THE PAST

Fuel cells have provided electrical power on spacecraft since the 1960s, but it was only in the late 1990s that the automakers began to seriously consider them as a replacement for the internal combustion engine. Fuel cells offer higher fuel efficiency than IC engines can ever produce by using hydrogen and oxygen as fuel (not petroleum) while emitting only water vapor.

At their simplest, fuel cells are electrochemical devices that convert the chemical energy of gaseous hydrogen and oxygen into electricity, heat and water. The handful of experimental vehicles announced and built thus far are fascinating (see Figure 17), but the technology is expensive and seemingly far out of reach for mass production. For example, Honda's FCX fuel cell demonstration cars have a price tag of approximately $2 million each. Another obstacle to making fuel cell vehicles a commercial reality is the lack of a hydrogen infrastructure; i.e., there are no service stations with hydrogen pumps for motorists to fill their tanks.

Figure 17
General Motor's Hy-Wire prototype fuel cell car recently drove the roads in Monaco. The Hy-Wire not only demonstrates advanced power technology, but also how vehicles can be redesigned. Note that the Hy-Wire's propulsion components are all underneath, and there's no hood in front of the car. -Photo courtesy of General Motors Corporation

Fuel cells received a boost in early 2003 as war loomed against Iraq — America questioned its continued dependence on foreign oil — and President George W. Bush pledged $1.2 billion to help create the "hydrogen fuel infrastructure" in his State of the Union Address. People disagree on whether the Bush initiative is strong enough to make a difference, but it has reenergized the alternative fuel vehicle debate. It is important to look at where fuel cell technology is, how it operates, the technical challenges to overcome, and when it will be ready for the mass market.

Another driving force behind fuel cell development is the ZEV mandate adopted by CARB in 1990 to reduce air pollution. The ZEV rule mandated that 10 percent of all new cars sold in the state by 2003 were to have zero emissions — something that only a battery-powered electric vehicle (EV) could do. Instead, battery EVs failed as the mass-market answered, and CARB has slowly backed away from its original ZEV mandate. Yet, the development of fuel cells might change the game.

PAYING THE HIGH PRICE OF ADMISSION

General Motors, Ford, DaimlerChrysler, Toyota, Honda and Nissan have all announced that they are testing demonstration fuel cell vehicles beginning in 2003. The public may be easily confused and believe that fuel cell powered vehicles are just at the cusp of mass production; however, as mentioned earlier, the costs of these devices have to be drastically lowered first.

The fuel cell test vehicles produced (or announced) thus far each cost many hundreds of thousands of dollars. The factors leading to this high cost are due to the fact that the 100 kilowatt fuel cell engine needed to power an average family sedan (equivalent to 133 horsepower), costs about $100,000─about $1,000 per kilowatt generated. To be commercially viable for automobile applications, fuel cell costs have to drop to about $50 to $35 per kilowatt generated, and that may not happen until the mid-2010s at the earliest.

Obviously, fuel cells are not yet ready for automotive introduction. The U.S. DOE, power companies and many automakers have announced that they are spending hundreds of millions of dollars to develop this technology, and it might be ready by 2015-2020. So, it is understandable that many consumers and policy makers believe commercially viable fuel cells are just around the proverbial corner, and the auto industry should abandon its other power technology development efforts. In reality, significant improvements and discoveries must be made to cut manufacturing costs and design effective and robust fuel cell engines.

Another problem slowing the development of fuel cells is the lack of a hydrogen fuel infrastructure capable of servicing such exotic cars. (This topic was mentioned briefly under the section dealing with hydrogen internal combustion engines, and we will look at it later in this paper.)

GOING FROM THE HORSE AGE TO THE SPACE AGE

Fuel cells work by generating electricity from combining hydrogen and oxygen, but this technology is not "new." Sir William Grove, a British scientist, actually discovered this process back in 1839. A half-century later, in 1889, Mond and Langer used porous electrodes in a stack arrangement, similar to modern fuel cell designs, to generate electricity. Seventy years after that, in 1959, alkaline fuel cells were used to power the Allis-Chalmers tractor – arguably the first fuel cell vehicle.

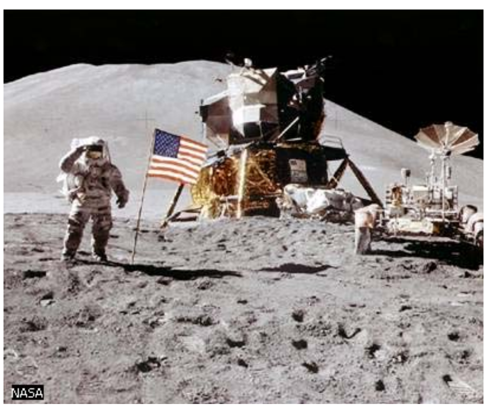

Figure 18
Apollo 15 astronaut James Irwin salutes as astronaut David R. Scott photographs Irwin and mission equipment on August 1, 1971, during their 67-hour lunar stay. Despite their high costs, fuel cells proved to be a valuable asset in the success of the Apollo program. - Photo courtesy of NASA

General Electric Corporation (GE) and other companies were also developing fuel cells in the 1950s. GE's ionic exchange membrane technology of that day is the forerunner of today's Proton Exchange Membrane (PEM) device.

Fuel cells became "space age" technology because they allowed NASA to overcome fuel storage and power generation problems on space capsules, including the Apollo moon landing missions (see Figure 18). During the past 40 years, approximately 4,000 fuel cell systems have been built and operated worldwide. However, before the 1990s, only a handful of fuel cells were built each year, and NASA used most of these. Now, fuel cells have been used on prototype buses, automobiles, stationary power generators, and portable power sources.

EXPLAINING FUEL CELL BASICS

A fuel cell works by converting gaseous oxygen and hydrogen into electricity and water by using a porous anode with a platinum catalyst, and a cathode separated by an electrolyte material (see Figure 19). Hydrogen enters the fuel cell through the anode where the platinum catalyst strips away its electrons, leaving a positive hydrogen ion (a proton). The electrons continue on to the cathode as an electrical current, while the hydrogen protons travel through the electrolyte to the porous cathode. Then another catalyst joins the hydrogen protons to oxygen (from the air) and the electrons to form water; the byproducts are electricity, heat and water.

This chemical reaction is difficult to achieve, and additional pollutants result if pure hydrogen is not used. Finally, the fuel cell is a complex system of pieces. It includes the fuel cell stack, which has a series of bi-polar plates (in PEM electrolytic cells), valves, plumbing, compressors and fans; as well as other parts, such as the heat exchangers and humidifiers, a fuel storage tank, a fuel processor, electronics and controls.

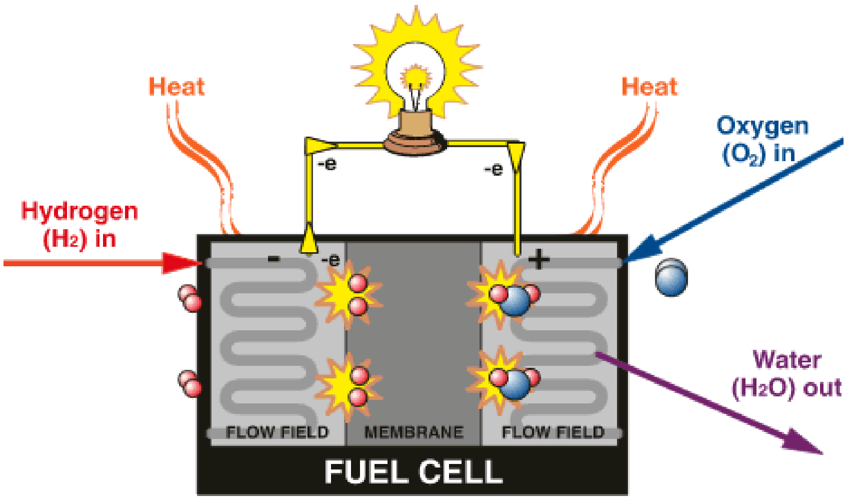

Figure 19
The illustration above depicts the electrochemical process where hydrogen combines with oxygen to produce electricity and heat. The purity of the gaseous hydrogen and the type of membrane used in the fuel cell are two of the keys to how this device works.

For all of its complexity, fuel cells are much more energy efficient than internal combustion engines for vehicle applications, 40-50 percent versus 20-35 percent. As a stationary power source, fuel cells excel, reaching a 70-80 percent efficiency rating versus 30-37 percent for IC engines.

DETAILING FUEL CELL TYPES

Fuel cells are classified according to the type of electrolyte used in the stack. That's because the electrolyte determines the device's operating temperature, cost and efficiency. The operating temperature is important, because high temperature systems require more time and energy to reach optimum performance levels, plus they are more costly and require thermal management devices. It is important to note that fuel cells that may be good for stationary applications, such as for commercial and residential buildings, may not be the best solution for the automotive industry. The six most common fuel cell types are: the Proton Exchange Membrane (PEM), Aqueous Alkaline (AFC), Phosphoric Acid (PAFC), Molten Carbonate (MCFC), Solid Oxide (SOFC) and Direct Methanol (DMFC).

- The Proton Exchange Membrane (PEM) fuel cell (see Figure 20) is widely regarded as the best option for use in cars. It has a relatively low operating temperature (70-80 degrees Celsius), high power density, and quick startup. The PEM may also be able to use a wide range of hydrocarbon fuels such as natural gas, methanol, and gasoline, where the hydrogen can be extracted and used. Its drawbacks are the high cost of its catalyst, sensitivity to carbon monoxide, and the necessity of a moist environment to work.

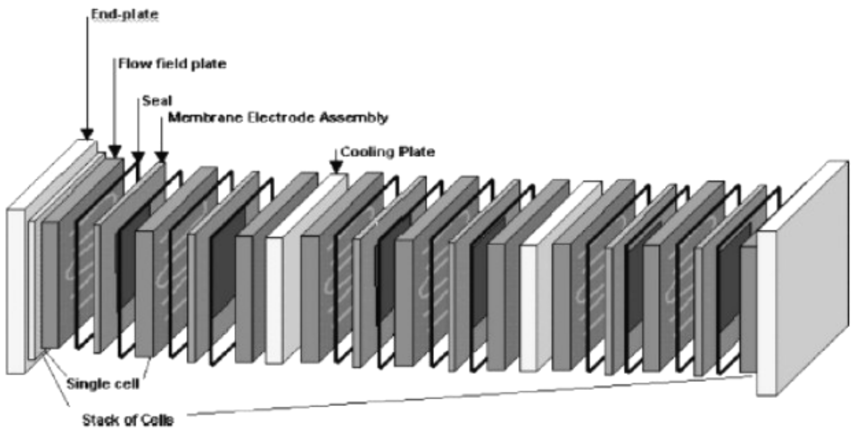

Figure 20
This illustration shows an exploded view of the internal makeup of a PEM fuel cell stack. (Reprint from Journal of Power Sources, 114, Viral Mehta and Joyce Smith Cooper, Review and analysis of PEM fuel cell design and manufacturing, p.33, 2002, with permission from Elsevier.)

- The Alkali fuel cell has good performance, relatively high power density and a low operating temperature (80-100°C), and it has been used in space applications since the 1960s. But, it requires pure hydrogen and oxygen as fuels and cannot tolerate even very low levels of carbon dioxide, which is difficult to remove from any potential fuel source.

- The Phosphoric Acid fuel cell must be preheated to 200-220°C before it will generate power, has moderate power density, and seems impractical for the rapid startups that car buyers would expect. However, it may be used for stationary powerplants.

- The Molten Carbonate fuel cell must operate at 600-650°C, and it exhibits a significant lag time in response to changing power demands. On the other hand, MCFCs may be used as stationary power plants, because they are 50-60 percent efficient and can provide exhaust heat.

- The Solid Oxide fuel cell also has a high operating temperature (1000°C) that makes it impractical for automobile propulsion use. They are being considered as auxiliary power units on vehicles to power systems, such as air conditioning, electronics, and power seats and windows. This would reduce loads on the engine, thereby improving fuel economy. However, the high temperatures of both SOFC and MCFC systems have a highly corrosive effect on their parts, creating durability problems.

- The Direct Methanol fuel cell operates similarly to PEM systems, with an operating temperature in the 70-80°C range, and it does not require a fuel processor to convert methanol to hydrogen. Its significant drawbacks are its low current density and low efficiency. It may be more suitable for portable power devices that require 1 kW or less to operate.

The key element for all fuel cells is the need for gaseous hydrogen. Although hydrogen is one of the most common elements in the universe, it does not exist in usable form, creating significant complexity and cost for automobile applications.

CREATING A HYDROGEN ENERGY ECONOMY

When looking at how a hydrogen economy might develop, it is useful to look back at the creation of the current petroleum economy and contrast the differences.

Arguably, the petroleum economy got its kick-start on January 10, 1901, when the world's first recorded oil gusher erupted from a Standard Oil drilling derrick in a field named Spindletop outside of Beaumont, Texas. Producing nearly 100,000 barrels of oil a day, Spindletop accounted for 60 percent of America's raw production. Spindletop and future oil gushers permitted a massive petroleum infrastructure to grow in America alongside the explosive growth of the automobile industry. While in Europe, the auto industry was much slower to develop, partly due to the comparative scarcity of petroleum.

Hampering the development of fuel cells is the fact that there is no hydrogen "Spindletop." Gaseous hydrogen is rare on earth, and the element is "locked up" in other forms. The real fundamental challenge that will cause a paradigm shift from fossil fuels to a new fuel economy is the discovery of the most cost-effective way to "refine" hydrocarbons and/or water into hydrogen. Whereas the early gasoline engine cars were competing with the horse and buggy, fuel cells are competing with highly developed low emission gasoline, clean diesels, and hybrids.

Current research programs looking into a hydrogen economy by the federal government and universities can be described, at best, as very preliminary attempts to discover a solution. If the United States is ever going to see a transition to a hydrogen economy, it probably will take a more comprehensive and coordinated program.

OVERCOMING HYDROGEN GENERATION CHALLENGES

Pure gaseous hydrogen must be generated (refined) from other energy sources, including coal, petroleum, natural gas, biomass, and water. This process takes up-front energy, which could be supplied by fossil fuels, hydroelectric, nuclear energy, solar, wind power, geothermal, or even tidal power sources. The jury is still out on which energy source, or combination of sources, will win out.

For perhaps the next 20 years, the raw material for hydrogen fuel will most likely be fossil fuels like natural gas and petroleum — a fact that does not bode well for those who think that the mass marketing of fuel cells will automatically translate into a petroleum free economy and energy independence from Middle East oil.

To convert fossil fuels into a hydrogen gas that is pure enough for fuel cells requires elaborate chemical processes involving catalysts (materials that help the chemical processes take place). Yet, better and more durable catalysts must be discovered through major advances in materials synthesis, surface science, computational chemistry, and reactor engineering than are currently available.

Or, if the idea is to extract hydrogen from water, a process called electrolysis must be practiced where electricity is used to split water into hydrogen and oxygen. The problem here is that excessive amounts of energy are used to create hydrogen, which outweighs the benefits of using hydrogen for fuel cells. The key to using water as a raw fuel supply could come with advances in solar, geothermal, wind, and nuclear power, or through harnessing thermochemical and biological processes, but much more research needs to be done in these areas.

And then, there are questions on where the hydrogen fuel should be processed and how it should be transported and stored. The price tag for all this work is easily estimated in the hundreds of billions of dollars. As an example of the kind of work being proposed, Shell Hydrogen, the Department of Energy, and General Motors created a partnership to develop a real-life demonstration of hydrogen fuel cell vehicles and a fueling infrastructure which would feature the nation's first hydrogen pump at a Shell retail gas station (see Figure 21). This is but a single example of the kind of infrastructure that would have to be created nation-wide.

Figure 21
Shell Hydrogen CEO Don Huberts, left, Secretary of Energy Spencer Abraham, and General Motors Vice President of Research, Development and Planning Larry Burns announce March 5, 2003, in Washington D.C. that they are creating a partnership to develop a real-life demonstration of hydrogen fuel cell vehicles and a fueling infrastructure in the Washington D.C. area. The demonstration, sponsored by GM and Shell Hydrogen, will feature the nation's first hydrogen pump at a Shell retail gas station. -Photo courtesy of GM/Shell Hydrogen

FUELS, PROCESSING AND STORAGE QUESTIONS REMAIN DAUNTING

In the near term, should central refineries create the hydrogen gas fuel or should reformers be made small enough for converting fossil fuels into hydrogen, either at the pump or in individual cars? That's the next major unresolved issue in creating a hydrogen fuel economy.

Oil companies have extensive experience making hydrogen from hydrocarbons using steam reforming or partial oxidation at a large, stationary refinery – using light hydrocarbons (i.e., natural gas or methanol rather than heavier petroleums like gasoline and diesel). Some of the characteristics of steam reforming include:

- Need for large reactors that use high temperatures where hydrogen must be stored and trucked or piped over long distances,
- Reforming natural gas (the least expensive way) at a cost of $4-$5 for the equivalent energy in one gallon of gasoline, and
- Development costs for a centralized fuel infrastructure, estimated at $405 billion to $565 billion.

Certain locales such as Iceland, with its geothermal energy, may be able to bring costs down to $2.50 for the equivalent of a gallon of gasoline. But these estimates are highly uncertain.

Other reprocessing methods could be used to create hydrogen, such as partial oxidation, or a combination of steam reforming and partial oxidation known as autothermal reforming. However, the purity of the hydrogen is unacceptable for PEM fuel cells, because the gas emitted from the autothermal reformer contains about 10 percent carbon monoxide (CO). The CO can be removed, but only through a complex series of large processors either by using a catalyst, using a water gas shift reactor, oxidizing the carbon monoxide and turning it into carbon dioxide (the greenhouse gas that we are trying to cut), or by passing the hydrogen through a palladium membrane to purify it.

Another major hurdle is the question of how to store a sufficient quantity of gaseous hydrogen for the world's vehicle fleet. Most current systems can only carry about 5,000 pounds per square inch (psi) of hydrogen (350 bars), which provides an inadequate driving range when compared to gasoline and diesel powered vehicles. In addition, the fuel tanks are either too expensive or bulky—imagine losing more than half of an average car's trunk space to hold a hydrogen tank. Although new tank designs may be able to hold 10,000 psi, costs are uncertain, and the volumetric density is inadequate.

EXPLORING ALTERNATIVES TO GASEOUS HYDROGEN

Storing gaseous hydrogen is a problem, but the alternative storage methods, liquid and solid, are also problematic. The volume of the hydrogen fuel can be significantly reduced if it is turned into a liquid, but to do so requires significant energy to chill the gas to –253°C. Metal alloy hydride storage might be used, but this method only stores 1-5 percent of hydrogen by weight, leaving significant waste.

More recently, DaimlerChrysler unveiled a way to use sodium borohydride which can be dissolved in water with a catalyst to produce hydrogen. This complex method leaves behind sodium borate, which must be reclaimed and recycled. It is unclear whether this technology can be made cost effective.

Because of the storage problems and costs associated with developing a hydrogen infrastructure from a centralized refinery to a service station, some have suggested that reformers should be placed on fuel cell powered cars, because there is a ready-made petroleum infrastructure. But, there are many technical challenges with this idea, such as:

- Reforming methods would produce emissions other than water vapor, so fuel cell vehicles would not qualify as ZEVs;
- Current reformers are bulky and complex, so the size of the equipment must shrink using more efficient catalysts (yet to be discovered), or by optimizing and creating smaller heat exchangers;
- Onboard reformers must create enough hydrogen for quick start-ups and variable rapid power demands while producing little or no pollutants at a low cost;
- Gasoline is not an easy fuel to reform, because it requires high temperature processing;
- Reformers must eliminate the sulfur content, detergents, antioxidants, and corrosion inhibitors found in the hydrogen created from gasoline before the fuel enters the fuel cell stack;
- It might be more effective for refineries to create a petroleum distillate that is suitable for fuel cells, but very little attention has been paid to this approach.

An alternative to gasoline is methanol, which can more easily be processed into a hydrogen-rich gas using steam or autothermal reforming, but it too suffers from a sulfur content problem and its carbon monoxide contaminates must be removed. Another issue is that the world's methanol infrastructure only produces the equivalent of six percent of the U.S. gasoline consumption. Significant investment would be required to produce and distribute methanol (estimated at $700-$800 per vehicle).

To sum it up, the hurdles in developing and marketing fuel cell powered vehicles is not only contingent upon inventing inexpensive, durable, more efficient fuel cell engines and discovering a practical storage medium, but on the development of a hydrogen-based economy. Although many developers have concluded that on-board reforming of gasoline is infeasible, it is probably too early in the fuel cell technology research phase to abandon this option. Table 2 summarizes the major challenges to be overcome before fuel cell technology is ready for commercialization in the automotive industry.

Table 2. MAJOR TECHNICAL CHALLENGES FOR PEM FUEL CELLS

Fuel Cell Engine • Long life, lower cost membranes • Low cost catalysts • Low cost designs and manufacturing	Fuel Processors • Better catalysts • Small heat exchangers • Sulfur removal or sulfur tolerant
Fuels • Large investment in methanol producers • Development of petroleum distillates for fuel cells	Hydrogen Production • Cost reduction for natural gas reforming • Cost reduction for electrolysis of water • Using solar, wind and other renewables
Storage • Higher capacity storage devices • Lower cost storage devices • Improved Safety	

CONCLUSION

GASOLINE ENGINES VERSUS THE ALTERNATIVES

The previous sections of this paper described the several power technology options that could provide significant improvement when compared with current gasoline engine fuel economy and emissions. Of course, fuel economy and emission improvements come with a high price tag — advanced gasoline, hydrogen IC engines, and clean diesels are predicted to be $1,000 to $3,000 more expensive than current gasoline technologies. Hybrid-electric technologies may cost $5,000 to $10,000 above the baseline, although Toyota and other manufacturers are selling hybrids at a $2,000-$4,000 premium. The true production costs of fuel cells are not known, but they will be very expensive. Added to this stark reality, the capital cost of building a new truck ICE engine plant is in the one billion dollar range.

Driveability and durability will not be affected by the introduction of most advanced IC engine technologies, but the same cannot be said for fuel cells or even hybrids, because they are still relatively new technologies for automobiles. Battery technology is a key issue for hybrids and fuel cell vehicles and, unfortunately, advanced batteries currently cost much more than current lead-acid batteries.

Nitric oxide and particulate emissions are issues associated with today's clean diesel technology. Control electronics become an issue for the electric drive systems associated with hybrids and fuel cells. Although significant advances have been made in solid-state power electronic designs and cost, this remains an area where there is added complexity and cost. Finally, because today's fuel cell designs require a system startup time, significant effort would be required to solve this cold-start problem.

The Power Technology Comparison chart in Table 3 shows the state of development of the various alternative power technologies discussed in this paper. It looks at their costs and compares their attributes with traditional gasoline engines (i.e., the baseline for mid-size passenger cars). Quantitative measures were obtained from the literature, information provided by the major automobile manufacturers, and CAR's internal expertise and experience. In those cases where quantitative measures could not be obtained due to the state of the technology or the confidentiality of the information, a qualitative assessment was conducted based on industry consensus. An examination of the table shows that no single technology is clearly superior across the various evaluation categories, and indicates that all have performance and cost tradeoffs.

When looking at alternative vehicle power options, it is easy to mistakenly believe that the perfect solution can readily be found. Unfortunately, cost-benefit studies, oil well-to-wheel analysis and other studies only measure known factors and miss many important variables that cannot be easily quantified.

New discoveries or inventions, petroleum availability (or lack thereof), and pricing will impact government regulations. Ultimately, consumer preference will drive the adoption of many technologies. Since pollution and fuel economy standards are likely to become more restrictive, the viability of various engine technologies will become more apparent in the future. The automotive manufacturers that are able to meet this demand will be the ones that will dominate the market.

Table 3. POWER TECHNOLOGY COMPARISON

Comparison Parameters \ Technology Options	Current Gasoline	Advanced Gasoline	Hydrogen ICE	Clean Diesel[1]	Hybrid			Fuel Cell[2]
					Mild[3]	Parallel–Non-Grid[4]	Parallel–Grid[5]	
State of Development	Very High	High	Medium	High, except for emission control	Medium	Medium	Low	Low
Cost	Baseline	+$1,000	+$2,000 to +$3,000	+$2,000	+$2,000	+$4,000 to +$6,000	+$10,000	Very High
Fuel Economy	Baseline	+20%	+20%	+30%	+10%	+20 to +30% (with diesel +50%)	+50%	+50%
Non-CO_2 Emissions	Baseline	Baseline	Very Low HC, CO, NO_x	NO_x and Particulate Problem	-10%	-20 to -30%	-50%	Low (but CO_2 with HC fuels)
Driveability	Baseline	Baseline	Baseline	Baseline	Baseline	Baseline	Baseline	Unknown
Durability	Baseline	Baseline	Baseline	Baseline	Should be similar, but there is added complexity.			Unknown
Battery	Baseline	Baseline	Baseline	Larger	Larger	Cost Key Issue	Cost Very Key Issue	Key Issue
Control Electronics	Baseline	Baseline	Baseline	Baseline	Advanced solid-state power electronics required. Expensive, difficult technology to manage interface between powertrain components.			
Cold Start	Baseline	Baseline	Baseline	Baseline	Baseline	Baseline	Baseline	Tough Problem

[1] Assumes low sulfur fuel.
[2] Series fuel/infrastructure problems.
[3] Mild: battery provides power boost only.
[4] Non-Grid: cannot be connected to electric power grid (Toyota Prius).
[5] Grid: can be connected to electric power grid.

TOO MANY UNKNOWNS TO DECIDE

At this time, there is insufficient knowledge for anyone to recommend one power technology over another. There are just too many unknowns to exclude any option or to declare one will survive over another. Advanced gasoline, hydrogen ICE, clean diesel, hybrids, and fuel cells are all potentially viable options that must be considered with an eye toward their marketability.

Today it appears that the gasoline engine will be here for the long-term future, as long as petroleum availability and price remain relatively stable. But, clean diesel could gain a significant market share here in the United States, as it has in Europe, if the nitric oxide and particulate problems can be solved without a significant price premium. Diesel engine plant capacity is very low in the United States, and many billions of investment dollars would be required to expand plant capacity.

The unknowns facing the auto manufacturers include:

- Is investing in clean diesel technology worth the time and money involved?
- Is this risk worth taking given the progress in hybrid technology?
- Is a low-cost, long-life battery on the horizon that will significantly change the cost feasibility for hybrids?
- Are fuel cells really 15 to 20 years away from being commercially available?
- What if key discoveries are made in the next two to three years that lead to an inexpensive hydrogen-based fuel that could easily be converted on-board to hydrogen, and an inexpensive and durable catalyst is found to improve fuel cell cost and reliability?
- Will a solution to the hydrogen storage issue be discovered?

Counterbalancing the risks are the promises that hydrogen ICE, clean diesel, and parallel (non-grid) hybrids will cut greenhouse gas emissions by about 30 percent, versus today's gasoline engines. Meanwhile, parallel (grid) hybrids and fuel cells cut emissions by as much as 50 percent.

AUTO MANUFACTURERS PURSUE DIFFERENT SOLUTIONS

Although the gasoline ICE has been the mainstay of the auto industry for a century, the doubts about which advanced power technology will win in the future is the reason why manufacturers need to pursue different solutions. There is not a uniform strategy going forward. Each automaker has different knowledge and experience with the technologies mentioned in this paper.

European manufacturers have invested heavily in diesel engines for cars, especially for high-end models like Mercedes and BMW. Japanese manufacturers have been aggressively pursuing hybrid options, and Toyota, for example, expects to sell several hundred thousand hybrids in the next couple of years. While, here in the United States, manufacturers like General Motors are planning hybrid introduction within the next several years, and investing heavily in fuel cells. Other manufacturers are also investing in fuel cell technology.

In other words, different manufacturers will pursue different paths for advanced power technologies.

ALLIANCES ARE NECESSARY TO SURMOUNT OBSTACLES

Investment in advanced power technologies is very expensive. No automotive manufacturer can afford to pursue these various options on its own. Alliances will have to be formed with other auto manufacturers, supplier companies, research firms, power and fuel companies, academia and the government at both the research and product development stages. The risks involved are:

- New automotive engine plants cost upwards of one billion dollars each. Battery development is costly and often fraught with many dead ends.

- History has shown that many hundreds of millions of dollars in research can be spent without a successful outcome.

- Furthermore, fuel cell development and infrastructure could easily be measured in the hundreds of billions of dollars before commercialization is realized.

The Ford, DaimlerChrysler, Ballard fuel cell development effort is a prime example of such an alliance.

CONSUMERS DECIDE, OTHER ISSUES INFLUENCE CHOICES

The ultimate decision maker for choosing winners and losers in the advanced power field will be the consumers, and the automotive manufacturers that are better able to meet this demand will be the ones that will dominate the advanced power technology future.

None of the proposed advanced power technologies are likely to be cost competitive with current technologies unless tax credits or other incentives stimulate demand. If the cost gap cannot be closed, short-term incentives might not prompt investment, as costs may be too high to ensure success. But, as time progresses, research will uncover new knowledge, and feasibility will become more certain. Petroleum availability and price will either remain stable or fluctuate, causing consumer preference to change. And, the regulatory climate will become more or less restrictive. All these factors will affect the viability of various advanced technology options. In the end, however, consumers will decide which technologies make it in the marketplace.

As vehicle power technology progresses, the Center for Automotive Research will continue to track it, creating a future report looking into the questions that have been left unanswered.