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Cleaner Vehicles

Handbook 4: Transport and the Environment

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As populations and economies expand, increasing quantities of natural resources are extracted and processed, more goods are moved, more people travel, more energy is used, and more wastes are generated. One outcome is over 800 million motor vehicles operating in the world today, consuming around 40 million barrels per day of petroleum, producing about half the urban pollution, and emitting over 1/10 of the world's anthropogenic greenhouse gases (IEA, 2000). This process is not sustainable unless energy and environmental performance is improved. In this chapter, we focus on the energy and environmental performance of land-based vehicles, especially those operating on roads. We examine internal combustion engine vehicles, electric-drive vehicles, and alternative fuels.

RECENT HISTORY OF ALTERNATIVE FUELS

History is filled with efforts to replace petroleum fuels and improve upon petroleum-powered internal combustion engines. Initiatives and investments have largely come and gone, succumbing to unanticipated successes in finding and extracting petroleum and reducing emissions from petroleum-fuels engines. A common theme through this long history is the growing importance of environmental impacts as a determining factor in energy production and use.

The modern history of alternative fuels begins in the mid-1970s, just after the 1973 Arab oil embargo (see Sperling, 1988, 1995). Nations began searching for ways to attain energy independence. They began to investigate the use of alternative resources – mostly coal, oil shale, oil sands, and biomass. Natural gas was virtually ignored in most countries since it was considered even scarcer than petroleum. By the late 1970s, a number of countries were beginning to invest vast sums in pursuit of energy independence. The US was investing tens of billions of dollars in synthetic fuel plants that converted mostly coal and oil shale into petroleum-like fuels. Brazil began a massive program to convert sugar cane into ethanol, and South Africa increased its coal-to-fuels investments.

Within a few years, by the early 1980s, perceptions began to shift. The costs of manufacturing petroleum-like fuels from coal and oil shale were greater than anticipated, and petroleum-like synthetic fuels did not help reduce persistent urban air pollution. After tens of billions of dollars of wasted investment in expensive synthetic fuel plants, the US shifted its focus to the use of methanol and natural gas in internal combustion engines. South Africa, however, expanded its commitment to coal-to-liquids technology as a means of resisting international sanctions over Apartheid, while Brazil increased its commitment to ethanol produced from sugar cane.

In the mid and late 1980s, with the drop in oil prices (from about \$30 per barrel to under \$15), the most capital-intensive alternative fuel investments evaporated, and environmental issues began coming to the

forefront. Attention began to shift toward natural gas fuels, and in the US to methanol made from natural gas. Both were cleaner burning than gasoline and diesel fuels, and natural gas was being found in increasing quantities around the world. Methanol never gained widespread acceptance, largely because it couldn't compete with dropping oil prices, while less expensive natural gas remained a minor option in many countries around the world.

Natural gas vehicles continue to have a small but expanding presence in many countries around the world. They may be seen as a small incremental enhancement, but they also require substantial investments in fuel stations. These vehicles mostly use conventional internal combustion (spark ignition) engines. They burn fuel that is compressed at local fuel stations and then placed in high-pressure tanks on board the vehicles. The tanks add some extra cost, but the fuel is usually somewhat less expensive than gasoline. Greenhouse gas emissions are about 20% less than on an energy cycle basis (taking into account emissions upstream at the production site), and air pollutant emissions tend to be somewhat lower (OECD, 1993). Natural gas has gained widespread use in urban transit buses in many cities, including in the US – replacing diesel engines – largely because they are much cleaner burning than 20th century diesel engines. (In Delhi, India, the Supreme Court required that all buses switch from diesel to natural gas in 2000 (Bose and Sperling, 2002).) As emissions of diesel engines are reduced in the first decade of the 21st century, it is likely that the switch to natural gas buses will be slowed or even reversed.

Other alternative fuel efforts persisted through the 1990s and early 21st century, but remain of modest scale. Brazil scaled back its ethanol program, from virtually all new cars running on ethanol in the late 1980s to ethanol currently being used only as a blending component with gasoline. The US has slowly expanded its heavily subsidized corn-to-ethanol program (scheduled to amount to about 3% of gasoline sales by about 2005), Canada is slowly expanding its modest investment in synthetic fuel plants that convert oil sands into petroleum-like fuels (about 10% of Canadian oil production in 2000, with plans to expand to 25%, equivalent to about 400,000 barrels per day), and South Africa continues its coal-to-fuels program (supplying about 40% of domestic transport fuel consumption) (Prozzi et al, 2002). Most recently, a number of major energy companies have been building processing plants in remote areas of the world to convert natural gas into petroleum-like fuels. These gas-to-liquid processes remain uncompetitive with gasoline and diesel fuels, but produce zero-sulfur clean fuels that are becoming increasingly attractive as governments impose low-sulfur requirements on fuel suppliers.

In all these cases, the internal combustion engine remained dominant. In all these cases, alternative fuels were being burned as gasoline and sometimes diesel fuel substitutes.

In 1990, a dramatic event marked the beginning of a new era. California adopted a new rule that required all major automakers to sell a certain percentage of zero emission vehicles (ZEVs), beginning in 1998. The mandate had two effects (Williams and Sperling, 2002). First, automakers accelerated their already intensive effort to reduce emissions from internal combustion engines – in part as a defensive measure against mandates for electric vehicles. And second, it accelerated the development of inherently cleaner burning electric-drive vehicle technologies. The ZEV mandate has been delayed and greatly transformed over the years. But its effect has been revolutionary.

INTERNAL COMBUSTION ENGINES

Internal combustion engines power virtually all motor vehicles. While the technology has been commercially available for over 100 years old, it continues to undergo substantial improvement, especially in terms of its environmental performance. Mostly two types are used. Spark ignition engines are used in most cars and

light trucks, usually powered by gasoline, and compression ignition engines are used in most trucks and buses, usually powered by diesel fuel.

Spark Ignition (Gasoline) Engines

Since the 1960s, huge improvements have been made in reducing pollution from gasoline engines. Emissions of conventional air pollutants have been reduced by 90 percent and more compared to their uncontrolled state. Further emissions improvements are expected, facilitated by reformulation of petroleum fuels, especially by reducing sulfur levels. The lower sulfur facilitates the use of even more effective pollution control devices. Modern gasoline cars have emissions that approach zero; they are barely measurable.

Energy improvements have been more difficult and elusive, not because of technology but mostly because of consumer preferences. In the US, the average gasoline-powered light duty vehicle sold in year 2000 had slightly worse fuel economy than the average vehicle sold in 1980 -- but weighed 21% more, had 79% more horsepower, and accelerated from 0 to 60 miles per hour in 26% less time, and also offered many more energy-consuming accessories and capabilities, including 4-wheel drive and air conditioning (NRC, 2002). From a technical engineering energy efficiency perspective, the modern US car is therefore about 30 percent more efficient than it was 20 years earlier, even though fuel economy is no better. Further efficiency improvements are continuing to be made -- in engine combustion, use of lightweight materials, and conversion of mechanical and hydraulic subsystems to electric control. In countries with more aggressive fuel economy (and greenhouse gas) policies, including Europe and Japan, fuel economy improvements are more likely to accompany fuel efficiency improvements. In the European Union, automakers have agreed to a 25% reduction in carbon dioxide emissions per vehicle kilometer between 1995 and 2008, and Japan adopted rules in 1998 requiring a 20-25% reduction in fuel consumption for most vehicle classes by 2010 (Plotkin, 2001). Of the major car-buying regions, only the US did not adopt more stringent fuel consumption rules during the 1990s.

Diesel Engines

Diesel engines are considerably more controversial, especially in the US and Japan (see Walsh, 2001; Brodrick et al, 2002). The governor of Tokyo and the air quality regulators in southern California launched campaigns in the late 1990s to ban diesel engines. Diesel engines are often viewed as inherently dirty and noisy, belching clouds of black soot. Indeed older diesel technology fit that image well. But there is another story.

Diesel engines are commonplace. Freight companies and bus operators rely almost exclusively on diesel engines for their trucks and buses. Indeed, diesel engines continue to increase their market share worldwide, now accounting for about 40 percent of all roadway fuel consumed. In Europe, diesel cars account for about 1/3 of sales -- compared to less than 1% of cars and 4% of light trucks in the US, and about 10% of cars in Japan -- and the share continues to increase. (Diesel cars are increasing market share in Europe in part because diesel fuel is taxed less than gasoline, and in part because automakers are pursuing diesel engines as the primary strategy to meet the 25% reduction in carbon dioxide emission rates.)

New diesel engines are vastly enhanced and nearly as clean and quiet as a gasoline engine. Diesel engines tend to produce much lower levels of carbon monoxide (CO) and hydrocarbons (HC) than gasoline engines, but much higher levels of nitrogen oxides (NOx) and particulate matter. Newer engines are being outfitted

with particulate filters that greatly reduce soot emissions, and are expected to bring particulate levels close to those of gasoline engines. However, even with continuing improvements, diesel engines are expected to continue emitting higher emissions of nitrogen oxides (precursors to photochemical ozone).

The controversy over diesel engines is likely to continue and even intensify. In the US, stronger pollution control rules are hindering the introduction of diesel engines in cars and light trucks, and disrupting heavy-duty engine manufacturing. But diesel engines are considerably more energy efficient than gasoline engines. Advanced direct injection diesel engines are up to 45 percent more efficient than current gasoline engines, and about 20 percent more efficient than advanced gasoline engines. European regulators have set less stringent NO_x and particulate emission standards for diesel cars, relative to gasoline cars, in order to allow their rapid introduction. The US has not done so, insisting that diesel cars meet the same emission standards as gasoline cars.

In summary, internal combustion engine technology is still evolving, especially diesel engines. Future engines will be even cleaner and more efficient – with improved aftertreatment devices, improved engine design and operation, and improved low-sulfur fuels. Internal combustion engines are here to stay for a very long time, operating mostly on petroleum fuels. They have compelling advantages that are difficult to replicate with other propulsion technologies and fuels.

TOWARD ELECTRIC-DRIVE VEHICLE TECHNOLOGY

Two factors suggest that even with improving internal combustion engine technology, a transition is about to occur to electric-drive technology. The first is intensifying calls for even cleaner, more energy efficient, and lower greenhouse gas emitting vehicles. The second is rapid innovation in lightweight materials, energy storage and conversion, power electronics, and computing. Indeed, the transition process is already underway.

Electric-drive vehicles are defined as those vehicles whose wheels are turned in part or entirely by electric motors, rather than by a mechanical drivetrain powered by an internal combustion engine. Electric-drive vehicles include not only those powered by batteries charged with household current, but also vehicles that generate electricity onboard or store it in devices other than batteries. Their common denominator is in the efficient electric motors that drive the wheels and extract energy from the car's motion when it slows down. Internal combustion vehicles, in contrast, employ a constantly running engine whose power is diverted through a series of gears and clutches to drive the wheels and to turn a generator for the electrically powered accessories in the car.

Although electrically driven vehicles have a history as old as that of the internal combustion engine, a number of recent technology developments provide promise that this form of transportation will eventually be efficient and inexpensive enough to compete with internal combustion engine vehicles. Overcoming the entrenched advantages of petroleum-powered vehicles will, however, take time and resources, and the transformation may occur in unpredictable ways.

Electric-drive vehicles are more efficient --and thus less polluting – than internal-combustion vehicles for a variety of reasons. First, because the electric motor is directly connected to the wheels, it consumes no energy while the car is at rest or coasting, increasing the effective efficiency by as much as 20%. Regenerative braking schemes--which employ the motor as a generator when the car is slowing down--can return as much as half an electric vehicle's kinetic energy to the storage cells, giving it a major advantage in stop-and-go urban traffic. Most important, the motor converts more than 90 percent of the energy in its

storage cells to motive force, whereas internal-combustion drives utilize less than 25 percent of the energy in a gallon of gasoline.

The question is: how and from where will the electricity be delivered in ways that preserve the inherent advantages of the electric motor and controls? The most attractive choices appear to be batteries, fuel cells, and hybridized systems of internal combustion engines and batteries. Each has a different set of positive and negative attributes relative to internal combustion engines – for both consumers and vehicle manufacturers.

Battery Electric Vehicles

Battery-powered electric vehicles have a long history, dating to the 19th century. Initially they competed successfully with early gasoline cars, but the high cost and large bulk of batteries eventually gave way to the more energy-dense and portable petroleum fuels, even though they were safer, quieter, and more energy efficient.

Battery electric vehicles have many positive attributes. They are quiet, provide an appealing driving feel, reduce energy use and greenhouse emissions, and are zero emitting. Even including pollution generated at the powerplant source, the pollution benefits are large in most cases. Regardless of how the electricity is generated, battery EVs would practically eliminate emissions of carbon monoxide and volatile unburned hydrocarbons, and greatly diminish nitrogen oxide emissions (Wang et al (1990). In areas served by dirty coal-fired powerplants, they might marginally increase the emissions of sulfur oxides and particulate matter. Electric vehicles' impact on air pollution would be largest, of course, where electricity is produced from solar, nuclear, wind, or hydroelectric power. The pollution benefits would be greatest in places such as California, where most of the electricity comes from tightly controlled natural gas plants and zero-emitting hydroelectric and nuclear plants, and France, where most electricity comes from nuclear power, but also in very polluted cities where reductions in tailpipe emissions are greatly valued -- such as Mexico City, Beijing, Bangkok, and Katmandu.

Other advantages include home recharging and the driving feel. In all drive clinics and surveys, the majority of electric vehicle drivers affirm that they prefer the smooth, hard acceleration associated with the high torque of electric motors (the effect is especially noticeable at low speeds) (e.g. Turrentine et al, 1992). Many people also see home recharging as desirable (Kurani et al 1994). Most people prefer not to patronize retail fuel stations, some strongly so (Sperling and Kitamura, 1986).

The key problem is the battery. Battery technology has improved dramatically since the 19th century, and continues to improve. Through the 1990s, entirely new battery technologies were commercialized that store more energy in less volume at less cost. The proliferation of portable consumer products, including laptop computers and camcorders, spurred the development of these improved batteries – resulting in nickel cadmium, nickel metal hydride and more recently lithium batteries. But scaling up these battery technologies has proved formidable, and even with the improvements, cost and bulk remain high.

Indeed, into the foreseeable future, batteries will not be cheap nor compact enough for battery-powered electric vehicles to be cost competitive with internal combustion engine vehicles – unless used in smaller vehicles with reduced performance expectation. In other words, the only attractive opportunity for battery EVs appear to be small neighborhood and city EVs, and perhaps electric scooters – vehicles with top speeds less than 100 kph and ranges less than 100 km (Sperling, 1994). More important markets for battery-powered vehicles to date have been off-road equipment where noise and pollution are especially offensive (especially within enclosed spaces). For these vehicles, not much energy is needed, and thus a relatively

small battery can be used. The additional cost of the battery in these cases can potentially be offset by the longer life of the electric powertrain, reduced maintenance, and lower energy cost – as well as by noise and pollution benefits.

Hybrid Electric Vehicles

Hybrid electric vehicles combine an electric motor with a combustion engine. By severing the direct connection between engine and wheels, the engine can operate at steady load near its maximum efficiency, as with stationary engines. The engine is downsized, with onboard energy storage devices such as batteries or ultracapacitors providing the power surges needed for hill climbing and passing.

In some sense, hybrids are a middling technology (Sperling, 1995). Compared to internal combustion engine vehicles, hybrids have better energy efficiency, easier-to-control emissions (since engines are operating at a steady load) and, like all electric-drive vehicles, a superior driving feel (the result of high torque and smoother acceleration at lower speeds). But due to redundant powerplants, they are inherently more expensive and possibly less reliable than combustion vehicles. Hybrids have longer range and fewer batteries than battery EVs, but are technologically more complex, generally lack home recharging (which appears to be highly valued in the US market), and present a less pure environmental image.

The first mass-produced hybrid electric vehicle was put on sale in Japan in December 1997. This Toyota Prius was updated for sale in North America and Europe in 2000. Honda unveiled a hybrid electric car in 2000 as well, and added a hybrid version of its popular Civic model in 2002. These early hybrid electric cars are priced about \$1500 to \$3500 more than comparable gasoline models. They have 25-50% better fuel economy. By mid 2002, Toyota had sold almost 100,000 Prius cars, and was claiming that they were not losing money on them (with the higher price). Most major automakers plan to unveil hybrid electric models during the first decade of the 21st century.

Hybrid vehicles are not a single uniform technology (An et al, 2001). They encompass a wide range of designs and technologies. Like fuel cells, they build upon electric-drive technology developed for battery electric vehicles. They could use any of a variety of combustion engines, including spark ignition, diesel compression ignition, and gas turbine engines, and may store electricity in a variety of devices, though batteries and perhaps ultracapacitors are the preferred technologies.

These various components may be combined in a variety of ways to achieve a variety of goals. Hybrids may be designed to minimize emissions by incorporating large battery packs and operating mostly in a zero-emissions mode (and also providing home recharging capability), to minimize energy consumption by operating a small combustion engine full time, to minimize changes in conventional petroleum-powered ICEV by using a very small battery pack mostly just to gain the energy benefits of regenerative braking, or to achieve a variety of cost and performance goals. In practice, a variety of hybrid designs will likely be commercialized, each responding to different government rules and subsidies, and targeted at different market segments. Initially, smaller battery packs are preferred, since it restrains costs.

Despite the early successes of Toyota and Honda, automakers are reluctant to make major commitments to hybrid electric technology. They are less risky and less expensive than battery EVs, but still more expensive to produce than conventional gasoline and diesel vehicles. They provide improved fuel economy, but unless fuel costs are high and the vehicle is driven intensively, the fuel savings does not offset the higher purchase price.

Will others follow Toyota and Honda? If fuel economy standards were toughened, or incentives provided to automakers and consumers, then demand would undoubtedly strengthen. But short of those conditions, and especially in the US, where fuel prices are near historical lows (adjusted for inflation), automakers will likely proceed cautiously.

Fuel Cell Vehicles and Hydrogen

Perhaps the most promising option is fuel cells (see Lipman and Sperling, 2002; DeCicco, 2001). Fuel cells have unique attributes that are attractive to both consumers and automotive suppliers. Though at an early stage of development, they are widely viewed as the most likely successor to the internal combustion engine. They have been termed the Holy Grail by automotive leaders, since they dramatically reduce energy and environmental impacts, while providing equal or better performance than internal combustion engines. Indeed, fuel cell vehicles provide the opportunity to shift from today's hydrocarbon-based energy system to a more sustainable hydrogen economy. It is this vision that explains much of the interest in fuel cells.

Fuel cells convert fuels directly into electricity, with no byproducts other than water. It is an electrochemical process. There is no combustion, and therefore no combustion byproducts. There are a number of different fuel cell technologies. At this time, the most attractive for vehicle applications is the Proton Exchange Membrane (PEM) system. In a PEM fuel cell, hydrogen is the fuel. The two inputs are hydrogen, delivered to the anode of the fuel cell, and air (containing oxygen) delivered to the cathode. The oxygen at the cathode has a magnet-like attraction for the electrons of hydrogen, and is the driving force behind the electrochemistry. The electrons travel from the anode through a wire, and the positively charged ions (protons) that have made the same trip through the electrolyte (the "proton exchange membrane"), react simply and elegantly, with the help of a catalyst, to form pure water and nothing more. The induced movement of electrons creates an electric current. And thus, fuel cells oxidize hydrogen to water vapor, emitting essentially no other effluents as they generate electricity.

Other fuel cell technologies also exist, but they operate at much higher temperatures or require pure oxygen. Neither case is suited to widespread vehicle use. Pure oxygen is expensive and difficult to supply, and vehicles are expected to power up in a matter of seconds. Fuel cells operating at high temperatures (such as solid oxide fuel cells) require up to an hour to power up. One other fuel cell type that may have promise is a variation of PEM fuel cells in which methanol is input directly into the fuel cell (instead of hydrogen). Direct methanol fuel cells are potentially attractive because methanol is more energy dense than hydrogen and can be stored more easily on the vehicle, and because it is less expensive to create a fuel distribution system for methanol than hydrogen.

The concept of the fuel cell traces its roots back to William Grove's experiments on water electrolysis in 1839, but the commercialization history of fuel cell technologies remains rather limited over 150 years later.

Fuel cell development received a boost in the late 1950s, when the US National Aeronautic and Space Administration (NASA) determined that fuel cell technology was the most promising option for producing electricity in space in a compact, efficient, and safe fashion. NASA used PEM and alkaline fuel cells, the latter requiring pure oxygen, in the Apollo, Gemini, and Space Shuttle programs. The first motor vehicle application was an experimental farm tractor in 1959. In the 1960s, General Motors began experimenting with fuel cell technology, demonstrating the world's first drivable fuel cell passenger vehicle in 1966. Interest in fuel cells subsequently lagged through the 1970s and '80s.

Interest in fuel cell vehicles revived in the early 1990s, motivated by California's ZEV mandate. The mandate had attracted attention to zero emission technology. Battery electric vehicles were the initial target. But it soon became apparent that the high cost and low energy density of batteries rendered battery electric vehicles infeasible as a mainstream option. Interest quickly shifted to other means of achieving inherently low emissions. Most attention is focused on the use of PEM fuel cells, running on either pure hydrogen or coupled with an on-board reformer device that could convert methanol or gasoline-like fuels into hydrogen. Other efforts include development of direct methanol fuel cells, and use of high temperature solid oxide fuel cells as auxiliary power units dedicated to powering accessories (such as refrigeration units in trucks and to heat truck cabins overnight while the driver sleeps).

Great strides have been made in reducing size and cost, and increasing performance. Ballard, the early leader in fuel cell development, was able to increase the power density of their fuel cell stacks eleven fold between 1989 and 1996, and their 2001 commercially available fuel cell even doubles that. General Motors and Toyota, two of the other leading developers have demonstrated similar progress.

Despite rapid progress, significant challenges remain for the commercialization of fuel cell vehicles. The principal challenges are:

- Development of a hydrogen refueling infrastructure;
- Compact, low cost on-board fuel reformers, if hydrogen is not available;
- Onboard hydrogen storage systems that are safe, compact, lightweight, inexpensive, and quick to refuel;
- Further cost reductions in fuel cell systems.

Fuel cells are attractive in part because they are potentially applicable to most types of vehicles – including not only light-duty passenger vehicles, but also urban buses, delivery vehicles, fork lifts, airport baggage handling vehicles, mining vehicles, golf carts, scooters, boats, and even airplanes, as well as auxiliary power units for heavy-duty trucks. Of these, the urban bus market segment has received the most attention initially, with fuel cell bus demonstration projects conducted in the late 1990s in Vancouver, Chicago, Sacramento, Palm Desert, and Washington D.C. Ballard Power Systems and DaimlerChrysler are delivering 30 fuel cell powered fuel cell buses to European cities beginning in 2002.

As of 2002, all major automakers had substantial fuel cell development programs. Test programs for light duty vehicles were underway in Sacramento (under the California Fuel Cell Partnership), Germany, England, and Japan.

Two principal concerns are hindering fuel cell vehicle commercialization. One is cost. Fuel cells are revolutionary new products. Their cost in mass production is not known, though there are no fundamental reasons, such as high material costs, that make them inherently more expensive than internal combustion engine systems. Indeed, they may eventually prove less expensive, especially on a lifecycle cost basis. Only with time, experience, and money will the cost question be answered.

The second concern is fuel. Fuel cells are simpler, less expensive and more energy efficient when operating on hydrogen. But hydrogen is not readily available and is difficult to store (it is the lightest element known). An alternative is to use methanol or a gasoline-like fuel, which can be provided much more easily, especially gasoline. A reformer device would be installed on the vehicle to convert those liquid fuels to hydrogen for use in the fuel cell, or methanol could be input directly. Prototype fuel cell vehicles have been built that run on hydrogen, methanol, and gasoline, and that store hydrogen as a cryogenic liquid, compressed gas, in metal hydrides, and as sodium borohydrate. In general, automakers agree that hydrogen is the ultimate fuel for fuel cell vehicles, and that future fuel cell vehicles are likely to operate directly on hydrogen. But there

are significant differences of opinion with regard to the preferred and likely evolution of vehicles and refueling systems over time.

Fuel cells are superior to internal combustion engines in several important ways, and it is for these reasons that automakers expect fuel cells to dominate eventually. They offer better environmental performance, better energy efficiency, quiet (but not silent) operation, rapid acceleration from a standstill due to the torque characteristics of electric motors, and potentially low maintenance requirements. Furthermore, fuel cell vehicles have the potential to perform functions for which conventional vehicles are poorly suited, such as providing remote electrical power (for construction sites, recreational uses, etc.) and possibly even acting as distributed electricity generators when parked at homes and offices and connected to a supplemental fuel supply. They also provide automotive designers with much more leeway in the design of vehicles, since they facilitate the elimination of mechanical and hydraulic devices and subsystems. Because of these attributes, fuel cell vehicles could provide additional value to the consumer and automaker, and therefore be perceived as superior to internal combustion engines. Even if they prove more expensive, these added attractions could make them more attractive to both consumers and automotive suppliers.

The potential energy and environmental benefits are large, especially when operating on hydrogen, enhancing their societal benefits. Hydrogen-powered fuel cell vehicles would emit essentially no air pollution, consume less than half as much energy as comparable gasoline vehicles, eliminate petroleum use, and sharply reduce greenhouse gas emissions. The quantity of greenhouse gas emissions would depend on how the hydrogen is produced and stored. If made from water using solar energy, the ultimate dream, greenhouse gas emissions are essentially zero. If made from natural gas, the expected production pathway into the foreseeable future, emissions would be reduced about 40% relative to gasoline vehicles. If made from petroleum, reductions would be small relative to gasoline vehicles, and about the same as diesel vehicles.

The process of introducing a revolutionary product such as fuel cells, where many of the attractions are outside the marketplace, is fraught with uncertainty. Fuel cells, like all nascent technologies, are characterized by high manufacturing costs, uncertain long-term performance and durability, and lack of a clear technological consensus or “dominant design” for the individual niches for which they are being considered. As commercialization of fuel cell technology proceeds, manufacturing volumes will increase, costs will fall, and long-term product performance and durability will be better understood. However, fuel cell systems will not easily or “automatically” penetrate automotive markets, despite their attractive qualities. This is due not only to uncertain durability of fuel cells and potential cost differences between fuel cell systems and competing systems, but also because the incumbent technologies are typically “locked in” and have a series of network relationships that reinforce their continued use.

The barriers are perhaps more forbidding in the transportation arena (compared for instance to the electricity market) because the motor vehicle system in place has evolved for over a century to support gasoline-powered, internal combustion engine vehicles. In most places of the world, the vehicle refueling infrastructure and vehicle service industries that support the use of motor vehicles are entrenched in a way that will make change away from the *status quo* inevitably difficult. Furthermore, due to environmental pressures and partly in response to progress in fuel cell development, other more conventional technology is a ‘moving target.’ Such options as hybrid-electric vehicles, with a small gasoline or diesel engine coupled with a battery-powered electric driveline, are capable of achieving impressive levels of efficiency and environmental performance at cost levels that fuel cell vehicles will be challenged to meet, especially initially.

Thus, a key aspect of the early commercialization of fuel cell systems is to develop market niches in which they have competitive advantages, and then to expand to other broader niches and segments as production volumes expand and costs drop. Almost all successful technologies move through this “virtuous cycle.” A key aspect of the virtuous cycle is the cost reduction that occurs through a combination of scale economies in production, and also learning that takes place with regard to both product and manufacturing process design. Using the concepts of “learning curves” and “experience curves,” one finds that many different products have shown a consistent pattern of cost reduction with increases in cumulative production volume. In essence, manufactured products tend to decline in cost by 10-30% with each doubling of *cumulative* production volume. Thus, if a product can gain an initial foothold in the market due to some competitive advantage, this can trigger the virtuous cycle and ultimately allow a new technology to break into a market that is dominated by an incumbent technology.

The desire to achieve zero tailpipe emissions for vehicles that operate in dense urban areas is a motivating force that could give fuel cell vehicles an important niche. The only zero-emission vehicle type other than direct-hydrogen fuel cell vehicles that is practical at the present time is the battery EV, and this vehicle type is characterized by short driving ranges, long recharge times, and potentially high lifecycle costs. To the extent that zero-emission vehicles are encouraged or even mandated in certain areas, direct-hydrogen fuel cell vehicles may have to compete only with battery EVs and not the entire suite of vehicle technology options. This could give them a much firmer foothold to break into motor vehicle markets.

The exact commercialization plans for fuel cell vehicles have not been disclosed by automakers, but they have suggested initial plans for introducing these vehicles. In general, introduction of fuel cell vehicles into limited fleet applications is expected in the 2003-2005 timeframe – in the hundreds, with broader introduction to private consumers expected in about 2008-2010. As costs come down and products enhanced, companies and governments will realign their policies and business strategies to accommodate fuel cell attributes and opportunities.

One can envision various scenarios and pathways by which fuel cells expand their presence. Shell International, well known for its sophisticated scenario planning, posits two energy scenarios for 2050 (Shell, 2001). One of them is centered around and motivated by fuel cell advances. In this scenario, fuel cell sales start with stationary applications for businesses willing to pay a premium for highly reliable power without voltage fluctuations or outages. They then spread to vehicles. By 2025, in this scenario, half of all vehicle sales in OECD countries, and one quarter worldwide, are fuel cell vehicles. It is entirely plausible, though far from certain, that fuel cells will eventually become the dominant energy conversion device across all sectors, fueled by hydrogen.

CONCLUSIONS

The transition to cleaner and more energy efficient vehicle technology continues. Internal combustion engine vehicles, burning gasoline and diesel fuels, will dominate into the foreseeable future. These vehicles will be cleaner burning and more energy efficient (though not necessarily with better fuel economy). In some parts of the world, alternative fuels will be used as niche fuels and complements to petroleum fuels, but they are not likely to displace petroleum in the foreseeable future.

The more momentous transition underway is toward electric-drive propulsion technology. Battery electric vehicles will increasingly be used in niche applications. The technologies more likely to play a major role are hybrid electric and fuel cell propulsion technologies. Fuel cells present more dramatic opportunities for major energy and environmental improvements, and for transforming the automotive and energy industries.

In the end, the future is highly uncertain. It appears likely that fuel cells will gradually enter niche applications where they offer clear advantages over other options. But when or whether fuel cells flourish remains unknowable. It is entirely plausible, for instance, that vehicles will follow a more incremental path from today's internal combustion engine systems, first shifting to hybrid electric vehicles with small combustion engines. And it may be that continuing refinements of these hybrid technologies will keep fuel cells at the margin, competitive only in specialized niches. What is virtually certain is that the environmental performance of vehicles will continue to improve.

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