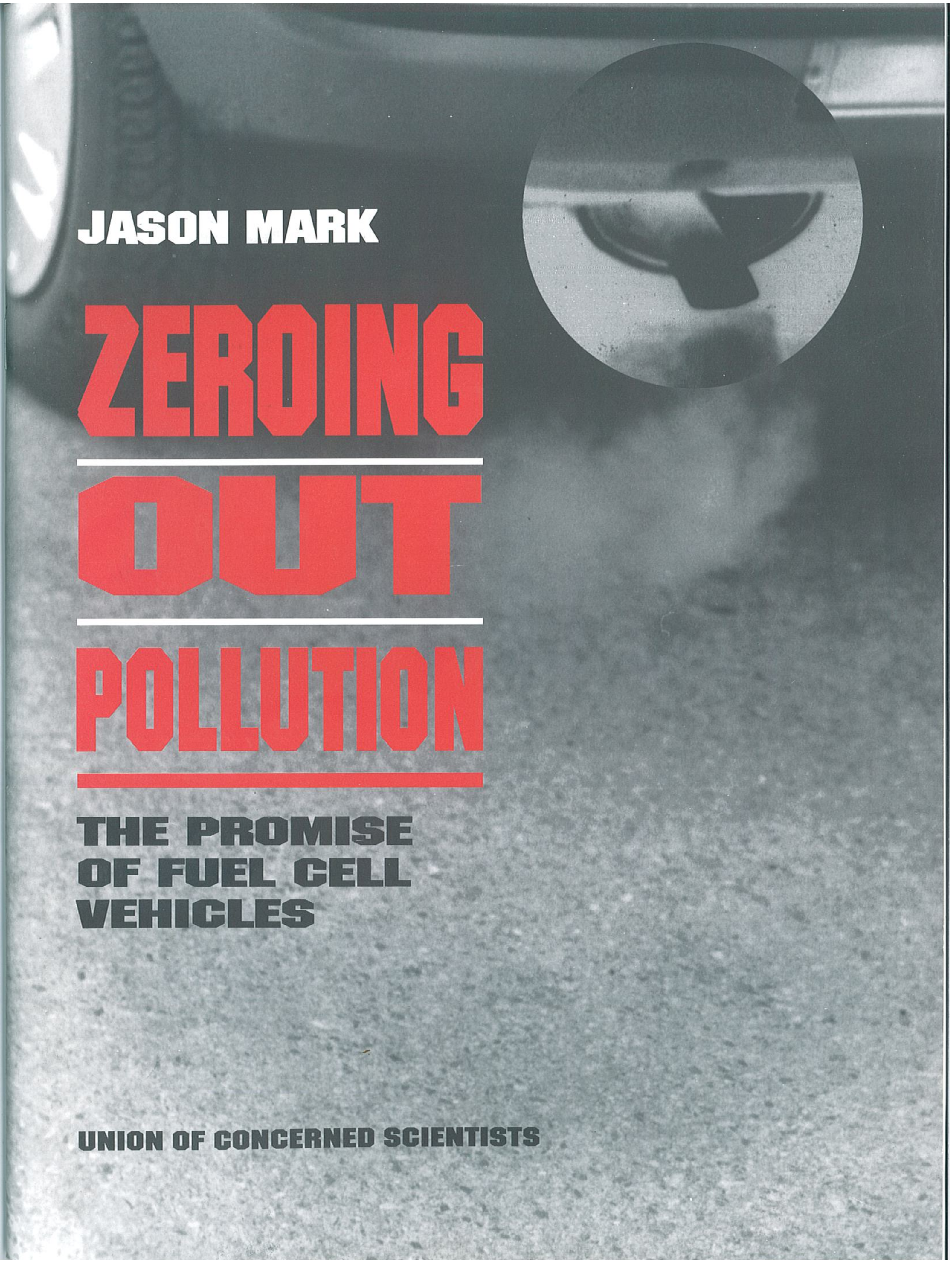

JASON MARK

ZEROING OUT POLLUTION

THE PROMISE OF FUEL CELL VEHICLES

UNION OF CONCERNED SCIENTISTS

Zeroing Out Pollution

The Promise of Fuel Cell Vehicles

Jason Mark

Union of Concerned Scientists

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Jason Mark is an energy analyst in UCS's Transportation Program.

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Executive Summary

On the eve of the automobile industry's centennial, our society is on the threshold of a major change in the type of car we drive. A new technology—fuel cell vehicles—promises clean and efficient travel for the 21st century, and these cars and trucks could soon be on the roads of Asia, Europe, and the United States.

The mobility that motor vehicle travel has brought to millions over the past 100 years has also carried unfortunate side effects. One in four Americans now breathes unhealthy air, fossil fuel emissions are having a measurable effect on the Earth's climate, and oil imports are approaching their highest levels in US history. Fuel cell vehicles can help mitigate these problems through their high efficiency, zero emissions, and use of nonpetroleum fuels.

The Drive for Fuel Cells

Fuel cell vehicles have captured the attention of policymakers and environmentalists because this technology can achieve important energy and environmental goals. The interest that major automakers are showing in fuel cells, however, suggests that they believe fuel cell vehicles will also meet consumers' needs. Many of the major world automobile manufacturers have launched programs to develop fuel cell vehicles, and bus demonstration programs in Europe and the United States are currently illustrating the benefits of zero-polluting travel. At the same time, these vehicles must overcome important cost and infrastructure hurdles if they are to become a viable competitor to the conventional gasoline vehicle. Additional efforts at both the public and private levels are necessary to ensure that our society reaps the benefits of fuel cells.

The Promise

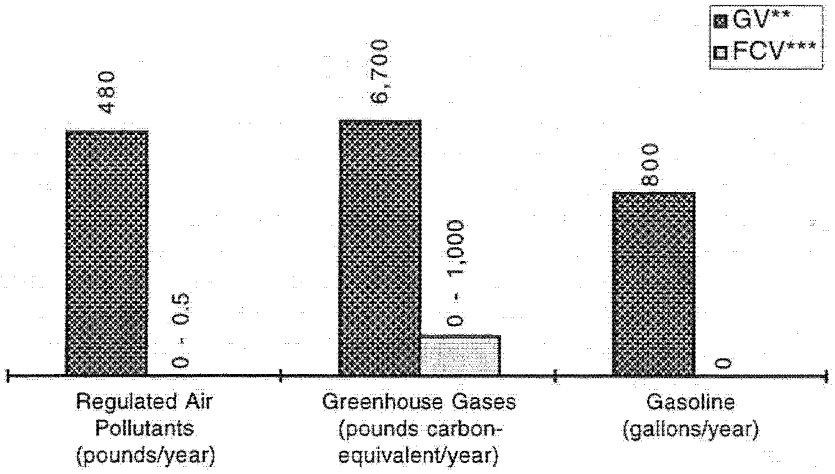
Clearing the Air. The fuel cell vehicle of the future promises to be 98–100 percent cleaner than today's cars, offering major air-quality benefits to smog-choked regions of the country. In the dirtiest US cities, the economic value of zeroing out pollution with these vehicles could total $4,300–$8,300 per car over its lifetime.

Stabilizing Climate. Fuel cells have an important role to play in mitigating the growing impacts of global climate change. When running on renewable fuels, fuel cell vehicles reduce emissions of heat-trapping gases by 85–100 percent. Even when their fuels are produced from natural gas, fuel cells reduce these emissions by 60–70 percent. The widespread adoption of fuel cells would thus permit the United States to achieve national goals for reducing emissions of heat-trapping gases and virtually eliminate these emissions from the national fleet of autos and small trucks by the middle of the 21st century.

Saving Oil. Widespread use of fuel cell vehicles would allow the United States to shift away from its overreliance on oil and tie our nation's energy future to domestic, clean, and renewable resources. By 2025, fuel cell vehicles can cut oil use from autos and small trucks by one-third, saving nearly twice as much oil as the United States currently imports from the Persian Gulf. By the middle of the 21st century, fuel cell vehicles could eliminate our nation's dependence on oil for personal driving.

Customer Satisfaction. With fuel cell vehicles, consumers do not have to give up their expectations of vehicle performance and range in order to achieve great energy and environmental benefits. A mature vehicle powered by a fuel cell will be capable of traveling 250–400 miles before refueling, accelerate from 0–60 miles per hour in less than 12 seconds, and achieve 70–80 miles per gallon. Mass-produced vehicles may ultimately cost about $1,000–$3,000 more than conventional cars, adding about 5–15 percent to the price of the average new car. But any higher cost that fuel cell vehicle owners experience up front may well be offset by lower costs over the life of the vehicle.

Figure ES-1. Annual Energy Budget and Emissions for a Typical Two-Car Family*



* Based on average emissions and fuel consumption rates totaled over 22,800 miles per year of travel (Davis 1995).
** Represents gasoline automobiles (GVs) with a fuel economy of 28 miles per gallon.
*** Represents fuel cell vehicles (FCVs) operating on renewable fuels (hydrogen or methanol); emissions vary depending upon specific fuel used.

Fulfilling the Promise

Although fuel cells offer considerable promise for reducing the impacts of vehicle travel while simultaneously meeting consumers' expectations, the transition from gasoline-vehicle dominance cannot occur overnight. Capturing the benefits of this technology means stepping up development today to overcome the remaining technical, cost, and infrastructure hurdles. A combination of market strategies, public education, technology development, and regulatory policies can hasten the necessary shift to a clean-transportation future.

Cleaner cars are not the only answer to our society's transportation problems, but they are an important part of the solution. Many options are available for dealing with the challenges of air pollution, climate change, and energy dependence, but few alternatives appear to simultaneously meet both the social and the consumer demands of future transportation as well as fuel cell vehicles do. Achieving that future—getting from here to there—means starting down the right path today.

The Transportation Challenge

The End of an Era

When Gottlieb Daimler and Karl Benz teamed up 100 years ago to produce some of the world's first gasoline-powered cars, they probably never imagined that their "driving machine" would play such a significant role in shaping the 20th century.[1] The combination of petroleum fuels and the internal-combustion engine has created a technological cartel in transportation, spawning some of the largest corporations ever to operate in the world economy.[2] Now, on the eve of the gasoline-automobile's centennial, Daimler-Benz is once again a leader in the push towards developing a new technology for transportation: fuel cell vehicles. This report examines the growing interest in fuel cells for vehicle applications, the vehicles themselves, and the ways fuel cell vehicles can help the United States achieve a clean-vehicle future.

Runaway Cars

US transportation will reach an unenviable milestone in 1996: for the first time ever, automobiles and light trucks *alone* will consume more energy in the United States than domestic oil producers can extract. Throw in all other uses of petroleum—freight and air travel, home heating, industrial uses, and electricity production—and one can see why our country must import about half of the oil we use (Davis 1995). But while many other energy-consuming sectors of the economy have begun to wean themselves from oil use over the past two decades, transportation continues to be 97 percent dominated by oil (Davis 1995), causing this sector to be just as vulnerable to oil shocks as it was during the 1970s.

The financial and political pressures of energy insecurity are compounded by the environmental harm that vehicles cause. About one in four Americans lives in an area whose air violates national health standards (EPA 1993), and motor vehicles generate more than one-half of the pollution in most urban areas. Regional officials are turning to increasingly stringent motor vehicle controls in their struggle to clean up the air.

Finally, the threat of global climate change has contributed an additional note of urgency to the goal of transforming transportation. Today, transportation accounts for one-third of all US emissions of carbon dioxide (the leading contributor to global climate change), and these emissions are increasing faster than those of any other segment of the economy (EIA 1994b; EIA 1995).

The annual costs of oil dependence, air pollution, and climate-change impacts may total \$50–\$230 billion in the United States alone (Delucchi 1995; Delucchi and Murphy 1995). These costs, including health care, military involvement to protect foreign oil supplies, and damage to crops and materials, are not accounted for in the payments that motorists currently make for vehicle services and, as such, act as hidden subsidies to driving (Hwang 1995). These subsidies are market inefficiencies and ultimately translate into misallocations of society's resources.

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[1] Daimler-Benz is the parent company of Mercedes-Benz, named after Karl Benz's daughter, Mercedes (Cannon 1995).

[2] Half of the top 10 Fortune 500 companies in 1995 were auto or oil companies (Fortune 1996).

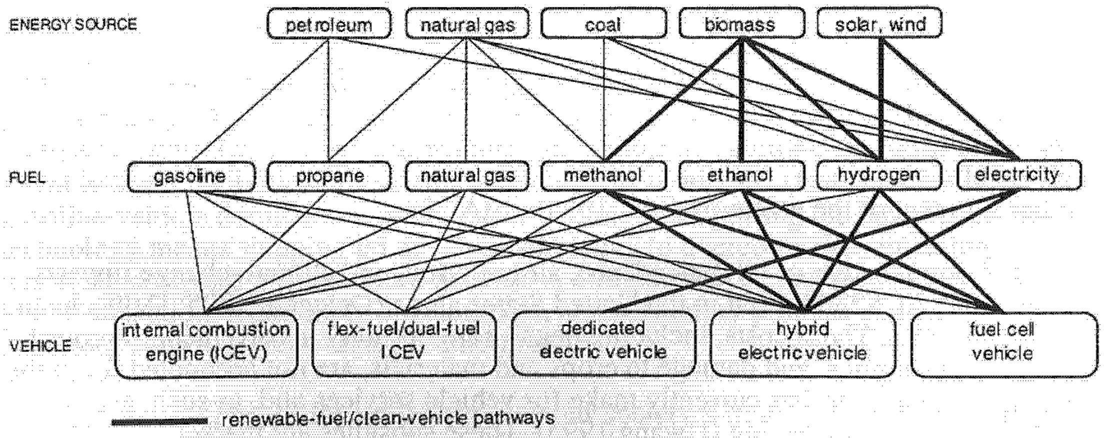
Transforming Transportation

Any efforts to transform transportation must necessarily involve the single largest energy consumers in this sector: automobiles and light-duty trucks.[3] This category—collectively called light-duty vehicles—accounts for 40 percent of total US oil consumption (Davis 1995), and one-half to three-quarters of nearly all pollution from transportation comes from this single category (EPA 1992).

As concern over oil dependence, air quality, and climate change has grown in the past 25 years among scientists, economists, planners, and the public, experts have proposed a myriad of solutions. Alternatives to the status quo include greater reliance on mass transit, production and use of cleaner and more-efficient cars, changes in land use, and reductions in travel. Although none of these approaches alone can succeed in solving all of our society's transportation-related problems, the current dominance of motor vehicle travel affirms that building cleaner cars is an important part of the solution.

Figure 1 shows the array of major options available for fueling US driving needs in the future. Although a single path—petroleum to gasoline to the internal-combustion-engine vehicle—has dominated the landscape for almost the entire 20th century, the number of alternatives is staggering. Sorting through the options and choosing winners and losers is an immense task that has been on the agenda of policymakers, industry, and environmentalists for nearly two decades. One way to approach the planning challenge is to establish a set of criteria for evaluating the options. For example, figure 1 highlights in bold the paths that combine the benefits of renewable fuels and low emissions. These two features are vital components of any transportation future, since they will help reduce dependence on fossil fuels and mitigate the negative environmental impacts of driving.

Figure 1. Alternative Fuel and Vehicle Options



With their potential to simultaneously satisfy consumer needs (cost, range, performance, safety) and social criteria (emissions and oil reductions), fuel cell

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[3] Light-duty trucks include pickups, sport-utility vehicles, minivans, and jeeps.

vehicles are one of the most attractive choices for the future. Although other options also merit further attention, this report focuses on the promise of fuel cells and achieving a fuel cell future that zeroes out pollution.

The Drive for Fuel Cells

Fuel cell vehicles (FCVs) offer the potential to maintain mobility while reducing our nation's reliance on foreign energy sources and mitigating the effects of vehicles on human health, local environments, and the global climate. This promise derives from three important characteristics of fuel cell vehicles:

- high efficiency
- zero emissions
- operation on nonpetroleum fuels

Major automobile manufacturers are also showing great interest in fuel cell technology, which suggests that they believe it might be an important competitor in the future market. Much of the current excitement surrounding FCVs stems from the realization that this technology is attractive to both regulators and industry, as it addresses both social and private goals. As a result, government-industry partnerships have been an important component of fuel cell research thus far.

Table 1 shows a list of the major fuel cell vehicle development activities worldwide. At least five fuel cell buses have been demonstrated to date, and the major automakers appear to be increasing their development of fuel cells for autos and light trucks. Besides the actual vehicle-production activities shown here, public and private organizations are spending millions of additional dollars to develop improved fuel cells, ancillary vehicle equipment, and fuels technologies. The table further highlights the fact that, besides the automotive applications discussed in this report, fuel cells are a strong candidate for urban buses. In fact, buses are likely to be the first commercial applications of fuel cells in transportation: bus applications can absorb the larger size and higher cost of first-generation fuel cells, and bus fleets typically refuel in central locations that can easily distribute new fuels.

Fuel cells for cars and light trucks are also on a rapid pace towards commercialization. Each of the Big Three automakers is working on vehicles with different fuel cell suppliers and plans to test and demonstrate vehicles near the turn of the century. Daimler-Benz, the parent company of Mercedes Benz, has publicly announced the most aggressive program to date. The German company has already produced a prototype and expects the first vehicles to be available in 2003 (Klaiber 1995a). Less is known about the activities of developers in Japan, but the international race is on to develop fuel cells for cars and light trucks.

Although fuel cells have garnered much attention to date, additional efforts at both the public and the private level are required to ensure that the benefits of FCVs are realized. Greater levels of research and development, early demonstrations, public and private investments, and reinforcing policies can help overcome the important hurdles that remain in fuel infrastructure, fuel and vehicle cost, and reliability.

Table 1. Major Known International Fuel Cell Vehicle Activities

LOCATION	PARTIES INVOLVED	TECHNOLOGY	NOTES
		Buses	
Vancouver, British Columbia	Ballard, SAIC, BC Transit, BC Government, Canadian Government	hydrogen-fueled PEM transit bus	1993, first hydrogen fuel cell bus 1994, second bus 3 additional buses expected in 1997
United States	DOE, SCAQMD, DOT and multiple contractors	methanol-fueled PAFC transit bus	3 hybrid buses 1994, first bus in operation 3rd bus under development
United States	DOT and multiple contractors	methanol-fueled PAFC and PEM transit buses	under development, to be delivered 1997–98
Chicago, Illinois	Chicago Transit Authority, Ballard	hydrogen-fueled PEM transit buses	3 buses expected pending final contract negotiations
Belgium	Netherlands, Italy, France, and Belgium	hydrogen-fueled alkaline fuel cell bus	1994, prototype hybrid bus two-city demonstration pending
Italy	Euro-Quebec Hydro Hydrogen Project	hydrogen-fueled PEM	bus to be field tested in Brescia
		Cars and Light Trucks	
Florida; Los Angeles, California	Energy Partners, Inc., SCAQMD	hydrogen-fueled PEM	prototype hydrogen fuel cell car 2 airport utility vehicles, first due in 1996
Palm Springs, California	Schatz Energy Research Center, Palm Desert, DOE, SCAQMD	hydrogen-fueled PEM	5 fuel cell golf carts 1995, first cart in operation
United States	GM/Allison, Ballard, PNGV	methanol-fueled PEM	under development
United States	Chrysler; Allied Signal, PNGV	hydrogen-fueled PEM	under development
United States	Ford; IFC, MTI, Tecogen, Energy Partners, H-Power, PNGV	hydrogen-fueled PEM	under development
Japan	Mazda	hydrogen-fueled PEM	1992, prototype golf cart
Japan	Toyota	no data	under development
Germany	Daimler-Benz, Ballard	hydrogen-fueled PEM	1994, prototype van: "NECAR"
Germany	Siemens, BMW	no data	under development

Sources: Bos and Borja (1994); MacKenzie (1994); Cannon (1995); Miller (1995)
Key: PEM = proton-exchange membrane; PAFC = phosphoric-acid fuel cell; DOE = US Department of Energy; SCAQMD = South Coast Air Quality Management District; DOT = US Department of Transportation

Greener Cars

Down to Earth

Fuel cells were invented as far back as 1839, but they were primarily a laboratory curiosity until NASA found extensive use for them in space applications. In the past decade, however, major technical improvements and cost reductions have brought fuel cells down to earth.

Fuel cell power plants around the world today produce over 65 megawatts of power in small niche applications such as hospitals and hotels.[4] Since fuel cell plants are composed of a series of individual cells, they are cost effective for such small loads. They are also valuable for locations that are remote from power lines or in which additional power needs cannot be met by an existing large power plant. Interest in fuel cells for these stationary applications is growing rapidly, and a 1991 estimate projected that the worldwide market would reach 4,000 megawatts per year by 2000 (Barnett and Teagan 1991).

Funding for fuel cell development in Europe, Japan, and the United States has averaged about one-quarter of a billion dollars per year in the 1990s (Bos and Borja 1994; ETSU 1994), indicating the broad interest in this technology for all kinds of applications. Several types of fuel cells are currently under development, including compact systems designed to fit under the hood of the automobile of the future.

Alkaline fuel cells are the oldest technology and were chosen early on by NASA for space missions (MacKenzie 1994). These fuel cells require pure hydrogen and oxygen to operate, and thus have limited cost-effective opportunities on earth. Phosphoric-acid fuel cells are commonly found in commercial-power applications as well as in some fuel cell buses. Because they are heavy and bulky, however, they may not be strong candidates for the light-vehicle market. Other technologies under development include molten carbonate, direct methanol, and solid oxide fuel cells. These options are further from commercial application but may prove attractive in the long term. The most promising fuel cell technology for cars and light trucks today is the proton-exchange membrane. A combination of low operating temperature, compact size, and rapidly declining costs make it an ideal candidate to replace the internal-combustion engine.

Refillable Batteries

A fuel cell is an electrochemical device that produces electricity directly from the reaction of hydrogen and oxygen (see box 1). The only by-product is water. Fuel cell vehicles are similar to battery-powered electric vehicles in that the fuel cell, like a battery, produces electricity that powers motors at the wheels. A battery must be recharged after all of the fuel inside of it has reacted, whereas a fuel cell is a "refillable battery," in the sense that recharging the vehicle only requires filling the fuel tank, much as one would with a gasoline car today.

Since the reaction in a fuel cell is extremely efficient, FCVs will ultimately use two to three times less energy than today's cars. Soon after the turn of the century,

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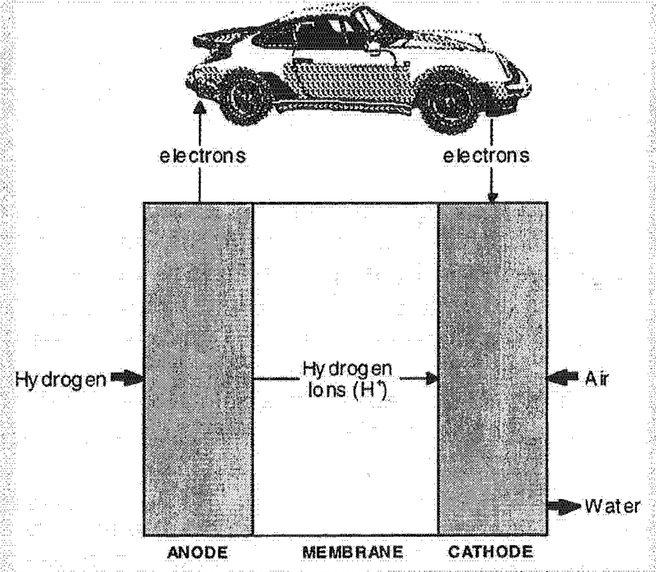
[4] For size comparison, a megawatt of power currently serves the combined peak load of about 500 average US households. Thus, if 65 megawatts were used for residential power, it could serve 32,500 households.

Box 1. How a Fuel Cell Powers a Car



The electrochemical reactions of a fuel cell begin when hydrogen enters one side of the fuel cell, where it is separated into an electron and a hydrogen ion. In the case of the PEM fuel cell, the ions move through a membrane to combine with oxygen on the other side, thus making water. Meanwhile, since electrons cannot pass through the membrane, they are forced to take an external route that carries them through an electric motor. Passing through the motor, the electrons transfer power from the fuel cell to the motor. The motor, in turn, drives the wheels of the car.

The controlled reaction of hydrogen and oxygen that occurs in a fuel cell is much more efficient than the typical burning (or combustion) process of a standard vehicle engine. As a result, fuel cell vehicles are expected to be two to three times more efficient than conventional cars and light trucks. Furthermore, because the only products are electricity, water, and some heat, the reaction is pollution free.

Sources: Sperling (1995); Swan et al. (1994)

when consumers are likely to first see light-duty fuel cell vehicles, a typical fuel cell car running on hydrogen might achieve the equivalent of 60 miles per gallon (mpg-eq).[5] As the fuel cell technology and auxiliary equipment are improved over time, fuel cell cars might reach 80 mpg-eq or greater in the long term.[6]

The reaction of hydrogen and oxygen in a fuel cell produces only electricity and water—nothing else. Mayor Daly of Chicago recently demonstrated how clean fuel cells are at the unveiling of his city's new hydrogen fuel cell bus program: he drank

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[5] This report adopts the convention of reporting fuel economy in terms of miles per gasoline-equivalent gallons, which is the distance a vehicle can travel on the amount of energy contained in one gallon of gasoline.

[6] See appendix A for a discussion of the sources for these values.

water that had come from the tailpipe of a fuel cell bus (Hydrogen & Fuel Cell Letter 1995). When the hydrogen comes from renewable sources, hydrogen fuel cell vehicles can be true "zero-emission vehicles" (ZEVs). Fuel cell vehicles that use methanol as the primary fuel will release very small amounts of pollution from fuel evaporation and processing (see box 2a), but these emissions are likely to be close enough to zero for the vehicles to qualify for full ZEV credit under state clean-car regulations.

Fueling the Future

Fuel cells run on hydrogen and oxygen. In most applications, oxygen can be taken directly from the ambient air, since about one in five air molecules are oxygen. Hydrogen is more difficult to come by in its pure form, despite the fact that about 93 percent of all atoms in the universe are hydrogen (MacKenzie 1994). Although hydrogen is so prevalent, it is chemically trapped in more complex compounds, such as water or methane, from which it must be separated out. Since most fuel cells require nearly pure hydrogen to operate effectively, a central challenge for widespread fuel cell use is the manufacture, distribution, and storage of hydrogen for vehicles (see boxes 2a–2c). The over 200,000 corner gas stations in the United States (EIA 1994a) are indicative of the large infrastructure that brings petroleum products to consumers; modifying or replacing that system to accommodate alternatives will require substantial effort and aggressive action.

Hydrogen is an attractive fuel for the future because it can be produced from many different sources, or feedstocks. As with electricity, this feedstock diversity will ensure that competition drives prices down as new sources become cost effective. Diversity also provides security against major price shocks if, for example, energy prices double or quadruple as they did in the oil crises of the 1970s. But just as with electricity production, the flexibility to manufacture hydrogen from many sources means that renewable feedstocks may be overlooked

Box 2a. Storing Fuel in a Vehicle

Most fuel cell vehicles demonstrated so far have run on gaseous hydrogen stored in tanks on the vehicle. This is by far the simplest method of operating fuel cell vehicles, but it requires relatively bulky and costly high-pressure storage tanks. Researchers are currently investigating ways to improve these tanks, as they are likely to be the storage device used in the first commercial vehicles. More advanced options include liquefying the hydrogen and storing it at low temperatures, using materials that absorb or bind hydrogen, or (in a more exotic system) accelerating the natural oxidation process of iron rusting to extract hydrogen from water.

The alternative to boarding hydrogen directly on a vehicle is to use a secondary fuel, such as methanol or ethanol, to carry the hydrogen. Methanol is receiving the most interest for fuel cell vehicles because it releases hydrogen relatively easily when combined with pressurized steam. A methanol FCV avoids the challenge of storing hydrogen gas directly, since the liquid fuel can be stored in an inexpensive and compact tank like the gasoline tank found on today's cars. The tradeoff, however, is that all of the equipment for extracting the hydrogen from methanol must fit on the vehicle. The technology—called a methanol reformer—has been demonstrated on buses; the challenge for FCV developers is to manufacture an inexpensive, light reformer that can extract hydrogen efficiently and rapidly to power a vehicle.

in favor of sources that offer some short-term economic benefits but fail to address important energy and environmental concerns. In the near term, hydrogen is likely to be made from natural gas, a fossil fuel, because it is currently the least expensive feedstock. As gas prices increase and conversion technologies improve, however, renewable sources of hydrogen will become economically competitive.

Methanol is a strong candidate for fueling fuel cell vehicles, since it is easily stored on a vehicle and can be readily transformed to hydrogen ("reformed") for use in the fuel cell (see box 2a). There is currently no consensus about which option—direct hydrogen storage or methanol reforming—is the best choice for the long term. The decision is not entirely up to the vehicle manufacturers, however, since a successful vehicle program requires an industry to supply fuel. This "chicken-and-egg" problem is an important hurdle to the deployment of new vehicles, since they cannot be sold before fuel is available, and fuel will not be available until vehicles to use it are on the road. The development of new fuels and new vehicles must thus occur simultaneously, requiring a high level of coordination among the relevant participants.

Daimler-Benz has decided to focus on methanol fuel cell vehicles, partly because the company believes that an infrastructure to supply their cars with methanol is more likely to be developed than one supplying hydrogen (Klaiber 1995b). This same consideration has caused some to focus on technology that can extract hydrogen from a fuel similar to gasoline. The technical hurdles to this approach appear larger than for methanol reformers or hydrogen storage, but there are obvious advantages to using the existing petroleum infrastructure in the near term. If a petroleum-powered FCV can be developed, it may make sense as a transition option, but it will not meet the aggressive energy and environmental criteria necessary for future travel. Truly transforming transportation means moving away from a dependence on fossil fuels and towards renewable energy sources, which offer abundant domestic supplies, minimal environmental impact, and local economic benefits.

Box 2b. Manufacturing Fuels

Hydrogen. The simplest way to produce hydrogen is to split water (which is composed of hydrogen and oxygen) using electricity; this process, called electrolysis, is really like a fuel cell operating in reverse. The electricity for electrolysis can be generated from conventional sources—coal, natural gas, oil, and nuclear energy—or from cleaner, renewable supplies like biomass, wind, and solar energy. Xerox Corporation is currently demonstrating a system that produces hydrogen using electricity from solar cells. The hydrogen is then burned in converted truck engines, similar to natural gas vehicles, that the company uses for its daily business (CAN 1995).

Electrolysis is an expensive way of making hydrogen, and most commercial hydrogen produced today is instead manufactured by chemically "reforming" natural gas. Reforming uses high temperatures and steam to release the hydrogen contained in natural gas. Fuel cells operated by electric-power utilities commonly use natural gas as the primary fuel, converting it along the way into hydrogen to power the fuel cell. Natural gas is a fossil fuel and is therefore not a long-term option for producing hydrogen, but it may be a good transition fuel to more sustainable sources.

Biomass, a term used to describe any biological matter that has energy value, is also a potential feedstock for hydrogen. Fast-growing trees and grasses, industrial and agricultural wastes, or even some forms of municipal waste can be "gasified" to release hydrogen. One source estimates that the United States could produce enough biomass on a sustainable basis to fuel the country's entire light-vehicle fleet two or three times over if it were powered by hydrogen fuel cells (Turhollow and Perlack 1991; Ogden et al. 1994a)

More advanced processes for generating hydrogen are also under way at the laboratory scale that may prove promising in the coming decades. Three processes under development produce hydrogen from water and light in the presence of bacteria, enzymes, or semiconductor materials. Researchers hope that such techniques can offer simple, efficient, and economical means of generating hydrogen in the future (DOE 1993).

Methanol. Today, methanol is made from natural gas and is used primarily as a chemical feedstock. The first step of the conversion process is similar to conventional hydrogen production, as natural gas is reformed to produce carbon monoxide and hydrogen. In a methanol plant, these components are then chemically combined to form liquid methanol. Because methanol is easily transported via ocean tankers, it is likely that a substantial portion of the future methanol supply, if made from natural gas, could come from foreign sources where natural gas is abundant and inexpensive (DOE 1990, Mark et al. 1994).

Like hydrogen, methanol can also be manufactured from biomass. The biomass is first gasified to release hydrogen and carbon monoxide, which are then synthesized to form methanol. The overall process is, in theory, slightly less efficient than making hydrogen from biomass (Ogden et al. 1994a), but the product is a compact, easily transported liquid. Coal can also be used to produce methanol through a similar method of gasification, but using coal would greatly undermine the climate-change benefits of fuel cell vehicles.

Box 2c. Supplying Vehicles with Fuel

Perhaps the single largest challenge for using hydrogen in vehicles comes from the new infrastructure that would have to be built to deliver the fuel to motorists. The United States has an extensive system for transporting natural gas, but most of it cannot carry hydrogen. Although low-pressure pipelines that carry natural gas short distances might be converted to hydrogen use with little difficulty, the high-pressure pipelines that travel long distances would suffer embrittlement (a structural weakening of the steel) if they carried hydrogen (Ogden et al. 1994b). Some methods of hydrogen production (especially from renewable sources) are, however, quite suitable for small-scale production right at (or near) the service station. These more decentralized hydrogen facilities could use shorter pipelines for delivering fuel to motorists and thus avoid the cost of constructing long-distance transmission. At the service station, refueling vehicles with hydrogen could be quite similar to refueling vehicles with compressed natural gas today. Compressed hydrogen could be pumped into a car's tank, filling it within a matter of minutes.

Methanol, being a liquid, is easier to transport than hydrogen. A large-scale methanol distribution system would probably look very similar to the existing system for gasoline. Tankers would ship methanol from overseas and up and down the US coastline, while barges would be used for inland waterways. Pipelines and trucks would carry methanol over land. Because methanol is more corrosive than gasoline, as well as susceptible to water contamination, some modifications to existing equipment are required. While still a technical uncertainty, the possibility of shipping methanol via existing petroleum pipelines holds promise for greatly reducing the cost of methanol distribution (DOE 1990; EEA 1989). At the pump, filling a methanol FCV would be nearly identical to gassing up a conventional car.

In the Showroom

Conventional cars are the standard by which manufacturers measure the consumer acceptability of alternatives, and fuel cell vehicles should look and act quite similar to today's gasoline cars.[7] An assessment of the current state of knowledge—based on analyses from industry, academia, and government agencies—indicates that fuel cell vehicles will be technically capable of delivering most or all of the amenities of today's cars.

Fuel cell vehicle manufacturers, like conventional automakers today, will be faced with many design decisions and trade-offs that affect vehicles' performance, look, and cost. The following sections discuss a range of possible vehicle attributes that consumers might encounter at the showroom of the future.[8]

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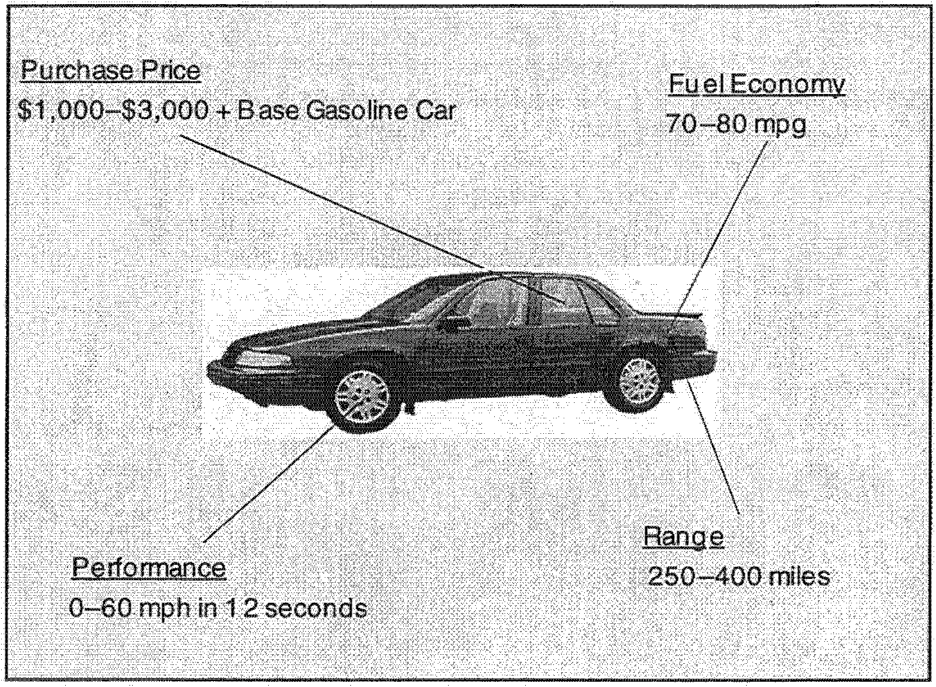
[7] As many authors have pointed out, however, a car that travels 300 miles or more without refueling, carries five to six passengers plus cargo, and accelerates from 0 to 60 mph in less than 12 seconds is overkill for the majority of our society's driving needs (Sperling 1995). Consumers have shown interest in vehicles that better match their needs in urban and short-range driving (Turrentine and Kurani 1995).

[8] See appendix A for a detailed treatment of the assumptions and projections used in this analysis.

Figure 2. The Sticker of the Future: Characteristics of Mature Fuel Cell Vehicles



Purchase Price and Operating Costs

The cost of fuel cells has dropped substantially in the past few decades, but analysts expect prices to come down further—by a factor of almost one thousand—once fuel cells are produced in mass quantities. In the long run, fuel cell engines should cost the same or less to manufacture than gasoline engines (GM/Allison 1993). The price of the engine is only one part of the cost equation, however. The drivetrains and fuel storage systems of fuel cell vehicles, for example, are different from those of gasoline vehicles. With all components of price rolled together, early FCVs might cost $4,000–$7,000 more than a comparable gasoline car (Ogden et al. 1994a). In large-volume production, the premium paid for FCVs should only be $1,000–$3,000 for a vehicle with a performance and range similar to those of a gasoline car (see appendix A for details).

Although car buyers may pay slightly more for a fuel cell vehicle at the dealership, they will pay less at the service shop and the gas pump. A fully commercial FCV should last longer and cost less to maintain than a gasoline car (Delucchi 1992), and drivers would no longer need oil changes or smog checks. Moreover, the high fuel economy of fuel cells will save motorists enough money in fuel payments to offset any premium they pay when they buy a fuel cell vehicle (Mark et al. 1994).

Range

Even the earliest commercial methanol fuel cell vehicles will be capable of traveling 300 miles or more without refueling. Hydrogen FCVs are likely to have somewhat shorter ranges in the near term because of the inherent limitations of hydrogen storage, although early indications are that the domestic automakers are designing vehicles with a range of over 300 miles for even their earliest vehicles.

Performance

Fuel cell vehicles can be designed to meet a range of performance criteria. As with gasoline cars today, however, vehicle manufacturers will be faced with choosing an emphasis among a variety of parameters, including cost, range, and performance. For example, improving acceleration in an FCV means increasing the size of the fuel cell or adding more electricity storage (for example, batteries), both of which increase cost and weight. General Motors has simulated the performance of the vehicle it is designing and has estimated that 0–60 miles per hour acceleration times will be 10–12 seconds for a warm vehicle, the same as gasoline cars and vans on the road today (GM/Allison 1993). Methanol fuel cell vehicles will be slower during the first few minutes after start-up (while the engine system is warming up), but hydrogen vehicles should experience little performance degradation when cold.

Safety

Vehicle safety is a critical concern for developers of alternative fuels and vehicles. Although our society has grown to live with the dangers of gasoline over the past century, no fuel is inherently safe. Dealing responsibly with safety issues of new fuels requires testing, protective regulations, and education to ensure their safe use.

Hydrogen presents several safety advantages over gasoline. Because it is lighter than air, hydrogen leaks disperse quickly in open areas. Should hydrogen catch on fire, the flames would travel up and away and release less energy than would burning gasoline. On the other hand, hydrogen ignites more readily than gasoline. The most significant hazard associated with hydrogen vehicles is thus the potential of hydrogen gas leaking from the storage tanks and becoming trapped in an enclosed space, such as a garage (ADL 1994). Proper ventilation can overcome this risk, however, and hydrogen can become more easily detectable with the addition of colorants and odorants. Today, safety regulators routinely test hydrogen storage tanks by overfilling them, placing them in fires, and shooting bullets at them to ensure that no major damage occurs (ADL 1994). In the future, advanced hydrogen storage technologies may be inherently safer than the current gaseous storage, since the advanced methods will bind the hydrogen to other materials.

Methanol is generally considered to be safer than gasoline because it has less chance of igniting and because, even if it does catch on fire, it releases about one-fifth the heat of gasoline (EPA 1989). Additives will likely need to be mixed in with the methanol to make it more visible when burning and to deter people from drinking it, since it is quite toxic to humans. Extensive methanol spills in large and moving bodies of water (for example, oceans and rivers) are expected to be less hazardous than oil spills, since methanol disperses and biodegrades more easily than does oil. But methanol leaks from storage tanks or other containers near drinking water supplies would present greater hazards because methanol mixes with water more readily than does petroleum (EPA 1989).

The Promise

Fuel cell vehicles hold great promise for improving local air quality, mitigating global climate change, and reducing reliance on foreign oil while simultaneously meeting consumers' need for mobility. This chapter links the use of fuel cell vehicles to specific public-interest goals, placing the social benefits in a policy context.

Cleaner Air

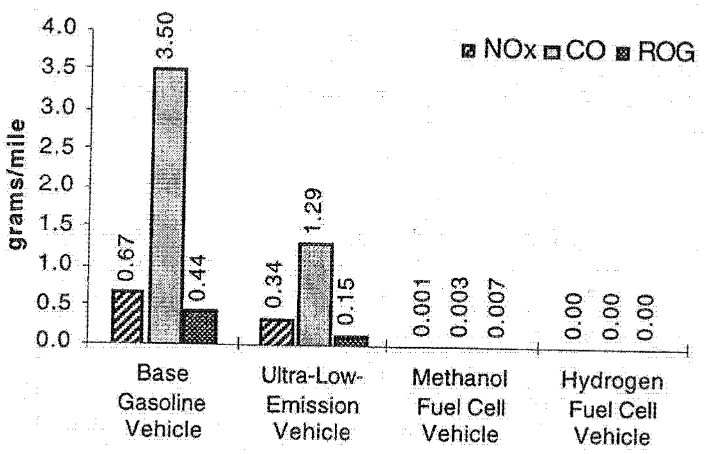
The pollution emitted by motor vehicles has been regulated for over a quarter of a century, and important progress has been made over that time in reducing the air-quality impacts of transportation. Today's cars release only 20–25 percent as much carbon monoxide and hydrocarbons as they did before regulations were imposed (Ross et al. 1995; Calvert et al. 1993), and emissions of nitrogen oxides have been reduced to 35–50 percent of their precontrol levels (Calvert et al. 1993). Despite this past success in reducing emissions from individual vehicles, however, cars and light trucks continue to be the largest source of urban air pollution, since Americans collectively drive twice as much as they did 25 years ago. And even when more stringent regulations are imposed, technical loopholes permit manufacturers to make cars that do not deliver major emissions reductions during real-world driving, even though they can pass strict tests (Ross et al. 1995). Malfunctioning vehicles and so-called offcycle driving, such as hard accelerations or high-velocity driving, are major contributors to the gap between real-world and regulated emissions.

Zeroing Out Pollution

Fuel cell vehicles offer an opportunity to leapfrog the problems of controlling emissions altogether, thereby saving regulators, manufacturers, and consumers time and money in meeting pollution standards. The clean and efficient reaction of a fuel cell does not release any pollution, and hydrogen FCVs are true zero-emission vehicles. Methanol fuel cell vehicles will release very small amounts of pollution from fuel evaporation and processing, but their emissions are likely to be close enough to zero to qualify as zero-emission vehicles under some existing state regulations.

Figure 3 shows estimates of lifetime emissions from gasoline cars and fuel cell vehicles on a per-mile basis. This chart compares FCV emissions against the pollution released from two benchmark vehicles: (1) a base gasoline vehicle that meets current federal emissions standards, and (2) an ultra-low-emission vehicle (ULEV). These two categories represent the likely range of emissions of future vehicles, since the base gasoline vehicle is today's standard vehicle, and the ULEV is the cleanest vehicle required under California's clean-car regulations that is not a zero-emission vehicle. As discussed further in appendix B, there is widespread agreement that the standard models used to calculate pollution from gasoline-powered vehicles underestimate emissions in real-world driving. The results shown in figure 3 should therefore be considered conservative with respect to the potential emissions savings from fuel cell vehicles.

Figure 3. Average Emissions from Automobiles in Los Angeles



Notes:

1. Emissions are averaged over the lifetime of an automobile operating in the Los Angeles Air Basin.
2. NO_x = nitrogen oxides; CO = carbon monoxide; ROG = reactive organic gases.
3. Base gasoline vehicle and ULEV emissions are calculated using California's mobile-source emissions models (see appendix B for details).
4. FCV emissions are calculated from existing test data on prototype fuel cells with additional engineering analysis.

The Value of Cleaner Cars

Fuel cell vehicles are 98–100 percent cleaner than today's cars and emit 94–100 percent less pollution than the cleanest gasoline cars to be sold in the future under current regulations (ULEVs). Such clean vehicles have an important role to play in addressing the air-quality problems of smog-choked areas like Los Angeles and the northeastern United States. Businesses, governments, and consumers are already paying substantial amounts of money to reduce the pollution in these regions, and fuel cell vehicles promise to be a cost-effective strategy for further improving air quality.

Calculations of the emissions saved over the life of a fuel cell automobile can be combined with estimates of the economic value of pollution reductions to give a monetary value to clean vehicles. Based on the most recent data available for the Los Angeles area (see appendix D for details), such calculations show that an FCV operating in the Los Angeles Air Basin is worth $5,100–$8,300 in avoided pollution-control costs when it replaces a base gasoline vehicle ($2,100–$3,300 when it replaces a ULEV).[9] These costs would otherwise be paid by industry and/or consumers to comply with existing air-quality regulations. In New York City, an FCV replacing a base gasoline vehicle might be worth about $4,300 in avoided pollution-control costs. The automakers have recently proposed a new set of standards, called the National LEV Program, that would allow manufacturers to opt

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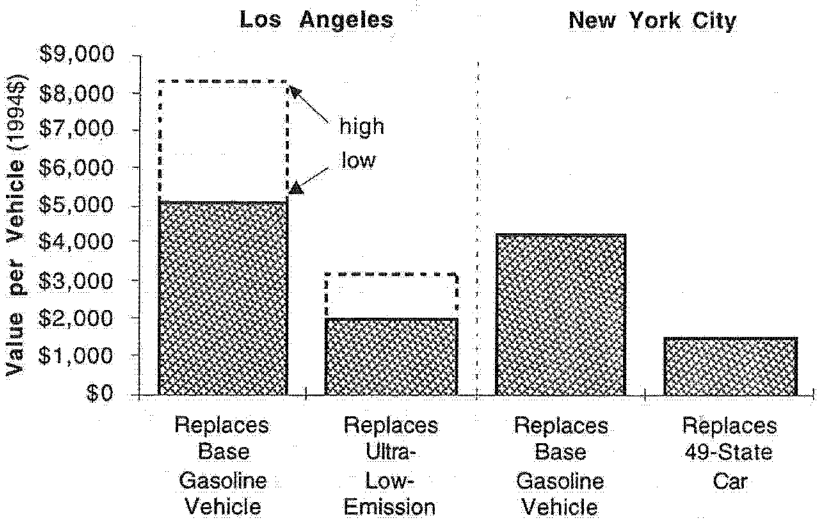
[9] The range of values corresponds to the uncertainty in estimating the emissions from motor vehicles, as discussed in appendix B. A similar range has not been calculated for the federal model used to estimate emissions benefits for the Northeast.

in to a program requiring them to achieve California's low-emission-vehicle (LEV) levels by 2001 (Federal Register 1995). The value of a fuel cell auto when it replaces this so-called 49-state car in New York City would be about $1,500 (see figure 4).

Figure 4. Value of Emissions Savings from Fuel Cell Automobiles



Notes:

1. Average lifetime emissions reductions from fuel cell autos are valued using a control-cost approach for avoided pollution; a 4 percent discount rate is used, per South Coast Air Quality Management District guidance (see appendix D for details).
2. The range of emissions values for Los Angeles is based on UCS estimates of the uncertainty of the mobile emissions models used to calculate savings. The low end of the range is based on the direct outputs of California's EMFAC/BURDEN7F models, while the upper end uses estimates of the real-world emissions from vehicles operating in California (see appendix B).

Placing a dollar value on environmental benefits is extremely difficult. The estimates chosen for this study represent the value of fuel cell vehicles to regions struggling to achieve air-quality standards. As the technology continues to enter the market in the next decades, interest in fuel cell vehicles as a pollution-control strategy will likely increase. A glimpse of this future can be found in the most recent air-quality plan for the Los Angeles area, which calls upon fuel cells to play an important role in reducing transportation emissions in that region by 2010 (SCAQMD 1994). The recently modified zero-emission-vehicle requirement in California, which includes ZEVs entering the market in the year 2003 at a 10 percent share of new auto and light-truck sales, is worth $180–$290 million per year to the South Coast in avoided emissions in the year 2010.[10] Fuel cell vehicles could play an important role in fulfilling the ZEV requirement or, as the South Coast's air plan suggests, providing additional emissions savings.

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[10] These numbers are based on runs of California's mobile emissions model (EMFAC/BURDEN7F) for the South Coast Air Basin in 2010 and the estimates of avoided emissions values discussed in appendix D.

Stabilizing Climate

In its 1995 report, the Intergovernmental Panel on Climate Change demonstrated broad consensus that the human-driven increases in carbon dioxide (CO_2) and other heat-trapping gases in the atmosphere will result in global temperature increases. These 2,500 scientists from 60 countries further agreed that atmospheric increases of these "greenhouse" gases will trigger severe impacts, such as extreme fluctuations in climate, stress on ecosystems, damage to human health, and dislocation of agriculture and commerce. Recent findings in the scientific community continue to support these conclusions and lend further credence to ongoing efforts to deal with climate change on an international scale.

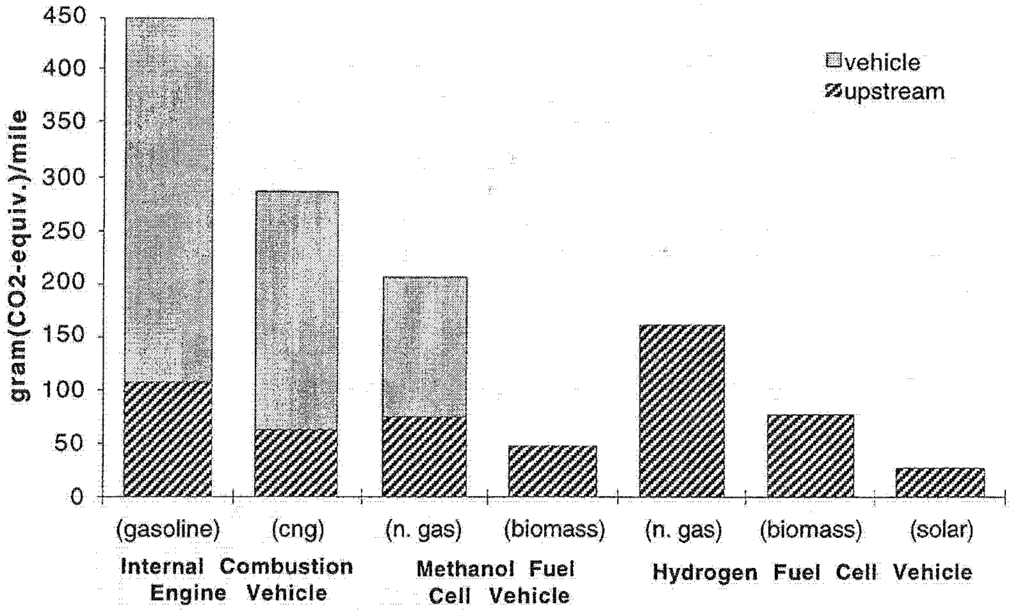
The transportation sector in the United States is a major source of the gases that cause climate change. Automobiles and light trucks account for about one-fifth of all US carbon emissions (Davis 1995)—the most significant contributor to climate change—and emit more carbon than all but five countries in the world, one of which is the United States (WRI 1994). Thus, international efforts to reduce emissions of heat-trapping gases will need to focus on the US transportation sector for important reductions.

Personal vehicles are also a logical target for achieving such reductions, since there is much room for improvement in the type and amount of energy they consume. The Clinton administration recognized the importance of personal-vehicle emissions reductions as part of its climate-change strategy and assembled an advisory committee in 1994 to develop policies towards that end. Although the committee—informally called Car Talk—failed to reach consensus among the auto, oil, and environmental members, the planning process identified several promising policies for reducing future emissions of heat-trapping gases. Car Talk's goal was to identify strategies for reducing automobile and light-truck greenhouse-gas emissions to 1990 levels by three future dates: 2005, 2015, and 2025. Although the 1990 target is useful for planning, even deeper reductions are necessary to truly address the threat of climate change. The following sections outline the role that fuel cell vehicles can play in meeting the administration's climate-change goals while providing even greater benefits in the long term.

Reducing Emissions of Heat-Trapping Gases

The combination of high efficiency and the use of renewable fuels in an FCV can greatly reduce emissions of heat-trapping gases from automobiles (see figure 5). Depending on the feedstock-fuel combination, fuel cell vehicles powered by renewable fuels release 85–100 percent fewer greenhouse-gas emissions than do conventional cars (see appendix C for details). Even in the near term, when fuels are likely to be produced from natural gas, fuel cell vehicles can reduce greenhouse-gas emissions by 60–70 percent. These estimates include all major heat-trapping gases, reported for ease of comparison in CO_2-equivalent emissions, and recognize that emissions associated with automotive use come from the production and delivery of fuel to the vehicle ("upstream" emissions) as well as from the vehicle itself.

Figure 5. Emissions of Heat-Trapping Gases from Automobiles



Notes:

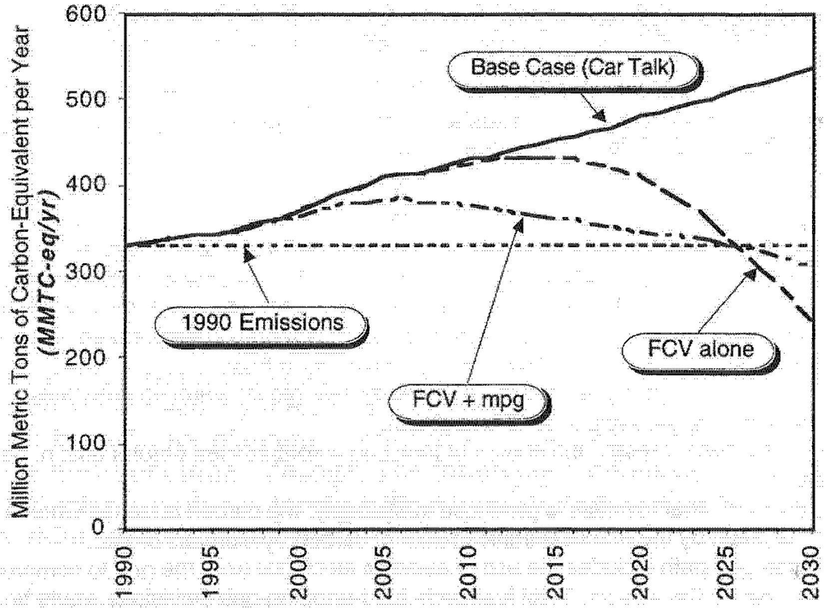
1. The figure shows emissions over the total fuel cycle, from fuel extraction (e.g., oil drilling) through final use in the vehicle. Fuel production and delivery constitute upstream emissions.
2. Emissions are based on a 31 mpg gasoline vehicle (the average new-automobile fuel economy in 2020, according to the Car Talk base-case analysis), 34 mpg-eq compressed natural gas vehicle, 70 mpg-eq methanol FCV, and 80 mpg-eq hydrogen FCV.
3. Emissions of all heat-trapping gases are weighted by their global-warming potentials to derive CO_2-equivalent values (see appendix C for details).
4. Items in parentheses represent the source of fuel: cng = compressed natural gas; n. gas = natural gas.
5. The figure assumes that biomass is produced sustainably: the carbon released when a biomass fuel is used is offset by the photosynthetic uptake of carbon by biomass crops.
6. The solar-hydrogen path includes the use of average electricity from the grid to compress hydrogen for use on the vehicle. Total fuel-cycle heat-trapping-gas emissions would be zero if all energy, including compression, came from renewable sources.

With the potential for such large reductions in greenhouse-gas emissions, fuel cell vehicles can become an important strategy for mitigating climate change. This study constructed two scenarios in which FCVs help return emissions of heat-trapping gases from cars and light trucks to 1990 levels. The first scenario ("FCV alone") relies on fuel cell vehicles alone to reduce emissions of greenhouse gases to 1990 levels by the year 2025. The second scenario ("FCV+mpg") illustrates that the development of fuel cell vehicles at a more moderate pace can meet the same goal when combined with modest fuel-economy gains for conventional vehicles. Fuel-economy improvements are only one example of how fuel cell vehicles can interact with other transportation strategies; a number of other policies might be used in concert with fuel cell vehicles to achieve reductions in emissions of heat-trapping gases. According to a majority report of the Car Talk committee, fuel-economy gains could be the cornerstone of a package of policies to return these emissions to

1990 levels (Car Talk Majority 1995). Other strategies, such as gas taxes, mass transit, and land-use shifts, also have important roles to play in achieving a low-emitting future. This analysis assumes that the fuel economy of the conventional-vehicle fleet could be improved by 30 percent by 2025.

Figure 6 shows the potential of fuel cell vehicles operating on renewable fuels to reduce greenhouse-gas emissions from the light-vehicle sector. These estimates are based on a detailed model of the US light-vehicle sector calibrated to the Car Talk baseline. Both scenarios return emissions of heat-trapping gases from autos and light trucks to 1990 levels by 2025, but they have widely different long-term impacts. The "FCV alone" scenario would nearly zero out greenhouse-gas emissions by the middle of the next century, while the "FCV+mpg" scenario does not achieve near-zero emissions until near the end of the 21st century.

Figure 6. National Emissions of Heat-Trapping Gases from US Autos and Light Trucks

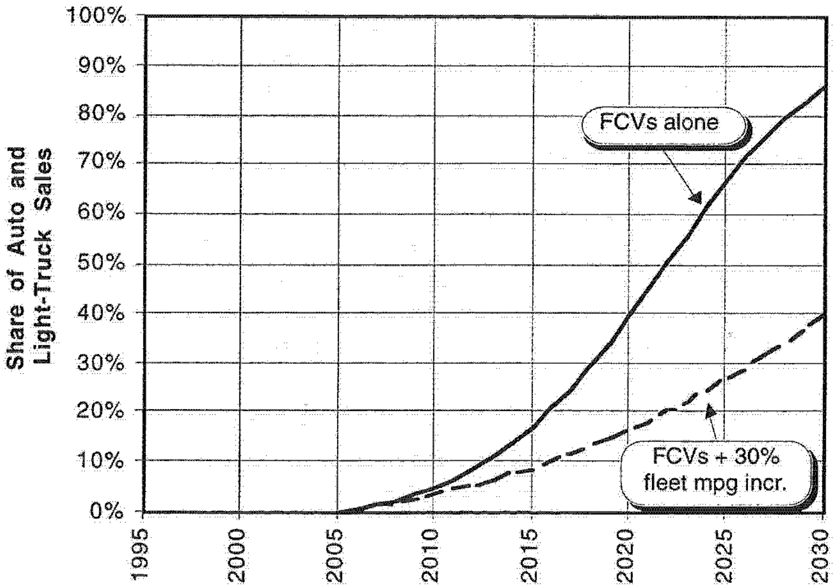


Notes:

1. The figure presents emissions of greenhouse gases over the total fuel cycle based on a detailed stock model calibrated to the Car Talk committee's analytical scenarios.
2. Base Case = the rising-fuel-prices base case of the Car Talk analysis; FCV + mpg = renewably fueled fuel cell vehicles plus a 30 percent fleet-average mpg improvement in 2025; FCV alone = renewably fueled fuel cell vehicles alone used to achieve greenhouse-gas reductions.

Aggressive development of vehicle and fuel technologies is required if fuel cell vehicles alone are to carry the burden of greenhouse-gas reductions. The benefits of such a rapid transition would be great, however, and models of consumer decisionmaking indicate that ample demand for FCVs could exist in the future (see appendix A). The "FCV+mpg" scenario does not require such a rapid development of fuel cells, as shown in figure 7, but it means an increase in the fuel economy of conventional cars. Improving the fuel economy of the entire fleet of cars and light trucks by 30 percent in 2025 requires increasing the average new-car fuel economy to just over 40 mpg over the next two decades. This is a modest task, considering the number of vehicles on the road today that already meet that goal. But since new-car fuel economy has been stagnant at around 28 mpg for over a decade, the political and economic signals for boosting efficiency are apparently not as strong as they need to be.

Figure 7. Fuel Cell Vehicle Sales Requirements to Achieve Reductions in Heat-Trapping-Gas Emissions



The Value of Reducing Emissions of Heat-Trapping Gases

Estimates of the value of reducing emissions of heat-trapping gases are necessarily uncertain, as the specific impacts of rising sea levels, shifts in precipitation, or habitat disruption are difficult both to estimate in quantitative terms and to evaluate economically. Estimates found in the literature range from $0–$200 per ton (carbon-equivalent) (Mark et al. 1994). The California Energy Commission used a value of $34 per ton (carbon-equivalent) (CEC 1991); adopting this number would put the economic worth of reducing greenhouse-gas emissions to 1990 levels at $6.6 billion in the year 2025 (measured in 1994 dollars).

Oil Savings

Americans spend roughly $100,000 per minute to purchase foreign oil,[11] and oil consumption constitutes an important part of the national trade deficit (Nivola and Crandall 1995). Considerable debate persists as to the dangers of this reliance on foreign oil, but the $61 billion spent by the United States on the Persian Gulf War demonstrates that the costs are significant and real (OTA 1994). Domestic

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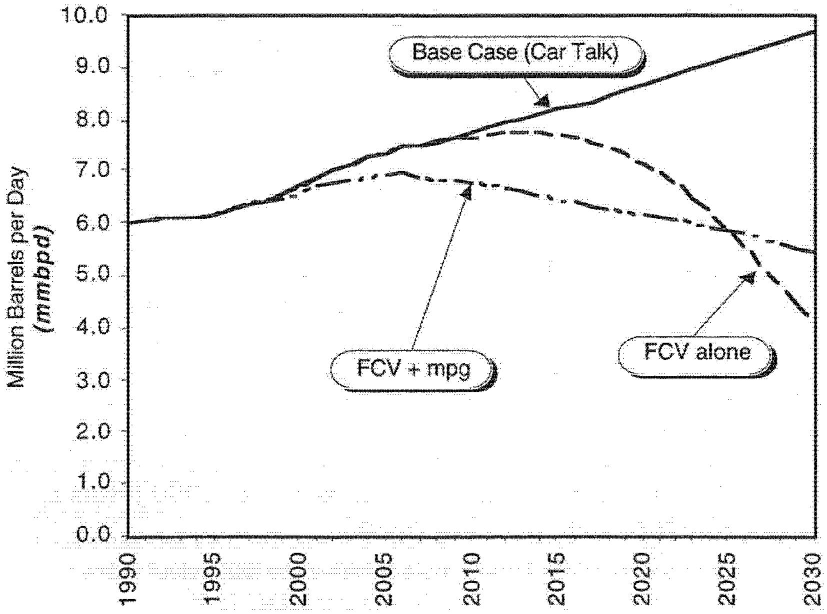
[11] This figure is calculated using the 1993 average price for crude oil ($16.41/barrel) and that year's import level (8.53 million barrels per day) (Davis 1995).

production of oil continues to decline as demand increases, causing imports to rise. If these trends continue, the Department of Energy estimates that 62 percent of US oil will be supplied from foreign sources by 2010 (EIA 1995). The last large oil discoveries outside of the Middle East were in the late 1960s, and estimates that two-thirds of the remaining oil resides in the Persian Gulf are cause for concern about the return of OPEC power.

A transition to fuel cell vehicles would sharply reduce US reliance on foreign oil, thereby reducing the vulnerability of our economy to oil price shocks, lowering the need for a military presence in the Persian Gulf, and reducing world oil prices across the board. Figure 8 shows the oil consumption of autos and light trucks in the United States (which today accounts for 10 percent of the entire world's oil use) under the two national scenarios discussed above. The benefits of energy independence from saving oil are only partially captured if conventional gasoline vehicles are replaced with fuel cell vehicles operating on an imported fuel. A significant portion of future methanol supplies might come from abroad, although from a more diverse range of countries than the oil-rich Persian Gulf. Domestic supplies of natural gas, however, would continue to be an important resource for methanol production, as would local biomass in the case of methanol produced from renewable sources. The hydrogen future is likely to be one of greater energy independence: because it is expensive to ship hydrogen over water, it is improbable that foreign suppliers will be able to compete with domestic hydrogen producers.

Figure 8. National Oil Consumption of US Autos and Light Trucks



Notes:

1. The figure presents oil consumption based on a detailed stock model calibrated to the Car Talk committee's analytical scenarios.
2. Base Case = the rising-fuel-prices base case of the Car Talk analysis; FCV + mpg = renewably fueled fuel cell vehicles plus a 30 percent fleet-average mpg improvement in 2025; FCV alone = renewably fueled fuel cell vehicles alone used to achieve greenhouse-gas reductions.

By 2025, either scenario will have reduced the oil consumption of autos and light trucks by one-third, saving nearly 3.3 million barrels of oil per day—almost twice the amount of oil the United States imports from the Persian Gulf today (EIA 1994c) or four times the potential production of the Arctic National Wildlife Refuge (API 1987). At 1993 oil prices, these reductions translate to nearly $20 billion saved in direct payments in 2025. And by 2030, the "FCV+mpg" scenario will have saved as much oil as was found in the North Sea and Alaskan Prudhoe Bay discoveries *combined* (the last two great oil discoveries, occurring nearly 25 years ago).

Summing Up

The strength of fuel cell vehicles lies in their ability to simultaneously address the three most important challenges of the US transportation future: air quality, climate change, and oil dependence. Very few other options could have such a substantial impact on each of these areas at once. Below is a summary of the key results of the analysis presented here:

- Fuel cell vehicles are 98–100 percent cleaner than today's cars.
- A fuel cell automobile is worth $4,300–$8,300 in avoided pollution-control costs in the dirtiest US cities.
- FCVs running on renewable fuels emit 85–100 percent fewer greenhouse-gas emissions than today's cars.
- Fuel cell vehicles can return greenhouse-gas emissions from autos and light trucks to 1990 levels by the year 2025 and virtually eliminate these emissions by 2050.
- The widespread adoption of fuel cell vehicles can reduce oil consumption from autos and light trucks by one-third by 2025, saving nearly twice as much energy as the United States currently imports from the Persian Gulf.

Fulfilling the Promise

Although manufacturers, policymakers, and the public are increasingly becoming aware of the promise that fuel cell vehicles hold for the future, the transition from 100 years of gasoline-vehicle dominance cannot occur overnight. The combination of gasoline and the internal-combustion engine has formed a technological cartel that will not easily yield to a new technology. At the same time, the United States continues to struggle with issues that warrant swift action, including dirty air, a changing climate, and energy dependence.

The interest in fuel cell vehicles from both the public and the private sector suggests that such a technology is capable of achieving a combination of social and industrial goals. Realizing that potential requires aggressive action today to overcome the remaining technical hurdles and to address the more significant institutional challenges facing the transition.

The Menu of Options

Over the past quarter century, experts have proposed numerous policies to address this country's burgeoning transportation problems.[12] These policies fall into four general categories—market strategies, technology development, public education, and regulation—although understanding the interactions between these categories is often critical to successful policymaking.

Market strategies include tax incentives for the production or purchase of new fuels and vehicles, user fees on gasoline consumption or the release of pollution, partial allocation of automobile insurance premiums to the price drivers pay at the pump, rush-hour toll increases on roadways, fees and rebates to encourage the purchase of cleaner and more-efficient cars, and tradable credits for emissions and fuel economy. Such measures are designed to send signals to producers and consumers in the market by taking societal costs into account as well as to overcome barriers to new technologies.

Technology development has traditionally focused on research and development (R&D), but some feel that federally sponsored R&D has languished in government laboratories and that federal research dollars have been readily accepted in the past by uninterested auto companies (Nadis and MacKenzie 1993; Sperling 1995). Two important changes, however—demonstration activities and cooperative research—have added new purpose to technology development. Large-scale demonstrations take new technologies out of the laboratory and put them on the road, where industry and consumers can see them in action. Cooperative research merges both funding and expertise from public and private groups, providing financial and technical leverage for technology development. A company that has invested some of its own time and money in a new idea is more likely to carry the momentum gathered during the research, development, and demonstration stages into the commercialization of a finished product.

Public education—informing decisionmakers and consumers about the impact of their current choices and the range of opportunities that lie before them—is a

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[12] See Gordon (1991) for a comprehensive discussion.

critical foundation for effecting policy changes. Examples of such programs in transportation include car-purchasing guides, fuel-economy stickers on new cars, educational curricula, and demonstration programs.

Despite the continuing trends towards deregulation occurring in many sectors of the US economy, regulation still holds an important place as an efficient and strong policy lever in the transportation sector. For example, the tradition of fuel-economy and emissions standards helped avoid even more severe air pollution and oil dependence than the United States faces today. Similarly, requirements that government fleets purchase alternative vehicles have expanded the sales of cleaner vehicles and offered an important early-market testing ground.

Moving Ahead with Fuel Cells

Any set of policies aimed at transforming transportation should generate verifiable benefits at minimal cost. Flexible policies that favor performance targets rather than specific technologies are preferable. Furthermore, industry and consumers need consistent policy signals over a long enough period to effect a permanent transition. The eight strategies below can help move the United States beyond the status quo and into a sustainable transportation future using cleaner cars:

- **Maintain the zero-emission-vehicle (ZEV) program.** The ZEV program in California and other states has fueled major technological advances in the development of electric vehicles. California's recently modified ZEV program, which maintains a significant ZEV sales requirement for the year 2003, continues to be an important force behind the development of clean vehicles. Most of the attention has focused on battery-powered vehicles, since they will be the first ZEVs on the road, but the ZEV requirement is also largely responsible for the aggressive pursuit of fuel cell vehicles. FCV developers see the ZEV market as an important target (Klaiber 1995a), and eliminating the ZEV requirement would risk slowing the rapid progress of these vehicles and restrict the growing level of investment. Furthermore, many of the electrical drivetrain components and storage technologies that are being developed for battery-powered vehicles in the near term are transferable to fuel cell vehicles. Thus, FCVs will build on the successes made by battery-powered-vehicle developers.

- **Reorient public funding priorities.** Public investments in energy technology should focus on programs that can effectively meet the important national goals of cleaner air, increased energy security, and reduced climate-change emissions. The hundreds of millions of federal dollars that are spent annually on fossil fuel research should be redirected towards more promising, sustainable options. Fuel cells for transportation, which were funded at only $22.5 million in 1995, are one such critical technology that warrants larger levels of support.

- **Develop regional demonstration programs.** Putting vehicles on the road is an important step in the process of proving a new transportation technology. To be successful, however, vehicles powered by clean fuels must have a supporting infrastructure for refueling and maintenance. A broad supply network for renewable fuels can be established within a geographic region to develop nodes of clean fuel and vehicle use, starting first with fleet vehicles and then expanding into the private sector. Regions with the most severe air-quality problems are the logical first sites for such demonstration programs.

- **Improve the Partnership for a New Generation of Vehicles (PNGV).** In 1993 the Clinton administration and the domestic automakers established the PNGV to build production prototypes of an automobile with triple the fuel economy of today's cars by 2004. Fuel cell vehicles are considered a strong candidate for meeting that goal, and the partnership is an important step in transforming automotive technology. The PNGV is, however, primarily an energy-efficiency initiative, with the added requirement that prototype vehicles cost no more than conventional vehicles. This venture, which was originally termed the Clean Car initiative, should be more aggressive on emissions reductions, giving credit to options such as fuel cell vehicles that can zero out pollution as well as improve fuel economy. Under the narrow goals of the program, the PNGV will ultimately select only one technology, excluding other promising options. Unfortunately, choosing one winner means eliminating funding for other viable and more beneficial longer-term technologies, thereby undermining an important goal of federal research: maintaining a diverse set of technological options. Because US industry is more focused on the short-term market, the role of the public sector is to invest wisely in longer-term, higher-risk endeavors that promise significant social benefits. Thus, partnerships like the PNGV, while potentially beneficial in terms of technology transfer and communication, must not derail long-term investment strategies.

- **Establish short-term clean-transport incentive funds.** An important challenge to introducing new technologies and fuels is overcoming the initial hurdle of higher costs for early purchasers. Although several federal, state, and local programs provide tax relief or rebates to purchasers of alternative fuels and vehicles, these incentives should be reoriented to include all options based on their air-quality or climate-change performance. Particular emphasis needs to be placed at the regional level on the development of refueling infrastructure through preferential zoning, tax incentives, and buying down the cost of new service stations. All incentives should include a provision to phase them out over time and should be funded by appropriate fees on the use of petroleum and on the pollution generated by conventional vehicles.

- **Expand clean-vehicle fleet requirements.** The 1988 Alternative Motor Fuels Act, the 1990 Clean Air Act Amendments, and the Energy Policy Act of 1992 all included aggressive requirements that federal and state governments purchase alternative-fuel vehicles. These provisions are helping to establish enough market demand for clean fuels and vehicles to make it economical for suppliers to produce them. These programs should be expanded to further encourage the purchase of the cleanest vehicles possible. Establishing fleet-average emissions requirements would maintain flexibility for fleet buyers but also guide purchasing decisions towards the cleanest technologies.

- **Establish a vehicle feebate program.** A system of fees and rebates is a promising market tool for encouraging the purchase of clean vehicles and fuels. Under such a scheme, purchasers of clean and efficient vehicles would receive a rebate based on the energy and environmental performance of their vehicle. The rebates would in turn be funded by an offsetting surcharge on conventional-vehicle sales. Informational stickers on all new cars would include vehicle rebate and fee information.

- **Establish tradable greenhouse-gas credits for fuel producers.** Incentives for fuel producers can help ensure that clean fuels will be readily available to motorists. A tradable credit system for fuel suppliers would encourage the production and marketing of lower-emitting fuels by giving each producer a specified number of credits to manufacture fuels that will release heat-trapping gases.

The policies proposed here combine market measures, technology development, public information, and regulation into a package of mutually reinforcing options for fulfilling the promise of fuel cell vehicles. This suite of policies would support other clean-vehicle technology options as well, since the incentives set out aggressive performance criteria rather than prescribe specific technologies.

Cleaner cars are not the only answer to our nation's transportation problems, but they are a necessary part of the solution. The challenges of oil dependence, air pollution, and climate change require aggressive action and innovative strategies. Given these pressures, fuel cell vehicles hold great promise to transform transportation into sustainable travel for the 21st century. Realizing that future—getting from here to there—requires starting down the right path today.

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Appendix A: Fuel Cell Vehicle Attributes and Vehicle-Choice Modeling

This appendix discusses the basis for the assumptions about fuel cell vehicle (FCV) characteristics made in this report, including fuel economy, vehicle cost, range, and performance. Because light-duty fuel cell vehicles are still in the development stage, these estimates should be regarded as preliminary. The values presented here represent the current state of knowledge based on an assessment of the best available public information from industry, academic, and government-agency sources. Using these inputs, the analysis employs a simple vehicle-choice model to demonstrate the potential consumer demand for fuel cell vehicles in the future.

Vehicle Attributes

New-Vehicle Efficiency

Fuel cell vehicles are often described as being two to three times more efficient than conventional gasoline vehicles. Although the theoretical efficiency limit of a fuel cell itself is an impressive 83 percent (Appleby and Foulkes 1993),[1] in-use efficiencies of 45–50 percent have been demonstrated for the entire system (pumps, compressors, other auxiliaries) in typical driving (Borroni-Bird 1995). This is still a substantial improvement over today's internal-combustion engines, which average a conversion efficiency of around 19 percent in vehicle applications (DeCicco and Ross 1994).[2] Engine, drivetrain, and platform-based modifications can improve the operating efficiency of conventional gasoline vehicles; a hybrid-electric vehicle powered by a small, gasoline internal-combustion engine could approach the efficiency of today's fuel cell vehicles. This study does not, however, address the viability of such alternative hybrid vehicles as sustainable transportation options.

Since public data on actual vehicle testing is limited, current estimates of FCV fuel economy are based on engineering models and laboratory tests. Ogden et al. (1994) report a near-term fuel economy gain for methanol FCVs of 140 percent compared to a vehicle similar to a Ford Taurus in size and performance. GM/Allison (1993) reports a slightly lower fuel-economy improvement—about 90 percent—over combined city and highway driving for a methanol FCV. Both of these estimates assume that the vehicle platform (chassis, panels, etc.) will be similar to that of a conventional gasoline vehicle, and the authors do not take advantage of energy-conserving measures that could boost both gasoline vehicle and FCV fuel economy.[3] The analysis in this study assumes that, in the near-term, a methanol FCV will achieve a 90 percent improvement over today's conventional

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[1] This number assumes a higher-heating value. The lower-heating value efficiency limit is 94 percent (Appleby and Foulkes 1993).

[2] This is measured as the conversion of fuel entering the engine into power entering the transmission.

[3] DeCicco and Ross (1993) suggest that platform-based improvements could boost conventional gasoline vehicle fuel economy by 25 percent or more in the near term. Lovins et al. (1993) predict even larger improvements through total vehicle redesign.

gasoline vehicles,[4] or a fuel economy of 54 miles per gallon-equivalent (mpg-eq) for an automobile.[5]

A hydrogen FCV is more efficient than a methanol FCV because it does not need a reformer. Estimates in the literature of the efficiency improvement of hydrogen FCVs relative to methanol FCVs range from 15–30 percent (Kumar 1993; Ogden et al. 1994; Thomas and James 1995). This study uses a value of 15 percent, although uncertainty persists as to the exact level of improvement a hydrogen vehicle can achieve. Under this assumption, hydrogen FCVs might be 120 percent more fuel efficient than gasoline vehicles in the near term, giving an automobile a fuel economy of 62 mpg-eq.[6]

The efficiency of both methanol and hydrogen FCVs will improve over time as losses from electrical resistance in the fuel cell stacks are minimized, auxiliary loads are optimized, regenerative-braking technology is improved,[7] reformers become more efficient, and hydrogen storage becomes denser. Without major changes to the vehicle platform, a fully optimized hydrogen FCV might achieve a fuel economy of 80 mpg-eq by 2020, or 2.8 times the fuel economy of today's cars. The corresponding long-term value for a methanol FCV would be 69 mpg-eq, or 2.5 times the fuel economy of today's cars.[8] Fuel economy might continue to increase beyond 2020 with improvements in storage or reformer technology. A hydrogen FCV, for example, might ultimately achieve a fuel economy improvement of nearly three times the equivalent gasoline vehicle (Delucchi 1992).

This analysis assumes that the fuel economy improvements estimated for automobiles are equally applicable to light-duty trucks. Thus, proportional increases in automobile efficiency can be applied directly to light-truck fuel efficiency, as shown in table A-1.

On-Road Efficiency

The fuel economy of new vehicles is typically defined as the value determined by the Environmental Protection Agency (EPA) in its Corporate Average Fuel Economy (CAFE) tests. CAFE-rated fuel economy is typically 15–25 percent higher than fuel economy experienced on the road, because the EPA test does not accurately reflect real-world driving conditions. Congestion, high levels of urban travel, and high highway speeds result in on-road fuel economies 15 percent lower than CAFE-rated values for automobiles and 24 percent lower for light trucks (Car

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[4] The sales-weighted average fuel economy of new cars in 1994 was 28.2 mpg. New light-duty trucks averaged 20.6 mpg (Davis 1995).

[5] This study adopts the convention of reporting fuel economy in terms of miles per gasoline-equivalent gallons, which is the distance a vehicle can travel on the amount of energy contained in one gallon of gasoline.

[6] This result is consistent with recent preliminary testing data on a hydrogen fuel cell stack with a simulated auxiliary and vehicle load (Miller 1995).

[7] This assumes that the vehicle is configured in a hybrid design with an energy-storage device (battery, flywheel, or ultracapacitor).

[8] These ratios are consistent with the analysis reported in Ogden et al. (1994).

Talk 1995).[9] Two-thirds of this fuel-economy "gap" is from urban driving and congestion effects (Maples 1993), where FCVs are likely to have an advantage over gasoline vehicles. An FCV equipped with a small peak-power device may be more efficient than gasoline vehicles during accelerations and can recapture some of the energy lost during braking. Furthermore, a fuel cell has lower energy requirements during idling than a gasoline vehicle, although FCVs still require some energy to operate when standing still (Miller 1995). In contrast to standard internal-combustion engines, however, the efficiency of fuel cells decreases as they approach full power. Thus, higher speeds over the highway cycle will lower the fuel economy of FCVs. Further testing and data are required to quantify the true impact of all sources of the fuel-economy gap on real-world FCV efficiency. Given the current level of uncertainty, this study assumes that FCVs will experience the same gap as gasoline vehicles.

Table A-1. Fuel Cell Vehicle Fuel-Economy Estimates
EPA-Rated Miles per Gallon (Gasoline-Equivalent)[a]

	—— Near Term (c. 2000) ——		—— Long Term (c. 2020) ——		Fuel-Economy Gap[b]
	Methanol FCV	*Hydrogen FCV*	*Methanol FCV*	*Hydrogen FCV*	
Automobiles	54	62	69	80	15 percent
Light Trucks	40	46	51	59	24 percent

a. Combined highway and city fuel economy over EPA CAFE test cycle. Estimates are for FCVs with weight and performance similar to today's vehicles.

b. Gap between on-road fuel economy and EPA-tested value; applies to both gasoline vehicles and FCVs.

One can also measure the fuel economy of different transportation alternatives over the entire fuel cycle, including all the energy that goes into producing and delivering a fuel as well as its use in a vehicle. Such analyses account for the fact that it takes less energy to produce and deliver gasoline than it does methanol or hydrogen. Based on the detailed fuel-cycle model discussed in appendix C, the fuel-cycle efficiency of a mature methanol FCV is 1.7–1.9 times that of today's conventional gasoline vehicle; a mature hydrogen FCV would be 2.1–2.9 times more efficient over the total fuel cycle. This type of comparison, however, masks the important differences among the types of energy used to serve driving needs. Since methanol and hydrogen are generated from natural gas or renewable sources, one must also consider the relative importance of consuming a unit of oil energy versus a unit of natural gas or renewable energy.

Purchase Price

The cost of fuel cell technology has declined rapidly in recent decades, but analysts expect prices to drop by a factor of a thousand when fuel cells are mass-produced. Daimler-Benz projects that, at a production volume of 100,000 systems per year,[10] a fuel cell system will cost \$140–\$280 per kilowatt, or two to four times the cost of an internal-combustion engine system (Klaiber 1995a). General Motors estimates

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[9] Although some analyses assume that this fuel-economy "gap" will increase significantly in the future (Maples 1993), the auto and light-truck values are held constant here, consistent with the assumption by Car Talk (1995).

[10] This is roughly equivalent to 10 percent of the California new-vehicle market.

that high-unit production would bring the cost of a methanol fuel cell system down to $65 per kilowatt, or about the cost of an internal-combustion engine system (GM/Allison 1993). Using the GM figures and a detailed engineering-cost model, Ogden et al. (1994) have estimated that in the near term the premium will be about $4,000 for a methanol FCV and $7,000 for a hydrogen FCV. These figures assume no major breakthroughs in storage or fuel cell technology in the next decade.

Ultimately, the cost difference between FCVs and gasoline vehicles will be driven by three major components: the fuel cell engine, the electric drivetrain, and the fuel storage and/or processing. An analysis of the cost of the materials that go into making an FCV projects that in mass-production methanol and hydrogen FCVs of the future will cost only $2,000 more than a comparable gasoline vehicle (Thomas and James 1995). Of course, should the technological hurdles to reducing costs prove more significant than expected, or if the future commitment to mass-producing FCVs falters, the additional costs of FCVs will remain higher than assumed here.

Any higher costs that an FCV purchaser might pay up front may well be offset by lower costs over the life of the vehicle. Because a fuel cell has few moving parts, FCVs should last longer and cost less to maintain than gasoline vehicles (Delucchi 1992), and the higher fuel economy of FCVs will reduce the amount that drivers will pay for fuel. Even if the methanol or hydrogen fuel costs 50 percent more than gasoline, one study shows that the fuel saved over the lifetime of an FCV would offset an initial purchase premium of $1,500–$2,500 (Mark et al. 1994).

Range

Although considerable evidence shows that consumers do not require a vehicle that travels 300 miles or more before refueling,[11] the range of gasoline vehicles continues to be the benchmark for assessments of alternative vehicles. Even the earliest commercial methanol FCVs should be capable of traveling 300 miles or more between refuelings, given a vehicle with a 12-gallon fuel tank (Ogden et al. 1994) and the near-term fuel economies shown in table A-1. Increasing the size of the tank would improve the range of methanol FCVs, with a moderate penalty in fuel economy from the additional weight of the storage.

The bulkiness of compressed hydrogen storage is likely to limit the amount of hydrogen that can be boarded on an FCV in the near term. A hydrogen FCV should be capable of traveling at least 200 miles without refueling, given the above assumptions for fuel economy coupled with an estimate of the hydrogen-storage capacity of a compressed tank (Delucchi 1992). On the other hand, domestic automakers are apparently designing for vehicles with a range of over 300 miles, so the ground-up estimates provided here may underestimate the potential of hydrogen FCVs. As storage technologies improve over time, the available range will increase.[12]

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[11] See, for example, Turrentine and Kurani (1995).

[12] For example, future carbon adsorption systems have the potential to double the storage density of hydrogen tanks (ADL 1994).

Performance

Since only a handful of FCVs have been built, very few assessments have been conducted on how they might perform under normal driving conditions. Performance will be determined partially by the exact vehicle configuration. FCVs that employ a secondary power device for start-up and peak power (such as a battery, flywheel, or ultracapacitor) can be designed to operate much like a conventional gasoline vehicle; peak-power devices add weight, cost, and complexity to the design, however. Performance will also be determined by the size of the fuel cell system, with weight and cost penalties being associated with larger, more powerful systems.

General Motors has modeled the performance of methanol FCVs over typical driving cycles and has developed a vehicle design in which the warmed-up FCVs perform similarly to gasoline vehicles in the same size class (GM/Allison 1993). Their vehicle designs accelerated from 0–60 miles per hour in 10–12 seconds, as do most cars today. During the first two minutes or so, when the methanol reformer is warming up, the 0–60 acceleration increased to 17–19 seconds.

A hydrogen FCV, on the other hand, should experience little degradation of performance at start-up, because the fuel cell itself operates at close to ambient temperature. Fuel is transferred directly from the tanks to the engine, eliminating the intermediate reforming step and permitting rapid responses to the fluctuating power requirements of the vehicle.

Vehicle-Choice Modeling

Analysts in the transportation community are increasingly using vehicle-choice models to project the future demand for alternative vehicles. For example, the Energy Information Administration (EIA) has recently added a choice-model component to the extensive energy-forecasting model used in its Annual Energy Outlook (EIA 1995). The UCS analysis in this study employed a simplified version of a vehicle-choice model used in planning exercises at the US Department of Energy. This model, the Alternative Vehicle Sales (AVS) model, is based on the same methodology and parameter coefficients as the more complex EIA model. The AVS model is a discrete-choice, multi-attribute logit model that simulates consumer purchase decisions by weighing vehicle price, fuel cost, fuel availability, fuel economy, range, and emissions.

Vehicle-choice models are based on two major sets of input data: (1) information describing how consumers make choices among vehicles, and (2) technical and economic data on vehicles and fuels. The information describing consumer choices is derived from stated-preference surveys, in which respondents are asked about the key factors in their decision to purchase one vehicle over another. Based on these surveys, a series of "logit functions" is constructed, which indicate the increase in the probability of a consumer purchasing a particular vehicle given, say, a reduction in its price.[13] Logit functions are then mathematically

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[13] These parameters enter the logit calculation through coefficients on vehicle price, fuel cost, range, emissions, and fuel availability. The values used in this study are taken from a similar model used by EIA (1995). In addition to coefficients relating to the properties of a vehicle, logit models also incorporate constants that are specific to each type of vehicle. The constant parameter for hydrogen FCVs was derived from Fulton (1994), combining his estimates of the utility associated with

combined with assumptions regarding the technical and economic aspects of the vehicles, many of which are discussed in this appendix. The result of the calculations is a projection of the probability that each vehicle type will be purchased, which is equivalent to the vehicle's potential market share.

Several shortcomings limit the value of vehicle-choice models in analyses of this kind. First, very few stated-preference surveys have been conducted to date because of their time and expense; most vehicle-choice models in use today are based on data collected by Bunch et al. (1991) in a survey of California motorists. Second, these models make the questionable assumption that consumer responses to a survey translate into real-world purchase decisions. Finally, even the most sophisticated models focus primarily on one side of the economic equation: demand. Since vehicle and fuel suppliers influence the types of vehicles that will become available to consumers, understanding their decision processes is critical for choice modeling (Train et al. 1994).

Given the current level of data and understanding, it may not be appropriate to place great stock in vehicle-choice modeling as a forecasting tool. Instead, this study used a choice model to understand how attractive FCVs might be to future consumers. Figure A-1 shows the results of the AVS model compared to the scenarios used in the analysis of climate-change stabilization for this study. The vehicle-choice model curve corresponds to the number of FCVs that utility-maximizing consumers might be willing to purchase based on the attributes of hydrogen FCVs discussed in this appendix.[14] The real-world penetration of FCVs will be constrained by supply-side limitations in the fuel and vehicle industries, thus lowering the near-term entry of vehicles. The UCS scenarios are not projections of the likely penetration of FCVs but rather estimates of the market share required to meet climate-change goals (see main text). The results of the vehicle-choice model suggest that sufficient consumer demand could exist to support either of these scenarios, but it says nothing about the infrastructure hurdles facing FCV development.

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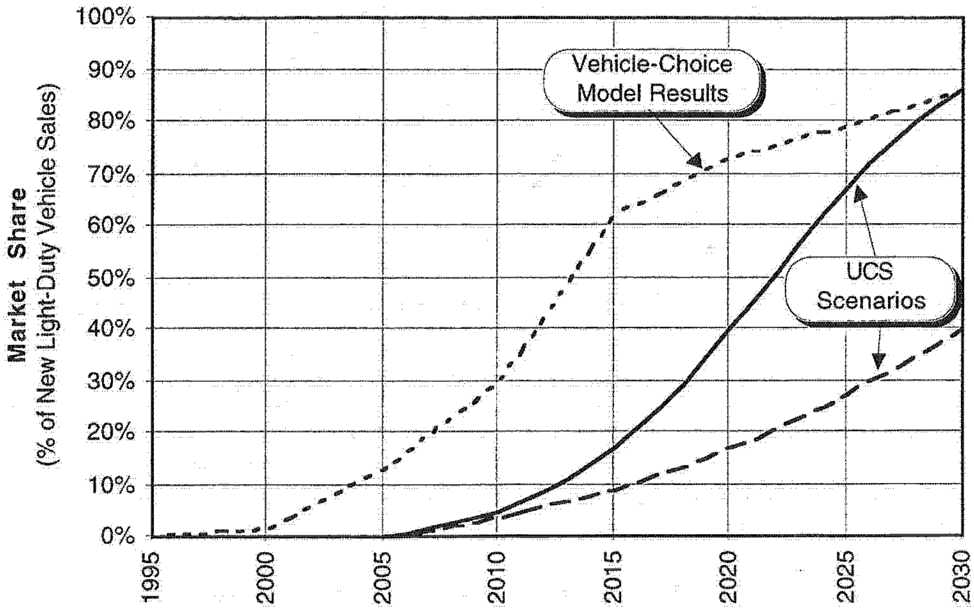
alternative fuel use and purchasing a hybrid electric vehicle to act as a proxy for the utility associated with an alternatively fueled FCV.

[14] In addition to vehicle price, range, and fuel economy, AVS requires assumptions about fuel parameters that were not explicitly treated in this study. The rough vehicle-choice modeling discussed here assumes that hydrogen fuel will cost twice as much as gasoline on an energy-equivalent basis in the near term, dropping to 50 percent more by 2030 based on an analysis of natural gas-to-hydrogen by Mark et al. (1994). This model run further assumes that consumers will perceive the availability of hydrogen to be quite limited and that only 1 percent of service stations will carry hydrogen in 2005, increasing to 5 percent by 2010, 10 percent in 2015, and 50 percent by 2030.

Figure A-1. Market Penetration Estimates: Vehicle-Choice Model Results



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Appendix B: Tailpipe Emissions

This appendix discusses the emissions estimates for both gasoline and fuel cell vehicles used in this analysis. The gasoline-vehicle emissions reflect calculations using standard emissions models developed for regional air-quality planning, while emissions from fuel cell vehicles (FCVs) represent estimates from preliminary test data and engineering calculations.

Emissions from Gasoline Vehicles

The two primary computer models employed for transportation air-quality planning in the United States are the US Environmental Protection Agency's (EPA) MOBILE5a model and the California Air Resources Board's (CARB) suite of models, EMFAC7F and BURDEN7F.[1] State and local planning agencies use these models to determine emissions from the transportation sector.

This study focused on two regional examples—the Los Angeles Air Basin and the northeastern United States—to estimate the emissions benefits of FCVs. Since California has established its own modeling capabilities for emissions planning, it is appropriate to use the EMFAC/BURDEN emissions models to estimate gasoline vehicle emissions for the Los Angeles region. Air-quality planners in the Northeast use the national model, MOBILE, to estimate transportation emissions. Strictly speaking, EMFAC and MOBILE are based on the same general methodology; their results vary, however, because each relies on different data, algorithms, and assumptions. This study employs each model for its appropriate location to demonstrate the role of FCVs in alleviating air pollution at the local level, recognizing that the results of the different models are not directly comparable.

California Emissions

This study calculated emissions savings for FCVs against two benchmark vehicles: (1) a gasoline vehicle designed to meet the Federal Tier I standards, and (2) a gasoline vehicle meeting the ultra-low-emission vehicle (ULEV) standard promulgated by CARB. These two base vehicles provide a reasonable range over which to compare FCV emissions performance. On the one extreme is the current Tier I vehicle required nationwide, while the ULEV represents the cleanest vehicle required under California regulations that is not a zero-emission vehicle (ZEV). Although ULEVs open up some opportunities for alternatively fueled vehicles, it is now generally assumed that a carefully controlled gasoline vehicle can meet the ULEV standard when operating on reformulated gasoline (Gushee 1992; OTA 1994).

Hwang et al. (1994) presented details of the emissions modeling; that study estimated gasoline-vehicle emissions in California for an analysis of battery-powered electric vehicles based on EMFAC/BURDEN7F. The authors noted clear evidence that CARB's models substantially underpredict real-world emissions from light-duty vehicles. Measurements of vehicular emissions from tunnel studies and air-quality monitoring indicate that earlier versions of EMFAC/BURDEN, version

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[1] CARB is currently updating its suite of emissions models and released a draft of the new version, the Motor Vehicle Emissions Inventory, in December 1995. Although the finalized model was not available for this analysis, the following sections address the likely implications of the model update.

7E, which was released in 1990, underpredicted reactive organic gases (ROG) and carbon monoxide (CO) emissions by factors of 1.5–2.5 (Fujita et al. 1992).

CARB is currently updating its model to account for real-world factors. Version 7F increased emissions predictions slightly (5–10 percent), and recent versions have done so more extensively. Table B-1 shows the results of the 7F model, as exercised by Hwang et al. (1994). Although the recent update—now called the Motor Vehicle Emissions Inventory (MVEI)—has not been finalized, early indications are that the model will generate increases in light-duty vehicle emissions of 31 percent for ROG, 91 percent for CO, and 66 percent for nitrogen oxides (NO_x) in the South Coast, when compared to version 7F for the year 1990 (Ellis 1995). Changes to the 2010 inventory are much less substantial, as a result of a new cold-start methodology, modified projections of the level of travel in the South Coast, and assumptions about emissions reductions from inspection and maintenance programs. Compared to version 7F, the light-duty-vehicle emissions for the South Coast as predicted by MVEI *decrease* by 19 percent for ROG, increase 23 percent for CO, and increase 18 percent for NO_x in 2010 (Ellis 1995).

The preliminary results from MVEI are in sharp contrast to the original changes proposed to the EMFAC/BURDEN model, sometimes called Preview 7G, which indicated fleet increases of 37 percent (ROG), 101 percent (CO), and 15 percent (NO_x) (Hwang et al. 1994). The differences between Preview 7G and MVEI appear to stem largely from CARB's assumptions about the efficacy of inspection and maintenance programs. Experience demonstrates that the benefits of such programs have been much lower than air-quality planners predicted (Ross et al. 1995). As a result, the ability of inspection and maintenance programs in California to offset the increases in ROG and CO that both Preview 7G and MVEI predict for real-world emissions is questionable.

Because of the uncertainty associated with the inspection and maintenance program assumptions imbedded in the preliminary MVEI results, the UCS analysis used the Preview 7G values as the basis for adjusting the 7F values to estimate real-world emissions from vehicles (see table B-1). These estimates assume that the inventory changes prescribed for 2010 in the Preview 7G runs apply to a single vehicle over its lifetime (versus a fleet of vehicles).[2] The improved model, MVEI, may still underpredict emissions (Washington 1994), in which case the true emissions benefits of FCVs would be larger than estimated here.

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[2] This approach was recommended by Mark Carlocke, CARB, Mobile Source Division, El Monte, Calif., April 28, 1994, for the analysis by Hwang et al. (1994).

Table B-1. Lifetime Average Emissions from Gasoline Automobiles in Los Angeles[a] *(grams/mile)*

	ROG Exhaust[b]	ROG Evap[b]	CO	NO_x	PM_{10}	SO_x
Base Vehicle (Tier I)[c]						
EMFAC7F Result	0.341	0.096	3.495	0.666	0.010	0.043
Estimated Real World[d]	0.516	0.121	7.071	0.737	0.010	0.043
ULEV[e]						
EMFAC7F Result	0.055	0.096	1.291	0.337	0.010	0.043
Estimated Real World[d]	0.088	0.121	3.141	0.373	0.010	0.043

a. Based on CARB's EMFAC/BURDEN7 model runs for the South Coast Air Basin (Hwang et al. 1994).

ROG = reactive organic gases; CO = carbon monoxide; NO_x = nitrogen oxides; PM_{10} = particulate matter (less than 10 microns); SO_x = sulfur oxides.

b. ROG exhaust emissions are from vehicle tailpipe; ROG evaporative emissions are from noncombustion sources.

c. Base vehicle meets the current federal Tier I standards of the 1990 Clean Air Act Amendments.

d. 7F results were adjusted by changes to the 2010 inventory predicted by Preview 7G runs (Hwang et al. 1994).

e. Ultra-low-emission vehicle under California's Low-Emission-Vehicle Program.

Northeast Emissions

Gasoline vehicles sold in the northeastern states are currently required to meet the federal Tier I standards promulgated by EPA. In a recent proposal, however, the domestic automakers have offered to meet a more stringent set of standards in exchange for eliminating the zero-emission-vehicle requirement in the 13 northeastern states known as the Ozone Transport Region. This "National LEV Program" would allow manufacturers to opt in to a program requiring them to achieve California's low-emission-vehicle levels in their sales mix by 2001 (Federal Register 1995). This analysis of FCVs in the Northeast, then, uses two benchmarks: (1) a Tier I vehicle required under current federal law, and (2) a low-emission vehicle that would be required under the so-called 49-state-car initiative.

A recent UCS study of battery-powered electric vehicles in the northeastern United States (UCS 1994) used EPA's motor vehicle emissions model, MOBILE5a, to develop gasoline-vehicle emissions. The current analysis applied the earlier UCS results with minimal modifications. In this study, emissions over the lifetime of a vehicle are determined from model-year-specific emissions rates for the year 2020. Thus, the emissions from a model year (MY) 2019 vehicle were taken to be equivalent to emissions from a one-year-old vehicle. Emissions from a MY 2007 vehicle correspond to a 13-year-old car.[3] Table B-2 summarizes the results of the analysis.

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[3] This approach is reasonable only if regulations and testing procedures are assumed to stay constant for 13 years previous to 2020, as they are in this analysis.

Table B-2. Lifetime Average Emissions from Gasoline Automobiles in the Northeast[a] *(grams/mile)*

	ROG Exhaust	ROG Evap	CO	NO_x	PM_{10}[b]	SO_x[b]
Base Vehicle (Tier I)[c]	0.592	0.169	8.009	0.847	n.a.	n.a.
49-State Car (LEV)[d]	0.102	0.169	2.930	0.243	n.a.	n.a.

a. Based on EPA's MOBILE5a model runs assuming an annual enhanced inspection and maintenance program, federal reformulated gasoline (phase II), and temperatures corresponding to the Northeast (UCS 1994). Emissions are averaged over a 13-year lifetime, weighted by the annual mileage in each year (EPA 1994). This study did not estimate the potential for MOBILE5a to undercount real-world emissions.

b. Not available from the MOBILE5a model.

c. Base vehicle meets the current Tier I standards of the 1990 Clean Air Act Amendments.

d. 49-State Car meets the standards of California's low-emission vehicle (LEV).

Compared to the results for California, the Tier I vehicle operating in the Northeast appears to have higher emissions of all pollutants considered. The majority of the discrepancy is likely due to the different databases used by EPA and CARB to develop their emissions input data. A portion of the differences in ROG can be attributed to the slightly higher volatility of gasoline sold in the Northeast under the federal reformulated gasoline program. Other variances may stem from differences in the specific algorithms and correction factors used in each model, the mileage accumulation rates, the rate of emissions deterioration over a vehicle's life, and the assumptions regarding inspection and maintenance programs or ambient temperature. Thus, one should not compare the results of the Northeast analysis directly with the estimates developed for the Los Angeles region. Furthermore, although table B-1 presents initial estimates of the real-world emissions of vehicles operating in the South Coast Air Basin, this study did not conduct a similar assessment for the Northeast.

Emissions from Fuel Cell Vehicles

Fuel cells produce nothing but electricity and water; hydrogen FCVs are thus zero-emission vehicles. If an FCV operates on methanol, however, minor emissions will result from the storage and conversion of the fuel. Methanol reformers combust a portion of the fuel to drive the process of extracting hydrogen, and thus release small amounts of CO, ROG, and NO_x. Furthermore, like any liquid fuel, a portion of the methanol stored on board the vehicle will evaporate because of temperature changes during the day and when the vehicle is running.

Reformer Emissions

Data on the in-use emissions of a methanol reformer is scarce. The few data points that do exist are for a demonstration fuel cell bus (Patil 1991). Light-duty vehicle emissions should be similar, but not identical, because of differences in power requirements and efficiency. CARB is currently seeking more information on the in-use emissions of methanol FCVs (CARB 1995), but the bus data offers a reasonable starting point. Patil (1991) states the emissions of FCVs to be 0.002 grams per mile for nonmethane organic gases (NMOG), 2 parts per million (CO), and 0.001 grams per mile (NO_x). The NMOG and NO_x data are used directly for this analysis, but a higher value of 10 parts per million CO is used as the permissible limit for CO entering a proton-exchange-membrane (PEM) stack (to prevent poisoning the catalyst). This CO limit is converted to a per-mile value of 0.0027 grams/mile (CO) using reformate data (Virji et al. 1995).

Evaporative Emissions

Evaporative emissions from methanol FCVs are estimated by adjusting detailed data on evaporative ROG from gasoline vehicles to account for four factors: (1) the smaller fuel tank required for a methanol FCV, (2) the lower volatility of methanol, (3) the lower operating temperature of the FCV, and (4) the lower ozone-forming potential of methanol. Evaporative emissions are composed of running-loss, diurnal, hot-soak, and resting-loss emissions. The lower volatility of methanol should affect all four of these emissions categories, as the fuel evaporates at only two-thirds the rate of the most severely reformulated gasoline.[4]

The higher efficiency of fuel cells relative to internal-combustion engines means that a methanol FCV will require less fuel to travel an equivalent distance; this should translate into a smaller fuel tank. To travel roughly the same distance as a Ford Taurus-like vehicle with a 16-gallon gasoline tank, a methanol FCV would only require a 12-gallon tank (Ogden et al. 1994).[5] A smaller fuel tank should reduce diurnal, running-loss, and hot-soak emissions, since all of these relate to the fuel tank. This study estimated the combined impact of lower volatility and smaller tank volume on evaporative emissions using the regression-derived equations of Delucchi et al. (1992).

A PEM fuel cell operates at 50°–80°C (Swan et al. 1994), a temperature significantly lower than the 1000°–2000°C+ found within the cylinders of an internal-combustion engine (Heywood 1988). Although the combustion of methanol, air, and fuel-cell exhaust gas that drives the reformer results in higher temperatures than those found in the fuel cell stack, the temperatures are lower than those achieved by gasoline burning in a higher pressure internal-combustion engine. Thus, since less heat is generated in a methanol FCV, running-loss and hot-soak emissions should be lower.

This study used the regression-derived estimates of the impact of volatility, tank size, and temperature in Delucchi et al. (1992) to estimate reductions in the four major components of evaporative emissions. These reductions were then weighted by the relative contributions of running-loss, resting, hot-soak, and diurnal emissions to the total evaporative emissions budget for 2010 as determined by EMFAC/BURDEN7F modeling for the South Coast. As a final step, additional credit was taken for the lower ozone-forming potential of methanol, as measured by the reactivity adjustment factor (RAF). Table B-3 summarizes the calculation method used for evaporative emissions.

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[4] Volatility is measured in terms of the Reid Vapor Pressure (RVP) of a fuel. The RVP for methanol is 4.6 pounds per square inch (psi) (EIA 1994), compared to 7 psi for California Phase II reformulated gasoline (Calvert et al. 1993).

[5] The higher efficiency of a methanol FCV is offset by the fact that a gallon of methanol only contains half the energy of a gallon of gasoline.

Table B-3. Evaporative Emissions Calculation for Methanol FCVs

Evaporative Emissions Component	Fleet-Average Emissions Breakdown[a]	Methanol FCV vs. GV Emissions Reductions[b]
Running Losses	61 percent	-99 percent
Resting Losses	6 percent	-34 percent
Hot Soak	12 percent	-75 percent
Diurnal	21 percent	-56 percent
Total (Unadjusted)		-83 percent
Total (RAF-Adjusted)[c]		-94 percent

a. Based on EMFAC/BURDEN7F runs for the South Coast in calendar year 2010. Average is for model year 1995–2010 automobiles.

b. GV=gasoline vehicle. Emissions reductions based on smaller fuel tank, lower fuel volatility, and lower operating temperature input to regression-based estimates of evaporative emissions in Delucchi et al. (1992).

c. Reactivity adjustment factor (RAF) for pure methanol is 0.37 (Wang et al. 1993).

Given the preliminary estimates made here, a methanol FCV might have only 6 percent the evaporative emissions of a gasoline vehicle. This value can be checked by considering testing data demonstrating that a methanol internal-combustion engine vehicle (ICEV) releases 8–18 percent as many evaporative emissions as does a gasoline vehicle (Wang et al. 1993). Taking into account the factor of two (or more) increase in fuel economy for an FCV, a methanol FCV might release half as many evaporative emissions as a methanol ICEV, or 4–9 percent as many as a gasoline vehicle. The calculated value of 6 percent is within this range. Based on an estimated lifetime average emissions rate for evaporative ROG of 0.121 grams per mile for a gasoline vehicle (table B-1), the average emissions of a methanol FCV might therefore be 0.007 grams per mile.

Results Summary

Fuel cell vehicles offer substantial reductions in vehicular emissions compared to gasoline vehicles. Hydrogen FCVs emit no pollution from the tailpipe and can therefore qualify as zero-emission vehicles under the California Low-Emissions-Vehicle Program. Methanol FCVs only release small amounts of pollution from fuel evaporation and conversion, but they appear capable of meeting the proposed equivalent-ZEV (or EZEV) standards, which are currently under negotiation. The EZEV standard considers the fact that battery-powered EVs, unless recharged with renewable energy, result in small quantities of emissions. The currently proposed EZEV is based on the in-basin power plant emissions for the South Coast. The estimates of methanol FCV emissions calculated here are preliminary, but they indicate that, with some additional control of evaporative emissions, the EZEV standard is attainable.[6]

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[6] The proposed EZEV requirements are one-tenth the ULEV standard, or 0.004 grams per mile of ROG, 0.17 grams per mile of CO, and 0.02 grams per mile of NO_x.

Table B-4. Lifetime Average Emissions from Gasoline Vehicles and FCVs *(grams/mile)*

	ROG	CO	NO_x
California Gasoline Vehicle[a]			
Tier I	0.437	3.495	0.666
ULEV	0.151	1.291	0.337
Fuel Cell Vehicle			
Methanol [b]	0.007	0.003	0.001
Hydrogen	0.000	0.000	0.000

a. Calculated using California's EMFAC/BURDEN7F models (Hwang et al. 1994). Values apply to automobiles operating in the South Coast Air Basin of California.

b. Calculated from existing test data on prototype fuel cells with additional engineering analysis.

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Appendix C: Greenhouse-Gas Emissions

This appendix describes the analysis of the greenhouse-gas (GHG) emissions associated with various vehicle alternatives using the most recent version of a model developed by Delucchi (1991). Delucchi's model calculates emissions over the entire fuel cycle, including:

- feedstock extraction (e.g., oil drilling)
- feedstock transmission (e.g., crude oil tankers, barges, and pipelines)
- fuel conversion (e.g., oil refining)
- fuel distribution (e.g., gasoline pipelines, barges, and trucks)
- vehicle refueling (e.g., gasoline stations)
- vehicle use

The first five stages of the fuel cycle are considered "upstream" emissions, since they occur prior to the final end-use stage. Previous analyses have demonstrated the importance of these upstream components of the fuel cycle for alternative vehicles (Delucchi 1991; Mark et al. 1994). Accounting for GHG emissions over the entire fuel cycle is the most equitable method of comparing alternatives because, unlike local air quality, global climate change is a problem that has no geographical limits. Thus, a ton of GHGs emitted anywhere in the world ultimately affects the climate of the entire globe. A number of gases contribute to the warming of the earth's atmosphere; the most important ones are listed in table C-1. For ease of comparison, all GHG emissions are reported in terms of CO_2-equivalent emissions using the conversion factors shown in table C-1.

Table C-1. Relative Weighting of Greenhouse Gases

	Carbon Dioxide (CO_2)	Methane (CH_4)	Nitrous Oxide (N_2O)	Carbon Monoxide (CO)	Nonmethane Hydrocarbon (NMHC)	Nitrogen Oxides (NO_x)
GWP[a]	1	21	270	2	5	4

a. GWP=global-warming potential, an index developed by the Intergovernmental Panel on Climate Change (IPCC) referring to the radiative forcing of a gas relative to carbon dioxide. Thus, a ton of N_2O would have 270 times the impact on climate change as a ton of CO_2 under these GWP assumptions. The GWPs quoted here are based on the IPCC's 1992 assessment, as developed by Delucchi (1995).

Methodology

Delucchi's work is the most comprehensive analysis to date of GHG emissions in the transportation sector, and it has been widely adopted by analysts studying climate-change mitigation strategies.[1] This UCS study used the most recent version of Delucchi's model (Delucchi 1995) to estimate GHG emissions from internal-combustion-engine vehicles (ICEVs) burning gasoline and natural gas as well as from various fuel cell vehicle configurations.

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[1] For example, the recently aborted advisory committee established by the White House to develop strategies for reducing GHGs from vehicles uses Delucchi's estimates (Car Talk 1995).

This analysis makes some necessary modifications to Delucchi's GHG model to assess additional FCV options not considered in his original work and to update some of the input data on hydrogen and methanol production. The general approach of the model is to combine estimates of the amount and kind of energy used in each stage of the fuel cycle and attach emissions values to the use of that energy. This study updated Delucchi's energy inputs for hydrogen and methanol production according to the detailed thermodynamic modeling explained in Williams et al. (1994). Furthermore, this study uses a slightly higher efficiency (~25 percent) for hydrogen compression than Delucchi assumes, based on more recent work by Ogden et al. (1995).

Delucchi only considers hydrogen produced from solar- or nuclear-generated electricity. His estimates of methanol produced from natural gas and biomass serve as the basis for constructing scenarios for hydrogen produced from these sources. The conversion of natural gas to methanol differs from the natural gas-to-hydrogen process in (1) the amount and type of energy consumed, (2) the regulated air-pollutant emissions associated with the conversion, and (3) the carbon released during the process. This study adjusted Delucchi's numbers for the amount and type of energy consumed using the data in Williams et al. (1994). The regulated air-pollutant emissions resulting from converting natural gas to methanol should be similar to natural gas-hydrogen production. Emissions from methanol production are overwhelmingly dominated by the high-temperature steam reforming of natural gas (EA Mueller 1990). This study assumes that steam reforming also dominates the emissions of a hydrogen plant, since the remaining processes (water-gas shift and purification) do not require additional combustion of the feedstock. Finally, although the carbon contained in the feedstock natural gas in a methanol conversion plant ends up mostly in the fuel product (methanol), all of the carbon contained in the natural gas is stripped away during the process of generating hydrogen in a natural gas-to-hydrogen facility. The resulting GHG emissions values for the fuel conversion stage of the natural gas-to-hydrogen cycle are therefore much higher than those of any other fuel cycle (see table C-2).

Fuel-cycle emissions for the biomass-to-hydrogen pathway are derived in a manner similar to that of the natural gas-to-hydrogen pathway. Using Delucchi's estimate for biomass-to-methanol (Delucchi 1995), this study develops the biomass-to-hydrogen emissions using adjustments for the amount and type of energy used in conversion (Williams et al. 1994).

Results Summary

Table C-2 shows the final estimates of the upstream GHG emissions from various fuel and feedstock combinations. The last row of the table refers to the quantity of CO_2 released when carbon-based fuels are used in a vehicle. Taken together, the upstream GHGs and fuel-based CO_2 emissions describe the climate-change impacts of various transportation fuels. The results of this analysis highlight the large GHG emissions reductions that can ensue from the use of renewable feedstocks (wood and solar energy). A comparison of the various fuels on an equivalent energy basis shows that renewables-based fuels release 50–100 percent fewer GHG emissions than do nonrenewable fuels (table C-2).

Table C-2 also demonstrates the importance of using fuels more efficiently. An ICEV burning methanol derived from natural gas releases roughly the same amount of GHG emissions as does a gasoline ICEV if the vehicles have the same fuel economy. A methanol FCV with double or triple the efficiency of a gasoline ICEV, however, will generate one-half to one-third the emissions of a gasoline vehicle, even when the fuel is made from natural gas. The GHG emissions reductions are even greater when an FCV operating on a renewable fuel, such as biomass-methanol or solar-hydrogen, replaces a gasoline ICEV.

Table C-2. Emissions of Greenhouse Gases for Various Fuel-Feedstock Combinations

***grams(CO_2-equivalent)/mmBtu of delivered fuel*[a,b]**

Fuel ➡	Gasoline[c]	CNG[d]	— Methanol —		———— Hydrogen ————			
Feedstock ➡	*oil*	*natural gas*	*natural gas*	*wood*[e]	*natural gas*	*wood*[e]	*solar + elec.*[f]	*all solar*
Well[g]	1546	3889	3790	0	2986	0	0	0
Fertilizer[h]	0	0	0	1435	0	1191	0	0
Feed Recovery	2239	1651	4285	5751	3350	4777	0	0
Feed Transmission	1920	0	1469	2384	1148	1979	0	0
Fuel Conversion	15319	1408	18974	8157	66856	18820	0	0
Fuel Distribution	2021	7596	7496	5024	15083	15083	15083	0
Total Upstream	23045	14544	36014	22751	89423	41850	15083	0
Fuel CO_2[i]	70400	52400	63300	0	0	0	0	0

a. Based on Delucchi (1991) and Delucchi (1995), with adjustments as discussed in the text.

b. Emissions of all GHGs are weighted by their global-warming potentials to derive CO_2-equivalent values (see table C-1). mmBtu = million British Thermal Units.

c. Reformulated gasoline.

d. Compressed natural gas.

e. Wood is assumed to be produced sustainably; thus, any wood consumed in the fuel cycle produces no net increase in carbon.

f. Solar-generated hydrogen with compression using electricity from the grid (US average fuel mix).

g. Includes CO_2 from natural gas wells and gas leaks and flares.

h. Includes fertilizer manufacture and emissions from applied fertilizer in the field.

i. Based on the carbon contained in the fuel that is released upon combustion (Delucchi 1995). In the case of wood feedstocks, all carbon contained in the fuel is assumed to be produced sustainably; hence, there is no net carbon addition from the use of that fuel.

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Appendix D: Emissions Valuation

This study employs a control-cost approach to economically valuing the emissions savings of fuel cell vehicles. These costs correspond to the payments that pollution-generating activities make to comply with existing regulations and standards and, as such, represent the "opportunity" cost to industry, business, and private consumers of controlling pollution. The basis for the emissions values are the recent revisions to the Best Available Control Technology (BACT) methodology as proposed by the staff of the South Coast Air Quality Management District (SCAQMD 1995). These costs represent the average costs that polluters pay in the Los Angeles Basin to meet air-quality standards.

Base Values

Table D-1 shows the values previously used in air-quality planning in the South Coast since 1988, along with the recent revisions. The 1988 values were adopted by the California Energy Commission (CEC) and have been used in previous assessments of the benefits/costs of avoiding pollution (for example, Hwang et al. 1994; Wang and Santini 1993). SCAQMD has recently updated its values to reflect cost reductions in control technology and a revised accounting methodology. As table D-1 demonstrates, the changes in control cost for most pollutants are substantial, although it is difficult to say how much of the change reflects true cost reductions and how much is the result of the different calculation technique.

Strictly speaking, BACT values are not the correct estimates to use for valuing emission reductions, which should be calculated from the marginal cost of controlling emissions. The methodology employed by SCAQMD, however, implies that it uses control costs to derive BACT limits, and the fact that the CEC has adopted the previous BACT values suggests that they do represent a reasonable measure of control costs for this sort of study. SCAQMD uses an analysis of average control costs to determine the upper limit on what a polluter must spend to control emissions under the BACT rules. For sulfur oxides (SO_x) and particulate matter (PM_{10}), this limit is equal to the arithmetic mean of the average control costs associated with recent air-quality measures in the South Coast Air Basin. For nitrogen oxides (NO_x) and reactive organic gases (ROG), the limit is slightly higher than the mean of the average control costs. This analysis uses the latest SCAQMD BACT limits to represent the avoided cost of controlling emissions in the basin, recognizing that these may be a slight departure from a strict avoided-cost analysis. Given the fact that the previous BACT limits were adopted as avoided-cost values in past analyses, however, and recognizing the paucity of data on control costs, the updated BACT estimates are a reasonable starting point.

Table D-1. Emissions Values for Planning in the South Coast Air Basin[a]
(1994$ per Ton)[b]

	Previous Values[c]	Current Values[d]	Ratio (Current:Previous)
Reactive Organic Gases (ROG)	$22,800	$18,000	0.79
Nitrogen Oxides (NO_x)	$31,900	$17,000	0.53
Sulfur Oxides (SO_x)	$23,800	$9,000	0.38
Particulate Matter (PM_{10})	$6,900	$4,000	0.58
Carbon Monoxide (CO)	$11,200[e]	$350	0.03

a. Values are from the Best Available Control Technology assessment by the South Coast Air Quality Management District (SCAQMD 1995).

b. All values are scaled to 1994 dollars using the Chemical Engineering, Marshall & Swift Equipment Cost Index (SCAQMD 1995).

c. Based on the 1988 BACT Guidelines using the average of marginal control costs for NO_x and ROG, average of average control costs for all other pollutants. These values were adopted by the California Energy Commission (CEC 1993).

d. Values proposed by SCAQMD staff for the 1995 BACT Guidelines (SCAQMD 1995).

e. CEC's own calculations using control-cost data for the South Coast.

Adjusted Values

The most stark reduction in control-cost values occurs for CO, whose value drops by a factor of over 30. The severity of the ozone problem in the South Coast has traditionally led regulators to focus on ROG and NO_x. As a result, CO has received relatively little attention,[1] and there is less data upon which to base a control value for this pollutant. The original value of $11,200 per ton adopted by the CEC was based on its own calculation of the average cost of controlling CO in the South Coast (CEC 1993). The revised value proposed by the SCAQMD was developed based on the cost of controlling NO_x ($17,000 per ton) adjusted for the relative health impacts of CO versus NO_x as embodied by the state's one-hour air-quality standard (SCAQMD 1995). Whereas the original CO value (see table D-1) was based on the actual cost of controlling the pollutant in the South Coast, SCAQMD's revised value is founded on the relative severity of the air-quality standards. This revision is a departure from the control-cost methodology adopted by SCAQMD and CEC in its cost-benefit analyses. To maintain consistency, this study derived a CO value that reflects control costs based on the original value of $11,200 per ton. As with the other pollutants under consideration, one might expect the cost of controlling CO to have dropped slightly over the past eight years since the original data was collected (CEC 1991). To account for cost reductions and changes in SCAQMD's accounting methodology, this study adjusted the original 1988 values by the average reduction in the cost of controlling all other pollutants that SCAQMD demonstrates in its revised plan.

Control costs will vary from region to region as a result of a given area's degree of noncompliance. Los Angeles is the worst-case scenario because it has the most extreme air-quality problem of any metropolitan region. Using the original values adopted by the CEC for California, Wang and Santini (1993) constructed pollution values for three other cities based on the severity of their air-quality problem compared to California's. This study applied the Wang and Santini ratios to the new data for Los Angeles to derive estimates for control costs in New York City, as shown in table D-2.

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[1] This may also be true for particulate matter.

The values shown in table D-2 represent the *average* cost of controlling pollution, calculated as the total cost of control equipment divided by the total reduction in emissions compared to the uncontrolled case. In theory, the appropriate value to use is the *marginal* cost of controlling pollution; data does not exist, however, to allow calculation of these values. Marginal costs will be higher than average costs, and costs may well increase in the future as the least-cost solutions are exhausted in the ongoing efforts to reduce emissions further to attain air-quality standards. As a result, the true value of emissions reductions may be understated in this analysis.

Table D-2. Emissions Values for Los Angeles and New York City *(1994$ per Ton)*

	Los Angeles[a]	New York City[b]
Reactive Organic Gases (ROG)	$18,000	$17,300
Nitrogen Oxides (NO_x)	$17,000	$14,400
Sulfur Oxides (SO_x)	$9,000	$1,400
Particulate Matter (PM_{10})	$4,000	n.a.[c]
Carbon Monoxide (CO)	$6,000	$2,100

a. Values are from the Best Available Control Technology assessment by the South Coast Air Quality Management District with adjustments to CO values per discussion in the text.

b. Based on the adjustments to the California values made by Wang and Santini (1993) that account for differences in air-pollution severity in New York versus California.

c. Data not available.

Per-Vehicle Benefits

The value of emissions savings from deploying a fuel cell vehicle is calculated by combining the difference in emissions over the lifetime of an FCV versus a gasoline vehicle (discussed in appendix B) with the economic value of avoiding pollution estimated here. The calculation takes the net present value of the stream of emissions saved over the 13-year life span of an FCV multiplied by the economic value of those reductions.[2] Although not detailed in appendix A (which shows average lifetime emission rates), the calculation of emissions savings takes into account differences in mileage accumulation and emissions rates over the life of a vehicle, so that savings are not identical for each year of a vehicle's life.[3] The results of the calculation for the South Coast Air Basin and New York City are shown in table D-3.

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[2] A 4 percent annual discount rate is used, per SCAQMD guidance (SCAQMD 1995).

[3] See Hwang et al. (1994) for details.

Table D-3. Value of Emissions Savings from Fuel Cell Vehicles[a] *(1994$)*

	Los Angeles		New York City	
	modeled[b] emissions	*real-world[c] emissions*	*modeled[d] emissions*	*real-world[e] emissions*
Replaces Base GV[f]	$5,090	$8,350	$4,280	n.e.[g]
Replaces ULEV[h]	$2,060	$3,250	n.e.	n.e.
Replaces National LEV[i]	n.e.	n.e.	$1,480	n.e.

a. Net present value of emissions saved over the lifetime of a vehicle combined with emissions values in table D-2. Discount rate is 4 percent/year, per SCAQMD (1995).

b. Based on EMFAC/BURDEN7F model runs.

c. Estimated real-world emissions savings from adjustments to EMFAC/BURDEN7F, as discussed in appendix B.

d. Based on MOBILE5a model runs.

e. Real-world emissions not estimated for MOBILE5a in this study.

f. Base gasoline vehicle meeting the federal Tier I emissions requirements.

g. Not estimated.

h. Ultra-low-emission vehicle.

i. National low-emission vehicle.

References for Appendix D

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UNION OF
CONCERNED
SCIENTISTS

UCS Headquarters
Two Brattle Square
PO Box 9105
Cambridge, MA 02238-9105
617-547-5552

Transportation Policy Program
2397 Shattuck Avenue, Suite 203
Berkeley, CA 94704
510-843-1872