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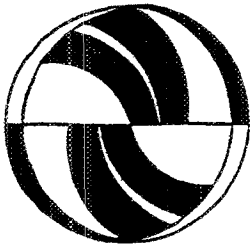
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The Case for Electric Vehicles

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The Case for Electric Vehicles

New technological developments have put practical electric cars within reach, but politics may slow the shift away from internal-combustion engines

by Daniel Sperling

Cars account for half the oil consumed in the U.S., about half the urban pollution and one fourth the greenhouse gases. They take a similar toll of resources in other industrial nations and in the cities of the developing world. As vehicle use continues to increase in the coming decade, the U.S. and other countries will have to address these issues or else face unacceptable economic, health-related and political costs. It is unlikely that oil prices will remain at their current low level or that other nations will accept a large and growing U.S. contribution to global climatic change.

Policymakers and industry have four options: reduce vehicle use, increase the efficiency and reduce the emissions of conventional gasoline-powered vehicles, switch to less noxious fuels, or find less polluting propulsion systems. The last of these—in particular the introduction of vehicles powered by electricity—is ultimately the only sustainable option. The other alternatives are attractive in theory but in practice are either impractical or offer only marginal improvements. For example, reduced vehicle use could solve congestion woes and a host of social and environmental problems, but evidence from around the world suggests that it is very difficult to make people give up their cars to any significant extent. In the U.S., mass-transit ridership and carpooling have declined since World War II. Even in western Europe, with fuel prices averaging more than \$1 a liter (about \$4 a gallon) and with pervasive mass transit and dense populations, cars still account for 80 percent of all passenger travel.

Improved energy efficiency is also appealing, but automotive fuel economy has barely budged in 10 years. Alternative fuels such as methanol or natural gas, burned in internal-combustion en-

gines, could be introduced at relatively low cost, but they would lead to only marginal reductions in pollution and greenhouse emissions (especially because oil companies are already spending billions of dollars every year to develop less polluting formulations of gasoline).

Electric-drive vehicles (those whose wheels are turned by electric motors rather than by a mechanical gasoline-powered drivetrain) could reduce urban pollution and greenhouse emissions significantly over the coming decade. And they could lay a foundation for a transportation system that would ultimately be almost pollution-free. Although electrically driven vehicles have a history as old as that of the internal-combustion engine, a number of recent technological developments—including by-products of both the computer revolution and the Strategic Defense Initiative (SDI) in the 1980s—promise to make this form of transportation efficient and inexpensive enough to compete with gasoline. Overcoming the entrenched advantages of gas-powered cars, however, will require a concerted effort on the parts of industry and government to make sure that the environmental benefits accruing from electric cars return to consumers as concrete incentives for purchase.

Efficiency Improves

The term “electric-drive vehicle” includes not only those cars powered by batteries charged with household current but also vehicles that generate electricity onboard or store it in devices other than batteries. Their common denominator is an efficient electric motor that drives the wheels and extracts energy from the car’s motion when it slows down. Internal-combustion vehicles, in contrast, employ a constantly running engine whose power is diverted through



a series of gears and clutches to drive the wheels and to turn a generator for the various electrically powered accessories in the car

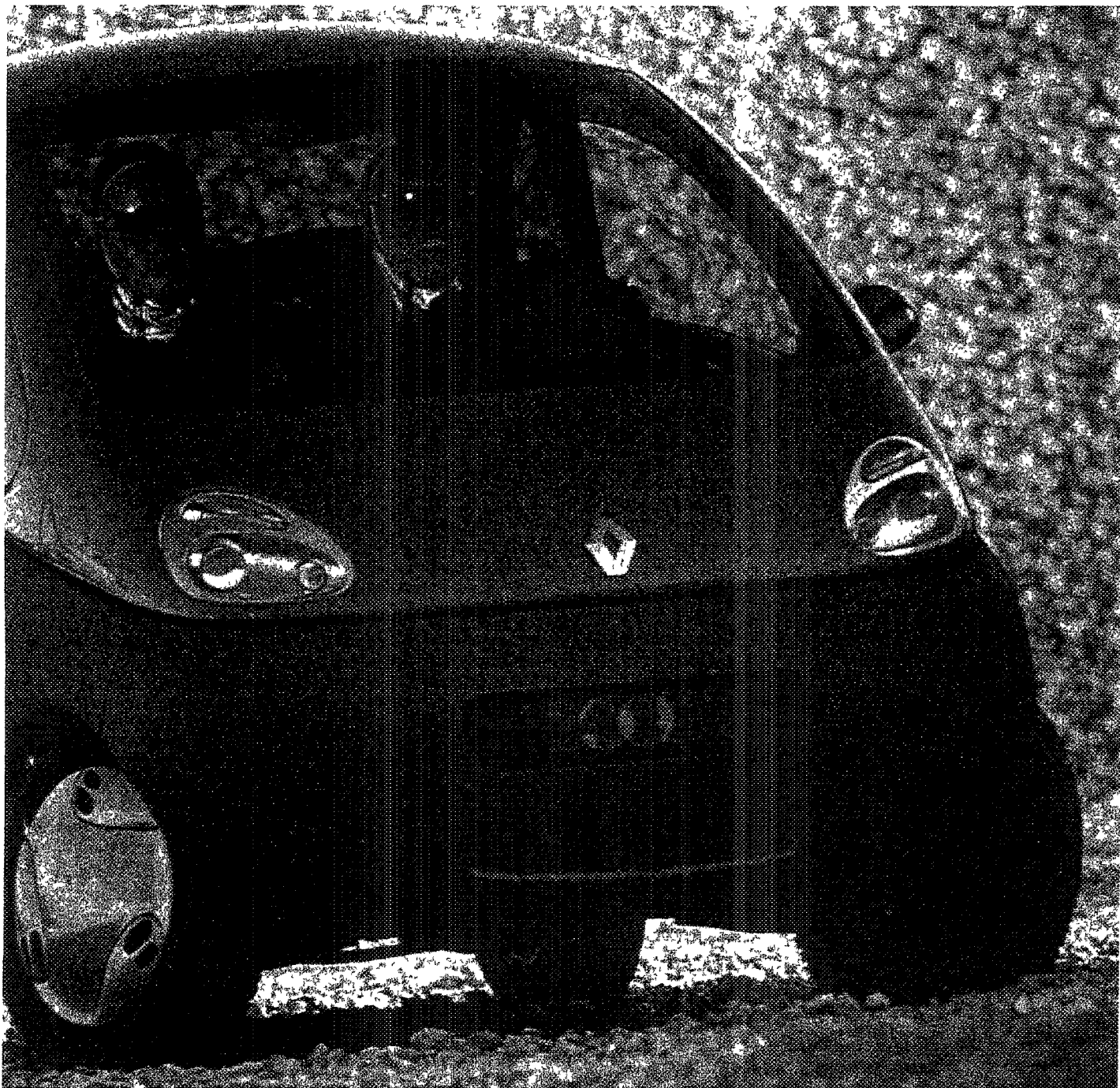
Electric vehicles are more efficient—and thus generally less polluting—than internal-combustion vehicles for a variety of reasons. First, because the electric motor is directly connected to the wheels, it consumes no energy while the car is at rest or coasting, increasing the effective efficiency by roughly one fifth. Regenerative braking schemes—which employ the motor as a generator when

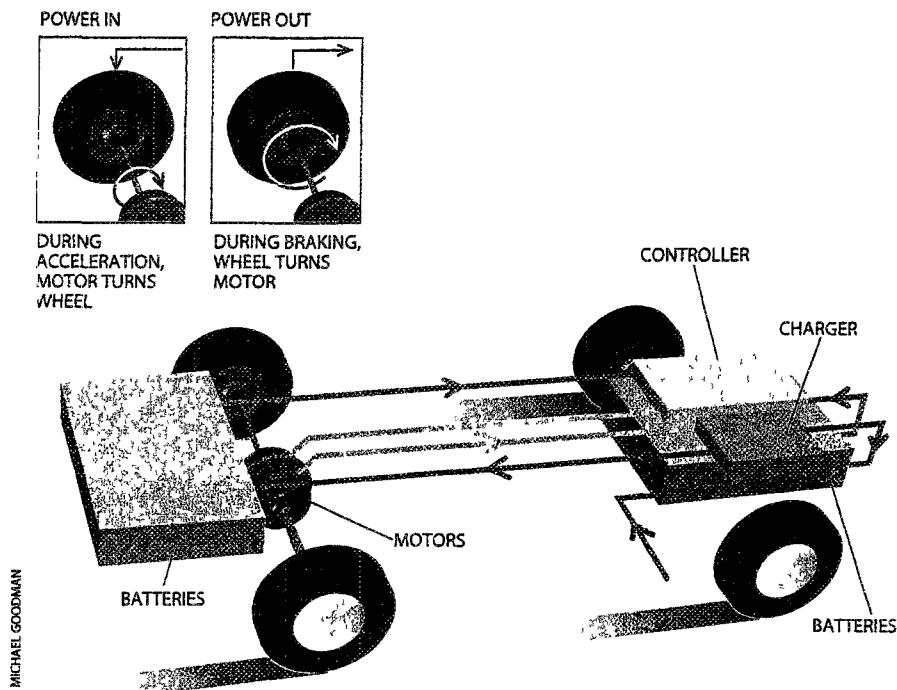
the car is slowing down—can return as much as half an electric vehicle's kinetic energy to the storage cells, giving it a major advantage in stop-and-go urban traffic.

Furthermore, the motor converts more than 90 percent of the energy in its storage cells to motive force, whereas internal-combustion drives utilize less than

25 percent of the energy in a liter of gasoline. Although the storage cells are typically charged by an electricity-generating system, the efficiency of which averages only 33 percent, an electric drive still has a significant 5 percent net advantage over internal combustion. Innovations such as combined-cycle generation (which extracts additional ener-

ELECTRIC VEHICLE built by Renault is made from lightweight components that reduce the load its motor must carry. Short-range "urban vehicles" may be one market niche particularly suited to the characteristics of electric cars.





KEY COMPONENTS of an electric vehicle are energy storage cells, a power controller and motors. Transmission of energy in electrical form eliminates the need for a mechanical drivetrain. Regenerative braking (*inset*) uses the motor as a generator, feeding energy back to the storage system each time the brakes are used.

gy from the exhaust heat of a conventional power plant) will soon make it possible for the utility power plants from which the storage cells are charged to raise their efficiency to as much as 50 percent. This boost would increase proportionately the fraction of energy ultimately delivered to the wheels of an electric vehicle. Fuel cells, which “burn” hydrogen to generate electricity directly onboard an electric car, are even more efficient.

Further air-quality benefits derive from electric drives because they shift the location from which pollutants disperse. Conventional cars emit carbon monoxide and other pollutants from their tailpipes wherever they travel, whereas pollution associated with electric power generation is generally located at a few coal- or oil-burning plants at a distance from urban centers.

Battery-powered electric vehicles would practically eliminate emissions of carbon monoxide and volatile unburned hydrocarbons and would greatly diminish nitrogen oxide emissions. In areas served by dirty coal-fired power plants, they might marginally increase the emissions of sulfur oxides and particulate matter. Pollution associated with the modern manufacture of batteries and

electric motors is negligible, however.

Hybrid vehicles (those combining small internal-combustion engines with electric motors and electricity storage devices) will reduce emissions almost as much as battery-powered electric vehicles; indeed, in regions where most electricity is generated with coal, hybrids may prove preferable. The impact of electric vehicles on air pollution would be most beneficial, of course, where electricity is derived from nonpolluting solar, nuclear, wind or hydroelectric power. Among the chief beneficiaries would be California, where most electricity comes from tightly controlled natural gas plants and zero-emission hydroelectric and nuclear plants, and France, where most electricity comes from nuclear power.

These environmental benefits could be very important. Many metropolitan areas in the U.S. have air significantly more polluted than allowed by health-based air-quality standards, and most will continue to be in violation of the law in the year 2000. Pollution in Los Angeles is so severe that even if every vehicle were to disappear from its streets, the city would have no chance of meeting the standards. Many other regions in this country have little prospect of

meeting their legal mandates, even with much cleaner-burning gasoline and improved internal-combustion engines. And elsewhere in the world, in cities such as Bangkok, Kathmandu and Mexico City, air pollution is more severe than in Los Angeles.

Energy Storage Is the Key

Electric vehicles now on the market rely on lead-acid batteries charged from a standard wall plug. They are unlikely ever to take the market by storm. Not only are lead-acid batteries expensive and bulky, they can drive a car little more than 150 kilometers between charges. This problem, however, is often overstated. First, there appears to be a significant market for short-range vehicles; second, new energy storage devices are even now making the transition from laboratory to production line.

A regional survey that my colleagues at the University of California at Davis and I conducted suggests that about half of all households owning more than one car—the majority of U.S. households, accounting for more than 70 percent of new car purchases—could easily adapt their driving patterns to make use of a second car with a range of less than 180 kilometers. Many respondents indicated a willingness to accept even much shorter ranges. Environmental benefits and the advantage of home recharging (many people actively dislike refueling at gasoline stations) compensate for the limited range.

Batteries are likely to play a diminishing role in electric vehicles. Among the replacements now being developed are ultracapacitors, which store large amounts of electricity and can charge and discharge quickly, flywheels, which store energy in a spinning rotor; and fuel cells, which convert chemical fuel into electricity, emitting water vapor.

Ultracapacitors owe much of their early development to the SDI's ballistic-missile defense program. Advanced manufacturing techniques can eliminate the tiny imperfections in a conventional capacitor's insulating film that allow charge to leak away. New materials make it possible to interleave a capacitor's carbon and liquid electrolyte much more finely than before. As a result, ultracapacitors can store about 15 watt-hours (enough energy to run a one-horsepower motor for about a minute) in a one-liter volume, and a one-liter device

can discharge at a rate of three kilowatts. Ultracapacitors are already available in small units for calculators, watches and electric razors.

Flywheels first saw use in transportation in the 1950s. Flywheel-powered buses traveled the streets of Yverdon, Switzerland, revving up their rotors at every stop. Since then, designs have changed substantially: now composite rotors spin at up to 100,000 revolutions per second, a speed limited only by the tensile strength of their rims. Magnetic bearings have reduced friction so that a rotor can maintain 90 percent of its energy for four days. The first high-powered ultracapacitors and flywheels are likely to appear in commercial vehicles around the year 2000. Because they can provide power very rapidly, they will be paired with batteries—the batteries will supply basic driving needs, and the capacitors or flywheels will handle peak requirements when the car accelerates or climbs a hill. This combination will allow the use of smaller battery packs and extend their service life.

Even the most optimistic projections for advanced energy storage technologies still do not compare with the 2,100 kilojoules stored in a 38-liter (10-gallon) tank of gasoline, for this reason, many researchers have predicted that the most popular electric-drive vehicles will be hybrids—propelled by electric motors but ultimately powered by small internal-combustion engines that charge batteries, capacitors or other power sources. The average power required for highway driving is only about 10 kilowatts for a typical passenger car, so the engine can be quite small, the storage cells charge during periods of minimal output and discharge rapidly for acceleration. Internal-combustion engines can reach efficiencies as high as 40 percent if operated at a constant speed, and so the overall efficiency of a hybrid vehicle can be even better than that of a pure electric drive.

Perhaps the most promising option involves fuel cells. Many researchers see them as the most likely successor to the internal-combustion engine, and they are a centerpiece of the ongoing Partnership for a New Generation of Vehicles, a collaboration between the federal government and the Big Three automakers. Fuel cells burn hydrogen to produce water vapor and carbon dioxide, emitting essentially no other effluents as they generate electricity. (Modified

versions may also use other fuels, including natural gas, methane or gasoline, at a cost in increased emissions and reduced efficiency.) Although the devices are best known as power sources for spacecraft, an early fuel cell found its way into an experimental farm tractor in 1959. Prototype fuel-cell buses built in the mid-1990s have demonstrated that the technology is workable, but cost is still the most critical issue. Proton-exchange membrane (PEM) fuel cells, currently the most attractive for vehicular use, cost more than \$100,000 per kilowatt only a few years ago but are expected to cost only a few thousand dollars after the turn of the century and perhaps \$100 a kilowatt or less—competitive with the cost of internal-combustion engines—in full-production volumes. Daimler-Benz announced in July that it could start selling fuel cell-equipped Mercedes cars as soon as 2006.

Sustainable Transportation

Fuel cells will generally be the least polluting of any method for producing motive power for vehicles. Furthermore, the ideal fuel for fuel cells, from both a technical and environmental perspective, is hydrogen. Hydrogen can be made from many different sources, but when fossil fuels become more scarce and expensive, hydrogen will most likely be made from water using solar cells. If solar hydrogen were widely adopted, the entire transportation-energy system

would be nearly benign environmentally, and the energy would be fully renewable. The price of such renewable hydrogen fuel should not exceed even a dollar for the equivalent of a liter of gasoline.

In addition to the power source, progress in aspects of electric vehicle technology has accelerated in recent years. A technological revolution—in electricity storage and conversion devices, electronic controls, software and materials—is opening up many new opportunities. For example, advances in power electronics have led to drivetrains that weigh and cost only 40 percent of what their counterparts did a decade ago. Until the early 1990s, virtually all electric vehicles depended on direct-current motors because those were easiest to run from batteries. But the development of small, lightweight inverters (devices that convert direct current from a battery to the alternating current that is most efficient for running a motor) makes it possible to abandon DC. AC motors are more reliable, easier to maintain and more efficient than their DC counterparts, they are also easier to adapt to regenerative braking. Indeed, the electric-vehicle motor and power electronics together are now smaller, lighter and cheaper to manufacture than a comparable internal-combustion engine.

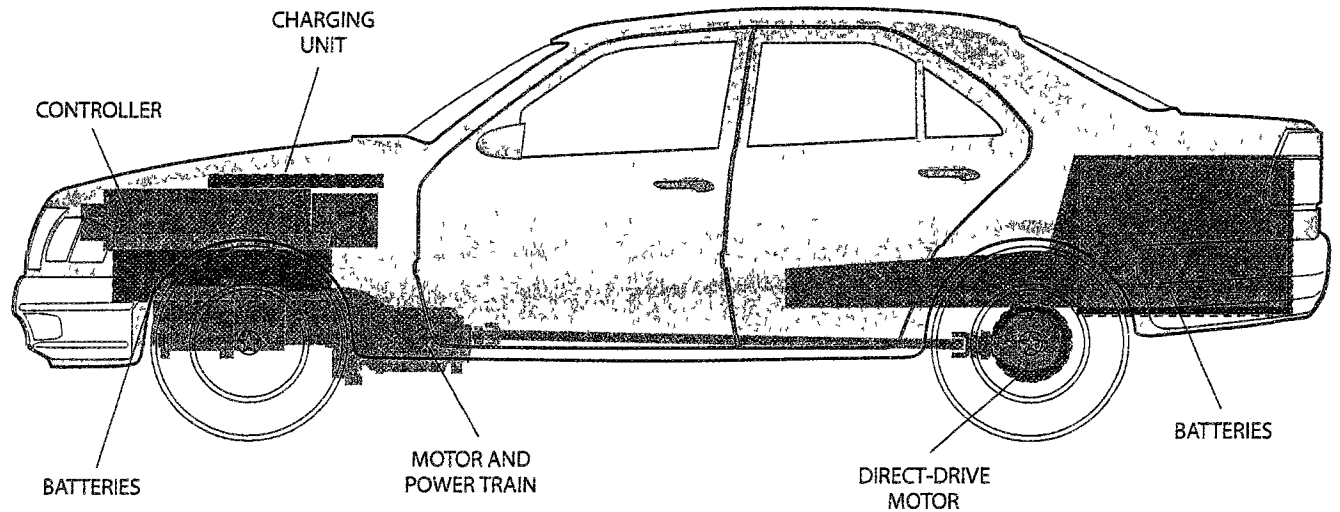
Every major automaker in the world is now investing in electric vehicle development as well as improvements in less critical technologies such as those underlying car heaters and tires. The re-

Electric Vehicles Reduce Pollution (Percentage Change in Emissions)

FRANCE	-99	-99	-91	-58	-59
GERMANY	-98	-99	-66	+96	-96
JAPAN	-99	-99	-66	-40	-10
U.K.	-98	-99	-34	+407	+165
U.S.	-96	-99	-67	+203	+122
CALIFORNIA	-96	-97	-75	-24	+15

SOURCES: Choosing an Alternative Fuel: Air Pollution and Greenhouse Gas Impacts (OECD, Paris, 1993). U.S. estimates are from Q. Wang, M. DeLuchi and D. Sperling, "Emission Impacts of Electric Vehicles," Journal of the Air and Waste Management Association, Vol. 40, No. 9, pages 1275-1284, September 1990.

BATTERY-POWERED electric cars, if they were accepted universally, would slash production of major urban pollutants, according to simulations. Pollution from power plants, however, would in some cases partially offset these gains or even increase certain kinds of pollution, especially in countries (such as the U.K. and the U.S.) that rely heavily on coal and oil.



MICHAEL GOODMAN

MINIATURIZATION of electronics and advances in batteries and motors have cut the weight of electric-vehicle storage cells and drive components by as much as 60 percent during the past 10 years (older devices are shown in gray in the schematic above,

newer ones in dark green and the overlap in light green). This reduction has in turn decreased the weight required for the car's suspension and structural components, making it possible to achieve equivalent performance with even smaller components.

sulting advanced components will be the building blocks for very clean and efficient vehicles of the future, but in the meantime many of them are finding their way into internal-combustion vehicles.

Although automakers worldwide have spent perhaps \$1 billion on electric vehicles during the 1990s, in the context of the industry as a whole this investment is relatively small. The auto industry spends more than \$5 billion a year in the U.S. alone on advertising and more than that on research and development. And oil companies are spending about \$10 billion in the U.S. this decade just to upgrade refineries to produce reformulated low-emission gasoline.

Much of the investment made so far has been in response to governmental pressure. In 1990 California adopted a zero-emission vehicle (ZEV) mandate requiring that major automakers make at least 2 percent of their vehicles emission-free by 1998, 5 percent by 2001 and 10 percent by 2003. (These percentages correspond to the production of about 20,000 vehicles a year by 1998.) Failure to meet the quota would lead to a penalty of \$5,000 for every ZEV not available for sale. New York State and Massachusetts enacted similar rules shortly thereafter.

The major automakers aggressively opposed the ZEV mandate but rapidly expanded their electric-vehicle R&D programs to guard against the possibility that their regulatory counterattack

might fail—and that markets for electric cars might actually emerge either in the U.S. or abroad. Their loudest complaint was that the rules forced industry to supply an expensive product without providing consumers with an incentive to buy them—even though local, state and federal governments were enacting precisely such incentives.

This past March California regulators gave in to pressure from both the automobile and oil industries and eliminated the quotas for 1998 and 2001, leaving only a commitment to begin selling electric vehicles and the final goal for 2003. Industry analysts expect that U.S. sales will be no more than 5,000 vehicles total until after the turn of the century.

One crucial factor in determining the success of electric vehicles is their price—a figure that is still highly uncertain. General Motors's newly introduced EV1 is nominally priced at \$33,000; Solectria sells its low-volume-production electric vehicles for between \$30,000 and \$75,000, depending on the battery configuration. (Nickel-metal hydride batteries capable of carrying the car more than 320 kilometers add nearly \$40,000 to the price of a lead-battery vehicle.) The adversarial nature of the regulatory process has encouraged opponents and proponents to make unrealistically high or low estimates, so it will be impossible to tell just how much the vehicles will cost until they are in mass production. Comparisons with the price histo-

ry of other products, including conventional automobiles, however, suggest that full-scale production could reduce prices to significantly less than half their present level [see illustration on opposite page].

An Uncertain Road

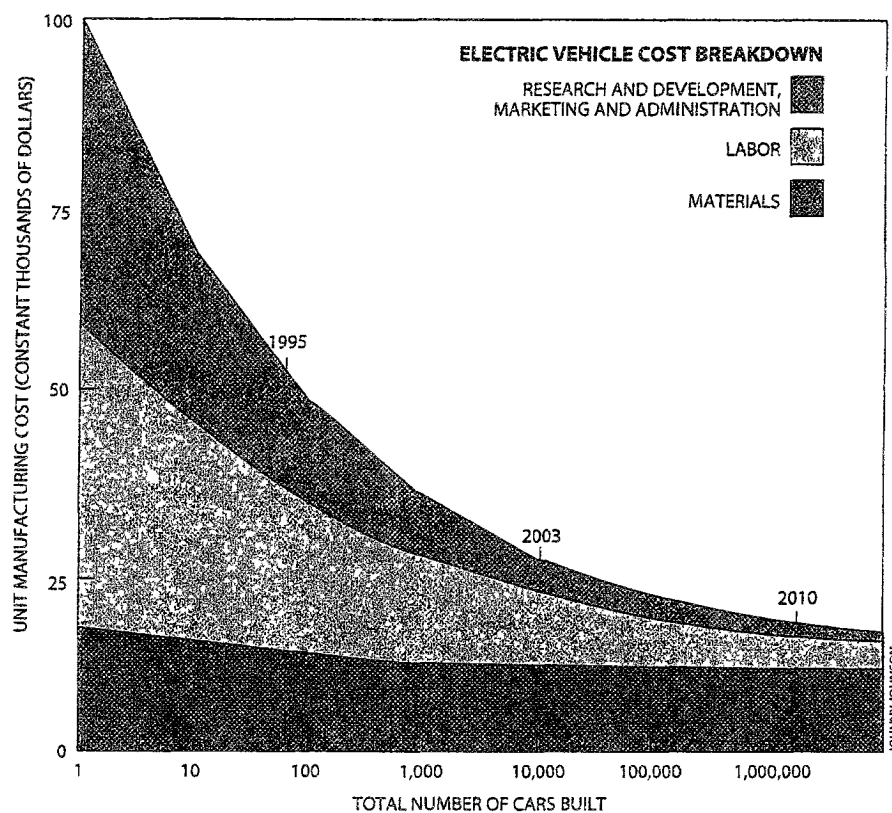
Faced with the inevitability of electric vehicle production, automakers are devising strategies to produce them inexpensively. Many (including Peugeot in Europe) are simply removing engines, gas tanks and transmissions from the bodies of existing gasoline vehicles and inserting batteries, controllers and electric motors with minimal modification. Others, including Ford, are selling "gliders" (car bodies with no installed drive components) to smaller conversion companies that then fit them with an electric drive. A third strategy is to build very small vehicles, such as the Mercedes Smart—known popularly as the Swatchmobile—targeted at the emerging market niche for limited-range urban vehicles. Of all the major manufacturers, only General Motors has thus far committed to mass production of an ordinary car designed from the ground up for electric drive.

The cost of batteries (and fuel cells) will probably always render electric vehicles more expensive to purchase than comparable gasoline vehicles. On a per-kilometer basis, however, the cost of an

electric and internal-combustion vehicle should eventually be about the same. Fuel for electric vehicles is inexpensive, maintenance is minimal, and it appears that electric motors last significantly longer than gasoline engines. Taking into account the cost of air pollution, greenhouse gases and other market externalities (that is, factors that society at large must now pay for) would tip the scale in favor of electric vehicles in many circumstances.

The challenge for policymakers and marketers is to assure that consumers take into account these full costs, a goal that has thus far been difficult to pursue. In California, where powerful air-quality regulators have led the way toward electric vehicles, progress has been slowed by opposition from both auto manufacturers and oil companies. On a national level, early hopes for the Partnership for a New Generation of Vehicles have foundered on inadequate funding, political infighting and excessive caution. As a result of this internal conflict, vehicles to be built in 2004 will ostensibly have their designs set in 1997, making it likely that the partnership will embrace only the smallest of incremental improvements rather than spearheading the introduction of fuel cells and other radically new technologies.

Nevertheless, it seems certain that electric-drive technology will eventually supplant internal-combustion engines—perhaps not quickly, uniformly nor entirely—but inevitably. The question is when, in what form and how to manage the transition. Perhaps the most important lesson learned from the current state of affairs is that government should do what it does best, provide broad market incentives that bring external costs such as pollution back into the economic calculations of consumers and corporations,



ECONOMIES OF SCALE should enable manufacturers to reduce the prices of electric vehicles once production volumes increase beyond their current level of a few vehicles a day. Eventually the cost of materials will dominate the total cost of electric vehicles. (These estimates are derived from experience with conventional vehicle manufacturing, in which a typical factory produces 100,000 or more vehicles a year.)

and target money at innovative, leading-edge technologies rather than fund work that private companies would be doing in any case.

The emergence of electric vehicles has important economic implications. Whoever pioneers the commercialization of cost-competitive electric vehicle technologies will find inviting export markets around the world. Electric vehicles will be attractive where pollution is se-

vere and intractable, peak vehicle performance is less highly valued than reliability and low maintenance, cheap electricity is available off-peak, and investments in oil distribution are small. Indeed, if the U.S. and other major industrial nations do not act, it is quite possible that the next generation of corporate automotive giants may arise in developing countries, where cars are relatively scarce today. ■

The Author

DANIEL SPERLING is director of the Institute of Transportation Studies at the University of California, Davis, where he is also professor of civil engineering and environmental studies. He has written two books and more than 100 articles about electric vehicles and other environmental issues in transportation. Sperling chairs a National Research Council committee on alternative transportation fuels. He is also a member of the National Academy of Sciences committee on transportation and a sustainable environment.

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