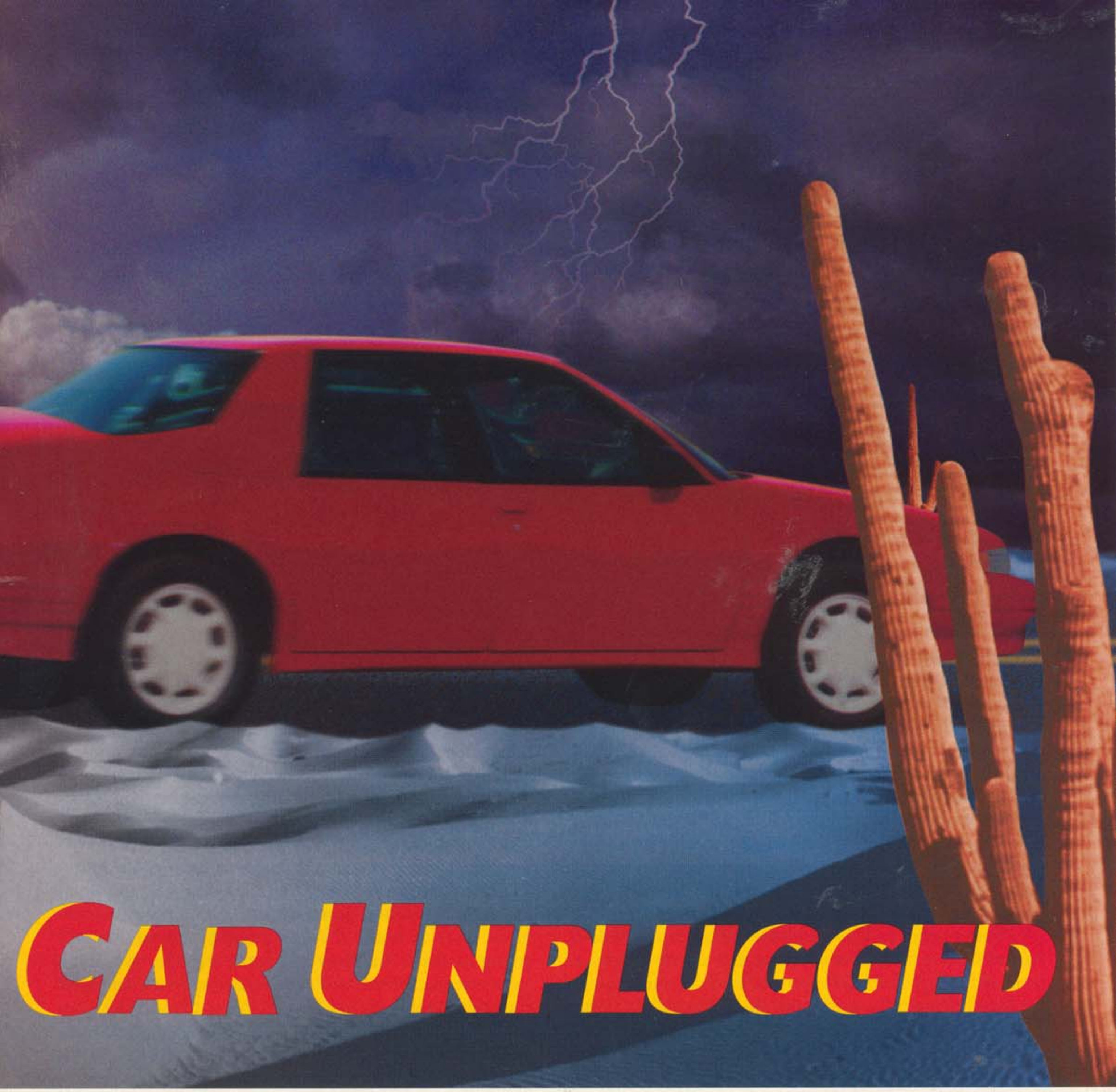
THE ELECTRIC

***L**ooking under the hood, a team of experts says the electric vehicles being developed today are inadequate and expensive and won't even notably improve air quality. So why are California and other states mandating that they be sold by 1998?*

ILLUSTRATIONS BY ROB SCHUSTER



CAR UNPLUGGED

To comply with the federal Clean Air Act of 1990, the California Air Resources Board has ruled that, by 1998, 2 percent of all vehicles offered for sale in the state must be so-called zero-emission vehicles. As a practical matter, California has mandated electric vehicles—the only available technology meeting the requirement that the power train produce no emissions. Two other states have followed suit. By 2003, roughly 10 percent of all new personal vehicles sold in California, Massachusetts, and New York must be electric.

The aim of these programs—to combat the smog that engulfs

BY RICHARD DE NEUFVILLE, STEPHEN R. CONNORS, FRANK R. FIELD III, DAVID MARKS, DONALD R. SADOWAY, AND RICHARD D. TABORS

Los Angeles and other cities—is worthy. Even the programs' focus on cars is appropriate because there is little question that auto emissions contribute greatly to urban air pollution. Unfortunately, however, the electric vehicle is not yet ready for large-scale commercial use. No such vehicle now sold meets the demands of a consumer market for road transport.

Highway-worthy electric vehicles for mass consumption have neither been produced nor tested in significant volumes over the range of likely driving conditions. Their reliability over a standard warranty period, such as 3 years and 50,000 miles, is unknown. Electric vehicles for actual road use are still highly experimental.

The mandate to produce and sell a significant number of electric vehicles thus needs careful scrutiny. The measure is unprecedented. Previous environmental mandates, such as the Clean Water Act, required the public to adopt the best available technology—whatever that turned out to be in different cases—for reducing pollution. The California rules, however, require a specific experimental technology, and mandate a tight schedule.

The effort to pursue electric vehicles on a large scale is also uniquely American. Britain uses electric vehicles for milk delivery, France has proposed pilot production of special urban vehicles, and the German Post Office wants to operate about a hundred delivery vans in the years ahead. In addition, Volkswagen has recently started to produce electric-powered Golf sedans at the rate of about one per day. But despite this interest in electric vehicles, the existing programs in other countries are orders of magnitude smaller than what is required by the California rules, which aim for manufacturers to sell some 18,000 electric vehicles in 1998 (some 2 percent of the 906,000 new cars registered in California in 1994).

Meanwhile, in the United States, the program to develop electric vehicles has already proved expensive. Ford and General Motors alone have reportedly spent hundreds of millions of dollars on R&D, and federal and state agencies have sponsored a wide range of demonstration programs. The budget for the U.S. Advanced Battery Consortium alone (an alliance of the U. S. Department of Energy, the Big Three automobile manufacturers, the Electric Power Research Institute, Southern California Edison, and others to develop batteries for the vehicles) is $260 million. In fact, the cumulative cost of research on electric vehicles in the United States is approaching $1 billion, roughly equal to half of the National Science Foundation's entire research budget.

The authors, none of whom has a financial stake in the development of electric or conventional vehicles, are all based at MIT. RICHARD DE NEUFVILLE *chairs the Technology and Policy Program and specializes in analyzing transportation systems.* STEPHEN R. CONNORS *directs the Energy Laboratory's Electric Utility Program.* FRANK R. FIELD III *heads the Materials Systems Laboratory, which has analyzed the cost of producing automobiles for more than a decade.* DAVID MARKS *directs the Program in Environmental Engineering Education and Research.* DONALD R. SADOWAY *is an electrochemist in the Department of Materials Science and Engineering. And* RICHARD D. TABORS *is associate director of the Laboratory for Electronics and Electromagnetic Systems.*

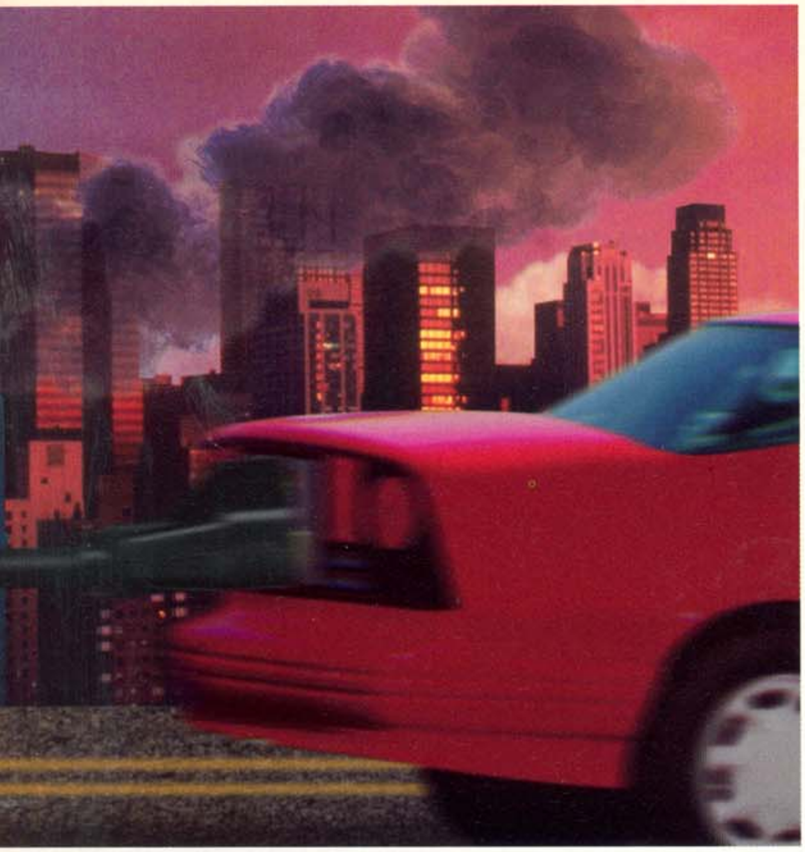
By any measure then, the commitment to manufacture and sell electric vehicles in large volume is a major piece of national industrial policy that aims to substantially reduce the nation's transportation and pollution problems. One supposes that such a mandate would have been preceded by a comprehensive analysis. Yet no investigation of the overall performance or effectiveness of electric vehicles—either by themselves or compared with alternatives—has been undertaken. Our research group found that available material either deals with just one element of the system, such as batteries, or is obviously partisan, coming from enthusiasts—such as electric vehicle makers, battery suppliers, or electric utilities—with a stake in the outcome.

To address this gap, our team assessed the total environmental and economic effects of the manufacture and use of electric vehicles made with different materials and powered by many types of batteries. We also attempted to compare the electric-car mandate to alternative systems for reducing air pollution.

In our judgment, the electric vehicle policy defined by the California Air Resources Board is neither cost-effective nor practical. Electric vehicles will not contribute meaningfully to cleaner air if they are introduced as now proposed; over the next decade their effect will be imperceptible compared with other major improvements in automotive and other combustion technologies. Furthermore, even if it could be justified on environmental grounds, the technology of electric vehicles is still far from meeting the needs of a mass consumer market and it is unclear when, if ever, it will do so. Finally, the projected costs of implementing the California electric vehicle policy are enormous, requiring subsidies as high as $10,000 to $20,000 per vehicle.

Displacing Emissions

Because conventional cars and trucks create significant emissions, the use of electric vehicles sounds like a good way to combat air pollution. But because producing electricity also creates pollution, electric vehicles do not eliminate emissions—they simply move them elsewhere. Unless this electricity comes from nuclear power plants (neither environmentally acceptable nor economically feasible right now) or renewable sources (unlikely to be sufficient), the power to propel electric vehicles will come



Generating the electricity needed to run electric vehicles will worsen air quality in regions downwind of fossil fuel-burning power plants.

from burning fossil fuels. But using fossil fuels to power electric vehicles is doubly pernicious. The fuel loses up to 65 percent of its energy when it is burned to produce electricity; 5 to 10 percent of what is left is lost in transmitting and distributing the electricity before it even gets to the electric car.

Of course, moving pollutant emissions elsewhere could arguably be worthwhile, but such a policy needs to be considered carefully. For regions upwind of power plants, electric vehicles would obviously reduce local pollution. Los Angeles, for instance, obtains part of its electric power from coal plants in the Four Corners region (where Arizona, Colorado, New Mexico, and Utah meet). Adopting electric vehicles in Los Angeles therefore simply increases pollution over large expanses of the Southwest.

Meanwhile, regions downwind of fossil fuel-burning power plants, such as Boston and the Northeast seaboard generally, will not escape the pollution produced by generating electricity for electric vehicles, which may be substantial. What's more, many discussions of electric vehicles have supposed that the plants used to create the extra power would be clean and inexpensive, since the electric cars would mostly be recharged "off peak." But this is unlikely to be the case. Much of the power from the cleanest and least expensive plants is already in use today even during off-peak hours; supplying the additional loads will inevitably require using older, dirtier, and less efficient facilities.

Even in areas where electric cars may lower urban air pollution, the great effort to get them on the road may not perceptibly improve the environment. For the past decade, new vehicles have met more stringent pollution standards, and the upgrading of the fleet has cut total U.S. automotive emissions dramatically. Even without electric vehicles, the fleet of cars now on the road will be almost completely renewed in this decade and thus the average emissions from cars will be almost halved. Ironically, the environmental benefit of each electric vehicle would be particularly small in the years ahead because it would substitute for another brand-new vehicle that will be far cleaner than the current average.

The schedule for the introduction of new electric vehicles implies that only about 4 percent of the total fleet in California, Massachusetts, and New York will be electric by the year 2005, and about 10 percent by the year 2015, some 20 years from now. And improvement will not be immediate: since only about 10 percent of the automotive fleet is renewed each year in the United States, it takes about a decade for the percentage of electric vehicles on the road to match the percentage of those sold each year. Thus given the small percentages involved and the long delays, electric vehicles will have only a modest effect on overall automotive pollution. This is true of any policy that imposes marginal improvements on a small fraction of the cars on the road. The important effects result from changes to the entire fleet. Thus the requirement that all cars use catalytic converters to limit carbon monoxide emissions improved air quality significantly, but the California mandate to introduce electric vehicles will not.

Not Ready for the Road

Many developers have demonstrated electric vehicles with adequate power and speed. Ford and General Motors each have a version that accelerates easily into freeway traffic and can cruise comfortably at the speed limit. The trouble is that these vehicles cannot sustain this performance for very long.

Range of travel is the major concern for electric vehicles. The technological question is whether it will be possible, at reasonable cost, to design vehicles that can reliably travel some 100 to 150 miles, in normal traffic, before their batteries must be recharged. This design range represents a round-trip distance from home to work plus an allowance for errands and safety. The implied commuting distance of 30 to 50 miles is high but appropriate for Los Angeles, New York, and Boston, the prime target areas today.

The desirable range is difficult to achieve in practice. A recent test of available models of electric vehicles conducted by the Environmental Protection Agency found actual driving ranges between 30 and 50 miles per battery charge. Driving on city streets involves stopping, waiting in traffic jams, starting, and constant changes in acceleration to cope with hills and variations in the speed of traffic—all factors that reduce the range that can be attained. Driving to work must also be done in cold weather when batteries tend to perform poorly. And in winter in Massachusetts and New York, as much energy will be needed to heat a car while it is being operated as to drive it—effectively cutting the electric vehicle's range in half. (This is vividly illustrated by the fact that Ford's electric "zero pollution" vehicle actually includes a diesel heater complete with tailpipe!) Of course, driving also requires lights and windshield wipers which use energy and further reduce the maximum practical range. Thus, record-breaking results occasionally reported in the press do not fairly represent what everyday drivers of electric vehicles may experience. What a professional test driver can achieve operating under optimal conditions on a flat track with no passengers or loads in no way compares with the range an ordinary commuter could hope to attain in the rain at rush hour.

Users of laptop computers will recognize the problem. The performance of rechargeable batteries is often half their rated capacity because performance relates to the way they have previously been discharged and the amount of power required for specific tasks. The net result is that similar batteries, nominally capable of supporting a computer the same number of hours, perform quite differently in practice.

Cost-effective batteries that can provide the desired range for electric vehicles may simply not be available in our generation.

The problem of providing electric vehicles with enough range is rooted in a fundamental physical reality: the batteries required to power electric vehicles are enormously heavy. Batteries store very little energy per unit of weight. The energy density of lead-acid batteries—the kind used in conventional cars —is about 35 watt-hours per kilogram, less than one-three-hundredth that of gasoline, which is about 12,000 watt-hours per kilogram. As a rule of thumb, 1 gallon of gasoline, weighing about 6 pounds, has the same energy content as 400 pounds of lead-acid batteries.

Golf carts are the prototype feasible electric vehicles at this stage. Their low range and speed require only about 1 percent of the power required of electric vehicles for highways. They can thus be powered by about 50 pounds of batteries. But because of their added demands, commuter cars could easily require batteries that account for one-third of the total weight of the vehicle. Thus, roadworthy electric vehicles developed so far are essentially battery packs on wheels.

The problem is a basic conflict between good performance per unit of weight and durability. For example, the ABB sodium batteries used by Ford produce good peak power but last only about a year and a half (some 600 cycles). The long-lasting nickel-iron batteries, on the other hand, have far less peak power as well as lower energy density.

Government and industry are spending considerable sums on developing better batteries for electric vehicles, efforts coordinated since 1993 by the Advanced Battery Consortium. Nevertheless, progress in electrochemistry has not been rapid. Materials scientists simply do not yet know how to make reliable long-life batteries even in the laboratory. Progress has been made primarily in engineering developments that push existing capabilities to their limits. And, in part because of the tight timetable required by the California mandate, money for batteries is going into engineering rather than into the basic research from which needed progress must come.

Even promising leads produced by this focus have tended to lose their appeal. The recent experience with sodium-sulfur batteries, which Ford chose to power its prototype electric vehicles, illustrates the point. Unfortunately, this technology has had major practical difficulties: in a German laboratory, sodium-sulfur batteries caught fire after one was overcharged, and a test vehicle caught fire in the parking lot of the California-based Electric

Power Research Institute (whose employees were knowledgeable enough, fortunately, to alert firefighters to the battery's makeup so they could avoid the dangers of mixing sodium with water).

Of course, we can only speculate on the future of battery technology. Breakthroughs are possible, and should be sought. Advances cannot be guaranteed, however. It is entirely possible that the kind of cost-effective batteries needed to achieve the desired range for electric vehicles in the United States may simply not be available in our generation. An attempt to legislate the results of the research and development process is therefore unrealistic and unworkable. It is one thing to goad manufacturers to stretch their capabilities within the framework of an existing technology, as was done for catalytic converters and air bags. It is quite another to force them into new technologies whose possibilities are not known. Both airbags and catalytic converters were demonstrably capable of meeting the required technical performance requirements when they were mandated. The situation is very different for electric vehicles.

Higher Cost, Poorer Performance

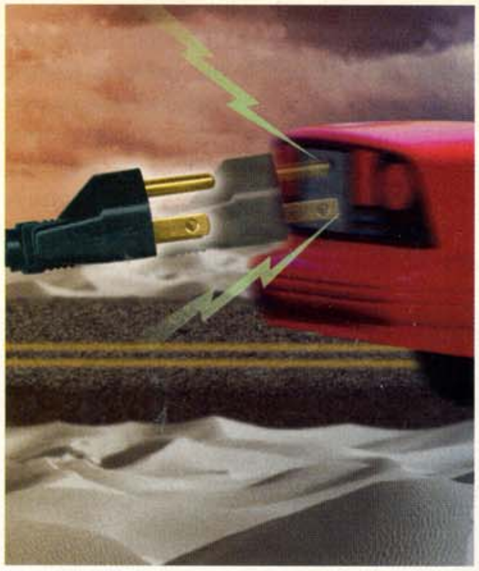
For the foreseeable future, electric vehicles manufactured for a broad consumer market will cost about twice as much as comparably sized conventional automobiles, even though the electric vehicles will have only about half the range. This conclusion is based on models of automobile manufacturing developed by the MIT Materials Systems Laboratory over many years and validated by comparisons with actual practice in the United States and Europe.

Some entrepreneurs making prototype electric vehicles report costs competitive with those of ordinary cars, but their experience cannot be extrapolated to full-scale production. Unlike prototypes, industrial production of automobiles must take into account the costs of marketing, distribution, and service; of extensive testing (to reduce product liability); and long-term relationships with labor (including health and pension benefits). These inescapable additional costs roughly equal the costs of manufacturing.

Moreover, the opportunities for reducing the costs of manufacturing electric vehicles through economies of scale or learning curves are limited. To take one example, the lightweight bodies required by electric vehicles are likely to be made of plastic that, on a per pound basis, is roughly three times as expensive as sheet steel. Because the lightweight plastic is also much less stiff than steel, considerably more material is needed to achieve comparable performance, offsetting the weight advantage. These two factors alone greatly increase the manufacturers' cost of producing the bodies of electric vehicles. And as automakers already know from using plastics in car bodies of specialty cars such as the Corvette, and in components of GM's Saturn line, plastics take an order of magnitude more time to fabricate than their steel counterparts. This limitation, which makes little difference in producing small numbers of cars, will require costly machinery for large-scale production and prevent the expected economies of scale.

The batteries for electric vehicles will also raise the lifetime costs of owning the car. Batteries wear out after roughly 1.5 to 2 years, or some 500 cycles of daily discharge and recharge. The cost of a set of batteries for an electric vehicle will drop as manufacturers produce them on a regular basis, but the replacement batteries are still projected to be in the range of several thousand dollars. Buyers will have to pay this cost at the time of purchase and every few years thereafter.

It seems clear that rational buyers will not spend twice as much for a car that has worse performance than competing vehicles. Even though electric vehicles may cost as much to produce as conventional luxury sedans, they will have to compete with the significantly cheaper compact and subcompact cars they resemble in appearance. To sell electric vehicles in the required quantities, then, manufacturers will have to discount them as much as $10,000 to $20,000 per car— far below their cost to produce and market. In effect, this means the public will pay handsomely to get electric vehicles on the road since car manufacturers will naturally pass these losses along to buyers of conventional cars. Manufacturers have done this before. To meet the Car Average Fuel Economy regulations spawned as part of the Clean Air Act, which stipulate that automakers sell cars whose average gas mileage meets certain stiffening goals each year, manufacturers sell their smallest cars at a loss and raise the prices on the others. The cost of a similar subsidy to implement the electric vehicle policy could average out to about $200 to $400 per new internal combustion car sold where California rules on electric vehicles prevail.



We estimate the total annual cost of the subsidy required to implement the electric vehicle policy in California alone will be somewhere between a quarter and half a billion dollars. Since the electric vehicle policy appears to yield imperceptible overall environmental benefits, the added cost is extremely hard to justify.

Driving Forward

Unfortunately, because today's policy fixates prematurely on a specific technological solution, it has diverted attention from the basic issue: How should we improve air quality in polluted urban areas? To obtain a practical result, we need to consider both the instrument of the problem—that is, the technology—and the cause of the problem, the users. We need to adopt a flexible strategy that permits us to choose the most effective options as they develop. We must also define approaches that can command the support of all the important participants.

Rather than mandate development of the electric vehicle on a short timetable, we should promote research and development over a broad front on a range of alternative vehicles. These should certainly include refined versions of currently accessible technologies such as ultra-low-emission vehicles that use catalytic converters and microelectronics to control combustion precisely; and so-called hybrid vehicles, which combine constant-speed (and therefore highly efficient) gasoline or diesel engines with electric generators to extend the range and power of batteries stored on board. Fuel-cell vehicles are a technological possibility that also requires investigation.

Development could also be divided into three phases. The first might focus on creating prototypes, culminating in a competition between technologies. The second phase could then concentrate on large-scale development and testing of finalist systems, leading to a final choice for implementing in the third phase. In light of all the uncertainties, it is unlikely that a particular schedule for such implementation, set a decade in advance, can work.

Organizational changes should also complement, or even replace, technological solutions. Perhaps the real issue is that communities such as Los Angeles are too dependent on the use of personal automobiles. Because the total level of pollution is of course the product of two factors—the dirtiness of the vehicle and the distance it travels—targeting the level of emissions produced per vehicle-mile addresses only half the problem. The fact is that the number of vehicle-miles traveled is growing steadily in the United States, particularly in the Los Angeles area. More people live farther away from jobs and travel more. If this trend continues, the resulting increase in pollution will counteract any reduction achieved by introducing electric vehicles. An effective policy to reduce total automotive pollution should thus include encouraging collective transport through the use of car pools and buses, reducing driving through disincentives such as higher parking fees and gas taxes, and facilitating alternatives to driving such as telecommuting.

In the first phase of any such plan, decision makers should identify actions that can produce immediate results cheaply—in essence, picking the low-hanging fruit. They should, for example, consider a program of buying up the most severely polluting vehicles— those among the 7 to 10 percent of vehicles that produce 50 percent of on-road generation of carbon monoxide and hydrocarbons. Because one of these mostly older, severely polluting vehicles produces roughly 10 times the pollution of an average vehicle, and because one electric vehicle will only reduce pollution equal to one-half of an average car, such a program would have 20 times the effect per vehicle and would be far more cost-effective.

Such a multifaceted and dynamic strategy would surely improve air quality more quickly than a proposed mandate that will have no perceptible effect on pollution for many years, if ever. ■