Electric Vehicles: Performance, Life-Cycle Costs, Emissions, and Recharging Requirements

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ELECTRIC VEHICLES: PERFORMANCE, LIFE-CYCLE COSTS, EMISSIONS, AND RECHARGING REQUIREMENTS

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Abstract—Electric vehicles (EV) are periodically promoted as quiet, pollution-free alternatives to gasoline vehicles. They have failed each time because of inferior performance and high costs. In this paper, we conduct an updated and detailed evaluation of the performance, costs, environmental impacts, and recharging requirements of electric vehicles. We find that considerable progress has been made in EV battery and powertrain technology since the last surge of interest in EVs in the 1970s. If the development of high-performance batteries continues as expected, advanced electric vehicles could have an urban range of over 150 miles and acceleration comparable to that provided by internal combustion engine vehicles (ICEVs). And if optimistic battery cost, life, and performance goals are achieved, mass-produced EVs will have lower life-cycle costs than comparable conventional gasoline vehicles. EVs will reduce emissions per mile of HC, CO, and NO_x, compared to stringently controlled ICEVs. By the turn of the century, electric passenger vehicles could be viable as second cars in multicar households and in other limited markets. If an economical form of fast recharging is developed, the potential role of EVs will be much larger. No longer does successful commercialization depend on technical breakthroughs.

INTRODUCTION

Pollution-free on almost every count, the electric vehicle (EV) is an attractive transportation option that has thus far eluded our grasp. A cost-effective, high-performance electric vehicle, recharged quickly by cleanly generated power, using widely available battery materials, would be an ideal transportation machine. This paper examines the prospects for, and implications of, developing such advanced electric vehicles.

Modern history of electric vehicles

Interest in electric vehicles has peaked three times in the past few decades. These peaks relate to early concern over air quality (mid-1960s), concern about imported petroleum (1974–1981), and renewed interest in reducing petroleum imports and pollution from automobiles (about 1985–present).

In the early 1960s, after "smog" had been traced to auto exhaust, EVs gained attention as an air pollution control strategy. In 1965–1966, three bills were introduced in the U.S. Congress to promote them (Hamilton, 1980a). None became law, however, and a major federal study that addressed the benefits and costs of EVs ended up recommending in 1967 that conventional automobiles be cleaned up instead (U.S. Department of Commerce, 1967).

The 1973–1974 oil crisis prompted another search for alternatives to petroleum, this time to reduce dependency on imported oil from unstable suppliers. In 1976 Congress passed the Electric and Hybrid Vehicle Research, Development and Demonstration Act, which sought to decrease the nation's dependence on foreign petroleum by developing the technologies needed to commercialize electric vehicles. A major initial R&D effort under this Act was the advanced electric test vehicle (ETV-1&2) program, aimed at developing a state-of-the-art EV that could be put into production in the 1980s. About the same time, General Motors (GM) announced its intention to manufacture a production-line EV by the mid-1980s.

After oil prices peaked in 1981, interest in EVs waned. The decline in interest in EVs was due not only to the decline in oil prices, but also to the failure of research and development efforts to produce the much hoped for breakthrough in electric vehicle battery technology (Hayden, 1988). GM's plan to produce an EV in North America was aborted in 1982.

However, while concern for energy security diminished, concern over air pollution was increasing. Most major metropolitan areas in the United States continued to violate one or more of the national air quality standards, even with repeated extensions of attainment deadlines. At the end of 1987, 107 metropolitan areas in the United States were still violating carbon monoxide or ozone standards, and motor vehicles continued to be the major source of these pollutants. This prompted many policy makers and researchers to look for clean alternatives to gasoline. At the same time, EV propulsion technology was progressing incrementally.

Today, interest in EVs and alternative fuels for internal combustion engine vehicles (ICEVs) is motivated by both environmental and "energy security" concerns. Many recent policy documents and legislative proposals encourage a switch to nonpetroleum alternative fuels to "clean up the air" and to provide for "energy security" (e.g. U.S. Department of Energy, 1987a; California Energy Commission, 1988). Although most reports and statements in the United

States emphasize methanol as a replacement for gasoline and diesel fuel, there is increasing awareness of the potential for advanced, relatively high-performance EVs to provide substantial air quality and petroleum conservation benefits, at comparatively low cost.

This paper updates and advances the evaluation of the performance, costs, and environmental impacts of EVs. There have been major changes in emission control technology for power plants and automobiles, and in emissions estimates for both, since the best available environmental impact analyses were published in 1980. Similarly, previous analyses of all aspects of life-cycle costs do not reflect the latest performance and cost data for powertrains and batteries. This paper provides a comprehensive overview and analysis of EVs and an updated assessment of their attractiveness.

We consider only battery-powered electric vehicles. Other kinds of vehicles with electric motors, such as hybrid electric–gasoline vehicles (see Renner, 1986; Davis and Cleveland, 1988; Wouk, 1988), fuel-cell vehicles (see Huff *et al.*, 1987; Patil and Huff, 1987), or electrified-roadway vehicles (see Southern California Association of Governments, 1984; Wang and Sperling, 1987; Shladover, 1988), are not likely to be commercially available as soon as advanced EVs.

PERFORMANCE OF ELECTRIC VEHICLES

Electric vehicles were commonplace in the United States at the turn of the century. However, by 1920 improvements in EV technology had so lagged the development of the ICEV that EVs became practically extinct (Hamilton, 1980a). With the resurgence of interest in EVs in the 1960s came promises of breakthroughs that were to make EVs as economical and high-performing as ICEVs. But a decade later the promised EV had still not materialized. As late as 1980, Agarwal could state that "it is generally agreed that electric vehicles will never match the cost and performance levels of petroleum powered vehicles . . ." (p. 5).

The efforts of the past decade, from the late 1970s to the present, still have not produced any dramatic breakthroughs. However, over that period the technology of EV batteries and powertrains has developed incrementally, and the cumulative result in a sense has been a "breakthrough." For example, advances in microelectronics have resulted in low-cost, lightweight dc-to-ac inverters, which make it attractive to use an ac motor instead of a dc motor. Although ac motors are 50% lighter and 75% cheaper than dc motors, until recently they were impractical to use because of the great weight, bulk, and cost of the inverter needed to convert dc from the battery to ac current (Hamilton, 1988a). With the improved inverters the whole ac system is cheaper, more compact, more reliable, easier to maintain, more efficient, and more adaptable to regenerative braking than dc systems (Hamilton, 1986; Chan and Ng, 1988). Similarly, the development of advanced batteries, particularly the high-temperature sodium/sulfur battery, has progressed to the point where successful commercialization does not depend on major technical breakthroughs, but on the resolution of manufacturing and quality control problems. BMW expects to mass-produce EVs with ac powertrains and sodium/sulfur batteries in the 1990s (Angelis *et al.*, 1987).

Experimental electric vehicles in the 1980s

One of the first major programs under the 1976 Electric and Hybrid Vehicle Research Development and Demonstration Act was a three-phase effort to improve the performance attributes and economic feasibility of EVs that could be produced in the 1980s. This effort culminated in 1981 with the development of the Electric Test Vehicle 1 (ETV-1), the most advanced EV of its time, and for several years the state-of-the-art (Kurtz, 1981). The ETV-1 used a lead/acid battery and a dc motor. The performance of the ETV-1 is shown in Table 1. At about the same time another electric vehicle, designated the ETV-2, was tested in the program. The ETV-2 had similar performance to the ETV-1 (see Table 1), but used a flywheel to store energy during regenerative braking, and lightweight plastics to reduce the weight of the vehicle and increase efficiency (AiResearch Manufacturing Company of California, 1981).

In 1981 Ford and General Electric proposed to the U.S. Department of Energy (DOE) a concept for a single-shaft ac powertrain, with the intent of advancing ac powertrain technology. A Mercury LN7 was selected for the test vehicle, and performance goals established. The vehicle, named the ETX-I, was successfully tested and met or exceeded these goals (Table 1) (Ford Motor Company and General Electric Company, 1987).

During the ETX-I program it was established that EVs most likely would be used first in urban van applications. Consequently, since the mid-1980s most EV development and demonstration projects in the United States have focused on vans. The Bedford electric delivery van (called the Griffon in the United States), manufactured in England and used by several U.S. utilities, is the first modern, production-line EV used in the United States in recent years. Like the ETV-1, the Griffon has a dc motor and a lead acid battery. Range and performance data are shown in Table 2. The planned successor to the Griffon is the G-van, the first modern EV to be produced in North America by a major automotive manufacturer (General Motors). The van is scheduled for production by Fall 1989 [Electric Vehicle Development Corporation (EVDC), 1988]. It has power brakes, power steering, and air conditioning, and uses an improved lead–acid battery [Electric Power Research Institute (EPRI), 1987] which requires watering only once every three weeks.

Table 1. Characteristics of selected electric passenger vehicles

	ETV-1	ETV-2	EV-20	ETX-I	1987 BMW	Projected: 1990 BMW	Projected: VW Jetta
Top speed, mph	†	62	60	60	53	75	78
Urban range, mi	Up to 75	66	<75‡	†	43–77§	62–124§	118
0–30 mph acceleration, secs	†	8	†	7	14	7	6
Mi/kwh from battery, city	3.41	3.14	†	3.61	†	3.73‖	†
Passenger capacity	4	4	2	2	4	4	4
Power train	dc	dc	ac	ac	dc	ac?	ac
Battery	Pb/acid	Pb/acid	Pb/acid	Pb/acid	Na/s	Na/S	Na/S
Approx. year of tests	1980	1980	1986?	1985	1987	1987	†
Reference	Kurtz (1981)	AiResearch (1981)	Wyczalek (1987)	Ford & GE (1987)	Regar (1987)	Regar (1987)	Angelis & Sedgwick (1988)‖

Top speed is maximum continuous cruising speed. Range and efficiency data for ETV-1, ETV-2, and ETX-I refer to FUDS (Federal Urban Drive Schedule); for Jetta, they refer to ECE (European) urban cycle.
†Not available.
‡Range is at constant speed of 25 mph.
§Lower range estimate at top speed; higher at 30 mph.
‖Based on ABB Na/S battery projections of Table 3, with an improved powertrain.

Beyond the G-van, significant changes in EV propulsion will be introduced, in several stages. The Chrysler TEVan, a light-cargo personal van scheduled for production in early 1991, will use a dc motor with a new nickel/iron battery. As shown in Tables 2 and 3, this battery offers better range and performance than do the lead/acid batteries used by the ETV-1, the Griffon, and the G-van. The TEVan will have an automatic battery watering system, an onboard charger, and an electronic instrument cluster that displays remaining range and battery state-of-charge (EVDC, 1988). Recently, a nickel/iron battery has been tested with a near-term ac motor, called the dual-shaft electric propulsion system (DSEP) (Heiselmann, 1986), in a Chrysler T115 minivan. The test-bed vehicle met or exceeded nearly all its performance goals (Table 2) (Kelledes, 1988).

The DSEP project is the near-term phase of a DOE program aimed at developing advanced powertrains and batteries for EVs. In the longer-term phase, DOE, Ford, General Electric, and Powerplex (a joint venture battery development group consisting of Magna and Asea, Brown, Boveri) hope to significantly advance the state-of-the-art in electric propulsion through the development of a second-generation single-shaft ac propulsion system, with a sodium/sulphur battery, in the ETX-II test vehicle. The ETX-II test vehicle will be a modified Ford Aerostar van (Stokes *et al.*, 1988). Improvements over the ETX-I include a slightly lighter, more compact dc-to-ac inverter; integrated digital control of

Table 2. Characteristics of electric vans

	GM Griffon	G-van	DSEP	Projected: Chrysler TEVan	Projected: ETX-II	Projected: G-van
Top speed, mph	53	52	60+	70	60	62
Urban range, mi	54	40	52	110+	113	136
0–30 mph acceleration, sec	11.4	12.9	†	7	†	11
0–50 mph acceleration, sec	†	†	20.5	†	20	
Payload capacity, lb	1900	1640	1200	1200	1100+	1800
Cargo space, ft^3	208	231	100+	120	†	256
Power train	dc	dc	ac	dc	ac	ac
Battery	Pb/acid	Pb/acid	Ni/Fe	Ni/Fe	Na/S	Na/S
Year of production	1985	1989	†	1991	†	†
Mi/kwh from battery, city	1.66	1.20	2.22	†	2.50	†
Reference	TVA (1988)‡	TVA (1988)‡	Kelledes (1988)§	EPRI (1987)	Altmejd & Dzieciuch (1988)‖	Angelis & Sedgwick (1988)¶

TVA = Tennessee Valley Authority.
†Not available.
‡Driggans and Whitehead (1988b). The authors report ac energy consumption of 0.6 kwh/km and 0.85 kwh/km in the TVA urban cycle, and battery plus charger efficiencies of 62.5% and 61%, for the Griffon and the G-van, respectively. The difference between the Griffon and the G-van was less in the SAE J228a/C cycle.
§Payload and cargo space are mission requirements. Urban range and city efficiency data from SAE J227a/D cycle.
‖Mi/kwh is goal; other data are from simulation. Urban range and city efficiency refer to FUDS. Performance shown here is based on current ABB-B11 Na/S battery technology of Table 3. The ABB Na/S battery projections of Table 3 would result in a longer range.
¶Payload and cargo space data from EPRI (1987). Urban range refers to ECE urban cycle. Based on ABB Na/S battery projections of Table 3, with an improved powertrain.

Table 3. Characteristics of EV storage batteries

Battery Reference	Volumetric energy density (wh/l)	Mass energy density (wh/kg)	Peak power (w/kg-%DoD)	Energy effic. (%)	Life cycles to 80% DoD	Projected OEM cost (1985$/kwh)	Type of estimate
Pb/acid							
USDOE (1988)	†	22	80–50%	†	500	124	JCI current gell cell module perf.
Hamilton (1988a)	†	35	†	70	800	95	Current battery performance‡
USDOE (1987b)	75–94	30–38	79–50%	75	375	58	DOE battery goals§ (50-mi range)
JPL (1987)	80‖	40‖	150–80%‖	†	400	50	JPL sealed Pb/acid cell goals
Ni/Fe							
USDOE (1988)	†	53	110–50%	†	500	†	EPI current module performance
Hamilton (1988a)	†	53	†	60	1100	150	EPI current battery performance‡
USDOE (1987b)	77–97	45–56	79–50	70	1125	125	DOE battery goals§ (75-mi range)
ZN/Br							
USDOE (1988)	†	55	88–50%	†	>35	†	JCI current battery performance
USDOE (1987b)	76–96	60–75		65	600	75	DOE battery goals§ (100-mi range)
EVD (1987): SNL (1988)¶	60	56	150–?	>70	†	†	SNL battery goals
Zagrodnik & Eskra (1988)	†	70–80	†	†	1000	55	JCI battery projections & goals
Li-mel/Fe-S							
Barlow & Chilenskas (1987)	†	60–120#	97–50%	85–97††	125	†	Current ANL/Gould module perf.
USDOE (1987b)	87–109	80–100	106–50%	75	600	91	DOE battery goals§ (100-mi range)
Beck *et al.* (1988)	150	100	150–?	†	1200	80–100	Canadian battery goals
Kaun *et al.* (1987)	†	200§§	200–80%	†	1000	†	ANL cell goals
Na/S							
Hamilton (1988a)	†	90	†	70	1000	118	CSPL current battery performance‡
Fischer & Shiota (1988)	97‖	86	127–80%	†	250‖‖	†	ABB-B11 current battery perf.
USDOE (1987b)	87–109	80–100	106–50%	75	600	91	DOE battery goals§ (100-mi range)
Fischer & Shiota (1988)	145‖	108	200–80%	†	600	†	ABB projected battery performance
Angelis (1987); Haase (1987)	129	120	188–?	†	1000	50##	1990 ABB/BMW goals (120-mi range)
EVD (1987): SNL (1988)¶	150	125	150–?	>70	†	†	SNL CSPL battery goals
Mulcahey *et al.* (1987)	†	143†††	140–50%†††	†	>2300	†	CSPL current cell performance
Metal/air							
USDOE (1988)	†	70	50–50%	†	>120	†	Current Fe/air cell performance
USDOE (1987b)	87–109	80–100	106–50%	75	600	91	DOE Fe/air goals§ (100-mi range)
Ross (1987)	53	106	200‡‡‡	66–70‡‡‡	650¶¶	80	LBL projections for Zn/air battery
LLL (1988); Sen *et al.* (1988)	167	320	140–?	†	†	See text	LLL projections for Al/air battery

ABB = Asea, Brown, Boveri; ANL = Argonne National Lab; CSPL = Chloride Silent Power Limited; DoD = depth of discharge; EPI = Eagle-Picher Industries; *EVD* (1987) = *Electric Vehicle Developments*; JCI = Johnson Controls Inc.; LBL = Lawrence Berkeley Lab; LLL = Lawrence Livermore Lab.; OEM = original equipment manufacturer; SNL = Sandia National Lab. ">" means "at least," and refers to ongoing work. "?" means information not supplied in reference.

†Not available. Wh or kwh, in wh/l, wh/kg, and $/kwh, generally refers to maximum deliverable energy (e.g., 2-hour discharge to 100% DoD).

‡OEM cost and battery life estimates are projections. Specific energy is nominal wh/kg delivered at 3-hr. constant discharge.

§The U.S. Department of Energy has established battery goals based on the mission requirements of an efficient, lightweight van using the Eaton DSEP system. The maximum power of the battery was limited to that required to accelerate the DSEP vehicle to 50 mph in 20 seconds, and the required range was 50, 75, or 100 miles, depending on the battery technology. The battery weight includes battery trays, thermal enclosure, and auxiliaries. Battery energy is maximum net energy delivered over FUDS. The low end of volume or mass energy density shown is the goal for late in life; the high end is for early in life, over modified FUDS. The $/kwh cost goal is the cost to an OEM and is based on 10,000 units/year (battery charger not included). Cost goals for the battery were set such that the EV would achieve "economic parity" with other modes of transportation in 1995.

‖2-hour constant discharge to maximum capacity.

¶Murphy and Diegle (1988). Wh/kg includes cell-to-battery scale-up losses. Efficiency includes energy used by auxiliaries.

#Low figure is for SAE D cycle; high figure is constant low-power output.

††85% efficient at constant discharge without regenerative braking; 97% over SAE D cycle with regenerative braking.

‡‡Early cell failure due to defective welds.

§§4-hour discharge rate.

‖‖Life-cycle estimate from Altmejd and Dzieciuch (1988), who also show 175 w/kg for peak specific power.

¶¶They state at least 100,000 km; we assume 160 km/cycle.

##Battery cost estimated to be 3000 DM, at "an industrial scale," which is $1630 or $50/kwh, a remarkably low cost.

†††The figures shown are cell performances adjusted to account for the 50% additional weight, in insulation and auxiliaries, that a battery would have. Specific energy is at 30 w/kg discharge rate.

‡‡‡Power is invariant with DoD in Zn/air batteries. It was projected to range from 183 w/kw at the beginning of battery life to 216 w/kg at the end.

the motor and the inverter, rather than separate analog/digital control; an interior permanent magnet ac motor, rather than an induction ac motor; an unsprung transaxle integrated with the rear axle, which eliminates the need for constant-velocity joints; and a sodium/sulphur battery (Bates *et al.*, 1988). Performance goals for the ETX-II are shown in Table 2.

Japan and Germany also have strong EV programs. Japan is strongly committed to the rapid development of EVs to reduce petroleum consumption and enhance energy security (Wyczalek, 1987; Akikawa *et al.*, 1988). The performance of a two-seat Toyota EV (the EV-20), using a lead/acid battery and an ac drivetrain, is shown in Table 1.

In Germany several automakers are working with Asea, Brown, Boveri (ABB), a major manufacturer of sodium/sulfur (Na/S) batteries, to develop advanced, high-performance EVs. ABB has projected that a Series 3 BMW, a VW Jetta, and a G-van, using advanced ac powertrains and optimized versions of current Na/S batteries, will have urban driving ranges well over 100 miles, high top speed, good acceleration, and seating for four (in the BMWs the battery is located in the space originally containing the ICEV drivetrain, exhaust system, and gasoline tank, so that the vehicles provide seating for four without sacrificing luggage space). The Jetta is projected to be able to climb a 10% grade at 30 mph (Angelis and Sedgwick, 1988). ABB and the auto companies believe that volume production of advanced EVs can begin in the 1990s. (For a review of EV activities in France, Britain, Canada, and elsewhere, see *Proceedings, the 9th International EV Symposium,* 1988).

In summary, the data of Tables 1 and 2 show that advanced EVs now under development, and projected to be commercially available within a decade, are expected to offer considerably better range and performance than state-of-the-art EVs of 10 years ago. Passenger vehicles and vans are projected to have an urban range of over 100 miles, high top speed and acceleration, and low energy consumption, without sacrificing seating or cargo capacity. With these performance characteristics, EVs could serve as the second vehicle in most multicar households (Lunde, 1980; Horowitz and Hummon, 1987), and in most urban van applications (Berg, 1985; Brunner and Wood, 1988). However, the successful development of advanced vehicles, and the attainment of even longer ranges than shown in Tables 1 and 2, still depend primarily on the commercialization of advanced battery technology now under development.

ELECTRIC VEHICLE BATTERIES

The present commercial lead/acid (Pb/acid) battery, used in virtually every EV on the road today, is essentially unchanged since the late 1800s; it is large, heavy, and expensive. EVs with Pb/acid batteries generally have a range of under 75 miles. If electric vehicles are to be more than a curiosity, better batteries must be commercially available.

In the near term, the successors to the standard Pb/acid battery appear to be the sealed Pb/acid battery and the nickel/iron (Ni/Fe) battery. Ni/Fe batteries are modest improvements over conventional Pb/acid batteries. Zinc/bromine (Zn/Br) batteries, in turn, are modest improvements over Ni/Fe batteries. Beyond these, substantial improvements are expected with the high-temperature batteries, sodium/sulfur (Na/S) and lithium-metal/iron-sulfide (Li-me/Fe-S), which may be commercially available before the turn of the century. In the longer term, metal–air batteries have the potential for very high performance and quick rechargability, but their successful development is very uncertain.

Near-term batteries: Sealed Pb/acid and Ni/Fe

In addition to having low energy density, conventional Pb/acid batteries require periodic watering, which increases vehicle maintenance costs. Consequently, Pb/acid R&D has focused on reducing maintenance requirements, as well as increasing performance. In the United States, the Jet Propulsion Laboratory (1987) is developing maintenance-free, sealed lead–acid batteries for use by urban vans. Cell development goals, shown in Table 3, indicate better performance than from conventional Pb/acid batteries.

However, unless there are dramatic and unforeseen improvements, even future Pb/acid batteries are likely to have much lower specific energy and cycle life than other advanced batteries under development. Many researchers believe that the Ni/Fe battery is the most likely near-term successor to the conventional Pb/acid battery. As shown in Table 3 (see also Blickwedel *et al.*, 1987), Ni/Fe batteries are lighter and more powerful than Pb/acid batteries, on an equal-energy basis, and thus deliver better performance, as shown in Table 2. Unfortunately, Ni/Fe batteries are expensive (due to the cost of the nickel), evolve relatively large amounts of hydrogen gas during recharging, and require a good deal of watering. Thus, many researchers look to other batteries to power advanced EVs in the long run.

High-performance batteries

In the past 20 years many electrochemical couples have been studied as potential high-performance batteries. And while experimentation has narrowed the field, R&D continues for at least four major options, excluding the metal/air batteries: zinc/bromine (Zn/Br), nickel/cadmium (Ni/Cd), Na/S, and Li-me/Fe-S (*Procs., the 9th Int. EV Symposium*, 1988). Of these, Na/S and Li-me/Fe-S batteries appear to be the most promising, according to recent battery assessments (Miller *et al.*, 1987; Ratner *et al.*, 1988), and have received the most support worldwide. Below, we review the prospects for these batteries (for a review of Zn/Br battery development, see DOE, 1988; Zagrodnik and Eskra, 1988; for a review of Ni/Cd development, see DOE, 1988; Viswanathan, 1988).

Sodium/sulfur (Na/S) battery. The Na/S battery is very different from other batteries. It has a solid ceramic electrolyte, rather than a liquid electrolyte as in conventional batteries, and liquid, not solid reactants. To keep the reactants liquid, the battery must be maintained at a temperature of about 300°C. When energy is being drawn from the battery it produces enough heat to maintain this temperature, but when it is idle it does not, and consequently the battery must be insulated to maintain the high temperature when the vehicle is not operating. This insulation maintains battery temperature for about two weeks; after that, auxiliary heating is required.

Na/S batteries have several advantages compared to Pb/acid and Ni/Fe batteries. As shown in Table 3, the battery offers very high performance—considerably greater energy and power density than the conventional Pb/acid battery, and more than the Ni/Fe battery. Unlike conventional batteries, Na/S batteries do not require watering, and are essentially maintenance-free. They do not evolve gases when they are charged. And, of great importance from an environmental and long-run economic perspective, the two reactants, sodium and sulfur, are relatively cheap, abundant, and widely available. Finally, Na/S batteries are charged with constant power, unlike lead–acid batteries, and thus charging is considerably more efficient—up to 98%, if a long charging period is used (Angelis *et al.*, 1987).

The vehicle performance projections of Tables 1 and 2 demonstrate the promise of Na/S batteries. Recent work at Argonne National Laboratory (ANL) suggests still greater potential: based on evaluations of eight cells made by Chloride Silent Power Limited (CSPL), ANL has projected that an "improved" ETV-1 vehicle could travel 195 miles in an urban cycle (SAE J227a/D) with a scaled-up version of an eight-cell Na/S battery, and would be able to climb a 6% grade for six minutes at 30 mph when the battery was 90% discharged. The simulations included an additional 50% battery weight for insulation and other hardware (Mulcahey *et al.*, 1987). Similarly, in a simulated Federal Urban Drive Schedule the DSEP van travelled 158 miles with the scaled-up CSPL cells. No cell failures have occurred in 2,300 cycles, through mid-1987. Performance goals are shown in Table 3.

The promise of such performance is the driving force behind the R&D on Na/S batteries. However, Na/S batteries must be improved in several areas before they can be made commercially available. The most important remaining technical problems are to develop more durable electrodes, and sulfur containers and seals that are resistant to the corrosive sodium polysulfide compounds formed at the sulfur electrode during discharge (Murphy and Diegle, 1988). Another problem is that the insulation required to maintain the high temperature of the battery is fairly heavy. Researchers would like to find lighter, more effective insulation. While these problems require improvements in manufacturing processes and quality control, they do not appear to demand technical breakthroughs.

Li-me/Fe-S batteries. Like Na/S batteries, Li-me/Fe-S batteries are high-temperature, high-performance, maintenance-free batteries (in Li-me/Fe-S batteries, however, the electrolyte is molten). They are relatively compact, light, and safe. Simulations and preliminary vehicle tests have demonstrated the great promise of Li-me/Fe-S batteries: in a simulation an ANL vehicle with a Li-me/Fe-S battery has driven 200 miles in stop-and-go traffic (Southern California Edison Company, 1987), and in an actual vehicle test a battery developed by Gould Inc. and ANL supplied a 109 mile range in a Chrysler TEvan, which consumed only 0.56 kwh/mi from the charger (Barlow and Chilenskas, 1987).

Early Fe-S cells lost capacity rapidly, at up to 0.25% per cycle. Recent work at ANL appears to have corrected this: Li-Al/Fe-S cells have cycled 250 times with only a 2%–4% loss of capacity (Kaun *et al.*, 1987). Li-me/Fe-S cell development goals (which are usually higher than goals for fully assembled, scaled-up batteries) are shown in Table 3; the battery team at ANL believes that there is a good chance of attaining these goals (Kaun *et al.*, 1987).

Li-me/Fe-S batteries have advantages and disadvantages compared to Na/S batteries. Corrosion of seals and casings is not a problem, and the lithium battery probably will be more compact. A study commissioned by DOE rates them as significantly safer than Na/S batteries (Ratner *et al.*, 1988). On the other hand, lithium is more expensive and less abundant than sodium.

Metal–air batteries

Metal/air batteries have a metal anode of aluminum (Al), zinc (Zn), or iron (Fe), and a cathode that uses atmospheric oxygen. All metal/air batteries offer high power and energy density. The main advantage of Al/air and Zn/air batteries, compared to Na/S and Li-me/Fe-S batteries, is the possibility of fast mechanical recharge. In regular batteries, charging requires either very large current flow or very long charging time. With the Al/air or Zn/air battery, however, the metal anode can be "recharged" simply by replacing the consumed metal with fresh metal, and the air provides an essentially inexhaustible source of fresh ("charged," in a sense) oxygen for the cathode. This makes "recharging" fast and easy—comparable, perhaps, to refuelling gasoline vehicles.

Aluminum–air batteries. In an Al/air battery, incoming air is scrubbed of CO_2 and directed to a fuel cell, where wedge-shaped aluminum plates are dropped by gravity between the air cathodes, and an alkaline electrolyte is pumped from a storage tank to the space between the electrodes. Performance projections for the Al/air battery designed at Lawrence Livermore National Laboratory (LLL, 1988) are shown in Table 3. Not shown are the attributes of a new design by Eltech, which has planar rather than wedge-shaped aluminum electrodes (Rudd, 1988). Eltech expects this battery to be much smaller and lighter than the LLL wedge design.

Al/air batteries would require two sorts of servicing, both of which are expected to take only a few minutes. First, water would be added periodically to the electrolyte solution, and aluminum hydroxide byproduct, formed by the generation of current in the fuel cell, would be removed. Researchers hope to attain 250 miles between these service intervals. Second, the aluminum plates, which gradually would be consumed in the fuel cell, would have to be replaced every 1,000–2,000 miles. Both of these services could be performed at home, since the reaction product could be stored safely in a garage, and a year's supply of aluminum would occupy only seven cubic feet.

Unfortunately, there are serious shortcomings to the Al/air batteries in their present state of development. The battery is relatively bulky. Considerable research is needed to develop air electrodes that have long lives and perform well under all conditions (LLL, 1988; Sen *et al.*, 1988). The aluminum electrode is susceptible to corrosion, which reduces cell efficiency. Finally, a carbon dioxide scrubber suitable for vehicles has not yet been designed.

In the long run, though, the most difficult problem may be battery cost. The aluminum required is relatively expensive, resulting in a fuel cost of 10–15 ¢/mile, depending on assumptions regarding vehicle efficiency, the energy/unit weight of aluminum, and the cost of aluminum (Cooper, 1984; LLL, 1988; Sen *et al.*, 1988). For a 30-mpg gasoline vehicle to have a fuel cost of 12.5 ¢/mile (the middle of the range above), gasoline would have to sell for $3.75/gallon. In addition, yearly maintenance for the Al/air battery, including removing precipitate and adding water, replacing the CO_2 scrubber, and maintaining the electrolyte, and the amortization of the battery unit itself, would add another 9 ¢/mile to life-cycle cost (Sen *et al.*, 1988).

Zinc–air batteries. Like the Al/air battery, the Zn/air battery requires CO_2 scrubbing, electrolyte control, and routine cleaning and flushing. If it is operated as a mechanically rechargeable system, the handling of materials and associated infrastructure will be similar also. Zn/air systems are projected to have lower life-cycle costs than Al/air systems, because of the lower cost of zinc, but also lower peak power and specific energy than Al/air systems (Sen *et al.*, 1988).

Lawrence Berkeley Lab is developing a Zn/air battery for the DSEP van (Ross, 1987). Battery projections are shown in Table 3. The developers argue that Zn/air systems are easy to manufacture, and use materials with minimal environmental impact. Other advantages of the Zn/air battery are that power is nearly invariant with the depth of discharge, and the tradeoff between energy and power density is modest. Important areas of resarch are the life of the air electrode, the hydrogen build-up as a consequence of overcharge, and start-up in low temperatures (Ross, 1987).

Table 3 summarizes current performance, performance projections, and performance goals for the batteries discussed above. Note that the DOE goals are generally conservative—they are based on the mission requirements of the DSEP van, and do not reflect ultimate technological objectives. The advantages and disadvantages of the various battery candidates are summarized in Table 4.

It is clear from this review that if advanced batteries meet the more optimistic goals and projections, they will provide a range of 150 miles or more in city driving, offer good acceleration, and last over 100,000 miles. Na/S batteries, one of the most promising near-term candidates, will be more powerful, more compact, longer lasting, and much lighter than current Pb/acid batteries. They probably will fit in the space devoted to the ICEV drivetrain, exhaust system, and gasoline tank, even in small cars. If mechanically rechargeable batteries are developed—a very uncertain prospect, at this point—then EVs will be quickly rechargeable as well.

LIFE-CYCLE COST OF ELECTRIC VEHICLES

Life-cycle cost is a pivotal criterion in a comparative evaluation of EVs and ICEVs. Even unimaginable breakthroughs in battery performance will not make EVs attractive if they are very much more expensive to own and operate over their life than comparable ICEVs. Unfortunately, estimating relative life-cycle costs is not easy. Several key parameters, such as the life of the EV, its maintenance costs, and the costs of advanced batteries, are not well known. Our analysis indicates that in the best case, EVs will have much lower life-cycle costs than ICEVs; in the worst case, they will have considerably higher costs. In the following sections we discuss inputs to our cost model, the results, and their implications.

The cost model calculates total, discounted life-cycle cost-per-mile for EVs, and the break-even gasoline price to equate with ICEVs. The breakeven price of gasoline is that retail price of gasoline, including current national and average state taxes, at which the full life-cycle cost of the EV is equal to the full life-cycle cost of the gasoline vehicle. We use a complete set of cost inputs for the EV, ranging from the cost of wiring the home for charging EVs to the difference in insurance premiums and registration fees for EVs and ICEVs. We estimate break-even gasoline prices for four-seat, high-mileage subcompacts and for urban cargo vans at two electricity prices—5 ¢/kwh and 9 ¢/kwh. Uncertainty is handled by using high and low estimates of input cost parameters.

Costs are calculated with respect to a baseline gas-

Table 4. Advantages and disadvantages of batteries

Battery	Advantages	Disadvantages/R&D issues
Pb/acid	Proven, commercially available technology	Low specific energy and power due to great weight of lead, decrease in voltage and performance as battery discharges
Ni/Fe	Durable, high cycle-life, good energy density	High initial cost of nickel, excessive hydrogen gassing, high water consumption, low efficiency
Zn/Br	High power, inexpensive	Bulky, complex, short life, corrosion, difficulty of containing bromine
Li-me/Fe-S	High specific energy and power, compact	High temperature, high cost and weight of insulation, high cost of current collectors, unstable cell components?
Na/S	High specific energy and power, inexpensive, widely available materials	High temperature, high cost and weight of insulation, corrosion of seals and casing, safety concerns
Zn/air	High specific energy and power, mechanically rechargeable	Complex, low cell efficiency, CO_2 scrubber needed, problems with air electrode and management of electrolyte
Al/air	Very high specific energy, high power, mechanically rechargeable	Complex and bulky, short life of air electrode, CO_2 scrubber needed, high cost of aluminum, low cell efficiency

Sources: Quinn *et al.* (1985), Walsh and Rajan (1985), Ross (1987), DOE (1988), Sen *et al.* (1988).

oline vehicle, for which all relevant baseline costs are shown in Table 5. All cost figures are $US 1985, unless otherwise stated. Where appropriate, cost items for the EV are expressed relative to the baseline costs for the ICEV (e.g. incremental retail cost, relative maintenance costs, increase in vehicle weight). We perform sensitivity analyses to test the effects of variation of some of the key baseline cost variables, such as the initial price of the vehicle and the interest rate.

Table 5. Base-case input data for the reference gasoline vehicles

Overall lifetime fuel economy, miles/gallon, subcompacts	30.5
Overall lifetime fuel economy, miles/gallon, cargo vans	19.0
The initial price of the subcompact, with tax and license, $	10,500
The initial price of the cargo van, with tax and license, $	14,000
Vehicle salvage value, related to initial price	3%
Miles driven over life or until resale	120,000
Miles driven per year	10,000
The driving weight of the subcompact, lb	2600
The driving weight of the cargo van, lb	4000
Insurance payments, $/month, first *n* years when coverage for collision damage is carried	46.24
n years collision damage is carried	5
Insurance payments, $/month, subsequent years, without collision	30.57
Maintenance costs, $/year	400
Parking and tolls, $/month	7.50
Four replacement tires, $/set	250.00
Life of tires, miles	50,000
Accessories, $/year	20.00
Oil, $/year	11.00
Registration fee for subcompact cars, $/year	25
Registration fee for vans, $/year	40
Inspection and maintenance fee, $/year	20
Gasoline tax, federal + average state, $/gallon	0.20
The real annual interest rate, for auto loans (base case)	9%
The real annual interest rate, for high-yield savings accounts	5%
Reduction in vehicle efficiency per 10% increase in vehicle weight	7%
Sales tax	5%

Note: Accessory cost, insurance cost, maintenance cost, and parking and tolls from FHWA (1984). Vehicle weight and efficiency correlation from EPA test data (Heavenrich *et al.*, 1987).

Finally, our cost analysis is an end-state analysis. We compare gasoline and electric vehicles on equal terms, assuming that both vehicles are mass produced, that repair shops and vehicle operators are just as familiar with EVs as ICEVs, and that parts for EVs are widely available. We assume that EVs use advanced ac powertrains with onboard chargers, and are powered by maintenance-free Na/S or Li-Me/Fe-S batteries. We make no particular assumption about when this situation might be achieved, and do not analyze intermediate cases. (Note too that there is no connection between the scenarios presented for illustrative purposes in the emissions analysis and this end-state cost analysis.)

Initial costs

Initial vehicle cost, including charger, excluding battery. There are considerable differences between an EV and ICEV powertrain. When the ETV-1 was evaluated in 1980, it was thought that the vehicle would cost considerably more than the comparable ICEV, battery excluded, under mass production [Solar Energy Research Institute (SERI), 1981]. However, with the advent of ac powertrains, and the development of low-cost inverters and onboard chargers, it is now thought that the initial cost of an EV (excluding the battery) will be about the same as that of its ICE counterpart, and perhaps lower. Ford and GE, developers of the ETX-I, suggest that advanced EVs will cost no more than comparable ICEVs, excluding the battery, at a "reasonable production volume" (Ford and GE, 1987), which may be as little as 10,000 units/year in the case of vans (Brunner *et al.*, 1987a). Similarly, a weight and cost model developed by General Research Corporation (Carriere and Curtis, 1984) projected that the initial cost of EVs and ICEVs will be close, assuming high-volume production. And these estimates may be conservative: progress in EV powertrain development since those estimates were made is expected to reduce the cost of powertrains by as much as $500–$1,000 (Hamilton, 1988a). We note too that EVs would not have pollution control equipment, which adds at least $400 to the initial retail price of an ICEV car (DeLuchi, 1989).

Presently, most commercial battery chargers are large and heavy, and cost close to $1,000 (Marfisi et al., 1978; Black and Oxley, 1979; and advertising literature for the Griffon van). However, future on-board chargers—probably charger/inverter packages for ac powertrains—using advanced microelectronics, are expected to be much lighter and much less expensive (DOE, 1988; Hamilton, 1988a). In fact, transformerless chargers for overnight charging can be so easily integrated with EV electronics that they probably will add less than $50 to the initial price of the vehicle (Hamilton, 1988b).

We conclude that an advanced, mass-produced EV would in the worst case cost the same as a comparable ICEV, excluding the battery and extra structural support, and in the best case cost $400 less. (The baseline ICE passenger car in this analysis costs $10,500, including tax, license, and dealer prep; the baseline ICE cargo van costs $14,000.)

Vehicle life. The life of the vehicle is a key element of amortized initial cost. EVs can be expected to have longer lives than comparable ICEVs because electric motors last much longer than ICEs. The life of an ICEV often is limited by the useful life of the engine. An electric motor, however, is not subject to the extremes of heat, pressure, and synchronized movement which wear down ICEs. There are no explosions and associated stresses, and fewer major moving parts.

The electric milk vans in Britain reportedly last three times as long as comparable ICE vans (Brunner *et al.*, 1987a). But while EVs clearly will last longer than comparable ICEVs, it does not seem reasonable to assume that as a general rule all EVs will be on the road three times longer than will comparable ICEVs. Before EVs reach such an age, it is probable that deterioration of some of the systems EVs have in common with ICEVs—brakes, steering, body—will be sufficient to force retirement of the vehicle. For example, in some areas of the United States, rusting of the body in part determines the life of the vehicle. Moreover, it is not clear how long EV advanced electronics packages can be expected to last or what kinds of failure can be expected. Finally, even if EVs do remain functional for a very long time, they may have relatively low value, simply because they are old and out of style, and may require additional aesthetic upkeep—new paint, new upholstery, new dashboards, etc.

Unfortunately, there simply are not enough data to specify narrowly the likely lifetime of EVs. We assume that EVs on average would last from 25% to 100% longer than ICEVs (150,000 to 240,000 miles, compared to 120,000 for the ICEV). [Brunner *et al.* (1987b) assume EV life is 83% greater than ICEV life.] At the end of its life, the EV is assumed to have the same salvage value, as a percent of initial cost, as the ICEV. (The battery is treated separately, as discussed below). We assume that maintenance costs do not increase dramatically in the extra years of life of the EV.

Extra structure. Passenger vehicles will require extra structural material to support the battery, but cargo vans generally will not if the battery is placed in the cargo area. Chassis material costs between $1.50 and $2 per pound (Carriere and Curtis, 1984). In the cost program the extra structural weight is determined by multiplying the weight compounding factor (discussed below) by the extra vehicle weight.

Cost of wiring the home for EV recharging. Kaiser and Graver (1980) and Harshbarger (1980) have estimated the cost of equipping a home with the branch circuitry, high-amp outlets, safety equipment, and load management equipment necessary to recharge EVs. If adequate electrical service is available, and ventilation equipment is not needed (either because sealed batteries, such as Na/S, are used, or recharging is done outside), it would cost $400 to equip a new house and $600 to retrofit an existing house.†
This installation cost is amortized over the 30-year life of the house. In the case of vans, we assume that several EVs share the cost of installing a recharging station, so that the effective cost per vehicle is $100.

Rate of interest. We assume in the base case that the purchase of the car is financed at a *real* rate of 9% per year. The real rate is used here because all costs are expressed in constant $US (1985$). In the sensitivity analysis a cash-purchase case is considered, with a 5% real rate representing the foregone real interest paid on high-earning savings accounts.‡

Battery costs

As discussed later, one of the most important parameters in an estimate of the life-cycle cost of an EV is the total cost contribution of battery: battery OEM (original equipment manufacturer) cost ($/kwh), cycle life, efficiency, energy density, total energy capacity, and salvage value. The uncertainty in each of these parameters is not large, but together

†In most cases, a 50-amp, 240-volt outlet (12 kw maximum power) will be sufficient for an eight-hour or longer recharge of a vehicle with an urban range of 150 miles or less. (The actual amount of power required depends on the energy capacity of the battery and the rate of recharging, which in turn depends on the type of battery.) Most houses have adequate electrical service to support the use of a 50-amp, 240-volt circuit, in the garage, providing all major electrical loads are not operated simultaneously. Kaiser and Graver (1980) estimated that in 1976 at least 26 million households in the United States (55% of all owner-occupied units) had sufficient unused electrical capacity to support recharging. Their estimate was conservative, since they used as an indication of adequate electrical service the presence of an electric range, and therefore missed houses with adequate service but without an electric range. Moreover, electrical service to houses generally has been increasing over the past two decades, and most houses in the United States have at least 100-amp service. Finally, inadequate service can be upgraded for about $1,000. We have not estimated the effect of this on EV life-cycle cost.

‡From 1983–1985 the nominal interest rate for auto loans was about 13% and the nominal interest on high-yield savings was 8%–9%. During the same period the consumer price index rose almost 4 %/year (U.S. Department of Commerce, 1987).

the multiplicative effect of the individual uncertainties is enormous. We specify battery cost parameters for future, optimized Na/S technology, based on data compiled in Table 3. We assume that the $/kwh estimate includes the cost of battery tray and auxiliaries, but not of the charger or the extra structure to support the battery. For passenger cars a 150 mile range at 95% depth of discharge (DoD) is assumed; for cargo vans, 100 miles. (We have chosen Na/S technology because, as noted earlier, major EV development projects in the United States, Germany, England, and elsewhere are using Na/S batteries. However, the input assumptions could be viewed as being representative of other technologies—most likely Li-Me/Fe-S—as well.)

Our analysis assumes that if the vehicle is scrapped before the battery, the value of the battery is directly proportional to its remaining life. This assumption is reasonable given the high cost of batteries, and further assuming that the life of the battery can be measured and that batteries will be easy to install and remove. We have assumed a 40%–50% markup from the OEM estimates of Table 3 to the incremental retail price (Carriere *et al.*, 1982; Hamilton, 1988a). We also apply a 5% sales tax (approximate national average; IntelliChoice Inc., 1988) to the cost of the battery.

Running costs

Running costs are those incurred periodically over the life of the vehicle: fuel costs, maintenance and repair costs, tire replacement costs, insurance fees, and so on. The cost per mile of a running cost is simply the cost per period divided by the miles driven per period, except in the case of tires, which are a very infrequent running cost and are treated differently, as discussed below.

Maintenance and repair costs. EVs are likely to have considerably lower maintenance and repair (M&R) costs (we exclude tires and oil) than ICEVs, for the same reasons, discussed above, that EVs should have longer lives. Most EV cost analyses have assumed that EV M&R costs are about half the M&R costs of a comparable ICEV (SERI, 1981; Asbury *et al.*, 1984; Edwards, 1984; Cohen, 1986).

Ample data and analyses support an assumption of lower M&R costs, although the quantitative estimates cover a wide range. Kocis' (1979) survey of consumer experience with EVs found that EV operators considered maintenance and operating costs to be substantially lower than for ICEVs. The electric milk delivery fleet in England was reported to have 65% the M&R costs of the comparable ICEV fleet (Hamilton, 1984). Marfisi *et al.* (1978), using data compiled by Hamilton *et al.* (1974) on the percentage of engine-related business at auto repair shops and parts stores, estimated that per-mile maintenance costs for the EV were only 34% of those for comparable ICEVs (they excluded tires, as we do, but included oil). However, a recent comparison of the electric Griffon van with conventional vans showed that the Griffon had 75% of the maintenance cost-per-mile of the ICEVs, excluding battery watering and oil, but including tire cost, for vehicles travelling 8,000 miles per year (Brunner *et al.*, 1987a, 1987b). Further analysis showed that costs related to the engine were only about 24% of total maintenance costs, a sharply lower figure than that in Hamilton *et al.* (1974) and Marfisi *et al.* (1978). Part of this relatively high M&R cost for Griffon vans is attributable to unfamiliarity with EVs. More importantly, however, the authors note that the ICE vans were withdrawn from service and sold before accumulating 60,000 miles, an age at which major repairs to engine and transmission are expected. This suggests that the electric Griffon would have substantially lower relative M&R costs over the second 60,000 miles of both vehicle's lives.

Our estimate, based on these data and analyses, is that the average lifetime M&R cost of EVs will be 50%–75% of the average cost for ICEVs [$400/year, according to Federal Highway Administration (FHWA) (1984) data]. We assume that EVs will have no oil costs, and that Na/S batteries, which do not require watering, will have no maintenance costs.

Tire cost. Our cost program estimates the present value of all tire replacement costs, and then amortizes this present value on a monthly basis. Since the present value of replacement costs is a function of the number of replacements and the time of occurrence, it is necessary to estimate differences in tire replacement intervals for EVs and ICEVs. Although tire wear is a function of vehicle weight, road conditions, and driving patterns, we assume that the only difference in the rate of tire wear between EVs and ICEVs would be due to vehicle weight. In the cost program tire life for the EV is decreased (relative to the 50,000-mile tire life for the reference gasoline vehicle) in proportion to the total extra weight of the EV. We have assumed that tires are not replaced if the last replacement interval falls within 7,500 miles of the end of life of the vehicle.

Insurance cost. Insurance costs are a function of many factors, including the amount and kind of protection, the value of the vehicle, the characteristics of the drivers and the area where the vehicle is driven, and the amount and kind of driving. Although any of these factors may or may not be systematically different with EVs than with ICEVs, the only difference that can be estimated confidently is that related to the value of the vehicle. EVs, with their very expensive batteries, will cost more than comparable ICEVs, and consequently collision insurance, which is based on the value of the vehicle, will be higher.

Typically, coverage for collision is carried for the first five to eight years of the vehicle's life, depending on the value of the vehicle. Our cost program specifies the monthly insurance rate with collision insurance, the number of years collision is carried, and the monthly rate without collision insurance, for the baseline ICEV, using FHWA (1984) data. The total monthly insurance rate after collision insurance is dropped is assumed to be the same for the ICEV and the EV. The total rate with collision coverage is higher for the EV, and is calculated by multiplying the difference between the with and without collision rates (this difference is equal to the cost of collision insurance) by the ratio of the initial cost of the EV to the initial cost of the ICEV. This procedure assumes that the collision damage fee is proportional to vehicle replacement cost.

Registration cost. The average fixed registration fee in the United States for the 20 states with fixed fees, is about $22. The average weight-based fee for a 3,000-lb vehicle, in 24 states, is $23. The remaining 6 states have value-based fees, ranging up to 4% of value, with an average of 2.75% (IntelliChoice, 1988). We use a weight-based fee because it is the most common, it produces results close to the average fixed fee, and has a solid rationale (road damage is proportional to weight). Our cost program assumes a $25 dollar yearly fee for the baseline passenger ICEV ($40 for the van), and increases the EV registration fee, compared to the ICEV registration fee, in proportion to the extra weight of the EV.

Inspection and maintenance (I&M). An increasing number of states are requiring I&M of pollution control equipment. In California the inspection is every two years, and costs about $20 if the car passes the first time. If the vehicle fails and has to be fixed, but has not been tampered with, the owner is required to spend up to $300 (if the vehicle is a 1990 or later model year) to repair it. If the pollution control equipment has been tampered with, the owner must pay all repair costs. We assume a typical, national biannual cost of $40 for post-1990 ICEVs. EVs, of course, emit nothing, and would not be subject to I&M.

Fuel cost. The fuel cost-per-mile of an EV is a function of the cost of electricity, the efficiency of the vehicle, and the amount of fuel or vehicle tax. The efficiency of an EV, relative to the efficiency of the baseline ICEV, is a function of relative powertrain efficiencies and the relative weights of the two vehicles. Each of these factors are analyzed next.

We consider two electricity price scenarios: 5 ¢/kwh, and 9 ¢/khw. The lower price can be viewed simply as a lower-bound price estimate, or as an incentive price for off-peak charging. The higher price can be viewed as an upper-bound price estimate, or as an optimistic estimate of the long-run price of electricity from "clean" energy sources. [The Energy Information Administration (EIA), 1988, projects about 7 ¢/kwh for residential power in the year 2000; Deluchi, 1989, estimates that solar power will cost between 7 and 17 ¢/kwh in the long run.)

The baseline gasoline subcompact passenger vehicle is assumed to weigh 2,600 lb loaded (curb weight of 2,300 lb) and average 30.5 mpg in combined city/highway driving; the figures for the baseline cargo van are 4,000 lb and 19.0 mpg. These fuel economy estimates were derived by taking EPA unadjusted 55%/45% city/highway mpg in 1987 for the vehicle weights chosen (Heavenrich *et al.*, 1987), applying EPA's 10% city and 22% highway reduction factors for real-world driving, and then assuming a 10% increase in efficiency for future vehicles. In the sensitivity analysis, we report the results of using different efficiency assumptions. The efficiency of the EV counterpart of this baseline ICEV is determined by estimating the efficiency of EV recharging, the efficiency of the EV battery (from Table 3), and ratio of the efficiency of the EV powertrain to the ICEV powertrain. The most important of these, the ratio of powertrain efficiencies, is analyzed in Table 6. For the EVs in Table 6, we show miles per kwh of *net* energy from the battery terminals (including regenerative braking) in an urban cycle [usually the Federal Urban Drive Schedule (FUDS) or the SAE J227a/D cycle for EVs], and the weight of the EV as tested (vehicle weight, including battery, plus test payload). We identify the comparable ICEV, and enter its unadjusted mpg efficiency (the actual dynamometer result, not the lower value reported in fuel economy guides) and test weight in the FUDS. We then calculate the FUDS efficiency of the ICEV at the test weight of the EV (to eliminate the effect of the extra weight of the EV on relative vehicle efficiencies, since vehicle weight is treated here as a separate variable), with the assumption that a 10% increase in vehicle weight increases energy consumption by 7% (Unnewehr and Nasar, 1982; DeLuchi *et al.*, 1987a; this calculation is not shown in Table 6.) The "result" column shows the ratio of powertrain efficiencies for equal-weight vehicles.†

The second consideration in fuel cost is the relative weight of the ICEV and the EV. We have analyzed this as three components: the weight of the EV battery, the difference in weight between EV and ICEV powertrain and related components, and the weight

†The results of Table 6 require one and perhaps two further adjustments. First, the SAE J227a/D cycle is not quite as demanding as the FUDS cycle, and EVs generally are slightly less efficient over the FUDs than the SAE cycle (see † note to Table 6). Second, there is some evidence that the difference between EV efficiency in the lab and in the real world is greater than the similar difference for ICEVs. The EPA estimates that ICEVs are 10% less efficient in real urban driving than as tested in FUDS. In contrast, LaBelle (1984) found that EVs used about 30%–60% more energy in the field than they did on track tests, and Margiotta (1982) also found relatively low efficiency for EVs in actual field use. However, the newer Griffon vans used by the Ontario Ministry of Transportation achieved about 1.33 mi/kwh from the outlet in actual use (Hsu and Duncan, 1988)–better than the 1.04 from the outlet as measured in tests over the TVA urban cycle (Driggans and Whitehead, 1988b). It is thus not clear if advanced EVs would perform significantly worse in the real world than in dynamometer and track tests. In any case, we assume conservatively that these two factors might cancel any likely future relative improvements in EV efficiency, and treat the results of Table 6 as upper bounds.

Table 6. Ratio of efficiency of EVs to efficiency of comparable ICE vehicles

Electric vehicle					ICE vehicle				Result	
Type of EV	Efficiency, mi/kwh			Test wt/ battery wt	Vehicle comparable to EV	Test wt.	Efficiency		Powertrain efficiency EV/ICEV	Reference
	Battery	Outlet	Test†				Mpg	Test		
ELVEC-EV	(4.13)	2.79	SAE D	3600/992	subcompact	2300	33.0	FUDS	6.4	Hamilton (1980b)
Audi	2.30	1.38	city	4630/1100	Audi 100	3500	16.8	city	6.2	Mueller & Wouk (1980)
ETV-1	3.41	—	FUDS	3960/1090	'79 Ply. Horizon	2500	27.6	FUDS	6.4	Kurtz (1981)
ETV-2	3.14	—	FUDS	3920/1066	'79 BMW 320i	2750	26.0	FUDS	5.7	AiResearch (1981)
Tr 2000 EV	(4.63)	3.33	SAE D	2560/400	Year 2000 ICEV	2110	35.6	FUDS	5.5	Carriere et al. (1982)
CitySTROMer	3.51	2.07	SAE C	3671/—	'85 VW Golf GTI	2500	28.3	FUDS	6.0	Driggans & Whitehead (1988a)
Griffon van	(1.66)	1.03	Urban	6775/2500+	'84 GMC vans	4200	17.5	FUDS	5.0	Driggans & Whitehead (1988b)
4-seat BMW	(3.73)	2.35	ECE	3600/584	'86 BMW 3 series	3100	27.0	comp.	5.6	Angelis et al. (1987)
ETX-1	2.99	—	FUDS	3800/1237	'83 Ford Escort	2500	28.0	FUDS	5.3	MacDowell & Crumley (1988)
ETX-II	2.5	—	FUDS	4500/1100	'88 Ford Aerostar	3500	18.0	FUDS	6.1	Ford‡ (1988)

Note: ELVEC EV and Yr 2000 EV data, and corresponding ICEV data, are from computer simulations. Fuel economy for ICEV Audi is from reference. In all other cases, fuel economy data for the ICEVs are from annual EPA emissions and fuel economy reports, using the year and vehicle indicated in the column "comparable vehicles." EV battery efficiencies in parentheses were calculated by dividing the reported efficiency from the outlet by the combined efficiency of the charger and the battery, as reported in the reference.

†FUDS is the Federal Urban Drive Schedule, which is used by the EPA to measure "city" fuel economy. The SAE cycles are urban test cycles designed specifically for EVs. The SAE D cycle has higher average speed and power than the FUDS, but lower maximum speed and power. The SAE C cycle is less demanding than the SAE D cycle. The European ECE cycle is a composite ("comp." for 4-seat BMW) of FUDs and the U.S. highway cycle (Unnewehr and Nasar, 1982).

‡Bates et al. (1988), Patil and Davis (1988), and Stokes et al. (1988).

of any extra support material needed for EVs. The weight of the EV battery is calculated by multiplying the energy density of the battery (Table 3) by the nominal battery capacity needed to supply the desired range, at the calculated vehicle efficiency (we assume that the wh/kg measure includes the weight of battery auxiliaries, but not of the extra structure needed to support the battery).†

An advanced electric powertrain is much lighter than the exhaust system, emission controls, engine, and transmission it replaces. Weight analyses of a 1974 EV Ford Pinto, the ETX-I, and the ETX-II showed that the curb weight of these EVs was 15%, 11%, and 12% less, respectively, than the curb weight of the comparable ICEV, battery support excluded (Unnewehr and Nasar, 1982; Ford and GE, 1987; Stokes et al., 1988). In all these cases, if test (loaded) weight rather than curb (empty) weight were the reference, the percentage reductions would be about 2% less, absolutely. The ETX-I also required 0.07 lb of structural reinforcement, to support the battery, per lb of battery and tray; the ETX-II van apparently has enough strength to support the battery, and so does not need reinforcing. Our assumptions regarding these three components of relative EV weight are shown in Table 7.

Fuel taxes. The final item in the fuel cost-per-mile is fuel tax. The gasoline vehicle base case assumes a national average state and federal tax of 20 ¢/gallon (U.S. Department of Commerce, 1987). The electricity sold at EV recharging stations could be taxed easily, but it would be more difficult to tax electricity used for home recharging: a separately metered household circuit or an on-vehicle meter would be needed. It seems more likely that either the vehicle would be taxed, per year or per mile of travel, or there would be no tax at all (this could be justified by the environmental benefits of EVs). We have assumed no fuel or vehicle tax. If it were assumed that EVs were taxed so as to produce the same revenue-per-mile as the current gasoline tax, the break-even gasoline prices for the EVs would be $0.20/gallon higher than shown here.

Results of the analysis

Based on the input data of Tables 5 and 7, Table 8 shows the total calculated cost per mile of passenger EVs and ICEVs, and the contribution to total cost of the important cost parameters, and Table 9 shows break-even gasoline prices for electric vans and passenger cars. If all low-cost conditions specified here are satisfied—high vehicle efficiency, high battery energy density, low-cost off-peak power, low initial battery cost, long battery cycle-life, long EV life, and low maintenance costs—then EVs will have much lower life-cycle costs than comparable gasoline vehicles, at any gasoline price. In fact, they will be competitive even if gasoline is free. As shown in Table 8, this is because in the low-cost case the bat-

†Because battery weight depends on vehicle efficiency, but vehicle efficiency depends on battery weight, an iterative calculation procedure must be used to ensure that battery weight is specified consistently throughout. Battery weight is first guessed and entered in the formula that calculates efficiency. The resultant efficiency, combined with desired vehicle range and battery energy density, is used to calculate battery weight, and the resultant battery weight is checked against the guess. The guess is adjusted as indicated by the divergence between the guess and the result, and the process is repeated until the guess and the result are the same.

Table 7. Base-case input data and calculated results for EVs

Cost Item	High	Low
Cost of off-peak electricity at the outlet, ¢/kwh	5.00	
Cost of solar electricity at the outlet, ¢/kwh	9.00	
Energy efficiency of the battery charger	0.90	0.95
Energy efficiency of the battery	0.70	0.75
EV powertrain efficiency/ICEV powertrain efficiency	5.50	6.10
Desired urban range, miles, subcompact, at 95% DoD	150	150
Desired urban range, miles, cargo van, at 95% DoD	100	100
OEM battery cost, $/kwh of nominal or rated capacity	110	80
Battery energy density, wh delivered/kg of battery system	100	125
Battery cycle life, at 80% DoD	800	1200
Battery salvage value, percent of initial price	5%	10%
Retail to OEM mark-up factor	1.50	1.40
Initial cost of EV (including charger but not battery) minus initial cost of ICEV, under mass production, $	0	−400
Cost of recharging outlet in new home, $	400	400
Cost of recharging station in new business, $/vehicle	100	100
Amortization period for cost of charging station, years	30	30
EV life/ICEV life	1.25	2.00
Weight reduction, excluding battery and battery support	10%	13%
Lb structural support per lb of extra weight, passenger cars	0.09	0.06
Cost of extra structure, $/lb.	2.00	1.50
Maintenance costs, percent of gasoline vehicle's	75%	50%
Oil costs, percent of gasoline vehicle's	0%	0%
Calculated results		
Battery initial cost, passenger car, $	7200	4000
Battery initial cost, van, $	7000	3900
Passenger car efficiency, mi/kwh from the outlet	2.37	3.38
Van efficiency, mi/kwh from the outlet	1.64	2.22

tery cost-per-mile is almost balanced by the much lower vehicle cost-per-mile of the EV, relative to the ICEV (due to the EV's much longer life), and because EVs have lower fuel and maintenance costs. Even if electricity costs 9 ¢/kwh, EVs still will have a lower life-cycle cost than gasoline vehicles in the low-cost case—in fact, electricity would have to sell for more than 14 ¢/kwh to push the break-even gasoline price above $0.90/gallon in the low-cost case.

However, it is impossible to estimate the likelihood of achieving all the low-cost conditions. Under high-cost conditions, which may be just as probable as the low-cost conditions, EVs will not be cost competitive until gasoline sells for $3–4/gallon. The

Table 8. Cost comparison of gasoline and electric passenger vehicles, calculated results, cents/mi

Cost item	Gasoline vehicle	Electric vehicle: Low	Electric vehicle: High
Energy,† including taxes	3.77	1.48	2.11
Battery	—	4.51	10.56
Initial price	13.94	9.90	12.55
Home recharging station	—	0.39	0.39
Insurance	4.69	4.67	5.21
Maintenance, oil, and tires	4.47	2.44	3.48
Reg., I&M, parking, accessories	1.55	1.38	1.43
Total	28.42	24.77	35.73

†Assuming $0.95/gallon, 5¢/kwh.

great difference between the high and low breakeven gasoline prices is due primarily to uncertainty regarding the battery OEM $/kwh cost, and EV life relative to ICEV life. The effect of the spread between the high- and low-cost estimates of these parameters on the breakeven price is revealed by switching the high-cost and the low-cost estimates in the cost calculations (and keeping all else the same). The results of several such switches are reported in Table 9. For example, if the high and low estimates of battery OEM cost and vehicle life are switched, and the real interest rate is 5% rather than 9%, then the breakeven gasoline price for the subcompact declines from $3.38 in the original high-cost case to $1.15. This result suggests that attempts to more narrowly estimate EV life-cycle costs should focus on reducing uncertainty in the cost of advanced batteries and in the life span of EVs.

Several other important results are shown in Table 9. A lower interest rate or higher initial ICEV cost makes EVs more cost competitive; the former reduces the amortized cost of the battery, and the latter increases the amortized cost of the ICEV, relative to the EV, because of the EV's longer life. Reducing the desired range reduces EV life-cycle cost considerably because it reduces battery costs. And increasing the efficiency of the baseline ICEV makes the EV more competitive because a more efficient EV needs less battery to achieve a given range.

These cost findings should be viewed with two thoughts in mind. First, given the considerable uncertainty in our estimates of EV life-cycle costs, the

Table 9. The price of gasoline (break-even price) equating the life-cycle cost of the electric and the gasoline vehicle

Vehicle	5¢/kwh Break-even, High	5¢/kwh $/gal Low	9¢/kwh Break-even, High	9¢/kwh $/gal Low
Electric van	$2.59	$0.06	$3.06	$0.41
Electric passenger vehicle	$3.38	$0.04	$3.90	$0.40
Uncertainty analysis for passenger vehicles				
200-mile urban EV range	4.54	0.50	5.12	0.88
$8,000 ICEV price	3.56	0.33	4.07	0.69
25.6 mpg, 3000-lb ICEV	3.55	0.35	4.07	0.71
36.6 mpg, 2250-lb ICEV	3.19	−0.35	3.70	0.01
$16,000 ICEV price	3.07	−0.57	3.58	−0.21
5% real interest rate	2.73	−0.44	3.25	−0.08
Switch high/low EV life	2.67	0.71	3.19	1.07
100-mile urban EV range	2.52	−0.36	2.98	−0.02
Switch high/low battery OEM $/kwh	2.45	0.59	2.97	0.95
5% and $16,000	2.41	−1.11	2.93	−0.75
Switch battery costs, EV life	1.75	1.27	2.27	1.63
Switch battery costs, EV life, and battery cycle life	1.29	1.71	1.81	2.07
5%: switch battery cost, EV life	1.15	0.77	1.66	1.13

Note: these break-even gasoline prices assume no fuel tax on the electricity used for recharging. A tax that generated the same revenue per mile as the $0.20/gallon average national gasoline tax would increase all the break-even prices shown here by $0.20/gallon. If the battery were swapped once a month, the break-even prices would be further increased $0.20–$0.50/gallon.

A negative break-even price of $$-x$/gallon means that the life-cycle cost of the EV and the ICEV would be equal if *stations* paid *motorists* $x gallon of gasoline.

low-cost results here may be most usefully viewed as indicating a set of conditions that will make advanced EVs economical. Second, our analysis treats private (consumer) costs only. As discussed in the next section, EVs will greatly reduce air pollution per mile of vehicle travel, in many scenarios. Thus, if EVs have a higher private life-cycle cost than ICEVs, one might ask if the environmental benefits compensate for the higher private cost. This suggests that, in addition to specifying estimates of battery cost and vehicle life more narrowly, researchers should attempt to estimate the costs of environmental damages and include these in a cost analysis.

AIR QUALITY IMPACTS OF ELECTRIC VEHICLES

One of the principal attractions of electric vehicles is the promise of improved air quality. As noted in the introduction to this paper, degradation of air quality continues to be a problem in most urban areas of the United States, and emissions from motor vehicles continue to contribute significantly to the degradation of air quality. Many researchers and policy makers believe that the use of EVs will greatly reduce air pollution from the highway sector. Recently, concern about the greenhouse warming problem also has begun to develop into a major environmental policy issue. In this section, we present the details of our analysis of the impacts of EVs on emissions of regulated pollutants and greenhouse gases.†

Although there have been several previous studies of the air quality impacts of EVs (Hamilton *et al.*, 1974; Marfisi *et al.*, 1978; General Research Corporation and Charles River Associates, 1980; Singh *et al.*, 1980; Carriere *et al.*, 1982; California Air Resources Board, 1985; Hempel and Press, 1988), none of them, because of their age, scope, or intent, provide an up-to-date, comprehensive, detailed, and generalizable characterization of the emissions reductions possible with EVs. The analysis described

†The substitution of EVs for ICEVs also will affect water quality and the production and disposal of solid waste. Evaluations of these environmental impacts depend heavily on the kinds of primary materials used in the battery and the kinds of fuels used to generate electricity. Two major studies by ANL found that EV use would have worse impacts on water quality and solid waste than would ICEV use, but that these impacts likely would be important only at the local level (Sharma *et al.*, 1980; Singh *et al.*, 1980; see also Science Applications Inc., 1977, for an earlier study of the environmental impacts of batteries, similar to the study by Sharma *et al.*). Most of the adverse impacts were caused by the manufacture or disposal of Pb/acid, Ni/Zn, and Ni/Fe batteries, and the production and use of nuclear and coal fuels. Neither study considered more environmentally benign scenarios, such as Na/S batteries and solar power. Research on such scenarios is needed. Hamilton (1981) found that the use of EVs would not reduce urban noise levels significantly.

in the next section is meant to fill this gap. It produces estimates of the percentage changes in emissions per mile resulting from replacing stringently controlled ICEVs with EVs using natural gas- and coal-based electricity, with several degrees of power plant emission controls. With these results, aggregate changes in emissions due to EV use can be estimated for any scenario of EV fuel use and market penetration. To illustrate this, we estimate per-mile emissions from an EV fleet using a projected national mix of electricity fuels in the year 2010.

Methods of the analysis

Emissions from the ICEVs that would be replaced by EVs are a function of the type of emission control, the mileage accumulated by the vehicle, the volatility of gasoline, the sources of emissions considered, the type of inspection and maintenance program, and more. Power plant emissions per mile's worth of energy consumed by EVs during recharging are a function of the type of power plant, the fuel used at the plant, the type of emission control, the efficiency of converting input energy to electricity, the efficiency of electricity distribution, and the efficiency of the electric versions of the replaced ICEVs. With respect to all these considerations (and others), we have bounded our analysis in the following ways.

First, we have limited our analysis to emissions of regulated pollutants: hydrocarbons† (HCs), nitrogen oxides (NO_x), carbon monoxide (CO), particulates (part.), and sulfur oxides (SO_x). Although gasoline vehicles and power plants emit other toxins, carcinogens, irritants, and oxidant precursors—including benzene, which has been receiving increasing attention from regulatory agencies (CARB, 1987)—available data do not permit a more extended comparative analysis.

Second, we have limited our analysis to significant sources of emissions for which there are data: exhaust and evaporative emissions from ICEVs, emissions from refuelling ICEVs and delivering gasoline to service stations, and emissions from powerplants supplying electricity to EVs. Other sources of emissions, such as from the resupplying of bulk gasoline-storage facilities, the recovery and shipping of the primary fuel feedstocks, the plants that manufacture vehicles and batteries, and so on, either appear to be relatively small on a per mile basis [U.S. Environmental Protection Agency (EPA), 1985a] or have not been measured or estimated.

Third, our analysis considers only coal and natural gas feedstocks for power plants. Of the many sources of energy for electricity production in the United States—coal, natural gas, oil, uranium, water, wind, biomass, geothermal steam, waste heat from other energy uses, solar radiation, and more—only coal, natural gas, oil, and biomass plants emit any of the five pollutants considered here (we are ignoring, in general, the environmental and health risks of nuclear power). However, biomass is and will continue to be a negligible input to electricity production, and so can be ignored. Similarly, oil will provide less than 8% of energy input to national electricity generation for the forseeable future (EIA, 1988), and is generally used as a peaking fuel (EVs recharging at night would be supplied by base-load power plants). Natural gas use, on the other hand, is projected to increase substantially by the year 2000 (EIA, 1988).

Fourth, we assume that ICEVs have the most stringent feasible emission controls, use low-volatility fuel, and are subject to inspection and maintenance programs to keep emission controls functioning properly. For EVs we consider emissions from uncontrolled, moderately controlled, and stringently controlled power plants. (It should be noted that the costs of *projected* emission control standards and technologies, for both powerplants and ICEVs, were not estimated in the preceding cost analysis.)

Fifth, we limit the analysis to the two classes of vehicles that can be electrified, given current projections of EV technology: vans (light duty trucks weighing less than 6,000 lb) and passenger cars (light-duty autos). (Light-duty trucks and light-duty autos have different emission factors, and thus require separate analyses.) Medium and heavy trucks typically require more power than electric powertrains are likely to be able to provide, and thus can be excluded. Motorcycles can be electrified, but are an insignificant source of emissions.

Finally, we perform the analysis for the year 2010. We estimate the difference in average emissions per mile between a hypothetical EV passenger car fleet in the year 2010 and the ICEV fleet that would have been in place had no EVs ever been produced. (As discussed below, the results of replacing ICE vans are similar).

Emission factors for ICE passenger cars and vans. In 2010 the replaced ICEV fleet would have consisted of a particular mix of new vehicles, one-yr old vehicles, two-yr old vehicles, and so on, up to the age corresponding to the model year first replaced by EVs. The average emission per mile in 2010 of the hypothetically replaced ICEV fleet is calculated by multiplying the per-mile emissions (discussed below) of each vehicle age class by the contribution of that age class to total fleet VMT, and summing over all age classes. We assume that ICE vans are replaced beginning in 1991, and passenger cars in 1994, and use data in CARB (1988b) to calculate the percentage contribution of each age class to total VMT.

To analyze a stringently controlled ICEV case, we assume that all 1991–1995 model year light-duty

†California regulates total organic gases (TOG) from automobiles, and HC emissions from power plants. TOG is a slightly larger category than HC. We have multiplied CARB TOG figures by 0.901 (CARB's conversion factor) to convert to HCs, for comparison with HCs from power plants.

trucks, and 1994–1995 light-duty autos, meet 1990 California emission standards, which are the most stringent in the nation. (The California NO_x standard is lower than the EPA 49-state NO_x standard, and California requires low-volatility gasoline and vapor recovery controls on gasoline refuelling, which reduce evaporative emissions.) It is likely that within that period the EPA will adopt refueling and gasoline volatility regulations similar to California's (Office of Technology Assessment, 1988). The California Air Resources Board's emission model, EMFAC7D (CARB, 1986, 1988b), estimates exhaust and evaporative emissions from vehicles meeting California standards as a function of the mileage accumulated by the vehicle and other factors. We have used these factors to estimate per-mile exhaust and evaporative (hot-soak and diurnal) emissions from 1991–1995 model year vehicles in 2010, except that we assume a 10% lower rate of increase in emissions with mileage, to represent the effects of I&M programs (EMFAC7D does not account for California's I&M program).

Model year vehicles 1996–2010 are assumed to meet the most stringent feasible exhaust standards for motor vehicles, as determined by Sierra Research (1988). For ICE light-duty autos these are: the 1990 California NO_x standard, an HC standard 30% lower than the 1990 California standard, and a CO standard 50% lower. Accordingly, we assume that in 1996 zero-mile emissions of HC are reduced by 30%, and CO by 50%, with respect to the 1990–1995 levels from EMFAC7D. For light-duty trucks, the most stringent feasible standards were the California NO_x and CO standards, and an HC standard 30% lower than the California Standard. We assume that zero-mile evaporative emissions decline only 10% in 1996, with respect to EMFAC7D's 1990 rate, since the main method of reducing evaporative emissions—requiring less-volatile fuel—has been used in California for many years and is incorporated into EMFAC7D emission factors.

We supplement the CARB data with estimates of SO_x emissions, HC running losses (emitted from the evaporative cannister and the gasoline fuel system when the vehicle is operating, as opposed to hot-soak and diurnal evaporative emissions, which occur when the vehicle is idle), and HC evaporative emissions during refueling (see notes to Table 10a). The final emission factors for the ICEVs hypothetically replaced by EVs in the year 2010 are shown in Table 10a.

Emission factors for electric vehicles. This analysis considers gasfired boilers (steam plants), combined-cycle gas turbines, coal-fired steam plants, and integrated gasification combined-cycle (IGCC) coal plants. At present, most gas-fueled plants are boilers, and virtually all coal-fired plants are steam plants. However, the use of combined-cycle gas-fired plants is expected to grow nationally (EIA, 1988), and by the turn of the century "clean coal" technologies, such as IGCC, may appear in significant numbers.

There are several types of NO_x, SO_x, and particulate control technologies for power plants (CO and HC emissions can be controlled by oxidation catalysts, but typically uncontrolled HC and CO emissions from power plants are quite low and do not require controls). This variety, combined with the relatively slow turnover of power plants, makes it more difficult to establish emissions scenarios for power plants than for ICEVs. Consequently, we estimate power plant emissions at three levels of control: no controls, moderate controls, and stringent controls. These scenarios, and our assumptions regarding power plant, electricity distribution, and EV efficiencies, are specified in the notes to Table 10b. The efficiency of the EV is estimated as a multiple of the efficiency of the ICEV to ensure consistency of specification, using the data of Table 6.

Table 10b shows the percentage change in emissions per mile of each of the five pollutants, resulting from substituting the EV passenger car fleet emission factors, calculated as described above and in the notes to Table 10b, for the ICEV passenger car fleet emission factors of Table 10a, for four kinds of power plants and three power plant control scenarios.

Results

The results of Table 10b show that on a per-mile basis electric passenger cars will nearly eliminate emissions of CO and HC, with any of the four kinds of power-generating plants analyzed, with no emission controls. NO_x emissions will be reduced substantially if at least moderate controls are used. Particulate emissions also will decrease if at least

Table 10a. Fleet emission factors for ICE passenger cars and vans,† gm/mi, year 2010

	Passenger cars	Vans
HC	0.80‡	0.87‡
CO	8.36	11.79
NO_x	0.74	0.91
SO_x	0.05§	0.09§
Part.	0.01	0.01

†Passenger vehicles are assumed to achieve 30.5 mpg in combined city/highway driving; vans, 19.0, as per discussion in cost analysis.

‡HCs include basic exhaust emissions, and running, hot-soak, diurnal, and gas-station evaporative emissions. Running losses are assumed to be 70% of hot soak and diurnal losses, per Federal Test Procedure (slightly less than the 75% measured by Simkins, 1987). Gas-station emissions (from vehicle refuelling and tanker deliveries) are assumed to be 0.7 gm/gal, from stations with Stage I and Stage II vapor recovery (Sierra Research, 1988).

§Gm/mi of SO_x can be approximated by multiplying grams of sulfur per gallon of gasoline by ICEV gallons/mile efficiency and then by two (S to SO_2), since most of the sulfur in gasoline is oxidized to SO_2. Gasoline contains about 0.03% sulfur by weight (Braddock, 1981).

Table 10b. Percentage changes† in emissions per mile resulting from replacing ICE passenger cars with EVs, for three power plant emission control scenarios, in 2010

Pollutant	Natural gas plants: Turbine NC‡/MC§/SC‖	Natural gas plants: Steam plant NC‡/MC§/SC‖	Coal plants: Steam plant NC‡/MC§/SC‖	Coal plants: IGCC¶
HC	−93	−99	−99	−99
CO	−98	−99	−98	−99
NO_x	−28/−82/−93	+8/−73/−89	+95/−51/−80	−86
SO_x	−98	−98	+7470/+657/+51	+26
Part.	+80	−69	+8690/−12/−82	−39

Note: Steam coal, steam gas, and IGCC plants assumed to be 36% efficient in the year 2010 (Hottenstine *et al.*, 1985; Spencer *et al.*, 1986); gas turbines, 40% (CARB. 1988a); and electricity distribution, 91% (EIA, 1988). EV mi/mmBtu (from the outlet) assumed to be 3.7 times greater than ICEV mile/mmBtu (of gasoline) (Table 6).

†Relative to the ICEV emission factors of Table 10a.

‡No controls. Uncontrolled emission factors (not shown) for gas boilers and conventional coal steam plants from EPA's AP-42 (EPA, 1985a). Uncontrolled gas-turbine emissions from CARB (1988a). SO_x emissions as SO_2, NO_x as NO_2.

§Moderate controls: 75% NO_x reduction, relative to uncontrolled emissions, from water injection, fuel gas recirculation, low-NO_x burners, thermal de-NO_x, overfire air, etc., singly or in combination (EPA, 1985a; McCartney *et al.*, 1987; CARB, 1988a): 90% SO_x reduction from scrubbers (EPA, 1985a; EIA, 1987; Ellison and Sedman, 1987; Weir, 1987; CARB, 1988a) and 99% particulate reduction from baghouses (EPA, 1985a; CARB, 1988a). Coal assumed to be 1.39% sulfur by weight, and contain 10,500 Btu/lb (1986 U.S. averages, EIA, 1987).

‖Stringent controls. 90% NO_x reduction from selective catalytic reduction (Ellison and Sedman, 1987; McCartney *et al.*, 1987; CARB, 1988a); 98% SO_x reduction from scrubbers and 99.8% particulate reduction from baghouses (see references in note §). Coal characteristics as in note §.

¶Data for IGCC based on emissions tests of pioneer 120 MW Texaco IGCC plant at Southern California Edison's Cool Water Station (Wolk and Holt, 1988). We have interpolated between SO_x emissions reported for 0.5% and 3.0% S coal to approximate SO_x emissions from 1.39% S coal. NO_x controlled by steam injection. Most sulfur removed before combustion.

moderate controls are used. SO_x emissions will be practically eliminated if natural gas is used, but will increase if coal is used—by several fold, in the case of uncontrolled or moderately controlled coal steam plants. It should be noted that at present light-duty autos and trucks are a major source of HC, CO, and NO_x emissions, but a very minor source of SO_x and particulates. Thus, a large decrease in HC, CO, and NO_x emissions from these vehicles would result in a significant change in ambient air quality, while a moderate increase in SO_x emissions would not.

If emissions due to electric vans were compared to the van (light-duty truck) emission factors of Table 10a, the results would be similar to the passenger car comparison just discussed. The main difference is that electric vans emit more particulates than electric passenger cars (because all EV emissions are inversely proportional to vehicle efficiency, and vans are less efficient than passenger vehicles), but ICE vans and passenger cars emit the same amount of particulates.

For illustrative purposes, we have calculated the percentage changes in per-mile emissions for an EV fleet (70% passenger cars, 30% vans) drawing from a projected national power mix in the year 2010, with moderate controls (Table 11). We assume that 40% of the electricity used by EVs comes from coal steam plants, 10% from IGCC plants, 9% from combined-cycle gas plants, 9% from gas boilers, and 32% from nonfossil sources (nuclear, hydro, and solar; nonfossil plants, of course, have no emissions). [The EIA's (1988) projection for the year 2000 is 54% steam coal, 3% gas combined-cycle, 10% gas boilers, 26% nonfossil, and 7% oil]. Again, there are large reductions in HC, CO, and NO_x emissions. SO_x and particulate emissions increase by several factors, due to only partial control of these emissions from coal steam plant plants, but as noted above the baseline contribution to these pollutants by ICEVs is relatively small.

Greenhouse gases

Fossil-fuel-burning power plants emit several greenhouse gases, as well as the regulated pollutants

Table 11. Percentage changes in emissions per mile, relative to gasoline base case (Table 10a), with an EV fleet using a projected electricity fuel mix for the year 2010, with moderate power-plant emission controls†

HC	−98.9
CO	−98.7
NO_x	−60.9
SO_x	495.8
Part.	570.5

†50% of all natural gas plants and steam coal plants have stringent NO_x controls (90% reduction), and 25% have moderate controls (75% reduction); 85% of steam coal plants obtain 95% and 99.5% reductions in emissions of SO_x and particulates, respectively.

discussed above. Emissions of these gases, relative to emissions from the use of gasoline and diesel fuel, depend on the source of power. Elsewhere (DeLuchi *et al.*, 1987b), we have estimated emissions of three important greenhouse gases—carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O)—from the production and transmission of power plant fuels and the generation of electricity. Table 12, based on that work, shows the results of substituting EVs for ICEVs, expressed as percent change per mile in emissions of a composite greenhouse gas (CO_2 emissions plus N_2O and CH_4 emissions converted to the amount of CO_2 having the same temperature effect). On a per-mile basis, the use of coal-fired power by EVs would cause a moderate increase in emissions of all greenhouse gases, relative to current emissions from the use of gasoline and diesel fuel. If natural gas were used, there would be a moderate decrease in emissions of greenhouse gases, primarily because of the low carbon-to-hydrogen ratio of natural gas. With natural gas use, emissions of CH_4 contribute significantly to the total of CO_2-equivalent emissions and make the reduction relative to gasoline less than it would have been had only CO_2 emissions been estimated. If nonfossil fuels (nuclear, solar or hydropower, or biofuels) were used, there would be essentially no emissions of greenhouse gases. Interestingly, if all these feedstocks (and oil) were used in the proportions they were nationally in 1985, emissions of greenhouse gases would be about the same as from the use of gasoline and diesel fuel in 1985.

In the greenhouse study, we concluded that of all the commonly considered alternatives to gasoline- and diesel-fueled vehicles, EVs using nonfossil power may offer the best opportunity to reduce or eliminate emissions of greenhouse gases from the highway sector. ICEVs using hydrogen made from water and nonfossil power also would emit only negligible amounts of greenhouse gases, but hydrogen vehicles are not likely to be commercially available as soon as EVs. ICEVs using methanol or natural gas derived from biomass likewise would emit only small amounts of greenhouse gases, but the biomass resource base is limited and the use of biofuels is much more polluting than the use of clean power by EVs (see DeLuchi *et al.*, 1988), and demands careful soil management (see Sperling, 1988). Therefore, the use of nonfossil electricity to power EVs could be an important strategy for reducing global warming.

Table 12. EV per-mile emissions of a composite measure of greenhouse gases, relative to ICEVs

EV power source	% change
Nonfossil electric plants	−100†
New natural gas plants	−18
1985 U.S. power mix	−1
New coal plants	+26

Note: See also Adams and Harvey (1988) for a discussion of the greenhouse effect and EVs.

†The EV case ignores, in the case of nuclear power, emissions of greenhouse gases from the use of energy to mine, transport, and process uranium.

RECHARGING ELECTRIC VEHICLES

Even if advanced EVs prove to be as high performing and economical as can be hoped, and are favored by public policy for their environmental benefits, there still will be one significant obstacle to very widespread consumer acceptance of EVs: the long recharging time. The difference between an eight-hr recharging time and one close to the time required to refuel a gasoline vehicle probably determines whether EVs gain a major share of the motor vehicle market in the United States.

The need for fast recharging

Most analyses of EVs assume that EVs would be recharged at home, after the work day, when the vehicle was parked for the night. Recharging would take 6 to 12 hours, depending on the current available from the house, the capacity of the charger, and the charging profile (i.e. the sort of taper and low-charge periods used). The advantage of this recharging scenario is that no new infrastructure would be required to recharge EVs. However, under this scenario EVs likely would be limited to the role of second or third car in multicar, home-owning households, because most households would want at least one vehicle that could make long trips without having to stop for eight hours to recharge, and, for the following reasons, because most renters probably would not buy EVs: a greater proportion of rental units do not have sufficient electrical service, compared to owner-occupied units, and do not have access to a private recharging outlets in the parking areas; and renters typically have only one car, which, as suggested above, is not likely to be electric (Kaiser and Graver, 1980)—unless outside, fast recharging is available. Furthermore, it is also possible that the recharging time of the EV in some cases will make it unacceptable even as a second vehicle: the users of the designated commuter vehicle in a multicar household may wish to have the *option* of making the long trips beyond the capacity of an EV, even if the second vehicle rarely is used for such trips.

In sum, the most important attribute of advanced EVs—even those with a range of 150 miles in the city, and perhaps up to 250 miles on the highway—is their recharging time, not the extent to which their range between charges is still less than a gasoline vehicle's. If EVs cannot make very long trips (e.g. San Francisco to Los Angeles, or New York to Washington, D.C.) in a single day, they may lose a substantial share of the passenger vehicle market.

On the other hand, if EVs can be recharged quickly at public stations, this limitation will not apply, and EVs will be suitable for all applications except those requiring more power than even advanced batteries can provide. What, then, are the prospects for fast recharging? Three types of quick recharging schemes have been proposed: (1) battery swapping, in which a depleted battery is replaced with a fully charged one; (2) ultra-high power recharging of depleted batteries; and (3) the use of metal/air batteries. In all three, battery energy can be restored in minutes, rather than hours. However, all three involve considerable technical and economic difficulties.†

Battery-swap stations

At a battery-swap station a motorist would pull into a stall, where the discharged battery would be removed from its compartment and a fully charged one installed. The exchange would take only a few minutes, and thus theoretically would make EV recharging as fast and easy as refueling a gasoline vehicle. The motorist would pay a fixed fee for the exchange and the energy in the new pack. Ideally, the motorist would receive credit for the energy remaining in the discharged pack. Discharged packs would be recharged at night, during off-peak, low-price hours, to the extent that the inventory of charged packs permitted.

There are no major technical barriers to the establishment and operation of battery swap stations. However, there are several institutional and economic problems (Bradford and Buss, 1977; Weeks, 1978; Black and Oxley, 1979; Pornin, 1979; Kaiser and Graver, 1980; Mueller and Wouk, 1980). First, battery packs, compartments, and connections would have to be relatively standardized, or at least limited to a few common configurations, so that almost any pack could be installed quickly in almost any vehicle. This would require a modest amount of cooperation between battery and vehicle manufacturers.

†Mueller and Wouk (1980) have suggested "biberonnage" (also referred to as "topping off")—recharging an EV when temporarily stopped, whenever and wherever possible, over the course of a day—as an alternative to battery swapping. Their experiments and calculations indicate that the daily range of the vehicle can be more than doubled. Kaiser and Graver (1980) estimate that the fee per recharge at a recharge station would be between $2 and $11 (US 1985), depending on the number of recharges per stall per day, and the average amount of energy per recharge. While biberonnage clearly can increase vehicle range, we feel that with the advent of high-capacity batteries and vehicles with a 150-mile urban range, it cannot do for EVs what battery swapping, fast recharging, or mechanical recharging can do: permit very long one-day trips. On the one hand, a 150-mile range on one overnight charge at home is quite adequate for virtually all urban applications, and thus makes "topping off" around town unnecessary for those with home recharging. On the other hand, about eight hours of biberonnage would be required during a 400-mile trip, and, as claimed above, it is reasonable to assume that most people would want at least one vehicle capable of making long trips without stopping for so long. With biberonnage only, that vehicle must be an ICEV; with battery swapping, fast recharging, or mechanical recharging, that vehicle can be an EV.

Second, there would have to be some form of accounting for the fact that exchanged packs might be of vastly different age and quality. Otherwise, individuals with new batteries would be reluctant to trade. To avoid this, battery packs would have to be owned by the swapping stations (which in effect would be battery-distribution centers) and leased to the drivers.‡ Leasing would reduce the initial cost of EV ownership, but increase life-cycle cost, because of the administrative costs and profit requirement of the lessor. It also would provide a means of assigning liability.

Third, battery swapping probably would be relatively expensive. The nonenergy costs are likely to be higher than those of a petroleum station because of greater capital, land, and labor costs (Bradford and Buss, 1977; Weeks, 1978). It has been estimated that a battery swap would cost between $4 and $10 ($US 1985; excluding the cost of electricity), depending on the size of the station, the frequency of swaps (which in turn depends on the range of EVs, and their use), and the rate of recharging (Kaiser and Graver, 1980; Carriere *et al.*, 1982; see also Pornin, 1979). If battery swapping did cost this much, and electricity cost between 7 and 9 ¢/kwh, then swapping once a month, to extend interurban trips, would add $0.20 to $0.50/gallon to the base-case breakeven prices calculated earlier (for the same yearly mileage). In other words, the additional cost per mile of swapping once a month, instead of home recharging, would be equivalent to a $0.20–$0.50/gallon increase in the price of gasoline.

It is difficult to make an overall assessment of battery-swapping. While none of the problems discussed above by themselves necessarily make battery swapping infeasible—institutional arrangements theoretically can handle the first two, and the cost of battery swapping would in the best case add only $0.20/gallon to the break-even prices for EVs—they may in aggregate result in enough restrictions, or place enough demands on motorists, to make battery swapping unattractive, especially in the high-cost scenario. Certainly, a scheme in which motorists recharged EVs the same way they refueled gasoline vehicles would be preferred for its familiarity and flexibility.

Fast recharge of electric vehicles

The EV analogy to gasoline refueling would be extremely fast recharging. A motorist would drive into a recharging station, get connected to an ultra-high-power charger, charge for a short period of time, be disconnected, and leave. The time required to recharge would depend on the charging power and the capacity of the battery. Faster charging

‡Even if battery packs were leased, motorists still would prefer new batteries to old ones because batteries lose capacity as they age. In some cases a motorist with a very old pack might have to make a special trip to a battery-swapping station simply to replace the pack.

would require higher power, which would require more current and more expensive equipment. Station operators presumably would offer the power capabilities and recharging options that best approximated the average consumer tradeoff between charging cost and time, within technical constraints. For this discussion, we assume that it would be desirable to reduce recharging time to as short as 20 minutes.

Fast recharging would have several major advantages over battery swapping: no battery inventory would be required, standardization of battery compartments and sizes would not be necessary, and there would be no restrictions on battery ownership. It would be procedurally familiar to motorists. Unfortunately, ultra-fast recharging has not been analyzed or even characterized in detail. Below, we outline the major issues.

At the national level, the development of fast recharging probably would not be restricted by the generating capacity of electric utilities, assuming that fast-charge stations would be used primarily by drivers making all-day, interurban trips. (This seems plausible, given that a 150-mile urban range on one charge would be adequate for practically all intraurban trips.) Even if fast recharging supplied the energy required for *all* the miles of travel that could not be supplied by overnight charging, and was concentrated in the middle of the day, total peak power demand probably would be less than 1% of U.S. summertime generating capacity.†

Fast-recharge installations themselves are technically feasible, although they would require large and specialized electrical equipment to handle the great currents: huge rectifiers and transformers, large fans to cool the equipment, and sodium-filled steel pipes to withstand the large magnetic forces (Ayres and McKenna, 1972). The size and weight of components connecting the power source to the batteries also would increase dramatically with the current flow.

The cost of fast-charge installations has not been estimated (Pornin, 1979, has estimated the cost of stations providing a 90-minute recharge, which we consider to be too long). However, if the cost of quick charging is comparable to the cost of battery swapping, which seems reasonable as a first approximation, then quick charging would add about \$0.20–\$0.50/gallon to the break-even prices estimated here. As noted above, this would not change the results of this cost analysis qualitatively, in the low-cost scenario.

The key issues in ultra-high power recharging center on the battery. Charging rate, or power, is the product of voltage and current. The charging voltage cannot exceed the maximum battery terminal voltage, which generally is 250 volts or less. The charging current cannot exceed the current-carrying capacity of the cell, or generate so much heat that the temperature sensors installed to prevent overheating shut down the charging process. The primary technical issue, then, appears to be whether cells can be designed with low enough resistance and high enough current-carrying capacity to receive currents on the order of 600 amps (625 amps of dc current are required to deliver 50 kwh to a 240-volt battery in 20 minutes).

It appears that batteries can be designed for ultra-high power (20-minute) recharging. Beck *et al.* (1988) state that experiments with Li-me/Fe-S batteries have shown 70% charging in 30 minutes, and imply that the same is possible with Na/S batteries. Researchers at ANL believe that with present Li-me/Fe-S cell technology an 80% charge in 30 minutes is possible, and that with R&D on fast recharging, 90% in 20 minutes might be possible (Chilenskas, 1988). The rapid delivery of more than 90% of a complete charge appears unlikely because of the need to precisely regulate current distribution to the cells as the battery nears a full state of charge. Similarly, developers of the Na/S battery at Chloride Silent Power in England believe that 20-minute recharging is electrochemically possible in principle (Mangan, 1988). A Na/S battery designed for fast recharging would be different from the batteries currently under development: it would have larger internal cabling to handle the higher current flows; lower-resistance cells; a redesigned sulfur electrode;

†To estimate national energy requirements of fast recharging stations, first estimate the amount of total VMT that could *not* be supported by *slow* charging, assuming a one-charge highway range of about 210 miles for future EVs. In 1977 there were 186 million vehicle trips over 200 miles (round trip), for a total of 104 billion VMT (round trip), by passenger vehicles and light trucks without camping equipment (U.S. Department of Commerce, 1979; we assume all other vehicle applications could not be electrified). Assuming that EVs would depart on such trips with a full charge (overnight, at home; enought for the first 200 miles), and return with relatively little energy (say 50 miles worth), because of the greater convenience and lower cost of home recharging, then 150 miles × 186 million vehicle trips = 26 billion VMT can be deducted from the 104 billion figure above. Furthermore, in 1977 79% of the trips had one or more overnight stops (U.S. Department of Commerce, 1979); in the EV scenario, overnight charging would be available at some of these stops (friends' houses, motels, and campgrounds). Assume conservatively that 25% of the VMT beyond the first 200 miles could be supported by overnight charging. This allows for another deduction of 22 billion VMT (including 25% of the 50-mile range leftover upon return). Thus, fast recharging would be applicable to 56 billion VMT in 1977—66 billion in 1985, at the same percentage of passenger and auto VMT.

Assuming that the EV fleet averaged 3 mi/kwh from the outlet in highway driving [which, given that EVs are about 3.6 times more efficient than ICEVs in end-use (Table 6), corresponds to 30.5 mpg for an ICEV fleet in *highway* driving], then 22 billion kwh would be required for fast recharging nationally, at 1985 national VMT, or 60 million kwh daily. If it is further assumed that the typical daily peak demand for fast recharging energy would be 30% of the total daily demand in the middle 3 hours (12.5%) of the day, then the peak power required would be about 6 million kw (6,000 mw). In 1985 U.S. summertime generating capacity was 655,000 mw (EIA, 1988).

and more electrolyte area, among other things. Fast recharging would not harm battery cells because charging would be shut off if the temperature or the voltage were too high.

In the final analysis, then, the most important open issue in fast recharging schemes may be the performance and life-cycle cost of batteries designed to accept ultra-fast charges. As noted above, batteries designed to accept very fast rechargers would have heavier cells and the internal cabling, and in some cases more electrolyte area, which would increase battery weight and reduce specific energy. Furthermore, these changes would probably increase the cost of the battery, relative to batteries not designed for 20-minute charging. Given that Na/S and Li-me/Fe-S batteries offer only minimally acceptable performance, relative to ICEV performance, and will be economical only in the most optimistic scenarios, any potential reduction in performance and cost-effectiveness is a serious concern.

Metal/air batteries

If metal/air batteries are developed successfully, EV recharging will be fast and easy, and require little, if any, dedicated infrastructure. If the aluminum plates could be replaced every 2,000 miles, as hoped, replacement could be handled like changing the oil in an ICEV, as opposed to refueling with gasoline. A supply of plates could be stored at home or in the vehicle or bought as needed from (presumably) a variety of stores; just as engine oil is available in grocery stores, department stores, automotive stores, etc. The more frequent servicing of the electrolyte system in metal/air batteries would require only a supply of water and a place to dispose of the precipitate. This presumably could be accommodated quite easily at existing gasoline stations.

In summary, EVs will never have more than a minor overall role in U.S. transportation *unless* the preferences of the driving population change considerably or fast refueling is possible. A long recharging time, by itself, makes it likely that the great majority of U.S. households would desire at least one non-battery-powered vehicle. If repowering time could be reduced to the point where it was no longer an inconvenience, without compromising battery life or performance, and at a reasonable cost—either by ultra-high-power recharging or the use of metal/air batteries—then EVs would become much more attractive. In fact, they could prove to be a viable alternative to gasoline vehicles in most applications.

SUMMARY AND CONCLUSION

If progress continues as expected, electric passenger vehicles with lightweight, efficient ac motors and high-performance batteries will have a city range of at least 150 miles, a cruising speed of at least 70 mph, and be able to accelerate as quickly as some comparable ICEVs. If all low-cost projections are fulfilled, EVs will have considerably lower life-cycle costs than comparable ICEVs, at most likely interest rates and electricity prices, even allowing for high vehicle taxes and occasional recharging away from home. Thus, by the turn of the century, EVs could be viable second cars in multicar households. Electric vans are expected to be attractive in fleet applications sooner. And although the successful commercialization of such EVs is far from guaranteed, no longer does it depend on breakthroughs—successful market penetration probably would result if incremental progress typical of the last 10 years continues, and if the lower-bound cost estimates are realized. This success would be very beneficial environmentally, because EVs would practically eliminate HC, CO, and NO_x air pollution attributable to highway travel, assuming stringent control of power plants emissions, and also could reduce emissions of greenhouse gases. These substantial environmental benefits, and the improving prospects for EV marketability, warrant policies and incentives promoting EV development and use.

The availability of an economical means of quickly recharging EVs, or the successful development of mechanically rechargeable batteries, may be the most critical factor in the future of EVs and could mean the difference between a minor and major role for EVs in transportation. Therefore, as R&D on powertrains and batteries continues, and the commercialization of advanced EVs draws near, R&D work on charging systems, and the cost and performance of batteries designed to accept very fast (20-minute) recharges, should commence. The development of a suitable infrastructure and the successful completion of advanced EV development programs will bring the electric vehicle dream much closer to reality.

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