2. A. J. Krupnick and P. R. Portney, *Science* **252**, 522 (1991).
3. E. L. Glover and D. J. Brzezinski, "MOBILE4 Exhaust Emission Factors and Inspection/Maintenance Benefits for Passenger Cars" (Tech. Rep. EPA-AA-TSS-I/M-89-3, U.S. Environmental Protection Agency, Washington, DC, 1989).
4. E. M. Fujita *et al.*, *J. Air Waste Manage. Assoc.* **42**, 264 (1992); E. M. Fujita, J. C. Chow, Z. Liu, *Environ. Sci. Technol.* **28**, 1633 (1994); W. R. Pierson, A. W. Gertler, R. L. Bradow, *J. Air Waste Manage. Assoc.* **40**, 1495 (1990).
5. N. Oreskes, K. Shrader-Frechette, and K. Belitz [*Science* **263**, 641 (1994)] argue that large computer models with multiple inputs should probably never be considered "validated." In Pennsylvania the EPA model was run with 27,000 inputs specific for each county. H.-C. Scherrer and D. B. Kittelson (Society of Automotive Engineers Tech. Pap. Ser. 940302, February 1994) have examined the impact of the centralized emission program implemented in 1991 in the Minneapolis–St. Paul metropolitan area. On 23 March 1995, testifying before the Subcommittee on Oversight and Investigations, Committee on Commerce of the U.S. House of Representatives, they stated: "What Minnesota has implemented is a mandated program that works in the computer models used by EPA to make public policy—not in the real world. This lack of linkage between EPA's model and real-world measurements leads to inappropriate policy decisions and wastes scarce resources. If we want to maintain public support for programs that claim to reduce air pollution, those programs must do what they claim in the real world, not just in the virtual world of the computer modeler."
6. J. G. Calvert, J. B. Heywood, R. F. Sawyer, J. H. Seinfeld, *Science* **261**, 37 (1993).
7. The remote sensor takes a 0.5-s snapshot of the infrared absorption of $CO_2$, CO, and HC in the exhaust gases behind a moving vehicle to determine the percent of these gases in the undiluted exhaust. A video camera records each license plate number so that the make and model year can be determined through state motor vehicle records [G. A. Bishop, J. R. Starkey, A. Ihlenfeldt, W. J. Williams, D. H. Stedman, *Anal. Chem.* **61**, 671A (1989); L. L. Ashbaugh *et al.*, in (*23*), pp. 885–898; D. R. Lawson, P. J. Groblicki, D. H. Stedman, G. A. Bishop, P. L. Guenther, *J. Air Waste Manage. Assoc.* **40**, 1096 (1990)].
8. D. H. Stedman *et al.*, "On-Road Remote Sensing of CO and HC Emissions in California" (Final Report, Contract A032-093, California Air Resources Board Research Division, February 1994).
9. Diesel-powered vehicles with ground-level exhaust systems were also measured by the remote sensor; they are always low emitters of CO and HC because the diesel combustion process occurs in the presence of excess air. We pulled over several gross polluters that were registered as diesel-powered (and thus exempt from the IM program) but were actually gasoline-powered and lacked any of the required emission controls. Heavy-duty diesel vehicles with elevated exhaust systems were not measured.
10. G. A. Bishop and D. H. Stedman, *Encyclopedia of Energy Technology and the Environment* (Wiley, New York, 1995), pp. 359–369.
11. T. C. Austin, F. J. DiGenova, T. R. Carlson, "Analysis of the Effectiveness and Cost-Effectiveness of Remote Sensing Devices" (Sierra Research Inc., Report to U.S. Environmental Protection Agency, May 1994).
12. This portion of the study was carried out with the cooperation of the California Bureau of Automotive Repair, the California Air Resources Board, and the EPA Mobile Source Emissions Research Branch.
13. D. R. Lawson, *J. Air Waste Manage. Assoc.* **43**, 1567 (1993); *ibid.* **44**, 121 (1994).
14. K. T. Knapp, in (*23*), pp. 871–884.
15. Increased vehicle prices may lead to decreased new car purchases, which may lead in turn to an older fleet. On average, older fleets produce higher emissions. Chrysler Corporation has stated that it will impose a surcharge that could exceed $2000 on all its new vehicles sold in California in 1998; the surcharge would allow Chrysler to offer a $45,000 electric minivan for around $18,000 so that Chrysler could sell enough of them to satisfy state laws ("Chrysler Electric Surcharge," *Rocky Mountain News*, 1 October 1994. p. 63A). Even electric vehicles, whose tailpipe emissions are zero, require electric power generation and have expensive batteries that require eventual replacement. Electric vehicle owners who continue to drive with weak batteries will cause traffic congestion, leading to an increase in the per mile emissions of the gasoline-powered vehicles in the fleet. This possibility is not considered in any model of future emissions from fleets containing realistically maintained electric vehicles.
16. R. M. Rueff, *J. Air Waste Manage. Assoc.* **42**, 921 (1992).
17. California Environmental Protection Agency, "Air Resources Board Staff Report, Proposed Amendments to the California Phase 2 Reformulated Gasoline Regulations, Including Amendments Providing for the Use of a Predictive Model" (22 April 1994).
18. OXY_EF_2 data provided by the Mobile Source Division, U.S. Environmental Protection Agency, Ann Arbor, MI.
19. "SCRAP, a Clean Air Initiative from UNOCAL" (Unocal Co., 1991); "SCRAP2" (Report to South Coast Air Quality Management District, 1994).
20. This is a conservative estimate. We assume that all pre-1980 vehicles can be purchased for only $700 each, the next 8 million newer vehicles for $1000 each, and the newest 3.4 million vehicles for $2000 each.
21. G. A. Bishop, D. H. Stedman, J. E. Peterson, T. J. Hosick, P. L. Guenther, *J. Air Waste Manage. Assoc.* **42**, 2 (1993).
22. The cost of on-road monitoring is assumed to be $20 per gross polluter identified, on the basis of a cost of $0.50 per remote sensing test and a two-test identification requirement. Economies of scale may bring testing costs down to $0.16 per test when only gross polluters need to be identified [W. Harrington and V. D. McConnell, in *Cost Effective Control of Urban Smog* (Federal Reserve Bank of Chicago, November 1993), pp. 53–75].
23. J. C. Chow and D. M. Ono, Eds., *PM10 Standards and Nontraditional Particulate Source Controls, AWMA/EPA International Specialty Conference*, *Vol. II* (Air and Waste Management Association, Pittsburgh, PA, 1992).


24. Supported by the California Air Resources Board, EPA, the American Petroleum Institute, the Coordinating Research Council, and the Colorado Office of Energy Conservation. The opinions expressed are solely those of the authors.


# Environmental Implications of Electric Cars


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California and the Northeast states have passed laws requiring that 2% of model year 1998 cars must be "zero emissions" vehicles—that is, electric cars (*1*). Required sales of electric cars are to increase after 1998. Electric vehicle technology has the advantage that it produces no air pollution at the point of use, so that if the electricity is generated in a distant place, electric cars are a means of switching the location of environmental discharges. A large crowded city such as Los Angeles or New York has large amounts of discharges, even if care is taken to protect the environment, because the millions of gasoline-powered vehicles in such cities emit large quantities of carbon monoxide, nitrogen oxides, and volatile organic compounds. Electric vehicle technology can move emissions to less crowded and less polluted locations. Centralized electric generation plants may also be able to achieve fewer emissions per vehicle mile than do internal combustion engines in vehicles (*2*).

The environmental effects of internal combustion engines are well known. Pollution controls have lowered emissions from a controlled car by 98% as compared with those from an uncontrolled car. For electric vehicles, generating electricity for recharging batteries can cause considerable environmental harm (*3*). Analyses have been done on the environmental effects of gasoline as compared with those of electricity generation (*2*). In response to the electric vehicle mandate, automakers have proposed ultralow emissions vehicles.

We focus on the environmental consequences of producing and reprocessing large quantities of batteries to power electric cars. For vehicles that are to be mass produced in late 1997, lead-acid batteries are likely to be the only practical technology. Smelting and recycling the lead for these batteries will result in substantial releases of lead to the environment. Lead is a neurotoxin, causing reduced cognitive function and behavioral problems, even at low levels in the blood (*4*). Environmental discharges of lead are a major concern. For example, eliminating tetraethyl lead (TEL) from U.S. gasoline greatly reduced blood-lead levels in children (*5*).

Alternative battery technologies that are currently available include nickel-cadmium and nickel metal hydride batteries, which are much more expensive than lead-acid batteries. In addition, nickel and cadmium are highly toxic to humans and the environment. Technologies such as sodium-sulfur and lithium-polymer batteries are unlikely to be commercially available for years.


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## Characteristics of Electric Vehicles and Batteries

A gasoline engine supplied with a 40-liter tank (less than 11 gallons) giving 15 km/liter (about 35 miles per gallon) allows a range of 600 km (about 375 miles). A kilogram of gasoline is equivalent to 13,000 watt-hours (Wh); in contrast, a typical lead-acid battery contains only 38 Wh per kilogram. Even adding in the engine, transmission, and so forth, a gasoline-powered car has more than seven times the range of an equivalent electric car using current technology.

The large weight of batteries needed to supply energy means that an electric car will be heavier, will cruise at lower speeds, and will have much less range than an equivalent gasoline vehicle (6). The focus of electric vehicle design is thus an extremely light-weight vehicle that is capable of carrying the batteries.

Range, acceleration, average velocity, and discharge rate for an electric vehicle are critical design and operation parameters (7). The practical range of a vehicle is less than the theoretical maximum range (8). Drivers must accelerate and stop, and they drive faster than the speed that maximizes range. Even with regenerative braking, starting and stopping decrease range. In addition, parasitic losses such as those from an air conditioner, heater, radio, and headlights decrease range. Fully discharging the battery at each cycle reduces overall battery life.

We considered a range of representative scenarios of battery and driving characteristics for a small automobile powered by lead-acid batteries (Table 1). These represent a current technology and technology goals for battery energy density and available charge-discharge cycles before replacement (*1*, 9).

The vehicle energy requirement (row 3 in Table 1) is a measure of performance, representing the average energy required for distance traveled. The required energy will vary with vehicle efficiency, driving demands, vehicle weight, and other characteristics. For example, parasitic losses can use 10 kWh per hour of operation if the heater or air conditioner is being used along with the headlights, radio, or power steering, and this would dramatically increase the energy requirements shown in Table 1. A car going 8 km/hour [5 miles per hour (mph)] in a snow storm could have a range of less than 24 km (about 15 miles), because of the parasitic losses and the reduced energy available from the battery because of low temperatures.

We assume an average distance per driving cycle of 80 km (50 miles). The maximum vehicle range would be higher, but discharging the batteries excessively in each charge cycle would reduce the battery life and the ultimate number of life-cycle miles. In addition, a driver would not risk running the battery to exhaustion on the road.

Direct comparison between the battery and vehicle assumptions shown in Table 1 and existing electric vehicles is difficult because of proprietary considerations and driving assumptions. For example, the range of a vehicle can be increased by elimination of accessory power drains and by careful driving to reduce acceleration cycles and maximum velocity. As one comparison, a General Motors 1994 test vehicle, the Impact, has a battery weight of 500 kg and an energy supply of 16.8 kWh, and reports a replacement cycle for batteries of 32,200 to 64,400 km (20,000 to 40,000 miles), which is within the range of (or more pessimistic than) the values shown in Table 1 (*10*). A Department of Energy test vehicle, ETV-1, reported a battery energy density of 37.5 Wh/kg and 500 driving cycles per battery, both of which are within the range of values shown in Table 1 (8).

Unlike gasoline, the amount of energy available from a battery depends on the rate at which energy is being withdrawn. A driver who wants to go from 0 to 97 km/hour (0 to 60 mph) in 8 s or one who wants to drive at high speed greatly lowers the range of the car. High-speed driving is especially costly. The high speed requires more energy per kilometer, and the rapid withdrawal of energy decreases the total amount of energy available from the battery.

**Table 1.** Typical lead-acid battery and electric vehicle performance.

| Battery and vehicle assumptions | Vehicle scenarios: Available technology | Vehicle scenarios: Goal technology |
|---|---|---|
| Energy density of battery (Wh/kg) | 18 | 56 |
| Number of driving cycles per battery | 450 | 1,000 |
| Vehicle energy requirements (Wh/km) | 310 | 310 |
| Average distance per driving cycle (km) | 80 | 80 |
| Energy for driving cycle (kWh) | 25 | 25 |
| Battery mass for driving cycle (kg) | 1,378 | 443 |
| Battery life-cycle distance (km) | 36,000 | 80,000 |
| Lead percentage of battery mass (%) | 70 | 70 |
| Battery lead mass (kg) | 964 | 310 |
| Battery lead per life-cycle kilometer (g/km) | 27 | 4 |
| Lead releases per life-cycle kilometer | | |
| Virgin production (4%) (mg/km) | 1,072 | 155 |
| Recycling production (2%) (mg/km) | 536 | 78 |
| Battery manufacture (1%) (mg/km) | 268 | 39 |

## The Life Cycle of Lead: Environmental Releases

Lead materials flow balances for the United States and the world are generally incomplete (5, *11*). The U.S. Bureau of Mines found that over a 49-year period, 6.5% of the primary lead production, 3.4% of the secondary lead production, and 1.1% of the lead processed in the manufacturing sector were released to the environment (*12*). Environmental regulations have lowered lead discharges; our best estimate of current discharges is that primary lead processing releases about 4% of its lead production to the environment, secondary lead processing releases about 2%, and the manufacturing sector releases about 1% of lead processed.

When the Environmental Protection Agency (EPA) examined individual production steps, the estimated uncontrolled air emission factors for point sources from primary lead processing averaged about 12% of lead processed (*13*). Fugitive emissions not subject to point control are estimated to be about 0.06% of production. Environmental control would have to be 90% effective to reduce the uncontrolled point air emissions of 12% to 1% of lead production. Our estimate of total environmental releases of 2 to 4% is likely to be an underestimate of lead discharges at least for the next few years.

Lead and lead compound releases and transfers off site from large manufacturing plants are reported in EPA's Toxics Release Inventory (TRI) (*14*). TRI reported that 1992 environmental releases were 1.2 Gg of lead and 6.1 Gg of lead compounds, and 15.7 Gg of lead and 184.4 Gg of lead compounds were transferred off site for recycling and disposal. Lead losses for these transferred materials are unknown.

Lead wastes are also tracked as hazardous materials (*15*). Control of lead emissions to the air and water has generated large quantities of solid hazardous waste to process and contain. For 1989, the most recent year of this information, the EPA reports that for its Resource Conservation and Recovery Act (RCRA) category D008 (lead-contaminated wastes), more than 830 Gg was generated in the United States, as reported by manifests and permits under RCRA. RCRA does not report the precise lead compounds, so we cannot estimate the quantity of lead. However, the TRI releases and RCRA lead waste can be compared to the 842 Gg of lead that was recycled in 1989 and the 491 Gg of lead from primary ore production.

Using 4% losses from virgin production, 2% losses from recycling and reprocessing, and 1% losses from battery manufacturing, we calculated the amount of lead discharged into the environment for the two vehicle scenarios in Table 1. The lead discharge ranges from 1340 mg of lead per kilometer (for the existing technology battery that has the lowest energy density and shortest lifetime distance and uses virgin lead) to about 117 mg of lead per kilometer (for a goal technology battery that has high energy density and long lifetime driving distance and uses scrap lead). If a large number of electric cars are produced, the demand for lead for batteries will surge, requiring that more lead be mined (*16*).

In 1972, leaded gasoline sold in the United States contained 2.1 g of lead per gallon. A vehicle of comparable size and weight to those of an electric car, the Geo Metro, gets about 19 km/liter (45 mpg) (*17*). Using leaded gasoline, this vehicle would emit 22 mg of lead per kilometer (or 35 mg per mile), with 25% of the lead retained in the engine and exhaust of the car. Thus, an electric car using batteries with newly mined lead releases 60 times the peak fraction released by combustion of leaded gasoline. If use of recycled lead and technology goal batteries is assumed, the lead releases are only five times the TEL emissions per kilometer.

The comparison is not as bad as these ratios suggest. Lead from gasoline went into the air in population centers, the route most likely to expose humans. Most of the lead discharged from lead smelting and reprocessing would go to land discharges where it is less available. However, according to 1992 TRI figures (*14*), 17% of the total lead and 11% of the lead compounds released to the environment from on-site lead processing facilities is emitted into the air. Lead in solid waste would slowly leach into the environment, exposing humans. Secondary lead smelters are located around the United States, with major facilities in the Northeast and California. Eventually, even some lead discharged in rural areas would find its way into water and windblown dust, exposing people in major cities. Recovery of lead discharged into the environment can be extremely expensive (*18*).

## Conclusions and Policy Implications

Electric cars have been criticized for their cost and poor performance as compared with current cars. The more fundamental problem is that these vehicles do not deliver the promised environmental benefits. A 1998 model electric car is estimated to release 60 times more lead per kilometer of use relative to a comparable car burning leaded gasoline. The United States banned TEL in large part for health reasons. Electric vehicles would introduce lead releases to reduce urban ozone, a lesser problem. These lead discharges would damage ecology as well as human health. Even with incremental improvements in lead-acid battery technology and tighter controls on smelters and lead reprocessors, producing and recycling these batteries would discharge large quantities of lead into the environment.

Electric vehicles will not be in the public interest until they pose no greater threat to public health and the environment than do alternative technologies, such as vehicles using low-emissions gasoline. Nickel-cadmium and nickel metal hydride batteries are much more expensive and highly toxic; they do not appear to offer environmental advantages. Sodium-sulfur and lithium-polymer technologies may eventually be attractive.

### REFERENCES AND NOTES


1. D. L. Illman, *Chem. Eng. News* **72** (no. 31), 8 (1994).
2. H. Dowlatabadi, A. J. Krupnick, A. Russell, *Electric Vehicles and the Environment: Consequences for Emissions and Air Quality in Los Angeles and U.S. Regions* (Technical Report QE91-01, Resources for the Future, Washington, DC, 1990).
3. L. Lave and L. Freeburg, in *Towards an Energy Policy* (Sierra Club, San Francisco, CA, 1973) pp. 63–109; L. Sagan, *Science* **177**, 487 (1972); *Nature* **250**, 107 (1974); Office of Technology Assessment, *Studies of the Environmental Costs of Electricity* (OTA, Washington, DC, 1994).
4. National Research Council, *Measuring Lead Exposure in Infants, Children and Other Sensitive Populations* (National Academy Press, Washington, DC, 1993); H. L. Needleman and P. J. Landigan, in *Annual Review of Public Health*, N. Breslow, J. Fielding, L. Lave, Eds. (Annual Reviews, Palo Alto, CA, 1981), vol. 2, pp. 277–298.
5. V. Thomas and T. Spiro, in *Industrial Ecology and Global Change*, R. Socolow, C. Andrews, F. Berkhout, V. Thomas, Eds. (Cambridge Univ. Press, Cambridge, UK, 1994), chap. 21.
6. R. U. Ayres and R. P. McKenna, *Alternatives to the Internal Combustion Engine* (Resources for the Future, Washington, DC, 1972).
7. T. Moore, *EPRI J.* **19** (no. 3), 6 (April–May 1994); J. Hopkinson, *ibid.* **6** (no. 8), 6 (October 1981); M. Wayne, *ibid.* **4** (no. 9), 6 (November 1979); L. E. Unnewehr and S. A. Nasar, *Electric Vehicle Technology* (Wiley-Interscience, New York, 1982).
8. D. W. Kurtz, T. Price, J. Bryant, in *Electric and Hybrid Vehicle Progress* (Society of Automotive Engineers, Warrendale, PA, 1981), pp. 111–124.
9. D. Linden, *Handbook of Batteries and Fuel Cells*, (McGraw-Hill, New York, 1984); C. D. S. Tuck, *Modern Battery Technology* (Horwood, Chichester, UK, 1991).
10. General Motors, "Impact specifications, electric vehicles" (General Motors, Detroit, MI, 1994).
11. D. T. Allen and N. Behmanesh, *Wastes as Raw Materials* (National Academy of Engineering, Washington, DC, 1994), pp. 69–89; R. A. Frosch, *Phys. Today* **47** (no. 11), 63 (1994).
12. W. D. Woodbury, D. Edelstein, S. M. Jasinski, "Lead materials flow in the United States 1940–1988," (unpublished technical report, U.S. Bureau of Mines, 1993); W. D. Woodbury, *Lead* (U.S. Bureau of Mines, Department of Interior, Washington, DC, 1993), pp. 657–683. During the 49 years of the study, more than 53 Tg (teragrams) of lead went into products, of which 26% were dissipative uses (such as leaded gasoline and paints), 42% became old scrap and was recycled, 31% entered a pool of products in use or was discarded without recycle by 1988, and less than 1% was exported as scrap.
13. *Metallurgical Industry Emissions Factors* (Technical Report, EPA, Durham, NC, 1994).
14. Office of Pollution Prevention and Toxics, *1992 Toxics Release Inventory* (Technical Report EPA 745-R-94-001, EPA, Washington, DC, April 1994).
15. *National Biennial RCRA Hazardous Waste Report* (Technical Report EPA 530-R-92-027, EPA, Washington, DC, February 1993).
16. Production of automobile SLI (starting-lighting-ignition) batteries in the United States in 1992 was 3.26 million units greater than in 1991, consuming about 33 Gg more lead. This represents a demand of about 10 Gg per million batteries, or about 10 kg of lead per battery. Electric vehicle batteries contain more lead per unit than do SLI batteries.
17. *Model Year 1995 Fuel Economy Guide* (Technical Report DOE/EE-0019/14, Department of Energy, Washington, DC, October 1994).
18. M. D. Royer, A. Selvakumar, R. Gaire, "Control Technologies for Remediation of Contaminated Soil and Waste Deposits at Superfund Lead Battery Recycling Sites," *J. Air Waste Manag. Assoc.* **42**, 970 (1992).


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