1992 ELECTRIC VEHICLE TECHNOLOGY AND EMISSIONS UPDATE

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ABSTRACT

This report presents the results of a 1990-92 assessment of electric and hybrid-electric technology status and the outlook for its commercial introduction in California. It also includes a detailed study of the air pollutant emissions impacts potentially attributable to the eventual widespread use of electric vehicles in the South Coast Air Basin. Findings suggest that mass-market electric battery-powered passenger cars are nearing commercial readiness and are likely to be introduced in California by major automakers in the mid-1990s. Principal problems deal primarily with battery technology but appear solvable. A variety of public policy and regulatory actions are suggested to further encourage EV use. The study's assessment of potential EV-induced emissions impacts in the SCAB found that large net in-basin emissions-reduction benefits would be gained from large-scale EV deployment over the next 20 years, confirming the results of other similar independent studies.

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Table 1.1
Comparison of CARB Vehicle Emissions Standards and Projected EV-related Emissions

California Standards for Passenger Cars (g/m) 50,000 mile Certification

	NMOG (ROG)	CO	NOx
Current	0.39	7.0	0.4
1993	0.25	3.4	0.4
Transitional LEV (TLEV)	0.125	3.4	0.4
LEV	0.075	3.4	0.2
Ultra-LEV (ULEV)	0.040	1.7	0.2
ZEV	0	0	0
Study findings: Year 2010 EV-related Power Plant Emissions (in-basin)*	0.0003	0.0094	0.0066

* This study's projections of electric utility emissions due to each mile of EV travel (using a conservative 20% in-basin power assumption). See discussion of Table 7.7 for further discussion of these values. These values would be lower if emission reductions associated with EV effects on other source categories, such as refineries, were included.

Source (rows 1-6): "Initial Statement of Proposed Rulemaking for Low Emission Vehicles and Clean Fuels," ARB Mobile Source Division, 8/13/90.

1.2. STUDY OBJECTIVES AND APPROACH

This study assesses recent and emerging advances in electric and hybrid-electric vehicle technology as well as related developments such as fuel cells and roadway-imbedded power sources for EVs. The report also considers EV economics and other commercialization barriers, and provides an updated analysis of likely EV emissions impacts in the SCAB under various scenarios. It concludes with possible initiatives for the ARB and others to help reduce air pollution emissions through electric and hybrid-electric vehicles.

Electric vehicle technology status and prospects were first assessed through literature reviews and discussions with researchers active in the field. This review indicated most-likely future EV performance and market-entry timing, leading to estimates of EV energy usage (kWh/mile) for the major classes of electric vehicles in the years 2000 and 2010. This in turn became a key input to the emissions analysis.

To show the effects of the most ambitious possible rate of conversion to electric vehicle use, the market-penetration targets used were 20% of all light and medium-duty vehicles by 2000 (1.7 million EVs) and 70% by 2010 (6.6 million EVs). This is essentially a maximum-EV case,

Chapter 1

INTRODUCTION AND SUMMARY

1.1. BACKGROUND

In early 1985 the California Air Resources Board (ARB) issued its first official review of electric vehicle (EV) technology and potential emissions impacts. That report, entitled "Electric Vehicle Systems: Emission Impacts in the South Coast Air Basin and Overview of Current Technology" (MS-85-002), brought together information from a wide variety of sources and added its own calculations of vehicle life-cycle cost, emissions impacts, and the resulting cost-effectiveness of achieving those impacts through EV use.

Much has happened in the years since that report's publication. For electric vehicles, different battery types have become dominant, many new vehicles have been developed and tested, and serious commercialization efforts are in progress both in the U.S. and abroad. For air pollution control, public concerns regarding emissions have increased as evidence of adverse health effects continues to mount.

California's South Coast Air Basin ("SCAB")--i.e., the Los Angeles/Orange County metropolitan area--continues to have the country's most pressing air pollution problems. There a new Air Quality Management Plan was published in 1990, including promotion of increased electric vehicle use, and the region's electric utilities and key public agencies have joined in supporting increased EV development, testing, and preparations for widespread use. In addition, the California Air Resources Board adopted "low-emission vehicles and clean fuels" (LEV/CF) regulations in September 1990 establishing the world's tightest vehicle emissions standards and the world's only production mandate for "zero-emission vehicles" (ZEVs)--basically electric vehicles--beginning with 2% of passenger cars and light-duty trucks (0-3750 lbs LVW) sold by major manufacturers in 1998.

Table 1.1 summarizes the LEV/CF emissions standards for comparison purposes. The bottom line of the table presents the study's estimates of year 2010 EV-related power plant emissions expressed in grams per mile travelled, with the assumption that 20% of EV power requirements are to be met by power plants within the SCAB. This is conservative: computer simulations by the California Energy Commission in support of Electricity Report-90, when summarized by SAI according to in-basin and out-of-basin power production, show that only about 10% of the in-basin electricity demand would be supplied by in-basin power plants. The table's projected EV-related emissions would also be lower if the effects of avoided gasoline refining, distribution, and dispensing emissions were included. These secondary-source EV benefits are covered in Chapter 7; see Chapter 6 for further explanation of scenarios.

It now appears probable that two other EV battery types may be ready for large-scale commercial use sometime during the second half of the 1990s: sealed lead-acid and sodium-sulfur (in that sequence). Other types may also become commercially ready by that time, but with less certainty. The top two cited here, particularly the sealed lead-acid variety since it is likely to be first, will make large-scale EV commercialization possible shortly after mid-decade. A major new factor in making this possible is the recent formation of the U.S. Advanced Battery Consortium by Chrysler, Ford, and General Motors (and supported by the U.S. Department of Energy, the Electric Power Research Institute and major individual electric utilities). The USABC will prioritize, coordinate and fund the development of advanced batteries for use by all three automakers.

Fuel Cells for Vehicle Use: Fuel cells for cars and trucks are being studied, developed and tested by a variety of manufacturers and others. This technology is a long-term zero-emissions alternative to batteries; instead of stored electricity, it uses a hydrogen-based fuel to generate electricity directly when needed, producing no emissions. However, despite many years of development for stationary power plant use, fuel cells still have many technical problems. Fuel cells also have inherently low power output rates; hence, in vehicle applications fuel cells are expected to be used in conjunction with batteries or other supplemental power sources in order to provide satisfactory acceleration. Despite their potential value, fuel cells are unlikely to be practical for vehicles for at least a decade. Still, their development should be encouraged.

Battery-Powered Vehicles: Largely due to the 1990 California zero-emission vehicle (ZEV) requirement, as well as provisions in the 1990 Clean Air Act Amendments allowing other states to adopt California-like standards, electric vehicle R&D efforts by major automakers are expanding rapidly both in the US and abroad. These efforts have already produced major technical advances, largely defining the powertrain and battery technology to be used in production EVs in the mid-1990s. Examples include the all-electronic drivetrain, original full-vehicle design optimized for battery propulsion, and a wide variety of battery improvement initiatives. Using these advances, prototype EVs have now demonstrated acceleration rivalling that of high-performance conventional automobiles, together with reductions in forecast overall per-mile life cycle cost and ranges of 120-150 miles between recharges.

Further progress is in store, and interest in the auto industry is correspondingly high: General Motors appears to be leading the industry in its commitment to EVs, and has announced it will manufacture an EV based on its Impact prototype by mid-decade or shortly afterward; a large development team has been assembled and the GM manufacturing plants have been identified, including a component plant in the Los Angeles area. Other automakers, such as Peugeot, have also announced more limited EV production plans. Prospects are good that by 2010, EVs will have been improved enough to provide ranges to 250 miles, and indications are that wide use of such EVs would produce few if any undesirable side effects.

Hybrid-Electric Vehicles: Combining electric and internal-combustion engine (ICE) propulsion, HEVs can capture some of the advantages of both. HEVs have recently been developed in a variety of configurations in the USA, Europe, and Japan, for use as passenger cars, trucks, and buses. Though these HEVs have been less numerous and generally less mature than pure EVs, automaker R&D activity is growing rapidly because of the hybrid's avoidance of the EV's limited range. This limitation is generally considered a serious market deterrent, although some experts disagree based on the low average daily miles traveled by conventional cars (under 40 miles per requiring that *all* cars and many of the light/medium trucks sold in the SCAB by the year 2000 and later be electric. The study also estimated the hourly changes in electricity generation to accommodate electric vehicles while still meeting mandated in-basin power plant emissions limitations. This relied on a variety of information sources, including qualitative information on electric utility planning and dispatching practices and production cost modeling output for prediction of power plant dispatch sequencing.

Based on our assumptions about market penetration and average energy use per mile for each of the EV types, the study scenarios resulted in an average EV energy use of 0.33 KWh/mile for the year 2000, and 0.28 KWh/mile for the year 2010. The three EV types included light-duty automobiles and light- and medium-duty trucks.

Both vehicular and electric power plant emissions in the Air Basin were estimated with and without EVs, as were various other secondary emissions sources such as in-basin gasoline refining and distribution, storage and refueling losses, and vehicle and component manufacturing and reclamation. The results of all these analyses were combined to yield the overall EV emissions impacts in the SCAB.

The assumed emissions from the conventional vehicles replaced by EVs were a key element in the analyses. A significant change in the expected nature of these vehicles occured during the course of this study: the California Air Resource Board's September 1990 establishment of stringent new tailpipe standards for vehicles manufactured in the late 1990s. Although the new standards were promulgated after the base analyses had been performed it seemed logical to calculate the effects of the electric vehicles as if they were replacing vehicles subject to the more stringent standards. However, the 2010 results were calculated using the new standards as a base while the year 2000 results were not; in the 1990s electric vehicles will replace vehicles made almost exclusively before the LEV standards take effect. In fact, even for the year 2010--when virtually all of the vehicles replaced by electric vehicles are subject to LEV standards--the use of these standards in the adjusted base case influenced the calculated results by less than 5% for all pollutants.

Many factors influence the levels of EV emissions impacts. The study included an assessment of the effects of key factors such as average EV mileage driven per day, EV energy efficiency, power plant fuel type, and numbers of vehicles sold. Many of these factors have been forecast very differently in various EV studies, and this "sensitivity analysis" was included to assist the reader in comparing their results and methods.

1.3. MAJOR FINDINGS

Electric Vehicle Technology and Economics

Battery Technology: We now have reliable tubular-plate lead-acid batteries for EV use, which will continue to be refined. These have been extremely important in the development and demonstration of credible EVs and of public policy in their support. However, this battery type will always be relatively large and heavy compared to others, which limits the amount of energy storage and hence range that the vehicle can have. By 1995 they will probably be used only in specialized limited-duty applications.

Assuming night-time EV recharging, when SCE and LADWP in-basin generators are not fully utilized, this additional electricity could be provided without building more power plants.

The 20%/2000 and 70%/2010 EV scenarios lead to substantial pollutant emissions reductions, even after the effects of the State's LEV regulations on conventional vehicle emissions. The net in-basin effect from EV-caused reductions in motor vehicle and motor-vehicle-related emissions, including offsetting increases in electric utility emissions, is shown in Table 1.2. These changes reflect the large portion of in-basin emissions due to motor vehicle-related emissions and the relatively small portion contributed by electric utilities. It is notable that the emission reduction in 2010, while significantly higher than the year 2000 reductions, are not proportional to the increased number of EVs in 2010. This is because in 2010, EVs are replacing much cleaner vehicles.

Table 1.2
Summary of Emissions Impacts of EVs in the South Coast Air Basin

	Net Emissions Reductions by Year, in Percent			
Type of Pollutant Emission	Year 2000		Year 2010	
NO_x (Oxides of Nitrogen)	4.7%	39.4 tons per day	12.1%	96.7 tpd
ROG (Reactive Organic Gases)	3.9	41.0 "	8.6	85.4
CO (Carbon Monoxide)	5.0	7.1 "	31.6	810
SO_x (Oxides of Sulfur)	5.0	18.9 "	14.6	18.7
Particulate Matter	0.9	159.3 "	2.4	58.4

How These Results Might Vary: The emission results listed in the above table were based on the best-available information on key variables such as power plant fuels, timing of recharging, EV efficiencies, and the characteristics of the vehicles replaced by EVs. Sensitivity tests on the effects of alternative values for each of these variables were performed to show how the net emissions effects might change under different assumptions. Electric vehicles produced a clear benefit under all scenarios tested. By far the most important variables proved to be those related to vehicular technology and marketability: conventional vehicle emissions, EV energy use per mile, average miles driven with EVs, and EV sales.

Many individuals have expressed concern that increases in power plant emissions caused by charging the electric vehicles would offset the emission decreases from replacing conventional with electric vehicles. The base case analysis results appeared to dispel this concern for the SCAB; EV-related power plant emissions were no larger than the *indirect* emissions savings of EVs (e.g., reductions in in-basin gasoline refining, transportation, storage, and refueling). This means that the total ICE vehicular emissions decreases due to replacements by EVs can be day in the Los Angeles area). Some vehicles, such as household second cars, may never reach this average. However, it must be noted that most vehicles must periodically make longer trips even if their daily average mileage is low.

Although expert opinion is divided, some studies suggest that each HEV could electrify about as much household travel as would a comparable EV. The logic here is that although HEV range may be greater, encouraging HEV use for more trips than EVs, average daily miles per vehicle driven on battery power are likely to be comparable between EVs and HEVs. On a per-vehicle basis, if designed to emphasize battery power and limit the use of the ICE appropriately, HEVs may provide virtually the same emissions-reduction benefits as pure EVs. If their longer range enables HEVs to capture a larger share of the market than pure EVs, their overall potential emissions benefits could be significant.

HEVs of the 1980s often relied much more heavily on their ICEs than on electric power from utilities. Their potential for reducing pollutant emissions and liquid fuel use was correspondingly limited. Future HEVs, however, will rely much more on electric power, although it is not clear whether series or parallel combinations of battery and ICE will be dominant: This is an important issue for regulators, since it potentially affects HEV emissions. These HEVs are likely to be basically EVs with part of the battery replaced by a small ICE which can give unlimited cruising range when needed. Ideally, in most urban driving the ICE would not be used; it would be started only on those occasional days when the HEV is driven beyond its range on battery power alone. It is also worth noting that any HEV's emissions will increase by an unknown amount over time as its ICE deteriorates. This factor must be considered in further analysis.

Roadway-Powered Electric Vehicle Technology: Beyond battery-powered vehicles, fuel cells, and hybrids, roadway-powered electric vehicles (RPEVs) represent the only other EV technology now under active study and development. RPEV technology involves the distribution of electric power through cables buried in the roadway, with power transferred to moving vehicles through air-gap induction couplings. This technology is still in a highly experimental stage of development. Even if successfully developed, it requires major modifications of public streets and highways in order to be put to use. RPEV technology may eventually prove both practical and cost-effective, as claimed, but because of its technical and logistical challenges it is unlikely to be deployed in any significant manner for several decades, if ever.

Emissions Impacts of Electric Vehicles

Principal Results: Under a wide range of expected and possible values for key variables, electric vehicles produce a substantial net emissions decrease. As one would expect, the key offsetting factor is emissions increases by power plants. However, power plant emission increases were found to be quite small in comparison to motor vehicle decreases; in fact the in-basin power plant increases were more than offset by emission decreases associated with just the refining of conventional fuels (less refining activity is expected due to the decreased use of gasoline when electric vehicle are used).

If 20% of EV-required electricity is generated by power plants in the SCAB, replacing 20% of light- and medium-duty vehicles with EVs by the year 2000 adds 5,248 MWh/day--or an additional 13%--to in-basin electric power generation in that year. If the EV population expands to 70% by 2010, EVs will add 15,382 MWh/day--a 27% increase--to that year's in-basin generation.

comprehensive than conventional ICE technology improvement, in that the long-term EV battery technologies under development will essentially require abandonment and replacement of the original battery types with completely new ones. Although the USABC initiative is an important assurance that the high level of R&D needed will continue, public agencies involved in EV commercialization must continue to monitor EV development progress and may need to support further public and private funding mechanisms to guarantee its success.

Alternative Electric Technologies for Vehicles
Both fuel cells and roadway-powered EV technology are long-term prospects only, but clearly deserve further study. In both cases, the most pressing needs seem to be economic and strategic studies to assure that the high R&D investments needed are warranted by the potential benefits, particularly in light of the well-understood benefits of battery-powered EVs both in vehicular emissions reduction and electric power generation efficiency.

Hybrid-Electric Vehicles
Although evidence is limited, hybrid vehicles may offer the potential to reduce overall emissions even more than pure EVs, due to their ability to meet the needs of a broader market. HEVs can be engineered to have about the same emissions benefits per vehicle as EVs on an annual basis (total miles of electric-powered travel) even though some types of HEVs may exhibit much poorer emissions performance when new and even worse as they age. This suggests that HEVs should be encouraged by public policy, although with important qualifications in order to gain the full potential HEV emissions benefits without undue risk of the opposite results. Enforcement rules for the present ZEV regulations could, for example, stipulate that "good citizen" HEVs such as those with a series-type battery/ICE configuration, a non-adjustable controller bias toward battery operation and incorporating ICEs with low power and low emissions be given special credits. Alternatively, a test cycle incorporating "worst-case" emissions conditions for each HEV could be used. Finally, further study of market preferences and trip-making flexibility should be undertaken to help resolve the current uncertainty as to whether HEVs could electrify more miles of travel per vehicle than could EVs.

considered as net savings. The sensitivity tests also addressed this concern by widely varying the assumed power plant fuels, electric vehicle energy requirements, and in-basin power generation. For example, in one sensitivity test it was assumed that all in-basin power used to charge electric vehicles was generated by coal-fired power plants (although none exist or are planned in the study area), and in another it was assumed that 100% of the EV energy requirement was generated in the SCAB with existing and planned power plants. Even in these hypothetical extremes, the total emissions increases from power plants were small in comparison to the decrease from conventional motor vehicles.

1.4. IMPLICATIONS AND RECOMMENDATIONS

EV Emissions in California Urban Areas

This study's results, together with those of other recent studies, clearly show that extensive EV use would be highly effective in reducing total ozone-precursor emissions in the South Coast Air Basin. No further effort need be expended to study this subject for the SCAB. However, although the SCAB is by far the State's worst area for such emissions, these promising findings should be verified for other major metropolitan areas whose vehicular travel characteristics, air quality, and electric power generation sources may differ significantly from the SCAB. This would make possible a valuable statewide assessment of EV benefits, and such an assessment should be considered by the several State agencies (CEC, CARB, PUC, etc.) involved in EV policymaking.

Electric Vehicle Development

The ARB's regulatory innovations have clearly passed the initiative in EV development from the electric utility industry and government to the auto industry, at least for the California market. This is a major milestone in the effort to employ electric vehicles in the battle against motor vehicle-caused air pollution. Policymakers can now be confident of the automakers' commitment and active progress toward early commercialization. At the same time, technical barriers remain; continued communication and cooperation is essential, as well as unwavering support and even reinforcement of the California zero-emission vehicle sales quotas and schedule.

To further propel EV commercialization and acceptance, electric utilities should be permitted and encouraged to offer supportive services such as the lowest possible off-peak recharging rates, underwriting of EV R&D, helping to educate and prepare the public, and assisting both technically and financially in home recharging station installation. The California Public Utilities Commission must be a strong advocate for such services. In addition, buyer inducements, particularly registration and licensing fee waivers (financed through fee surcharges on higher-emission vehicles) should be developed now to be sure of readiness when the first EVs are introduced. Non-financial user incentives such as carpool lane and restricted-parking use by EVs should be given further study now to better assess their value as additional inducements before including them in EV implementation planning.

EV Battery Development

There appear to be no serious barriers to electric vehicle powertrain development (motors, controllers, and power transfer mechanisms such as differentials and transmissions). However, battery development still needs a high level of R&D throughout this decade, not only to assure completion of the expected batteries for the near term but also to develop more advanced battery technologies for the next generation of longer-range, higher-performance EVs. This is far more battery now in production: the tubular-plate lead-acid battery of Chloride Motive Power used in today's electric G-vans.

The tubular lead-acid battery is included in Table 2.1 as a benchmark, since it is the only one actually in commercial use as of 1991. The next three were rated as the least risky candidates under development which met the other Sheladia criteria of performance, cost, ruggedness, resource conservation, and safety/environment. Each of the remaining entries in Table 2.1 has certain advantages for electric vehicles. However, they not only appear riskier but also appear unlikely to make breakthroughs to new levels of performance or cost.

Table 2.1:
Projected 1995 Battery Characteristics
(based on 1988 DOE Battery Assessment)

Battery Type	Level of Risk	Performance* Available kWh	Performance* Efficiency	Capital Cost, cents/kWh#
Tubular lead-acid	1**	16	0.70	31
Nickel-iron	1	32	0.65	25
Sodium-Sulfur	3	55	0.80	21
Sealed lead-acid	3	28	0.75	17
Zinc-bromine	4	37	0.55	17
Lithium-iron sulfide	5	42	0.70	25
Flo-thru lead-acid	5	42	0.75	25

* -lifetime average for minivan battery in fleet duty
\# -initial retail cost less 7% salvage, divided by lifetime output in kWh
**-dropped from Assessment due to low performance; projection above based on 1988 commercial product

Status and Outlook for the Most Promising Batteries

Sealed Lead-Acid: Because battery depreciation is a major factor in overall EV life-cycle costs, it must be reduced as much as possible. Battery depreciation is what makes electricity expensive for vehicle propulsion. One kWh of electricity direct from a utility costs only about 5 cents during overnight recharge at typical off-peak rates. One kWh of electricity delivered from a battery costs an additional three to six times that in depreciation alone, as Table 2.1 shows.

Projected cost for the sealed lead-acid (Pb-acid) battery in Table 2.1 is below even that of sodium-sulfur. This alone could justify further development of lead-acid systems, but there is another more compelling reason which Table 2.1 does not show because it was based on the relatively undemanding minivan application. Unlike most other entries in the table, sealed lead-acid can readily provide the high power output required for high-performance cars like the Impact. To achieve its very high acceleration capability, the prototype GM Impact car gets about three times the specific power from its lead-acid battery as does the TEVan from its nickel-iron battery: nearly 250 W/kg, vs 80 W/kg for the TEVan. Redesign of the other batteries for higher specific power is possible, but this may compromise energy storage and cost, especially in the case

Chapter 2

ELECTRIC VEHICLE BATTERY TECHNOLOGY

2.1. CHAPTER OVERVIEW

This chapter presents a general review of current and emerging battery technologies for electric and hybrid-electric vehicles. With this chapter we seek to identify the most promising batteries under development for both near-term and longer-term introduction, review their advantages and problems, and suggest some realistic expectations for their commercial readiness during the coming decade.

The chapter also includes reviews of vehicular fuel cell and induction roadway-powered vehicle technologies, as potential future supplements or replacements for EV batteries.

2.2. CURRENT BATTERY DEVELOPMENTS

Though battery development is notoriously slow and unpredictable, the past decade has brought substantial progress. With today's much-improved vehicle and powertrain technology (next chapter), today's battery technology is adequate for attractive electric and hybrid-electric vehicles. Moreover, more battery research is being done now than ever before. Still, there is much to be desired, and projections of progress in battery technologies during the coming decade are uncertain at best.

The Sheladia Battery Assessment

Over twenty different electric vehicle battery technologies are now under development, and some of the most promising ones today were unknown ten years ago. Others now discounted or even unknown may move to the top in the coming decade. However, although there are no sure winners, there are some important indications of the most likely candidates. One of the most valuable efforts was a major battery assessment assembled during 1988 by the U.S. Department of Energy, drawing on the expertise of a dozen experts in the field, plus information packages contributed by over 40 battery development projects worldwide. Often referred to as the Sheladia assessment (after the consulting firm which organized it), the exercise provided what is probably still the most substantial appraisal of future battery prospects available today. Its principal results are summarized in Table 2.1.

Table 2.1 on the following page shows projected characteristics of the six battery developments deemed least risky (on a scale of 1 to 10, with 1 representing least risky) in the Sheladia Assessment. "Risk" here refers to the likelihood of failure to reach all development objectives needed for commercial success. Also included, as a benchmark, are characteristics of the best EV cells in complex series/parallel configurations, are more tolerant of individual cell failure but at the same time they multiply the number of cells and interconnections where failures can occur.

Because individual sodium-sulfur test cells have long demonstrated excellent life, the potential for long battery life is clearly there--but only if extraordinary quality control in manufacturing keeps failure probabilities of individual cells and connections at very low levels. Achieving this control at acceptable cost will require sophisticated production automation which may take several cycles of improvement to mature.

The housing required for a sodium-sulfur battery poses additional problems. Costly space-age insulation is required to keep heat loss from the battery at a minimum, since excessive losses must be made up from electric energy supplied during recharging. Furthermore, hot, corrosive battery materials must be safely confined in the event of accident or collision. Finally, the housing must not be so heavy, bulky, or costly as to negate the basic advantages of the bare cells.

Zinc-Bromine: This low-cost, flow-type battery has been under development both in the U.S. (by Johnson Controls for DOE) and Japan as well as Austria, and is being considered for use in an inexpensive Swiss "Swatch" minicar. Austrian (SEA) batteries are being delivered to Texas A&M's Center for Electrochemical Systems and Hydrogen Research for both lab and in-vehicle testing. Although a 125-mile range is forecast, zinc-bromine cycle life is uncertain and it has a low power density which makes it suitable only for low-performance vehicles.

Lithium-Iron Sulfide: This battery, originally developed at Argonne National Laboratory, is probably several years behind sodium-sulfur. It uses more expensive but nonreactive materials than in sodium-sulfur batteries, with correspondingly greater safety despite its even higher operating temperature (400-450°C.). Main problems are cost, thermal management, and cycle life. Lithium batteries are widely used in special military applications, but are difficult to scale up to EV size and display problems of cycle life and calendar lifetime. A disulfide version of the lithium-iron battery may be able to boost the range of EVs to over 300 miles, but is still at a very early stage of development.

Flo-Thru Lead Acid: Despite a relatively high Sheladia rating, this near-term battery type is apparently no longer under active development because of its technical problems and lack of research support. It uses a circulating electrolyte to improve storage density, but has been plagued by low cycle life.

Other EV Battery Candidates

Zinc-Air: The Zn-air battery was just off the Sheladia top-rated list of Table 2.1. The Zn-air battery now being developed (by DEMI) is electrically rechargeable and bipolar, and development progress to date has been rapid. However, substantial cost and performance problems remain. In addition to the cost of the air electrode, the zinc electrode's even shorter life (currently 2-3 per air electrode) is a limiting factor. The need for CO_2 scrubbing (since the electrolyte cannot tolerate exposure to CO_2) continues to be a problem. In addition, the Zn-air battery is relatively bulky for in-vehicle use and its power density tends to be low, making Zn-air (and all metal-air) batteries most suitable for cruising power for hybrid-electric vehicles.

of nickel-iron. Use of two types of batteries together, with one providing higher specific power and the other lower-cost range, may be a possible future compromise.

For sealed lead-acid, the key problem seems to be performance; existing products already achieve creditable cycle life and, if produced in high volume, could reach acceptable levels of cost. Much higher performance (and life) has been achieved at the cell level but not yet extended to the module and battery level. Promising innovations have yet to be fully evaluated and new manufacturing techniques for them have yet to be developed. These include axial plate compression to improve retention of active materials, horizontal orientation of plates, and grids woven of coextruded lead wire. In addition, improved chargers with control of individual cell or module currents may be necessary to achieve full life potential in EV batteries. Still, they are available now and offer acceptable cost and performance for many first-generation EVs including the high-performance Impact.

Nickel-Iron: Nickel-iron (NiFe) was rated the least risky development in Table 2.1, based on its then-expected advantages over Pb-acid including a doubling of energy storage capacity and a 20% reduction in depreciation cost (its high initial cost is theoretically offset by very long life). But during 1991 this battery type's prospects have dropped from promising to doubtful, primarily due to persistent pilot production problems such as electrode quality control. In addition, cost is still a key problem, with forecast pilot-plant production costs rising at the same time that expected battery life and reliability have fallen.

Nickel-iron batteries have another significant problem: they produce a profusion of hydrogen gas during charging. The associated hazards of explosion and fire necessitate achieving new levels of efficiency and reliability in the automatic watering and venting systems with which nickel-iron batteries must be equipped. This appears difficult but still feasible.

Sodium-Sulfur: The advanced sodium-sulfur (NaS) battery type offers the highest performance projected in Table 2.1, with only a little more risk predicted in the Sheladia assessment than that of nickel-iron. NaS energy storage is over three times that of the benchmark lead-acid battery. Moreover, projected depreciation cost is more attractive: at 21 cents per delivered kWh, it is 33% below that of the benchmark.

For the sodium-sulfur battery system, like the sealed lead-acid, capital cost also seems to be the key problem although for quite different reasons . Unlike nickel, sodium and sulfur are cheap materials. Their containment in a working battery, however, is no simple matter. Battery operation requires that they be kept liquid, i.e., at very high temperatures: 270-410 degrees Centigrade (about 520-770 degrees F.). As hot liquids they are aggressively corrosive, attacking the containers and seals which confine them within individual cells of the battery. Moreover, freezing and remelting of the sodium and sulfur in each cell may be unavoidable, so cell seals and containers must also be able to withstand resultant contraction and expansion repeatedly without cracking or splitting.

These problems are multiplied when sodium-sulfur cells are connected in batteries. In contrast to other battery types, sodium-sulfur batteries sized for EV propulsion utilize hundreds or even thousands of inter-connected cells--primarily for safety reasons. Such batteries, with many smaller

A similar battery development consortium is also underway in Japan. This is reported to be a ten-year project, much like the USABC. Announcement of specific battery types to be pursued is expected by mid-1992.

Performance projections of Table 2.1 continue to appear realistic for Pb-acid and NaS batteries, since most of them have already been achieved by experimental batteries. Attaining these performance levels in production batteries which simultaneously meet the target capital cost projections shown in the table, however, is still a major challenge. It may require several cycles of product revision based on experience with batteries actually operating in the field. Because the capital cost projections are based on tested battery lifetimes of 3-10 years, each full cycle of product revision based on field experience may be lengthy.

It therefore seems probable that sealed lead-acid and sodium-sulfur batteries will eventually achieve the performance and cost projections of Table 2.1, but probably not all at once or by 1995. Sealed lead-acid, with its established manufacturing base and relatively short life, seems to have about an even chance of reaching its projection only a year or two later. Sodium-sulfur development is likely to take longer, until nearer 2000; its progress is likely to be slower due to the complex novelties of sodium-sulfur systems. However, sodium-sulfur developers are moving rapidly with pilot plant battery production and plans for full-scale production facilities, so this estimate may be conservative.

The other batteries discussed above, including nickel-iron, are all less likely to reach commercialization by the year 2000. In all of these, development is substantially less advanced and less R&D effort appears to be dedicated to each worldwide. Some, such as the lithium-iron disulfide and lithium-polymer types, are generally acknowledged as only long-term battery possibilities; commercialization for these is unlikely until well into the 2000-2010 period or later.

New and often unexpected changes in the EV battery outlook will continue to occur. These include both disappointments and new opportunities. For example, in contrast to the recent downgrading of the NiFe technology, the latest new EV battery possibility is nickel-metal hydride technology. Developed primarily for small-cell applications, it is a direct challenge to nickel-cadmium in the non-EV market. The nickel-metal hydride battery is also beginning to be viewed as a promising new candidate for vehicles because of its similarity to NiCad in performance and avoidance of NiCad toxicity problems. However, no EV applications to date were found and the timing of development for EV use is unknown. SAFT of France is a major developer of this technology.

2.3. FUEL CELLS FOR VEHICLES

A Potential Complement to Batteries?

The fuel cell is an energy-storage option that--in theory--could make electric vehicles as easily refueled as ICE vehicles, with a comparable range, and no vehicle-based emissions. It would also be very different from batteries: Instead of storing electricity taken from a wall socket, the fuel cell "manufactures" electricity from a fuel.

Nickel-Cadmium: Ni-Cad technology is relatively mature and widely used for many small sealed-cell non-EV uses. Japanese and European manufacturers are known to be working on adapting this technology for EVs. Prototype Ni-Cad batteries have been tested in vehicles by a number of major automakers worldwide, and fall between nickel-iron and sodium-sulfur in performance. However, because of the scarcity and cost of cadmium such batteries are expected to remain prohibitively expensive. To date, EV Ni-Cad batteries are not sealed, since they exhibit limited gassing and require some periodic water replacement. There are also potentially serious disposal issues associated with cadmium's toxicity. (See comments on the new nickel-metal hydride battery on page 2-6.)

Bipolar Lead-Acid: This is a novel version of the sealed lead-acid battery, and has been under development until recently by ENSCI, Inc. with support from the Jet Propulsion Laboratory and Southern California Edison. Arias Research is also developing a bipolar lead-acid battery. Compared with the best conventional lead-acid EV batteries or with nickel-iron's original expectations, bipolar lead-acid appears to offer improved efficiency and performance. However, cost, life, and manufacturability are still concerns, and research support is currently limited.

Lithium-Polymer: This long-term candidate may eventually be an ideal 300-mile-plus battery. It is under development by a Hydro Quebec/Yuasa Battery joint venture as well as others in Britain, Japan and the U.S. Using new conducting polymers, lithium-polymer technology is at a very early stage of development, with small sizes and low power ratings. Challenges include dissipating the heat generated during charging without damaging the polymer electrolyte.

Other New Developments in Batteries

Since the Sheladia assessment in 1988 some significant changes have occurred. In addition to those noted above, sealed lead-acid EV batteries are already being offered by several manufacturers, and General Motors is currently planning to utilize a Pb-acid battery in its initial EV rollout (currently targeted for mid-decade or slightly later). However, the pilot manufacturing plant planned by the Electric Power Research Institute (EPRI) and other sponsors for nickel-iron batteries has been suspended due to technical problems, and the future of NiFe is in doubt. For NaS, both major developers--Asea Brown Boveri (ABB) and Chloride--are now operating small-scale pilot plants for production of batteries for test purposes, and NaS development is continuing.

In 1991 the U.S. "Big Three" automakers Chrysler, Ford, and General Motors formed the U.S. Advanced Battery Consortium as a collaborative R&D venture to identify and develop the most promising technologies for future EVs. The U.S. Department of Energy, the Electric Power Research Institute, and individual electric utilities are also supporting and participating in the USABC. The apparent consensus among USABC sponsors is to focus on demonstrating the feasibility and capability of processing and producing sodium-sulfur batteries at pilot plant scale by 1994. By then, the consortium also wants to have demonstrated, with a full-size experimental battery, the feasibility of designing a plant to manufacture the even more advanced lithium-metal disulfide and lithium-polymer batteries. USABC may select as many as five battery technologies for further development.

Hydrogen Combustion vs. Fuel Cells
Since fuel cells use hydrogen as their energy source, it is worthwhile here to indicate why direct combustion of hydrogen is not more widely considered as an alternative. The German automaker BMW has been studying the use of liquid hydrogen in autos for ten years, seeing LH_2 as a long-term future prospect for pollution-free intercity vehicles (complementing their interest in sodium-sulfur batteries for city and suburban cars) under the assumption of eventual worldwide transition to photovoltaic (PV) solar energy technology for generating both electricity and hydrogen. BMW's most recent LH_2 test vehicle is a converted 735iL sedan [Reister, 1991]. Daimler-Benz is also examining the use of hydrogen as a vehicle fuel.

BMW notes a variety of problems which make near-term use of hydrogen combustion impractical. Most important is the large amount of energy required for the production of the liquid hydrogen using current fossil-feedstock or alkaline electrolysis of water, as well as for cryogenic LH_2 distribution and fueling. The BMW hydrogen vehicle uses some 155-470% as much primary energy as its conventional gasoline-powered counterpart. This is why BMW links hydrogen vehicle use to solar photovoltaic generation of electricity to drive the electrolysis process without excessive emissions; without such pollution-free electricity generation, the power plant emissions would overshadow the vehicle's emissions savings. A completely new infrastructure for hydrogen production and distribution would also be needed, in contrast to the existing widespread availability of electricity in adequate quantities for EVs.

Other problems include the large storage tank required: the BMW performance target for fuel consumption is three times as high as that of the 735iL gasoline engine it replaces, and its storage tank is 50% larger while allowing only half the original range. In addition to its high fuel volume, the very low temperature of liquid hydrogen (-250°C., or -418°F.) necessitates the use of extensive insulation of the fuel tank and lines, adding to space and cost requirements. Safety valves are also needed, to vent the hydrogen gas which evaporates--at up to 2% per day--due to residual heat intrusion into the tank despite the insulation.

BMW is currently using an external-combustion engine for expedience, noting that internal combustion is best for fuel economy, emissions, noise level, power output, avoidance of backfire, and weight and cost of production but requires highly sophisticated engine design and use of new materials. The status of development efforts on an internal-combustion LH_2 engine, by BMW or others, is unknown.

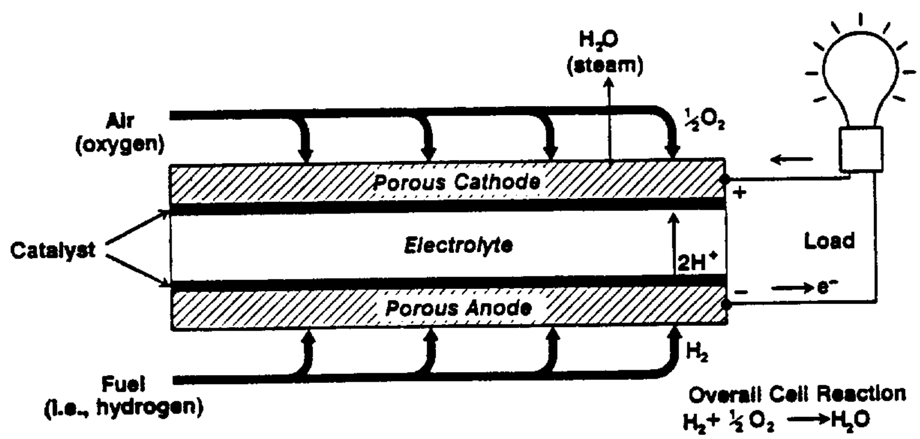
Given the many impediments to widespread vehicular use of liquid hydrogen combustion until well after the turn of the century, it does not yet appear to be a viable alternative to fuel cells or other alternative-fuel technologies. The first photovoltaic bulk power generation is at least a decade away and is forecast to be cost-competitive only at limited times and locations. Substantial use of hydrogen combustion for vehicles, according to BMW, makes sense only with PV power. The low-cost, widespread PV bulk power needed will require further major R&D advances and is likely to take decades longer. At present, then, fuel cell technology appears to be the most promising hydrogen-based technology for vehicle use.

Fuel Cell Types
Types of fuel cells are defined by the substance used as the electrolyte (e.g., a phosphoric acid fuel cell has a phosphoric acid electrolyte). Researchers are exploring a variety of fuel cell

A relatively simple device, the fuel cell electrochemically transforms hydrogen into electricity, with pure water droplets and vapor as its by-product. A "sandwich" of an anode, an electrolyte, and a cathode comprise the fuel cell "stack." Hydrogen--either produced on-board from methanol or another fuel, or taken from on-board hydrogen storage--diffuses through the platinum-coated anode and strips off electrons, creating electricity. The protons continue through the electrolyte to the cathode, where the protons, electrons, and oxygen combine to form water (See Figure 2.1.).

A typical scenario suggested for fuel cell vehicles involves coupling several fuel cells with an on-board reformer, a device that produces the necessary hydrogen by converting methanol stored in the vehicle fuel tank. At least 60 kW would be needed for a small car, which could be provided by using twelve 5-kW cells, each weighing about 90 pounds, in series for adequate voltage. A bus would require about 120 kW.

Figure 2.1
How a Fuel Cell Works



Overall weight and size for a fuel cell vehicle would probably be comparable to those of a conventional electric vehicle. Although the fuel cell system would include a fuel storage tank, fuel pump, and reformer not needed in an EV, the weight and space requirements of this equipment would be offset by the smaller size of the fuel cell stacks, compared to EV batteries.

Because fuel cells have inherently low power densities, it is likely to prove necessary to use fuel cells in conjunction with conventional EV batteries to provide the acceleration needed for buses and high-performance cars. During acceleration, the fuel cell and battery would both provide power for vehicle propulsion. At other times, the fuel cell would provide the power, as well as additional energy to recharge the battery. However, the presence of the battery would add to the weight, complexity, and cost of the vehicle.

Alkaline Fuel Cells: Used in the space shuttle, an alkaline fuel cell operates at temperatures between 140°F and 175°F. Very pure reactants are required. With an alkaline electrode, the electrochemical activity level is somewhat higher (i.e., the alkaline level remains pure longer on the alkaline side) than with acid electrodes, which makes the energy conversion efficiency higher. Some fuel cell experts believe this technology offers great promise, while others are skeptical.

Monolithic Solid-Oxide Fuel Cells (MSOFC): Now in the earliest stages of development, this technology may eventually prove the best for vehicle applications, because no separate reformer is required. This is because the operating temperature of MSOFC systems is very high--around 2000°F--which can break down natural gas into hydrogen within the system. Materials research at Argonne National Laboratory is focusing on reducing the operating temperature to around 1500°F.

Other Developments: Bell Communications Research, the research arm of the Bell operating companies, disclosed a patented new type of fuel cell in late 1990. Consisting of a thin layer of an aluminum compound between two layers of metals such as platinum or nickel, the device reportedly works without pure gases and could be rolled into compact spirals. Details are not yet available.

Refueling the Stack

There are two options for providing hydrogen to the fuel cell stack: fueling the vehicle directly with hydrogen, and using a reformer to convert methanol or another fuel to hydrogen.

Hydrogen Storage: The principal limitation of hydrogen-fueled vehicles, in general, has been the difficulty of storing hydrogen. Proposed systems have included high-pressure tanks to store compressed hydrogen, cryogenic storage of liquid hydrogen, and conversion of hydrogen to metal hydrides. High-pressure storage would be most suitable for large vehicles, which could better afford the size and weight of the tanks. The other storage options are relatively expensive. Although Daimler-Benz and BMW are developing hydrogen storage technologies for use in vehicles with internal combustion engines, the technology is not yet fully mature. In addition to concerns about size and cost, the safety of on-board hydrogen storage remains an issue--although some experts maintain that hydrogen vehicles would present no greater risk than gasoline vehicles.

Reformer Technology: Used primarily in the petrochemical industry, a reformer uses a thermo-chemical process to convert hydrocarbons into other forms--in this case, to a hydrogen-rich gas, carbon dioxide, and a tiny amount of carbon monoxide.

The principal fuel type proposed for use in fuel cells is methanol (M100). Methanol reformer technology is now considered ready for use with PAFC systems. A reformer intended for use in a 120-kW fuel cell bus measures around 2' in diameter and 3.5' in height and weighs about 300-350 pounds. Research is underway to improve its heat transfer and heat exchange properties.

The methanol reformer is also being considered for use with PEM cells in a passenger car, although the device must be scaled down considerably. One problem has been that the carbon monoxide produced by the reformer can "poison" the platinum in PEM cells and significantly impair their performance. The problem has been addressed by introducing a secondary reaction technologies, with some appearing more suitable for vehicle applications than others. The five principal fuel cell technologies are listed in Table 2.2, and their applicability to vehicles is described in the following paragraphs.

Molten Carbonate Fuel Cells (MCFC): Although promising for power plants, MCFC technology is considered unsafe for vehicle applications because of the acid exposure risks and its high operating temperature (around 1200°F), which necessitates a long startup time for warmup.

Phosphoric Acid Fuel Cells (PAFC): PAFC fuel cells operate between 300° and 400°F, and the acids are safely contained in a silicon carbide matrix. PAFC technology and the associated methanol reformer are now considered sufficiently mature for demonstration as an urban bus propulsion system. The size of the cells and reformer, however, appear to make this technology

Table 2.2
Fuel Cell Technologies and Properties

Technology	Operating Characteristics	Development Status (Vehicles)	Developers for Vehicles
MCFC	1200°F	unsuitable	none
PAFC	300-400°F	"mature"	DOE/Fuji Electric many others
PEM FC	160°F greater energy density, faster start-up than PAFC	"promising"	Ballard several others
Alkaline FC	140-175°F	"emerging"	Elenco (Belgium)
MSOFC	2000°F no separate reformer	earliest stages	Argonne N.L.

impractical for use in a car or other small vehicle; in comparison to the PEM technology (discussed below), which is a tight fit in a car, a PAFC is about a third heavier and two-thirds bulkier. In addition, PAFC power density is particularly low--about a third that of the PEM.

Proton-Exchange Membrane (PEM) Fuel Cells: Offering greater energy density, faster start-up, and a lower operating temperature (around 160°F) than PAFC cells, PEM technology is now being developed for vehicles. Also known as a Solid Polymer Fuel Cell (SPFC), the PEM system uses sulfonic acid bound up in a perfluorinated sulfonic acid polymer membrane. The technology has been demonstrated with hydrogen used directly as the fuel, but the methanol reformer technology for use with PEM cells is not yet complete.

incorporate a supplemental propulsion battery. Plans call for project completion by the fall of 1992.

Ballard is also developing a methanol reformer that, according to company spokespeople, should be sufficiently small and efficient for vehicle applications. The company projects completion of the reformer by June 1992. Ballard envisions using the reformer in a load-driven fuel cell application, meaning that it will supply hydrogen as needed for vehicle operation.

General Motors: GM is now working with Ballard, Dow Chemical, the Los Alamos National Laboratories, and other organizations to evaluate a 10-kW fuel cell system for vehicle use. Further phases of this project would build and evaluate larger systems, eventually leading up to a fuel-cell car. Work under way in this project includes research at Los Alamos National Laboratory to build a small and efficient reformer. Although progress has been made, sources at the U.S. Department of Energy estimate that it may take seven years or longer to build the first prototype car containing a fuel cell.

Texas A&M University: More basic fuel cell research is underway at Texas A&M's Center for Electrochemical Systems and Hydrogen Research. Center staff have been conducting experiments with both PAFC stacks and individual PEM cells. The PEM testing has focused on air and water management for 'air-breathing' cells. Other work is exploring means to reduce the platinum required in the catalyst to about one-tenth that currently used in PEM fuel cell stacks.

DOE Fuel Cell Bus: In a project that has been under way for several years, the U.S. Department of Energy (DOE) is developing a fuel-cell bus using PAFC technology and an EV battery for supplemental power. Originally, two systems were tested: a liquid-cooled PAFC system with a lead-acid battery, built and tested under the management of Booz-Allen & Hamilton; and an air-cooled PAFC system with a nickel-cadmium battery, built under the supervision of Energy Research Corporation. Test results for both systems have confirmed the technical feasibility of the concept.

The second phase of the project was begun in September 1991. The project sponsors, which include DOE, the Department of Transportation, and the South Coast Air Quality Management District, chose the liquid-cooled system for future development. This phase of the project will build at least three fuel cell buses, by a team that includes H-Power (of Bloomfield, NJ), Booz-Allen & Hamilton, Fuji Electric (supplying the fuel cell plates), and bus manufacturers. The first of the three buses is scheduled for completion by the summer of 1993, and the other two should be built within nine months of the first. One of the buses will be sent to Southern California, one will go to Chicago, and one will be used at Georgetown University. This deployment will allow data collection in three distinct climates.

Energy Partners "Green Car" Program: This is an initiative of a private company in Florida, seeking partner companies to participate in development of a PEM fuel cell car. An existing sports car with a lightweight advanced composite body is to be the test vehicle.

American Academy of Sciences: A prototype fuel cell vehicle, the LaserCel 1™, has already been built by the American Academy of Sciences in Independence, Missouri. The fuel cell, based on PEM technology, consists of two stacks of cells, one to power the vehicle drive system, and the other to power vehicle accessories. The cell measures approximately 9" by 10" by 6" and weighs about 75 pounds. The on-board metal hydride (hydrogen) storage vessel weighs about 300 pounds and provides a range of about 188 miles. (The organization estimates that a more "modern" electrical propulsion system could increase the range to 250 miles.)

Elenco: Located in Dessel, Belgium, Elenco is the developer of an alkaline fuel cell for vehicle applications. The company tested a 15-kW alkaline fuel cell system in an electric van, with a total vehicle weight of three tons. The components were undamaged by the shocks and vibrations of vehicle operation. Elenco has since begun a project to incorporate the alkaline fuel cell with a battery in a large urban transit bus using on-board hydrogen and a battery. The company says if the project is technically successful, "commercialization may be expected from 1995 onwards." Its target market would primarily be buses, but the company is also interested in developing smaller vehicles.

Other Overseas Companies: Japanese automakers are reported to be working on fuel cells for vehicles, but no vehicular applications have been announced. The Ministry of International Trade and Industry (MITI) is reported to have demonstrated stationary fuel cell units with over 40% efficiency; 50-60% is expected "shortly." MITI research covers phosphoric acid, molten-carbonate, and solid-oxide types for land-based uses plus lightweight alkali fuel cells for space applications. In France, Peugeot explored fuel cells for vehicle uses in the past, but abandoned the work due to the high cost of materials. The Italian government is reportedly interested in fuel cells for bus applications.

Fuel Cell Pros and Cons

Efficiency: Fuel cells are inherently twice as efficient as internal combustion engines. For this reason, fuel cells may prove more practical, in the long-term, than hydrogen-powered combustion engines.

Range: Fuel cell vehicles are expected to offer a range comparable to gasoline-powered vehicles, with a similar ease of refueling. The use of air conditioning, power steering, and other auxiliary power systems would affect vehicle range comparably to gasoline-powered vehicles, i.e., not seriously. In contrast, such systems pose a considerable challenge to the development of conventional electric vehicles, because the systems can rapidly drain the propulsion battery.

Performance: With their relatively low energy densities, fuel cells operating without a supplemental power source may not provide adequate acceleration for many vehicle applications. The problems associated with hybridization, as described above, could be minimized if an ultracapacitor is used rather than a conventional electric vehicle propulsion battery.

Environmental Impacts: The only emissions from an operating fuel cell are water droplets and water vapor. An on-board reformer will also produce some carbon dioxide. Other emissions are associated with making the fuel for the vehicle, whether methanol or hydrogen (for a vehicle without a reformer). However, because a fuel cell is twice as efficient as an internal combustion engine, the fuel cell would require only half the fuel for the same distance travelled. Thus in addition to its elimination of emissions while in use, a methanol fuel cell's fuel production emissions would be half those of an equivalent methanol-fueled ICE.

Safety: Although the actual safety of fuel cell vehicles is a subject for speculation only, due to the lack of vehicles in on-road applications, developers foresee few inherent problems. The operating temperatures of PAFC and PEM systems are relatively low, and the acids are bound in matrices that should limit any exposure in the event of a crash. There is a very slight risk of ignition for the hydrogen within the cell itself. Also, the fuel storage technology poses some risks, whether on-board hydrogen or methanol is used. Many vehicle designers consider on-board hydrogen unacceptably risky, although some experts contend that the risk is really no greater than for using a gasoline-powered vehicle. The risks of methanol use would be no different than for a conventional methanol-fueled vehicle. Finally, the added weight of the fuel cell system, compared to today's vehicles, poses design considerations that should not be overlooked.

Cost: A study conducted in connection with the DOE bus program concluded that PAFC technology would be somewhat more cost-effective than diesel buses (on a life-cycle basis), when the cells are manufactured in the hundreds. The most costly part of the system is fuel cell plate manufacturing, which could be done with greater automation when demand exists. However, this conclusion depends on an extensive array of uncertain assumptions concerning fuel cell life and component costs.

In general, fuel cells may be inherently more expensive than electric vehicle batteries, largely because of the high cost and limited availability of platinum. Long-term research is exploring platinum alloys and non-precious-metals catalysts. An alkaline fuel cell may need very little platinum, and its costs may eventually approach electric vehicle battery costs.

Fuel Supply: Eventually, the U.S. may adopt a hydrogen economy, and a national hydrogen distribution system could be developed. Some fuel cell proponents claim that the transition could begin within 10 years, but the economics of petroleum production appear to suggest that the transition may not begin for several decades. However, the California zero-emission vehicle requirements may accelerate this transition, especially if buyers balk at EV range limitations. Support for this possibility is provided by the example of the diesel infrastructure for trains, which developed very rapidly because of diesel's clear superiority to coal-fired steam engines.

In the meantime, using methanol is considered a more practical alternative. It must be kept in mind that the methanol used in fuel cells must be pure. The M85 (85% methanol, 15% gasoline) proposed for use in methanol-fueled combustion-engine vehicles cannot be used in fuel cells--so fuel cell vehicles could not just refuel at M85 pumps.

Reliability: The fuel cell itself is relatively simple, and could last as long as most vehicles. Fuel cells require little maintenance; the associated systems include pumps and other moving parts which would be expected to require occasional replacement. On the other hand, one authority with years of experience with stationary fuel cells says that the technology will not easily withstand the "random duty cycles" to which most consumer vehicles are subjected.

Fuel Cell Prospects

Fuel cells appear to be a promising, longer-term alternative to internal combustion vehicles and to conventional electric vehicles. The associated technical problems do not appear insurmountable, although the widespread availability of either hydrogen or M100 is a considerable barrier to adoption.

The first use for fuel cells will probably be fleet buses with PAFC technology. The problems of fuel availability can be somewhat alleviated by central refueling. Some developers claim that PAFC-powered buses could be used in fleets by the mid-1990s, which may be an over-optimistic assessment. PAFC technology does not appear suitable for other vehicular applications, but PEM fuel cells may hold more promise for cars and other light vehicles. However, the ambitious nature of the performance and cost targets for PEM cells suggest that light-duty fuel cell vehicles may not be ready for 20 years or more.

In conclusion, fuel cells are an intriguing electric-vehicle alternative that may soon be ready to replace conventional buses, but many years of development may be needed before this technology is ready for use in passenger cars. Fuel cell developers are optimistic, but the hurdles facing them are at least as great as those facing electric vehicle battery developers.

2.4. ROADWAY-POWERED VEHICLE TECHNOLOGY

Background and Status

The roadway-powered electric vehicle (RPEV) concept involves the use of electricity supplied to the vehicle from the roadway itself. Electricity supply cables buried in the roadway surface transfer power to the vehicle's on-board battery via an inductive coupling operating over a small air gap between the roadway and a pickup core on the vehicle's undercarriage. When not on the electrified roadway, the vehicle draws its electric energy from its on-board battery. The advantages of the RPEV approach are based on reducing the need for large on-board batteries as well as overcoming the persistent range limitations of purely battery-powered EVs. The concept may also result in higher overall transportation energy efficiency and reduced emissions, even compared to conventional EVs, because of the high efficiency of the inductive coupling versus battery charging.

Modern development of this concept, which actually originated in the 1890s, dates from the mid-1970s. The U.S. Department of Energy's Electric and Hybrid Vehicle program sponsored about $1 million in development work through 1982, including construction of a short test roadway and vehicle at Lawrence Livermore Laboratory. That program ended due to Federal funding cutbacks.

In 1979 a separate RPEV effort was begun in Santa Barbara to provide a system of small electric buses to serve a pedestrian-oriented downtown area. Sponsored by the local transit authority, the project was funded by private industry and Caltrans. RPEV development proved to be too slow to meet local needs, and eventually the R&D activities were transferred to the University of California at Berkeley's Richmond Field Station under the guidance of its Program on Advanced Technology for the Highway (PATH) and continued Caltrans funding.

A 400-foot test track was built at PATH's Richmond site. To date the original Santa Barbara RPEV test bus and an electric G-Van have been run on the track, with reportedly encouraging results [Schladover].

Prospects for Future RPEV Development and Application

The RPEV concept faces a variety of challenges which may be even more formidable than those confronting battery electric and hybrid vehicles. A central one is the road-to-vehicle air gap; the smaller the gap, the more efficient the energy transfer--but the higher the cost. Even if the technology proves to be practical and reliable, the cost tradeoffs needed to achieve adequate efficiency may be too high. Other cost/efficiency tradeoff examples include the sophistication of the inductor and the current used in the roadway.

Many political issues must also be faced. Since it requires the coordinated development and implementation of both a new form of public roadway infrastructure and a new form of private vehicle, an unusual degree of government/industry consensus will be required. Initial capital costs will be very high in order to electrify enough roadway to make the vehicles feasible, and crucial funding policy and design tradeoffs will need to be made concerning the nature and extent of electrified roadway versus vehicle battery size, cost subsidies versus user and manufacturer incentives, and the ultimate distribution of costs and benefits.

At least one recent study [Nesbitt *et al*] suggests that RPEV life-cycle costs, including roadway power installation, may be competitive with ICE vehicles under some conditions. Environmental benefits may be similar to those of other electric-vehicle technologies, with some differences due to the timing of power demand and types of power plants used. For minimum vehicle cost, on-board battery size must be minimized, but this would require that most of the electric power required by RPEVs be generated when used (i.e., during daytime travel hours). This would add further peak-period demand to the electric utility system and require more peak-period power plants--and hence higher electricity costs.

At present, given these considerations, it seems safe to conclude that RPEV deployment even under the best of circumstances would occur only slowly and after much debate concerning its costs, performance, impacts, and financing relative to other technical options and public priorities. With such uncertainties, it is assumed for the purposes of this review that RPEV technology will not play a significant role in urban transportation and air pollution reduction until after the 2000-2010 study period.

Perhaps most central to the RPEV debate is the expected pace of EV battery development. Deployment of RPEV technology--essentially a competitor to long-range batteries--would take several decades. If on-board batteries can be developed successfully within that period or less to permit cost-competitive longer range between charges (perhaps 200 miles), then the value of RPEV technology is in doubt unless it can be shown to be notably cheaper and cleaner. Such studies should be pursued.

Chapter 3

ELECTRIC VEHICLE TECHNOLOGY DEVELOPMENTS

3.1. CHAPTER OVERVIEW

Recent EV R&D projects in the US and abroad have largely defined the powertrain and battery technology available for production EVs in the early and middle 1990s. Thanks to the rapid progress of the past 10-15 years, practical EVs have now demonstrated acceleration rivalling that of high-performance conventional automobiles, together with major cost reductions and ranges of 120-150 miles between recharges. Further progress is in store, interest in the auto industry is correspondingly high, and General Motors has announced it will manufacture its Impact electric car at a plant in Michigan, for sale through several of its automotive divisions. Prospects are good that by 2010, EVs will provide ranges to 250 miles, and indications are that wide use of EVs would produce few undesirable side effects.

This chapter briefly reviews recent progress in EV technology: motors, controllers, batteries, and complete vehicle systems. It then offers performance projections and a set of "nominal" EVs to represent, for air pollution analysis, typical on-road vehicles for the years 2000 and 2010. Finally, it offers comments on potential side effects of large-scale vehicle electrification.

3.2. KEY EV AND POWERTRAIN DEVELOPMENTS

The G-Van: An Update

Any review of recent electric vehicle developments must begin with the G-Van, the best-known electric vehicle currently available in the United States. Originated and underwritten primarily by the EPRI (Electric Power Research Institute) Electric Transportation Program, the G-Van is a standard General Motors Vandura one-ton panel van re-engineered and retrofitted by Conceptor Industries of Canada with a lead-acid battery and dc drivetrain by Chloride EV Systems in Britain. It has the distinction of being the only EV with U.S. Federal Motor Vehicle Safety Standards (FMVSS) certification, based on full-scale crash testing results.

The G-Van was developed in the late 1980s as a demonstration of available, useful EV technology, and represented a major step in EV reliability and practicality. Its performance characteristics are limited, but acceptable for many functions. Because the G-Van is a retrofit of an existing conventional vehicle and is produced only in small quantities, its cost is high--currently $50-60,000. It was originally intended primarily for testing and public education by electric utilities and others, but also has potential uses in a variety of other industries where there is interest in gaining early experience with EVs. Some 130 have been built since serial production began in late 1990, and most of these vehicles are involved in an extensive in-service evaluation by EPRI. Production is expected to continue, and G-Vans will be marketed outside the electric power industry for various functions such as short-range delivery, mobile repair, and personnel transport.

Some Major Steps Toward the Future

The technology of EV motors and controllers has progressed very rapidly during the past decade. The 1980s saw a startling 60% reduction in the weight and cost of the EV propulsion motor with its associated electronic controller. Thanks basically to the rapid evolution of available power semiconductors and computer chips, the EV's motor-controller combination now is much smaller and lighter than a comparable internal-combustion engine (ICE). It will also be cheaper to manufacture; and in automotive service it will provide a much longer operating life, with much less need of maintenance and repair. Continuing research into advanced motor technology may further increase performance per unit of weight and cost.

The capabilities and characteristics of two important current EV developments in the U.S. are summarized in Table 3.1. The first, the Chrysler TEVan, is representative of the minivan projects which dominated U.S. EV R&D from 1985-1989. The second, the GM Impact, is a high-performance passenger car representative of new technological directions for the 1990s.

Table 3.1
Representative Recent EVs*

	TEVan	Impact
VEHICLE PERFORMANCE		
Range, miles (FUDS**)	120	120
Acceleration time: 0--30 mph, seconds	7	3
0-60 mph, seconds	NA***	8
Energy draw from battery: Wh/mile	300	95
Wh/(ton-mi)	120	80
Recharge Requirement, Wh/mi	550	150
VEHICLE CHARACTERISTICS		
Curb weight, lb	4350	2200
Test payload, lb	600	150
Tire rolling resistance	0.0083	0.0055
Aerodynamic drag coefficient	0.46	0.19
Motor type	dc	ac
Peak motor output, hp	65	114
Drivetrain type	2-speed transaxle	fixed-ratio red'n gear
BATTERY CHARACTERISTICS		
Weight, lb	1770	870
Net output, kWh	35	11
Specific energy, Wh/kg	44	29
Type	nickel-iron	sealed lead-acid

* Performance data from manufacturers
** Federal Urban Driving Schedule (a standardized hypothetical trip for testing purposes)
*** 0-60 time not available; 0-50 mph time is 16.3 seconds

The Chrysler TEVan
The TEVan is Chrysler Corporation's prototype conversion of its popular minivan to electric drive. Chrysler recently announced plans to produce a minivan based on the TEVan prototype by mid-decade. The TEVan offers a practical approach (in performance and utility) to EVs for the commercial fleet market, a market which is well-defined but limited in size. Though other minivan projects of the 1980s utilized theoretically more efficient ac drives, the TEVan extracts competitive performance from its dc motor and FET chopper controller. With its nickel-iron battery, it provides a range of about 120 miles, several times that of benchmark EVs ten years ago.

Four Phase I prototypes were produced in 1990 for testing; three used prototype nickel-iron batteries, while the fourth employed existing lead-acid technology. In 1991, eight Phase II prototypes (all with NiFe batteries) were built for use in long-term durability tests. In 1992, 20 additional TEVans are expected to be built for further field testing with electric utilities and others. Batteries to be used in these latest TEVans include SAFT nickel-cadmium as well as nickel-iron, although both types may eventually be replaced by SAFT's nickel-metal hydride battery in Chrysler's production minivan.

The General Motors Impact
The Impact prototype, unveiled in early 1990, is of special interest for the broad-based technological leap it embodies. It is an electric vehicle system built from the ground up for energy-efficient yet high-performance passenger transportation. Existing passenger cars are ill-suited for conversion to electric propulsion because they lack suitable space and structure for carrying the propulsion battery. (Minivans, in contrast, accomodate the battery beneath their cargo floors.) The Impact is literally built around its battery, which is carried in a central structural tunnel constituting the spine of the vehicle. The Impact's special low rolling-resistance tires, very low wind resistance, and innovative ac powertrain provide the maximum possible performance and range from the limited energy storage of the battery.

As Table 3.1 shows, the Impact offers nearly three times the acceleration capability of the TEVan--enough to challenge sports cars at stop signs, as GM has pointed out, and forever dispel the notion that EVs are necessarily sluggish. The TEVan's performance, in contrast, is typical of 1980s electric cars and vans: sufficient for street and freeway travel, but not equal to comparable ICE vehicles. It should be noted, however, that the Impact's acceleration capability puts extraordinary demands on its battery, requiring further battery development to avoid early battery failures due to high power demand.

More important than the Impact's high acceleration, however, is its extraordinary efficiency as a complete vehicle system. Its rolling resistance (a key determinant of city driving range) is only two-thirds that of the TEVan, thanks to specially-developed Firestone tires. Its aerodynamic drag coefficient, a vital factor at freeway speeds, is less than half that of the TEVan (and below that of any ICE passenger car now in production). Finally, its ac powertrain provides superb efficiency despite its very high power rating. With a separate motor for each front wheel, the Impact eliminates the weight and energy losses of the multispeed transmissions and differentials used in recent electric minivans. Its powertrain efficiency averages well over 80% in urban driving, compared with a little over 70% for the TEVan and other 1980s electric minivans.

All this allows the Impact to achieve a range of 120 miles--despite using a low-cost lead-acid battery of relatively conventional design. For equal range, the TEVan requires a nickel-iron battery delivering half again as much energy output per unit weight as does the Impact's lead-acid battery. Put another way, the Impact requires only 80 watt-hours of energy from its battery per ton-mile of travel. This is a third below the TEVan's requirement, and only half that of most other recent EVs. In comparison with the best EVs of ten years ago, the Impact provides twice the range from a given battery. It follows that over the life of the battery, the Impact will also provide twice as many total miles of travel, cutting per-mile battery depreciation charges in half.

Because battery range limitations and depreciation costs have always been seen as the primary obstacle to practical EVs, the importance of this technological advance can hardly be overemphasized. General Motors has announced plans to build and market a vehicle based on the Impact later in this decade, and has backed this announcement with a large technical staff effort in design and production engineering as well as public selection of the plant (the former Buick Reatta production facility in Lansing, Michigan) at which the new EV will be built. Three related component plants have also been named, including one in the Los Angeles area.

3.3. OTHER CURRENT EV DEVELOPMENT EFFORTS

As in the United States, electric vehicle R&D activities abroad are expanding rapidly. We have identified no foreign automakers matching the level of General Motors funding and staff dedicated to EVs. However, many if not most major automakers in Europe and Japan are now developing, showing, and testing prototype vehicles and may in some cases be moving toward near-term production. Massive evidence of these activities was seen in 1991 at the Frankfurt and Tokyo motor shows, where manufacturers display their most recent innovations and concept vehicles as well as new commercial models. At the Tokyo show in October, 15 Japanese EVs were displayed in addition to five battery-powered motorbikes.

Some examples of these activities follow.

BMW is working closely with ASEA Brown Boveri (ABB), one of the major sodium-sulfur battery developers, to develop practical electric drives. To date, BMW has developed and tested a two-speed automatic transmission and a two-speed manual gearbox for EVs. The company has built eight EVs based on the 325iX sedan, using a sodium-sulfur battery, a dc motor, and a monitoring system for all drive components including the battery. Reported range is about 96 miles in city traffic, with a top speed of 96kph (60mph). Current performance targets are 200km (124 miles) in city traffic, 75mph top speed, and 0-50kph (0-31mph) acceleration in about 7 seconds.

Daimler-Benz is currently testing a variety of EV batteries in 190-series cars; we have no reports of vehicle design efforts.

Ford announced in April 1991 a program to build an international demonstration fleet of 70-100 electric vehicles based on the European Escort minivan. The Ford EV will incorporate a 35kWh sodium-sulfur battery, 56kW ac induction motor, and single-speed front-wheel transaxle. Half of the vehicles will be range-extender hybrid-electrics, with a 22kW on-board generator driven by a small (as yet undetermined) IC engine. Production is to start in late 1992, and vehicles are to be leased to government, utilities, and other private users in the U.S. and Europe for a 30-month test period with Ford responsible for all maintenance. Ford says that this vehicle will not be sold commercially, but that it expects to be producing advanced EVs for sale in the second half of the 1990s.

Nissan has built several EVs, including most recently the high-style FEV (Future Electric Vehicle) coupe with reported performance similar to high-mileage economy cars. Unveiled at the Tokyo motor show in 1991, it uses a nickel-cadmium battery which Nissan says is rechargeable in 15 minutes. (It should be noted that this requires both that the battery be capable of withstanding such a high charge rate without damage and that the electricity supply capacity be much higher--100 amps at 400 volts--than now available to residences.) Other projects include a conversion of a 4-door sedan, with a prototype expected in 1992.

Mitsubishi is working jointly with Tokyo Electric Power Company to build a practical EV based on the 4-passenger Lancer station wagon. It is to use nickel-cadmium batteries placed under the floor. Performance targets are modest, including a 125-mile range (25mph constant), 70mph top speed, and 0-30mph in under 8 seconds. Both dc shunt and ac induction motors are to be tested in prototypes scheduled for completion in early 1992.

Peugeot has been selling its lead-acid battery-powered small utility vans (primarily in France) since mid-1990, with several hundred reportedly purchased by electric utilities and municipalities. These are electric versions of existing conventional vans. The company is also developing a very small "city car" EV for commercialization by 1995, as well as hybrid vehicles for highway use. No plans for export of such vehicles to the U.S. have been announced.

Renault is also active in EV development, with plans for offering limited quantities of two types of small utility EVs for sale in 1992. There are no apparent plans to export these models to the U.S. Both are to use dc motors and either lead-acid or nickel-cadmium batteries. An electric compact car, the Clio, is also under development.

Tokyo Electric Power Company uses about 40 EVs and cosponsors EV research with Mitsubishi, but in an unrelated project TEPCO recently unveiled what the company believes to be "the fastest electric-powered car in the world." Targets are 110 mph top speed and a 300-mile range (at 25 mph constant speed). The car is built of lightweight tempered plastic and is powered by a nickel-cadmium battery driving dc brushless motors in the wheels.

Toyota developed two small EV prototypes with zinc-bromine batteries and ac induction motors in the late 1980s, and is now building a vehicle with an ac motor and nickel-cadmium batteries. There are also reports of work on turbine-based hybrid-electric vehicle drives.

3.4. PROBABLE FUTURE EV PERFORMANCE

With selected batteries as described in Chapter 2, the TEVan would achieve approximately the ranges shown in Table 3.2. Appropriately redesigned versions of these batteries, in cars tailored for them using the Impact's technology, might give the approximate car ranges also shown in Table 3.2. (Because of power limitations, however, the nickel-iron and sodium-sulfur cars might not match the acceleration of the sealed lead-acid car, or the Impact.)

Given the timing of battery development discussed in Chapter 2, it is likely that EVs using both sealed lead-acid and sodium-sulfur batteries will be on the road around the year 2000. It is quite possible that both batteries will still be competing for shares of the EV market in 2010. The details cannot be reliably forecast, yet some kind of specific future EVs are

Table 3.2
Projected EV Range with post-1995 Batteries

	Range, miles	
	Van	Car
Sealed lead-acid	100	150
Nickel-iron	120	175
Sodium-sulfur	180	250

required here as a basis for calculating EV impacts on air pollution. For this purpose, it seems appropriate to choose "nominal" EVs exemplifying the possibilities likely to be most numerous on the road in 2000 and 2010.

Characteristics of nominal EVs for 2000 and 2010 are summarized in Table 3.3. The vans for 2000 combine TEVan technology with improved sealed lead-acid batteries, since nickel-iron batteries which are cost-competitive in fleet van applications now appear less likely to appear commercially than formerly expected. Cars for 2000 combine technology like that of the Impact with improved sealed lead-acid batteries, giving 150-mile range. By 2010, sodium-sulfur batteries are assumed for both vans and cars. In addition, vans are assumed to be all-new products rather than conversions, with technology as efficient as that of the Impact.

Table 3.3
Nominal EVs for 2000 and 2010

	2000	2010
VANS		
Working range, miles	100	250
Recharge requirements, wh/mi:		
small vans	600	400
large vans	900	600
PASSENGER CARS		
Working range, miles	150	250
Recharge requirements, wh/mi:		
2-passenger	180	180
4-passenger	240	240

A Note on Effects of Charging Inefficiencies: It has been suggested that estimates of energy usage for electric vehicles based on driving-cycle tests and known charger efficiencies, as used in this study, may seriously underestimate the actual efficiency in practice. The principal concern is with the inefficiency inherent in overcharging a battery, or possible decreases in charging efficiency as the battery's charge approaches 100 percent.

Some relevant evidence is found in the current G-Van experience. Several problems have been reported with the G-Van's charging, such as incorrect charge profile, too-frequent "topping-off" and overcharging through failure to turn off (at one extreme). At the other extreme, incomplete charges are repeatedly administered without a periodic full equalizing charge, both through equipment malfunction and driver preferences. This results in charge imbalances among battery modules, which in turn causes inefficient charging. Consequently observed G-Van energy use has been from 10 to 20 percent higher than in the vehicle's controlled cycle testing. However, it can be expected that future EV manufacturers will employ more reliable and "smart" charging regimes which avoid inefficiency--for example by adapting the extent of charge to the vehicle's actual intensity of use. Consequently we believe that excessive and inefficient overcharging will not be a significant factor.

3.5. SIDE EFFECTS OF LARGE-SCALE EV USE

Potential Impacts of EVs

The major impacts of large-scale EV use are usually considered to be on air pollution and petroleum consumption, but there are a host of other environmental, economic, and infrastructure issues and impacts which have also been analyzed in the past. Among them:

- traffic noise
- safety and integrity of batteries in accidents
- reserves and resources of battery materials
- hazardous emissions from batteries during use
- solid waste (i.e., battery) disposal and landfill requirements
- liquid waste disposal and water pollution
- disposal of used motor oil
- employment and investment in the motor vehicle and battery industries
- shifts in regional economic activity
- international commodity prices and balance of payments
- energy requirements of EV and battery production
- pollutant emissions of EV and battery production
- costs of household recharging stations
- feasibility of quick-charge and battery-swap stations

The Argonne Impact Study

No "show-stoppers" have been identified, and negative impacts of EVs generally appear modest. Details on a wide variety of potential EV impacts are available in the exhaustive impact analysis completed in 1980 by Argonne National Laboratory.[3] It integrates the results of some four dozen individual analyses which attempted to identify and quantify all the important effects of a shift from ICE vehicles to electric and hybrid vehicles in the United States. The findings are still broadly relevant today. Some specific conclusions include the following:

- The hazards posed by properly safety-engineered EV batteries seem alarming primarily because of their novelty; the hazards of gasoline in ICE vehicle tanks are probably greater (due to gasoline's volatility, explosiveness, and relative lack of protection).

- While US lead resources are relatively abundant, US nickel resources are quite limited; nevertheless, imported nickel could readily support tens of millions of EVs with nickel-iron, nickel-cadmium, or nickel-metal hydride batteries, and recycling would make maximum use of the available nickel.

- Quick-charge and battery swapping stations generally appear economically infeasible (This is likely to hold true still, because of their inherent high cost and inconvenience to the user as well as their likelihood of early obsolescence).

- Installation of charging stations for EVs at typical single-family residences would cost $400-$600 including wiring and safety features; more if ventilation of battery gases is needed.

- Economic impacts of EV production would principally fall on the battery industry (which could grow substantially, require new capital, and become subject to increased regulation).

- EVs would reduce high-speed traffic noise--the major US noise problem--only a little, because of the importance of tire noise plus engine noise from trucks and motorcycles. Low-speed noise on local streets would be more substantially reduced by EVs, assuming that high-frequency noise from EV controllers can be controlled.

Additional EV Impact Issues
Recycling: Some batteries which have emerged since the Argonne study, such as the nickel-cadmium and lithium variants, have raised concerns of toxic waste disposal/recycling if used in very large quantities. There are as yet no definitive studies of the extent of this problem. Apart from this, the broader topic of environmental and health effects of battery recycling in general appears to pose no insurmountable problems. The battery recycling industry is well developed for conventional lead-acid batteries; the majority of lead-acid batteries are now recycled, additional capacity exists, and more can be developed readily. There appear to be no inherent technical barriers to safe recycling of other types of EV batteries, including those involving reactive materials such as sodium. This is not to say there will be no problems. For example, the latest lead-acid batteries involve lead deposited on plastic substrates and sometimes doped with other materials; recycling in such situations may be difficult and costly.

Crash safety: The other concern repeatedly voiced is crashworthiness of EVs, primarily because of the various toxic, corrosive and reactive materials found in some battery types. Detailed fault-tree and toxicology analyses of the risks related to the potential for battery rupture are routinely required both by governmental regulators and insurance companies, and either have been or will be done for all EV batteries to be commercially used. The general result is that batteries are extremely unlikely to break or expose persons to dangerous materials. For example, one such study done for the (now-defunct) zinc-chlorine EV battery--probably the most potentially dangerous battery for EVs--concluded that the fatality risk rate (per million miles) for that battery was essentially equal to that of the conventional ICE vehicle's gas tank.

One result of such studies is that vehicle and battery designs are adjusted to improve safety. For example, the Chloride sodium-sulfur battery's numerous very small, independently encased modules serve not only to minimize the effects of cell failures on the battery's performance but also to reduce the amount of sodium and sulfur that could be exposed if the battery were ruptured. Battery case designs are also exhaustively designed and tested for crash and explosion containment.

The public perception of risk is perhaps the real issue here; generally the public's perception of such dangers exceeds the reality. Detailed information on battery safety should be made public and widely communicated as an important part of the EV introduction process. For example, more public information is needed on the relative safety of HEVs, which typically involve both a flammable or explosive liquid fuel system and a battery-electric system which may pose other dangers. No authoritative treatment of HEV risks was found during this review, although there is no reason to expect that HEV risks would not be acceptable.

Chapter 4

HYBRID-ELECTRIC VEHICLE TECHNOLOGY DEVELOPMENTS

4.1. CHAPTER OVERVIEW

Because of the range limitations of "pure" electric vehicles, at least for most of the current decade, renewed interest in hybrid-electric vehicles (HEVs) is emerging. This chapter outlines the various major types of hybrids and describes some of the more important recent HEV development efforts.

These HEVs use an internal-combustion engine or some other source of power to supplement the EV battery, thereby extending the possible range between battery recharges. Other benefits such as improved acceleration may also be provided in some types of HEVs. At the same time, emissions characteristics may vary substantially among these types.

4.2. HYBRID-ELECTRIC VEHICLE CONFIGURATIONS

A hybrid vehicle utilizes more than one type of propulsion in order to gain some of the advantages of each. There are a great many possibilities, but this report addresses only one: hybrid-electric vehicles, and in particular those hybrids propelled by a combination of:

- an ICE (or another easily refuellable power source such as fuel cells); and
- an electrically-rechargeable battery, electric motor, and controller.

Hybrids of this sort date from the earliest days of the automobile, when developers sought to supplement the easy starting and smooth power of the electric propulsion system with the endurance of the ICE system [Pieper]. After the introduction of the "self-starter" in the 1912 Cadillac, however, the ICE quickly became predominant. ICE vehicles still include an electric motor and secondary battery, but not for propulsion. Instead, their role has been reduced to the bare minimum: The motor merely cranks the ICE to get it started [Flinck].

In the past 25 years, however, air pollution and oil shortages have provided important incentives for major expansion of the role of the electric motor and battery in vehicle propulsion. All-electric vehicles like those of Chapter 2 have had the most attention; they carry this role expansion to the extreme. Between the pure EV and the pure ICE vehicle, however, two intermediate types of HEV have also been investigated:

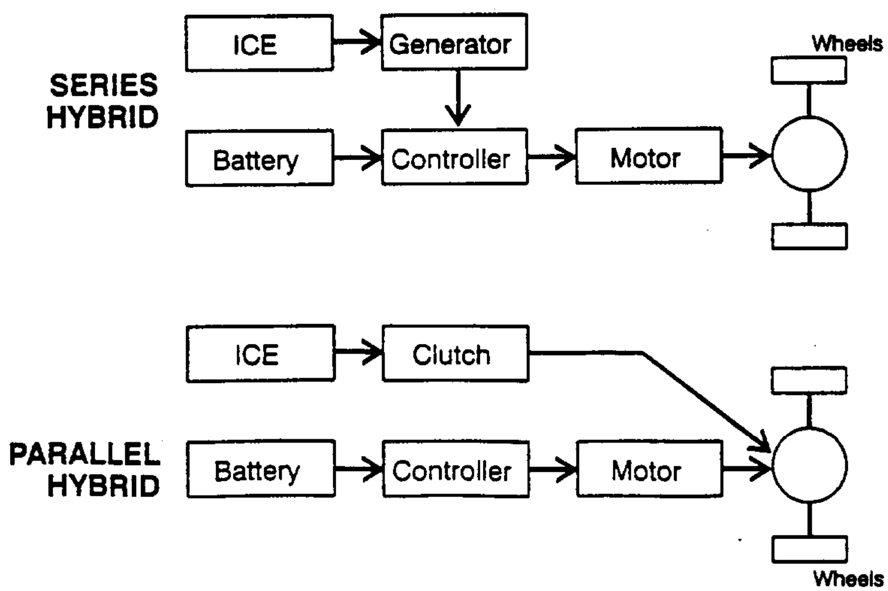
A. HEVs largely or entirely dependent on refuellable power sources such as an ICE, fuel cell, or batteries such as aluminum-air--using electrical components as a sort of sophisticated transmission allowing regenerative braking and "load-leveling" for the ICE;

B. HEVs largely dependent on stored electricity from the utility grid, using other fuels to supplement available electric power only when the occasion demands it.

This review addresses only Type B hybrids. So far as energy and environmental impacts are concerned, Type A hybrids are very much like other ICE vehicles, although with their own levels of emissions and fuel economy. Type B hybrids, however, are quite different. Both their emissions and their fuel use are manifest largely through the electric utility system, with consequences much like those of pure EVs.

The two main configurations of hybrid propulsion systems are illustrated in Figure 4.1. Both have been exploited since the early days of the automobile. In the 1970s and 80s, most developers of hybrids opted for the parallel configuration. Continuing advances in EV technology, however, argue for a resurgence of the series configuration.

Figure 4.1
Basic Hybrid Configurations



Parallel hybrids: In this alternative, a direct mechanical path is provided from ICE to driven wheels, paralleling and bypassing the electrical components of the powertrain--and their losses. Because power delivered by the ICE can be added to the power delivered by the electric motor, each can aid the other. Consequently, the electric motor may be much smaller than in the series HEV, and it may be assigned a correspondingly small role in vehicle operation. Finally, the parallel configuration eliminates the weight and cost of the generator: The propulsion motor (in its regenerative mode) converts surplus ICE power into electricity as needed for recharging the battery.

However, some parallel hybrids may have much higher emissions than others, depending on the degree to which the ICE is used rather than the battery. The dc motor/controller technology available for EVs in the 1970s and 80s was relatively heavy and expensive. This favored the use of relatively small motors and large ICEs arranged in the parallel HEV configuration. It also facilitated the use of existing automotive ICEs and transaxles--proven components available at low cost from volume production. In operation, however, such vehicles relied on frequent ICE operation, with attendant exhaust emissions and liquid fuel use.

Series Hybrids: In this hybrid form (see Figure 4.1), an ICE and generator supply electric power as needed to recharge the battery of an ordinary electric propulsion system. This arrangement is easy to implement and control. The ICE and generator (or alternator) may be installed in an existing EV, for example. In use, the ICE may simply be run at constant speed and load, as needed, to optimize ICE efficiency and minimize emissions. Efficiency, however, can be an important problem in the series configuration: all the power from the ICE must flow through the generator, controller and motor--with attendant losses--before it reaches the driven wheels. Furthermore, although the ICE can be quite small, the electric motor must be large enough to supply all the power required for high speed and acceleration.

The advent of low-cost, light-weight ac drive technology in the late 1980s has shifted the balance towards greater reliance on electric power in HEV designs. The new EV technology also makes the series hybrid configuration more attractive--or even mandatory. The motorized transaxle designs of the Department of Energy's ETX test vehicles, for example, provide no reasonable point of access for introducing mechanical power from an ICE. The more recent powertrain of the GM Impact car, as used in the GM HX3 hybrid-electric vehicle (described below), not only minimizes the loss penalty of the series configuration due to its exceptional efficiency, but also defies introduction of mechanical power from an ICE with its two-motor, fixed-gear layout.

4.3 RECENT HYBRID-ELECTRIC VEHICLE DEVELOPMENTS

The DOE HTV

The most ambitious of earlier U.S. hybrid-electric vehicle developments was completed in the early 1980s by General Electric for DOE's Electric and Hybrid Vehicles Program. The "HTV" which emerged from the DOE development was a parallel hybrid passenger car. At low levels of speed and acceleration it operated entirely on the electric drive. For higher acceleration and speed than the electric motor alone could provide, the ICE was started and stopped as needed. For long trips, the HTV relied primarily on the ICE.

The HTV powertrain included a 34-kW dc motor and controller from GE, a 56-kW Audi 4000 engine system from Volkswagen, a modified GM 3-speed transaxle, and special lead-acid batteries. The HTV solved such problems as instant ICE startup on demand, blending of ICE and electric power, and automated gear-shifting with smooth disengagement and engagement of engine and motor clutches. However, its petroleum savings in typical household use were projected to be relatively modest, and although not reported, it is likely that emissions were little if any reduced [Trummel].

The VW Hybrid-Electric "Golf" Car

VW has described its most recent hybrid as ready for "possible production" [Automotive Engineering, 9/87]. A parallel-configured hybrid version of the Golf passenger car, it is functionally similar to the DOE HTV but mechanically far more compact, accessible, and maintainable. Its powertrain includes the standard Golf ICE and multispeed manual transaxle, but substitutes a "pancake" ac induction motor less than 3 inches thick for the usual Golf flywheel, clutch, starter motor, and alternator. Rated at 6 kW, the pancake motor is integrated with two clutches; one clutch disengages the motor from the ICE to allow all-electric operation, while the other disengages both motor and ICE from the transmission during gear shifts.

For stop-and-go, slow-speed urban driving, the Golf hybrid's electric power suffices. When the driver requires higher speeds and accelerations, however, or when battery charge falls to a low level, the ICE is started automatically to provide performance like that of the standard Golf. VW reports that the Golf hybrid's typical use of utility electricity is about 200 Wh/mi, giving reductions in gasoline use of 25-55% compared to the production ICE Golf. Emissions, however, are little changed, possibly due to its frequent start/stop cycling. This illustrates an extreme case of the potential emissions-reduction pitfalls of parallel hybrid-electric vehicles.

Range-Extended EVs

EPRI's XREV Van: After the HTV, hybrid development in the United States slowed sharply [Levin, Hardy]. Meanwhile, EPRI made a fresh HEV assessment and focused on a very simple HEV, almost the opposite of the complex HTV. This "XREV" (eXtended-Range EV) is a series hybrid, an electric G-Van equipped with a small (7kW) Onan Emerald III 4-cycle engine-generator package (a commercial unit ordinarily supplied for motor homes). To minimize weight and cost, the engine-generator is being sized only to extend EV range by a limited amount (50-100%) in typical service (Renner & O'Connell].

As of early 1992, the XREV van is undergoing performance tests. Initial emphasis is on ICE/battery interface efficiency, and the engine manufacturer is also sponsoring emissions testing. Utility field testing is to follow, and a later phase of EPRI's research will focus on emissions minimization. No production plans have been announced.

The RXEV concept has also emerged in the "LA 301" electric vehicle under development by Clean Air Transport, a Swedish company which entered the competition for electric vehicles initiated by the City of Los Angeles in 1988. Although intended for all-electric operation in most urban driving, the LA 301 is a parallel hybrid. It is expected to provide a range of 60 miles on battery power alone, or over 150 miles with use of its Auxiliary Power Unit, a 4-cycle ICE intended to meet California Ultra-Low Emission Vehicle (ULEV) requirements [Clean Air Transport]. The prototype vehicle was unveiled in mid-1991.

The most recently announced range-extender prototype is Ford's conversion of the European Escort minivan. About 35-50 of these are to be built beginning in late 1992 as part of a 70-100 vehicle demonstration project involving both battery-only and hybrid-electric versions of the minivan. See Chapter 3 (p. 3-4) for further details on this project.

The GM HX3

The most recent among U.S. HEV developments is the GM HX3 concept vehicle, unveiled in January 1991. Not intended for production, the HX3 is a 5-passenger "sedan of the future" with "lounge seating" and a silhouette like that of a minivan. GM calls it a test bed for technologies that will "...help the industry achieve new benchmarks in vehicle emissions and fuel economy"[General Motors, 1/91]. It clearly indicates the most likely new directions for HEV development in the 1990s.

Configured as a series hybrid, the HX3 utilizes the high-efficiency, dual-motor ac propulsion system and sealed lead-acid battery pack developed for the GM Impact car (see Chapter 2). To this it adds an engine-alternator package which can deliver up to 40 kW of electric power. The HX3 is primarily a battery-powered vehicle. But when its battery is depleted, its engine starts automatically (although the driver can override engine start to maintain zero emissions). The engine is conventional: a 4-cycle, 0.9-liter, single-overhead-cam, gasoline-fueled ICE weighing under 150 lbs which runs at a constant 2500 rpm, its most efficient and lowest-emission speed.

The maximum output of the engine-alternator is less than half of the power required by the electric powertrain for maximum acceleration. Still, in the hybrid mode, the HX3 reportedly achieves a level of performance and driving range similar to today's minivans. Specific test results have not been reported for the HX3, but because it weighs nearly twice as much as the Impact car (which uses the same battery pack and electric powertrain), its range and acceleration capabilities will be roughly half those of the Impact. This implies a range capability for the HX3 on battery alone of about 60 miles, with acceleration capability of 0-60 mph in about 16 seconds.

Other Hybrid-Electric Development Efforts

In Europe and Japan there have been a number of other noteworthy experimental HEVs. These include the Lucas series- or parallel-hybrid car in the UK and the Toyota gas-turbine series hybrid car in Japan [Harding; Watanabe & Fukuda; Saridakis]. Little information is available on these activities. In France, Peugeot's HEV program is reportedly developing a vehicle with a diesel-powered generator to recharge batteries during highway use. In a second phase, Peugeot is planning to replace the diesel-driven generator with a high-speed turbine powering a turbine-generator. Renault also reports on a gas turbine hybrid concept, but without details on development status (see Gas Turbine section later in this chapter).

4.4. HYBRID-ELECTRIC BUSES AND TRUCKS

Hybrid buses have been actively developed and demonstrated in Europe for over a decade. Available batteries could not provide sufficient range for a full day's service, so hybrid buses were tested along with all-electric buses relying on quick battery exchanges and fast end-of-route recharges to extend range. In 1979, 20 Daimler Benz series diesel-electric hybrid buses were put into regular service in Stuttgart and Wesel. Performance was reportedly satisfactory and air pollution reduced, but fuel savings were negligible; no further results were available. In Italy, however, an experimental series diesel-electric bus built by Fiat researchers cut diesel fuel use by 21%. Performance and emissions were not reported [Brusaglino; Wouk].

In Japan, a fleet of hybrid delivery trucks was built in the early 1980s to reduce noise in urban areas, where they were reportedly able to operate on electricity alone [Brusaglino]. Hybrid bus development is now under way in the United States. A cooperative program to develop fuel-cell hybrid buses is being sponsored by the US Departments of Energy and Transportation and by California's South Coast Air Quality Management District [Christianson; Kevala & Marinetti; Romano]. The project's early studies indicate that a phosphoric acid fuel cell/battery power urban bus may be technically feasible, while its life-cycle cost appears acceptable. It should be recognized, however, that these buses are "Type A" hybrids (see p. 4-2): the fuel cell system, not the electric utility system, is to supply most or all of the required energy. Unlike the European hybrid buses, then, these U.S. hybrids are functionally like low-pollution liquid-fueled vehicles, not electric vehicles powered by the utility system.

4.5. PROJECTED HEV PERFORMANCE AND COST

As noted in Section 4.3, recent advances in electric motors, controls and batteries clearly favor a shift from vehicles like the VW Golf hybrid to vehicles like the GM HX3 hybrid, i.e. from vehicles based primarily on ICE propulsion to vehicles based primarily on electric propulsion, and from vehicles with modest electric capability to vehicles with modest ICE capability. The result will be HEVs which--like the HX3--offer most of the advantages of pure EVs, yet provide unlimited cruising range when needed.

Though HEV development lags that of pure EVs, it is possible now to sketch the most likely major characteristics of future HEVs for the late 1990s and 2000s:

- Their acceleration capability on electricity alone will rival that of pure EVs.
- Their range on stored electric power will be somewhat less than that of pure EVs.
- Their range on ICE power will be unlimited.
- Their cost will be slightly above that of pure EVs.

This future HEV may be viewed as an EV in which part of the propulsion battery has been supplanted by a small ICE. In such an HEV, the ICE would probably be sized to provide only enough power for continuous freeway and highway cruising, plus a reserve for adverse road conditions and for slow battery charging. This would allow the battery to supply occasional power bursts for highway passing maneuvers and ascending grades.

The power requirement for freeway cruising is only a fraction of that ordinarily available in an ICE vehicle. Thus the ICE required in the future HEV is likely to be relatively small: about 15 kW for a compact car which might ordinarily be equipped with a 60-kW ICE system. Since ICE systems typically weigh 2-4 kg per kW of rated output, estimated weight of the complete ICE system (assuming the parallel configuration) would probably be under 40 kg [Hamilton, 1989].

When powered by the ICE, fuel economy of the HEV in highway travel will most likely approximate that of a comparable ICE car. The extra weight of the battery in the HEV would be offset by operation of its ICE at its optimum settings, where efficiency will be higher than that of the larger, lightly-loaded ICE in a conventional car. HEV emissions per mile during ICE operation are expected to be low since the ICE in this type of HEV would not be idled or throttled, and its catalytic converter could be preheated to minimize cold-start effects. In most urban driving, emissions of such an HEV would be zero because the ICE would probably not be started at all.

Substituting the ICE system for part of the battery in a compact electric car could supplant as little as 10% of battery weight, since the propulsion battery in such cars typically weighs 400-500 kg (see Chapter 2). Range of the resultant parallel-type HEV on electricity alone could thus approach 90% of that of the pure EV [Hamilton, 1989].

EV cost (including battery) would be little affected by substituting an ICE system for an equal weight of battery, because battery and engine costs per kg are similar. As shown in Table 4.1, costs of small ICE systems for HEVs are estimated at $10-15 per kg for advanced two-stroke ICE technology and for conventional automotive ICE technology respectively. In comparison, costs of future nickel-iron and sodium-sulfur batteries are projected at $12-17 per kg.

Table 4.1
Costs of HEV ICE Systems and Propulsion Batteries

	20-kW HEV ICE Conv.	20-kW HEV ICE Adv.	Late '80s 67-kW ICE
Specific Weight, kg/kW	3.5	2.1	3.2
Specific Cost, $/kW (retail)	53	21	22
Cost per kg (retail*), $	15	10	7
	1995 Batteries NIF-220	**1995 Batteries Na-S**	**Late '80s Pb-Acid**
Specific Energy, Wh/kg (3 hr)	53	90	31
Specific Cost (OEM), $/kWh	160	125	100
Cost per kg (retail*), $	13	17	5

* Contribution to retail vehicle price, assumed to be 1.5 times OEM price

Use of the series hybrid configuration would require addition of an alternator to the ICE system. While available references did not provide detailed weight, cost, and performance projections for this alternative, preliminary review suggests that the cost of the HEV (including battery) should remain little affected, while battery weight and electric range should be reduced by 15-20% at most relative to a pure EV version.

4.6 ADVANCED ICEs FOR HEVs

Improved automotive ICEs, such as advanced two-stroke engines and automotive gas turbines, have been under development by motor vehicle makers for many years. Their potential application in HEVs was appraised in detail in 1984 during DOE's HEV analyses which followed development of the HTV [Schneider].

Two-Stroke Engines

For conventional vehicle use as well as in hybrids, the leading prospect in 1984 was deemed to be advanced two-stroke engines: hi-tech, cleaned-up versions of conventional two-stroke designs. Conventional two-stroke engines are very simple, compact, and powerful for their weight--but so dirty and inefficient their use has been largely confined to chain saws, lawn mowers, and outboard motors. Progress with advanced two-stroke concepts seemed encouragingly rapid in the mid-80s: major motor vehicle manufacturers worldwide showed off experimental engines and at the beginning of 1988, two-stroke engine prospects made the cover of Business Week [Hampton]. Now, however, it is over three years later and automotive two-stroke ICEs have yet to be commercialized. When--or whether--they will reach the market remains uncertain.

<u>The General Motors CDS-2</u>: GM, an aggressive player in the two-stroke competition, unveiled its advanced "CDS-2" two-stroke engine in early 1990. CDS is an acronym for Computer-controlled, Direct injection, Stratified charge, two-stroke. It reflects GM's approach to two-stroke development: "...no valves, no supercharger...just high tech engineering" [General Motors, 1990]. The GM approach rests on precise electronic control of fuel delivery, ignition, and other operating variables, together with the air-assisted, direct-injection combustion process developed by the Orbital Engine Company of Australia. The CDS-2 is a 3-cylinder, 1.5-liter engine which weighs only 165 lbs, yet reportedly delivers 110 hp with the smoothness of a 6-cylinder 4-stroke engine.

Advantages of the CDS-2 in comparison with conventional four-stroke engines include a very low profile, with reductions in weight (about 60%) and component count (about half) which could bring cost savings. GM believes that because of the two-stroke engine's small size and weight, it could be a major advance in vehicle packaging as well as an improvement in fuel economy and emissions. Doubts persist, however, about emissions for two-stroke engines in general--particularly NOx.

The CDS-2 was exhibited in a specially-designed show car, but the engine is not ready for production and was never intended for production in its present form. GM statements indicate that much testing remains to be done. Nonetheless, it apparently could be as soon as the mid-1990s.

Gas Turbine Engines

Automotive gas turbines, the other leading alternative to conventional automotive ICEs, have been under development since the 1950s, when Chrysler first put a fleet of turbine-powered test cars on the road. New high-temperature ceramic materials have given the technology a boost: the AGT-5 engine under development by General Motors, the Dept. of Energy, and the NASA Lewis Research Center will rely on parts fabricated from silicon nitride and silicon carbide by a variety of processes [Gardner].

Thermal efficiencies of 47% are anticipated for the AGT-5 turbine, well above the 20-33% of conventional ICEs. Furthermore, the turbine is inherently clean: its untreated exhaust is expected to meet federal clean air standards. Engineers at GM's Allison Gas Turbine Div. say small fleets of experimental turbine-powered vehicles should be in operation by 1995 [Gardner]. This does not necessarily mean, however, that mass production of turbine engines with satisfactory cost and durability will soon follow. Here again, commercialization cannot yet be confidently forecast.

Renault has reported [Koslowski, 1992] on its Espace hybrid vehicle concept incorporating a gas turbine. This is a series hybrid using a NiCad battery and a single-shaft turbine with a permanent-magnet high-speed alternator driving ac asynchronous motors. The gas turbine is radial, with a centrifugal compressor; fuel/air premixing and prevaporization is used to reduce emissions, and addition of a catalytic combustion system is under consideration. However, no details have been forthcoming as to the status of turbine development.

An American firm, NoMac Energy Systems, Inc., is also developing an advanced, single-shaft gas turbine-driven generator for HEV use. Its 24 kW continuous rating is sufficient to propel an automobile at maximum legal speed in the United States. For hill climbing and passing, 30 kW is available. The unit uses a circumferential recuperator to increase efficiency. Production units will have catalytic combustion. A catalytic combustor/gas turbine generator combination is forecast to produce emissions at a grams per mile rate that would be on the same order as required by a power plant to produce the electricity to power an electric vehicle.

Suitability of Existing ICE Technology for Hybrids

It should be noted that successful development of advanced ICEs is not required to make HEVs feasible and practical. HEVs would generally benefit from cheaper, lighter, more efficient ICEs; series HEVs would especially benefit from more compact ICEs operating at the high speeds needed to minimize alternator weight. Nevertheless, existing automotive ICE technology suffices for HEVs with potential sales, use, and benefits potentially far exceeding those of pure EVs.

Moreover, HEVs are expected to utilize ICE power for only 10-20% of their total travel. HEVs would thus benefit less from advanced engines than would conventional vehicles, which must rely on ICE power for 100% of their travel. A major advance in ICE technology might even weaken the competitive position of HEVs.

It is also possible that HEVs will be able to make good use of ICEs unsuitable for conventional vehicles. In comparison with conventional vehicles, HEVs impose relatively modest demands on their ICEs. Operation can be at (or near) constant speed and load, under conditions chosen for fuel economy and low emissions per hp-hr, with little throttling and no idling. Moreover, the engine's required operating life should be relatively short: typically only 10-20% of the operating life of the vehicle itself, depending on its all-electric range. For HEV configurations which permit vehicle operation on the HEV alone, this also depends on timely replacement of the batteries as needed. Emissions deterioration during HEV life should be correspondingly reduced; and because startup of the HEV ICE can be planned in advance, preheating of catalytic converters will be possible to minimize cold-start emissions.

4.7 PROJECTED HEV USAGE AND MARKETABILITY

Analyses based on household travel data suggest that each future HEV could electrify as much or more household travel than would a competing EV, despite the HEV's shorter all-electric range. The basic reason for this is simple: Households with an EV will have to use an ICE vehicle for the entirety of any trip beyond the EV's range capability, whereas households with an HEV will be able to use it to make part of even the longest trip on electricity.

The major market for EVs is in multicar households, where an ICE car would be available for travel beyond the EV's range. At a typical multicar household, an EV with 100-mile range would electrify about 57% of household travel, as shown in Table 4.2. A hybrid with only a 60-mile electric range, however, would electrify an equal amount of travel.

Table 4.2 was developed from a series of travel simulations based on the extensive data of the Nationwide Personal Transportation Survey, which periodically interviews a national sample of about 25,000 households, recording the details of every trip taken by each household member on the survey day: timing, purpose, mode, vehicle used, origin and destination, etc. In the simulations, an ICE vehicle at each multicar household was replaced by an EV or HEV utilized according to various plausible strategies. The amount of household vehicle travel which could be accomplished electrically was then determined by actual assignment of individually reported trips to the EV or HEV and to other household vehicles [Kiselewich & Hamilton].

In assigning vehicles to trips in the simulation, it was assumed that the EV or HEV would be used in preference to other household vehicles wherever possible, i.e. where seating capability was adequate and, in the case of an EV, sufficient range capability remained available. The preference assumption seems reasonable in view of the lower operating costs of EVs and HEVs together with improved future performance (more like that of the GM Impact).

Table 4.2
Percent of Household Travel Electrified with one Four-Passenger EV or HEV per Multicar Household

Electric Range, mi	Household Travel Electrified EV	HEV
40	34	48
50	40	53
60	45	57
80	52	63
100	57	66
125	61	69
150	64	70

It was also assumed in the simulations that the typical HEV would be operated on ICE power only after its battery's range is exhausted (i.e., battery discharged to its minimum safe level). This seems likely for several reasons:

- ICE use for battery recharging will be expensive. Fuel costs are estimated at 15-20 cents/kWh for the XREV, for example. This is far above the 5 cents/kWh considered representative of rates for off-peak utility power used in overnight recharging.
- ICE use will increase propulsion noise and vibration noticeably.
- ICE operation will necessitate repeated visits to service stations for fuel and maintenance which would otherwise be unnecessary.

Moreover, in the HEV a computer will control the operation of the powertrain. To reduce costs, liquid fuel use, and exhaust emissions, HEV manufacturers are likely to program this computer to ensure the maximum practical reliance on stored electricity for propulsion, i.e., to minimize ICE use.

Electric range of the HEV will typically be at or above rated range during much of battery life. Near the end of battery life (usually taken as 80% of rated capacity), both remaining battery capacity and maximum available power will begin to decline rapidly. The consequent reduction in electric range can be offset by additional operation of the ICE, maintaining its utility--but at a significant cost penalty, as noted above.

In the future commercial HEV as projected here, using a very small ICE (whether in a series or parallel configuration), ICE operation would provide only part of the power required for full acceleration in the HEV. To the extent the battery is unable to supply the remainder, the HEV's acceleration capability would be impaired. On ICE power alone (i.e., with a dead battery, or one in a series configuration merely supplying power as provided in real time by the ICE), HEV acceleration would be sluggish--probably below levels of even the slowest of conventional autos.

Market studies show that limited daily range is the EV's principal drawback for prospective buyers [Beggs]. Not surprisingly, they also show a much larger potential market for HEVs which are essentially EVs without this range limitation. One quantitative analysis found potential HEV sales for household use to be nearly 5 times larger than for EVs [Hamilton, 1989]. While market data is scant at best and such estimates vary widely, the available evidence indicates that the HEV's long-range capability will probably ensure it a larger market share than that of the pure EV.

This view is not unanimous. For example, one respected researcher suggests that range may not be such a critical factor; as EVs become more familiar, many consumers may find that EV range is acceptable--as some interpretations of travel survey data suggest. If so, then other differences between EVs and HEVs may become more important. For example, the HEV's greater complexity, maintenance requirements, noise, and need to visit gas stations may make it much less attractive than the EV. And if ARB penalizes the HEV for its worst-case emissions instead of granting it preferred status, its environmental image as well as its cost-competitiveness may suffer [Sperling].

Despite such possibilities, we believe that EV range limitations will dominate the decisions of many buyers, making HEVs likely to become more numerous than EVs. HEVs may also have correspondingly greater emissions-reduction benefits despite their use of ICEs for part of their travel. On a *per-vehicle* basis, HEVs (of the "enforced-benign" type envisioned here) and EVs could reduce air pollutant emissions about equally because of the more extensive use of the HEVs. Future HEVs seems likely to electrify as much or more urban travel as an equal number of future EVs, reducing vehicular emissions and increasing powerplant emissions just as EVs would. Unlike EVs, these HEVs will also travel occasionally on ICE power, but their pollutant emissions during this travel should be no larger than those of the ICE vehicles which otherwise would be used.

As noted earlier, these conclusions depend on factors such as the battery capacity, ICE size and emissions characteristics, choice of series or parallel configuration, and the battery/ICE operating strategy. The hybrid configuration and operating strategy must be designed to favor battery use, and the ICE must be designed and controlled to minimize emissions. This topic is discussed further in Chapter 8 regarding HEV regulatory issues.

Chapter 5

ELECTRIC VEHICLE ECONOMICS

5.1. ISSUES AND APPROACH

Economic Issues for EVs

What are the key issues in EV (and HEV) economics? The most common question is whether EVs can be price-competitive with conventional or other clean-fuel vehicle propulsion alternatives. Although most often applied to near-term, limited-production electric vehicles, this question is also centrally important to future high-volume mass-produced EVs. Many studies have been conducted to predict the price-competitiveness of electric vehicles.

But there are other important economic issues for EVs. For example, what cost elements should be included? How are these costs to be distributed? Costs unique to EVs (and which must eventually be recovered in vehicle pricing or other associated revenue) include not only the first costs of unique components such as batteries, but also much of the initial R&D and product-development costs, electricity service and charging station installation, sales and maintenance infrastructure setup, costs of capital and new-technology risk, and unique component disposal/recycling costs. Even if EVs can eventually be price-competitive based on their theoretical production costs, these other cost elements must be included in any overall cost comparison.

Ultimately the most important economic issue concerns the motivation of producers to enter the market and of buyers to accept the product. For necessary economies of scale to develop, large numbers of vehicle buyers must choose EVs over other vehicles, and at a price that permits EV manufacturers to earn an acceptable rate of return on their investment. What will induce buyers to choose or reject EVs? Is it primarily cost? Will buyers perceive significant risks in EVs, and will they be only financial? How can such risks be managed so that EVs can penetrate the market to the necessary degree? And what does it take to convince a major producer to accept the investment and risk of committing to EV development? Without mechanisms to address these issues there can be no successful EV commercialization.

This leads to broader societal issues, such as the question of whether EVs should even be expected to be cost-competitive with other vehicles, in light of the unique "external" EV benefits such as emissions reduction, reduced oil dependence, and primary energy efficiency. Stated another way, if EVs not only provide transportation to individual buyers but also help solve other problems for the whole society, how should those solutions be financed? Surely not only by the EV buyer, but then by whom, and how?

Most of these issues have not been addressed systematically in studies to date. Emphasis instead has been directed primarily to the relatively narrow question of initial EV price or life-cycle cost-competitiveness based on production and operating costs assumed to be paid by the owner in direct comparison to conventional vehicle practices. However, the broader economic issues such as those just cited need to be examined and debated more openly if appropriate financial mechanisms are to be created.

Assessment Scope and Approach
This EV economics review seeks to address the broader range of issues just identified, as a way of encouraging their consideration in public policy formulation by ARB and others. In the first section below, we review experience in EV cost forecasting and comparison, and offer some general conclusions about the results and significance of such efforts. Next we take a comprehensive view of the process of introducing EVs into the marketplace successfully, including factors such as producer and buyer motivations, to illustrate a broader range of economic concerns. Finally, we consider the role of societal benefits of EVs--the "externalities" of conventional vehicle use--and suggest some ways to allocate costs in recognition of such important EV benefits.

5.2. EV COST-COMPETITIVENESS

Advocates of electric vehicles have long contended that in the long-term, EVs will be equal or superior to conventional ICE vehicles (CVs) on a life-cycle cost basis. In fact, careful life-cycle cost analyses generally conclude that the long-term costs for both technologies will be roughly similar. However, the costs of EVs in the initial years of lower-volume production are generally found to be somewhat higher than those of conventional vehicles.

Projected Life-Cycle Costs
Electric vehicle economics have been the subject of many papers and studies. Examination of EV economics have focused on the comparison of life-cycle costs for EVs and conventional vehicles; since only a few prototype EVs actually exist, these studies have relied on forecasts and assumptions regarding the key factors. DeLuchi et. al. (1989) and Hamilton (1988) performed detailed cost comparisons with up-to-date cost assumptions and thorough reviews of previous literature.

Table 5.1 (next page) presents the results of both studies. Although they included different cost items and chose different costs, the findings generally agree that the overall life-cycle cost difference between EVs and CVs is within about 10% for the vehicles studied. Both of thesed were projected passenger cars with 150-mile sodium-sulfur batteries. Under the assumptions most favorable to CVs and least favorable to EVs in Table 5.1, the total annual cost premium for operating EVs is only about $700. And under the conditions most favoring EVs, their annual life-cycle cost savings would be no more than about $350. Considering the many possible differences in assumptions, these cost differences are very small.

Assumptions and Uncertainties in Cost Forecasting
It is important to understand the technical limitations of such forecasted cost comparisons. For example, life-cycle costs for both vehicle types are highly sensitive to power-supply costs: the price of gasoline for CVs, and electricity cost, battery cost, and battery life for EVs. Assumptions regarding the cost of capital, maintenance expenses, depreciable vehicle lifetime, and both intermediate resale and eventual salvage costs are also important.

Table 5.1
Electric (NaS Battery) vs. Conventional Vehicle Life-Cycle Costs, ¢/mile

	DeLuchi *et al*			Hamilton	
	Gasoline Car	Electric Car Low Est.	Electric Car High Est.	Gasoline Car	Electric Car
Energy w/tx	3.77	1.48	2.11	3.4	1.5
Battery		4.51	10.56		7.6
Vehicle	13.94	9.90	12.55	7.8	5.8
Plug-in		.39	.39	n/c*	n/c
Insurance	4.69	4.67	5.21	n/c	n/c
Maintenance	4.47	2.44	3.48	3.7	2.9
Misc.	1.55	1.38	1.43	n/c	n/c
Total ¢/mile	**28.42**	**24.77**	**35.73**	**14.9**	**17.9**

*not considered

Fuel cost assumptions provide an example of such effects. The gasoline price used in the studies cited earlier was $1.30 per gallon (Hamilton) and $1.15 (DeLuchi), both realistic numbers at the time the respective analyses were performed. However, the price of gasoline may rise far beyond these levels due to many factors, such as political uncertainties worldwide, and future prices cannot be predicted with confidence. EV electric power costs are more likely to remain fairly constant or even decrease within the next few decades. The 5-cent per kWh rate used in both studies cited above is unlikely to increase faster than the overall rate of inflation.

Many other examples could be cited. EV battery cost and service life were fairly comparably forecast (on average) in both studies, but could improve dramatically if anticipated technology breakthroughs are realized. For example, lithium-polymer batteries could offer both cost reductions and improved battery life. DeLuchi incorporated a wide variety of such possible variations in developing his high and low-cost scenarios; Hamilton's estimates of variability, if he had included them, would probably have been similar.

The choice of the vehicle's cost elements to include is obviously a major determinant of the result of any cost comparison. Some EV cost-competitiveness forecasts have tended to focus on an estimated vehicle production cost, without markups by manufacturer, distributor, and dealer. Since such markups are included in the corresponding CV price, the EV may appear more competitive than it actually would be. Similarly, the costs of in-home charging circuits, outlets, and related requirements are sometimes overlooked. Hamilton excluded insurance cost because he expected it to be similar for both vehicle types; DeLuchi included variations based on expected vehicle cost differences, assuming insurance costs to be related to vehicle cost (although acknowledging that they might not).

Yet another key assumption is the choice of vehicle characteristics. Most of the existing cost comparisons--although not the two cited here--focus on current or near-term, limited-production EVs. Costs of current and near-term EVs such as the G-Van must be based on low-volume production and less comprehensive, cost-optimized vehicle and component designs. When compared with highly developed conventional vehicles, these EVs are clearly at a disadvantage. But future EVs, best exemplified by the GM Impact prototype, can be designed "from the ground up" specifically for electric power and dedicated mass production facilities, and may therefore be more cost-competitive. At the same time, conventional gasoline and various clean-fuel vehicle technologies will also be continually improved to an unknown degree. This means that any forecasts of future EV cost-competitiveness will be highly uncertain.

Cost-Competitiveness Conclusions
With consideration of uncertainties inherent in the predicted cost elements, the cost-competitiveness of EVs (including HEVs) can be summarized in these points:

> ...Near-term EVs will be more expensive to buy--possibly much more--although their operating costs may be lower. Near-term EVs are unlikely to be cost-competitive on a life-cycle basis.
>
> ...The initial price of more advanced later-model, mass-produced EVs, if batteries are included, is still likely to be higher than that of comparable CVs. However, such advanced EVs may have life-cycle costs similar to those of CVs--probably not lower, and possibly still somewhat higher.
>
> ...the difference in forecast cost between EVs and CVs is particularly sensitive to battery life and cost, gasoline price, and the EV price minus batteries.

Altogether, these uncertainties suggest that EVs are unlikely to become *less* competitive with CVs, but cannot be reliably predicted to fully overcome their near-term disadvantage. This suggests the inadequacy of reliance on such analysis and a need for a broader perspective as described in the following section.

5.3 SOCIETAL BENEFITS AND COSTS

Vehicle cost-competitiveness is only one aspect of EV economics. A much broader perspective is necessary, including not only long-term theoretical cost-competitiveness but also capital investment, buyer needs and preferences, societal costs and benefits, and management of the transition from zero to large-scale EV production and sales.

The most important factor in favor of EVs is air quality: EVs are the cleanest motor vehicle alternative even when power plant emissions are taken into account, as the emissions analyses of this study (Chapter 7) and others demonstrate. They also offer a degree of primary energy-source independence not possible with any other alternative, since electricity can be generated from a variety of sources both within and outside the country. And overall primary energy efficiency may increase due to the improved efficiency of the electric power generation system with nighttime EV charging to level overall power demand.

There are other EV benefits as well. For example, EVs would reduce the need for gasoline service stations and their attendant land use, soil contamination, traffic, and refueling emissions as well as the traffic hazards and road wear attributable to fuel delivery trucks. Reduced need for oil extraction, transportation, and refining due to EVs would avoid the negative effects of these activities. Accidents related to flammable vehicle fuels would also be reduced.

It is unrealistic to expect that these societal benefits should be achievable without cost. Yet achieving the societal benefits of EVs poses a major challenge: to find ways to encourage the production and sale of the first, expensive, EVs and build a market base so that large-scale production eventually becomes feasible. In other words, how can the builders and buyers of the first EVs avoid being penalized for taking the risks of investing in EV technology?

The full societal costs of operating CVs are much higher than typical cost studies indicate, because externalities such as the air quality effects of CV tailpipe emissions (which are excluded from cost studies since the vehicle owner does not pay for them) have significant adverse societal impacts. The costs of these externalities are now borne primarily by the society at large. Conventional vehicle owners pay only for their own emissions-control equipment which, in the case of for vehicles in the SCAB, is overwhelmed by the magnitude of the problem. In principle, then, it is desirable that EV buyers not be expected to bear the full cash cost of EVs since a portion of that cost is attributable to environmental cleanup well beyond the degree possible with CVs.

5.4. EV SELLER AND BUYER MOTIVATION

To achieve the air quality benefits of EVs, their large-scale deployment is essential. Yet there are a variety of factors that will act to inhibit consumers from purchasing the first commercial EVs. We will look at each of the following in turn:

- High purchase price
- Need for product confidence
- Competition with existing array of sophisticated CVs

Similarly, potential EV producers face substantial technical challenges as well as financial risks in investing in EV technology. In this section we consider the barriers to EV production and ways of overcoming them.

High Purchase Price
In general, the first limited-production EVs are expensive, with prices around 50 to 100% higher than for their CV counterparts. The first production run of the full-size G-Vans -- full-size cargo and passenger vans -- each cost $50,000 and up. For later in this decade, General Motors has projected that the purchase price for its planned small passenger car based on the Impact prototype could be over $20,000 in 1990 dollars. These costs reflect the higher production costs for new EVs and the need to recoup substantial investments.

However, there is only a very limited market for vehicles, even EVs, costing substantially more than the norm. Many institutions, such as electric utilities and public agencies, can justify the purchase of premium-priced EVs on the basis of benefits such as displaying the versatility of its product (utilities) or making a visible commitment to air quality (public agencies). But before most commercial or private consumers will buy EVs, they will need to perceive them as cost-competitive.

The life-cycle cost analyses performed by some commercial fleet managers may not offer a valid model for purchase decisions by many private individuals. Consumers often substantially discount future costs such as repair and fuel (two of the factors most favoring EVs), and usually weight first costs heavily (which favors the lower first-cost CVs). Mechanisms are needed to balance the scales more fairly in the consumers' eyes--that is, by reducing the purchase price of EVs relative to that of comparable CVs.

Need for Product Confidence

Many consumers are risk-adverse, and especially so when making such important decisions as the purchase of a new vehicle. In order to compete with the many reliable CVs on the market, EVs must appear no more risky an investment than CVs, for example by offering comparable--or superior--warranties and other assurances of acceptable risk in safety, reliability, cost of ownership and perceived status. In other words, EVs must be backed by the full strength and reputation of the major automakers. This might require innovations such as quick-response mobile repair, premium maintenance service, a resale/buyback market, and even a guaranteed retrofit/upgrade program to reduce concerns about the possible obsolescence of initial vehicles due to expected rapid technology advances during the first few years of EV sales. These requirements further add to EV cost.

Competition with Conventional Vehicles

Consumers value a variety of choices in vehicle size, style, price, configuration, performance, and many other factors. Until manufacturers have built whole families of EVs, competition with the many CV alternatives will hinder EV commercialization. If each of the three major U.S. automakers were to offer an electric commuter car and a light-duty van or pickup truck, there would still be only six EV options compared to the far larger array of CVs now available. This means that rapid market penetration by EVs cannot be expected to occur until more EV choices become available.

Moreover, EV technology is at a much earlier stage of development, and the first vehicles are likely to compare poorly to CVs in performance characteristics such as acceleration. Addition of higher-performance capabilities will require tradeoffs among other features such as cost and range, thereby also limiting the market.

Conclusions on EV Buyer Motivation

In sum, consumers will only buy EVs if they are convinced that the risk is low and the benefits of switching from CVs are high. EVs must be technically reliable and fully warranted, with a good resale value, and financially attractive in first-cost or lease payment terms. Ideally, they should also offer high performance and as much "prestige" as possible. Together, these criteria call for the active involvement of the major auto manufacturers, who have the expertise and financial stability needed to underwrite EV commercialization.

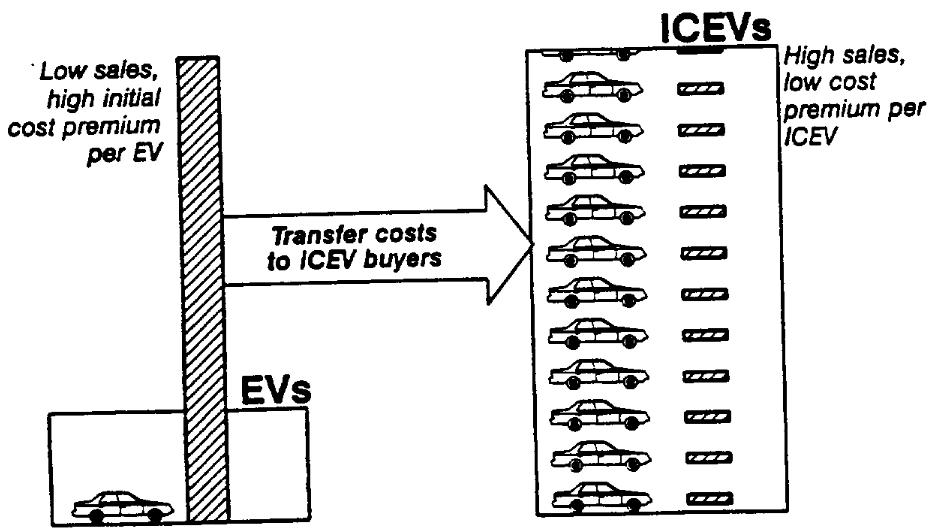
Manufacturer Motivation
Automakers, like other producers, are motivated largely by perceptions of risk versus potential profit and market position relative to other opportunities. If one company concludes that there is a substantial market for EVs at an achievable price--with enough return to compensate for the investment risk--it will be motivated to build them. And others are likely to follow suit to avoid a risk of decline in their long-term market share and return to investors.

The major U.S. automakers are already active in developing EV technology, as are most major competitors worldwide. Ford, Chrysler, and General Motors have each conducted R&D in this field for many years, and each has recently built and tested its own concept vehicle representing the state-of-the-art in EV engineering. But this developmental work will lead to commercial production only if the vehicles can be priced competitively. As already noted, it is likely that this will require ways to distribute EV costs between buyers and the society at large.

5.5. MECHANISMS FOR EQUITABLE EV COST ALLOCATION

The Transfer Payment Principle
In theory, a portion of EV costs can readily be transferred to CV buyers or owners of existing CVs. Through tax surcharges or voluntarily pricing their CVs slightly higher, manufacturers could recoup the extra expense of developing and building EVs and still offer the EVs for sale at prices competitive with CVs. Alternative funding sources include other taxes on sales or income, which would then be allocated to EV producers. Figure 5.1 illustrates the principle.

Figure 5.1
Transfer Payment Mechanism for EV Purchases



The numbers on the figure are used only to illustrate the magnitude of the necessary per-vehicle "transfer payment" and do not represent costs. The actual numbers will vary considerably, depending on the EV market penetration rate and how quickly EV production costs drop. To illustrate, assume that the price of a CV would normally average $15,000. If the first EVs cost $30,000 but would realize a market share of 2% if competitively priced, then the CV would only have to be priced at $15,300 to allow similar pricing of the EV. In other words, the $300 surcharge added to 98% of total vehicle sales -- the CVs -- will provide sufficient funds to offset the $14,700 price penalty for the 2% of sales that are EVs.

As the market share of EVs grows, their unit costs should drop gradually relative to CV costs. This should reduce the required transfer payment to cover the extra costs of EV production, but since fewer CVs would be sold the cost per CV could be relatively constant.

The California Approach

There are many possible ways to effect the transfer-payment principle. Taxes on vehicle sales, registration and/or gasoline would achieve the desired results. However, mandated EV sales quotas may be one of the most straightforward strategies. Such quotas are included in the "low-emission vehicles and clean fuels" (ZEV/CF) regulations passed by the California Air Resources Board in September 1990. Automakers desiring to sell their conventional vehicles in California will eventually be required to sell zero-emission vehicles (ZEVs) as well--2% of their combined annual sales of passenger cars and light-duty trucks (≤3750 lbs LVW) in California by 1998, increasing to 5% in 2001 and 10% in 2003. In order to sell the ZEVs (primarily EVs), the manufacturers will find it necessary to price them competitively, but in order to avoid losing money, they will either have to sustain a loss until the new vehicles become both popular and more economical to produce, or to increase the price of the conventional vehicles (and perhaps other alternative-fuel vehicles)--in effect, a pollution penalty.

For light-duty vehicles, the ARB plan also requires each manufacturer to comply with a non-methane organic gas (NMOG) emissions requirement, averaged over all its vehicles sold in California. This provides an additional incentive for EV production, because fewer EVs need to be sold to meet the requirement than if the automakers favored other "clean" fuels. For example, if another type of clean-fuel vehicle had only 50% of CV emissions, its manufacturers would have to replace two out of ten CVs with those vehicles to yield the average emissions that they could achieve by replacing only one out of ten CVs with a "zero-emission" EV.

The timing of the ARB plan will challenge the manufacturers. EV technology still needs refinement, followed by commercial vehicle design, production engineering, and tooling as well as buyer education and EV market-entry marketing. Manufacturers can be expected to seek delays if their progress lags in these activities.

The 2% of California vehicle sales in 1998 earmarked for ZEVs may amount to as many as 30,000 to 40,000 vehicles, according to ARB estimates. At this volume, the additional costs of EV development and early cross-subsidy by each manufacturer will be substantial. The ARB approach attempts to "level the playing field" by requiring all but the smallest manufacturers to sell EVs (mid-volume manufacturers--those selling up to 35,000 vehicles per year in California--also get a five-year grace period). Nonetheless, vehicles are sold under market pricing rather than cost-based pricing, so competition among manufacturers (or distributors and dealers) may make it impossible to transfer EV cost premiums to CVs. If this occurs, or if more rapid EV penetration is desired, the present ARB approach may have to be altered or augmented by broader societal funding.

Hybrid-Electric Vehicles: A Special Case

Because HEVs are not zero-emission vehicles, they do not benefit from the EV sales mandates of the LEV/CF regulations. However, HEVs are likely to have similar problems of high initial production cost and resulting need for cross-subsidy in order to be marketable in the early years. But because HEVs necessarily have higher (and more uncertain) average operating emissions per mile than do EVs, HEV sales quotas and other incentives are more difficult to justify.

In Chapter 4 it was suggested that HEVs might prove to have similar or higher total (daily or annual) emissions-reduction potential than EVs, despite higher average emissions per mile, because of the HEV's capability to meet more of a household's trip needs and thus avoid use of a CV for the longer trips. This may be true for multi-car households with the flexibility to choose which vehicle to use on a given trip, but single-car households (or individuals in multi-car households unable to shift their vehicles to suit trip lengths) with only an EV would probably change their travel patterns to avoid trips beyond the EV's range. Such users would always create more emissions if they had an HEV instead of an EV, since at least some of its travel would use the ICE.

It was also noted in Chapter 4 that HEV production costs are likely to approximate those of pure EVs, because of similar weight and cost per pound of the complete propulsion system including batteries. However, the HEV's greater flexibility should make it more valuable to most if not all buyers, so its needs for cross-subsidy should be smaller. Automakers may be willing to cross-subsidize HEVs (like other "ultra-low-emission vehicles") without further inducement, in order to lower their overall fleet emissions averages to meet increasingly stringent requirements. If not, and if overall HEV emissions prove to be much lower than other future alternative-fuel options, society may benefit from further regulatory action such as HEV sales quotas or an emissions-weighted combined EV-HEV sales quota.

5.6. CONCLUSIONS ON EV/HEV ECONOMICS

The economic issues of EV introduction go far beyond the production cost of EVs relative to comparable CVs. Electric vehicles may cost slightly more, even in the long term, but society gets more: transportation and cleaner air, with greater fuel flexibility and lower energy imports as well. In order to commercialize EVs, it will be necessary to transfer the EV industry's startup costs to CVs or to other means of payment by the society at large. These costs, which would be relatively small on a per-CV or per capita basis, can be justified as the CV driver's or society's responsibility for urban air quality.

Recent ARB regulations on EV introduction operate in this manner. However, achievement of more rapid EV market penetration than the low levels targeted in these regulations may require more powerful transfer-payment mechanisms such as higher percentage-of-sales EV quotas. The pending Fleet Rule 1601 (South Coast Air Quality Management District), which may include fleet quotas for EVs, is another potentially powerful incentive, particularly since commercial light-truck and auto fleets may be the most important initial buyers of EVs.

Other incentives to vehicle producers and buyers may also be necessary, such as emissions "taxes" or "fee-bates" on vehicle buyers based on certified vehicle emissions. Such fees could also be levied to owners of vehicles based on their smog-check results, with cash payments to registrants of EVs or other zero-emission vehicles. Income tax credits for ZEV owners are also possible but politically difficult. Non-monetary incentives such as free parking and use of freeway carpool lanes are of unknown value and are difficult to enforce; further study of such options is warranted.

More experience is needed with hybrid-electric vehicles in order to assess their costs, emissions-reduction benefits, and buyer preferences. In the best case, HEVs may prove to need no further buyer or producer incentives, yet provide clear environmental benefits. Potential EV/HEV buyer motivations need to be better understood, especially with regard to tradeoffs between vehicle range, price, maintenance needs, environmental "status," and other attributes which may differ between EVs and HEVs. As HEV research and assessment continues, results may warrant stronger incentives such as those already enacted for EVs. Development of emissions-minimizing HEV designs and in-use testing of HEV emissions are particularly needed.

Chapter 6

ELECTRIC VEHICLE PENETRATION SCENARIOS

6.1. CHAPTER OVERVIEW

In this chapter we describe future scenarios of electric vehicle characteristics, usage, and power sources, focusing on the South Coast Air Basin in the years 2000 and 2010. These scenarios provide the basis for assessment of future EV effects on air pollutant emissions, described in Chapter 7. They are augmented by sensitivity tests on key variables such as EV energy efficiency, daily usage, EV sales, and the sources of their electricity, in order to cover the most likely range of possible EV impacts.

6.2. SCENARIOS IN OTHER RECENT STUDIES

This study's scenarios complement and extend several other recent studies dealing with the potential impacts of electric vehicles in the South Coast Air Basin. Included among those are a comprehensive Electric Power Research Institute study, cofunded by the South Coast Air Quality Management District and conducted by Resources for the Future (1990); an equally detailed analysis done at the University of California at Davis [Wang *et al*], similar studies by Ford (1991, draft) and the Claremont Graduate School (1989), and an internal study by the Southern California Edison Company (Ducat, 1989).

Those related studies were different in several ways which makes their interpretation difficult. Among those differences were assumptions regarding future electric vehicle types, future conventional vehicle characteristics, EV energy efficiencies, daily usage, individual EV charging profile (i.e., charge duration and hourly demand), and hours in which charging was to be permitted. Different levels of EV market penetration were also investigated by the different studies, ranging from about five to fifty percent of the Basin's total vehicles.

All studies focused primarily on the peak summer demand period in the year 2010, but their assumed electricity generation profile "base case" (without EVs) differed somewhat. The studies also took quite different approaches to the determination of EV electric power generation sources. Most important, some studies forced the use of in-basin power plants to their maximum capacity, while others used production cost modeling or other decision rules to incorporate more optimal use of out-of-basin power production capacity and bulk power purchases.

Each of these differences can have a major impact on the resulting forecast of EV emissions impacts. Together, they make interpretation difficult at best; at worst, they can lead to outright errors in users' conclusions because of confusion about the underlying assumptions and their effects on the results. Consequently this study seeks to provide an easily understandable basic forecast of EV impacts, with its assumptions clearly identified, plus estimated tradeoffs in emissions impacts resulting from changes in each of the key assumptions.

6.3. SCENARIOS FOR THIS STUDY

The emissions analysis portion of this study has been designed around two central electric vehicle penetration scenarios: we hypothesize that future electric vehicles will number approximately 20 percent of the vehicle fleet in the year 2000, and approximately 70 percent of the vehicle fleet by the year 2010. The 70% penetration is the highest possible, since to achieve it 100% of all autos and light trucks sold from the year 2000 onward would have to be electric. These estimates are in contrast to other electric vehicle studies hypothesizing much lower penetration projections (for example, ARB's 1985 electric vehicle study hypothesized a 5 percent penetration scenario for the year 2000).

One key difference between the 2000 and 2010 scenarios should be noted. The ARB promulgated new tailpipe and evaporative emission standards after all the base analyses for this study had been completed. It was decided to re-analyze the year 2010 scenario based on the new standards; in this scenario, the electric vehicles would be replacing a cleaner conventional fleet. The discussion of year 2010 analyses is now based on the new analysis; the year 2000 discussion is not, because of the insignificance of any possible effects that early. The impact of not re-analyzing the impact for the year 2000 is minimal due to the small percentage of the region's vehicle fleet subject to the LEV standards prior to 2000 and to the relatively small number of EVs assumed in 2000. However, the conditions under which the new analyses were performed led to a situation where the scenarios differ somewhat. These differences do not affect the study's overall findings but should be kept in mind if detailed, year-by-year comparisons are made with this or other studies.

One of the primary objectives of this study was to learn what emissions reductions opportunities could be associated with electric vehicles. One way to accomplish this was to assume extreme electric vehicle use; if high EV penetration levels were not capable of generating substantial emission reduction benefits, then lower and more readily achieved penetration scenarios would certainly be disappointing emission control strategies. Consequently, ARB instructed the project team to evaluate the 20 and 70 percent penetration scenarios.

Specifically, the targets were to project 20 and 70 percent penetration of the combination of all light-duty passenger vehicles; all light-duty, non-diesel, catalytic trucks; and all medium-duty, non-diesel, catalytic trucks. Given these penetration targets, we constructed the scenarios as realistically as possible--taking into consideration earliest reasonable start-up dates for electric vehicle production and the need to gradually increase production capability in response to rising consumer demand.

Two noteworthy points emerged while constructing the EV penetration projections. First, our scenarios had to rely heavily on passenger car electric vehicle penetration to achieve our target goals. This finding is in contrast to some other studies which project most electric vehicles to be vans. As discussed in earlier sections, vans are likely to be the first electric vehicles to reach the commercial market (see, for example, Mader, 1989). However, vans make up less than 7 percent of the total vehicle fleet, and it was necessary to assume that substantial numbers of passenger cars would have to be electric if the 20 and 70 percent penetration goals were to be realized.

Second, while constructing the scenarios, it became quickly apparent that fleet turnover rates would inhibit the ability of a new vehicle type to substantially penetrate the auto market. To illustrate this point, national data show that over 60 percent of the vehicles from a given model year are still likely to be in use 10 years later [MVMA, 1989]. In California, driving conditions and climate allow cars to last longer than in much of the rest of the country. The implication is that older conventional cars will still be on the road long after electric vehicles take to the streets. Our scenarios had to balance the need to reasonably project electric car production as a small start-up effort that rises to more substantial production levels over time, against the need to meet this study's substantial overall EV penetration goals. The result was that our scenarios were forced to contain extraordinarily high EV penetration rates for each scenario's later years. In order to reach the year 2010's 70 percent EV penetration goal, for example, we had to assume that fully 100 percent of all passenger cars sold from the years 2001 through 2010 would be electric. While this is obviously unrealistic, it was chosen in order to examine the limits of possible EV impact in this study; it is not a target.

Additionally, the scenarios assume that only 20 percent of the power needed to charge electric vehicle batteries is produced within the SCAB, with the remaining 80 percent produced outside the basin. This split is roughly in line with projected in- versus out-of-basin power supply; according to CEC projections (CEC, 1990), slightly under 10 percent of in-basin power demand will be serviced by major in-basin power plants in the years 2000 and 2009. The electric utility analyses were based on demand for an August "peak day" to coincide with the time of year when both utility emissions and ozone concentrations are likely to be highest.

Although some readers will find this study's optimistic scenarios difficult to accept as a likely portrait of future electric vehicle use, they should still accept the value of such scenarios in better understanding potential electric vehicle emission impacts. This study also uses sensitivity analyses to test alternative scenarios; however, the 20 and 70 percent penetration scenarios are the ones most illustrative of the maximum potential emission reduction benefits inherent in electric vehicle technology.

In this study EVs are assumed to replace conventional as well as clean-fuel or reformulated-fuel vehicles in the same proportions as such vehicles exist in the region. This makes the study's results somewhat more conservative than if EVs were assumed to replace only "dirty" cars. The effects of such assumptions is discussed more thoroughly in Chapter 7.

The remainder of this discussion describes in greater depth the study's two main scenarios: the 20 percent year 2000 scenario, and the 70 percent year 2010 scenario.

Year 2000 Electric Vehicle Penetration Scenario

The year 2000 scenario is built upon ARB projections for future California automobile use. The ARB predicts automobile use as part of the agency's efforts to help forecast mobile source emissions; these projections then become inputs to mobile source emission modeling tools used by air quality planners throughout the state. This study utilized ARB's projections, and, as discussed in the next chapter, the emissions analyses were conducted using ARB's emission modeling programs (i.e., EMFAC and BURDEN).

ARB forecasts include a wide range of information concerning future California vehicles, for example, the number of motor vehicles that will be introduced in each model year, how long each model year's vehicles will remain on the road, and how far they will be driven. This study developed electric vehicle penetration scenarios by modifying the ARB forecasts. The scenarios substituted electric vehicles for conventional light-duty passenger cars and for mini- and full-size vans.

Timing of EV Introduction: We assumed that electric vehicle market entry would begin in 1991 with limited production of full-size electric vans (This actually occurred with the G-Van, although not to the extent assumed). We assumed large-scale production of electric mini-vans to begin in 1994, and electric passenger car production to begin in 1996. These 1990 assumptions could now be adjusted slightly; no electric mini-van is known to be scheduled for 1994 production, but the GM Impact-based electric car could be available as early as 1995. Effects of these changes on the study results would be small.

EV Energy Efficiencies: Estimated EV energy efficiencies were derived in Chapter 3 for three vehicle types, including four-passenger autos, light-duty vans, and medium-duty vans. These efficiencies, expressed in kilowatt-hours (at the wall socket, thus incorporating charger inefficiencies) per mile, are presented in Table 6.1 for the years 2000 and 2010.

Table 6.1
Assumed EV Energy Efficiencies by Vehicle Type, Years 2000 and 2010, in kWh/mile

	2000	2010
Autos (4-passenger)	0.24	0.24
Vans (light-duty)	0.60	0.40
Vans (medium-duty)	0.90	0.60

Vehicle Types: We assumed that assembly-line vans would be the only types of electric light- and medium-duty trucks through 2010. Pickups, although the majority of light-duty trucks, tend to be either too low-cost or too specialized in use for economical near-term EV versions to be likely, while medium-duty trucks other than vans were felt to be too varied in configuration. However, specific vehicle models such as mini- and full-size vans are not explicitly identified within ARB vehicle forecasts. We approximated the number of electric vans from ARB forecasts for light- and medium-duty trucks. ARB defines light-duty trucks as trucks with a gross vehicle weight (GVW) less than 6,000 pounds; medium-duty trucks are defined to be greater than 6,000 but less than 14,000 pounds (ARB, 1990); however, this study did not consider vehicles over 8,500 pounds due to the category definitions in the commercial data sources used. Such heavier vehicles are generally custom-bodied such that EV versions are unlikely to be cost-effective.

The limited available data indicates that the van fleet currently constitutes about 25 percent of all light- and medium-duty trucks; that mini-vans are approximately 60 percent of the van fleet and are analogous to light-duty trucks; and that full-size vans are approximately 40 percent of the van fleet and are analogous to medium-duty trucks. Recent trends point to increased truck and van use as a mode of personal transportation (e.g., see MVMA, 1989), and we have assumed that in later years (from the mid-1990s through the year 2010) mini-vans may represent as much as a third of all light-duty trucks. We did not, however, include any use of battery power in pickups, either for commercial or personal use. Despite the large numbers of pickups sold each year, these tend to be primarily lower-cost, special-purpose vehicles, many of which have range requirements exceeding EV capabilities. However, a niche market probably exists for some pickup EVs, and both Southern California Edison and the Sacramento Municipal Utility District are pursuing conversion opportunities for pickups. In any case, inclusion of pickups in this study's EV population would merely reduce the overall EV sales penetration rates slightly for other classes of vehicles in order to achieve the same emissions benefits.

Table 6.2 lists the electric vehicle penetration rates assumed for each model year from 1991 through the year 2000, for light-duty autos, and light- and medium-duty non-diesel, catalytic trucks. By the 2000 model year, annual EV market penetration rates in Table 6.2 represent approximately 100 percent penetration of the available fleets of light-duty cars, mini-vans, and full-size vans.

Table 6.2
Assumed Electric Vehicle Market Penetration Rates

Year	EV Market Penetration Rates by Type and Year		
	Light-Duty Automobiles	Light-Duty Trucks	Medium-Duty Trucks
1991			1%
1992			3
1993			7
1994		4%	12
1995		11	20
1996	15%	21	28
1997	54	25	35
1998	80	26	44
1999	90	27	44
2000	99	28	44
2001	100	28	44
2002	100	30	44
2003	100	31	44
2004	100	32	44
2005	100	32	44
2006	100	32	44
2007	100	32	44
2008	100	32	44
2009	100	32	44
2010	100	32	44

Year 2010 Electric Vehicle Penetration Scenario
All of the year 2000 scenario conditions were carried over into the year 2010 scenario. By the early part of the first decade of the 21st century, electric vehicles are assumed to have effectively penetrated 100 percent of the light-duty passenger cars, mini-vans, and full-size vans being produced in each model year (see Table 6.2).

Other Assumptions for Scenarios
Despite the possibility of longer vehicle life with EVs due to their simpler propulsion system, in this analysis no additional service life is assumed. Similarly, daily average usage of each EV is assumed to be the same as for comparable ICE vehicles, since at the high levels of EV sales projected here it is unlikely that an appreciably higher average mileage would occur for EV users.

Hours of EV Recharging: EV recharging is assumed to occur entirely during off-peak hours for the electric utilities, generally between 10 pm and 6 am. This is the most desirable situation for electric utilities, and can readily be assured through incentives such as special off-peak electricity rates and various utility load control strategies. Exact recharging times are assumed to be controlled through load management systems such that the highest possible 24-hour electric utility baseload is maintained and the midday peak loads are reduced as much as possible.

Gasoline/Diesel Production and Distribution: In-basin gasoline and diesel fuel production and distribution is assumed to be reduced by the total amount which would have been used by ICE vehicles displaced by EVs.

Changes in Assumptions for the Year 2010
Electric Vehicle Sales: The principal change in assumptions between the years 2000 and 2010 is in the very large increase in EV sales; fully 70% of the small-vehicle fleet is assumed to be electric by 2010. As in 2000, this target is based on goals of the region's most recently proposed Air Quality Management Plan. With this increased use of EVs, 9 out of 10 EVs are estimated to be automobiles, primarily because of the relatively small numbers of light trucks and vans in the region's overall vehicle inventory.

Conventional Vehicle Emissions Characteristics: As noted earlier in this chapter, a further difference between year 2000 and 2010 assumptions is the emissions characteristics of the conventional vehicles being replaced by EVs during the intervening years. In the 2010 analysis these are consistent with the most recent ARB rules governing low-emission vehicles; for the year 2000 analysis they are not, although this has little effect on the results to be described in Chapter 7. One additional scenario is modeled for 2010: The EVs are also modeled against an extended implementation schedule for low-emitting vehicles. Model year emission factors and fleet composition for these scenarios were provided by the ARB.

EV Energy Efficiency: As shown in Table 6.1, the energy efficiency of electric autos is assumed to be unchanged during the period 2000--2010. This is mainly because of the already high efficiency predicted for earlier electric cars from GM Impact data. Electric trucks and vans, however, are expected to gain in efficiency through gradual adaptation of advanced drivetrains, batteries, and vehicle structures which will be first used in autos--again as already demonstrated in the GM Impact prototype. Emerging technologies such as fuel cells may also help.

Chapter 7

ELECTRIC VEHICLE EMISSIONS IN THE SOUTH COAST AIR BASIN

7.1. OVERVIEW

This chapter analyzes the air pollutant emission changes in the Southern California Air Basin (SCAB) that could result from the electric vehicle use scenarios described in Chapter 6 for the years 2000 and 2010. The analysis focuses mostly on four pollutant categories: ozone precursors (nitrogen oxides and reactive organic gases), sulfur oxides, carbon monoxide, and particulates. As mentioned in Chapter 6, changing regulations for motor vehicles have necessitated the use of two slightly different base case scenarios in 2000 and 2010. In 2010, the conventional vehicles replaced by electric vehicles are assumed to comply fully with the September 1990 low emitting vehicle standards while in 2000 they are not.

The emissions estimates in this analysis are dependent on assumptions of the energy demands of electric vehicles, fuels burned by power plants, the number of miles driven per day by electric vehicles, conventional vehicle standards, and the amount of power produced within the SCAB to charge electric vehicle batteries. A key goal of this analysis is to clarify the effect of such assumptions on study results by explicitly varying these assumptions in sensitivity tests. This approach is intended to facilitate a better understanding of (1) which variables are most important in effecting emissions changes, and (2) key differences between electric vehicle studies.

Electric vehicle use within the SCAB is likely to affect emissions outside the Los Angeles area since much of the electricity generated to power these vehicles is produced outside of the Los Angeles area. This study, however, is limited to estimating emission changes within the Los Angeles area's South Coast Air Basin. As discussed in Chapter 6, this analysis assumes that 80 percent of the power needed to charge electric vehicle batteries will be available from outside the SCAB.

In addition to estimating emission changes for nitrogen oxides (NO_x), reactive organic gases (ROG), sulfur oxides (SO_x), carbon monoxide (CO), and particulates, this section also examines emission impacts for benzene (an air toxic) and greenhouse gases (CO_2 and methane). The emission changes estimated for the years 2000 and 2010 are placed in the context of anticipated emissions that would result without increased electric vehicle use, and are qualitatively assessed with respect to the region's ozone air quality problem. Note that recognizing the distinction between an emission analysis and an air quality analysis is important to understanding this study's scope. The emission estimates included in this analysis reflect changes in the quantity of pollutants emitted into the atmosphere. Complex chemical and meteorological phenomena control the extent to which these emission changes affect ambient pollutant concentrations. Estimating these changes quantitatively requires the use of modeling techniques beyond this study's scope.

The remainder of this chapter discusses the analytical approach and our results. Section 7.2 presents major findings; these are discussed with respect to several sensitivity tests in section 7.3. The methodology section (7.4) describes the methods used to estimate emission changes.

7.2. MAJOR FINDINGS

As described in Chapter 6, we analyzed three electric vehicle scenarios in this study: a year 2000 20% electric penetration scenario, and two year 2010 70% electric penetration scenarios. One 2010 scenario examines the effect of electric vehicles when replacing a fleet complying with the ARB's most recent new motor vehicle regulations (LEV standards and oxygenated fuel requirements). The other examines the effect when replacing a fleet subject to extended implementation of the ARB's LEV standards. The basic assumptions were summarized in Chapter 6 and include (1) the number of conventional vehicles replaced by electric vehicles, (2) the characteristics of the conventional vehicles being replaced (considering by-model year emission factors under various regulatory scenarios), (3) the energy requirements in kWh per mile of electric vehicles (which differ in different scenario years and by vehicle category), and (4) estimates of transmission line losses. As stated in Chapter 6, the percentages of electric vehicles assumed are not meant to be "best guesses" at future electric vehicle use. Their purpose is to illustrate the potential emission impacts associated with substantial electric vehicle use.

Assessment of Emission Changes for Criteria Pollutants

The scenarios are estimated to cause a dramatic reduction in criteria pollutant emissions. Tables 7-2 and 7-3 summarize the major results of the emissions analysis. These tables, and Table 7-2 in particular illustrate emmission changes for each source category affected by EVs (How do utility emissions change? How do vehicle emissions change? How do these changes compare with the total in-basin emission inventory?), for several scenarios (are EVs still effective when low emitting vehicle standards are in place?), and for all criteria pollutants. The base case and electric vehicle scenario emissions are each listed for the four major emission categories that are affected by electric vehicles: vehicles themselves, utilities, refineries, and gasoline storage and refueling. This last category is comprised of underground tanks (working loss and breathing loss), and vehicle refueling (vapor displacement and spillage). Other potential categories not considered due to lack of reliable estimations include possible reductions in emissions from auto manufacturing. The vehicle classes affected are light duty autos and trucks, and medium duty trucks. The base case emissions are listed for these vehicle categories only; heavy-duty trucks and off-road mobile sources are included in the 'total emission inventory' columns. Some explanation may be helpful in interpreting the results of this table. The "base" column presents emissions of the source category in the absence of electric vehicles. The "EV" column presents emissions of the source category when EVs are present. For example, in Table 7-3, 161.8 tons per year of NO_x emissions from motor vehicles were emitted in the absence of EVs. Under the EV scenario, 71.7 tons per year of NO_x are emitted.

The net in-basin effect from reductions in motor vehicle and motor-vehicle-related emissions, and from increases in electric utility emissions, is significant. In fact, emissions reductions from refineries (caused by decreased demand for gasoline under electric vehicle scenarios) more than offset emissions increases from electric utilities. In 2000, for example, utility emissions of all criteria pollutants increase by 0.0 to 0.7 tons per day while refinery emissions decrease by 0.4 to 3.0 tons per day. In 2010, this result is also observed, although the changes are of greater magnitude (the extent to which utility emission increases are offset by refinery emissions decreases is greater). The methodology for modeling motor vehicle emissions, assumptions regarding utility fuels burned, the manner in which power plants are 'ramped up' to meet the increased demand for charging electric vehicles, and assumptions used in calculating the effects of decreased gasoline demand on refining and gasoline storage and refueling are described in section 7.4.

These net changes reflect the large portion of in-basin emissions due to motor-vehicle-related emissions and the relatively small portion contributed by electric utilities. It is also interesting to compare equivalent emission factors of electric vehicles and conventional vehicles. The electric utility emissions associated with producing power to charge electric vehicles were divided by total vehicle miles travelled by electric vehicles to calculate an equivalent average gram per mile emission rate for electric vehicles. It should be kept in mind that the electric vehicle 'emissions' were calculated separately for different vehicle classes and associated energy requirements to calculate the numerator in this equation (for energy requirements see footnotes on Tables 7.6 and 7.7. EV "emissions" are listed in Tables 7.2 and 7.3). These were compared with equivalent grams per mile for conventional vehicles (subject to both the LEV and the extended LEV standards - for example, total CV emissions were divided by toal CV VMT; these are also average over vehicle classes and ages where individual emission rates vary). The electric vehicle emissions are generally two orders of magnitude smaller than the conventional vehicles, as shown in Table 7.1.

Table 7.1
Comparison of Gram per Mile Emission Factors for Electric Vehicles and Conventional Vehicles

Vehicle Type	NO_x	ROG	SO_x	PM	CO
Electric Vehicles (20% of required power produced in-basin)	0.0066	0.0003	0.0002	0.0007	0.0094
Electric Vehicles (100% of required power produced in-basin)	0.033	0.002	0.001	0.004	0.047
Conventional (LEV)*	0.41	0.31	0.05	0.20	3.12
Conventional (Extended LEV)*	0.36	0.27	0.04	0.17	2.56

* Note that gram per mile standards for new vehicles are significantly lower (i.e., .04 - .41 for LDA HC); the values in this table include significant numbers of older vehicles with higher emission rates.

Table 7.2
Emission Rate Summary (tons per day): Two base case comparisons with electric vehicle scenario for year 2000

Base Scenario and Pollutant	Affected Vehicle Categories[1]		Utilities		Refining		Gasoline Storage and Refueling		Total Emission Inventory		Percent Reduction for Total Inventory with EVs
	Base	EV	Base	EV	Base	EV	Base	EV	Base	EV	
2000 (20% penetration)											
NO_x	250.4	211.4	6.9	7.4	7.0	6.1	0.0	0.0	847.3	807.9	4.7
ROG	237.6	201.8	0.3	0.3	13.9	12.2	12.5	9.5	1046.6	1005.6	3.9
SO_x	17.3	13.2	0.2	0.2	24.6	21.6	0.0	0.0	141.3	134.2	5.0
PM	69.6	51.2	0.7	0.8	4.2	3.6	0.0	0.0	2222.1	2203.2	0.9
CO	1929.5	1769.9	9.2	9.9	3.5	3.1	0.0	0.0	3180.2	3020.9	5.0

[1] Light-duty autos, light-duty trucks, and medium-duty trucks.

Table 7.3
Summary Base Case and Electric Vehicle Scenarios 2010 LEV and 2010 Extended LEV Emissions (tons per day)

Base Scenario and Pollutant	Affected Vehicle Categories[1]		Utilities		Refining		Gasoline Storage and Refueling		Total Emission Inventory		Percent Reduction for Total Inventory with EVs
	Base[2]	EV[3]	Base	EV	Base	EV	Base	EV	Base	EV	
2010 No LEV:											
NO_x	260.7	97.0	7.3	8.5	7.2	4.3	0.0	0	926.7	761.3	-17.8
ROG	230.5	77.1	0.4	0.5	14.3	8.6	14.0	4.2	1120.3	951.5	-15.1
SO_x	19.4	5.9	0.2	0.3	25.3	15.2	0	0	134.0	110.5	-17.5
PM	83.7	20.7	1.0	1.1	4.3	2.6	0	0	2421.8	2357.2	-2.7
CO	1417.8	527.2	12.5	14.0	3.6	2.2	0	0	2819.5	1974.0	-30.0
2010 LEV:											
NO_x	168.4	71.7	7.5	9.3	7.0	5.2	0.0	0.0	797.3	700.6	-12.1
ROG	123.0	47.8	0.4	0.5	13.9	10.3	9.9	3.2	997.3	911.9	-8.6
SO_x	18.2	5.8	0.2	0.3	24.7	18.4	0.0	0.0	128.0	109.3	-14.6
PM	77.8	20.7	1.0	1.2	4.2	3.1	0.0	0.0	2415.8	2357.4	-2.4
CO	1260.4	447.8	12.8	15.5	3.5	2.6	0.0	0.0	2567.17	1757.1	-31.6
2010 Extended LEV:											
NO_x	143.9	71.7	7.9	9.3	6.7	5.2	0.0	0.0	772.8	700.6	-9.4
ROG	107.1	47.8	0.5	0.5	13.3	10.3	8.7	3.2	979.6	911.9	-6.9
SO_x	15.9	5.8	0.2	0.3	23.5	18.4	0.0	0.0	124.6	109.3	-12.3
PM	67.5	20.7	1.0	1.2	4.0	3.1	0.0	0.0	2404.8	2357.4	-2.0
CO	1019.4	447.8	13.3	15.5	3.4	2.6	0.0	0.0	2326.4	1757.1	-24.54

1 Light-duty autos, light-duty trucks, and medium-duty trucks.

2 Values differ across base case scenarios due to different base numbers of EVs (some are present in LEV scenarios) and clean vehicles.

3 The "EV case" vehicle emissions are identical in both the LEV and the extended LEV case because "extra" LEVs in the extended LEV case are replaced by EVs (because of the assumed 100% penetration rate in later years). Therefore, the final fleet in both the LEV and extended LEV scenarios after EVs are introduced are identical.

Qualitative Assessment of Emission Changes from Greenhouse Gases and Toxics
Emission changes for benzene and the greenhouse gases methane and CO_2 were also estimated and are listed in Table 7.4. The analysis of the net effect of electric vehicles on criteria pollutants alone is not comprehensive given current concerns about a wide variety of toxic air pollutants. Benzene was selected as a representative toxic compound in order to qualitatively estimate the effects of electric vehicles on toxic emissions. CO_2 and methane are key components of greenhouse gases. Emissions of these gases may be drastically changing the chemical composition of the atmosphere and causing potential global warming trends that could have far-reaching effects on agriculture, sea-level, and ecological stability.

Benzene Emissions
Benzene emissions were calculated by using EPA speciation information [EPA, 1988r] on the percent of benzene and other compounds present in any of approximately 250 different sources. The information is commonly referred to as "speciation profiles" and is developed through gas chromatographic testing of organic species present in various fuels and source categories. The categories of interest in this analysis include summer blend gasoline for the motor vehicle categories and natural-gas-fired external combustion boilers for electric utilties. The reported percent benzene (1.62% for vehicles and 4% for utility boilers) was multiplied by the calculated base and scenario ROG emissions to estimate benzene emissions.

Table 7.4
Emissions of Benzene, CO_2, and Methane (Tons per Day) for Base and EV Cases

	2000		2010		2010	
Pollutant/ Emission Category	**Base**	**EV**	**Base 1 (LEV)**	**EV**	**Base 2 (Extended LEV)**	**EV**
Benzene: Vehicles	3.8	3.3	1.98	0.77	1.74	0.77
Benzene: Utilities	0.012	0.012	0.02	0.02	0.02	0.02
CO_2: Vehicles	195,579	147,044	234,061	68,855	NA	NA
CO_2: Utilities	24,111	27,234	33,545	42,697	NA	NA
Methane: Vehicles	26.14	22.2	13.5	5.26	15.83	5.26
Methane: Utilities	0.17	0.17	0.22	0.28	0.28	0.28

Greenhouse Gas Emissions
Greenhouse gas emissions were calculated in a fashion similar to that for benzene. Methane is another species reported in the EPA document discussed above; methane emissions were also calculated proportionately to ROG. According to this document methane is 56 percent of utility boiler emissions and 11 percent of vehicle exhaust emissions. CO_2 emission factors (in grams per mile travelled) for motor vehicles were obtained from EPA data [EPA, 1990] and were reportedly 550 grams per mile. This value may be higher than what would be typical of later model year vehicles subject to more stringent fuel economy requirements. It is quite possible that actual emission factors would be closer to approximately 400 grams per mile, which would decrease the estimates of vehicle-related CO_2 in Table 7.4 by about 27 percent. CO_2 emission factors for electric utilities were obtained from a CEC utility emission factor report [CEC, 1989b].

7.3. SENSITIVITY TESTS

The electric vehicle penetration scenarios studied raise as many questions as they answer; for example, "What would happen if EVs were not as energy efficient?" "What if more of the electricity generated to power EVs were produced within the Los Angeles Basin?". This discussion covers a number of sensitivity tests used for evaluating the robustness of our major findings. Four tests are discussed here; Appendix A covers two others which were later incorporated into the base case assumptions for the year 2010 (these examine the impact of EVs when the conventional vehicles replaced are subject to oxygenated fuel and LEV standards. Results of these sensitivity tests are summarized in Table 7.5 (on the following several pages).

In broad terms, there are three central issues that govern what emission reductions can be achieved with EVs: (1) the number and characteristics of the conventional cars (and their usage) to be replaced by EVs, (2) the amount of electricity required to power the EV fleet; and (3) the characteristics of the electric utility plants used to generate the power. Numerous variables are built into each of these three considerations. Assumptions important to each variable play a role in determining the final energy use and emissions estimates.

Conventional Vehicles Replaced by EVs
Vehicle Emissions Characteristics: Since emissions standards for conventional vehicles are constantly tightening in California, the assumed emissions characteristics of the vehicles to be eliminated by EVs are important. First, EVs will replace new vehicles, not old or "fleet-average" ones, because they will compete in the new-car market. Retirements of older vehicles are unlikely to be affected by EVs. However, each production year's new vehicles to be replaced by EVs will begin to have lower emissions as the ARB's 1990 LEV regulations go into effect in the late 1990s. This means that the impact of EVs must now be measured against cleaner conventional cars, so EVs will have smaller benefits. This change has essentially no effect on emissions avoided through EV use during the 1990s, because EV sales volumes will be low in those initial years. But by 2010, with EVs comprising 70% of the region's light and medium duty vehicles, the effect of the new lower-emission LEV baseline will be significant.

For 2010, we modeled both the old and new (LEV) emission standards (as well as an "extended LEV" case using more stringent hypothetical LEV regulations) and found that ARB's 1990 LEV standards made a major difference in the potential emissions savings attributable to EVs. These effects varied substantially by specific pollutant; for example, the LEV regulations eliminated about 14% (129 tons per day) of the region's total NOx emissions, which in turn reduced potential NOx savings of EVs by 69 tons per day (from 165 to 96 tpd). The hypothetical "extended LEV" regulations would have saved an additional 25 tpd of NOx, further reducing the amount left for EVs to remove (probably by about 13 tpd, or to 80-85 tpd as the residual EV impact on NOx. Effects of these baseline differences had similar although somewhat smaller effects on the other pollutant categories studied.

EVs Within the LEV Base Case: It should be noted that ARB's new LEV standards used as this study's base case actually includes a significant number of EVs. Under those standards most automakers must sell at least 2% of their passenger car and light-duty truck (0 - 3750 lbs LVW) EVs beginning in 1998, increasing to 5% in 2001, and growing to 10% by 2003. This results in a total year 2010 vehicle inventory which includes about 5% EVs. However, in this study those EVs are credited with no specific emissions benefits because they serve merely as an aid in reaching the average sales-weighted emissions standards that each manufacturer must meet each year. But because this volume of EVs was already present in the base case, we reduced the number of EVs in the 2010 EV scenario to about 65% so that the total number of EVs (including both those in the base case and the added intensive market penetration of EVs) would conform to the 70% we estimated to be the maximum possible in that year. This means that our EV emissions-impact results for 2010 are caused by only about 65%/70% or 93% of the EVs actually present. Thus our estimated EV emissions impacts are, in a sense, underestimated by as much as 7%/93% or 7½%--except that this additional impact is translated into higher allowed emissions for conventional vehicles by the LEV standards.

Number of Vehicles Replaced: The importance of this assumption is obvious; both EV energy use and CV emissions eliminated depend directly on the quantity of CVs displaced by EVs. We assumed the maximum possible speed of EV introduction (given the outlook for commercial EV technology development and production feasibility), growing to 100% of all cars sold annually in the SCAB by 2000 and each year thereafter--leading to about 70% of the total inventory of cars in the region by 2010. This was done to demonstrate the maximum possible effects of EVs. Other studies can quite reasonably make less extreme assumptions, which will more or less proportionally affect EV energy use and overall emissions impacts.

The number of LEVs replaced by EVs was in proportion to their fraction of a model year fleet. For example, in 1997 25% of 1995 cars must conform with LEV requirements and 2% must conform with ULEV requirements. 25% of the 1997 EVs were assumed to replace LEVs. A similar approach was used for the extended LEV scenario.

Electricity Use by EVs

Electric Vehicle Characteristics: What will future electric vehicles be like? We conclude that the GM Impact car shows that future EVs will probably use less electricity per mile than previously thought--about 0.25 kWh/mile, or less than half the amount assumed in some studies. Electricity use is more or less directly proportional to emissions, so this is a crucial assumption. Future electric cars can differ in weight (or weight per person), aerodynamics, and powertrain efficiency (which were all breakthroughs in the GM design), but the difference is even more pronounced depending on the type of vehicle assumed. A small two-passenger commuter car will obviously use much less electricity than a large van. Thus studies assuming that the initial mass-produced EVs will be vans will conclude that electricity use--and hence emissions--will be much higher than we estimated based on Impact technology in small cars. The difference is approximately a factor of two, or even three, so this is a very important assumption.

Electric Vehicle Use: How much will EVs be driven in comparison to other vehicles? We assumed that there would be no difference between EV usage and that of other vehicles of the same age and type (about 38 miles per day on average in 2010), and that the total miles driven in the region would be unchanged by the introduction of EVs. Some other studies have assumed different degrees of EV use (e.g., RFF [1990], at 80 mpd for EVs). Such differences in assumed EV use have very large effects on total electricity use, which is directly proportional to the EV mileage driven.

As part of the sensitivity analysis, we changed the assumptions regarding the number of miles per day EVs were assumed to drive. In the basic scenarios we simply assumed they would be driven the same average distances as conventional vehicles; if a 2010 model year conventional vehicle was assumed to be driven 55 miles per day than so was a 2010 electric vehicle. In this sensitivity test we examined the effect of the alternative assumption that EVs would be driven up to their maximum range each day (here assumed to be 100 miles). Holding the total VMT in the basin constant, we calculated the new emissions using proportional adjustments for all emission categories (for example, total motor vehicle emissions in the basic scenario divided by total miles travelled by conventional vehicles is equal to a fleet average emission factor). Motor vehicle emissions were reduced by approximately 48 percent for all pollutants.

Power Plant Emissions

What are the emissions implications of needing more electric power? How will it be produced, and what differences in emissions might result from different choices?

Gas vs. Coal Power: In the Los Angeles basin, nearly 100 percent of electric power is produced with natural gas. Occasionally gas curtailment requires the use of oil. The substantial use of natural gas in power production leads to low emissions as compared with a case where a fuel such as oil or coal is used. We performed two senstivity tests to examine the effect of burning coal or oil. In one, we assumed oil was burned 20 percent of the time (for the in-basin units). This case was applied in the year 2000 and changed total inventory emissions by less than 0.1 percent. As a more extreme bounding case, we calculated NO_x emissions as if all in-basin electric vehicle demand were supplied by coal-fired power plants. This is not realistic; currently no caol-fired generatin units are located in-basin. The scenario is used as a "worst case" bounding test. In this case, the net inventory NO_x decrease is 10.4 percent rather than the 12.1 percent calculated in the base scenario. In other words, if all in-basin power for charging EV batteries were produced with coal it would affect the net results by 1.7 percent.

In-Basin vs. "Imported" Electric Power: One other test on the effect of utility emissions was to drop the assumption that only 20 percent of the needed power for charging EV batteries would be produced within the Basin. As discussed in Chapter 6, this assumption is actually somewhat conservative for estimating the effects of EVs; according to Energy Commission projections [CEC, 1990] less than 10 percent of in-basin power demand will be met by in-basin power plants in the years 2000 and 2009. However, the 20 percent in-basin generation assumption was a major one and changing it was effective in bounding the results.

In the sensitivity test, we assumed 100 percent of the required power for changing EVs would be produced in-basin. In the year 2000, this would be possible to accomplish and still stay within Rule 1135 emission limits and maintain an 18 percent reserve margin. Utility emissions increase by about a factor of five but adding electric vehicles still results in a clear net benefit for the emissions inventory. In 2010 not all demand could be serviced without building additional generating units. However, the scenario would **double** the amount of in-basin electricity assumed to be generated in 2010 in the absence of electric vehicles. This implies the conversion of 70% of the vehicle fleet to EVs in 2010 would effectively increase SCAB electricity demand by approximately 10% over the baseline scenario. Under this extreme scenario, the net NO_x decrease is still in the neighborhood of 10%[1].

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[1] In the original scenario total NO_x decreases by almost 17% (as compared with about 18% assuming 20% in-basin power). Rough calculations on the new base case (with EVs replacing conventional vehicles subject to ARB LEV standards) assuming approximately the same net impact imply a net reduction of 10% instead of 12.1%.

Table 7.5
Relative Importance of Variables and Assumptions Imbedded in this Electric Vehicle Anaysis

VARIABLE	BASE ASSUMPTIONS	SENSITIVITY STUDY ASSUMPTIONS	DEGREE OF ESTIMATED EFFECT* AND SENSITIVITY STUDY RESULTS	IMPLICIT OR EXPLICIT VARIABLE**	POLLUTANTS MOST EFFECTED	COMMENTS ON EFFECTS
I. BASECASE PROJECTIONS						
Baseline Emission Projections	SCAQMD 1989 Tier I AQMP adjusted with rule 1135 compliance estimates, and using CEC emission factors	—	H	I	All	Baseline emissions projections have fundamental effect on all estimates of emission changes.
Population and Economic Growth Forecasts	SCAQMD AQMP (Table 6-8)	—	H	I	All	Population and economic growth projections are the basis for many baseline emission projections.
II. CV EMISSIONS ASSUMPTIONS	BASED ON EMFAC7E AND BURDEN7C					
Miles per Day Driven by CVs	Fleet Average 35.7 in 2000, 32.2 in 2010	Year 2000, total miles held constant, assume EVs drive 100 MPD	Approx. 40% reduction in overall baseline emissions (H)	I	CO, NOx, ROG, SOx	Emissions drop substantially as CV miles per day drop due to relative increase in EV miles per day.
Fleet Characterization	Vehicle fleet composed of vehicles of various age and technology	---	H	I	NOx, CO, ROG,	Newer CVs emit less pollutants per mile than older CVs; changes in the assumed mix of older and newer vehicles can significantly change emissions estimates.
Tailpipe Emission Standards	Assume LEV standards in effect in 2000 for all LDA, LDT, and MDT CVs	ARB emission standards in effect before Sept. 1990.	54 % change in ROG and 39 % change in NOx from basecase (which assumes pre-9/90 standards) (M-H)	I	ROG, NOx	The effect of more stringent standards is to reduce the emissions benefit of EVs somewhat (since EVs would be replacing cleaner CVs than was assumed in the basecase.)

SCAQMD = South Coast Air Quality Management District
AQMP = Air Quality Management Plan

(continued)

Table 7.5 (continued)

VARIABLE	BASE ASSUMPTIONS	SENSITIVITY STUDY ASSUMPTIONS	DEGREE OF ESTIMATED EFFECT* AND SENSITIVITY STUDY RESULTS	IMPLICIT OR EXPLICIT VARIABLE**	POLLUTANTS MOST AFFECTED	COMMENTS ON EFFECTS
Reid Vapor Pressure	Reduce to 7.8 psi	9.0 psi	Basecase exhaust ROG increased by 1 ton/day; basecase evaporative ROG increased by 17 tons/day in 2010 (L)	I	ROG	With 7.8 psi, anticipate 24% reduction overall in diurnal emissions, 26% reduction for hot soak evaporative emissions, 1% reduction in exhaust hydrocarbons, and 1% reduction in running loss evap. emissions. Emissions reducing effectiveness of adding EVs only diminished by 0.1%.
I/M Program Effectiveness	Assumes I/M program effectiveness in EMFAC7E BERs	—	M	I	NO_x, CO, ROG, SO_x	If I/M program effectiveness is overestimated, EV penetration emission reductions will have been underestimated, and vice versa.
III. ELECTRICAL UTILITY ASSUMPTIONS						
In-Basin vs. Out-of-Basin Supply Mix for Servicing EV Demands	Assumed 80% out-of-basin supply; 20% in-basin supply	Removed 20% in-basin power restriction (tested for year 2000 scenario only) Assumed 100% in-basin supply for EVs	NO_x emissions increase by 3.3 tons/day in 2000 (L)	E	NO_x, PM, CO	While % supply mix has substantial effect on in-basin electrical utility emissions, basin-wide emission inventory shows relatively little change. EV emissions reductions eclipse utility emissions increases even when 100% electrical power for EVs is supplied in-basin (year 2000)
In-Basin Power Supply - Oil and Gas Fuel-Mix	Assumed 100% gas fuel for in-basin plants	Tested 80% - 20% gas and oil fuel-mix for in-basin plants	SO_x emissions increased by 1 ton/day in 2000, 4.7 tons/day in 2010 for both basecase and EV scenarios (L)	E	SO_x, NO_x, CO, PM	While in-basin utility gas/oil fuel ratio has some effect on utility emissions, basin-wide emissions are affected by less than 0.1%. Emission reductions resulting from EV penetration far outweigh gas/oil fuel ratio emissions variations.

* Degree of a variable's estimated effect is with respect to that varible's effect on overall emission inventory.
** Implicit variables are those variables which are implicit in computer models or estimates (fixed assumptions). Explicit variables are those variables used in analyses which are assumed by the study authors and could be different than those used in other studies.

H = High degree of variability
M = Medium degree of variability
L = Low degree of variability

Table 7.5 (continued)

VARIABLE	BASE ASSUMPTIONS	SENSITIVITY STUDY ASSUMPTIONS	DEGREE OF ESTIMATED EFFECT* AND SENSITIVITY STUDY RESULTS	IMPLICIT OR EXPLICIT VARIABLE**	POLLUTANTS MOST AFFECTED	COMMENTS ON EFFECTS
In-Basin Power Supply Fuel Source: Coal	Assumed no coal used for in-basin fuel supply (100% gas assumed)	Tested 100% coal for fuel of in-basin plants (tested only for NOx emissions changes)	2000 utility NOx emissions more than double; 2010 utility NOx emissions more than quadruple (L)	E	NOx, SOx, PM, CO	While in-basin utility fuel-type affects utility NOx emissions, overall basin-wide NOx emissions are increased by only about 4% in 2010. NOx reductions as result of EV penetration are still dramatic even with coal as in-basin utility fuel-source.
Assumptions Regarding Utility Emission Factors	Used plant-specific emission factors and Rule 1135 emissions caps reductions	—	L	E	CO, NOx	While in-basin utility emission factors have significant effect on utility emissions, utility emissions are relatively small fraction of basin-wide emissions.
Nightime In-Basin Power Supply Available from Specific Facilities, Plant Dispatching Methodology, and Assumptions Regarding Specific Plant Loads	Used CEC ELFIN projections for specific SCE and LADWP plant loads and supply; dispatched by heat rate	—	L	E	NOx, CO, SOx,	Plant specific emissions vary substantially plant-by-plant in-basin, however utility emissions are relatively small fraction of basin-wide emissions.
System-wide Load Shapes	Based on hourly load shapes averaged over 1980-1987 (ER90); same shape for 2000, 2010	—	L	E	NOx, CO, SOx, PM	Load shapes dictate mix of plants generating power during the day and each plant's individual capacity factor. Emissions are a function of each plant's individual characterisitics and utilization (i.e. load)
Timeperiod Selected for Analysis	Maximum energy demand (August peak day)	—	L	E	NOx, CO	Assumed a "worst-case" timeperiod in terms of base energy demand to maximize utility loads prior to EV penetration. Utility emissions factors vary by load, but in general using this timeperiod will tend to bias toward higher utility emissions. Timeperiod also coincides with adverse ozone conditions.

* Degree of a variable's estimated effect is with respect to that varible's effect on overall emission inventory.

** Implicit variables are those variables which are implicit in computer models or estimates (fixed assumptions). Explicit variables are those variables used in analyses which are assumed by the study authors and could be different than those used in other studies.

H = High degree of variability
M = Medium degree of variability
L = Low degree of variability
SCE = Southern California Edison
LADWP = Los Angeles Department of Water and Power

Table 7.5 (continued)

VARIABLE	BASE ASSUMPTIONS	SENSITIVITY STUDY ANALYSES	DEGREE OF ESTIMATED EFFECT* AND SENSITIVITY STUDY RESULTS	IMPLICIT OR EXPLICIT VARIABLE**	POLLUTANTS MOST AFFECTED	COMMENTS ON EFFECTS
IV. ELECTRIC VEHICLE ASSUMPTIONS						
Total EV Penetration Values for 2000, 2010	2000 (20%); 2010 (70%)	—	H	E	All	EV penetration rates directly proportional to emission reductions. Note however, these penetration rates represent near maximium rates. In 2010 scenario, all new vehicles after 1999 must be electric.
Approach Taken to Achieve EV Penetration Goals	Gradual introduction of EVs to simulate capabilities/demands for electric cars and vans	—	L-M	E	All	The sooner EVs penetrate, the earlier CVs are replaced with consequential reduction in emissions. Emission reductions are limited by fleet turnover rates, and in penetration scenarios constructed, the fact that CVs being replaced would be relatively new, lower emiting vehicles than older CVs.
Type of CV Replaced by EVs	Assumed penetration of three vehicle classes: light duty autos (passenger cars), light duty trucks (and mini-vans), medium duty trucks (mid-sized vans)	—	L	E	All	Emission characteristics of vehicles replaced by EVs determines overall emissions change. Our study assumed EVs penetrated each of three vehicle classes in proportion to their fractional contributions to the vehicle fleet.

* Degree of a variable's estimated effect is with respect to that varible's effect on overall emission inventory.
** Implicit variables are those variables which are implicit in computer models or estimates (fixed assumptions). Explicit variables are those variables used in analyses which are assumed by the study authors and could be different than those used in other studies.

H = High degree of variability
M = Medium degree of variability
L = Low degree of variability

Table 7.5 (concluded)

VARIABLE	BASE ASSUMPTIONS	SENSITIVITY STUDY ASSUMPTIONS	DEGREE OF ESTIMATED EFFECT* AND SENSITIVITY STUDY RESULTS	IMPLICIT OR EXPLICIT VARIABLE**	POLLUTANTS MOST AFFECTED	COMMENTS ON EFFECTS
V. PETROLEUM PRODUCTION, REFINING, DISTRIBUTION						
Assumptions about Reduced Gasoline Demand and Effect on Refinery Activity	Assumed direct proportionality between gasoline demand (calculated by BURDEN) and refinery activity	—	L	E	SO_x, ROG NO_x	Assumed refineries would cut back production in response to reduced gasoline demand. In reality, southern California refineries export gasoline to other regions; exports may increase with EV use, thus limiting the emission benefits estimated by this study. However, emissions decreases associated with refineries were slightly higher than emissions increases associated with utilities.
Gasoline Storage and Refueling	Assumed linear proportionality between gasoline demand and storage/refueling emissions reductions	—	L	E	ROG	Emissions from these sources are a small portion of total ROG inventory (approx. 1.2%). Thus subtle changes in the calculational methodology for estimating effect of EVs on this category of emissions has little overall effect on total emissions estimates

* Degree of a variable's estimated effect is with respect to that varible's effect on overall emission inventory.

** Implicit variables are those variables which are implicit in computer models or estimates (fixed assumptions). Explicit variables are those variables used in analyses which are assumed by the study authors and could be different than those used in other studies.

H = High degree of variability
M = Medium degree of variability
L = Low degree of variability

7.4 METHODOLOGY

This section discusses our methodology for estimating emission changes from increased electric vehicle use. For each emission source category explored (e.g., utility emissions), we established "base case" projected emissions for the years 2000 and 2010. These base case conditions assumed no further EV penetration (some EVs are present in 2010 fleets subject to the LEV standards). We then projected emission changes that would result from EV use, and contrasted the base case scenarios with those hypothesizing EV penetration.

Our methodology included the following general steps:

- Use ARB mobile source emission models to calculate changes in motor vehicle emissions.
- Estimate electric utility emissions increases due to electric vehicle charging.
- Estimate emission changes for additional sources using statistical and economic information, existing emission factors, and anticipated changes in source activity levels due to electric vehicle use.

The following discussion of this approach is organized into four main parts:

1. Motor Vehicle Emissions: Discussion of the approach used to estimate emission changes from mobile sources

2. Electric Utility Emissions: Approaches used to estimate emission changes resulting from the increased electric power demands of EVs

3. Emission Changes Associated with Petroleum Production and Refining: Discussion of emissions changes associated with reduced demand for gasoline as conventional vehicles are replaced by EVs

4. Qualitative Assessment of Emission Changes from Additional Sources: Discussion of emission changes for benzene and greenhouse gases (methane, CO_2)

Motor Vehicle Emissions

Motor vehicle emission estimates rely on traffic volume data and vehicle emission factors. In the SCAB, estimation of traffic volumes is the responsibility of the Southern California Association of Governments (SCAG). Development of emission measurements and emission factors by vehicle type is the responsibility of the California Air Resources Board (ARB). The ARB developed the computer programs EMFAC and BURDEN to calculate emission factors and to total on-road motor vehicle emissions for each county or air basin. The most recent versions of these programs, EMFAC7E and BURDEN7C, were released in August 1990 and were utilized in this study. A detailed discussion of these two models is contained in Appendix A.

<u>Use of EMFAC and BURDEN to Model Emission Changes</u>: In the EV penetration scenarios evaluated in this study, EVs are assumed to constitute 20 percent of the total number of light and medium duty vehicles in the year 2000; 70 percent are assumed to be electric in the year 2010. Technology and market considerations used to construct these scenarios led us to assume that

full-scale commercial production of electric vehicles would begin in 1991 for full-size vans, 1994 for mini vans, and 1996 for light duty passenger cars. Production is assumed to begin slowly, and then increase over time until the electric vehicle penetration goals are met, as shown in Table 6.2 (Chapter 6). The scenarios imply that electric vehicles replace relatively new cars, i.e., they replace conventional vehicles that are cleaner than the average fleet vehicle because of their newness and increasingly stringent emission standards that take effect in future model years.

The use of EMFAC in this study made it possible to explicitly consider the gradual penetration of EVs into the total vehicle fleet. To represent EV penetration, we altered the vehicle fleet data inputs used by EMFAC. Conceptually, this procedure derives a weighted average emission factor (zero mile level and deterioration rate) for each model year. The weights are a function of the proportion of each model year that is a conventional, low emission, transitional low emission, or ultra-low emission vehicle. The result was a gradual reduction in the size of the conventional vehicle fleet. We then linked EMFAC data to BURDEN and ran BURDEN for the years 2000 and 2010, producing electric vehicle scenario emission estimates for CO, TOG, ROG, NO_x, SO_x, and particulate matter.

Electric Utility Emissions

The substitution of electric for conventional vehicles reduces motor vehicle emissions while increasing electric utility emissions. We developed future-year base case emissions for electric utilities by considering the California Energy Commission's (CEC) preliminary (as of November 1990) baseline power generation forecasts and utility emissions factors, and by considering Southern California Edison (SCE) and Los Angeles Department of Water and Power (LADWP) plans for complying with the South Coast Air Quality Management District's (SCAQMD) Rule 1135 (i.e., NOx emission limits of 0.25 lbs/MWh).[2]

The CEC forecasts are based on the Environmental Defense Fund's production cost model ElFin (for Electric Financial) [EDF, 1990]. ElFin predicts the specific power plants and capacity factors which will be used to meet projected demand. The 1989 Air Quality Management Plan (AQMP) prepared by the SCAQMD used projections from the most current CEC information available at that time (these were known as ER7); we used the more recent draft projections for the 1990 electricity report (known as ER90). This report, although still preliminary, is currently being used in support of an interagency working group (SCAQMD, ARB, CEC, Public Utilities Commission (PUC), Southern California Association of Gevernments (SCAG)) organized by SCAQMD to assist them in assessing the impacts of the 1989 AQMP on air quality and energy demand [McAuliffe, 1990].

The remainder of this discussion reviews in greater detail how we assembled base case and electric vehicle electric utility power generation and emission scenarios.

<u>Base Case Utility Power Generation</u>: Hourly base case (without electric vehicles) utility emissions were estimated using draft ER90 projections of (1) the resource mix (i.e., what fuels are used to power utilities), (2) projected peak demand, (3) average load shape, and (4) emission factors for gas-fired power generating facilities in the basin. Each of these elements is described below.

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2 SCE and LADWP together are the major providers of Los Angeles area electric power.

Resource Mix: The resource mix describes how much power is supplied, on an annual average basis, by coal, nuclear, hydroelectric, gas, purchased power, qualifying and other facilities. The resource mix is critical to the emissions analysis since utility emissions vary substantially with fuel use. The resource mix projected in ER90 includes the specific power plant units which will be used to meet electric power demand in future years. Appendices A and B include detailed discussions of key variables and assumptions used in this part of our analyses. ER92 is now in the early stages of development (modeling in support of development is scheduled for completion in mid-June). ER92 is expected to contain more demand side management geothermal, and other alternative resources than ER90. In addition, it will include the planned retirement of a large nuclear unit and the concellation of some long-term purchase contracts. It is unlikely that the net effect of these changes would substantially affect the results of our analysis.

Peak Day Load Curves: In order to estimate base case power demand (and emissions) and the amount of power available to supply any increase in demand (such as electric vehicle charging), it is useful to know hourly power demands (loads). ER90 predicts the peak power demand for the peak hour for each year, and includes hourly load shapes for an average day. The hourly loads projected in ER90 are based on hourly load shapes averaged over the period 1980 to 1987. Our methodology for predicting hourly demands based upon these load shapes is detailed in Appendices A and B.

Electric Utility Emission Factors: Electric utility emissions vary greatly from plant to plant depending on the plant's efficiency (as defined by the heat rate),[3] its emissions factor (measured in pounds of pollutant per unit of energy input), and the amount of power the plant produces. In addition, emissions vary significantly within a given plant depending on its load. Because of these variations in each plant's emissions, our approach to estimating emissions and electric-vehicle-related emission increases involved using heat rates, emission factors, and energy generation for each individual plant. Further, since NOx emissions in the SCAB are carefully regulated because of their role in ozone formation, variations in NOx emissions resulting from plant load were considered.

Our analysis utilized individual plant information from the following sources:

- Emission factors for ROG, PM, SOx, and CO were obtained from the CEC [CEC, 1989b].

- Emission factors for NOx were obtained from Southern California Edison (SCE) and the Los Angeles Department of Water and Power (LADWP) in the form of nonlinear equations describing NOx emissions as a function of plant load for each plant in their systems.

- Utility Rule 1135 compliance plans submitted to SCAQMD were used to develop reduced NOx emission factors appropriate for plants that are projected to install more stringent emission controls in response to Rule 1135. Subsequent to this analysis, Rule 1135 plans were developed which incorporated emission bubble

[3] The heat rate is a measure of the amount of energy required to produce a unit of power and is stated in units of MMBtu/MWh for electric generation.

concepts and longer time-lines for control technology phase-in periods. In the near future, utilities may participate in the South Coast's RECLAIM program (an innovative emission trading program), which would further affect Rule 1135 compliance. The effect of these changes on the study results should be examined in future updates to this analysis. It should be noted, however, that the results of the sensitivity studies showed that much larger changes than those caused by alternative Rule 1135 plans had small effects on the net emission results.

- Individual plant heat rates projected in ER90.

A detailed description of the emission factors and proposed control technologies for complying with Rule 1135 is contained in the Appendix B.

Electric Power Requirement for Electric Vehicles: The electric power requirement for electric vehicles was estimated according to the following relationship:

$$D = EFF_x * MPD_{x,y} * PCT_{x,y} * VEH_{x,y} * 1.07$$

where

D = Increased electric demand

EFF_x = Energy efficiency for vehicle type x (for example, 0.24 kwh/mile for light duty autos, or 0.6 kwh/mile for medium duty vehicles in 2010)

$MPD_{x,y}$ = Miles per day driven by vehicle type x in model year y

$PCT_{x,y}$ = Percent of vehicle type x in model year y that are electric vehicles

$VEH_{x,y}$ = Number of vehicles of type x in model year y (i.e., number of LDA in 1997)

1.07 = Multiplier to account for transmission line losses

Tables 7.6 and 7.7 list the projected energy demand by model year and vehicle class.

Electric Utility Emissions from Electric Vehicle Battery Recharging: Emissions were estimated by assuming that increased power demands due to electric vehicles would be met by having electric vehicles recharge during the night. Night-time recharging coincides with "off-peak" periods when utilities have excess power-generating capacity.

Actual emission changes will depend on which specific plant units are used to meet the additional demand and what load they will operate under to meet the demand. Important elements include the boiler type, heat rate, fuel burned and control technology in use. While it is likely that all plants in the basin after the year 2000 will burn natural gas, emissions from these plants differ because the plants have different efficiencies and will use various control technologies to reduce NOx emissions.

A number of studies (for example, Wang et al., 1989; Hempel et al., 1989) have used average emission factors for a utility system and multiplied these by the increased demand due to electric vehicles in order to calculate electric vehicle emission impacts. This study adopts an alternative approach that captures the complexity of the utility system and the fact that average emission factors are far different at night (when we assume the electric vehicles will be charged) from those during the day. Our approach models emissions based on typical nighttime load patterns and dispatch practices.

Load Management Practices: Generally, in-basin power demand at night is serviced by out-of-basin coal, nuclear, and hydroelectric facilities, and by gas facilities (both in and out of basin) running at their minimum possible operating loads [Stern, 1990]. Increased load at night from electric vehicles would be serviced by "ramping up" the gas plants running at minimum loads to higher loads [Stern, 1990; Tenaka, 1990]. This would be done by adding power from the most efficient plant first (the plant heat rate in MMBtu/MWh for a given operating rate is the measure of efficiency) [Stern, 1990]. We assumed that plants are not ramped all at once to their maximum operating rates; rather, they are ramped up from their current operating rate to their next highest operating rate (Hoffsis, 1990).

Gasoline Storage and Marketing Emissions

In addition to producing emission estimates, the model BURDEN7C also estimates gas consumption changes associated with changes in the vehicle fleet. For 2000, the changes in fuel consumption determined for each scenario from the BURDEN7C output were multiplied by the emission factors [ARB, 1982] for vehicle refueling (vapor replacement and spillage), underground tank working losses, and underground tank breathing losses to estimate emission reductions associated with electric vehicle use for these emission categories. For 2010, gas consumption was provided by ARB and treated in approximately the same way. The ARB values were substantially higher than those calculated by BURDEN since they were simple averages. (Later model year vehicles are driven more often and are subject to more stringent fuel economy targets but this factor was not weighted in the same manner as in BURDEN. These emission factors are weighted to reflect the percent of sources with vapor recovery control.

Emission Changes Associated with Petroleum Production and Refining

Emission changes associated with petroleum production and refining were estimated by identifying the percent of fuel refined in the SCAB for gasoline, and then assuming that the amount of gasoline refined would decrease proportionately with electric vehicle penetration. To estimate base gasoline refining activity, we assumed that Los Angeles area refineries' operations were similar to those of Southern California as a whole. Statistics reported in the California Fuels report [CEC, 1989a] state that in 1988 (the latest year reported), 44.7 percent of southern California region refinery production was for gasoline. Refinery emissions reported in the SCAQMD 2000 and 2010 baseline emission inventories were assumed to be allocated evenly across refinery outputs; emissions due to gasoline refining could therefore be treated as proportional to the total amount of refinery activity.

Reductions in refining activity were assumed to be proportional to reduced gas consumption due to EV penetration. Gas consumption changes were estimated as part of the mobile source emissions analysis. (BURDEN7C calculates gas consumption.) This calculation assumes that (1) all gasoline refined in southern California is sold in southern California, and (2) refineries will cut back production in response to decreased demand for gasoline. It is also important to note that refinery operations are probably not as elastic as assumed here. Refineries may not be able to scale back production in response to sharply decreased demand; many might simply stop operating. Further, not all gasoline produced within the basin is used there; some portion is exported

[CEC, 1989c], and emissions associated with this portion would not be reduced as we are assuming here. We did not have data available on the portion exported; therefore, we have assumed that all gasoline production would be affected.

Table 7.6
Projected conventional and electric vehicles and estimated additional energy demand due to electric vehicles (Year 2000).

Light Duty Automobiles

	Projected Base Case Conventional Vehicles				Projected Electric Vehicles		
Model Year	Percent Total VMT	Percent Total Vehicles	Absolute Number of Vehicles	Annual Number of EVs	Average Miles per Day per Vehicle	Miles/Day Driven by EVs	Total MWh/Day Required by EVs*
1976	0.3	0.5	33,997		18	0	0
1977	0.3	0.6	35,146		18	0	0
1978	0.3	0.6	36,230		18	0	0
1979	0.3	0.5	33,742		18	0	0
1980	0.3	0.6	38,207		18	0	0
1981	0.4	0.7	44,267		18	0	0
1982	0.5	0.9	60,085		19	0	0
1983	0.8	1.4	89,873		20	0	0
1984	1.1	1.9	120,554		21	0	0
1985	1.5	2.5	156,528		22	0	0
1986	2.1	3.1	199,137		24	0	0
1987	2.4	3.4	219,420		25	0	0
1988	3.2	4.3	272,808		27	0	0
1989	4.0	5.1	324,984		28	0	0
1990	4.7	5.6	360,130		30	0	0
1991	5.2	5.9	377,607		31	0	0
1992	5.9	6.3	403,376		33	0	0
1993	6.5	6.6	423,022		35	0	0
1994	7.2	6.9	441,519		37	0	0
1995	7.9	7.2	461,484		39	0	0
1996	9.0	7.8	494,525	74,179	41	3,073,344	789
1997	9.7	7.9	504,730	272,554	44	11,938,388	3066
1998	10.1	7.8	494,971	395,977	46	18,335,078	4708
1999	9.9	7.2	460,017	414,015	49	20,264,188	5204
2000	6.5	4.6	292,135	289,214	51	14,753,689	3789
TOTALS:	100	100	6,378,495	1,445,939	---	68,364,686	17,556

* Energy required equals miles per day driven by EVs multiplied by energy in KWh/mile, multiplied by 1.07 (to adjust for transmission line losses). Energy requirement in 2000 is 0.24 KWh/mi for passenger cars, 0.6 KWh/mile for light duty trucks, and 0.9 KWh/mi for medium duty trucks.

Source: EMFAC7E input files [ARB, 1990a] and EV scenario assumptions described in Section 5.

Table 7.6 (continued)

Light Duty Trucks and Electric Mini Vans

	Projected Base Case Conventional Vehicles				Projected Electric Vehicles		
Model Year	Percent Total VMT	Percent Total Vehicles	Absolute Number of Vehicles	Annual Number of EVs	Average Miles per Day per Vehicle	Miles/Day Driven by EVs	Total MWh/Day Required by EVs*
1977	0.3	0.7	11,304		15	0	0
1978	0.3	0.7	11,304		15	0	0
1979	0.3	0.7	10,428		15	0	0
1980	0.3	0.7	10,428		15	0	0
1981	0.3	0.7	11,226		15	0	0
1982	0.4	0.8	12,367		16	0	0
1983	0.5	1.0	14,931		18	0	0
1984	0.6	1.1	17,214		19	0	0
1985	0.8	1.5	23,014		20	0	0
1986	1.8	2.9	46,059		22	0	0
1987	2.3	3.6	57,003		23	0	0
1988	3.0	4.3	67,541		25	0	0
1989	4.0	5.4	84,192		27	0	0
1990	5.0	6.4	99,357		29	0	0
1991	6.1	7.2	112,600		31	0	0
1992	6.7	7.4	115,226		33	0	0
1993	7.5	7.7	120,714		35	0	0
1994	7.6	7.3	113,929	4,557	38	172,063	110
1995	7.8	7.0	108,691	11,956	40	483,975	311
1996	8.1	6.8	105,752	22,208	43	963,649	619
1997	9.2	7.2	112,053	28,013	47	1,303,228	837
1998	9.9	7.2	112,475	29,243	50	1,458,204	936
1999	10.8	7.3	114,367	30,879	53	1,650,650	1,060
2000	6.0	3.8	59,990	16,797	56	945,637	607
TOTALS:	100	100	1,563,468	143,654	—	6,977,406	4,479

* Energy required equals miles per day driven by EVs multiplied by energy in KWh/mile, multiplied by 1.07 (to adjust for transmission line losses). Energy requirement in 2000 is 0.24 KWh/mi for passenger cars, 0.6 KWh/mile for light duty trucks, and 0.9 KWh/mi for medium duty trucks.

Table 7.6 (concluded)

			Medium Duty Trucks				
	Projected Base Case Conventional Vehicles				Projected Electric Vehicles		
Model Year	Percent Total VMT	Percent Total Vehicles	Absolute Number of Vehicles	Annual Number of EVs	Average Miles per Day per Vehicle	Miles/Day Driven by EVs	Total MWh/Day Required by EVs*
1977	0.0	0.0	0		0	0	0
1978	0.4	1.0	4,717		13	0	0
1979	0.4	1.0	4,717		13	0	0
1980	0.4	1.0	4,717		13	0	0
1981	0.4	1.1	4,878		12	0	0
1982	0.5	1.3	5,917		13	0	0
1983	0.6	1.6	7,246		14	0	0
1984	0.8	1.8	8,455		16	0	0
1985	1.0	2.1	9,660		17	0	0
1986	1.2	2.4	10,869		18	0	0
1987	1.4	2.6	12,073		20	0	0
1988	1.8	3.1	14,248		22	0	0
1989	2.4	3.7	16,906		24	0	0
1990	3.0	4.3	19,563		26	0	0
1991	3.7	4.8	22,216	222	28	6,176	6
1992	4.5	5.4	24,873	746	30	22,517	22
1993	5.4	6.0	27,531	1,927	33	63,142	61
1994	6.4	6.6	30,188	3,623	36	128,852	124
1995	7.6	7.1	32,841	6,568	39	253,689	244
1996	9.0	7.8	35,981	10,075	42	422,482	407
1997	11.0	8.8	40,331	14,116	46	642,625	619
1998	13.5	10.0	45,885	20,189	49	997,915	961
1999	16.7	11.4	52,262	22,995	54	1,234,033	1,188
2000	8.1	5.2	23,687	10,422	57	594,606	573
TOTALS:	100	100	459,762	—	90,884	4,366,037	4,204

* Energy required equals miles per day driven by EVs multiplied by energy in KWh/mile, multiplied by 1.07 (to adjust for transmission line losses). Energy requirement in 2000 is 0.24 KWh/mi for passenger cars, 0.6 KWh/mile for light duty trucks, and 0.9 KWh/mi for medium duty trucks.

Table 7.7
Projected conventional and electric vehicles and estimated additional energy demand due to EVs. (Year 2010)

Light Duty Automobiles

	Projected Base Case Conventional Vehicles				Projected Electric Vehicles		
Model Year	Percent Total VMT	Percent Total Vehicles	Absolute Number of Vehicles	Annual Number of EVs	Average Miles per Day per Vehicle	Miles/Day Driven by EVs	Total MWh/Day Required by EVs*
1986	0.3	0.6	41,926		19	0	0
1987	0.3	0.6	41,926		19	0	0
1988	0.3	0.6	42,988		19	0	0
1989	0.3	0.6	42,988		19	0	0
1990	0.3	0.6	43,767		19	0	0
1991	0.4	0.7	52,195		19	0	0
1992	0.5	1.0	70,042		20	0	0
1993	0.8	1.4	102,407		22	0	0
1994	1.2	1.9	136,331		23	0	0
1995	1.6	2.5	177,053		24	0	0
1996	2.1	3.2	225,211	33,782	25	858,786	221
1997	2.5	3.5	248,157	134,005	27	3,601,321	925
1998	3.2	4.2	300,848	240,679	28	6,836,851	1756
1999	4.0	5.1	358,355	322,520	30	9,686,528	2488
2000	4.7	5.6	397,165	393,193	32	12,483,996	3206
2001	5.2	5.9	416,428	416,428	34	13,977,359	3589
2002	5.9	6.3	444,828	444,828	35	15,784,195	4053
2003	6.5	6.6	466,499	466,499	38	17,496,644	4493
2004	7.2	6.9	486,895	486,895	40	19,306,176	4958
2005	7.9	7.2	508,850	508,850	42	21,334,147	5479
2006	9.0	7.7	545,323	545,323	44	24,168,453	6206
2007	9.7	7.9	556,583	556,583	47	26,077,766	6697
2008	10.0	7.7	545,890	545,890	50	27,035,119	6943
2009	9.8	7.2	507,292	507,292	52	26,560,488	6821
2010	6.5	4.5	322,095	322,095	55	17,580,244	4515
TOTALS:	100	100	7,082,045	---	5,924,861	242,788,072	62,347

* Energy required equals miles per day driven by EVs multiplied by energy in KWh/mile, multiplied by 1.07 (to adjust for transmission line losses). Energy requirement in 2010 is 0.24 KWh/mi for automobiles, 0.4 KWh/mi for light duty trucks, and 0.6 KWh/mi for medium duty trucks.

Source: EMFAC7E input files [ARB, 1990a] and electric vehicle scenario assumptions described in Section 5.

Table 7.7 (continued)

			Light Duty Trucks				
	Projected Base Case Conventional Vehicles				Projected Electric Vehicles		
Model Year	Percent Total VMT	Percent Total Vehicles	Absolute Number of Vehicles	Annual Number of EVs	Average Miles per Day per Vehicle	Miles/Day Driven by EVs	Total MWh/Day Required by EVs*
1986	0.3	0.7	13,367		16	0	0
1987	0.3	0.7	13,367		16	0	0
1988	0.3	0.7	13,890		16	0	0
1989	0.3	0.7	13,890		16	0	0
1990	0.3	0.7	13,890		16	0	0
1991	0.3	0.8	14,040		16	0	0
1992	0.4	0.9	16,000		17	0	0
1993	0.5	1.0	18,408		19	0	0
1994	0.6	1.1	21,209	848	20	17,002	7
1995	0.9	1.5	28,378	3,122	21	67,030	29
1996	1.8	3.0	56,774	11,923	23	274,536	118
1997	2.4	3.8	70,272	17,568	25	433,807	186
1998	3.0	4.3	80,092	20,824	26	551,087	236
1999	4.0	5.3	99,845	26,958	28	764,780	327
2000	5.0	6.3	117,824	32,991	30	1,003,532	430
2001	6.1	7.2	133,525	37,387	33	1,218,961	522
2002	6.7	7.3	136,643	40,993	35	1,432,689	613
2003	7.5	7.7	143,140	44,373	37	1,662,705	712
2004	7.6	7.2	135,093	43,230	40	1,736,458	743
2005	7.8	6.9	128,895	41,246	43	1,776,006	760
2006	8.1	6.7	125,404	40,129	46	1,852,130	793
2007	9.2	7.1	132,890	42,525	49	2,104,049	901
2008	9.9	7.1	133,375	42,680	53	2,263,842	969
2009	10.8	7.3	135,616	43,397	57	2,467,754	1056
2010	6.0	3.8	71,150	22,768	60	1,363,151	583
TOTALS:	100	100	1,866,976	—	512,961	20,989,520	8,983

* Energy required equals miles per day driven by EVs multiplied by energy in KWh/mile, multiplied by 1.07 (to adjust for transmission line losses). Energy requirement in 2010 is 0.24 KWh/mi for automobiles, 0.4 KWh/mi for light duty trucks, and 0.6 KWh/mi for medium duty trucks.

Table 7.7 (concluded)

			Medium Duty Trucks				
	Projected Base Case Conventional Vehicles				Projected Electric Vehicles		
Model Year	Percent Total VMT	Percent Total Vehicles	Absolute Number of Vehicles	Annual Number of EVs	Average Miles per Day per Vehicle	Miles/Day Driven by EVs	Total MWh/Day Required by EVs*
1986	0.4	1.1	6,184		14	0	0
1987	0.4	1.1	6,184		14	0	0
1988	0.4	1.1	6,184		14	0	0
1989	0.4	1.1	6,184		14	0	0
1990	0.4	1.1	6,184		14	0	0
1991	0.4	1.1	6,184	62	13	807	1
1992	0.5	1.3	7,188	216	14	3,052	2
1993	0.6	1.5	8,356	585	15	8,988	6
1994	0.8	1.8	9,748	1,170	17	19,510	13
1995	1.0	2.0	11,140	2,228	18	40,354	26
1996	1.2	2.3	12,537	3,510	20	69,044	44
1997	1.4	2.6	13,929	4,875	21	104,105	67
1998	1.8	3.0	16,435	7,231	23	167,652	108
1999	2.4	3.6	19,497	8,579	25	215,894	139
2000	3.0	4.1	22,564	9,928	27	271,289	174
2001	3.6	4.7	25,626	11,276	30	334,571	215
2002	4.4	5.3	28,688	12,623	32	406,658	261
2003	5.3	5.8	31,756	13,973	35	488,650	314
2004	6.3	6.4	34,818	15,320	38	581,739	373
2005	7.5	6.9	37,880	16,667	41	687,210	441
2006	8.9	7.6	41,504	18,262	45	817,352	525
2007	10.8	8.5	46,520	20,469	49	994,726	639
2008	13.4	9.7	52,923	23,286	53	1,228,687	789
2009	16.6	11.0	60,280	26,523	57	1,519,419	975
2010	8.0	5.0	27,324	12,022	61	732,150	470
TOTALS:	100	100	545,819	—	208,804	8,691,856	5,580

* Energy required equals miles per day driven by EVs multiplied by energy in KWh/mile, multiplied by 1.07 (to adjust for transmission line losses). Energy requirement in 2010 is 0.24 KWh/mi for automobiles, 0.4 KWh/mi for light duty trucks, and 0.6 KWh/mi for medium duty trucks.

Chapter 8

CONCLUSIONS AND IMPLICATIONS

8.1. TECHNOLOGY AND ECONOMICS ASSESSMENT

Electric Vehicle Energy Storage/Delivery Technologies
This review included on-board storage batteries, fuel cells, and roadway-powered EV technology. Of these, by far the most important for the coming decade is battery technology because of its much more advanced state of development and support.

EV Battery Prospects: Battery technology has improved steadily over the past several years, but remains the greatest barrier to large-scale EV commercialization. However, for the most promising near-term batteries at present--sealed lead-acid and sodium-sulfur--many of the basic conceptual and design problems are now solved and the focus is shifting more to production issues such as packaging, component quality, and design adjustments to reduce manufacturing costs. Pilot battery plants are being developed, and the inauguration of the U.S. Advanced Battery Consortium is bringing an unprecedented degree of coordination and resources to bear on the remaining problems.

It now appears virtually certain that these two "least risky" batteries will be ready for commercial application shortly after mid-decade. The sealed lead-acid battery is the most probable candidate for use in the earliest mass-market EVs around 1995 (such as the Impact-based passenger car announced by General Motors), since current versions appear to be capable of good performance and have the fewest remaining problems. Sodium-sulfur should follow somewhat later but still probably within the 1990s. Sodium-sulfur battery use will make possible the introduction of second-generation, longer-range EVs.

Other more advanced batteries, notably the various lithium options, are unlikely to become available for use until the next decade and in some cases after 2010. Widespread commercial use of nickel-cadmium is not expected, despite its relative maturity, unless concerns over its cost and toxic waste problems can be resolved. The zinc-air battery (and other metal-air options) is unlikely to be available in this decade and will probably be used only in hybrids for cruising power. However, completely new battery options such as nickel-metal hydride continue to emerge and may yet change this picture completely.

Fuel Cells and Roadway Inductive Power: These are both long-term prospects only. Fuel cells deserve further attention as an alternative to battery storage for zero-emission vehicle technology, but much work remains to be done. Roadway-powered EV technology also merits further study, particularly of its economics and timing, in order to judge whether it has advantages over--or will be overwhelmed by--EVs and HEVs relying solely on forecast post-2000 batteries for electric power.

Battery-Powered Vehicle Development
1990 was a turning point for EV development, due to the California Air Resources Board's new regulations and the dramatic increase in major automaker involvement and expenditures. At least one (General Motors) very high-efficiency EV powertrain has been demonstrated, probably setting the standard for those to be used in production EVs during the 1990s and even beyond. Virtually all major automakers worldwide are developing prototype mass-market EVs, and some have announced production plans. Prospects are good that by 2000, a variety of competing EVs will be on the world market; by 2010, EVs may well have ranges of 250 miles.

Hybrid-Electric Vehicle Development
Automaker interest in hybrids is growing fast, with more prototypes appearing along with statements of commitment to the HEV concept from some companies (e.g., Peugeot). HEVs can now be developed fairly quickly because the needed components, from ICEs to batteries, integrated drives, and controls, appear to pose no major developmental challenges. Since HEVs may attract many more buyers than EVs and have the potential to "electrify" as many miles per year per vehicle, their development should be encouraged. At the same time, ways need to be found to discourage HEV variants--specifically some parallel-drive configurations with high-emissions ICEs--which could lead to high rates of emissions if the owner does not maintain or make effective use of the battery. This point is discussed further in Section 8.3.

8.2. EMISSIONS ANALYSIS

Overall Emissions Impacts
Electric vehicles substantially reduce pollutant emissions. For the scenarios studied, pollutant-by-pollutant EV emission impacts strongly reflect the relative importance of light and medium duty vehicles as one of the single largest source categories for nitrogen oxides (NOx), reactive organic gases (i.e., reactive hydrocarbons) (ROG), and carbon monoxide (CO). These findings are apparent in the summary emission findings listed earlier in Tables 7.1 and 7.2.

NOx Emissions: Electric vehicles substantially reduce NOx emissions by replacing conventional cars and trucks. Together, conventional passenger and light- and medium-duty trucks are projected to account for approximately 30 percent of the base NOx emission inventories in the years 2000 and 2010 (see data in Tables 7.1 and 7.2). In contrast, electric utilities in the SCAB account for less than 2 percent of the NOx inventory (SCAQMD, 1991). Petroleum refining accounts for another 1 percent, and gasoline storage and refueling do not significantly contribute to base NOx emissions. The large fraction of NOx emissions originating with conventional vehicles means that EVs significantly lower these emissions--by about 5 percent in the year 2000, and by 9.4 to 12.1 percent in the year 2010.

ROG Emissions: Reactive organic gases (ROG) emissions are projected to decrease due to EVs by approximately 4 percent in the year 2000 and by 7 to 8.6 percent in the year 2010; 88 percent of the year 2000 emission reduction is directly associated with reduced conventional vehicles, as is about 90 percent of the year 2010 emission reduction. The remaining benefits derive from reduced petroleum refining, storage, and vehicle refueling; utility emissions remain essentially unchanged.

CO Emissions: With respect to single pollutant effects, electric vehicles have their greatest impact on lowering carbon monoxide emissions. In the base inventory (i.e., before the introduction of EVs), light- and medium-duty vehicles account for approximately 60 percent of the overall CO inventory in the year 2000, and 50 percent of the year 2010 inventory. Electric vehicles achieve appoximately a 5 percent reduction in CO emissions in the year 2000, and a substantial 24 to 32 percent reduction in the year 2010 (see Tables 7.1 and 7.2). The other sources studied, including utilities, petroleum refining, and gasoline storage and marketing, contribute minor fractions of the total CO inventory and are therefore relatively insignificant in altering the overall emission reduction benefits achieved from replacing conventional vehicles.

SOx Emissions: Past electric vehicle studies focusing on national impacts or other parts of the country cited concern over projected increased SOx emissions due to electric vehicle penetration [e.g., Hamilton et al., 1974; Marfisi et al., 1978; GRC and CRA, 1980]. These concerns were principally associated with the use of coal-fired utility power plants as electricity generation sources to service EVs. There are no coal-fired plants in the South Coast Air Basin (SCAB), and given this study's mandate to focus on emission changes solely within the SCAB, overall SOx emissions are projected to substantially decrease with the introduction of electric vehicles. The projected impacts are a 5 percent reduction in year 2000 emissions, and 12.3 to 14.6 percent reductions in year 2010 emissions. Credit for these reductions needs to be shared between two source categories: reductions in SOx emissions from conventional vehicles, and reductions associated with reduced petroleum refining in response to lowered gasoline demand.

Particulate Matter: Of the five primary pollutants analyzed, the least significant emission changes achieved with electric vehicles are those associated with particulate matter. None of the emission categories analyzed constitutes a substantial role in the base particulate matter inventory (approximately 80 percent of the inventory is road dust), and reductions are less than 1 percent in the year 2000 and less than 3 percent in the year 2010.

Dynamics of Emissions from Conventional Vehicles

The dynamics of the emissions reductions EVs will achieve center on the replacement of conventional vehicles. How great an emissions reduction benefit will be achieved from electric vehicles, therefore, is strongly dependent on the composition and pollution-emitting characteristics of the conventional auto fleet.

The EV scenarios we hypothesized forecasted a gradual introduction of electric vehicles into the vehicle fleet. By the year 2000, most of the EVs in our scenario had been recently introduced. For example, electric vehicles were forecasted to replace portions of the medium-duty truck fleet over the 10-year period 1991-2000, but about 60 percent of all the medium-duty truck EVs forecasted to be on the road in the year 2000 had been introduced in just the previous three years. The trend was similar but not as pronounced for the year 2010; for example, the year 2010 forecasts hypothesized that electric cars had been replacing conventianal light duty automobiles for 15 years; about 60 percent of all the electric cars on the road in 2010, however, had been introduced in just the previous seven years.

Generally, our scenarios were constructed so that EVs replaced newer vehicles; newer vehicles are driven more miles than older vehicles, but they are also "cleaner" (more stringent emission controls apply to these vehicles, and their control systems have not deteriorated). The net result is that the emission benefits from replacing newer, cleaner vehicles, are less than the benefits of replacing older vehicles. These changes are not uniform, however, across pollutants or vehicle class. Emission controls which apply to light-duty autos in some future year do not necessarily apply to medium duty trucks; emission controls may be instituted for one pollutant in a given year but not another. These differences help to account for the pollutant-by-pollutant variations observed in this study's estimated emission-reducing effectiveness of EVs.

Comparison with Other Electric Vehicle Emissions Studies

The report findings from this study generally support those of other electric vehicle studies recently completed or currently in progress, but differ in some ways [e.g., Hempel *et al.*, 1989; Wang *et al.*, 1990; Portney *et al.*, 1990]. None of these studies seem to be "wrong" in any important way despite their various differences in results. By their nature, electric vehicle studies incorporate numerous assumptions; examples include the hypothesized electric power EVs need on a per-mile basis; the fuels used to power utilities generating electricity for EVs; and the penetration scenarios designed to forecast electric vehicle use.

When the various EV emissions studies are compared, it becomes apparent that their differences in results are mostly due to their varying assumptions about the future. Consequently it would be most useful to have a summary of the extent to which differences in key assumptions lead to changes in the results (i.e., forecast effects on regional emissions). Table 7.5 and its discussion in Section 7.3 presented the results of this study's sensitivity tests on some of those key assumptions. Conclusions may be drawn concerning EV characteristics (which determine how much electricity is needed), the nature and extent of conventional vehicles replaced by EVs, and the EV-related emissions from power plants.

Our sensitivity tests showed that the assumptions made on many variables may each affect the emissions impacts of EVs--so much so, in fact that reviewers of the various studies must take great care to identify these assumptions and be aware of their effect on the results. Among the most powerful--and sometimes widely varying--assumptions concern EV energy efficiency, the number of EVs sold, how many miles they are driven relative to the fleet average, and the emissions characteristics of the vehicles which they replace. Because direct vehicular emissions savings from elimination of ICE vehicles tend to be so large, the various indirect emissions sources such as gasoline refining and distribution, fuel storage and refueling, and electric power generation prove to be of relatively marginal significance. In our study, even generation of the in-basin portion (20%) of EV electric power from coal (if it were possible) would still result in substantial net emissions savings; the same is true for generation of all (100%) EV power from the existing or planned power plants within the SCAB. We did not test a 100% coal scenario.

8.3. IMPLICATIONS FOR PUBLIC POLICY

Environmental Effects of Electric Vehicles

The results of this study's emissions analysis, together with those of the several other recent independent assessments of EV emissions in the South Coast Air Basin, should clearly assure California policymakers of the importance of EVs in air pollution control. Though the various studies differ in detail, their results all indicate that EVs will prevent far more pollutant emissions from motor vehicles in the SCAB than they will cause in increased power plant emissions.

Moreover, the net emissions reductions from EVs, when widely used, are greater than those of any other single measure. Clearly, in this light, EVs should be encouraged as much as possible.

Although this study did not include a detailed analysis of other EV environmental effects, our review of other studies and authorities indicates that no major problems are likely. Crash safety, particularly with high-temperature and reactive batteries such as sodium-sulfur, should be studied and tested thoroughly but is likely to be at least as great as that of conventional gasoline vehicles--which themselves were once thought to be unacceptably dangerous before they became familiar. For the most promising battery types, raw materials are plentiful and other life-cycle environmental concerns such as toxic materials disposal appear to be nonexistent.

Ozone Air Quality Implications

As noted earlier, the primary focus of this study is to analyze the emissions changes that could result from replacement of 20 and 70 percent of conventional fueled vehicles in the SCAB with electric powered vehicles. Complex meteorological and chemical processes control the extent to which these emissions changes will affect ambient pollutant concentrations. In the case of ozone, a photochemically derived pollutant (i.e., not directly emitted), key emitted pollutants controlling ozone formation include hydrocarbons, nitrogen oxides, and, to a lesser extent, carbon monoxide. Ozone is formed in the atmosphere when photochemically reactive compounds such as HC and NOx are mixed in the presence of sunlight.

Of particular importance to the formation of ozone in an urban atmosphere are the relative amounts of hydrocarbons and nitrogen oxides--referred to as the hydrocarbon-to-oxides-of-nitrogen ratio. If this ratio is either unusually high or low it can affect the relative importance of each pollutant with respect to ozone formation. This study's scope precludes the use of sophisticated air quality modeling techniques to assess the ozone impacts of emission changes from electric vehicles; however, this discussion presents in qualitative terms the potential implications of those emission changes with respect to ozone formation.

The use of electric vehicles will result in the reduction of emissions of HC, CO, and NOx from vehicle exhaust and vehicle fuel evaporation, from refueling losses, and from refining and gasoline distribution. These emission reductions are expected to be distributed widely throughout the urban area of the SCAB. However, the emissions changes associated with vehicle use are not distributed evenly throughout the area in time (time of day or time of week), or in location. Emission changes associated with vehicle use follow several unique temporal and spatial patterns depending on the purpose of the vehicle trip (e.g., home to work, home to shop), and on the characteristics of the emission source (e.g., exhaust emissions or diurnal emissions, where diurnal refers to evaporative emissions from a vehicle as it is parked unused). The temporal distribution of most vehicular emissions is primarily centered on the early morning and afternoon work commute trips, with an additional midday peak. Nighttime hours, particularly between midnight and sunrise, exhibit a marked decrease of vehicular activity and therefore decreased emissions.

The reduction of daytime vehicular emissions of photochemically reactive pollutants from conventional vehicles reduces the available ingredients necessary for the formation of ozone. Since vehicles are assumed to be widely distributed throughout the SCAB and we assume that the emission reductions due to the use of electric vehicles will not alter the spatial patterns of the remaining photochemically reactive emissions (i.e., emissions from sources other than cars and electric utilities), it is possible there will be a reduction of ambient ozone concentrations.

Some additional electricity demands to charge the electric vehicles may result in increased emissions from fossil fuel powered plants. The principal pollutant of concern from power plants is NOx emissions. A key assumption of this study is that electric vehicles will be charged at night, which is a time when minimum electric power is needed for other purposes. If the electricity is not generated at in-basin power plants during late night hours, the resulting emissions may combine with other emissions to form ozone.

However, several variables complicate the ozone formation process and make it difficult to predict. It is difficult to qualitatively assess how the spatial and temporal changes in emissions resulting from EV use may affect ozone concentrations. The principal pollutant of concern, NOx, is released from the combustion of fuel to generate heat to produce electricity. At utilities, the exhaust flue gases from this process are released to the atmosphere through tall stacks resulting in elevated emission plumes. If these emission plumes occur at night, they are likely to occur above a stable portion of the atmosphere (referred to as an inversion layer); however, during the day under certain meteorological conditions this air layer can become mixed with ground-level pollutants. Changes in ozone concentrations may result depending upon the degree to which the elevated NOx emissions travel out of the air basin during the night (wind speeds above the inversion layer are often much higher than those near the stable ground layer).

In summary, it is difficult to predict ozone changes without performing sophisticated ozone air quality modeling. The sensitivity of ozone formation to the spatial and temporal patterns of the HC/NOx ratio makes qualitative assessments of ozone formation difficult. Despite these uncertainties, however, we believe that the use of electric vehicles is likely to improve ozone air quality in the SCAB.

These findings may differ if electric vehicles are shown to emit significant amounts of either hydrocarbons or NOx; under conditions where EVs emit hydrocarbons or NOx, the basic assumptions inherent in this analysis will change and the emissions and air quality results will differ. This last point is particularly important in the case of "hybrid" electric vehicles that contain both electric and conventional gasoline engines. Unless the vehicle has a bladder tank, the gasoline engine, even when not in use, still emits evaporative hydrocarbons, thus limiting the emission benefits to be derived from the introduction of electric vehicles.

Encouragement of EV/HEV Commercialization

It seems clear that recent California initiatives encouraging major automakers in EV development have been successful so far. Given the level of commitment already exhibited by some manufacturers, electric vehicles appear to be headed for the showroom in California within the 1990s. However, many obstacles remain, and more can and should be done by public policymakers and regulators to promote continued enthusiasm and successful EV commercialization as early as possible.

Additional Automaker Inducements: To achieve the desired levels of EV use, it may be necessary to mandate a continued period (i.e., beyond 2003) of further increases in the required EV (ZEV) proportions of each automaker's sales. However, such measures should be withheld pending the initial results of the present regulations; if automakers are successful in EV cost reduction and marketability, such mandates would be unnecessary.

Electric Utility Inducements: Successful EV commercialization depends in large part on the willingness and ability of local electric utilities to offer advantageous off-peak electricity rates for EV recharging, support EV development activities, help to educate the public, and provide electrical installation assistance, among other services. Such activities are largely controlled by the State's Public Utilities Commission, which can recommend them and approve or deny their costs as allowable rate-base components. The PUC has been highly supportive, but should continue to be encouraged to facilitate such activities by electric utilities to the maximum extent possible.

EV Buyer Inducements: Potential efforts to encourage buyers could include not only reductions or waivers of motor vehicle registration and licensing fees, but even a rebate rather than a registration fee for EV (or any ZEV) owners. This could be financed through additional registration charges to buyers of higher-emission vehicles, possibly on a sliding scale based on each vehicle's California-certified emissions. This approach could be extended still further through an annual licensing surcharge/rebate based on the vehicle's smog-check results.

State (and Federal) income tax credits may be less attractive politically, but are worth consideration. Non-monetary measures such as free downtown parking and use of carpool lanes are less certain as motivating forces, and are also difficult to enforce, since it is unlikely that EVs (or other ZEVs) would be readily recognizable as such by the general public as well as traffic control personnel. More study of such potential inducements is needed.

Charger Installation Cost Offsets: Credit should be given in some way for installation of an EV charger outlet. These are fairly costly and could be a barrier for many buyers. Individual owners could receive a tax credit; if installed and owned by the electric utility or another service organization, that organization should also be allowed either a tax credit or accelerated writeoff. Another alternative is direct subsidy, perhaps drawn from the high-emission vehicle registration/license surcharge suggested above. Yet another mechanism for this is a rebate from the automaker to cover the typical wiring cost. This approach could be funded in a variety of ways; however, it should be the same principle of transferring costs of clean-fuel vehicles from their owners to the owners of higher-emissions vehicles. Automakers could build this cost into their internal method of transferring EV cost premiums to buyers of their other vehicles, or could be reimbursed by the State from registration fee surcharges as described earlier.

Similar mechanisms could be used for encouragement of away-from-home "emergency" recharge stations. Although such facilities would typically use peak-period electricity, it could be priced to reflect full marginal cost of such power plus dispensing facilities. They would thus provide reassurance to potential EV buyers for emergencies rather than routine range extension aids. Providers of such facilities must be relieved of some of the risk of early obsolescence, possibly through rapid writedown of the installation costs.

Hybrid-Electric Vehicle Regulation

The potential emissions reductions of HEVs should not be ignored or discouraged, but must be balanced against the uncertainties of long-term HEV emissions performance. There are several problems in HEV emissions control that can be addressed constructively through regulation.

One is the question of battery deterioration--or driving habits--which might lead to increased use of the ICE and thereby loss of the vehicle's originally intended low-emissions characteristics. This is actually a problem only when two conditions are both met: first, the vehicle is a parallel hybrid, allowing it to run on ICE power without batteries; and second, it uses an ICE powerful enough to propel it reasonably well. Series hybrids avoid this problem altogether, since the ICE can power the vehicle only by charging the battery through a generator. Thus consideration should be given to awarding special certification to series hybrids as well as to parallel hybrids with low-power ICEs--perhaps under 25 percent of the maximum battery output. In this type of parallel hybrid the ICE would be used primarily for acceleration. In all parallel hybrids careful consideration must also be given to ICE emissions characteristics and controller logic, as noted in the following paragraphs.

A second problem with HEVs is the use of "dirty" ICEs such as current small two-cycle engines, whether in series or parallel configurations. In theory, these high emissions may be balanced against their limited degree of running time to yield good overall emissions, so they may be acceptable. However, with such ICEs the use of parallel hybrid designs is particularly questionable since the driver can choose to use the ICE excessively. Such designs should therefore be discouraged.

A possible third problem is with HEV controller logic biased toward unnecessarily high acceleration with the ICE--for example by permitting ICE kick-in at stoplight stops or at very low speeds. This problem is worsened if the controller logic is adjustable in the shop, since this would invite circumvention of the vehicle's low-emission features--much like tampering with conventional ICE emissions controls today. This can only be avoided by discouraging production of such configurations.

Yet another problem is in predicting the overall emissions of any hybrid, since HEV emissions are determined by trip length and other driver decisions. A testing and certification procedure is needed to assure that the repeated cold-start/hot-soak ICE cycling is adequately represented in any emissions rating given to an HEV. Such a procedure might involve a standard city/highway driving cycle such as the Federal Urban Driving Schedule (FUDS), LA-4, the C-cycle or a special "hybrid cycle." Parallel hybrids capable of running solely on their ICEs might be tested both with and without the battery, or a special limited cycle used for testing the ICE's emissions.

These various problems suggest that a "good citizen" HEV criterion could be helpful in directing automakers toward the most favorable HEV designs for long-term, reliable emissions reduction. This might take the form of special emissions-measurement credits for series hybrids and those with low-power, low-emissions ICEs. Environmentally friendly HEV controller logic, which strictly limits the ICE use and emissions, could also be rewarded in this manner.

Appendix A

METHODOLOGIES FOR EMISSIONS ESTIMATES

OVERVIEW

This Appendix discusses the study's methodology for estimating the emission changes from increased electric vehicle use reported in Chapter 7. For each emission source category explored (e.g., utility emissions), we established "base case" projected emissions for the years 2000 and 2010. These base case conditions assumed no further EV penetration. We then projected emission changes that would result from EV use, and contrasted the base case scenarios with those hypothesizing EV penetration. The rest of this discussion is organized into four parts:

- **Motor Vehicle Emissions:** Discussion of the approach used to estimate emission changes from mobile sources
- **Electric Utility Emissions:** Approaches used to estimate emission changes resulting from the increased electric power demands of EVs. This discussion includes detailed information concerning
  - Base case utility power generation
  - Peak day load curves
  - Power plant emission factors
  - Electric power requirements of EVs
  - Utility emissions associated with EV recharging
- **Base Case Emission Inventory and Key Assumptions in Inventories and Models Used**

The methodology included the following general steps:

1. Use ARB mobile source emission models to calculate changes in motor vehicle emissions; this detailed approach was consistent with current ARB-approved methods for evaluating motor vehicle emission effects on an area's overall emission inventory.

2. Estimate electric utility emissions increases due to electric vehicle charging; accomplished by constructing spreadsheet models with assumed base load (i.e., nighttime) plant use and plant dispatching algorithms; these algorithms broadly estimated plant use based on least cost dispatching.

3. Estimate emission changes for additional sources using statistical and economic information, existing emission factors, and anticipated changes in source activity levels due to electric vehicle use.

METHODOLOGY FOR CALCULATING MOTOR VEHICLE EMISSIONS

This study modeled the effects of electric vehicles on motor vehicle emissions in the SCAB by altering EMFAC7E and BURDEN7C inputs. Both of these models are maintained by the California Air Resources Board and are used for developing emission factors in grams per unit distance or time (EMFAC) and tonnage emissions (BURDEN). EMFAC7E calculates emission factors for various vehicle types and requires the input of motor vehicle fleet description data (prepared by another ARB program called E7DWT) as well as model year specific emission rate equations (the ARB developed model year emission data through extensive analysis of vehicle test results; the data are incorporated into the ARB computer program CALIMFAC). BURDEN7C produces county-level emission estimates; it uses vehicle activity data (vehicle trips, speeds, and miles travelled) and EMFAC7E emission factors. These two models are described briefly below. The manner in which they were used in the electric vehicle emissions analysis is described next.

EMFAC and BURDEN Descriptions

EMFAC7E calculates composite emission factors (average factors for a fleet of vehicles with an assumed age and mileage distribution) for total organic gases (TOG), reactive organic gases (ROG), carbon monoxide (CO), nitrogen oxides (NOx), sulfur oxides (SOx), lead (Pb), and particulate matter, for the following five vehicle types:

Light-Duty Automobiles (LDA)

Light-Duty Trucks (LDT), gross vehicle weight (GVW) less than 6000 lbs

Medium-Duty Trucks (MDT), GVW between 6000 and 8500 lbs

Heavy-Duty trucks (HDT), GVW greater than 8500 lbs

Motorcycles (MC)

Emission factors are broken out by noncatalyst, catalyst, and diesel technologies, and are presented for the following emission categories:

Cold start emissions--occur when the engine and emission control system are at ambient temperature and not performing at optimum levels;

Hot start emissions--occur when an engine has been restarted after being turned off, but not cooled to ambient conditions;

Hot stabilized emissions--reflect emissions from an engine which has operated long enough for all systems to have achieved stable operating temperatures;

Diurnal emissions--represent fuel vapor which is expelled from a partially filled tank due to the expansion of the fuel-air mixture inside the tank during periods of rising ambient temperature;

Hot soak emissions--are generated when fuel is vaporized by the residual heat of the engine compartment after the vehicle is shut off; and

Running loss emissions--evaporative emissions generated while a vehicle is operated.

BURDEN7C uses county-wide estimates of vehicle miles travelled (VMT), the percent of VMT accumulated at various speeds, the percent of trips occurring at various speeds, and Inspection/Maintenance program (I/M) effectiveness, combined with the emission factors output by EMFAC7E to estimate total daily emissions disaggregated by the pollutants and operating modes described above.

Use of EMFAC and BURDEN to Model Emission Changes

In the EV penetration scenarios evaluated in this study, EVs are assumed to constitute 20 percent of the total number of light- and medium-duty vehicles in the year 2000; 70 percent are assumed to be electric in the year 2010. As discussed in Chapter 7, two year 2010 scenarios were analyzed: one evaluated 70% penetration of EVs against a backdrop of conventional vehicles subject to LEV and oxygenated fuels standards; the other evaluated 70% penetration of EVs when the conventional vehicles they replaced were subject to an extended implementation scenario for LEVs.

Both of the LEV scenarios include a small number of electric vehicles; the EV scenarios added EVs to the conventional fleet until the 20- and 70 percent targets were reached. Technology and market considerations used to construct these scenarios led us to assume that full-scale commercial production of electric vehicles would begin in 1991 for full-size vans, 1994 for mini vans, and 1996 for light duty passenger cars. Production is assumed to begin slowly, and then increase over time until the electric vehicle penetration goals are met. The penetration scenarios were described in Chapter 6.

The scenarios imply that electric vehicles replace relatively new cars, i.e., they replace conventional vehicles that are cleaner than the average fleet vehicle because of their newness and increasingly stringent emission standards that take effect in future model years. Therefore, because the electric vehicle scenarios are defined such that only 1995 and newer model years are replaced, the percent changes in emission rates are significantly different from the penetration rate, and also differ by pollutant and vehicle class. For example, hydrocarbon changes are less than the 20 percent penetration rate, particularly in the year 2000, for two principal reasons: (1) a large portion of the fleet is still composed of older vehicles certified to the higher emission standard, and (2) EVs are replacing predominantly newer, lower emitting conventional vehicles. However, for MDTs, emission changes are nearly equal to the EV penetration rate (approximately 20 percent) because emission rates are relatively stable across model years, and therefore the percent change in hydrocarbon emissions is roughly the same as the percent reduction in vehicles. The same effect is noted for carbon monoxide emissions, and to a lesser extent for NOx.

The use of EMFAC in this study made it possible to explicitly consider the gradual penetration of EVs into the total vehicle fleet. To represent EV penetration, we altered the vehicle fleet data inputs used by EMFAC. The result was a gradual reduction in the size of the conventional vehicle fleet. We then linked EMFAC data to BURDEN and ran BURDEN for the years 2000 and 2010, producing electric vehicle scenario emission estimates for CO, TOG, ROG, NO_x, SO_x, and particulate matter.

Particulate matter (PM) emissions are calculated by EMFAC7E strictly as a function of VMT, and the percent reductions for PM are in close agreement with those for VMT. The difference in VMT reductions as opposed to percent changes in vehicles is accounted for by the assumption inherent in the models that newer vehicles travel more miles per day than older vehicles. Therefore, percentage changes in VMT are larger than the corresponding vehicle percent changes. Changes between vehicle classes are accounted for by the scenario definition, which had greater penetration of LDAs than the two truck classes in order to achieve an overall penetration of 20 percent and 70 percent in the years 2000 and 2010, respectively.

SOx emissions are calculated in the models strictly as a function of fuel sulfur content, and thus the percent changes are proportional to those for fuel consumption, which is strictly a function of VMT.

METHODOLOGY FOR CALCULATING ELECTRIC UTILITY EMISSIONS

The substitution of electric for conventional vehicles reduces motor vehicle emissions while increasing electric utility emissions. We developed future-year base case emissions for electric utilities by considering the California Energy Commission's (CEC) preliminary baseline power generation forecasts and utility emissions factors, and by considering Southern California Edison (SCE) and Los Angeles Department of Water and Power (LADWP) plans for complying with the South Coast Air Quality Management District's (SCAQMD) Rule 1135 (i.e., NOx emission limits of 0.25 lbs/MWh).[1] The CEC forecasts contain the CEC's formal "best-guess" electric demand and generation forecasts based on projected fuel prices, population and demand growth, resource additions, and other key variables.

The CEC forecasts are based on the Environmental Defense Fund's production cost model ElFin (for Electric Financial) (EDF, 1990). ElFin predicts the specific power plants and capacity factors

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1 SCE and LADWP together are the major providers of Los Angeles area electric power.

which will be used to meet projected demand. The 1989 Air Quality Management Plan (AQMP) prepared by the SCAQMD used projections from the most current CEC information available at that time (these were known as ER7); we used the more recent draft projections for the 1990 electricity report (known as ER90). This report, although still preliminary (as of November, 1990), is currently being used in support of an interagency working group (SCAQMD, ARB, CEC, PUC, SCAG) organized by SCAQMD to assist them in assessing the impacts of the 1989 AQMP on air quality and energy demand (McAuliffe, 1990). The conclusions of this working group will be used to generate much of the 1990 AQMP. Throughout the remainder of this report, we will use the term "ER90" to refer to the draft CEC projections.

The remainder of this discussion reviews in greater detail how we assembled base case and electric vehicle electric utility power generation and emission scenarios. The discussion covers the following:

- Base case utility power generation projections
- Peak day load curves used in the analysis
- Electric utility emission factors used in the analysis
- Electric power requirement for electric vehicles
- Electric utility emissions from electric vehicle battery recharging

Base Case Utility Power Generation

Hourly base case (without electric vehicles) utility emissions were estimated using draft ER90 projections of (1) the resource mix (i.e., what fuels are used to power utilities), (2) projected peak demand, (3) average load shape, and (4) emission factors for gas-fired power generating facilities in the basin. Each of these elements is described below.

The resource mix describes how much power is supplied, on an annual average basis, by coal, nuclear, hydroelectric, gas, purchased power, qualifying and other facilities. The resource mix is critical to the emissions analysis since utility emissions vary substantially with fuel use. The resource mix projected in ER90 includes the specific power plant units which will be used to meet electric power demand in future years. CEC projections are only available to the year 2009; therefore, we estimated demand and capacity in 2010 with a straight-line projection using the projections from 2005 through 2009. CEC projections identify each individual facility by name along with the amount of power it is projected to produce in the modeled year. CEC projections do not distinguish between in- and out-of-basin produced power. Lists of plants that are located within the South Coast air basin were obtained from the SCAQMD (1990) and verified by the ARB (Frazier, 1990) and LADWP (Pelote, 1990).

Other key variables predicted in ER90 which were used in our analyses include (1) whether plants are "must run" (i.e., whether they are turned on and run at minimum operating loads 24 hours per day), (2) whether the plant's capacity is 100 percent committed to serving in-basin needs, (3) whether the plant's capacity is "firm" (i.e., is available for use at any time), (4) whether plants use turbines that are combustion (which can be started up quickly), combined cycle (several hour start-up period), or slow starting (which take 24 to 48 hours to start), and (5) plant heat rates for average operating loads. These are all key indicators of which specific plants will come on-line to meet increased demand.

Peak Day Load Curves

In order to estimate base case power demand (and emissions) and the amount of power available to supply any increase in demand (such as electric vehicle charging), it is useful to know hourly power demands (loads). ER90 predicts the peak power demand for the peak hour for each year, and includes hourly load shapes for an average day. The hourly loads projected in ER90 are based on hourly load shapes averaged over the period 1980 to 1987. Our analysis used these average load shapes and the predicted peak demand to derive an hourly load curve based on the relative hourly demands implied by the load shape.[2] (The load shape shows the daily cycle of in-basin electric power demand and the amount of power potentially available during off-peak hours to service electric vehicles).

Electric Utility Emission Factors

Electric utility emissions vary greatly from plant to plant depending on the plant's efficiency (as defined by the heat rate),[3] its emissions factor (measured in pounds of pollutant per unit of energy input), and the amount of power the plant produces. In addition, emissions vary significantly within a given plant depending on its load. Because of these variations in each plant's emissions, our approach to estimating emissions and electric-vehicle-related emission increases involved using heat rates, emission factors, and energy generation for each individual plant. Further, since NOx emissions in the SCAB are carefully regulated because of their role in ozone formation, variations in NOx emissions resulting from plant load were considered.

Our analysis utilized individual plant information from the following sources:

- Emission factors for ROG, PM, SOx, and CO were obtained from the CEC (CEC, 1989b).

- Emission factors for NOx were obtained from Southern California Edison (SCE) and the Los Angeles Department of Water and Power (LADWP) in the form of nonlinear equations describing NOx emissions as a function of plant load for each plant in their systems.

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2 With the advent of time-of-use pricing, future load shapes may in fact be quite different from today's. Future CEC projections will consider varying load shapes for each year because of the effect of demand side management programs (SCE, 1990).

3 The heat rate is a measure of the amount of energy required to produce a unit of power and is stated in units of MMBtu/MWh for electric generation.

- Utility Rule 1135 compliance plans submitted to SCAQMD were used to develop reduced NOx emission factors appropriate for plants that are projected to install more stringent emission controls in response to Rule 1135.

- Individual plant heat rates projected in ER90.

A detailed description of the emission factors and proposed control technologies for complying with Rule 1135 is contained in Appendix B.

Electric Power Requirement for Electric Vehicles

The electric power requirement for electric vehicles was estimated according to the following relationship:

$$D = EFF_x * MPD_{x,y} * PCT_{x,y} * VEH_{x,y} * 1.07$$

where

D	= Increased electric demand
EFF_x	= Energy efficiency for vehicle type x (for example, 0.24 kwh/mile for light duty autos, or 0.6 kwh/mile for medium duty vehicles in 2010)
$MPD_{x,y}$	= Miles per day driven by vehicle type x in model year y
$PCT_{x,y}$	= Percent of vehicle type x in model year y that are electric vehicles
$VEH_{x,y}$	= Number of vehicles of type x in model year y (i.e., number of LDA in 1997)
1.07	= Multiplier to account for transmission line losses

Electric Utility Emissions from Electric Vehicle Battery Recharging

Emissions were estimated by assuming that increased power demands due to electric vehicles would be met by having electric vehicles recharge during the night. Night-time recharging coincides with "off-peak" periods when utilities have excess power-generating capacity. These periods were illustrated in the load curves evaluated for the study. The electric vehicle demand was met by filling in the "valleys" in the load curves, i.e., by smoothing the slope of the load curve during the off-peak hours between 10:00 p.m. and 6:00 a.m.

Actual emission changes will depend on which specific plant units are used to meet the additional demand and what load they will operate under to meet the demand. Important elements include the boiler type, heat rate, fuel burned and control technology in use. While it is likely that all plants in the basin after the year 2000 will burn natural gas, emissions from these plants differ because the plants have different efficiencies and will use various control technologies to reduce NOx emissions.

A number of studies (for example, Wang et al., 1989; Hempel et al., 1989) have used average emission factors for a utility system and multiplied these by the increased demand due to electric vehicles in order to calculate electric vehicle emission impacts. This study adopts an alternative approach that captures the complexity of the utility system and the fact that average emission factors are far different at night (when we assume the electric vehicles will be charged) from those during the day. Our approach models emissions based on typical nighttime load patterns and dispatch practices. With assistance from SCE (Stern, 1990) and LADWP (Tenaka, 1990), we identified the plants and operating rates that would typically apply at night, and developed emission estimates specific to these plants and their nighttime load characteristics.

Load Management Practices

As a general rule, in-basin power demand at night is serviced by out-of-basin coal, nuclear, and hydroelectric facilities, and by gas facilities (both in and out of basin) running at their minimum possible operating loads (Stern, 1990). Increased load at night from electric vehicles would be serviced by "ramping up" the gas plants running at minimum loads to higher loads (Stern, 1990; Tenaka, 1990). This would be done by adding power from the most efficient plant first (the plant heat rate in MMBtu/MWh for a given operating rate is the measure of efficiency) (Stern, 1990).

We assumed that plants are not ramped all at once to their maximum operating rates; rather, they are ramped up from their current operating rate to their next highest operating rate (Hoffsis, 1990). We assumed that these "steps" are typically around 25 percent of the total plant capacity. Each step has a unique heat rate associated with it. Highest (i.e., least efficient) heat rates are most often associated with plants running at maximum loads; therefore, plants are generally ramped up to the last step prior to full load (approximately 75 percent load), and full load is generally avoided to the extent possible (Hoffsis, 1990).

Our emission modeling scheme consisted of the following steps (for each hour of the charging period):

1. Assume minimum demand without electric vehicles is being met by out-of-basin facilities and in-basin gas "must run" facilities running at minimum operating rates.

2. To meet demands above the minimum, ramp up the "must run" facilities to the last load step prior to 100 percent load (this is approximately 75 percent load). For the 2010 analysis, it was assumed that four gas units had been reclassified as "must run" facilities in order to meet the increased demand.

3. If necessary, ramp up "quick start" combustion turbines to approximately 75 percent load.

4. If all possible plants are running at 75 percent load and more power is required, ramp up plants to 100 percent load based on their heat rates.

5. Calculate incremental emissions in lbs/hour by multiplying the incremental load (in MW) served by each plant by the emission factor for that plant (in lbs/MMBtu) (and load factor, for NOx) and the plant heat rate (in MMBtu/MWh).

Both SCE and LADWP stressed that this approach was an approximation to production cost modeling. It is also important to note that the approach is dependent on production cost model runs made in the absence of electric vehicle demand. The runs might have shown a significantly different resource mix and allocation of plants to "must run" and/or firm capacity had they included the projected load requirement for electric vehicles. However, as shown in the sensitivity analyses, and in the overall results, these factors are not significant enough to change the general result for the scenarios under study.[4]

BASE CASE EMISSIONS CALCULATION

Assembly of the Base Case Inventory

The overall emission impacts of electric vehicles were analyzed with respect to estimated baseline future emissions. This section discusses the methodology we used to develop baseline projections, and the major assumptions underlying the projections.

Our approach utilized base case year 2000 and 2010 projections contained in the 1989 South Coast Air Quality Management Plan (AQMP) (SCAQMD, 1989b). We also made several modifications to the SCAQMD projections to update them and increase their relevance to the EV scenarios under study; these modifications included:

1. SCE and LADWP projections of control technology and associated emissions reductions for complying with Rule 1135 were used in place of District emission projections (which were made in the absence of any assumptions regarding Rule 1135 as it had not been adopted at the time of the preparation of the AQMP).

2. Utility base case emissions were estimated using CEC emission factors and assumptions of fuel heat content and sulfur content (SCAQMD AQMP projections were not detailed enough for use with this study).

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[4] One of the goals of this study was to detail the assumptions that are often imbedded and difficult to discern in other electric vehicle studies. We chose to "manually" construct the EV power generation scenarios to facilitate a better understanding of the key factors that can influence utility emission estimates. The manually generated results, though less accurate than production cost modeling, are more transparent with respect to their implications for EVs and for testing the sensitivity of the emissions estimates to different power generation scenarios.

3. Motor vehicle emissions were projected using the newly released (August, 1990) EMFAC7E and BURDEN7C; this updated the motor vehicle emission control standards and I/M program status implicit in the motor vehicle emissions projections made by the District using EMFAC7D and BURDEN7B (earlier versions of these models).

4. Gasoline marketing and distribution emissions were calculated using ARB emission factors and BURDEN7C fuel consumption estimates.

It should be noted that projections of baseline future emissions are subject to revision given new estimates of economic activity and population growth and newly adopted control measures. the emission projection and control measures utilized and refered to in this study are current as of November 1990.

ASSUMPTIONS

This section outlines assumptions related to the base case emissions inventory and the EV scenarios. A number of assumptions must be made in order to make projections of future emissions. Below we discuss assumptions included in the SCAQMD estimates, in the motor vehicle emissions models EMFAC7E and BURDEN7C, and in the utility emission estimates.

Assumptions in SCAQMD Baseline Projections

The SCAQMD AQMP (SCAQMD, 1989b) lists future baseline projections of criteria pollutant emissions. The projections are based on the following key assumptions:

- Emissions are forecasted from the base year 1985 utilizing control measures in effect prior to December 1987.

- Population and economic growth forecasts were made by the Southern California Association of Governments (SCAG) (SCAQMD, 1989a).

Assumptions in EMFAC7E and BURDEN7C

EMFAC and BURDEN are designed to quantitatively estimate motor vehicle emissions. They are based on a combination of direct data on vehicles and statistical analysis of the data to develop motor vehicle emission estimates for situations in which data have not yet been collected. As with any model attempting to describe complicated real-world phenomena, numerous assumptions are made in order to lower data requirements. In EMFAC and BURDEN, most assumptions are embedded in the model inputs and calculations although some are changeable by a knowledgeable user. Examples of embedded assumptions include the following:

- **Basic Emission Rate (BER) Equations:** These include emissions rates for new cars and deterioration rates describing emission increases as a function of a vehicle's accumulated mileage. The equations are developed using a data base of measured vehicle emission rates and are generalized for the vehicle fleet as a whole through regression analysis. The data base includes measurements of vehicle emissions at specific speeds tested under the Federal Test Procedure (FTP). A different BER is given for each model year, each vehicle class (e.g., light-duty catalytic auto), and each pollutant.

- **Speed and Temperature Correction Factors:** Correction factors are used to adjust the BERs for speeds and temperatures other than those at which emissions were measured. The factors are developed through regression analysis of relationships between emissions and speed or temperature observed in the data.

- **Fleet Characterization:** The vehicle fleet is composed of vehicles of various ages and technology types. EMFAC describes the fleet with the use of historical and projected registration distributions by vehicle class and with assumptions of the proportions of vehicle miles travelled by vehicles of each model year.

A number of additional assumptions are made which also have important effects on calculated motor vehicle emissions but which can be explicitly changed by a model user. These assumptions include tailpipe emission standards, the number of vehicles, number of miles travelled by various vehicle types, the number of trips by various vehicle types, and the average miles per vehicle trip.

Electric Utility Base Emission Assumptions
Base assumptions in the electric utility analysis take into consideration the following:

- The effect of Rule 1135 NOx controls
- The fuel burned by major power generation facilities after 2000 (gas)
- Percentage of in-basin power demand serviced by in-basin power plants

Our electric utility base case emissions included the effects of Rule 1135, a control measure designed to reduce utility NOx emissions by as much as 90 percent by the year 2000. The rule (adopted August 4, 1989) limits utility NOx emissions to a daily average of 0.25 lb/MWh by 1999. Additionally, the rule specifies daily NOx limits for each utility system in the basin. By the end of 1999, Southern California Edison (SCE) may not emit more than 29,900 lbs per day of NOx, and the Los Angeles Department of Water and Power (LADWP) may not emit more than 14,700 lbs per day. The cities of Burbank, Glendale, and Pasadena have daily limits of 550, 390, and 580 lbs per day, respectively. We obtained Rule 1135 compliance plans from SCE and LADWP in order to calculate base case NOx emissions. Their plans are presented in Appendix B.

Emission factors for pollutants other than NOx were obtained from the CEC draft report "Emission Factors for Existing California Power Plants" (CEC, 1989b). Important assumptions included in these emission factors are as follows:

- Heat content of natural gas is 1,050 Btu/scf.
- Natural gas fuel sulfur content is 0.0007 percent, based upon source testing by the air pollution control districts.

Base-case in-basin emissions were calculated using the following assumptions:

- Natural gas is the only fossil fuel used in major electric generating units in the years 2000 and 2010.
- Based on the CEC's ER90 report and the list of in-basin utility generating facilities provided by the ARB, the annual average in-basin electric utility production was calculated to be 8.4 percent of total in-basin demand in the year 2000 and 9.5 percent in the year 2010.
- Hourly in-basin demand serviced by in-basin power plants was assumed to be proportional to the average in-basin demand serviced by in-basin power plants.
- The load factors used to calculate NOx emissions were for plants at minimum operating rates. Since NOx emission factors tend to be higher near minimum and maximum loads, this assumption will tend to bias the estimates upward.

Appendix B

ELECTRIC UTILITY EMISSION FACTORS

OVERVIEW

This appendix provides further detail on how utility emissions were estimated. The analyses discussed in the report's main text rely on three data inputs further discussed in this appendix:

(1) pollutant emission factors for each power plant in the South Coast Air Basin;
(2) compliance plans for utilities to meet Rule 1135 emission limitations (these were used to develop NOx emission estimates); and
(3) expected effectiveness of the Rule 1135 compliance plans as described by utility staff.

Pollutant Emission Factors
Individual emission factors were used for each power plant unit. Emission factors for SOx, Total Suspended Particulants (TSP), CO, ROG, and CO_2 were obtained from an internal California Energy Commission report [CEC, 1989] that calculated gas and oil emission factors for each power generating facility in the state. The CEC report based its calculations on EPA AP-42 emission factors for gas and residual oil fired boilers, from the ARB emissions data system for gas and distillate oil fired boilers, and from average heat contents and percent sulfur content of fuels used by each plant. Before applying these emission factors, we compared them with ARB factors [Appendix III of ARB, 1990] to verify their accuracy. The factors matched those in the published document but not the measured emission factors. Our methodology utilized the theoretical emission factors since measured factors for future years are--of course--unavailable.

NOx Emissions Calculations
NOx emission calculations involved two broad steps: first, identification of "NOx Curves" emission factors, and second, adjustment of NOx emission factors to consider Rule 1135 requirements.

<u>Emission Factor Identification: The Use of NOx Curves</u>: Emission factors for NOx were obtained from compliance plans for Rule 1135 submitted to SCAQMD by SCE and LADWP [SCE; LADWP]. SCE's compliance plans include "NOx curves" for uncontrolled plants. NOx curves are non-linear equations describing NOx emissions as a function of plant load. They are specific to individual plants. LADWP's compliance plans presented NOx emission factors for various percent loads (25%, 50%, 75% and 100%). These NOx curves are presented in Tables 1 and 2 of this appendix for SCE and LADWP respectively.

<u>Adjustments in Consideration of Rule 1135: Overview</u>: The NOx curves provided by the utilities did not take further controls into consideration that will have to be implemented due to the promulgation of Rule 1135. (This rule further restricts utility NOx emissions; see main report text

for a more detailed description.) We adjusted NOx emissions in consideration of Rule 1135 based on information from utility representatives [Bazes; Pelote] regarding the percent of NOx removal to be expected from the addition of the controls. The utility representatives shared Rule 1135 compliance plans which detailed anticipated additional NOx controls. The plans contain timetables for boiler controls such as enhanced stoichiometric firing, urea injection, flue gas recirculation, and selective catalytic reduction (SCR). The phase-in schedules for these additional controls provided by each utility are printed in Tables 3 and 4.

Calculations to Adjust for Rule 1135: We estimated the efficiency of the anticipated Rule 1135 NOx removal measures as follows:

- Emissions from all plants were assumed to be reduced 10% from initial levels from operator training improvements.
- Urea injection was assumed to lower NOx emissions by 35%.
- Subsequent additions of SCR to units already equipped with urea injection was assumed to lower the remaining 65% of emissions by 90%.
- Most combustion controls were assumed to result in 10% emission decreases (some result in 30%).
- Subsequent additions of SCR to combustion controlled units were assumed to reduce the remaining emissions from these sources by 90%.
- Repowered units were assumed to emit NOx at a rate of 0.1 lb/MWh.

The anticipated emissions reductions from these control technology applications were applied to appropriate utility units as described in the utility compliance plans. The result was a "Rule 1135-modified" NOx emission factor for each of the units to which Rule 1135 applied.

TABLE 1. NO_x emissions equations for boilers and turbines--natural gas and oil firing.

SCE BOILER UNITS - Coefficients for Exponential Equation

OWNER	LOCATION	UNIT	MW	GAS FIRING NOx CURVES Ao	A1	A2	A3	OIL FIRING NOx CURVES Ao	A1	A2	A3
SCE	Alamitos	1	175	63.5	1.7532	0.79	0.02475	43.4	1.4582	2.60E-05	8.93E-02
SCE	Alamitos	2	175	57.7	1.0963	5.27	0.02152	-12.8	2.4648	12.80	-7.09E-01
SCE	Alamitos	3	320	-939.7	-1.2611	963.22	0.00153	104.0	-0.0416	62.69	8.13E-03
SCE	Alamitos	4	320	-4.8	0.8101	0.57	0.01756	-1597.1	-3.5371	1700.51	2.01E-03
SCE	Alamitos	5	480	-448.9	-0.9011	436.14	0.00247	757.9	-1.0392	216.69	6.18E-03
SCE	Alamitos	6	480	-626.7	-1.1154	627.25	0.00229	365.6	0.3695	3.60	1.07E-02
SCE	El Segundo	1	175	-2.8	1.0682	6.67	0.02143	-4695.3	13.2990	4723.68	-2.70E-03
SCE	El Segundo	2	175	-1749.4	-4.5845	1807.15	0.00269	-299.8	6.7032	392.98	-9.20E-03
SCE	El Segundo	3	335	-752.7	2.0785	793.76	-0.00235	5.4	2.1950	99.73	-2.55E-02
SCE	El Segundo	4	335	-21.7	-0.0592	51.56	0.00655	42.1	2.3278	1.30E-47	2.02E-01
SCE	Etiwanda	1	132	57.8	0.8790	1.92	0.02979	105.8	-0.0569	36.67	9.65E-03
SCE	Etiwanda	2	132	18.8	0.6971	0.62	0.03247	31.4	2.4200	8.70E-14	-1.81E-01
SCE	Etiwanda	3	320	-16.6	-0.0626	32.94	0.00826	-10.8	2.3864	10.81	-2.12E-01
SCE	Etiwanda	4	320	-137.2	-0.6150	169.63	0.00482	-31958.8	15.4931	32095.75	-4.54E-04
SCE	High Grove	1	33	-1.8	3.4905	0.0041	0.27410	-20.2	6.7087	20.12	-1.65E-01
SCE	High Grove	2	33	-10.9	4.9231	1.70E-09	0.58720	-41.3	7.1369	36.29	-2.50E-01
SCE	High Grove	3	45	-18.6	3.0722	0.079	0.14150	-13.9	1.2758	29.81	6.31E-02
SCE	High Grove	4	45	-99.7	-6.4611	134.77	0.03071	-90423.3	-161.7777	90473.50	1.78E-05
SCE	Huntington Beach	1	215	-7.5	1.5197	2.82	0.00895	6.8	-1.1560	113.25	9.57E-05
SCE	Huntington Beach	2	215	-41.2	1.2336	84.59	-0.00167	-1894.9	6.4653	1901.44	-2.58E-03
SCE	Huntington Beach	3	215	110.4	0.0526	4.74	0.01978	34.3	-0.2730	89.36	8.85E-03
SCE	Huntington Beach	4	225	-356.9	-1.1468	347.95	0.00497	129.9	-0.0921	60.03	1.03E-02
SCE	Mandalay	1	215	-250.9	3.8891	338.23	-0.00916	40.1	1.4089	8.32	1.37E-02
SCE	Mandalay	2	215	37.2	0.6421	17.28	0.00996	65.6	1.0011	0.02	3.68E-02
SCE	Ormond Beach	1	750	-25136.5	-9.9460	25149.84	0.00038	-509.4	3.2734	604.07	-3.39E-03
SCE	Ormond Beach	2	750	-23.9	0.7273	10.99	0.00483	-6952.2	-7.0086	7254.37	8.96E-04

TABLE 1. Concluded.

SCE BOILER UNITS - Coefficients for Exponential Equation

OWNER	LOCATION	UNIT	MW	GAS FIRING NOx CURVES Ao	A1	A2	A3	OIL FIRING NOx CURVES Ao	A1	A2	A3
SCE	Redondo (Plnt 1)			[See Page 4]							
SCE	Redondo Beach	5	175	-7.3	1.0671	0.11	0.04836	-48.1	-0.4165	81.12	1.27E-02
SCE	Redondo Beach	6	175	-7600.3	11.6879	7595.05	-0.00135	12.3	2.0749	4.9E-05	9.12E-02
SCE	Redondo Beach	7	480	-2203.5	-1.3636	2175.76	0.00089	153.9	1.2000	1.00	1.08E-02
SCE	Redondo Beach	8	480	20.3	0.1120	20.12	0.00701	-69501.1	-19.6750	69851.44	3.84E-04
SCE	San Bernardino	1	63	-26.8	1.5498	31.02	-0.03055	2.1	2.3770	2.40E-07	2.20E-01
SCE	San Bernardino	2	63	2.2	0.8769	5.30E-42	0.01020	16.9	2.0755	2.25	-4.44E-02

NOTES: Coefficients for gas and oil firing NOx curves (SCE units) are related as follows (exponential equation):

Y = Ao + A1(x) + A2 * [exp A3(x)];

where: Y [=] lbs/hr of NOx

x [=] MW of boiler

With the exception of boiler units at Redondo Plant 1 (Units 1 through 4), all SCE NOx curves take the form of the above exponential equation.

Redondo Plant 1 consists of units 1-4, composed of boilers with I.D. #11 through 17.
Equation for determining NOx emission rate is in the form of a 3rd order polynomial equation.

Source: SCE Rule 1135 Compliance Plan (Bazes, 1990)

TABLE 2. Emission control plan for Rule 1135 tabulated data for NO_x control projects.

Electric Power Generating Units and NOx Controls	Permit Application Date	NOx Emissions Lb/(MW*Hr) at 25% Load	at 50% Load	at 75% Load	at 100% Load	Unit Net Capacity, MW Max / Min
Haynes 1						
OS	N/A	0.87	0.45	0.60	1.00	222 / 70
OS + UI	08/01/90	0.87	0.38	0.48	0.80	
OS + UI + SCRe + SCRd	09/01/97	0.20	0.20	0.20	0.20	
Haynes 2						
OS	N/A	1.20	0.80	0.85	1.00	222 / 70
OS + UI + SCRe + SCRd	06/01/91	0.20	0.20	0.20	0.20	
Haynes 3						
OS	N/A	0.65	0.65	0.80	1.10	222 / 50
OS + FGR	08/15/90	0.22	0.47	0.63	0.98	
OS + FGR + UI	06/01/92	0.22	0.40	0.50	0.78	
OS + FGR + UI + SCRe	08/01/95	0.22	0.35	0.35	0.35	
Haynes 4						
OS	N/A	0.65	0.65	0.80	1.10	222 / 50
OS + UI	07/01/91	0.65	0.55	0.64	0.88	
OS + FGR + UI + SCRe	09/01/96	0.22	0.35	0.35	0.35	
Haynes 5						
OS	N/A	0.79	0.66	0.72	1.13	341 / 120
OS + UI + SCRe + SCRd	02/01/95	0.20	0.20	0.20	0.20	
Haynes 6						
OS	N/A	0.94	0.69	0.73	1.00	341 / 120
OS + UI + SCRe + SCRd	07/01/93	0.20	0.20	0.20	0.20	
Scattergood 1						
OS	N/A	0.75	0.64	0.75	1.05	179 / 40
OS + UI	10/01/91	0.75	0.64	0.60	0.84	
OS + UI + SCRe + SCRd	07/01/99	0.25	0.25	0.25	0.25	
Scattergood 2						
OS	N/A	0.75	0.64	0.75	1.05	179 / 40
OS + UI	10/01/92	0.75	0.64	0.60	0.84	
OS + UI + SCRe + SCRd	09/01/98	0.25	0.25	0.25	0.25	
Scattergood 3						
OS	N/A	0.75	0.50	0.38	0.68	447 / 60
OS + UI + SCRe	07/01/94	0.20	0.20	0.20	0.20	
Valley 1						
OS	N/A	0.70	0.41	0.65	1.40	95 / 15
OS + UI	01/01/97	0.70	0.35	0.52	1.12	
Valley 2						
OS	N/A	0.70	0.61	0.64	1.57	99 / 15
OS + UI	10/01/96	0.70	0.52	0.51	1.26	
Valley 3						
OS	N/A	0.70	0.29	0.50	0.78	163 / 40
OS + UI	08/01/96	0.70	0.25	0.40	0.62	
Valley 4						
OS	N/A	0.70	0.31	0.57	0.94	163 / 40
OS + UI	06/01/96	0.70	0.26	0.46	0.75	
Repowering Projects						
Harbor CC with SCR	Complete	0.15	0.15	0.15	0.15	240 / 60
Alternative Resources						
Generic Resource	07/01/96	0.00	0.00	0.00	0.00	- / 0

Source: LADWP Emission Control Plan for Rule 1135. Submittal to SCAQMD, June 1990.

Rev: 3/27/90

TABLE 3. Edison unit NO_x control additions.

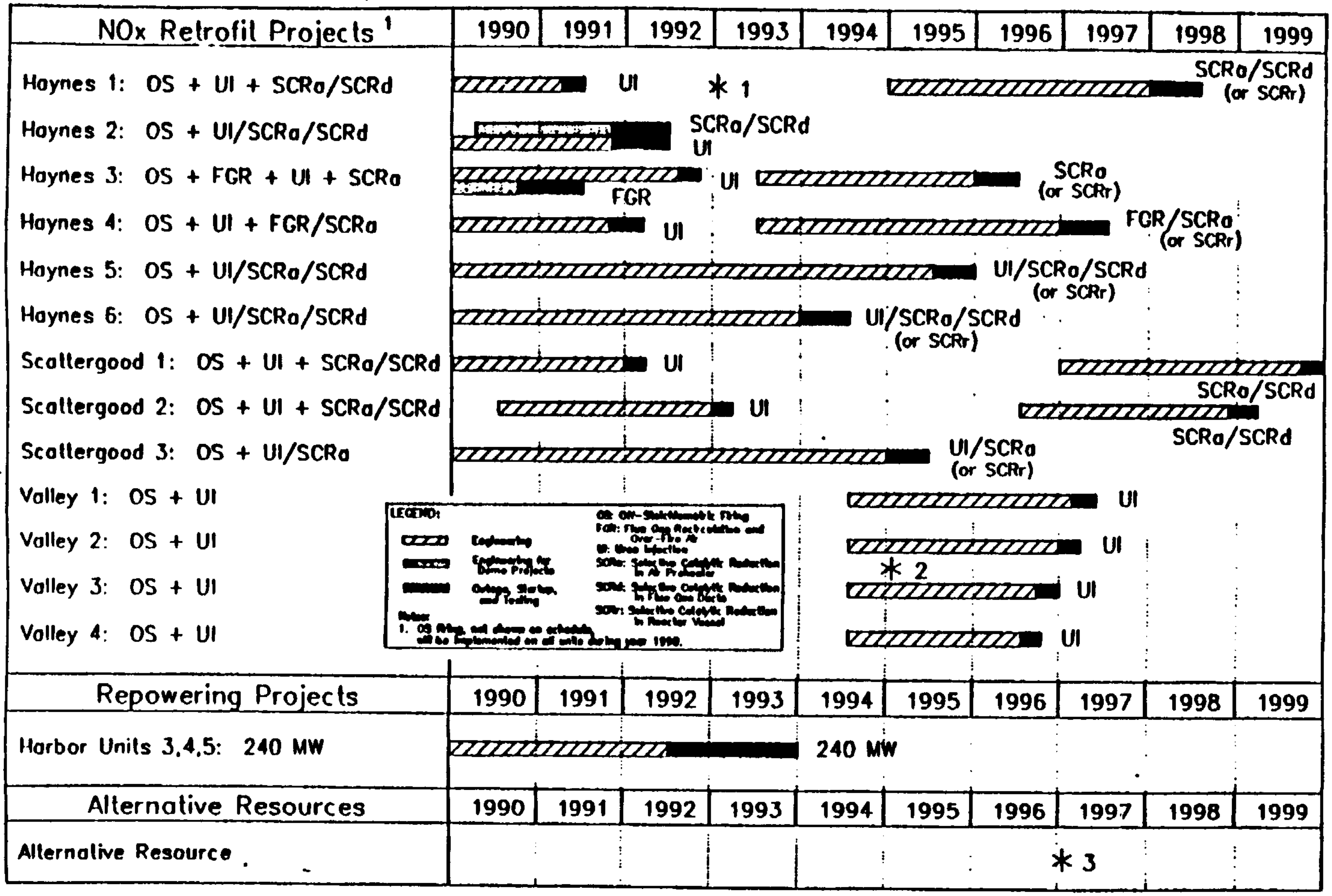
Generating Unit	Equipment Start-Up: Urea	Equipment Start-Up: Combustion Control	Equipment Start-Up: SCR	Equipment Start-Up: Repower	Outage Requirement: Urea	Outage Requirement: Combustion Control	Outage Requirement: SCR
Alamitos 1	Nov-93		Aug-96		1 Mo.		3 Mos
Alamitos 2	Jan-94		Nov-96		1 Mo.		3 Mos
Alamitos 3	Mar-94	Apr-94			1 Mo.	2 Mos	
Alamitos 4	Mar-91		Jan-98		1 Mo.		3 Mos
Alamitos 5	Dec-90		May-97		1 Mo.		4 Mos
Alamitos 6	Nov-91		Jan-94		1 Mo.		4 Mos
El Segundo 1	Dec-90		Dec-98		1 Mo.		3 Mos
El Segundo 2	Feb-91		Dec-98		1 Mo.		3 Mos
El Segundo 3	May-91	Apr-95			1 Mo.	2 Mos	
El Segundo 4	Jun-91	Jun-95			1 Mo.	2 Mos	
Etiwanda 1	Jun-93	Feb-95			1 Mo.	2 Mos	
Etiwanda 2	Jun-94				1 Mo.		
Etiwanda 3	Dec-90	Dec-94			1 Mo.	2 Mos	
Etiwanda 4	Dec-90		Jan-98		1 Mo.		3 Mos
Huntington 1	Mar-92	Dec-95			1 Mo.	2 Mos	
Huntington 2	May-92		Jan-00		1 Mo.		2 Mos
Huntington 3	Mar-94		Mar-99		1 Mo.		2 Mos
Huntington 4	May-94				1 Mo.		
Redondo 5	Dec-91		Jul-99		1 Mo.		3 Mos
Redondo 6	Feb-92				1 Mo.		
Redondo 7	Dec-92		May-96		1 Mo.		4 Mos
Redondo 8	Feb-93	Mar-95	May-95		1 Mo.	2 Mos	4 Mos
San Bernardino 1	Nov-94				1 Mo.		
San Bernardino 2	Dec-94				1 Mo.		
Highgrove 3				Jun-99			

NOx Reduction Level Assumptions: Urea @ 35 %, Combustion Control w/ FGR @ 30 %, SCR @ 90 %
Note: Dates indicate completion of installation and beginning of operation
SCR = Selective Catalytic Reduction -- FGR = Flue Gas Recirculation

ATTACHMENT 1

Source: SCE Rule 1135 Compliance Plan 1990. (Bazes, 1990).

TABLE 4. Los Angeles Department of Water and Power emission control plan for Rule 1135.



Decision Points (*):

*1 –SCR Configuration– If demo projects are not successful, SCRa and SCRd will be replaced by reactor vessel SCR.

*2 –Valley G. S. Options– Install NOx controls, repower, or retire.

*3 – Alternative Resources– Credit under rule 1135 may be received to the extent that in-basin capacity is retired.

Rev: 3/27/90

Source: LADWP Emission Control Plan for Rule 1135. Submittal to SCAQMD June, 1990.

Attachment 1

Appendix C

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