PROGRESS IN ELECTRIC VEHICLE TECHNOLOGY AND ELECTRIC VEHICLES FROM 1990 TO 2000: The Role of California's Zero Emission Vehicle Production Requirement

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EXECUTIVE SUMMARY

THE ZERO EMISSION VEHICLE (ZEV) PRODUCTION REQUIREMENT AND ELECTRIC VEHICLE (EV) TECHNOLOGY

In 1990, California implemented a zero emission vehicle (ZEV) production requirement on the sale of 2% ZEVs for the year 1998 by several major auto manufacturers. This production requirement was intended to start a competitive industry for clean cars that need no emissions systems testing, suffer no long term degradation of emissions control equipment, and will help to eliminate emissions from urban centers in California.

Since late 1990, the attention of the auto industry, electronics industry, battery industry, consumer groups, federal and state clean air programs, federal energy programs, electric utilities and a host other parties has been focused on the potential market for electric vehicles created by the ZEV production requirement. The effects of this attention have been dramatic. The rapid improvements in EV technology during the past decade have delivered vehicles for tests and practical use which are beyond what many thought possible in 1990 or were only hoping could be developed. Electric vehicles have been transformed from golf carts, plant vehicles, and converted curiosities into high performance, high quality transportation tools. Old technologies have been rediscovered and improved. New technologies have been developed. New inventions and innovations have sprung out of research and development programs, some that arose directly from the ZEV production requirement and others that were revitalized by it. ZEV production requirement s have lead to road-proven EVs that are well liked by those consumers and fleets who have had the opportunity to drive them during the past few years.

A great deal of this progress can be attributed to the position taken by CARB, that if the automobile manufacturers can build ZEVs, and if ZEVs are required to ensure that Californians can breathe clean air, then ZEVs ought to be made available in the marketplace. The strength of the ZEV production requirement has been the promise of a market for these clean technologies, making car makers and suppliers take a giant step forward during the past decade.

One important barometer of this progress is the General Motors Impact. Superficially, it may appear there has not been much progress in EVs in the past ten years judging by the appearance of the EV1. Yet, the latest generation EV1 shows evolution from a show car to a practical (yet still exciting) sports car, which happens to be electric. The latest EV1 is more powerful than the first, and its components are more reliable, and less costly. It has improved electronics, more consumer amenities, better air conditioning and improved range instrumentation. Also, the new EV1 offers at least two types of battery packs, each much more reliable than any pack in the past. The NiMH pack allows a range well beyond previous expectations and the new advanced lead acid pack an unexpected level of practical power, life, and affordability. Also, there was only one Impact in 1990-there are hundreds of EV1s in 2000, being driven every day by drivers who praise the vehicle and who contribute to the continuos improvement of EV technology with their front line experiences. Finally, the EV1 has become the launch pad for a whole program of advanced vehicle technologies at General Motors including hybrid electric, fuel cell, and other light-weight vehicle technologies.

A decade of progress in EV technologies like that above can be found for each maker of vehicles, batteries, electronics, motors, chassis, steering systems, air-conditioning units and tires. Moreover, the substantial numbers of EVs to be sold in California in 2003 under the current ZEV production requirement should sustain the manufacturing demands for what are now proven technologies and will lead to continuos refinement of the wide range of technologies underlying EVs.

THE EFFECT OF THE ZEV REQUIREMENTS IN THE EARLY 1990S

It is easy to forget how much influence the ZEV production requirement had on manufacturers in the early 1990s. We recall a previous study we completed in 1995 in which the majority opinion of a wide range of experts surveyed and interviewed was that the ZEV production requirement had spurred renewed interest, significant technical advances, and significant new investment in a variety of electric vehicle technologies (Turrentine and Kurani, 1995). The following three findings summarize the 1995 survey answers across all technology types.

- Over half of the respondents replied that the key ZEV technology they knew best had existed prior to 1991, but that the ZEV production requirement had spurred renewed interest in the application of these technologies to vehicles.
- Nearly sixty percent gave full credit to the production requirement for spurring significant technical improvement in a wide variety of technologies; almost eighty percent gave full or partial credit to the production requirement for these advances.
- Nearly 9 out of 10 of our survey respondents fully or partially agreed that the production requirement has spurred significant new investments in EV technologies.

FROM GOLF CARS TO RACE CAR TO YOUR CAR

An important process in the development of modern transportation has been the impact of racing competition on gasoline vehicle technologies. One general result of the ZEV production requirement has been the growth of various electric vehicle competitions. Electric vehicles of the 1970s and 1980s were inventive and innovative, but most had poor acceleration and low top speeds. If the public thought of golf cars when asked about electric vehicles, there were few examples to dissuade them. This is no longer true. The list of recent performance benchmarks set by electric vehicles shows that over the past decade EVs have become “racing” cars.

- **Acceleration.** Early in the 1990s, an electric Honda CRX built by AC Propulsion accelerated from 0 to 60 miles per hour in 6.2 seconds. In 1999, AC Propulsion bested that time—the 0 to 60 mph acceleration time of their t-zero sports car was recently measured by Road & Track magazine at 4.1 seconds. Almost no production gasoline vehicle can match this time.
- **Top Speed.** In 1994, a modified General Motors Impact set the speed record for production class EVs at 183 miles per hour. That record was broken shortly thereafter an Italian-built electric Bertone (188.9mph).
- **Range per charge.** In the 1997 American Tour de Sol, a production class Solectria EV (a converted Geo Metro) traveled 249 miles on a single charge of its nickel metal-hydride battery pack. In the 2000 American Tour de Sol, a GM EV1 with a Generation II drive train and NiMH batteries covered 224. 75 miles on a single charge.
- **Range per day (and fast charging).** Another Solectria vehicle, using EPTI’s (Electric Power Technology Inc.) rapid charging technology traveled 832 miles in a 24-hour period.

  AC Delco equipped a converted Geo Metro with a quick-change battery pack. This vehicle traveled 1319.2 miles in a 24-hour period.

  Aerovironment demonstrated their fast charging technology by traveling 1,020 miles in 24-hours on Los Angeles streets in a converted Saturn coupe in 1996. In 1998, they traveled 777 miles in 24-hours in a distinctly less aerodynamic electric Chevrolet S-10.

- **Fuel efficiency.** A Solectria Force—a converted Geo Metro—achieved a calculated 130 miles per gallon gasoline equivalent in the 1997 Tour de Sol. A gasoline Geo Metro running the same course, on the same day, attempting to meet the same time goals achieved 42 miles per gallon.

  The same AC Propulsion t-zero sports car that set the zero to 60mph acceleration time cited above is more efficient than the recently released non-rechargeable hybrid from Honda.

Many of these benchmarks were set in specially designed events. How might EVs fair in day-to-day, real world driving? CARB's preliminary draft staff report documenting the May 31 Workshop of the ZEV 2000 Biennial Review lists numerous examples of EVs moving into the real world (CARB, 2000). These range from the more than 2,300 EVs delivered for lease or sale in California during the MOA period, to the application of NiMH batteries in numerous EVs, Nissan's first ever use of lithium-ion batteries in EVs, to the 3.5 million all-electric miles accumulated by Southern California Edison's fleet of EVs. Advanced batteries continue to extend range per charge; fast charging technology and drivers adaptive behaviors continue to extend range per day.

FROM LABORATORY TO MARKET: AGGREGATE MEASURES OF INNOVATION

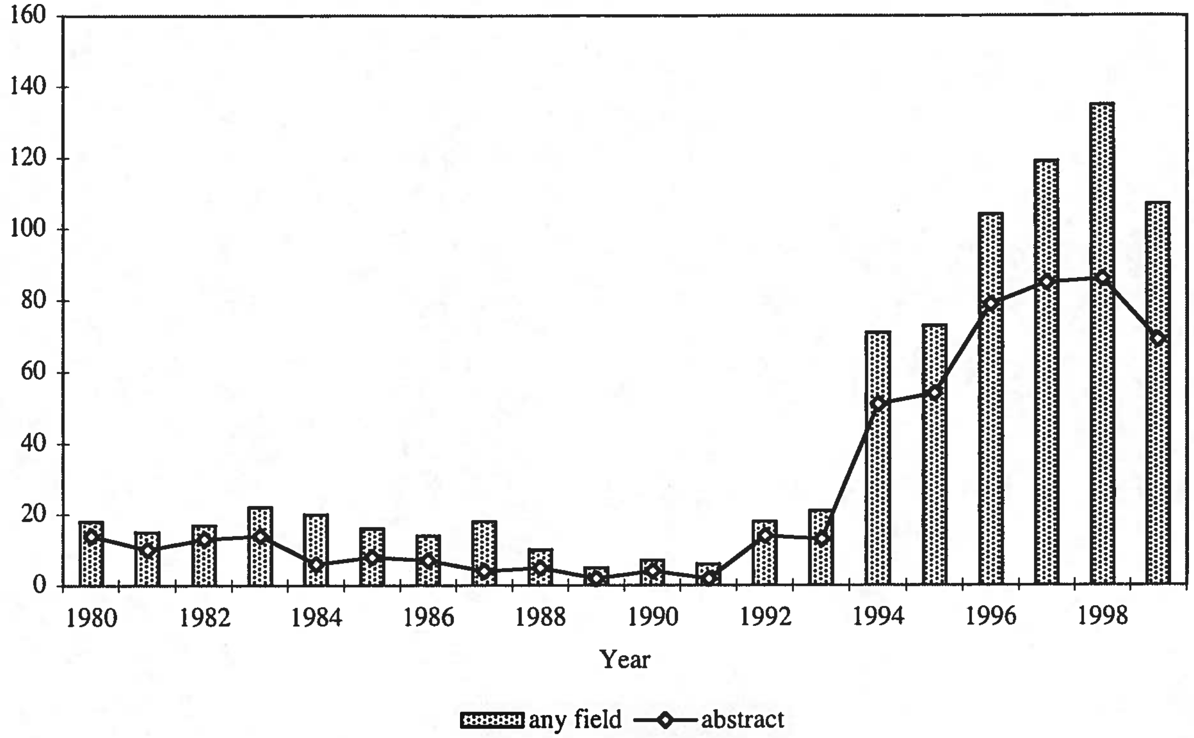
Not all patents represent ideas or products that are successful in the market. However, taken as a whole, the rate at which patents are filed and granted in a particular area is an index of inventive and entrepreneurial activity. The basic measure of patent activity we examine is the number of patents related to EVs that were issued by the U.S. Patent and Trademark Office (USPTO) between the year 1980 and the present. Whether a patent is "related to EVs" was determined by comparing search results for the incidence of the terms "electric vehicle" or "electric vehicles" in the patent, and then reviewing the patent abstract to insure each patent was in fact related to EVs. The data are illustrated in the figure below.

Between 1980 and 1991, EV-related patent activity starts low and then declines. From 1980 to 1987, typically 15 to 20 patents were issued per year. The annual number of patents then fell, such that in 1991, the year the ZEV production requirement was first announced, only six patents related to EVs were issued. There was a small increase in the number of patents in 1992 and 1993. There was a pronounced increase in 1994. From that time through 1998, the number of patents continued to grow. In 1998, patents for EV technologies grew to 133, with a small decline in 1999.

The basic measure of total patent activity passes the test of whether changes are contemporaneous with the announcement of the ZEV production requirement. In fact, it is interesting to note that despite a federally funded R&D program in electric and hybrid electric vehicles during the late 1970s and early 1980s, patent activity was low. During the 1990s, the ZEV production requirement affected overall efforts to patent inventions related to EVs in a way that federal research dollars did not in the 1980s.

Is the simple fact that increased EV-related patent activity was contemporaneous with the announcement of the ZEV production requirement proof the production requirement caused these increases? No. Perhaps something about the patent system or the world at large changed in the early 1990s such that all patent activity increased. Maybe all patents increased faster than EV patents. Maybe, but no. The next chart compares the number of all EV-related patents to the total number of patents for inventions issued by the USPTO for the years 1980 to 1998. The number of each category has been indexed to the year 1980. That is, at each year the chart shows the number of patents issued in that year divided by the number of patents issued in 1980.

FIGURE ES1: ANNUAL NUMBER OF EV-RELATED UNITED STATES PATENTS GRANTED FROM 1980 TO 1999.



During the years of low and declining patent activity related to EVs (1980 to 1991), all patent activity in general was increasing. In fact, all patent activity increased slowly and steadily throughout the period from 1980 to 1998, such that by 1998 the number of patents issued that year was 2.3 times the number issued in 1980. In the time period 1991 to 1996, the rate of patent activity related to EVs increased faster than all patent activity. By 1991, EV-related patent activity had dropped to only 0.14 times that in 1980; by 1998, over 6 times as many EV-related patents were granted every year as had been in 1980.

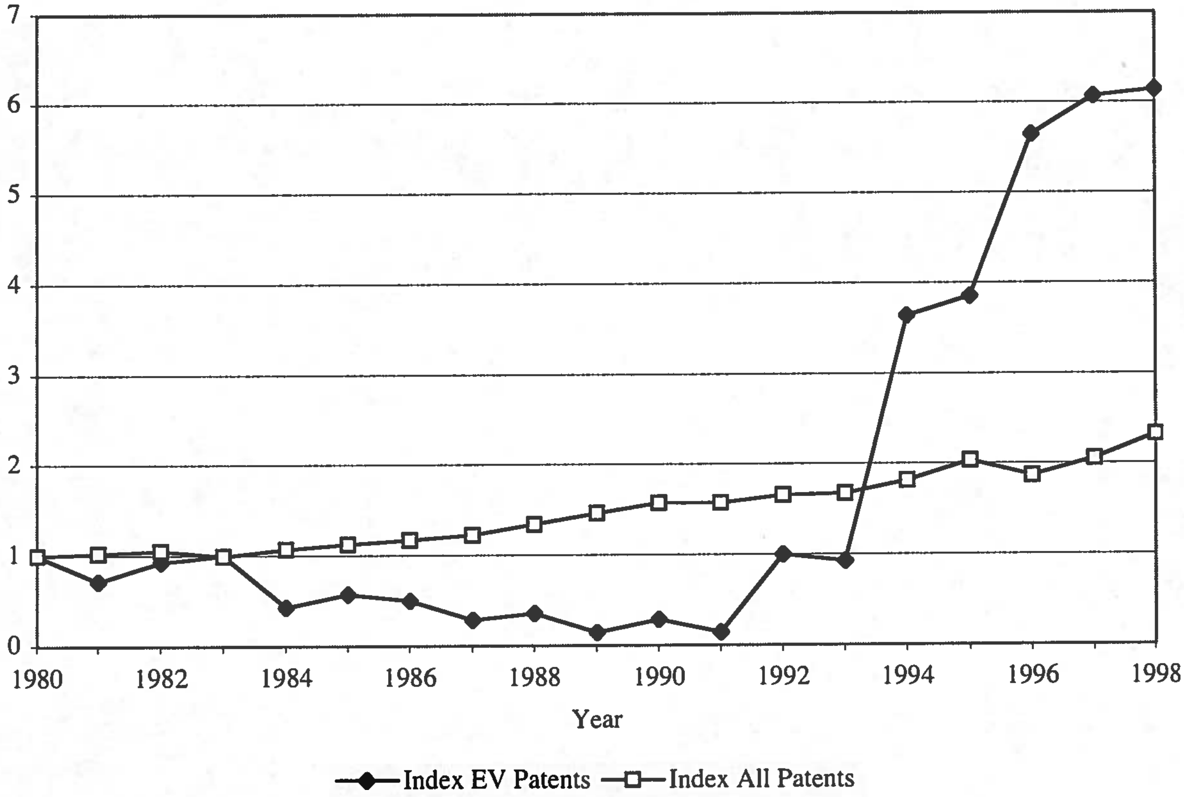
These observations suggest, and statistical analyses of these data confirm, that increases in the number of EV related patents are not correlated with increases in overall patent activity. We are therefore more inclined to attribute the upturn in EV-related patent activity to the fact that after 1990 most all automobile manufacturers had to develop EV technology to meet the ZEV production requirement.

FROM LABORATORY TO MARKET: IMPROVEMENT IN EV TECHNOLOGY

Drive trains, alternating current

Alternating current (ac) electric motors and high voltage, solid state electronics provide power that is cost competitive with modern internal combustion engines. The power of ac drive trains is up, their cost is down, and their reliability is proven. The volume of ac drive trains has shrunken to where they fit easily into the under hood areas. There are at least seven competing designs of ac drive trains now in limited production. EV drive trains have progressed from the use of mismatched components that were not originally designed for use in vehicles, to fully engineered, purpose built systems. The new design not only has fewer components, but those new components handle more power and have wider bandwidth than those they replace. All but two of the companies required to make EVs available according to MOAs signed with the State of California used ac drive trains in their vehicles.

Figure ES2: Annual Number of EV-Related and All United States Patents Granted from 1980 to 1998. Indexed to 1980.



Drive trains, direct current

A new generation of brushless dc systems has been developed. The power densities in these motors is impressive, and will become the preferred motor for many hybrid systems as well as EVs. Brushless dc motors rely on sophisticated electronics, rather than simplistic mechanical systems to switch their current. As such, they are more akin to modern ac systems than older dc systems. At least three manufacturers have built modern, high performance brushless dc motors, using rare earth magnets, and the power electronics to control them. Two of the MOA vehicles (Toyota RAV4 and Nissan Altra) demonstrated by the OEMs use brushless permanent magnet (BPM) dc motors.

Energy (battery) management systems and instrumentation

Energy management systems control battery recharge and discharge to prevent operating conditions that reduce battery life. More and more these are used to increase the efficiency of the vehicle, and even out the power of the systems over the life of the vehicle. These systems monitor battery conditions, both in real time and as stored histories of charge/discharge cycles. They incorporate this information into the processes of the battery recharging and discharging. Several systems have been developed to control recharging. Increasingly, on-board energy management systems use computers to control the real time functioning of the power electronics. In effect, these systems do not control battery discharge (with the possible exception of limiting final depth of discharge), but leave the decision of whether to continue operating in a mode that may cause irreversible battery damage to the driver. In their ultimate form, such systems would control all energy flows onboard the vehicle including regenerative braking and accessory loads. Further, they will provide for improved state-of-charge measurements—the equivalent of a more accurate fuel gauge on a conventional vehicle.

Regenerative braking systems

Internal combustion engine vehicles can not recover the kinetic energy of vehicle motion; electric vehicles can. Instead of just turning the energy of the moving vehicle into heat with standard brakes, the sophisticated control electronics in electric vehicles can return that energy to the batteries or other storage devices such as flywheels or capacitors. Each of the OEM MOA vehicles demonstrated a regenerative system, and these systems continue to be refined. One EV manufacturer has demonstrated, over a real world test route, that 30 percent of the total energy originally stored in the battery and used to provide forward motion of the vehicle can then be recovered and reused. These systems will also reduce the replacement of brake linings.

Computer controlled Level 3 and 2+ charging

While the first paper suggesting that lead-acid batteries could be fast charged was written in the early 1970s, the process was not pursued at that time because small, inexpensive, powerful computers were not available to control the charging process. Only since the production requirement have practical technologies been developed to fast charge lead-acid batteries. Computer controlled "smart" charging can not only provide for faster charging of batteries, it will eventually enable EV owners to get a diagnostic report on their vehicle when they plug in to charge. Additionally, high-powered inverter technology allows for onboard charging at Level 2 plus power (up to 50 kWh).

How fast is Level 3 charging? From a 20 to 30 percent state of charge, a battery can be charged to an 80 percent state of charge in less than 10 minutes. While fast charging won't be convenient for everyone everyday because the high power levels required to fast charge are not available in residences, there is growing evidence that not only is fast charging of lead-acid batteries possible, it may be beneficial to some types of batteries. Electricité de France, the French national electric power utility, reports they have "reconditioned" valve regulated lead-acid (VRLA) batteries in poorly performing battery packs, recovering virtually full vehicle range. Similar results have been reported in the North America for systems from EPTI and Norvik. Not only can apparently worn out batteries be restored, but fast charging may extend battery life, vastly improving the operating economics of EVs. Also, fast inductive charging devices have been safety rated by the Society of Automotive Engineers (SAE), the Federal Communications Commission (FCC), Underwriters Laboratory (UL) and they conform with the National Electrical Code (NEC).

Air conditioning and heating

Because of the need to use energy efficiently in EVs, new concepts and designs for climate control have been developed in the early 1990s, tested in OEM programs and redesigned several times for greater efficiency and better performance over a wide range of climates and moisture conditions. Efficient heat pump air conditioners have been developed and other concepts, such as heating or cooling the seats rather than the air in the vehicle, are being applied. Since EVs are often connected to an electric power source (other than their batteries) for recharging, it is possible to pre-cool or pre-heat the vehicle. Additionally, these HVAC systems have been adapted to assist with thermal management of the battery.

Low mass, low resistance

A host of other technologies have been developed and applied to improve the energy efficiency of electric vehicles. Tires that have as much as 40 percent less rolling resistance are now available from four different tire manufacturers. Vehicle construction techniques are making use of existing and developing materials and processes such as aluminum space frames, composite material frames and bodies, and lighter weight steel designs. Vehicle shapes and surfaces are formed with great attention to aerodynamic effects. The coefficient of friction for the Impact 3 is 0.19—far below that of any conventional vehicle. While not all aerodynamic treatments can be applied for all EVs, one aerodynamic advantage EVs can have over conventional vehicles is a smooth underbody because of the absence of an engine exhaust system.

THE ZEV PRODUCTION REQUIREMENT CONTINUES TO SPUR SIGNIFICANT TECHNICAL ADVANCES.

In 1995, we wrote the following:

> "The advances in electric vehicle technology that have been made since the ZEV mandate was adopted in September 1990 have resulted in vehicles whose only performance limitation compared to gasoline vehicles is driving range...Our society is approaching a confluence of technological and social trends. Rapid technical progress continues to be made in batteries, motors, and electronics. Many consumers have evaluated EVs in both hypothetical and real world situations. Many believe EVs are practical transportation alternatives as well as expressions of an environmental ethic....The need for clean transportation remains. Consumers appear ready and supportive. The ZEV mandate has been instrumental in advancing technology to the point where electric vehicles can become a practical reality." (Turrentine and Kurani, 1995)

Continued progress in EVs and EV technologies between 1995 and 2000 has largely confirmed what some might have interpreted as our premature optimism.

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1. INTRODUCTION

The purposes of this report are to detail changes in on-road electric vehicles (EVs) and EV technology during the years 1990 to 2000, with particular emphasis on the years since 1995, and to look forward to the year 2003 and beyond. But the changes to EVs and to EV technology and EV-related policy over the last 5 to 10 years must be judged in the context of the status of EVs prior to January 1990. While we will describe the evolution of EVs and EV technology after 1990, the unveiling of General Motor's Impact EV at the Los Angeles automobile show in January 1990 represented a quantum leap in almost any possible measure of EVs

THE 1970S: ENERGY CRISES AND EVS

The energy crisis of the early 1970s renewed focus on EVs. Spurred by the lines of frustrated Americans lined up in their vehicles at gasoline stations in 1973 and the passage by Congress of the Electric Vehicle Act of 1976, the guiding principle for EV development in the US was energy independence. The highest selling on-road EV in America during the 1970s, and quite possibly still the best selling on-road EV, was the Sebring-Vanguard CitiCar.

Sebring-Vanguard is believed to have marketed 2,200 CitiCars over a period of just a few years in the early 1970s. The car was a tiny 2-seater. Its top speed is variously stated as 32 mph (www.edisoncars.com/index2.htm), "in excess of 30 mph" (www.econogics.com/ev/citicar.htm), or 44 mph (ev2.inel.gov/sop/general_info/history.html). This last source credits the CitiCar with a cruising speed of 38 mph and a range per charge of 50 to 60 miles (driving cycle not specified). Another observer credits it with a "reliable range of 40 miles in warm weather" (www.econogics.com/ev/citicar.htm).

The small, wedge-fronted 2-seaters were built in Sebring FL. The battery pack consisted of eight 6-volt flooded lead-acid golf-cart batteries. They were powered by a 3.5hp motor. The vehicle weighed 980 pounds without batteries and about 1,400 pounds with batteries. Built of ABS plastic, the bodies are not subject to rust or corrosion. Some are apparently still in operation nearly 30 years after they were built.

However, the vehicle was excoriated by Consumers Union, who rated it as grossly unacceptable. The October 1973 issue of Consumers Reports condemned the CitiCar with the phrases "imperil the lives," "sulfuric acid pouring from ruptured batteries," "foolhardy to drive," "dismal to virtual uselessness" (Taylor). The Consumers Union report is credited by some as ending the market reign of the CitiCar (ibid.).

One of the CitiCar's competitors was the Elcar. Some 500 Elcars are believed to have been produced from 1974 to 1976. (http://www.econogics.com/ev/citicar.htm). A 2-door, 2-seater light electric car that had a top speed of 45 mph, a range of 60 miles (drive cycle not known), and a price between $4,000 and $4,500 (http://ev2.inel.gov/sop/general_info/history.html). Wakefield (1993) credits the Elcar with only a 30 mile range and a top speed of 30 mph. These figures seem to be more in keeping with the vehicles modest 96 volt system and 2.7hp d-c motor. Elcars were built by Zagato of Italy in the mid-1970s; the North American Elcars were assembled in Elkhart, IN. They had fiberglass bodies and their suspension components drew heavily from Fiat cars of the period, notably the Fiat 124. This vehicle was also strongly criticized by Consumers' Union.

Of the then Big 4 US automakers, only American Motors marketed EVs in the 1970s. In 1975 the United States Postal Service purchased 350 electric delivery jeeps from the American Motor Company to be used in a test program. These jeeps had a top speed of 50 mph and a range of 40 miles at a speed of 40 mph. Heating and defrosting were accomplished with a gas heater and the recharge time was 10 hours (http://ev2.inel.gov/sop/general_info/history.html).

1980S: FEDERAL LABORATORIES AND HOME WORKSHOPS

Renewed interest in EVs was spurred by the second oil crisis in 1979. The decade of the 1980s saw several different EV conversions in the hands of hobbyists and a few prototype vehicles from the auto companies and the national energy laboratories. The 1980s were years of quiet development, much of it occurring at the federal energy laboratories or the laboratories of prime contractors to DOE. Advances in motors, electronics, and batteries (especially experimentation with high temperature batteries) were made. If (as we will do so later) we take patents as a measure of innovative activity, the federal DOE and its contractors (such as Gould, Inc., later to become GNB) would receive more patents for EV-related inventions than any other organizations during the 1980s.

In this period, no manufacturer of EVs can lay claim to any real market presence, much less leadership. One EV company, Electricar (formerly Solar Electric) reported sales of 104 EVs in 1992. This was more than they had sold in their previous ten years of business. (Turrentine and Kurani, 1992).

It is likely that the most popular EV of the 1980s was in fact a converted gasoline vehicle containing a 96-volt lead-acid battery pack matched to a 20 horsepower motor—a standard conversion kit offered through the Electric Automobile Association. This kit used a (by today's standard) crude voltage chopper as a motor controller. Because of the limitations on the motors and power electronics, most conversions had to retain their standard automotive transmissions in order to reach speeds of 50 to 60mph.

We interviewed a sample of 100 EV owners in California in 1992. Despite the interviews being conducted in the 1990s, the EVs these people owned were typical 1980s-vintage vehicles. The median reported top speed from this sample was 60mph. The median range, at a steady 35mph and with a new battery pack was 50 miles (ibid.).

1990: EVERYTHING CHANGES

In the year 1990, everything changed. In January of that year, General Motors announced its electric sports coupe, the Impact, at the Los Angeles Auto show. In September of that year, based in part on General Motors' claims regarding the Impact, the California Air Resources Board decided to require major auto makers sell increasing percentages of Zero Emissions Vehicles (ZEVs) in California, starting in 1998. These events set into motion technology, policy, and market processes that continue today. The Impact demonstrated and integrated a whole range of new or improved technologies for EVs. The ZEV production requirement set the clock for the introduction of EVs into mass markets.

Despite the revolutionary integration of EV technology in the Impact, many EV technologies needed further development. In particular, the Impact used (what we might now call, "old style") lead-acid batteries. New power electronics, a new ac drive train, and attention throughout to energy efficient design, provided better speed and greater range than previous vehicles using lead-acid batteries. But the batteries were expensive, and could not be expected to last more than 2 to 3 years at the most.

The goal of the ZEV production requirement was to start a commercial market for electric vehicles. To do so, it was recognized that a better battery, with greater energy storage and longer life was needed. And while the Impact demonstrated an integrated package of technologies, it was hoped that further improvements in vehicle and component efficiencies and further weight reductions could be made. With such improvements, the performance of EVs could rise while their costs fell.

1990 TO 2000: CHANGE AND PROGRESS

Much has happened since 1990. Electric vehicle performance has improved. The cost of many components and auxiliary technologies, from power electronics, motors, and batteries to heating and air conditioning systems has fallen while efficiency, power, and other measures of technical performance have risen. New EV technologies have been invented, patented, improved, or transferred from other industries. Remarkably, some technologies that were declared dead have improved so dramatically that they have again become contenders for EV market share. For example, the oft-maligned lead-acid battery continues to improve.

1996: Resetting the Clock

The primary effect of California's ZEV production requirement was to set the clock for production and sale of electric vehicles. When the ZEV production requirement was first implemented, that clock was set to the year 1998. During its 1996 biennial review, the CARB Board reset the clock to the year 2003. All other effects—changes in technology and vehicles, changes in investments, ties to other policy directives—may be traced to this primary effect. The ZEV production requirement is important, not simply because it provides impetus to electric transportation, but because it sets a schedule for the implementation of electric transportation.

The policy changes in 1996 caused changes in the technology and market contexts for EVs. These changes can be summarized in three actions taken by CARB.

First, the ZEV sales production requirement for 1998 through 2002 was cancelled. In 1996, the California Air Resources Board (CARB) cancelled the zero emission vehicle (ZEV) sales production requirement for the years 1998 (2 percent ZEVs) and 2001 (5 percent ZEVs). CARB did retain a 10 percent ZEV sales production requirement for the year 2003.

Second, Memoranda of Agreement with the automobile makers were substituted for the ZEV production requirement for the period between 1997 and 2003. In 1997, CARB signed a memorandum of agreement (MOA) with each of the seven auto manufacturers who would have had to meet the 1998 ZEV sales requirements. The decision to negotiate these MOAs was made at the time of the decision to drop the 1998 and 2001 sales production requirement. The MOAs required the car companies to deploy a significantly smaller number of ZEVs than had been required under the original ZEV production requirement. To spur advanced battery development, the MOAs required those ZEVs to use batteries that have a specific energy (kWh/kg) higher than that of lead-acid. As of today, the "MOA-period" is effectively over as almost all seven of the auto manufacturers have met their obligations. Those automobile manufacturers who have fulfilled their MOA obligation do not have to deliver any more EVs until 2003.

Third, new vehicle emissions regulations adopted in 1998 provided additional flexibility to the ZEV production requirement. In 1998, CARB outlined a set of new rules that have come to be known as "LEV-II." LEV-II retains the 10 percent ZEV sales requirement for the year 2003, but with three significant qualifications. One, only 40 percent of the 10 percent need be ZEVs, that is, 4 percent of all new light-duty vehicles sold in California in 2003, must have no emissions from the vehicle. Two, a wide-variety of vehicles could qualify for partial-ZEV credits. The rules for calculating credits are complex, but under a variety of conditions, the types of vehicles which can earn credits include conventional gasoline, alternative fuel (for example, natural gas), hybrid-electric, and fuel-cell electric vehicles. In general, vehicles with electric-drive can earn larger credits. It is possible for a vehicle to earn more than one full credit. Three, ZEVs with ranges above 100 miles can earn two to four ZEV credits.

The affected manufacturers are "large" and "intermediate" manufacturers. Large and intermediate status is determined by the total number of passenger cars and light-duty trucks sold in California.

Starting in 2003, the auto makers subject to this production requirement will be those who sell in California more than 35,000 vehicles whose laden weight is less than 3,750 lb. They must offer for sale a sufficient number of ZEVs that at least 10 percent of all the vehicles (under the weight limit) that they offer for sale are ZEVs. This 10 percent production requirement is flexible in two more ways. First, sales of ZEVs weighing between 3,750 lb. and 5,750 lb. are not required, but any such ZEVs will count toward the production requirement. Second, auto manufacturers can save, trade, buy, and sell ZEV credits.

2000: LOOKING TO 2003

The main story is that the ZEV production requirement has lead to improved technology and road-proven EVs that are well liked by those consumers and fleet drivers who have had the opportunity to drive them during the MOA period. The substantial numbers of EVs to be sold in California in 2003 under the current ZEV production requirement will create the manufacturing demands for what are now proven technologies and lead to further refinement of the wide range of technologies underlying EVs.

A great deal of this progress can be attributed to the position taken by CARB, that if the automobile manufacturers can build ZEVs, and if ZEVs are required to ensure that Californians can breathe clean air, then ZEVs ought to be made available in the marketplace. The strength of the ZEV production requirement has been the promise of a market for these clean technologies, making car makers and suppliers take a giant step forward during the past decade.

There are several sub-plots that we will develop.

- Proven fast charging technologies widens the applications of EVs; in particular, range per battery charge is less important in many applications than is daily range (the product of range per charge and charges per day). As part of these advances, one manufacturer has demonstrated charging faster than level 2 without resorting to an off-board charger.
- A high-quality, long lived lead-acid battery appears to be ready for market.
- NiMH batteries remain, and are forecasted to remain, expensive until large orders are placed that can facilitate reductions in manufacturing costs. But they are ready for market, having been proven in hundreds of on-road EVs during the MOA period.
- Efficient, high-power drive trains are ready to go to market, and trends show continued improvements in weight, performance, and price.
- Auxiliary systems, such as heating and air conditioning, are ready for market, and trends show continued improvements.
- New flexible design, lightweight vehicle platforms for EVs and hybrids open the door to wider variety of body styles and larger vehicles.

THE GOALS OF THIS REPORT

We measure the effect of the 1990 California Zero Emissions Vehicle (ZEV) production requirement on the technological progress of EVs. We focus on the time period from 1995 to the present. As such, we must address the more complex context created by modifications made to the ZEV production requirement during and since 1996. We do so by examining changes in patents for EV technologies, by cataloging measurable improvements in technology, and by relating the responses of EV technology experts. Sorting out the effects of the production requirement from the other forces and developments in this emerging worldwide industry is difficult. We do have a clear time frame in which we can identify certain developments, but measures of change must be defined. We employ three general types of measures:

- assessment of overall innovative activity associated with EVs;
- demonstrated changes in EV performance; and
- quantifiable changes in EV component performance.

We measure overall activity through changes over time in the number of patents filed. EV performance is measured against several benchmarks. First, we assess the quantum leap forward that the GM Impact represented. We move on to describe how this vehicle itself has progressed. Then we examine the increasing variety of vehicle and battery types, focusing primarily on those vehicles that were available once the MOA period began. These vehicles include offerings from dedicated EV producers such as Solectria and AC Propulsion, not just the vehicles from companies who signed an MOA with CARB.

The third area of demonstrated technology change is components. We detail specific improvements of electric vehicle components and vehicle subsystems. The subsystems we address are the following:

- drive trains;
- recharging;
- energy storage, primarily batteries;
- on-board energy management;
- vehicle control systems, e.g., steering and brakes; and
- accessory loads such as heating and air conditioning.

The data to assess these measures come from a variety of sources. Patents are searched using the United States Patent and Trademark Office's on-line search capability. (Due to time constraints, we do not address European or Japanese patents.) Descriptions of various vehicles and technologies are contained in conference proceedings, newsletters, other published works, and on-line sources. We augment these sources with surveys of, and interviews with, engineers, inventors, entrepreneurs and researchers in industry, government and academia. We asked them to tell us what the important technological advances have been made since 1995, to assess the effect of the production requirement in bringing about these technical changes, and to assess the effect of the production requirement on fundamental decisions regarding investments in research, development and production. Finally, much of the progress between 1990 and 1995 that we use as a basis for the discussion in this paper is recorded in, and drawn from, our previous report (Turrentine and Kurani, 1996).

2. SETTING A BENCHMARK

CHANGES IN POLICY

The 1996 biennial review of the ZEV production requirement produced changes in the policy intended to spur technological development along certain paths. The several forks in the path to ZEVs were presented in the revision of the Low Emission Vehicle program now referred to as LEV II. Both of these changes have been summarized in the previous chapter and are detailed in the preliminary draft CARB staff report from the May 31, 2000 workshop held as part of the 2000 biennial review. We start here by setting a technological benchmark against which to assess changes and advances in EVs and EV technology during the 1990s.

A BENCHMARK VEHICLE

The electric vehicles and component technologies developed in the period from 1960 to 1990 laid the groundwork for many advances made since then. Automobile manufacturers around the world had had EV research programs going back to the 1960s. These programs had been reinvigorated by the oil price shocks of the 1970s. Some were assisted during the 1980s by funding from the newly formed federal Department of Energy. In particular, one of the most important developments in the late-1980s was ac induction drive trains with silicon-based circuit rectifiers. Some of this history is summarized in Chapter 4. (For a more comprehensive review of the history of EVs up to and including 1990, see Wakefield (1993)).

But the year 1990 represents a clear leap forward in EVs and EV technology. As we will show in Chapter 4, many automobile manufacturers developed a variety of innovative vehicles and technologies. But fairly or unfairly, the company given general public acclaim for pushing EVs out of workshops and laboratories and into the public eye is General Motors and their Impact EV. The vehicle was announced at the Los Angeles Automobile show in January, and unveiled in Chicago in February 1990. That first GM Impact demonstrated the potential of these, and other, technologies to yield a passenger vehicle with good acceleration, high top speed, and hundred mile range—and all this while using rather ordinary lead-acid batteries.

A brief history of General Motors' Impact EV

GM was quick to point out that they announced the Impact at the Los Angeles Auto Show nine months prior to the announcement by the Air Resources Board announcement of the ZEV production requirement. They have publicly traced the history of the Impact vehicle to their ongoing EV research since the 1970s and, in particular, to the development of the Sunraycer solar vehicle in the mid-1980s. Because the Sunraycer was solar powered, energy efficiency was even more important to that vehicle than to a battery-powered vehicle. Lessons learned in vehicle design and electric drive trains were applied to the Impact. A brief summary of some of the changes in design details made between the Impact I and the current Generation II EV1 are given in Table 2.2 below.

The Impact is an electrically powered, two-seat sports car. Its design has evolved slightly, but it remains true to the original concept. Its sporty nature was demonstrated in a series of staged events against gasoline vehicles, including a quarter-mile drag race against a Mazda Miata and a hill-climb race against an Acura Integra. The Impact won both. In its1998 form with lead-acid batteries, GM claimed the EV1 has a range of 70 miles in city driving and 90 miles in highway driving. Time to accelerate from 0 to 60 mph is 8.5 seconds. Top speed is electronically limited to 80 mph for a one speed system. The car is equipped with a full array of safety features and consumer amenities including: anti-lock brakes; traction control; dual air bags; electronic door locks; cruise control; power door locks; power mirrors; power windows; and stereo system with CD player. Its heat pump air conditioning system can pre-heat or pre-cool the car. It has a large trunk. In every way, the EV1 is a high quality, high amenity, electrically-powered car.

TABLE 2.1: CHANGES IN THE SPECIFICATIONS BETWEEN THE IMPACT 1 AND GENERATION II EV1

Generation and Battery:	**Impact 1, 1990, VRLA**[1]	**Impact 3, 1994, VRLA**	**Generation I EV1, Delphi VRLA**[2]	**Generation II EV1, Ovonic NiMH**[3]	**Generation II EV1, Panasonic VRLA**[4]
Curb weight, lb.	2,200	2,970	2,922	2,848	3,060[5]
Length, in.	163.0	169.8	169.7	169.7	169.7
Width, in.	68.2	69.3	69.5	69.5	69.5
Height, in.	47.5	50.5	50.5	50.5	50.5
Drag coefficient	0.19	0.19	0.19	0.19	0.19
Drive train	front wheel drive, one motor for each front wheel	front wheel drive, single motor	front wheel drive, single motor	front wheel drive, single motor	front wheel drive, single motor
Motor(s)	ac induction	ac induction	ac induction	ac induction	ac induction
bhp	114 (2 x 57)	137	137	137	137
Power Electronics	MOSFET	IGBT	IGBT	IGBT	IGBT
Recharging	Conductive,	Inductive, 6.6kW	Inductive, 6.6kW	Inductive, 6.6kW	Inductive, 6.6kW

1. Wakefield, 1993
2. USDOE, OTT, Field Operation Program, Baseline Performance. http://ev2.inel.gov/sop
3. USDOE, OTT, Field Operation Program, Baseline Performance. http://ev2.inel.gov/sop
4. Most data assumed to be the same since there were no changes in the vehicle dimensions and general layout in moving from Generation I to Generation II.
5. Weight taken from Mendoza and Argueta, 2000

However, in view of both market realities and the technological progress detailed in the rest of this report, we believe that the year 2000 vintage EV1 suffers from two decisions taken prior to 1990, early on in its design process. To produce a lightweight, aerodynamic, and safe vehicle, GM designed the Impact as a two-seat coupe. Further, they adopted an inductive charge system for higher power recharging and left the heavy and bulky recharger off-board the vehicle. (A 1.1 kW "convenience" conductive charger was left on-board the vehicle.)

The first choice guaranteed the EV1 small market share—sales of all true two-seaters are tiny regardless of propulsion systems. A four-seat vehicle will be required to capture significant market share. The second choice was repeated by other OEM motor vehicle manufacturers. (In fact, OEMs who adopted conductive connections for high power recharging also have left much of the charging equipment off-board their EVs.) While safety is a noble goal and weight reduction remains an important design consideration, placing the high power recharging capability off-board the vehicle fundamentally changed the nature of EVs, from vehicle that could potentially be charged anywhere a parking space and electrical service did, or could, coincide, to vehicles that could only be charged at the locations of one specific type of recharging appliance. This is not to say the advances in inductive charge systems in the past decade are not impressive.

Today, while the state of charging technology is still somewhat in flux, may be the last opportunity to ask whether the type of charging system being built is really the best possible. To the criteria of recharging safety, reliability, and vehicle weight, we would add cost effectiveness—made up of a comparison of the least system cost (not least component cost) and the highest convenience, flexibility, and value to EV drivers.

THE AFFECT OF THE ZEV PRODUCTION REQUIREMENT THROUGH 1995

We briefly summarize the results of our 1995 survey of EV experts regarding their opinions of the affect of the ZEV production requirement, during the period 1991 to 1995, on the state of EVs and EV technology. A more complete discussion can be found in Turrentine and Kurani (1996).

1. The ZEV production requirement greatly expanded the number, and commitment, of car companies involved in electric vehicle R&D. General Motors has complained recently they would have started producing the Impact in 1995 (not 1998 as required under the 1990 version of the ZEV production requirement) if not for the production requirement. They argued that they believed the Impact was the most advanced EV in the world when it was unveiled in 1990. They stated they would have developed it into a marketable product, built production facilities and implemented service and sales infrastructure and procedures. They say however, that since the production requirement required all their major competitors to produce and market EVs in the same year, GM had no incentive to pursue introducing the Impact prior to 1998.

2. The production requirement took EVs out of the hands of well meaning amateurs and put them into the hands of companies who could make reliable vehicles. Most EVs in this country, prior to the production requirement, were low performance, very limited range vehicles. They were largely built in the garages of hobbyists making their own conversions or by small conversion or assembly shops. The electric motors were not designed specifically for motor vehicles applications. (One of the more popular motors was a starter motor for jet engines.) Because of limitations on motors and electronics, those EVs had to retain a standard automotive transmission. Other elements of the drive train consisted of similarly mismatched parts. The lack of modern high power electronics limited most vehicles to systems of no more than 120 volts. Batteries were just as likely to be standard SLI car batteries as they were to be only slightly more appropriate deep discharge marine batteries. By almost any measures of engineering and performance, the EVs sold in the 1970s and 1980s were vastly inferior to conventional gasoline-powered vehicles.

The production requirement forced large corporations, who have the requisite engineering, manufacturing and financial resources, to create EVs. The large auto makers are capable of a higher level of systems engineering than are hobbyists and small shops. As we will show, the advances in EVs caused by systems engineering includes the integration of several key technologies into a vehicle. This synthesis of technologies was as important as developments in any one of those technologies.

3. The production requirement attracted significant new private and public money to numerous R&D programs. The production requirement was directly responsible for the formation of USABC and at least indirectly responsible for

the formation of the ARPA consortiums. At the time it was formed, the United States Advanced Battery Consortium represented an unprecedented level of cooperation between the domestic vehicle manufacturers—General Motors, Ford, and (then) Chrysler. These three joined with the Electric Power Research Institute and several utilities. It is funded by its members and USDOE. In response to the formation of the USABC, several other competing battery consortiums were formed. These included the Horizon Program (with EPRI), the Advanced Lead-acid Battery Consortium (ALABC) and Japanese and European consortia. Through these organizations and through increased investments by battery developers outside these consortia, the ZEV production requirement caused millions of new research dollars to be poured into battery development.

WHAT CREDIT DID EXPERTS GIVE THE ZEV PRODUCTION REQUIREMENT BACK IN 1995?

It is easy to forget the influence the ZEV production requirement had on auto manufacturers back in the early years of the decade. During September and October 1995, we surveyed and interviewed a wide variety of engineers, scientists, entrepreneurs, and managers involved in the development or marketing of EVs and EV technologies. A brief survey was faxed to 450 persons. The survey asked respondents to identify key technological developments related to EVs in the previous few years. They were then asked to choose one of these technologies and based on their knowledge of its history, to provide detailed technical measures of performance and design changes and an assessment of the role of the ZEV production requirement in prompting those changes. Fifty-five responses were faxed back to us. Phone and personal interviews have been conducted with over 50 other people. These interviews were typically more free flowing than the survey and typically examined a particular technology or vehicle in greater detail.

The overall opinion of most of the experts whom we surveyed and interviewed was that the ZEV production requirement has spurred renewed interest and significant new investment in EV technologies. These have resulted in real improvements. While the insights of those who completed our survey and those whom we interviewed are reported throughout this document, here we report their assessment of the role of the production requirement in the technical changes that have occurred since 1991.

Our survey included a series of five questions that asked about the effect of the production requirement on the development of EV technologies. Each respondent answered all our questions only with respect to the technology they identified as a key technology about which they personally were knowledgeable. A summary of the types of technologies identified by our 55 informants is presented in Table 2.2 below. The answers to the questions regarding the effect of the ZEV production requirement are summarized across all 55 respondents and presented in the Tables 2.2 to 2.7. Because of the differences in the survey and interview formats, we have not incorporated interview results into the survey data presented below

In general, our respondents were less likely to credit the production requirement with spurring the invention of a key technology than they were to give it credit for sparking renewed interest in existing technology and spurring significant technological improvements in those technologies between 1990 and 1995. While just 1 out of 5 of our respondents gave full credit to the production requirement for the invention of key technologies, almost 3 of 5 gave full credit to the production requirement for spurring renewed interest in the technology. Three out of 5 also gave full credit to the production requirement for spurring significant improvements. In Table 2.7, we see that a high percentage of our respondents credit the production requirement with spurring significant new investments in these EV technologies—87 percent give full or partial credit to the ZEV production requirement.

TABLE 2.2: KEY TECHNOLOGICAL DEVELOPMENTS PERTINENT TO EVS AND EV INFRASTRUCTURE SINCE 1991.

Technology group	Number of respondents identifying this technology
Batteries	19
Recharging	10
Power electronics	7
Power trains (other than electronics)	3
Fuel cells	4
Energy management systems	3
Other	9
Total	55

TABLE 2.3: THE 1991 ZEV PRODUCTION REQUIREMENT SPURRED THE INVENTION OF THE TECHNOLOGY

Level	**Count**	**Probability**	**Cumulative Probability**
Agree	13	0.24	0.24
Partly agree	13	0.24	0.47
Disagree, don't know or doesn't apply	29	0.52	1.00
Total	55		

TABLE 2.4: THIS TECHNOLOGY EXISTED PRIOR TO 1991, AND THE ZEV PRODUCTION REQUIREMENT SPURRED RENEWED INTEREST IN ITS APPLICATION TO VEHICLES.

Level	**Count**	**Probability**	**Cumulative Probability**
Agree	31	0.56	0.56
Partly agree	14	0.25	0.82
Disagree, don't know or doesn't apply	10	0.18	1.00
Total	55		

TABLE 2.5: THIS TECHNOLOGY EXISTED PRIOR TO 1991, AND THE ZEV PRODUCTION REQUIREMENT SPURRED SIGNIFICANT TECHNICAL IMPROVEMENTS.

Level	Count	Probability	Cumulative Probability
Agree	32	0.58	0.58
Partly agree	11	0.20	0.78
Disagree, don't know or doesn't apply	12	0.22	1.00
Total	55		

TABLE 2.6: THE 1991 ZEV PRODUCTION REQUIREMENT SPURRED ACTUAL PRODUCTION OF THIS TECHNOLOGY.

Level	Count	Probability	Cumulative Probability
Agree	20	0.36	0.36
Partly agree	23	0.42	0.78
Disagree, don't know or doesn't apply	12	0.22	1.00
Total	55		

TABLE 2.7: THE 1991 ZEV PRODUCTION REQUIREMENT SPURRED SIGNIFICANT NEW INVESTMENT IN THIS TECHNOLOGY.

Level	Count	Probability	Cumulative Probability
Agree	32	0.58	0.58
Partly agree	16	0.29	0.87
Disagree, don't know or doesn't apply	7	0.13	1.00
Total	55		

3. AGGREGATE MEASURES OF EV-RELATED ACTIVITY, 1980 TO 1999

PATENT ACTIVITY

Not all patents represent ideas or products that are successful in the market. However, taken as a whole, the rate at which patents are filed and granted in a particular area is an index of inventive and entrepreneurial activity. In this section, we identify changes in the number of patents related to electric vehicles that were issued over the time period from 1980 to the present and assess whether changes in total patent activity are contemporaneous with the ZEV production requirement. In cases where corroborating statements can be found, for example, claims by automakers that their electric vehicle research programs have produced patents, these are included.

We searched for patents granted in the United States of America using the US Patent and Trademark Office's (USPTO's) on-line search facility (http://www.uspto.gov/). The patent database was searched for the years 1980 to 1999. 1980 marked a convenient year to track patents issued related to EVs during the "federal energy policy period" described in the introduction. During this time, much of the EV-related research was supported by USDOE. 1999 is the last complete year for which data are available.

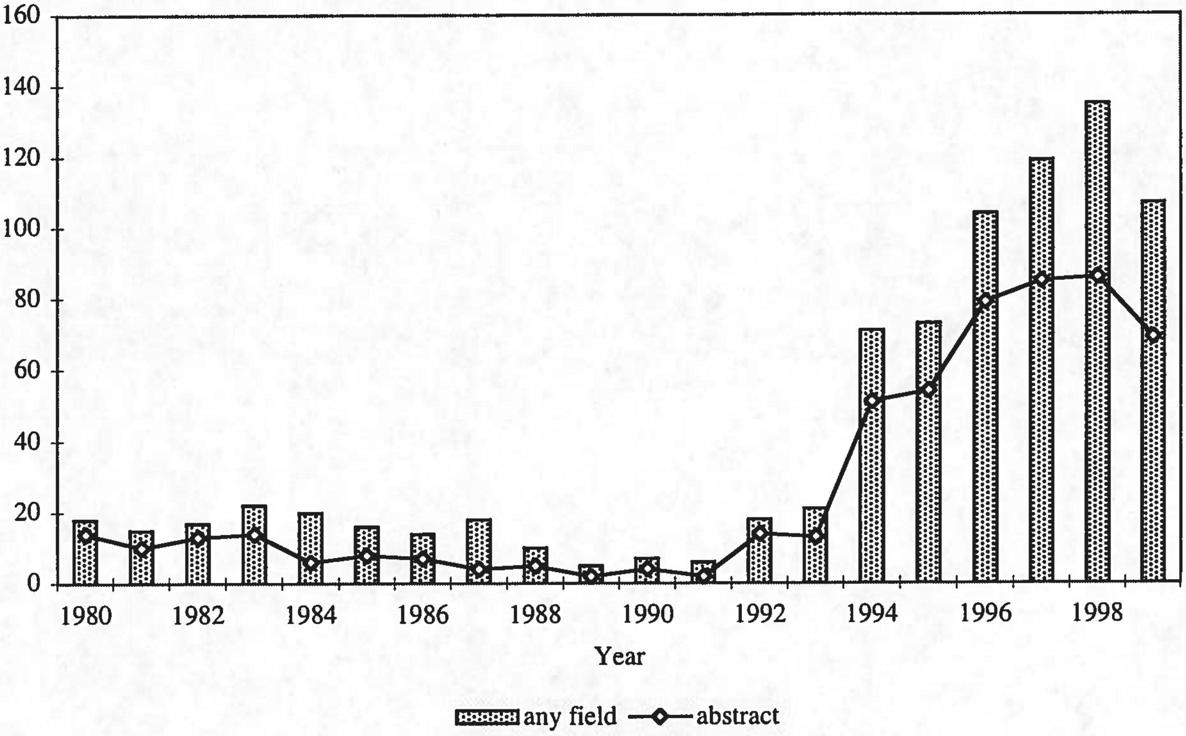
Patents were searched for the phrase "electric vehicle*." The star character is a wildcard, allowing the search to return patents containing "electric vehicle," "electric vehicles," or "electric vehicle's" in one search pass. Further, the search was run twice—once to search all data fields of the patent for the occurrence of the search phrase, and once again to search only the patents' abstracts. Patent abstracts were reviewed to insure the patent was indeed related to the subject matter at hand. A few patents were rejected—some related to toy electric vehicles and some related to electrically actuated or powered devices for vehicles, i.e., the phrase "electric vehicle" was not an adjective (electric) modifying a noun (vehicle), but in fact two adjectives modifying a subsequent noun. As an example, a patent for an "electric vehicle coupling device" was not a means to connect electric vehicles, but an electrically powered device for coupling railway cars together. The results of the search are illustrated in Figures 3.1 and 3.2.

As illustrated in Figure 3.1 below, between 1980 and 1991, EV-related patent activity started low and then declined. From 1980 to 1987, typically 15 to 20 patents were issued per year. The annual number of patents then fell, such that in 1991, the year the ZEV production requirement was first announced, only six patents related to EVs were issued. There was a small increase in the number of patents in 1992 and 1993. There was a pronounced increase in 1994. From that time through 1998, the number of patents continued to grow. There was a sharp downturn in 1999; but one year does not make a trend, and only time will tell whether this measure of EV-related activity will continue to decline.

The basic measure of total patent activity passes the test of whether or not an upturn in EV-related inventive activity was contemporaneous with the announcement of the ZEV production requirement. In fact, it is interesting to note that despite a strong federally funded R&D program in electric and hybrid electric vehicles during the early 1980s, patent activity was low. During the 1990s, the ZEV production requirement affected overall efforts to patent inventions related to EVs in a way that federal research dollars did not in the 1980s.

Is the simple fact that increased EV-related patent activity was contemporaneous with the announcement of the ZEV production requirement proof the production requirement caused these increases? No. Maybe something about the patent system or the world at large changed in the early 1990s such that all patent activity increased. Maybe all patents increased faster than EV patents. Maybe, but no. Figure 3.2 illustrates trends the number of all EV-related patents to the number of all patents for inventions issued by the USPO for the years 1980 to 1998. The number of each category has been indexed to the year 1980. That is, at each year the chart shows the number of patents issued in that year divided by the number of patents issued in 1980.

FIGURE 3.1: ANNUAL NUMBER OF EV-RELATED UNITED STATES PATENTS GRANTED FROM 1980 TO 1999.

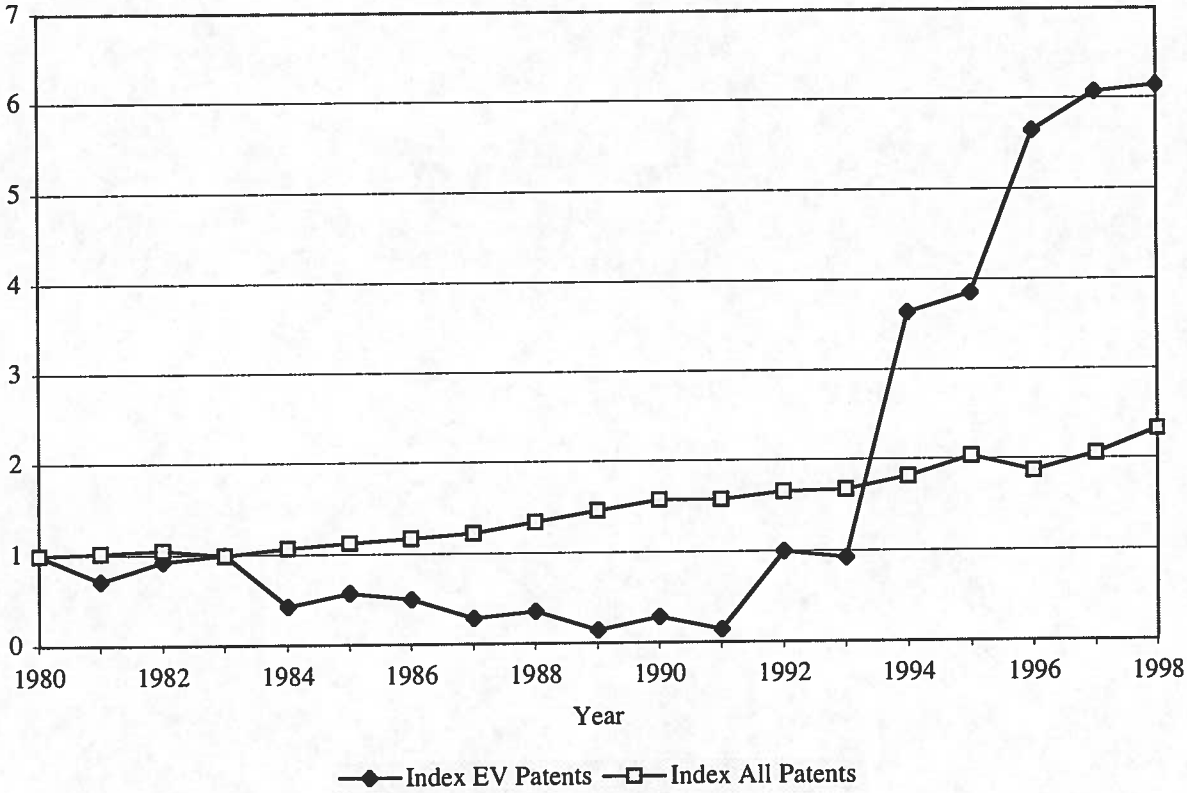


During the years of low and declining patent activity related to EVs (1980 to 1991), all patent activity in general is increasing. In fact, all patent activity increased slowly and steadily throughout the period from 1980 to 1998, such that by 1998 the number of patents had increased by a factor of 2.3. In the time period 1991 to 1996, the rate of patent activity related to EVs increases faster than all patent activity. By 1991, EV-related patent activity had dropped to only 0.14 times that in 1980; by 1998, over 6 times as many EV-related patents were granted every year as had been in 1980.

These observations suggest, and statistical analyses of these data confirm, that increases in the number of EV related patents are not correlated with increases in overall patent activity. (Details of the statistical analysis are contained in Appendix A of this report.) We are therefore more inclined to attribute the upturn in EV-related patent activity to the fact that after 1990 all automobile manufacturers had to develop EV technology to meet the ZEV production requirement.

Our patent search was conservative and we undoubtedly under-counted EV-related patents, as we counted only those patents which specifically mention electric vehicles in their texts. That is, there may be any number of inventions that could be and have been applied to EVs, that did not mention this application in the patent itself. For example, we did not include many battery patents. The reason is that many battery patents do not limit the use of the battery to electric vehicles. Many materials related patents, especially those having to do with developing lightweight vehicle frames and bodies are not included here. Certainly though, such advances are important to, if not specific to, EVs. We do not report here on such broadly applied patents because it is beyond the scope of the present study. Further, the data presented here in are for US patents only and do not account for Japanese or European patents.

FIGURE 3.2: ANNUAL NUMBER OF EV-RELATED AND ALL UNITED STATES PATENTS GRANTED FROM 1980 TO 1998. INDEXED TO 1980.



NUMBER OF ON-ROAD ELECTRIC VEHICLES

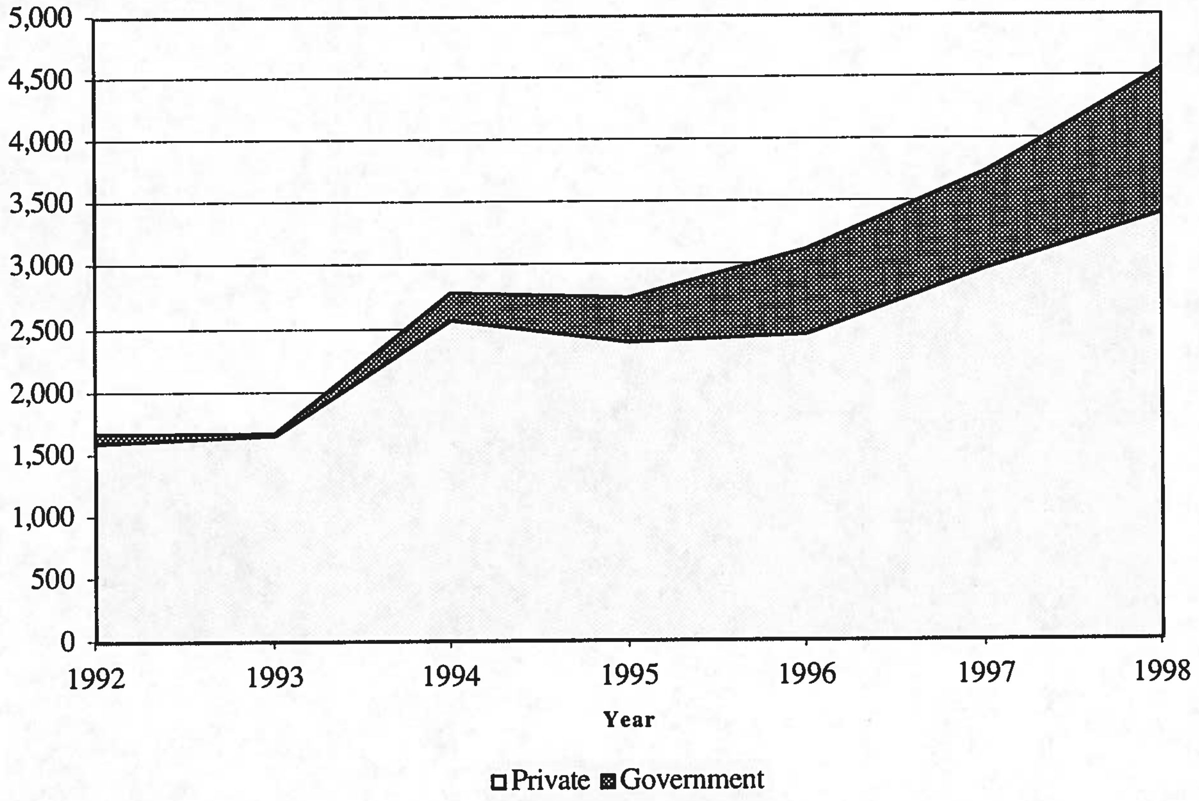
The U.S. Department of Energy, Energy Information Energy Agency publishes estimates of the number of on-road EVs in the United States. We present these data, and then present the number of EVs delivered to consumer or fleet operators in California under the terms of the MOAs signed between the automobile manufacturers and the State of California. According to the data in Table 3.1 (illustrated in Figure 3.3), the number of on-road, light-duty electric vehicles in use in the US increased by 172 percent between 1992 and 1998.

TABLE 3.1: NUMBER OF ON-ROAD LIGHT-DUTY EVS IN THE UNITED STATES

	Private	Government	Total
1992	1,588	92	1,680
1993	1,657	14	1,668
1994	2,572	207	2,779
1995	2,400	351	2,751
1996	2,451	675	3,126
1997	2,966	776	3,742
1998	3,398	1,164	4,562

Source: U.S. DOE Transportation Energy Data Book, 15, 17, 18.

FIGURE 3.3: NUMBER OF ON-ROAD, LIGHT-DUTY EVS IN THE UNITED STATES



The schedule for the delivery of ZEVs in California is shown in Table 3.2. Since the MOA period was intended to spur technological development, especially for batteries, CARB set minimum performance standards for vehicles intended to earn credit toward the MOA requirements. In 1998, a vehicle had to have traction batteries with a specific energy of 40 Wh/kg; in 1999 and all later years, 50 Wh/kg. Manufacturers could earn more than one vehicle credit for surpassing these goals, thus the actual number of ZEVs delivered in California differs from the schedule. CARB staff estimate that based on these additional credits, a total of 1,800 ZEVs will have been placed in California under the MOAs—less than half the nominal 3,750 vehicles required.

Toyota and Honda have completed delivery of all vehicles. CARB staff project that Daimler-Chrysler, Ford, and GM will finish on, or ahead of schedule, in the year 2000. Nissan has been granted a one-year extension to fulfill its requirement. The actual number of ZEVs delivered in California by each manufacturer is shown in Table 3.3.

Table 3.2: Schedule of ZEV Deliveries per MOAs between Automobile Manufacturers and the State of California

Calendar Year	Chrysler	Ford	GM	Honda	Mazda	Nissan	Toyota	Total
1998	51	181	182	101	28	70	135	748
1999	103	363	365	202	55	141	271	1,500
2000	103	363	366	203	55	141	271	1,502
Total	257	907	913	506	138	352	677	3,750

Source: California Air Resources Board (2000) Preliminary Draft Staff Report: May 31 Workshop ZEV 2000 Biennial Review.

Table 3.3: Actual Deliveries of ZEVs in California per Additional Credits Granted for Exceeding Battery Performance Goals

Daimler-Chrysler	Ford	GM	Honda	Nissan	Toyota
EPIC, Pb-A: 17 EPIC, NiMH: 93	Ranger, Pb-A: 52 Ranger, NiMH: 327	EV1, Delco Pb-A: 606 EV1, Panasonic Pb-A: 0 EV1, NiMH: 162 S-10, Pb-A: 110 S-10, NiMH: 117	EV Plus, NiMH: 276	Altra, Li-ion: 81	RAV4, NiMH: 486

Source: California Air Resources Board (2000) Preliminary Draft Staff Report: May 31 Workshop ZEV 2000 Biennial Review.

4. FROM GOLF CAR TO RACE CAR TO YOUR CAR

CHANGES IN VEHICLE PERFORMANCE SINCE 1990.

In 1990, there was only one EV—the GM Impact —which had the acceleration and high speed performance to compete with (and under some conditions, beat) gasoline vehicles. Its performance inspired many to think that EVs could be practical for drivers. But, this was a prototype. Most of its parts and its chassis were hand made. While the Impact represented a quantum leap forward, marketable EVs still appeared to be a long way off.

But since 1990 a wider array of electric vehicles—sedans, wagons, SUVs, vans, pick-up trucks, and even transit buses have been developed and marketed. Many of these are capable of freeway travel. Advances in battery, power electronics (affecting efficiency and recharging) have extended daily range (the product of miles per battery charge and recharging opportunities per day) to hundreds of miles for some vehicles and some drivers. EVs are proving they can be more reliable than gasoline vehicles. More and more they are being built with mass produced components designed for EVs, not borrowed from other applications.

COMMERCIAL EVS IN THE EARLY 1990S

In 1992, when UC Davis conducted a test drive of electric vehicles and other alternative vehicles for consumers in Pasadena, there were few EVs available. The Impact was not available (there was only one). A Chrysler TEV van was tested, but was determined by research staff to be unsafe for test drives by EV novices. The brakes had not been redesigned to match its increased mass.

The best example of an EV we were able to present was built by Solectria, a small EV and components manufacturing firm in Massachusetts. The Solectria Force was a converted GM Geo Metro. The gasoline engine had been removed to make room for the electric motor and power electronics. It accelerated well up to about 40 miles per hour. However, the Force did not have adequate instrumentation, had a noisy belt drive. Its suspension was overloaded by its batteries, and it did not have adequate power for acceleration above 40 mph. The regenerative braking was designed so that it started to brake when the driver's foot was lifted from the accelerator pedal. While this may become common place among EVs, it was an unfamiliar sensation to the members of the public who participated in the test drive. Despite these limitations and differences, many drivers liked this vehicle and thought it fun to drive (Turrentine and Kurani, 1995).

In the early 1990s, small commercial EV makers, like Solectria and U.S. Electricar were forced to use automotive OEM vehicle chassis, suspensions, brake systems, transmissions, and other systems designed for gasoline vehicles and electric components designed for industrial machines. They often had to buy intact new gasoline cars, and remove the engine and other components before modifying (cutting and welding sometimes) the chassis to accommodate the electric motors, electronics, and batteries. The process of converting was expensive, wasteful, and slow. The results were not always great. The heavy frames and bodies of gasoline vehicles were unsuited to the efficiency needs of EVs. There was no supply of purpose built instruments, no auxiliary systems such as electric steering, braking, and climate control designed specifically for EVs.

The motors, controllers, and batteries available were adequate for some research programs, but inappropriate for real driving demands. Battery and automobile makers had not yet learned how multi-module battery sets packed together for high voltages in EVs behaved, and battery makers had yet to develop batteries that met the reliability demands of EVs. And the power electronics capable of meeting the high voltage demands for rapid acceleration, high speeds, and regenerative braking were not available. Modern solid state power electronics for some of these early 1990s EVs were hand made by engineers like Alan Cocconi and James Worden. It is reported that the power control module for the first GM Impact contained over 9,000 hand soldered connections.

WHAT A DIFFERENCE A DECADE MAKES

Ten years later each of the large OEM automobile companies has developed batches of purpose built EVs including batch production runs of electronics, motors, and other vehicle systems designed for EVs not borrowed from gasoline vehicles or industrial applications. Battery manufacturers have developed purpose built battery packs—not just individual battery modules—for EVs In particular, there has emerged a wide array of power electronics, motors, and other drive-train components, spurred by potential demand from EVs, fuel-cell vehicles and hybrids. EV development programs in the automotive companies have progressed, not only overcoming the limitations of the early 1990s' vehicles, but each manufacturer was able to build and distribute several hundred EVs with advanced ac or dc drive trains, advanced batteries, including advanced lead acid, NiMH, and Li-ion. While only one of these vehicles—the by now venerable EV1—used an advanced vehicle platform designed to reduce weight and optimize aerodynamics, all of these vehicles demonstrated the potential practicality, reliability, and consumer satisfaction with EVs. In one decade, EVs had moved from design shops to market. Had UC Davis held a drive test today, it would have its pick of at least ten vehicle types.

The movement over the last decade from laboratories and conversion shops to OEM EVs has been a complex process. It has involved many parallel development pathways, such as:

- The development of specialized EV motors, electronics, instrumentation, braking, batteries (as opposed to the use of components developed for other products—such as industrial machine motors and controllers);
- Continuous improvements in power and efficiency of the drive train and auxiliary systems;
- The development of NiMH and advanced lead-acid battery packs with thermal and battery management systems to ensure long life;
- The continued development and implementation of fast charging equipment and the demonstration of on-board, high power recharging equipment;
- The application of reliability engineering and production expertise to EV components and development of small batches of vehicles across multiple generations of technology;
- The largely complementary development of hybrid and fuel cell technologies (batteries, power electronics, electric steering, aerodynamics, lightweight platforms, etc.)

While many car companies had worked on prototype EV designs from the 1960s through the 1980s, it was GM who pushed advanced EV designs into the public eye in 1990. However, California's ZEV production requirement, the subsequent formation of the United States Advanced Battery Consortium, the Advanced Lead Acid Battery Consortium, the DARPA electric transportation consortia, the 1993 United States Partnership for New Generation of Vehicles, and other efforts pushed all of the car companies into long range development programs for advanced EVs. Below is a review of some of these automotive company programs and their main projects. We focus on those major OEMs subject to the ZEV production requirement.

The GM EV program illustrates processes that have been most important about EV technology developments in the 1990s. Not the least of these is the evolution from the hand-built prototype Impact 1 to the small batch production of the Impact 3, then on to the first and then second generation EV1 made in batches of several hundred.

TABLE 4.1 HIGHLIGHTS OF EV RESEARCH AND DEVELOPMENT PROGRAMS OF THE OEM AUTOMOBILE MANUFACTURERS SIGNING MOAS WITH THE STATE OF CALIFORNIA

OEM	OEM vehicle forerunners, 1980 to 1990	Prototypes 1990-1996	Batch production 1997-2000	Near-Future EV Programs and Alternatives
General Motors	G-Van[1]	Impact, Generations 1 to 3	EV1, Generation I and II drive trains Chevy S-10	Triax Modular Platform, Generation III drive train
Ford	ETX I and ETX II Van	Ecostar Modular Electric Vehicle Program	Ford Ranger	TH!NK City and Neighbor EcoStar Electric Drive Systems (jointly with DCX)
Daimler-Chrysler (DCX)	Chrysler/GE ETV-1	Chrysler TEV Van Mercedes 190 Electric	EPIC Minivan	Hybrid Intrepid ESX II, Hybrid Citadel EcoStar Electric Drive Systems (jointly with DCX)
Honda		Honda CUV-4	EV Plus	Hybrid Insight
Mazda				See Ford
Nissan	March EV-1 March EV-2	Future Electric Vehicle (FEV), Avenir	Altra, Hypermini	Hypermini
Toyota	EV10-50	Town Ace	RAV4, e•com	e•com Hybrid Prius

1. Body and chassis of a GM Vandura full-size van, power train built by Chloride, vehicle assembled by Magna International/Conceptor Industries (OECD, 1993)

Ford did not have a chassis development program like that for the EV1. Instead of a purpose built chassis, Ford converted a small, European delivery van to produce the Ecostar. Wakefield (1993) credits Ford, and their partners GE and the USDOE, with creating "possibly the first truly viable electric vehicle for general purpose use." The Ecostar used an ac drive system and high temperature sodium sulfur batteries. Two Ecostar vans were delivered to the USDOE in December 1988—two years before the Impact was unveiled.

After a number of problems with the high temperature batteries, Ford switched its EV development to a Ranger truck platform, ostensibly to serve fleet markets. Despite suffering the inherent disadvantages of a heavy steel platform and a body shape with poor aerodynamic performance, the electric Rangers has been successfully applied to fleet use. The U.S. Post Office has just announced it will buy 500 electric Rangers, with possible future orders totally thousands more. (Ford successfully outbid GM, who had sought to sell its electric S-10 trucks to the Post Office.)

One of Honda's developmental steps was the Clean Urban Vehicle (CUV) 4. Honda met its obligations during the MOA period with the EV Plus. It was built on a Civic-like platform with a distinct body. The vehicle, while relatively heavy, proved to be a reliable and well liked vehicle. Unfortunately, Honda, a world leader in efficient and clean vehicles has not applied EV technology to lightweight platforms. Instead lightweight chassis program have been dedicated to the hybrid developments, such as the Insight. We are, for now, left to wonder what level of performance Honda would have achieved had it developed a lightweight platform with good aerodynamic performance for its EVs.

Toyota had had a long term EV development program, with several variants of EVs. The EV20 was a fairly conventional looking subcompact sedan using lead-acid batteries and an ac induction motor. The EV30 was a two seat, off-road vehicle that had a zinc-bromine battery. It had a range of about 100 miles at a constant 20mph, and a top speed of 25mph. In the early 1990s, Toyota developed a Town-Ace minivan. These vans used ac induction motor and nickel-cadmium batteries. It also incorporated a number of important pre-cursors to systems that would become important in the later 1990s, including an improved battery state of charge metering system and electric steering. In response to its MOA requirements Toyota has followed a similar strategy to Ford, and used a relatively heavy, but well liked vehicle, a compact sport utility vehicle, the RAV4. It was adapted to EV drive trains and battery weight. This vehicle, while lacking good aerodynamic design and being heavy, has proven to have an extremely reliable drive system.

Nissan's March EV-1, introduced in 1983, incorporated an early ac motor and nickel-iron batteries. Ward's Communications (1993) reports the vehicle had a 99-mile cruising range, but no drive cycle is reported for this figure. The March EV-2 incorporated advances to the ac motor. The FEV was a four-seat, two-door coupe. Ward's also reports the FEV had several significant design features that foreshadow GM's Impact. The FEV had an aluminum frame, and some plastic body parts. It used two ac motors each driving separate wheels. The aerodynamic drag coefficient is reported to be the same as that of the Impact—$C_d = 0.19$. Nickel-cadmium batteries were used. Nissan developed several recharging options, including fast charging. Following its Avenir vehicle and lead acid battery program, Nissan developed the most conventional sized vehicle of all the OEMs for the MOA period. While the 5-passenger Altra was conventional in appearance, it was the only vehicle offered with something other than a lead acid or NiMH battery. Nissan used an advanced lithium-ion battery. Because of battery supply difficulties, Nissan has been given one additional year to deliver all its vehicles required by its MOA.

Chrysler was one of the manufacturers to make a public showing of EVs early in the 1990s. The TEV van was based on Chrysler's Caravan body, and from that vehicle (the now) DaimlerChrysler developed the EPIC minivan. While originally equipped with advanced lead-acid batteries, the EPIC is now equipped with NiMH batteries—specifically to meet the terms of its MOA. (The MOAs do not require NiMH batteries, but they only give credit for implementing battery technologies that have better specific energy than do lead-acid batteries.) Chryslers' program is impressive for its demonstration of the feasibility of fast charging NiMH batteries.

In addition to these OEM car company programs, there continue to be innovative independent programs that develop new technology. AC Propulsion, located in San Dimas, CA, was founded by some of the original team hired by GM to develop the Impact. The Massachusetts-based firm Solectria continues to convert and build groundbreaking vehicles and technology. They have a more than decade long winning streak in the American Tour de Sol, setting numerous single charge and multi-day driving range records along the way. Other companies, such as Unique Mobility, Baker Electromotive, and US Electricar made their marks as technology and vehicle developers. University engineering programs supported by USDOE and the National Science Foundation continue to push EV technology.

ON-GOING AND NEAR FUTURE EV-RELATED PROGRAMS

Nearly all OEM automotive manufacturers have expressed interest in continuing electric drive train development, but their goals appear to be hybrid EVs and fuel-cell vehicles, though we don't list fuel-cell programs in Table 4.1. Nearly all manufacturers have announced plans for continued vehicle development that *could* include EVs. GM's prototype Triax platform is designed to support EV, hybrid, and ICE drive trains. Ford has turned some attention to low speed and small vehicle designs, acquiring PIVCO, the Norwegian manufacturer of a two-seat electric city car. These vehicles, plus neighborhood electric vehicles, electric bicycles, as well as advanced technologies such as fuel cells have been organized into Ford's new TH!NK division. Daimler Chrysler's recent announcement that it intends to spend one billion dollars to insure it will market fuel cell vehicles within two years appears to be a clear indication of their future plans.

Hiroyuki Watanabe, (managing director and a member of the board for Toyota Motor Corporation (TMC)) outlined Toyota's vision of the future in a presentation to the Society of Automotive Engineers' 2000 Future Car Congress. He omitted any reference to battery ZEVs; he did discuss both hybrid EVs and "fuel cell-hybrid" vehicles. This, and the language Toyota uses to describe their e•com, may signal Toyota does not consider vehicles such as those offered during the MOA period as viable parts of the multi-propulsion system future. As recently as a May 31, 2000 press release Toyota promoted an innovative transportation concept to promote car-sharing mini electric vehicles, while seeming to diminish any other role for EVs:

> "A program demonstrating innovative shared usage of mini electric vehicles illustrates Toyota's view of how battery electric vehicles could perhaps play a role in the automotive marketplace. (Toyota Motor Company press release. May 31, 2000)

The apparent implication is that privately owned, freeway cruising EVs are not part of an electric vehicle future envisioned by Toyota.

The car companies are now nearly universal in their acclaim for the technical, and therefore market, possibilities of hybrid and fuel cell vehicles. Some automobile manufacturers give credit to the advances in EV technology as facilitating any future hybrid and fuel cell vehicle development. In a speech to the 1999 North America Electric Vehicle and Infrastructure conference, John Wallace, the recently appointed executive director of Ford's TH!NK Group characterized rise of the electric drive train as the most important development in the past 20 years. At that same conference, GM's Robert Purcell stated "The electric drive and control systems that you develop for battery electric vehicles are the fundamental enablers for hybrid electric or fuel cell electric. So as a technology development platform, the battery-powered EV has a very critical role in the development of all of these advance vehicles for the future." (Summaries of both Mr. Wallace's and Mr. Purcell's comments can be found at www.evworld.com/conferences/naevi99/panel.html). We will return to the topic of future directions in Chapter 6.

PERFORMANCE IMPROVEMENTS IN THE 1990S

The result of a decade of pushing technology has paid off. Electric vehicles are sophisticated, batteries are reliable, and overall practicality of the EVs available in the late 1990s is the direct result of a visionary push in the early 90s by regulators as well as scientists, engineers. We discuss these vehicles briefly below in terms of several attributes:

- Daily range
- Single charge range
- Acceleration and top speed
- Reliability
- Efficiency

But first, we interject with a few record-setters. Racing and other forms of record setting have a history of pushing the limits of transportation technology. Electric vehicle technology is no different. Throughout the period from 1990 to the present, advances in electric technology allowed a variety of performance records to improve. Speed and acceleration, as well as range per charge and range per time have all improved. In this section, we note some of these achievements.

It should be noted that many of these records were set with purpose-built vehicles running over carefully selected courses, and, with regard to range, unrealistic drive cycles—but that is the nature of racing and record setting. We do not offer these benchmarks as measures of everyday performance—but no race records are. We do offer them as examples of how far the performance limits of EVs and EV technology have been expanded.

TABLE 4.2: EV PERFORMANCE RECORDS

Performance Measure	Record	Date	Vehicle	Battery Chemistry	Comments
Top Speed, mph	245	October 1999	World Record Associates "White Lightning	PbA	Purpose-built speed record vehicle. Records calculated as the average speed of two flying 1-mile runs within 1 hour of each other.
	183	1994	Modified GM EV-1	PbA	
	174	1974	Roger Hedlund's "Battery Box"		
0 to 60 mph acceleration, sec.	4.1	1999	AC Propulsion t-zero	PbA	December 1999. Timed by Road and Track magazine.
1/4 mile drag race, time (sec.) and speed (mph)	8.861 sec 147.12 mph.	(no date)	Current Eliminator	PbA	This is a true dragster type vehicle, under 10 sec. speed has forced it into dragster sanctioned events
	11.202 sec 108.31 mph	August 1999	converted Mazda		This is a non-dragster street vehicle
Range per charge, miles	478	February 15, 1997	ZAT minivan	Zinc-air	Sub-zero temperatures throughout drive. Drive cycle not reported
(by battery and vehicle type)	375	May 1996	Solectria	NiMH	Non-Production Class EV. Built on a lightweight composite and aluminum frame. Set in 1996 Tour de Sol
	249	May 22, 1997	Solectria, converted Geo Metro	NiMH	Production Class EV built on a "standard" steel chassis. Set in the 1997 Tour de Sol
	340	1992	Horlacher Sport	NA-S	Pre-production prototype of 2+2 coupe. Drive cycle not reported.

Table continues on next page

TABLE 4.2: EV PERFORMANCE RECORDS, CONTINUED

Range per 24-hours, miles	1,328	December 1999	Mitsubishi Motors prototype	Li-ion	Run on test track. Recharged 20 minutes, every hour.
	1,020	1996	converted Saturn coupe	Lead-acid	Aerovironment trials featuring their fast charging equipment. Vehicle fast charged several times. Miles driven on city streets in Los Angeles
	777	October 1998	Chevrolet S-10 production electric		Aerovironment trials featuring their fast charging equipment. Vehicle fast charged several times. Miles driven on city streets in Los Angeles
Fuel efficiency, miles per gallon equivalent	130	May 19 to 22, 1997	Solectria, converted Geo Metro	NiMH	Production Class EV Record set in the 1997 Tour de Sol Gasoline-powered Geo Metro averaged 42 mpg running the same course on the same day.
Pikes Peak Climb, min:sec	15:33	July 4, 1997	Chevrolet S-10, production EV	NiMH	"Race" version of production S-10. Modifications from true production vehicle not reported.
	15:45	1993	Honda Civic conversion		

DAILY RANGE OF VEHICLES

Improvements in battery and charger technology have vastly increased the distance that an EV can be driven in a day. There is a link between *miles per battery charge* and *daily driving range* that is moderated by recharging technology. Specifically, how far you can drive an EV on any given day is not simply the range afforded by the battery pack. Rather, daily range is a function of 1) total energy storage capability of the battery pack, 2) whether or not recharging capability is carried on-board the vehicle, 3) the availability of recharging outlets, and 4) the speed at which the combination of charger technology and electrical service levels at those outlets can recharge a battery. Whereas 1980s vintage EVs could be driven 40 or 50 miles before requiring a 10 hour recharge, today we witness a Chrysler EPIC van traveling 350 miles in 10 hours while recharging multiple times. (www.daimlerchrylser.com).

Perhaps, the most revolutionary development for electric vehicles during the 1990s has been rapid charging equipment, both on-board and off-board the vehicle. Rapid charging can recharge a battery in few minutes rather than hours. While this technology is not yet widely available, it seems at this point that it is ready for market. Potential barriers and uncertainties loom. One barrier is standards; one uncertainty is driver behavior. (As this report is not about behavioral adaptations, we will not follow up on this particular aspect. We simply note anecdotal reports of EV1 drivers changing their away-from-home recharging behavior after they switch from lead-acid to NiMH batteries that provide more miles per charge.)

Considerable progress has been made on some standards. The Infrastructure Working Council, a coordinating organization for manufacturers, electric utilities, standards agencies, and regulators, has codified three levels of recharging. Roughly, these are Level 1 (110/120 volt), Level 2 (220/240 volt), and Level 3 (440/480 volt). Level 1 recharging was the old de facto standard for EVs up to the 1990s. Recharging batteries at higher rates required higher quality batteries, battery management systems capable of dynamically balancing battery charge levels, and other advances in power electronics. Level 2 charging capability is now regarded as "standard equipment" for EVs, and Level 1 capability is offered only as an emergency precaution. (Though we note that a Level 1 charging connection could also be sufficient to provide pre-cooling and pre-heating of the passenger compartment, battery equalization, and other "plugged-in" benefits of EVs.) Rapid charging is Level 3 charging.

Prior to the development of Level 2 and 3 it took several hours to recharge a battery at Level 1, and therefor was not possible to charge a vehicle more than once a day, with the exception of "topping" off the battery for a few miles.. And while the daily driving habits of most Americans seldom exceeds the miles per charge of most modern EVs, there are days of greater need which could discourage potential EV buyers (or renters). Level 2 charging raises the possibility of two complete charges per day, and certainly two or more partial charges per day for many drivers. Level 3 charging pushes this limit even farther. With Level 3 charging, some commercial fleets could use all EVs, as their vehicles can fast charge during lunch and other worker breaks, essentially multiplying their daily range. For example, using fast charging a Daimler-Chrysler EPIC van single charge range of 90 miles can be increased to a daily range of 300-400 miles. Ironically, such high rates of charging were originally thought to damage batteries but the pulsing algorithms used to charge the batteries can actually extend the life of the battery. There are currently 158 Level 3 fast charge installations across the USA.

A Chrysler van, using nickel-iron batteries and fast charging equipment, drove from Detroit to Los Angles in March 1993. The late 1990s Chrysler EPIC minivan has been developed especially with this type of fast charging in mind. Its NiMH batteries (from Saft) are liquid cooled to manage heat during very fast charging with a 60 kW Aerovironment charger. (For comparison, the Level 2 charge level for most vehicles is 6.0 or 6.6 kW.) SAFT claims the batteries can be recharged from

40 percent to 80 percent state of charge (SOC) in 12 minutes and that fast charging can be done across a wide range of temperatures (-10ºC to 50ºC) (Madery and Liska, 1999). An airport van service in Los Angles has been using these EPIC vans and fast charging every day during 1999 and 2000 with great success. The reference above to an EPIC van traveling 350 miles in 10 hours was to a feat accomplished at the 1999 North American Electric Vehicle Infrastructure (NAEVI) Conference in Atlanta, Georgia, where an EPIC accumulated 353.1 miles on Atlanta streets and expressways in a 10-hour period.

In 1994, a Solectria E-10 pickup truck (a converted Chevrolet S-10) using a computer aided charging system from EPTI set a new 24 hour distance record of 821 miles in Georgia on a test track. The battery pack was recharged 13 times in the 24 hours. Each recharge required 15 to 20 minutes to recover 80 percent of the battery charge. In 1998, using its 60kW equipment, Aerovironment set an "on-road" record for daily mileage of 777 miles on the Pomona urban loop used by SCE for EV testing. The vehicle was an S-10 pickup truck.

The remaining issue with recharging standards is that two equipment standards have been promulgated to correspond to the two types of recharging equipment that are currently available. The automobile manufacturers have arrayed themselves into two camps—one favoring inductive charging and another favoring conductive charging. Throughout the early 1990s various arguments regarding cost, safety, and efficiency were made in favor of one system or the other. Today, it appears there is little that separates the two technologies on any of these criteria. Oros (1999) does claim conductive chargers will be cheaper under mass production. Prices for conductive units manufactured in the tens of thousands are stated to cost between $150 and $750; inductive chargers at similar production levels are estimated to cost $500-$1,000.

One other criteria that might drive a choice between the two is whether on-board conductive systems offer a more simple system in the long run, as on board power systems become more robust. Charging levels higher than Level 2 have previously been implemented only through off-board charging equipment. A new development in charging is on-board "Level 2+" charging developed by AC Propulsion. The technology is "an extension of the SAE J1772 conductive charging standard, and features backward compatibility for existing vehicles configured with level 2 systems." (www.acpropulsion.com) While EVI describes Level 2+ charging as being in the range of 20kW to 40kW (Oros, 1999), AC Propulsion claims power levels of up to 75 kW are possible. At its highest rate, the Level 2+ charger allows an AC Propulsion vehicle to recharge one mile of driving range per minute (T. Gage, personal communication, June 2000). A recharging network built around this technology system could allow drivers to recharge at a greater number of locations than the current technology systems which require that high power recharging (level 2 or higher) be done only at the vehicle's corresponding type of off-board recharging appliance. However, the decision to build such a recharging network would require continued development of both technology and standards. For good reason, existing standards do not allow an EV driver to plug into just any high power electrical service.

High-power charging required off-board chargers to convert line current (ac) to direct current (dc). The AC Propulsion vehicle demonstrates it is possible to integrate this function into the car, so the off-board charger and its cost are eliminated. Oros (ibid.) estimates that the total "hard" cost of recharging equipment to be $2,000 rather than $45,000 for an off-board 40kW charger. An AC Propulsion press release quotes Craig Toepfer, a Ford EV infrastructure development engineer, as saying "Infrastructure cost is a big barrier to EV commercialization. Now, with high-power [on-board] ac charging, that barrier is dramatically reduced." (http://www.acpropulsion.com/Press%20releases/Level%202+.htm).

Proponents are claiming that only conductive charging equipment can economically provide the faster Level 2+ charging (www.acpropulsion.com). They argue that inductive charging equipment, which currently requires an off-board charger, is less adaptable to high-power charging for cost reasons. We note that these proponents are all members of the "conductive charging camp" more formally known as the Electric Vehicle Conductive Charging Coalition, or EVC3. While their position regarding high power, on-board charging may prove itself in the long-run, for now we observe that the period of EV technology evolution started in1990 has brought us many advances previously thought impossible. At the same time, certain technological pathways are starting to be squeezed off by old technology choices and standard setting activities based on those old choices.

SINGLE CHARGE RANGE—MILES PER CHARGE DOUBLES? TRIPLES?

The driving range of vehicles continues to improve, regardless of battery type. In the 1960s and 1970s, driving ranges for vehicles using lead-acid batteries were commonly 30-50 miles depending on the body type. Now it is common to have vehicles with valve regulated and other new designs for lead-acid batteries that are getting 50-100 miles of range reliably. A few examples are described below. It should be noted that most of these marks were set under a variety of conditions and therefore cannot be directly compared to each other.

The data in Table 4.2 are from more systematic tests of vehicle range. Data are from two programs of the Field Operation Program (FOP) of the Office of Transportation Technology of the USDOE. Pomona Loop data are collected by Southern California Edison (SCE). These data are collected from test drives around the Pomona Urban Driving Loop and Pomona Freeway Driving Loop. Details of SCE's procedures can be found in Argueta *et al*, 1999. In general though, the SCE energy data for EVs are based on "real-world" driving on urban streets and freeways. Baseline Performance data are collected by a consortium consisting of Electric Transportation Applications (ETA), Arizona Public Service (APS), Salt River Project (SRP), and Potomac Electric Power Company (PEPCO). Their test procedures are available on-line at http://ev2.inel.gov/sop. Baseline Performance data are based on both dynamometer and road testing. A total of 20 vehicle models have been tested since 1994. As of mid-year 1999, the program had accumulated over 400,000 miles on 65 vehicles involved in two other FOP programs—Accelerated Reliability and Fleet testing (Francfort *et al*, 2000).

Francfort *et al* (ibid.) report that over the time period from 1994 to 1999 that driving range measured in all three of the Baseline Performance tests more than doubled. This conclusion is based on averaging the results for each year. So for example, from 1994 to 1999 the average range of the vehicles tested each year on the SAE J1634 cycle increased from about 45 miles to about 105 miles. These results can also be found at (http://ev2.inel.gov/sop).

There are several problems with attempting to measure change by averaging vehicles tested each year, and Francfort *et al* (ibid.) do note some of them—primarily that each year's average is dependent on which particular vehicles are tested each year—not all vehicles are tested every year. Thus the number of vehicles tested changes from year to year and the influence of one extremely good or poor performance carries different weight from year to year. In fact, only in 1994 (when nine vehicles were tested) were more than three vehicles tested in any given year.

Another way to look at the data is to try to track similar vehicles over time. This approach also suffers from the small number of vehicles tested, and from the limited variety of vehicles for which this approach is even possible. However, it does reduce apparent differences across years caused by changes in body styles and vehicle weight of the vehicles tested from year to year. The Baseline Performance database contains four Ranger pickup trucks. Two were conversions by non-Ford shops (a Unique Mobility (UM) and a Baker) tested in 1994. Ford's own version of the electric Ranger were given baseline performance tests in 1998 (Delphi VRLA batteries) and again in 1999 (Panasonic NiMH batteries.) We drop the Baker because it was unable to complete significant portions of baseline performance testing and failed a number of minimum performance standards.

TABLE 4.2: MILES PER SINGLE CHARGE FOR SELECT VEHICLES

Year of test, Vehicle, and battery type	SCE Urban Pomona Loop[1,2]	SCE Freeway Pomona Loop[1,2]	Baseline SAE J1634[3,4]	Baseline, constant 60 mph[4]	Baseline, constant 45 mph[4]
1994 BAT Metro (Optima prototype Pb-A)			37.9	39.6	47.1
1994 BAT Metro (flooded Pb-A)			49.5	51.6	88.4
1994 Solectria Force (Metro) (sealed Pb-A)			45.4	26.6	49.5
1995 Solectria Force (Metro) (NiMH)			84.5	70.9	105.9
1994 US Electricar Prizm (sealed Pb-A)			45.9	41.5	59.3
1996 GM EV1 (Delco VRLA)			78.2	89.1	135.2
1997 GM EV1 (Delco VRLA)	60.1 – 80.1	74.1 – 90.5			
1998 EV1 (NiMH)[5]			140.3	160.6	220.7
2000 EV1 (Panasonic VRLA)	72.6 – 90.3	91.8 – 113.6			
1994 Unique Mobility Ranger (Optima prototype Pb-A)			43.3	38.3	53.5
1994 Baker Ranger (flooded Pb-A)			21.1	44.0	55.4
1997 Ford Ranger (Pb-A)			65.1	57.9	86.9
1998 Ford Ranger (Pb-A)	58.3 – 72.1	51.6 – 66.4			
1999 Ford Ranger (NiMH)	62.7 – 80.6	68.8 – 76.5			
1999 Ford Ranger (NiMH)			82.4	74.2	115
1994 US Electricar S-10 (sealed Pb-A)			68.6	47.3	70.7
1997 GM S-10 (Delphi VRLA)	30.3 – 42.7	37.0 – 40.6			
1997 GM S-10 (Delphi VRLA)			43.8	38.8	60.4
1999 GM S-10 (Delphi VRLA)[6]	36.4 – 49.9	42.6 – 57.2			
1998 GM S-10 (NiMH)	60.4 – 70.4	73.1 – 84.2			
1998 GM S-10 (NiMH)			95.3	87.7	130.6

Table continues on next page.

TABLE 4.2: MILES PER SINGLE CHARGE FOR SELECT VEHICLES, CONTINUED

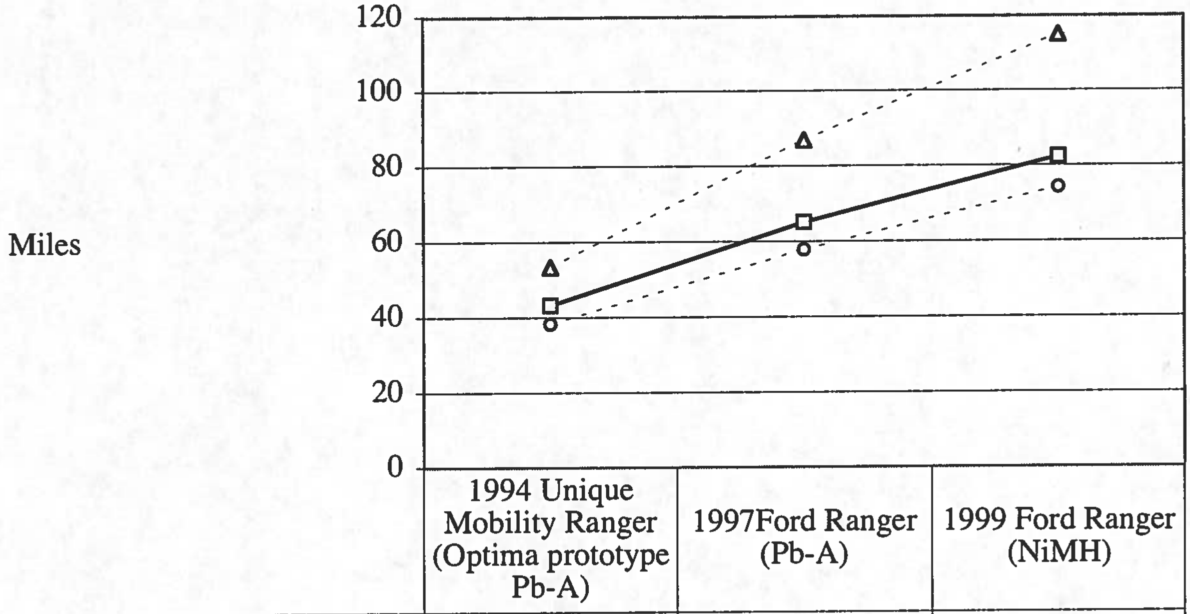
Year of test, Vehicle, and battery type	SCE Urban Pomona Loop[1,2]	SCE Freeway Pomona Loop[1,2]	Baseline SAE J1634[3,4]	Baseline, constant 60 mph[4]	Baseline, constant 45 mph[4]
1996 Toyota RAV4 (VRLA)			68.2	54.7	81.7
1998 Toyota RAV4 (NiMH)			94.0	86.9	110.9
1999 Toyota RAV4 (NiMH) Inductive	68.9 – 92.8	75.3 – 79.9			
1999 Toyota RAV4 (NiMH) Conductive	72.3 – 93.0	74.6 – 82.3			
999 Chrysler Epic (Pb-A)	46.2 – 58.6	54.7 – 60.8			
1999 Chrysler Epic (NiMH)	63.6 – 82.0	68.6 – 99.3			
1999 Chrysler Epic (NiMH)			79.1	81.2	116.1
1994 Honda CUV-4 (Pb-A)			66 (FUDS)		
1997 Honda EV Plus (NiMH)	81.7 – 105.3	78.8 – 90.6			
Nissan Altra (Li-Ion)	73.7 – 121.5	79.8 – 95.0			

Battery types: Pb-A—lead acid, configuration not specified; VRLA—valve regulated lead acid; NiMH—nickel metal hydride; Li-ion—Lithium ion.

1. First number is with auxiliary loads (air conditioning, lights, and radio) and maximum rated payload; second number is with no auxiliary loads and driver only. The Urban Pomona Loop is approximately 20 miles in length. It consists entirely of local streets. It contains approximately 50 stops signs and lights. The elevation difference between the lowest and highest points is approximately 600 feet. The Freeway Pomona Loop is approximately 37 miles in length, and consists almost entirely of urban freeways. The elevation difference between the lowest and highest point is approximately 400 feet. Further details are available in Argueta *et al*, 1999.
2. Southern California Edison, Vehicle Performance Characterization Summaries. Available at http://ev.inel.gov/sop
3. Baseline Test Results. Available at http://ev.inel.gov/sop. Data are for ambient temperature of 77°F.
4. The SAE J1634 test is performed on a dynamometer. The test cycle is a combination of the Urban Dynamometer Drive Schedule (UDDS) and the Highway Fuel Economy Driving Schedule (HFEDS). Other conditions include: no accessory loads, payload of 332 lbs., tires inflated to 50 psi, and ambient temperature equal to 77°F±9°F.
5. Same vehicle as tested by SCE in September 1997. Vehicle re-tested in February 2000 with new battery pack.
6. Same vehicle as tested in September 1997. Retest done in October 1999.

Range data for the 1994 Unique Mobility Ranger, the 1997 and 1999 Ford Ranger are plotted in Figure 4.1. These data show that for this vehicle, the general conclusion of Francfort *et al* (ibid.) that range approximately doubled between 1994 to 1999 holds true. The UM Ranger scored 43.3 miles on the drive cycle test in 1994; the Ford Ranger scored 82.4 miles in 1999. (We say "scored" rather than "drove" since these are dynamometer data.)

FIGURE 4.1: CHANGES IN DRIVING RANGE, ELECTRIC RANGER PICKUP TRUCK. BASELINE PERFORMANCE DATA.



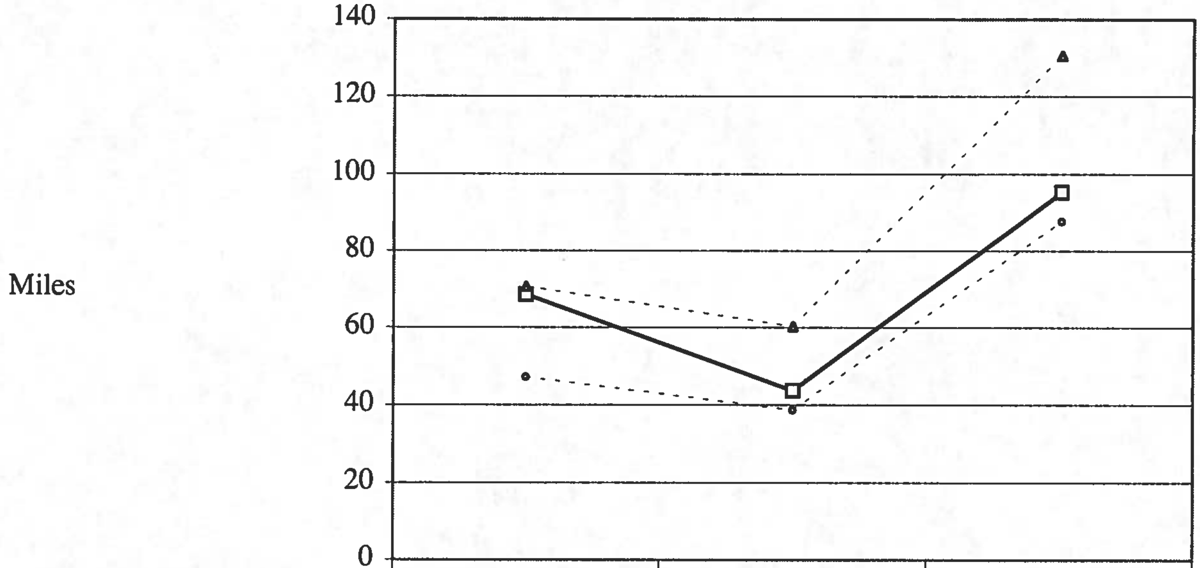
	1994 Unique Mobility Ranger (Optima prototype Pb-A)	1997Ford Ranger (Pb-A)	1999 Ford Ranger (NiMH)
—□— SAE J1634	43.3	65.1	82.4
- - -○ - - Constant 60 mph	38.3	57.9	74.2
- - -△ - - Constant 45 mph	53.5	86.9	115

Source: USDOE, OTT, Field Operation Program, Baseline Performance. http://ev2.inel.gov/sop

But the range improvements from 1994 to 1999 are actually even larger. There were important qualitative and quantitative differences between the performances of the UM and Ford vehicles. Note that even the Ford vehicle with lead-acid batteries scored about 50 percent better than the UM truck. Further, the UM truck was tested with a payload of only 111 lbs. This is 539 lbs. lighter than that required by the testing guidelines. The 43.3 mile score on the drive cycle test does not meet the minimum performance criteria established by the FOP. Finally, the UM vehicle required nearly 11 hours to recharge, again failing to meet a performance criteria. The Ford vehicles met all performance criteria, including significantly larger payloads (669 lbs. in 1997 and 1,206 lbs. in 1999). If tested with payloads as light as that in the UM truck, the Ford trucks would have scored even higher ranges.

In Figure 4.2 we examine the performance of variety of S-10 pickup trucks. The truck tested in 1994 was built by U.S. Electricar (USE). GM products were tested in 1997 and 1998. In this case the measured range on the drive cycle increases by a factor of only about 1.5 between 1994 and 1998. Changes measured at a constant 45 and 60 mph do increase by a factor of 1.8. Part of the explanation for the lower apparent increase in range is the fact that the USE truck performed much better than did the UM truck. In fact the USE truck outperformed GM's 1997 vehicle. The USE truck was tested at a lower payload, but the difference was smaller than had been the case with the UM truck. The USE truck carried a payload of 538 lbs.; the 1997 GM S-10 carried 951 lbs. The USE truck also failed to meet the performance criteria for recharging time—taking nearly twice as long as the 8 hour time limit to recharge.

FIGURE 4.2: CHANGES IN DRIVING RANGE, ELECTRIC S-10 PICKUP TRUCK



	1994 US Electricar S-10 (Hawker sealed Pb-A)	1997 GM S-10 (Delco VRLA)	1998 GM S-10 (Ovonic NiMH)
—□— SAE J1634	68.6	43.8	95.3
- - -●- - Constant 60 mph	47.3	38.8	87.7
- - -▲- - Constant 45 mph	70.7	60.4	130.6

Source: USDOE, OTT, Field Operation Program, Baseline Performance. http://ev2.inel.gov/sop

Three S-10 trucks equipped with Delco VRLA batteries were part of the Accelerated Reliability testing program of the FOP. Results are reported in Francfort *et al,* (1999). As part of the Accelerated Reliability testing, the trucks were periodically evaluated on the Pomona Urban Loop. The average distance traveled by each vehicle over all of its tests were 36.3, 34.7, and 37.8 miles. (Range data from the tests were interpreted from charts showing miles per test) Differences between these values are not statistically significant. Thus on average this small sample of the electric S-10 truck could travel about 35 miles on the Pomona Urban Loop. The author's do report that temperature had a large effect on range, citing differences of 10 miles driving range between cool and warm conditions (ibid.). In fact, the range of distances across all vehicles and all tests spanned 14 (yes, fourteen) to 48 miles.

Other vehicles tested in the FOP more than once include GM's EV1, Toyota's RAV4, Chrysler's EPIC, and Solectria's Force. Each of these vehicles was tested twice. The data are included in Table 4.2 above. In each case the single greatest difference between each pair of vehicles was the battery. Examples were first tested with lead–acid batteries; one to two years later examples were tested with NiMH batteries.

- In the case of both the Force and the EV1, range scores on the SAE J1634 drive cycle increased by a factor of 1.8 between the earlier models equipped with lead-acid battery models and later models with NiMH batteries.
- In the case of the RAV4, range increased by a factor of 1.4 in going from the lead-acid to NiMH battery.
- And in the case of the EPIC, urban range increased 40 percent, and freeway range between 30 and 60 percent, depending on auxiliary equipment loads and payload.

Possible Determinants of Changes in Range over Time of Vehicles with NiMH Batteries

As regards the RAV4, this vehicle was part of the USDOE's Field Operations Program Accelerated Reliability testing. Three NiMH-equipped RAV4s were tested by SCE. The testing guidelines call for vehicles to accumulate 25,000 miles in one year. These three vehicles had accumulated 20,060, 24,560, and 25,643 miles respectively. During the test year all three vehicles were occasionally tested on the Pomona Urban Loop, under condition UR1—minimum payload and no auxiliary loads. Range data from these tests are reported in Francfort *et al*, (2000a). Two vehicles were tested five times over the period of one year; one was tested four times.

All three vehicles were driven an average of 96.0 miles on these tests; standard deviation was 6.4; minimum range was 87.5; maximum was 107.5 miles. Statistical analysis shows that the mean range of each of the three vehicles were not different from each other at better than $\alpha = 0.05$. The authors report that anecdotal evidence suggested that driving range declined with time (ibid.), or perhaps more accurately, with a combination of time, charge/discharge cycles, and miles. The variables available in the data that could explain differences in range are vehicle, test sequence, and ambient temperature. Multiple regression reveals that only ambient temperature is significantly associated with range on these tests—higher ambient temperature (with in the range of 58 to 85°F) was associated with increased range. This analysis also fails to find a difference between vehicles. The test sequence, as a proxy for the passage of time and accumulation of charge/discharge cycles and miles, is not statistically related to changes in miles driven on these UR1 tests on the Pomona Urban Loop.

Empirical testing subsequent to the Accelerated Reliability testing suggests that the pattern of charge/discharge cycles may explain range deterioration. Frequent shallow charge/discharge cycles may decrease available range, which appears to be recovered with even one deep discharge/charge cycle (ibid.).

Is the Switch to NiMH Batteries the Big Difference in Range?

One of the consistent differences between the vehicles offered by the OEMs during the MOA period is the eventual switch from lead-acid to NiMH batteries. This is to be expected given the terms of the MOAs. The automobile makers only earned credit toward meeting their MOAs if they used batteries with higher specific energy than typically available from lead-acid batteries. (Solectria is not subject to an MOA).

Data for the EV1 does allow an interesting comparison between switching from lead-acid to NiMH vs. simply switching to a better lead-acid battery. Unfortunately, a precise comparison is not possible based on the Baseline Performance data. An EV1 with the Panasonic lead-acid battery has not been tested. And in the case of the Pomona Loop data, an EV1 with the NiMH batteries has not been tested. (Further, even if these vehicles were available, they have Generation II drive trains in addition to different batteries.) We take two approaches. The first is to match test conditions between the Baseline Performance testing and the Pomona Loop data. The second is to use all the Pomona Loop data, and control statistically for differences in the test conditions. The Pomona Loop data for the EV1 are shown in Table 4.3.

First, the SAE J1634 drive cycle used in the Baseline Performance tests stipulates that auxiliary loads should be off. The payload for the EV1 in the Baseline Performance tests was 440 lbs. These two conditions closely correspond to the Pomona Urban Loop UR3 and the Pomona Freeway Loop FW3 test conditions. SAE J1634 stipulates that ambient temperature should be 77°±9°F. This temperature range was satisfied for three of four data points—UR3 and FW3 for the Delphi equipped vehicle and UR3 for the Panasonic equipped vehicle. The temperature was only one degree too cool for the day the FW3 test was made with the Delphi-equipped vehicle.

TABLE 4.3: POMONA LOOP DATA FOR THE EV1

	Delphi Pb-A battery			Panasonic Pb-A battery		
Test	Payload, lbs.	Ambient Temp., °F	**Range, miles**	Payload, lbs.	Ambient Temp., °F	**Range, miles**
UR1	185	79	**80.1**	185	65	**90.3**
UR2	185	76	**64.7**	185	72	**79.7**
UR3	460	73	**74.8**	447	70	**88.9**
UR4	460	78	**60.1**	447	71	**72.6**
FW1	195	80	**90.5**	185	64	**113.6**
FW2	195	91	**77.9**	185	78	**105.6**
FW3	460	82	**83.2**	447	67	**112.1**
FW4	460	82	**74.1**	447	72	**91.8**

Source: USDOE, OTT, Field Operation Program. http://ev2.inel.gov/sop

Test Key:
UR/FW—urban or freeway loop
1—minimum payload, no auxiliary loads
2—minimum payload, A/C on High, Headlights on Low, Radio On
3—maximum payload, no auxiliary loads
4—maximum payload, A/C on High, Headlights on Low, Radio On

- Comparing the two vehicles for the cases of UR3 and FW3, the Panasonic battery vehicle traveled 19 percent further than the Delphi battery vehicle on the urban loop and 35 percent further on the freeway loop.

The second approach is to use all the Pomona Loop data, and test for the differences in range that are due to each of the four sets of factors—battery type, payload, auxiliary loads, and urban vs. freeway loop. Details of the analysis of variance are contained in Appendix B.

- The results indicate that, averaged over all other factors (in the data set), the Panasonic battery added about 18.7 miles of range per battery charge. This is about 25 percent more than the range provided by the Delphi battery.

The changes in miles per charge between 1994 and today have been dramatic. For some types of vehicles, the distance that can be driven per single, full charge has doubled. Some of this has been accomplished through changes is batteries, some through changes in power train designs. Battery changes have included both the switch from lead-acid to NiMH batteries and in at least one case, a switch to an improved lead-acid battery. And while Ford's greatly improved range in its Ranger indicates it may have done a better job of design and integration than an earlier attempt by Unique Mobility, the performance of the USE S-10 and the Solectria Force indicate that these earlier EVs set high standards for the automotive OEMs to beat.

RELIABILITY

Battery Cycle Life

Next to the development of fast charging, we regard the second most important development in EV technology during the 1990s has been the improved reliability of batteries. It is clear to many engineers that electric drive trains—motors and control electronics—will be inherently more reliable than gasoline vehicles. Batteries had been less reliable, but recent advances point to battery design, manufacturing experience, and quality control as the cause of past poor performance. Combinations of improved quality control, much more sophisticated battery monitoring/charging, and thermal management of batteries are extending the life of batteries beyond expectations of the early 1990s. Both charging and discharging can now be brought under computer control to monitor temperature levels, individual battery cell and module performance, and other parameters affecting battery life. These advances are leading to increased cycle life.

At the close of the 1990s, NiMH batteries have proven themselves to be reliable. This is a battery technology that was not even an acknowledged contender for EV applications in 1990. Initial excitement grew around NiMH batteries when bench tests from the early 1990s demonstrated a life of 400 cycles at 80 percent depth of discharge. Now, manufacturers have shown a measured bench cycle life over 1,000 cycles. Some bench tests of NiMH show 1,500 cycle lives (VARTA). Toyota's RAV4 with NiMH packs have proven to be reliable, proving out the belief among EV developers that EVs are potentially more reliable than vehicles powered by internal combustion engines. Real world use is showing laboratory bench tests did not produce unreasonable expectations.

If NiMH battery technology appeared to come out of nowhere in the 1990s, then lead-acid battery technology is the one that refused to go away. After the disappointment surrounding the real-world performance of Electrosource's Horizon battery, and Delco's lead-acid battery in Generation I EV1's, many believed that lead-acid battery technology would be left behind. Thus, these same people have been surprised by the recently developed Panasonic VRLA battery series. This battery has been bench tested to at least 1,000 cycles (Hoshihara, 1999). In the early 1990s, most lead-acid batteries, regardless of design, would last only a few hundred cycles at best. The lead-acid battery industry goal for 1998 was 800 cycles.

The new Panasonic battery surpassed these barriers primarily it seems through high quality control in manufacturing. Together with small improvements in specific power, increased cycle life has pushed lead-acid battery technology back into the realm of practicality for some EVs. While this battery has yet to be around long enough to actually demonstrate its longevity in the real world, early reports from users are that the miles per charge is increased over other lead-acid batteries. This is due in part to the fact the battery is so reliable that it delivers consistent top range. We have heard reports from General Motors that one EV1 with this battery has logged over 50,0000 miles.

Results of USDOE's FOP Accelerated Reliability Testing

To date, final Accelerated Reliability Testing Final Reports have been filed on the Toyota RAV4 (NiMH) (Francfort *et al*, 2000) and the GM S-10 (lead-acid) (Francfort *et al*, 1999). We briefly summarize their conclusions regarding these two vehicles.

ETA offered these observations:

> "The S-10 vehicles tested by ETA have provided over 50,000 miles of service with minimal maintenance requirements and no breakdowns. With a reliable driving range of 40 miles in moderate ambient temperatures, proper mission selection and driver training for the S-10 is critical. However, in the appropriate mission, the S-10 has the potential to provide excellent performance and reliability. (Francfort *et al,* 1999)

SCE offered the following conclusions:

> "The S-10 Electric has acceleration, handling, and payload capabilities that match or exceed most electric vehicles currently on the market. The vehicle's driving qualities and the comfort of the driver are considered very good by most of those at SCE who have driven it. The problems SCE has experienced have been largely related to the Delphi 12 Volt battery modules. In that regard, GM has been diligently making an effort to replace battery packs of SCE's S-10s with more reliable and better performing lead-acid or nickel/metal-hydride batteries. Future lead-acid battery equipped S-10s will have Panasonic modules. SCE has found that these batteries are more reliable, and give at least 20 percent more range. With the new batteries, and a reliable range of over 50 miles, SCE can recommend more widespread use of the S-10 Electric." (ibid.)

As regards the Toyota RAV4, these vehicles' Accelerated Reliability testing took place solely at SCE in Los Angeles. The conclusions of the final report state:

> "The RAV4s proved to be very reliable and useful over the 1-year test period...At the conclusion of the reliability testing, all three vehicles remain in the same type of service and in good operating condition. As of March 2000, each of the three vehicles has been driven approximately 35,000 miles....as of this writing SCE has 245 RAV4 electric vehicles in its fleet, with almost 2 million miles driven. These vehicles are used in the daily operations of SCE to conduct company business. They have become an integral part of the SCE fleet, and their reliability is critical. The large number of RAV4 electric vehicles in the fleet attest to the faith SCE has in the vehicle to reliably complete company missions. This trust is a result of experience, as well as the knowledge obtained from the high-mileage Accelerated Reliability testing program." (Francfort *et al*, 2000)

These conclusions represent primarily fleet users' evaluations. They do confirm that the performance of the batteries was central to defining whether the vehicles were regarded as being reliable. We will return to the issue of battery thermal management raised in the comments from ETA regarding the S-10 later in this report.

EFFICIENCY: INITIAL PROGRESS, THEN POSSIBLE DECLINES

Efficiency is typically measured in two ways. Efficiency based on energy out of the battery is called "dc efficiency" (because the current out of the battery is direct current). In contrast, efficiency based on measuring energy flowing into the charger is known as "ac efficiency." The difference between these two numbers is a measure of energy losses through the recharging electronics and the battery. In the data reported in Table 4.4, both types of measures are reported. In particular, the Pomona Loop data are ac efficiencies; data from Baseline Performance testing are dc efficiencies. In neither case is any accounting is made for energy returned to the battery during regenerative braking—meaning the true value of efficiency—ac or dc—is not as good as the figures reported in Table 4.4.

- A combination of increased drive train efficiency and reduced vehicle weight has resulted in at least a doubling of overall vehicle efficiency since the 1970s.

While it typically took 0.50 kWh to travel one mile in an EV in the 1970s, less than 0.25 kWh/mile can be used today. The efficiency of the 1993 Ford Ecostar was reported to be 0.149 kWh_{dc}/mile (Quong *et al*,1994). While this seems an excellent value (and it was for its time), it should be noted that this figure is for the Urban Drive Schedule only, it is a dc efficiency measure (and therefore does not include losses through the charger or the battery), and that the Ecostar was equipped with a high-temperature sodium-sulfur battery. These batteries are very efficient, but it also takes energy to keep them hot. This thermal management energy is not included in the figure reported.

- The most efficient vehicle in these tests is GM's EV1. The EV1 with Panasonic VRLA batteries, minimum payload (185 lbs.) and no auxiliary loads was rated at 0.223 kW/mile on the Pomona Freeway Loop. On the Urban Loop, with its maximum payload (447 lbs.), the air conditioning on high, headlights on low, and the radio on, this vehicle achieved 0 .312 kW/mile.

As we did for miles per charge in the section on range above, we trace changes in efficiency through a select set of vehicles in this table. The vehicles are Ranger and S-10 pickup trucks. The dc efficiency data from the Baseline Performance testing are plotted in Figures 4.3 and 4.4. Lower scores indicate better efficiency.

- In Figure 4.3, we see that Ford's own Ranger showed improved efficiency over Unique Mobility's conversion on two of three tests—SAE J1634 drive cycle and constant 45mph. However, Ford shows no further improvement between the truck with lead-acid batteries and NiMH batteries.
- In Figure 4.4, we see that GM's own S-10 showed improved efficiency over U.S. Electricar's conversion on all three test cycles. As with Ford, there is little or no subsequent improvement in GM's truck.
- The vehicles built by Solectria early in the 1990s show better efficiency than all the OEMs vehicles built throughout the 1990s except the EV1—and the Solectrias are very nearly as efficient as this vehicle. In fact, both the 1994 and 1995 Solectria Force's were measured to be more efficient than the EV1 with NiMH batteries on the SAE J1634 cycle; the NiMH EV1 scores higher than both Solectrias on the constant speed tests; and the lead-acid EV1 is somewhat more efficient on all tests.

TABLE 4.4: EFFICIENCIES OF EVS DEVELOPED IN THE 1990S, KWH/MILE

Test Year, Vehicle, and battery chemistry	SCE Urban Pomona Loop, kWh$_{ac}$/mile [1,2]	SCE Freeway Pomona Loop, kWh$_{ac}$/mile [1,2]	Baseline SAE J1634, kWh$_{dc}$/mile [3,4]	Baseline, const. 60 mph, kWh$_{dc}$/mile [4]	Baseline, const. 45 mph, kWh$_{dc}$/mile [4]
1993 Chrysler TEVan			0.313 (UDS)[5]		
1993 Ford Ecostar			0.149 (UDS)[5]		
1994 BAT Metro (Optima prototype Pb-A)			0.349	0.180	0.240
1994 BAT Metro (flooded Pb-A)			0.235	0.219	0.164
1994 Solectria Force (Metro) (sealed Pb-A)			0.145	0.199	0.171
1995 Solectria Force (Metro) (NiMH)			0.173	0.199	0.137
1994 US Electricar Prizm (sealed Pb-A)			0.260	0.282	0.209
1997 GM EV1 (Delco VRLA)			0.164	0.164	0.115
1997 GM EV1 (Delco VRLA)	0.304 – 0.281	0.291 – 0.240			
1998 EV1 (NiMH)[6]			0.179	0.168	0.127
2000 EV1 (Panasonic VRLA)	0.312 – 0.296	0.263 – 0.223			
1994 Unique Mobility Ranger (Optima prototype Pb-A)			0.427	0.299	0.332
1994 Baker Ranger (flooded Pb-A)			0.436	0.378	0.321
1998 Ford Ranger (Pb-A)			0.337	0.356	0.237
1998 Ford Ranger (Pb-A)	0.480 – 0.400	0.500 – 0.400			
1999 Ford Ranger (NiMH)	0.503 – 0.391	0.490 – 0.409			
1999 Ford Ranger (NiMH)			0.337	0.356	0.242
1994 US Electricar S-10 (sealed Pb-A)			0.304	0.404	0.296
1997 GM S-10 (Delphi VRLA)	0.668 – 0.396	0.433 – 0.475			
1997 GM S-10 (Delphi VRLA)[7]			0.292	0.307	0.215
1999 GM S-10 (Delphi VRLA)[8]	0.595 – 0.493	0.526 – 0.408			
1999 GM S-10 (NiMH)	0.850 – 0.780	0.790 – 0.690			
1998 GM S-10 (NiMH)			0.276	0.310	0.214

Table continues on next page.

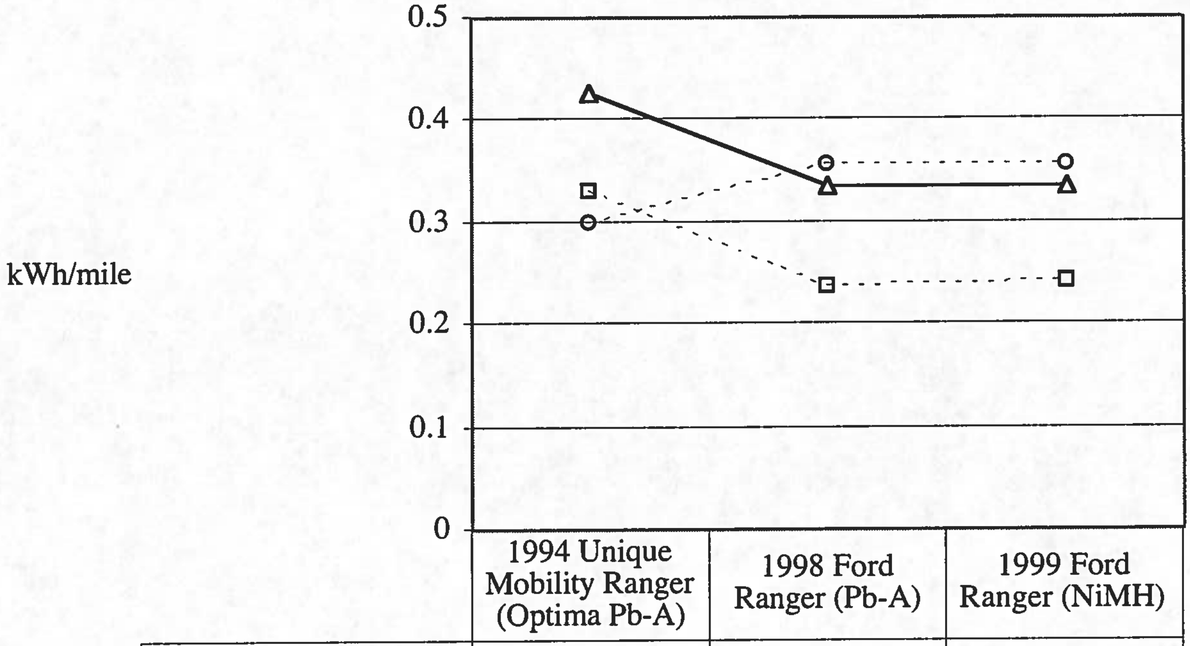
TABLE 4.4: EFFICIENCIES OF EVS DEVELOPED IN THE 1990S, CONTINUED

1996 Toyota RAV4 (VRLA)			0.235	0.289	0.198
1998 Toyota RAV4 (NiMH)			0.245	0.316	0.210
1999 Toyota RAV4 (NiMH), Inductive	0.434 – 0.329	0.418 – 0.404			
1999 Toyota RAV4 (NiMH), Conductive	0.436 – 0.355	0.410 – 0.374			
1999 Chrysler Epic (NiMH)	0.823 – 0.663	0.799 – 0.542			
1999 Chrysler Epic (NiMH)			0.372	0.340	0.245
1997 Honda EV Plus (NiMH)	0.550 – 0.380	0.560 – 0.450			
Nissan Altra (Li-Ion)	0.392 – 0.225	0.384 – 0.315			

Pb-A—lead acid, configuration not specified; VRLA—valve regulated lead acid; NiMH—nickel metal hydride; Li-ion—Lithium ion.

1. For the SCE data, energy is measured from the utility side of the recharger. Thus, these figures are "ac efficiency." First number is with auxiliary loads (air conditioning, lights, and radio) and maximum rated payload; second number is with no auxiliary loads and driver only. The Urban Pomona Loop is approximately 20 miles in length. It consists entirely of local streets. It contains approximately 50 stops signs and lights. The elevation difference between the lowest and highest points is approximately 600 feet. The Freeway Pomona Loop is approximately 37 miles in length, and consists almost entirely of urban freeways. The elevation difference between the lowest and highest point is approximately 400 feet. Further details are available in Argueta *et al*, 1999.
2. Southern California Edison, Vehicle Performance Characterization Summaries. Available at http://ev.inel.gov/sop
3. Baseline data are "dc efficiencies," that is, energy is measured out of the battery. Data are for ambient temperature of 77°F.
4. Baseline Performance Test Results. Available at http://ev.inel.gov/sop
5. Quong *et al* (1994). Vehicle tested during 1994 American Tour de Sol. Dynamometer test, Urban Drive Schedule (UDS) only.
6. Same vehicle as tested by SCE in September 1997. Vehicle re-tested in February 2000 with new battery pack.
7. Francfort *et al* (2000) report ac efficiency figures of 0.444 and 0.463 kWh_{AC}/mile respectively for two S-10 trucks in the FOP Accelerated Reliability Testing.
8. Retest of same vehicle as tested in September 1997 done in October 1999

FIGURE 4.3: CHANGES IN EFFICIENCY, ELECTRIC RANGER PICKUP TRUCK. BASELINE PERFORMANCE DATA.



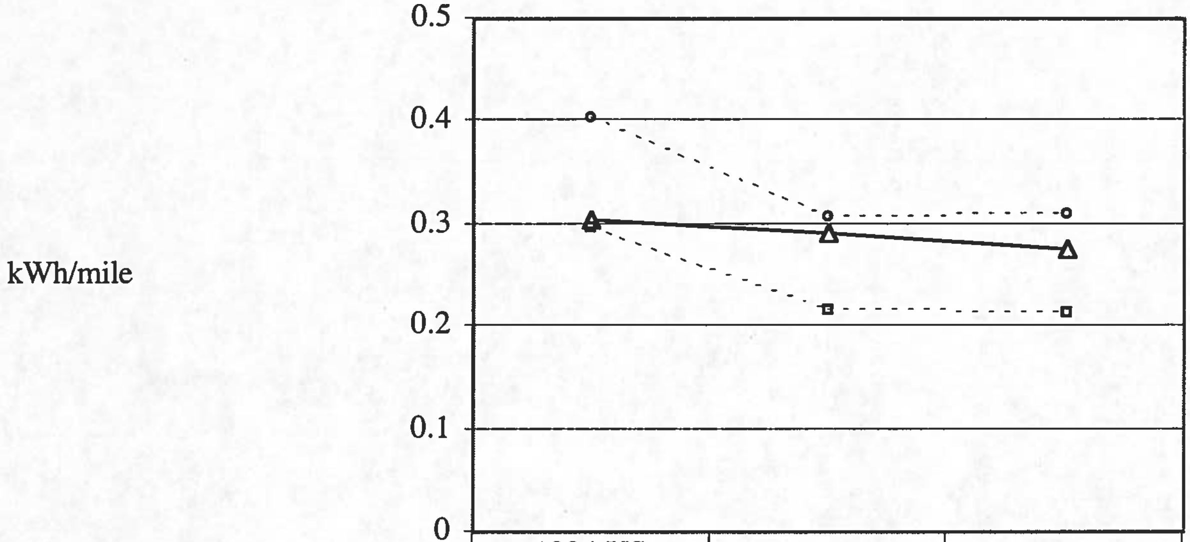
	1994 Unique Mobility Ranger (Optima Pb-A)	1998 Ford Ranger (Pb-A)	1999 Ford Ranger (NiMH)
—△—SAE J1634	0.427	0.337	0.337
- - ○ - - Constant 60 mph	0.299	0.356	0.356
- - □ - - Constant 45 mph	0.332	0.237	0.242

Source: USDOE, OTT, Field Operation Program, Baseline Performance. http://ev2.inel.gov/sop

Table 4.4 also shows that, in general, all the OEM vehicles equipped with NiMH batteries are less efficient—they consume more energy per mile of travel—than their immediate, lead-acid equipped, predecessors. This is apparent in both the Pomona Loop and Baseline Performance data. This result is expected since NiMH batteries are less efficient both during recharging and discharging than are lead-acid batteries. In addition to being less efficient, NiMH battery packs typically require active (read: energy consuming) thermal management during recharging in order to keep their temperature below damaging levels, especially on warm days. Thus, even if two vehicles are otherwise identical, the vehicle with NiMH batteries will be less efficient than one with lead-acid batteries.

Details of the analysis of variance of the Pomona Loop data for the Ranger and S-10 can be found in Appendix C. The analyses are summarized below in Table 4.5. These analyses (and those for the EV1 and EPIC also found in Appendix C) must be regarded as exploratory. There is only data for one example of each type of vehicle in each year. Results of the type of analysis discussed here would be more robust with data from a larger number of vehicles.

FIGURE 4.4: CHANGES IN EFFICIENCY, ELECTRIC S-10 PICKUP TRUCK. BASELINE PERFORMANCE DATA.



	1994 US Electricar S-10 (sealed Pb-A)	1997 GM S-10 (Delco VRLA)	1998 GM S-10 (NiMH)
—△—SAE J1634	0.304	0.292	0.276
- - -○- - - Constant 60 mph	0.404	0.307	0.31
- - -□- - - Constant 45 mph	0.296	0.215	0.214

Source: USDOE, OTT, Field Operation Program, Baseline Performance. http://ev2.inel.gov/sop

This analysis indicates that the Ford Ranger confounds the expectation that a vehicle equipped with a NiMH battery will be less efficient than an identical vehicle equipped with a lead-acid battery. Controlling for other factors in the data, the NiMH Ranger was not significantly less efficient than the lead-acid Ranger on the Pomona Loops. The analysis shows that payload and auxiliary loads affect efficiency, but averaged over all other test conditions (loop, payload, auxiliary loads) there was no measured difference in ac efficiency between the Ranger tested in 1998 with lead-acid batteries and the one tested in 1999 with NiMH batteries. Only payload and auxiliary loads affected the measured ac efficiency of the Ranger on the Pomona loops.

The S-10 on the other hand shows a dramatic decrease in efficiency in going from lead-acid to NiMH. Using the model results from Table 4.5, we calculate that energy consumption increased by between 48 and 73 percent, depending on test conditions. For the test in which the S-10 achieved its poorest efficiency (UR4: urban loop, maximum payload, auxiliary loads on) the truck equipped with NiMH batteries consumed 48 percent more energy per mile (again, where energy is measured at the utility side of the charger) than did the vehicle with lead-acid batteries. For the test in which the S-10 achieved its best efficiency (FW1: freeway, minimum payload, no auxiliary loads), the truck equipped with NiMH batteries consumed 73 percent more energy per mile.

TABLE 4.5: COMPARISON OF TEST DATA AND MODEL VALUES OF EFFICIENCY FROM POMONA LOOP DATA

Vehicle	Test Condition[1]	Battery	Test Data	Model Value[2]
Ford Ranger	FW1	Delphi Pb-A	0.400	0.408
		NiMH	0.409	0.405
	UR4	Delphi Pb-A	0.480	0.497
		NiMH	0.503	0.494
GM S-10	FW1	Delphi Pb-A	0.404	0.392*
		NiMH	0.475	0.677*
	UR4	Delphi Pb-A	0.538	0.597*
		NiMH	0.668	0.883*
GM EV1	FW1	Delphi Pb-A	0.240	0.227*
		NiMH	0.223	0.240*
	UR4	Delphi Pb-A	0.304	0.306*
		NiMH	0.312	0.319*
Chrysler EPIC	FW1	Pb-A	0.520	0.502
		NiMH	0.542	0.568
	UR4	Pb-A	0.720	0.744
		NiMH	0.823	0.810

1. All vehicles scored highest on efficiency for test condition FW1, and lowest on UR4. For definitions of test conditions, see notes at bottom of Table 4.3.

2. Model is an analysis of variance on efficiency with one-way effects of battery type, driving loop, auxiliary loads, and payload.

* Differences between battery types significant at better than 0.05 probability.

These modeled differences are far greater than the observed differences. This may mean there are interaction effects between factors that we are unable to model with the current data, or that the data themselves contain random variation that would tend to be minimized if a larger number of vehicles were tested. The S-10's ac efficiency also varied according to whether it was driven on the urban or freeway loop, and whether auxiliary loads were on or off.

The switch from Delphi VRLA to Panasonic VRLA batteries in the EV1 had no statistically significant effect on ac efficiency. Whether the EV1 was driven on the urban or freeway loop did have an affect—the vehicle is more efficient on the freeway loop. Also, the auxiliary loads represented by running the air conditioning on high, the headlights on low, and the radio on significantly decreased the efficiency of the vehicle. Payload appears to have little affect. Details are in Appendix C. These results are similar to those reported by Mendoza and Argueta (ibid.), though the methods of comparing results across tests differ.

The switch from VRLA to NiMH batteries caused a statistically significant decrease in the ac efficiency of the Chrysler EPIC. However, auxiliary loads and driving speeds had an even greater effect. For example, the NiMH EPIC driven on the FW1 test (freeway loop, no auxiliary loads, minimum payload) was more efficient than the lead-acid EPIC driven on all of the urban tests, but none of the freeway. Further, the EPIC was one of two vehicles for which increased payload reduced efficiency (the other being the Ford Ranger). We also note that the 1993 Chrysler TEVan tested during the 1994 American Tour de Sol compares quite favorably to the 1999 Chrysler EPIC. The comparison is inexact to be sure since the drive cycles are different, batteries are different, and drive trains are different. But the technology differences would seem to be the point. As a complete package, whatever performance measures improved between the TEVan and the EPIC, efficiency does not appear to be one of them.

In conclusion, significant progress in EV efficiency was accomplished early in the 1990s. But little progress has been made since then in vehicles from the large OEM manufacturers who were signatories to MOAs. In fact, there is some evidence to indicate that while they have held vehicle bodies and chassis designs constant since 1996, efficiencies of their vehicles have declined as they substituted less efficient NiMH batteries for lead-acid.

In contrast, small EV manufacturers appear to have accomplished more. In 1996, a Honda Civic hatchback converted to electric drive by AC Propulsion set a range record of 145 miles over the Pomona Urban Loop. Consumption over the range test was 0.126 kWh/mile, the equivalent of 266 miles per gallon. AC Propulsion claims no other EV, including advanced prototypes from major automakers, has matched this level of efficiency. Recall also that Solectria's conversions of Geo Metros in the early 1990s have bested all products of the large OEMs built later in the decade, with the exception of the EV1 equipped with lead-acid batteries.

However, these results are based on test results for single examples of each type (make, manufacturer, and battery) of vehicle. [1] The data are also somewhat ambiguous as to what conditions—speed, payload, auxiliary loads, ambient temperature, battery type, etc.—have the greatest affect on efficiency. Given the available data, all factors cannot be tested for all vehicles, all factors cannot be analyzed simultaneously, nor can all interactions between factors be tested. Comparing the test data itself limits the general aspects of the results; our statistical results are slightly more generalizable as different factors can be controlled in examining the effects of any one factor. However, either approach is severely limited by the fact that data exists for only one example of each vehicle.

ACCELERATION AND TOP SPEED

EV users and designers have been familiar for years with how dc electric motors offered peppy, fun acceleration at lower speeds. However, dc motors in the past had been used in lower voltage systems and with crude chopper power control. Battery packs were limited in the total amount of power they could provide and motors operated over more limited rpm range. Thus, acceleration at higher speeds was poor and overall top speeds were limited. Many pre-ZEV vehicles had top speeds of 50-60 miles per hour, or less (see the discussion in the Introduction of the most popular EVs of the 1970s and 1980s). Wakefield (1993) cites few examples of published acceleration figures up to even 50 mph for EVs built prior to 1990. Some examples are shown in Table 4.6, along with more contemporary performance marks. Acceleration times and top speeds are reported

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[1] A small amount of data from the Baseline Performance testing suggests that variation between specific examples of the same vehicle may not be a large source of variation. We reported above that average distance covered by three Toyota RAV4 vehicles on the Pomona Urban Loop (under conditions UR1) were statistically equivalent. A similar result is found for three different examples of electric S-10s.

at 100 percent state of charge unless otherwise indicated. Vehicles tend to be both quicker and faster when batteries are fully charged.

The GM Impact introduced the world to the potential of high performance ac drive trains, which offer a wider range of motor speeds and excellent acceleration across a wide range of speeds. High voltage, solid state power electronics, especially inverters to convert dc current to ac current (and back) that were not widely available in the 1980s. Even the power electronics in the GM Impact were hand-made—reportedly containing over 9,000 hand-soldered connections. The Impact 1 had two 57 hp motors (for a total of 114 hp), one at each front wheel. It accelerated from 0 to 60 miles per hour (mph) in 8 seconds.

There were improvements in subsequent generations of the Impact. The Impact 3, a more consumer oriented product accelerated from 0 to 60 mph in 8.5 seconds, despite weighing 30 percent more than the Impact 1. The Impact 3 laid to rest images of EVs as low speed vehicles when in 1994 a modified Impact set a new speed record for EVs at 183 mph. The next year, in May 1995, the Italians took the title away with a clocked speed of 188.9 mph in a ZEV Bertone (Turrentine and Kurani, 1996).

The GM EV1 now contains a second generation drive train. There is now one102kW, three-phase, ac induction motor. The vehicle is considerably heavier than was the Impact. Still, GM claims a 0 to 60mph acceleration time of "less than 9 seconds." (www.gmev.com/specs) The EV1 recorded a 6.3 second 0 to 50mph time in FOP Baseline Performance testing.

Other OEM automotive manufacturers have also made improvements in the acceleration capabilities of their vehicles, although none seem to be pursuing the power in the GM and AC Propulsion designs.. GM's own 1997 S-10 truck cut the 0 to 50mph acceleration time of the U.S. Electricar S-10 conversion in half, from 18.7 seconds to 9.75 seconds. Improvement in the performance of the Ranger was even more dramatic in going from the conversion built by Unique Mobility to Ford's own vehicles. The 0 to 50mph acceleration time was cut from 30.9 seconds to 11.6 seconds, and then again to 10.3 seconds for the 1999 Ranger Electric. Toyota's 1998 RAV4 shows a modest improvement in acceleration over the 1995 model.

It should be noted that the top speed of modern EVs is generally electronically limited. As the top speed records for the Impact show, EVs can reach very high top speeds. The current world record holder for purpose-built, straight-line speed is the White Lightning. Using an AC Propulsion drive train, this vehicle posted a record 245.5 mph. The top speeds shown for vehicles after 1995 in general are a function of this self imposed limit, not of the capabilities of modern electronics and motors. The limit is generally imposed to allow for a single speed transmission at the current bandwidth in IGBT and other electronic controls..

In 1995, AC Propulsion's converted Honda Civic built accelerated from 0 to 60 mph in 6.2 seconds. Its ac induction drive train (motor and power electronics) delivers 200 hp and weighs only 190 lb. Its new t-zero accelerates to 60 mph in 4.1 seconds. While such performance may seem like an excessive goal, it is actually related to other more practical goals. High-voltage systems allow the vehicle to more effectively capture the high power created by regenerative braking and facilitates AC Propulsions' on-board level 2+ recharging.

The future of EVs acceleration, top speed and over all power is brighter still. Lighter platforms, higher power density drive trains, and higher voltage systems offer even greater speeds—or more importantly—longer range and on-board, high power recharging.

TABLE 4.6: EV TOP SPEEDS AND ACCELERATION TIMES

Year	Make	Motor Type	Battery Type, Traction Voltage	Top Speed, mph[1]	Acceleration to Speed, seconds (interval)
~1970s[2]	Linear Alpha Thunderbolt (converted Ford Pinto)	Series wound dc	Pb-A, 108V	60	8 (0 to 30 mph)
1989[2]	Soleq Evcort	Separately excited dc	SLA, 108V		32.5 (0 to 55mph)
1990[2]	GM Impact	ac induction	recombinant Pb-A, 320V		8.0 (0 to 60 mph)
1993[2]	Ford Ecostar	ac induction	Sodium-sulfur,	70 – 75	12 (0 to 50mph)
1994[3]	Honda CUV4	dc brushless	SLA, 288V	80	19.1 (0 to 60 mph)
1994[4]	Solectria Force (converted Geo Metro)	ac induction	SLA 180V	70 @ 50% SOC	27.0 (0 to 60 mph @ 90% SOC)
1994[4]	Unique Mobility Pickup Truck (converted Ranger)	dc	SLA, 180V	70 @ 50% SOC	30.9 (0 to 50mph@ 90% SOC)
1994[4]	U.S. Electricar Pickup (converted Chevrolet S-10)	ac induction	SLA, 312V	71 @ 50% SOC	18.7 (0 to 50mph@ 90% SOC)
1995[4]	Solectria Force (converted Geo Metro)	ac induction	NiMH, 185V	69.9 @ 50% SOC at 1 mile	18.3 (0 to 50 mph @ 100% SOC)
1995[4]	Toyota RAV 4		VRLA, 288V	77.9 @ 50% SOC at 1 mile	13.2 (0 to 50 mph @ 100% SOC)
1995	AC Propulsion converted Honda Civic				6.2 (0 to 60mph)
1997[4]	GM S-10		VRLA, 312V	69.3 @ 50% SOC at 1 mile	9.75 (0 to 50 mph @ 100% SOC)

Table continued on next page.

TABLE 4.6: EV TOP SPEEDS AND ACCELERATION TIMES, CONTINUED

Year	Make	Motor Type	Battery Type, Traction Voltage	Top Speed, mph[1]	Acceleration, seconds (speed interval, SOC))
1997[4]	GM EV1	ac induction	VRLA, 312V	80.4 @ 50% SOC at 1 mile	6.3 (0 to 50 mph @ 100% SOC)
1998[4]	Ford Ranger	ac induction	VRLA, 312V	74.5 @ 50% SOC at 1 mile	11.6 (0 to 50 mph @ 100% SOC)
1998[4]	GM S-10		NiMH, 343V	71.0 @ 50% SOC at 1 mile	9.9 (0 to 50 mph @ 100% SOC)
1998[4]	Toyota RAV4	Permanent magnet dc	NiMH, 288V	78.8 @ 50% SOC at 1 mile	12.8 (0 to 50 mph @ 100% SOC)
1999[4]	DaimlerChrysler EPIC		NiMH, 336	78.1 @ 50% SOC at 1 mile	12.3 (0 to 50 mph @ 100% SOC)
1999[4]	Ford Ranger	ac induction	NiMH, 300V	74.6 @ 50% SOC at 1 mile	10.3 (0 to 50 mph @ 100% SOC)
1999[4]	Nissan Altra	Permanent magnet dc	Li-ion 345V	75 @ 100 and 20% SOC	15.56 (0 to 60 mph @100% SOC)
1999[4]	GMEV1	ac induction	Panasonic VRLA 312V	82 @ 100% SOC	8.04 (0 to 60 mph @ 100% SOC)
1999[4]	GMEV1	ac induction	NiMH, 343V	79.6 @ 50% SOC at 1 mile	6.3 (0 to 50 mph @ 100% SOC)
1998	AC Propulsion t-zero	ac induction	VRLA	90	4.1 (0 to 60 mph)

Note: Battery state of charge for acceleration test is assumed to be 100 percent where SOC not explicitly indicated.

0. The top speed of “modern,” mid- to late-1990s EVs is electronically governed to typically 80 mph or less in order to preserve energy to prolong range.

2. Wakefield (1993)

3. Suzuki and Mathison. 1994

4. USDOE, FOP Baseline Performance data. http://ev2.inel.gov/sop

Other sources include vehicle manufacturer specification sheets and web sites.

STANDARDS

Standard setting involves not only technology, but institutions. Regulatory agencies, regulated industries, consumer groups all play a role in defining standards. The expertise of engineers, technicians, designers, end-users, policymakers, and lawyers all are required for the successful definition and negotiation of meaningful and useful standards. The 1990s witnessed the revitalization of many institutions, the formation of new ones, and the undertaking of new standard setting activities by recognized standard setting agencies. We describe only a few here, along with the important standards they defined and implemented.

Energy Consumption, Range Testing and other Performance Measures

Test standards represent one of the positive steps forward for EVs and EV technology during the 1990s. Perhaps one of the greatest symbols and steps of the rapid improvements in electric vehicle performance in recent years is that in 1993, the Society of Automotive Engineers (SAE) issued a new standard for evaluating EVs. SAE J1634 is the definition of drive cycles and associated conditions under which range and energy consumption of electric vehicles are to be determined. This standard changed the driving test pattern for EVs to be comparable to that for ICEVs. Earlier EV driving tests had maximum speeds of 50 km/hr for EVs and moderate acceleration episodes. If they were conducted in any systematic manner, they tended to be based on the Federal Urban Drive Schedule (FUDS). This was due to the fact that in the 1970s and 1980s, a 70 km/hr top speed was considered fast for an EV.

The SAE driving test cycle is now the same for EVs and ICEVs. It includes both highway and urban driving conditions based on the Highway Fuel Economy Driving Schedule (HFEDS) and the Urban Dynamometer Driving Schedule (UDDS). Further test condition stipulations include an ambient temperature of 77°F±9°F and no accessory loads. Recharging conditions are stipulated, as well as conditions for measuring energy consumption, and other performance parameters.

Safety

All EVs built by the major automobile OEMs are subject to nearly identical sets of safety standards as are conventional vehicles. The Federal Motor Vehicle Safety Standards for EVs are different from those for conventional vehicles only in the details, not in the overall level of safety. For example, there are additional standards regarding the protection of occupants from electrical hazards. On the other hand, there is no need to apply standards intended to protect occupants from the hazards of gasoline. Overall, the crash protection standards are the same.

Many safety issues were explored early in the 1990s under the auspices of the Infrastructure Working Council (IWC), the Electric Power Research Institute (EPRI), the USDOE's EV Environmental, Health, and Safety Program (see for example Hammel and Hunt, 1994; and Hunt, 1996). Batteries in particular were the subjects of a series of reports on environmental, health, and safety considerations.

In 1997 the International Center for Technology Assessment released their comparative analysis of environmental and safety issues, regulations and programs for EVs and conventional vehicles (ICTA, 1997). The analysis examined eleven major areas: 1) fire; 2) steam burns; 3) heat burns; 4) chemical burns; 5) refueling; 6) electric shock; 7) collision; 8) rollover; 9) toxic fumes; 10) noise; and, 11) manufacturing defects. Further, they specifically examined battery issues such as hydrogen gassing, electrolyte spillage, electric shock, and toxic fumes. CTA reported that all four of these areas had either been grossly exaggerated as a concern and/or thoroughly addressed by safety organizations. Overall, CTA rated EVs as safer than gasoline vehicles in nine of the eleven categories, and equal to gasoline cars in collision and electric shock.

Charging

SAE has also implemented two recharging standards, as discussed above. Standards 1772 and 1773 relate to conductive and inductive recharging systems, respectively. These standards come out of the work of the Infrastructure Working Council. As a further step toward safety certification, charging equipment manufacturers proudly display the Underwriters Laboratories certification for equipment that has been UL listed.

Performance testing standards, safety standards for vehicles and recharging are all products of efforts that have come to fruition since 1990.

5. IMPROVEMENTS IN SYSTEM COMPONENTS

PATENTS BY TOPICAL AREA

As a general index of inventive and innovative activity within specific technology areas we show EV-related patents granted between 1980 and the present (actually, June 20, 2000) by the US Patent and Trademark Office in Table 5.1. We've classified patents according to broad technology areas. The table shows the total number of patents within these areas granted from 1980 to 1990 and from 1991 to the present.

Only in the case of vehicle designs—generalized, and sometimes ornamental, descriptions of overall vehicles—were more patents issued in the 11 years from 1980 through 1990 than were issued in the almost 10 years since the ZEV production requirement was announced. In general though, three to ten times as many patents were granted in each technology area since the production requirement than had been in the previous eleven years.

TABLE 5.1: EV-RELATED U.S. PATENTS BY TOPICAL AREA, JANUARY 1, 1980 TO JUNE 20, 2000

Technology Area:	January 1, 1980 to December 31, 1990	January 1, 1991 to June 20, 2000
Controller/Power Electronics	41	137
Motors	8	25
Drive Train	16	45
Battery	17	40
Charging	8	116
Battery Management	4	36
Battery/SOC Instrumentation	3	39
Vehicle Design	8	7
Regenerative Braking	3	31
HEV/FCEV	2	58
HVAC	2	37
Battery Swapping/Replacement	0	22
Other	40	72

EV DRIVE SYSTEMS

Most commercially available electric vehicles in the 1970s and early 1980s were slow and unreliable. Most of these vehicles had dc motors rated at 10 to 50hp peak and used chopper motor controllers. The power electronics were not designed specifically for electric vehicles and were combined in less than optimal systems. There were a few ac drive trains in test vehicles and prototypes, but the electronics in these vehicles were quite expensive, in part because the system voltages were up to three times higher than previous EV systems. Wakefield (1993) credits both

Ford and GM with developing vastly improved ac drive trains prior to the announcement of California's ZEV production requirement—drive trains that allow electric vehicles to accelerate and cruise as fast as their conventional gasoline competition.

It is only since the production requirement that the prospect of mass production of these systems promises to make them affordable. They will be essentially maintenance free, weigh between 100 and 200 lb. And last the life of the vehicle. In 1990, there were only a few of these integrated ac power systems in vehicles. Today, ac drive trains are available in limited production from several companies including AC Propulsion, Wavedriver, General Electric, Hughes Dolphin Drives, Solectria, Motorola and Westinghouse. The Westinghouse system is modular, allowing for systems with different voltages. These modular power systems can be built for applications ranging from small electric vehicles to large buses. Compared to the scattered prototypes of ac drive trains available in 1990, in 1995 there were as many as 1,000 high power ac drive trains in use.

Drive systems, including drive line layouts, motors, controllers and other aspects of power electronics have been the largest area of inventive and innovative activity, as measured by U.S. patents. Since the beginning of 1991, 137 patents have been granted to inventions in the area of control and power electronics; 25 to motors; and 45 to drive train designs and components. These exclude those patents in these areas that were granted specifically to hybrid or fuel cell EVs.

Today there are not only ac induction motors in EVs, but also several dc drive trains which use brushless permanent magnet motors (BPM). As shown in Table 4.6 in the previous chapter, both the Toyota RAV4 and the Nissan Altra utilize dc permanent magnet motors. Because of their higher power density, dc brushless permanent magnet motors are also being used in hybrid EV designs. This is an area of development that appears to be directly linked to the ZEV production requirement. At least seven drive train engineers with whom we talked, or who filled out our questionnaire in 1995, agreed that the production requirement lead directly to the decisions to develop these new drive trains. Development programs, especially those in GM, AC Propulsion, and General Electric have resulted in reductions in size, complexity, volume, weight, and cost.

TABLE 5.2: VOLUME AND POWER DENSITY OF DRIVE TRAINS

Vehicle	Volume, liters	Power density kW/ liter
Honda EV Plus	177	0.28
GM Generation I	152	0.66
GM Generation II	(na)	(na)
Ford Ranger	143	0.47
Toyota RAV4	163	0.38
AC Propulsion Generation 1	128	1.17
AC Propulsion Generation 2	111	1.35

Source: AC Propulsion.

The voltage of these systems continues to increase. In Table 5.3 we show nominal battery pack voltage as a proxy for system voltage. Higher battery pack voltages allow for higher power motors. Higher power motors mean not only faster acceleration but also more efficient recovery of the high power energy created by regenerative braking. Early ac systems were limited to much lower voltage (and thus, power), primarily because of limitations on power electronics.[2]

TABLE 5.3: NOMINAL BATTERY PACK VOLTAGE INCREASES FOR DRIVE SYSTEMS

Vehicle	Nominal Battery Pack Voltage	Motor type
1968 Linear Alpha[1]	144	ac induction
1988 General Electric ETX-1[1]	192	ac induction
1988 Nissan ac drive[1]	130	ac permanent magnet, synchronous
1988 Toyota EV 30	106	ac induction
1990 GM EV1	320	ac induction
1994 Honda CUV4	288	BPM
1996 RAV 4 Pb-A	288	BPM
1996 Chrysler EPIC Pb-A	324	ac induction
1998 Toyota RAV 4 PbA	288	BPM
1998 Honda EV Plus	288	BPM
1998 Toyota RAV 4 NiMH	288	BPM
1998 Ford Ranger Pb-A	312	ac induction
1999 Ford Ranger NiMH	300	ac induction
1999 Nissan Altra Li-ion	345	BPM
1999 EPIC NiMH Saft	336	ac induction
1999 EV1 PbA (Panasonic)	313	ac induction
1999 EV1 NiMH	343	ac induction

Sources: Except where noted, all data are taken from specifications published by either the manufacturers or the USDOE FOP.

1. Wakefield 1993

RELIABILITY OF DRIVE TRAINS

Based mostly on experience with industrial motors and controllers, it has been expected by many engineers that electric vehicle drive systems should be very durable and maintenance on such systems should be quite low. Westinghouse advertises that its drive trains are maintenance free for 100,000 miles. One engineer from Westinghouse notes that the reliability of power controllers has increased ten times in five years while the price has dropped several times for the integrated circuits used in them.

This expectation has been born out in several of the test programs for electric fleet vehicles. After more than 3 million test miles on its fleet of EVs, Southern California Edison reports 4 percent

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[2] Battery pack voltage and the system voltage rating are not identical, but are highly correlated. For example, the 1990 GM EV1 had a battery pack nominal voltage of 320 volts and the power electronics were rated at 400 volts. (Wakefield, 1993). We use battery pack voltage because the electronics system voltage rating is not as commonly reported, especially for older vehicles.

drive train problems on a very diverse fleet of EVs. In particular, the fleet of 244 Toyota RAV4s proved extremely reliable, while accumulating 1,530,100 miles of use (Wehrey 1999).

POWER ELECTRONICS

A revolution has occurred in power electronics to control EV and other industrial motors in the past five years. The price, size, and efficiency of the solid state electronics to invert and control the direct current out of batteries to alternating current for the ac motor has improved by as much as a factor of four in the last five years alone. For example, the original Impact contained 280 metal oxide semi-conductor field effect transistor (MOSFET) circuits in its controller, itself an enormous improvement over previous silicon rectifiers. Those 280 MOSFETs have were replaced by 60 IGBTs (Integrated Gate-Bipolar Transistors) in the Impact 3.[3] In the Generation II drive train for the EV1 dual IGBTs were used to reduce further the complexity of the device (www.gmev.com). IGBTs allow a 400 percent increase in bandwidth and cost reduction from $1/kW to $0.1/kW. The importance of the decrease in price is clear. Approximately 2/3 cost of motor controllers for ac system and about 1/2 the cost of motor controllers for BPM systems is the IGBTs. IGBT silicon costs are expected to drop 20 percent further over the next two to three years (Lipman, 1999). The increase in bandwidth relates to increased ranges of motor speed. The increased bandwidth of power electronics is one of the improvements that have allowed EV builders to dispense with transmissions and create a single speed system.

TABLE 5.4: REDUCTIONS IN POWER ELECTRONICS SIZE AND PRICE FOR GM IMPACT AND EV1

Vehicle	Drive train	Inverter	Price/ volume reduction
I990 Impact 1		280 MOSFETs[1]	
1994 Impact 3	GM Generation 0		
1997 EV1	GM Generation I	60 IGBTs[1] (6 IGBT modules)	
1999 EV1`	GM Generation II	30 IGBTs (3 dual-IGBT modules)	• 50% of volume • 50% of cost • 33% of # of parts. • Power electronic unit 40% smaller than Generation I[2]
2000+ Triax, Precept	GM Generation III		Power electronics 1/3 of Generation II[2]

1. Interview with Alan Cocconi, 1995

2. GM Press releases

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[3] Several sources indicated there were only 6, not 60, IGBTs in the new AC power electronics of the Impact 3. In talks with the power electronics designer of the Impact 1 though, we learned that a single circuit board typically has 10 separate IGBTs attached to it, and there are typically 6 such circuit boards in the power electronics system. Thus the comparison is 60 IGBTs to 280 MOSFETS. Interview with Alan Cocconi, 1995

Components aren't the only things to change in power electronics. Reductions in size, weight, and cost, as well as increases in efficiency are cumulative. An engineer from Westinghouse notes that the reliability of power controllers has increased ten times in five years while the price has dropped several times for the integrated circuits used in them. (Turrentine and Kurani, 1996). GM press releases regarding their Generation II drive system include the following description of changes in power electronics:

> "The first generation has three interconnected boxes in the power electronics bay. Up-integration permitted locating everything in one new box that's significantly smaller, lighter, and less expensive....
>
> "Electronic circuits previously housed in an accessory power module and a power steering control module have been moved into the main power electronics bay. Two significant internal changes saved space, weight, and cost. One is replacing a total of six single IGBTs with three dual IGBTs....The second change is the integration of the DC-DC converter function, which is analogous to an alternator. The DC-DC converter now use modular power supplies instead of discrete components, saving cost and reducing size. This saved one metal housing and a number of interface wires....All together we trimmed nearly 40 pounds of weight and were able to position more circuits within a smaller power electronics bay thanks to up-integration aided by the rapid advancement of electronics technology during the past two years." (Savagian, 1998)

An industry analyst at the investment firm of Frost and Sullivan expects this industry to grow from $561 million in 1996 to $782 million in 2003. In particular, the IGBT market has become quite competitive, driving down costs. (Press release from Frost and Sullivan web site). Additionally, these improvements have allowed whole new circuit typologies, further reducing costs, improving reliability and eliminating redundancy. The higher voltages and new controllers have allowed for more powerful, more efficient motors. In 1994, Alan Cocconi developed his own motor, a 200 hp, air cooled design that weighs 120 lb. The controller weighs only 70 lb. This system is in the Honda Civic listed in Table 4.6 as accelerating from 0 to 60 mph in 6.2 seconds. Some other companies are developing even higher motor speeds and power densities for use in larger vehicles. SatCon has built a 145 lb. BPM Motor they claim delivers 500 hp.

DC DRIVE TRAINS AND OTHER MOTORS

Competition from these new ac drive trains, has spurred development of more efficient direct current (dc) brushless, permanent magnet motors. The efficiency of dc motors has increased from 85 percent to 95 percent with the introduction of high-strength, permanent magnet motor designs that replace series or shunt wound motor designs. Three companies in particular, Unique Mobility, Toyota, and Honda are developing multi-phase dc brushless motors. DAX now offers new, higher voltage controllers for dc brushless systems.

TABLE 5.5: COSTS OF MOTORS

	dc brush	ac induction	brushless permanent magnet
Current $ per kWh	7.2	10.1	16.3

Source: Lipman, 1999

The specific application determines whether an ac or a dc brushless system is appropriate. Brushless dc systems can have higher power than ac systems, but they operate best within a more limited range of motor speeds than ac systems. Thus ac systems may be better suited to cars and trucks that must be able to operate over a wide range of vehicle speeds. Switch reluctance motors are another type of motor which have received increased attention in recent years. They are currently finding applications in electric scooters and other small motor applications.

REGENERATIVE BRAKING

One additional source of on-board recharging is to recapture the kinetic energy of a moving vehicle as it is slowed through the use of regenerative braking. Theoretically up to 50 percent of the energy of a moving vehicle is available for capture. (communication with Tom Gage, AC Propulsion, June 2000) Laboratory tests on the ETV-1 at the Jet Propulsion Laboratory reported 42 percent recovery (Riley, 1994). In gasoline vehicles, the kinetic energy of the moving vehicle is simply wasted as heat in the braking system when the brakes are applied to slow the vehicle. In electric vehicles, it is possible to capture much of this energy through the motor-controller system and return it to the batteries. The motor is simply operated as a generator, used to brake the vehicle, and the generated energy is delivered through the power electronics to the battery.

There are two primary ways to do this. In so-called "blended" braking, the driver actuates both the mechanical brakes and the regenerative braking with the brake pedal. Most of the OEM automobile manufacturers EVs use blended braking. Typically, the initial travel of the brake pedal activates the regenerative capacity, and harder braking engages the hydraulic brakes. The second scheme uses the accelerator pedal to actuate regenerative braking, reserving the brake pedal for the mechanical brakes only. Depressing the accelerator pedal causes the vehicle to accelerate, easing off the pedal causes the regenerative braking to be applied. This system is used by AC Propulsion. This method creates a more efficient regenerative braking system, but the feel of the system is different from conventional vehicles. Thus it is less familiar to consumers. The EV1 uses a combination of both, with an light regeneration applied when the foot comes off the accelerator and heavier when the brake is applied. The driver can turn off the accelerator regenerative to coast. The AC Propulsion system allows the driver to adjust the regenerative power with a dial effect.. Table 5.6 provides some manufacturer claims as to energy recovered by their systems. In real-world driving, it is typical that energy recovery is lower.

TABLE 5.6: REGENERATIVE BRAKING SYSTEMS

Vehicle	Type	Manufacturer Claims as to percentage energy recapture
GM Impact 1	Blended Brake	25%
Toyota RAV4	Blended Brake	20-30%
AC Propulsion Generation 1	Accelerator	30%

There is much patent activity around regenerative systems. We counted 31 patents granted in the U.S. for new types of regenerative systems in the post-production requirement period between January 1991 and June 2000. Only three U.S. patents were granted for regenerative braking systems for EVs during the pre-production requirement period between January 1980 and December 1990.

BATTERY PACKS FOR EVs

Battery research was one of the thrusts of federally-sponsored EV and HEV research in the 1980s. So, the number of battery patents issued in the 1980s vs. the 1990s shows as much balance as any technology area. Still, we count only 17 EV-related battery patents between 1980 and 1990, and 40 patents between 1991 and mid-year 2000.

During the 1996 biennial review of the ZEV production requirement, a panel of battery experts announced that although they did not believe other advanced or mid-term batteries would be ready for the 1998 deadline, advanced lead-acid batteries would be ready. The panel was impressed by the progress made on a variety of batteries and reported to the Board that the ZEV production requirement seem to have affected battery research and development. As part of the 2000 biennial ZEV review another battery panel has been convened. Readers are referred to that panel's report (Anderman *et al*, 2000) for more details on the current state of EV traction batteries. We note however, that the panel's report is limited to NiMH, Li-ion, and Li-polymer batteries.

There were no NiMH batteries in vehicle-sized packs or modules in 1990. Five years later, Ovonic Battery Company had produced at least 35 such packs; 25 in vehicles. One of these vehicles was driven 238 miles on a single charge in a Solectria Sunrise. In the 1996 Tour de Sol, Solectria was able to drive its Sunrise 375 miles on a single charge. Ovonic now produces vehicle size NiMH packs numbering in the hundreds, and is looking to move into 1/4 scale production. Today, Nissan is the only manufacturer to *not* use NiMH batteries in meeting its MOA obligations. According to data provided by CARB. Ford, General Motors, DaimlerChrysler, Toyota, and Honda have delivered a total of 1,461 vehicles with NiMH battery packs.

Lithium-ion batteries are a relatively new technology, introduced in 1990 by Sony. Lithium-ion batteries are competing with another relative newcomer, nickel metal-hydride (NiMH) batteries, for market share. In October 1995, Nissan announced it had driven a minivan 120 miles on a lithium-ion battery pack. By 1999, Nissan was delivering Altra vehicles equipped with Li-ion batteries. While these batteries will not be ready for production in 2003, they show great promise.

What about advanced lead-acid batteries?

Many articles and pundits in the past few years have stated that lead-acid batteries have remained essentially unchanged for seventy years. In fact, the ZEV production requirement refocused attention on lead-acid batteries. Many major car battery companies began to redesign and improve lead-acid batteries during the 1990s. These companies included Optima, AC Delco, Hawker, GNB, Trojan, Electrosource, SAFT, Sonnenschein, and others. This new research lead to rapid progress.

As was the case for NiMH and Li-ion batteries, there were no vehicle-sized packs of advanced lead-acid batteries in 1990. Today hundreds of these packs are being made per year by several companies. Recently, advanced lead-acid batteries have been used in vehicles driving over 100 miles. The 1999 EV1 with Panasonic lead-acid batteries traveled over 100 miles on the Pomona Freeway Loop under three of the four test conditions—only failing to surpass 100 miles while carrying its maximum payload and with auxiliary loads on (see Table 4.3). Specific-energy of lead-acid batteries increased from 20Wh/kg in the 1970s to 35Wh/kg in the 1990s. Though not a success story for other reasons, the Electrosource Horizon lead-acid battery was demonstrated by EPRI to store 44Wh/kg.

Additionally, new computer controlled, rapid charging has been demonstrated with conventional (i.e., flooded) and advance lead-acid batteries. Not only do these "smart" chargers allow rapid charges from 20 percent to 80 percent recharge in 10-15 minutes and full charges in one hour, but such charging has been demonstrated to improve the life of the battery. During 1995, Arizona Public Service recharged U.S. Electricar vehicles with lead-acid batteries daily with 30-minute fast charges. The batteries showed no signs of battery capacity loss. In fact, evidence shows that the fast charging may be better for lead-acid batteries than conventional charging algorithms.

Data on the progress of advanced lead-acid batteries during the 1990s are shown in Table 5.7.

TABLE 5.7: CYCLE LIFE OF LEAD-ACID BATTERY PACKS

	1998 ALABC Goals[1]	1992 ALABC VRLA test[1]	1995 Mean and (Range) for 6 VRLAs[2]	1997 Delphi VRLA[3]	1999 Panasonic EC-EV1260,[4]
Cycle life, (SFUDS)	800	75	517 (400 – 600)	400	1,000 (DST)[6]
Specific Power, W/kg[5]	150	150	167 (90 – 253)		200[7]
Regenerative Specific Power, W/kg	-	-	-	-	60
Specific Energy, Wh/kg[5]	48[2]	25	33.7 (30 – 37)	33.8[8]	35
Fast charging, from 20% to X %, minutes	50%: 3 80%: 10 100%: 30	50%: 5 80%: 15 100%: 240	-		80%: 10
Price, $/kWh[5]	150	200	146 (110 – 195)	150	450 (150)[9]

1. Moseley (1996). Figure reported is the number of recharging cycles based on the batteries being discharged in a manner consistent with the driving load presented by the Simplified Federal Urban Driving Schedule (SFUDS).
2. Moseley (1996) Testing conducted by ALABC. Specific batteries not reported.
3. Personal communication.
4. Hoshihara *et al*, 1999. Matsushita manufactures three size modules in this battery line. The 1260 is the module used in the 1999 GM EV1.
5. Battery Module only.
6. Batteries discharged in a manner consistent with the Japanese DST cycle.
7. Peak specific power (at 0 percent DOD) >350kW, at 25°C; 280kW at 0°C. At 50 percent DOD, 25°C, specific power > 300kW.
8. Calculated value from 1997 GM EV1 specifications published in USDOE, FOP Baseline Performance data.
9. Small run price currently is around $450, estimate of $150 was given to AC Propulsion by Panasonic for production runs.

1999 Matsushita Panasonic Lead-Acid Battery

As much as any other battery development in the last year, Matsushita Battery Industrial has surprised the world with its new line of Panasonic advanced lead acid batteries. Although the specific energy of the battery is not spectacular—merely a good 35 Whr/kg—the battery has proven cycle life as good as NiMH. The batteries are achieving well over 1,000 cycles, and under appropriate (and plausible) conditions, up to 1,700. Peak specific power (on discharge) is 200kW/kg. These goals exceed those set by the ALABC. The battery currently is very high priced. We speculate that this is due more to the excellent market position that this battery gives to Matsushita than to any reason inherent to the battery.

Increased specific energy, fast charging, improved cycle life, and lower cost make lead-acid batteries attractive for many applications in which single-charge range over 100 miles is not required. Lead-acid batteries could certainly be used in EVs for several years to come, including the first years of the 2003 production requirement. Their low initial cost may even carry them well into the next century for many applications.

Nickel-metal hydride battery

NiMH batteries are already considered by many auto manufacturers to be the EV battery of choice—at least for the MOA period. They were used by almost all the OEMs in production of the MOA vehicles (with the exception of the Li-ion battery in the Nissan Altra).These batteries are also rapidly replacing nickel-cadmium batteries in the small cell, rechargeable battery market for things like hand-held power tools and laptop computers, and soon will be the battery of choice in the large market for starter batteries on motorcycles in Asia. A race is on between major battery producers, including giants such as Panasonic and SAFT, to capture these markets. The United States Advanced Battery Consortium awarded $32 million to Ovonic and $27 million to SAFT to develop NiMH batteries. Basic specifications of NiMH battery modules from these three manufacturers are presented in Table 5.8.

TABLE 5.8: SPECIFICATIONS OF CURRENT NIMH BATTERY MODULES

	Ovonic 13-EV-90, 90Ah[1]	SAFT NH12.2, 96Ah[2]	Panasonic, 95Ah[3]
Cycle life	>600 (DST, to 80% DOD)	1,250 (to 80% DOD)	>1,200 (to 80% DOD)[4]
Specific Power, W/kg[5]	200[6]	150	200
Specific Energy, Wh/kg[5]	70	66	65

1. Corrigan (1999)

2. Madery, C. and J.L. Liska (1999)

3. Panasonic EV Energy Co., Ltd. (1999)

4. Cycle life is affected by temperature. Cycle life @ 80 percent DOD is rated at 1,000 at ambient temperatures of 30°C, 500 at 50°C. Similar results likely hold for all NiMH batteries.

5. Battery module only.

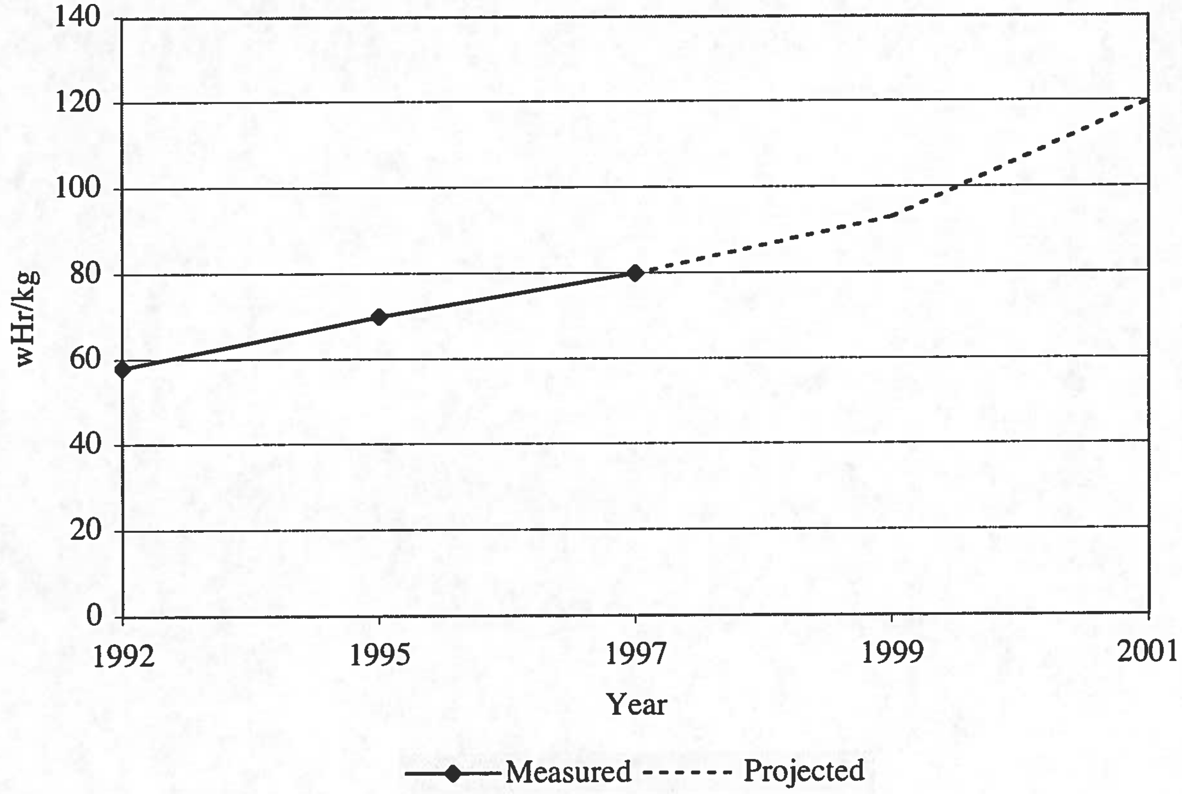
6. For 30 seconds @ 80 percent DOD

NiMH batteries have demonstrated energy densities as high as 81Wh/kg. Depending on longer-run production costs, because of their greater energy density, some analysts believe the cost of NiMH batteries may be lower over the life of the vehicle than lead-acid batteries, even if lead-acid batteries match the cycle life of NiMH. (However, the new Panasonic PbA might challenge this idea.) Lightweight, efficient vehicles may travel 200 miles on a single-charge of a NiMH battery pack.

NiMH battery modules are sealed, recharging produces no gases, and the battery is comparatively safe for the environment. The most attractive feature of NiMH is their long cycle life. In laboratory testing, NiMH batteries have shown lives up to 1,500 cycles. In real world, vehicles are approaching 1,000 cycles. In a vehicle with 120 miles of range per charge, this could mean a battery life of 120,000 miles. If the real-world cycle life of NiMH cells approaches 1,500 cycles, this could mean batteries which last 160,000 miles or more in lightweight vehicles (Corrigan, 1999).

Increases in specific energy of NiMH batteries throughout the 1990s are illustrated in Figure 5.1. Specific energy increased some 33 percent from 1992 to 1997.

FIGURE 5.1: INCREASES IN SPECIFIC ENERGY OF NIMH BATTERIES (DATA FROM OVONIC)



Projected values are from Corrigan, 1999. Cited in Lipman, 1999.

The high miles per charge afforded by NiMH batteries (and by extension, the possibilities afforded by any battery with high specific energy), especially in small, efficient vehicles, has been demonstrated many times.

- A Solectria Force (a converted Geo Metro) using an Ovonic NiMH battery pack won the Open category for sedans in the 1994 Phoenix 500. The car traveled 125 miles without recharging. Its average speed was 65 mph.
- Panasonic and Toyota demonstrated a NiMH battery in a small sport utility vehicle: this vehicle traveled over 200 miles on one charge in the 1995 Swedish Electric Car Rally.
- A Solectria Force set a Production category range record in 1997 when it was driven 249 miles in the 1997 Tour de Sol.
- The 1998 GM EV1 with Generation II drive train and Ovonic NiMH batteries "drove" 140.3 miles on the SAE J1634 cycle, 160.6 miles at a constant 60mph, and 220.7 miles at constant 45mph in USDOE, FOP Baseline Performance testing.
- Still, the apparent record holder for any on-road vehicle is a Solectria Sunrise with an Ovonic NiMH battery. This vehicle traveled 375 miles on a single charge in the 1996 American Tour de Sol.

In 1995, Ovonic produced 35 full-scale automotive battery packs: 25 were put in cars. Today, thanks to the ZEV production requirement and the MOAs, Ovonic, Panasonic, and SAFT each have hundreds of their NiMH battery packs, representing thousands of modules, on the road.

Nickel Cadmium

Nickel cadmium (Ni-Cd) batteries were part of the mix of EV traction battery technologies that competed for market share during the 1990s. For now, it would seem as if they are losing. Ford's new TH!NK division is still planning on using Ni-Cd batteries in its small TH!NK City, but possibly only because that was the battery in the City's precursor, the PIVCO City Bee.

Ni-Cd batteries do have excellent cycle life and better specific energy than lead-acid batteries. Typical specific energy values for Ni-Cd batteries are between 50 to 55 Wh/kg. In limited production, battery packs for vehicles cost $20,000, comparable to NiMH costs at similar production levels. Early in the 1990s, Ni-Cd batteries were showing up in many prototypes and some production vehicles; one French EV manufacturer used them in its first production EV. A potential drawback is cadmium is toxic; Varta has said they will not produce Ni-Cd batteries for the EV market because of the toxicity problem. However, SAFT will produce them for the French automotive industry and opened a new 50 million dollar factory for EV battery packs expected to produce 5,000 packs per year beginning in 1996. In 1995, we observed that many experts thought Ni-Cd batteries would fall out of the running for long term vehicle applications. For now, this appears to be true.

Lithium-ion

Lithium-ion batteries are a recent development, first announced by Sony Corporation in 1990. Only in September 1995, did Sony announce a lithium-ion, rechargeable battery for EVs. While Nissan originally was intending to use a Sony Li-ion battery, Sony dropped out and Nissan has worked with Matsushita. Li-ion batteries have been used recently in laptop computers and other consumer electronics products. If further development proceeds as expected, this will be a midterm battery with similar capabilities to the NiMH battery. It may, however be significantly cheaper because of low cost for materials as it has no expensive metals. Varta says it has plans to market a full line of lithium-ion batteries, ranging from AAA cells to battery packs for electric vehicles. In 1995, the USABC awarded $18 million to Duracell/Varta to develop a lithium-ion battery for electric vehicles. A Nissan Access minivan was driven 120 miles on a lithium-ion pack in October 1995. The California Air Resources Board has estimated that a light-weight vehicle with such a pack could travel 190 miles. Specifications released by Sony indicate their battery had an energy density of 100 Wh/kg and a power density of 300 W/kg. Additionally, they claim a cycle life of 1,200 cycles in laboratory testing of small cells. Specifications from two suppliers of Li-ion modules sized for application as EV traction batteries are shown in Table 5.9.

Nissan is the only vehicle manufacturer to use Li-ion batteries in vehicles intended to meet the terms of their MOA with the State of California. In effect, these batteries are now getting their on-road, real world testing for durability and cycle life. This process got off to an inauspicious start when Nissan had to negotiate a one-year extension to the term of their MOA because their battery supplier could not meet delivery deadlines. There is a long and difficult way to go, but if these claims are substantiated in real world tests of vehicle battery packs, then a lithium-ion battery pack in a light weight vehicle could potentially provide as many as 200,000 miles of travel over its life.

TABLE 5.9: SPECIFICATIONS OF LITHIUM-ION BATTERIES FOR EV TRACTION APPLICATION

	Sony LiCoO2, 94 Ah modules[1]	Shin-Kobe LiMn2O4, 90 Ah modules[1]
Cycle life	1,200	na
Specific Power, W/kg[2]	300	350
Specific Energy, Wh/kg[2]	90	91

1. Atkins, L. (1999)

2. Battery module only.

Lithium Polymer

This is a battery that some people hope will make EVs' driving ranges comparable to those of gasoline vehicles. But this battery chemistry is a long way from commercialization in vehicle size packs and most information about it is derived from laboratory experiments. These batteries use metallic lithium, lithium alloys, or lithiated carbon compounds as the anode, a variety of materials as the cathode, and solid polymer electrolyte. The energy density is likely to be between 100 and 200 Wh/kg. St-Pierre (1999) reports that Hydro-Québec has produced small modules with specific energy of 155Wh/kg and specific power of 315W/kg. Based on such figures, some believe driving ranges of 300 miles will be possible.

Li-polymer batteries are made largely of relatively inexpensive materials. The battery should be much safer than some other lithium battery chemistries because the solid polymer electrolyte has lower reactivity with lithium than does the liquid electrolyte used in other designs. Lithium batteries with solid polymer electrolytes are more accurately called "near-ambient" temperature batteries. While some lithium polymer batteries have operating temperatures in the range of 100 to 130°C, recent development efforts aimed at vehicle applications have reduced the operating temperatures to between 50 and 60°C. Such batteries would require some thermal management, but the demands would be much less than the high temperature batteries. However, this battery is still in early stages of its development; there are no lithium polymer batteries in a vehicle. Thermal management in larger module sizes is a problem. The manufacturing process is still undeveloped, although Batelle Corporation has announced one way of mass producing the thin films to be used in the batteries.

DEVELOPMENT OF PRE-ASSEMBLED EV BATTERY PACKS

At the beginning of the 1990s, there were no battery companies selling pre-assembled battery packs for EVs. Conversion companies and prototype projects assembled their own packs, made their own battery trays, interconnections, and other pack equipment. In fact, few battery companies had tested whole sets of batteries together, and little was understood about need for the equalization of cell charges across the battery pack, and its critical role in longevity of the battery pack.

At the end of the 1990s, there are several lead-acid and NiMH packs manufactured in batches, but not yet true mass production. By the year 2000, the manufactures had begun to assemble pre-equalized and closely matched modules with higher quality control. Panasonic makes special packs for compact sized vehicles, "City" EVs, and fully freeway capable EVs.

TABLE 5.10: EXAMPLES OF PRE-ASSEMBLED BATTERY PACKS FOR EVS

Vehicle	Battery Type	amp-hour, modules	kWh, pack	Total weight, kg
1990 Impact	Pb-A	42.5	13.6	489
1994 Honda CUV	Pb-A	60	16.0	480
1996 RAV 4	Matsushita Pb-A	55	15.8	450
1997 EV1	Delphi Pb-A	48	15.0	489
1999 EV1	Panasonic Pb-A	60	18.7	534
1999 EV1	NiMH	77	26.4	481

All information from OEM specification sheets and USDOE FOP Baseline Performance testing.

BATTERY PACK THERMAL MANAGEMENT

As a further step to designing pre-assembled packs, manufacturers are designing and developing packs with built in thermal management systems. For example, SAFT has integrated a water jacket into the design of their NiMH battery packs to cool these highly exothermic batteries in warm temperatures and to heat the batteries in cold weather. Over the last five years, it seems to have been recognized that in order to realize the full potential of front-running candidate battery technologies for EVs, effective thermal management of the battery pack is required. There are prototype batteries now that have built-in channels in their cases to circulate coolants.

Each battery technology has its own specific thermal characteristics, and the thermal management system must be configured accordingly. For example, the performance of lead-acid batteries drops with decreasing temperature, so for cold ambient temperatures it would make sense to design a thermal management system that can provide heat to the battery modules under certain conditions. Thermal management of EVs under harsh winter conditions has been proven by the Vermont Agency of Natural Resources (Garabedian, 1999).

AC Propulsion's approach to thermal management of battery packs has evolved over the past few years. Initially, their strategy was to provide heat to the entire battery pack using efficient heating pads. The amount of heat to be supplied was based on an air temperature read from within the battery pack tunnel. Recently, they implemented a system capable of applying heat to individual battery modules as required. Since lead-acid batteries self-heat during charging and discharging (normal vehicle operation), heating is only required during periods of very low ambient temperatures, or when the vehicle sits for extended periods of time. Under most conditions, heating is done when the vehicle is connected to the charger, so energy consumption from the battery pack is not required. The performance of lead-acid batteries also drops with increasing temperatures, but for a well-ventilated battery pack operating under most normal ambient conditions, even in warmer climates, extraordinary cooling measures are not usually required.

On the other hand, NiMH batteries have inherently higher internal resistance than lead-acid batteries. Thus significantly more heat is generated during charging and discharging. If this heat is not effectively removed it will cause the temperature to rise to a point where the battery will be permanently damaged. Furthermore, there is a significant drop in battery performance and cycle life with increasing module temperature. (See for example, the effect of temperature on battery cycle life in Panasonic EV Energy Co., Ltd. (1999).) Battery cooling will be required for operation even in moderate climates. As opposed to lead-acid batteries, the self-heating characteristic of NiMH batteries makes them better suited for operation in cold climates, i.e. the thermal management system for a NiMH battery pack need not be so concerned with heating the batteries.

It's interesting that two of the leading battery technologies for EVs, lead-acid and NiMH, have almost opposite thermal characteristics, and require quite different strategies for battery pack thermal management.

Early to mid-1990s State-of-the-Art

GM Impact and AC Propulsion, Inc.

Well into the 1990s, battery modules were assembled into packs in a configuration consistent with the packaging requirements of the host vehicle—in short, they were made to fit any way possible. Sometimes battery modules were simply exposed to air in the surrounding vehicle environment, often they were fully enclosed. But battery ventilation was either left to chance, or at best, a simple blower was used to circulate air through the pack.

Arguably, the first purposeful attempts at a battery pack thermal management system were those employed in GM's Impact and in the vehicles retrofitted by AC Propulsion, Inc., (most often Honda Civics). These EVs used an I-shaped battery pack, with modules stacked two deep, oriented front-to-rear in the vehicle, i.e. a battery "tunnel" that runs the full length of the vehicle interior, starting at the firewall, between the left and right occupants. Other than obstruction by the battery modules themselves, the airflow path was relatively straight and in-line with the direction of movement of the vehicle. This provided the possibility to use ram airflow to cool the pack under most conditions, i.e. high static pressure air admitted at the front of the vehicle and exhausted to lower static pressure air at the rear of the vehicle. When ram airflow was inadequate, as indicated by the battery tunnel air temperature rising above a certain point (~30°C), a variable-speed blower was used to move more air through the tunnel. Under most ambient and vehicle operating conditions, the system could maintain the battery pack temperature between 30 and 40°C, the ideal operating range for lead-acid batteries. AC Propulsion's system could also provide pack heating, the GM Impact's system could not.

Intermediate State-of-the-Art (pre-MOA Demonstration Program)

GM EV1 (Generation I, 1997 model year) and Chevrolet S-10 Pick-Up

For the EV1, Impact's I-shaped pack was dropped and a T-shaped pack was adopted. The forward half of the pack between the occupants was similar to the Impact—that is the long leg of the T was oriented as the I had been in the Impact. But a portion of the modules were in the top of the T that was laid across the width of the vehicle between the rear wheels. The same battery pack thermal management system as had been used in the Impact was retained, i.e. ram airflow supplemented by a variable-speed blower as require. However, the T-shaped pack was more tortuous for the airflow than the Impact's I-shaped pack, and pack cooling could be problematic under certain operating conditions in high ambient temperatures, e.g. successive charge cycles, high-speed driving, rapid accelerations, and/or a lot of regenerative braking. As was the case for the Impact, the EV1's pack could not be heated if the problem was batteries that were too cold.

Chevrolet's S-10 EV, on the other hand, was a retro-fitted ICEV, and a different battery pack strategy was required since extensive modification of the vehicle platform was not possible. A rectangular pack was designed with two layers of 12 and 14 modules enclosed in a case that was installed beneath the bed of the pick-up truck between the frame rails. Since there was little hope of any significant ram airflow cooling for such a pack, a different battery pack thermal management strategy had to be employed. Air that was pre-conditioned by the vehicle's HVAC system was admitted to the front of the pack, flowed through and around the modules, and exited through holes in the top of the pack's case.

The S-10's pack thermal management system was the precursor to the similar system employed by the Generation II EV1, albeit for a different reason, introduced as the 1999 model year vehicle. Because the S-10's pack could be cooled with "refrigerated" air, NiMH battery technology was introduced by GM as a battery pack option prior to its being available in the EV1.

The Accelerated Reliability Final Report on the S-10 pickup truck offered these conclusions regarding this battery thermal management system.

> "Charge times also varied significantly due to environmental factors. The S-10 Electric battery pack is actively cooled by the vehicle's air conditioning system. Refrigerant is diverted to a battery pack evaporator/fan when battery pack temperatures exceed 45°C. The high ambient temperatures in Phoenix presented a significant challenge to the pack cooling system. During summer daylight hours, air conditioning resources were always diverted to pack cooling, leaving the cabin without air conditioning. It was only well after dark that the pack would ever cool enough for pack cooling to stop and divert refrigerant back to the cabin. This was the source of many negative driver comments with regard to cabin comfort. The high battery pack temperatures also frequently extended charge times as the chargers significantly reduced charging power at high battery temperatures." (Francfort *et al,* 1999)

Current State-of-the-Art (1998 to 2000)

The RAV4EV and the EV Plus both use Panasonic NiMH batteries. Since both vehicles are conversions of existing ICEV platforms, albeit rather extensive in the case of the EV Plus (Honda Civic-based), they use an underfloor-mounted battery pack consisting of a single layer of battery modules to minimize the height of the pack.

Toyota RAV4 EV

In spite of the heat generation and high temperature sensitivity of NiMH batteries, the RAV4 EV's pack is cooled using ambient temperature air similar to the thermal management system employed by the Impact, Generation I EV1, and AC Propulsion's EVs. Since the modules are arranged in a one layer, rectangular array, the airflow path through the pack is simplified compared to the Generation I EV1, and greater success might be expected with the thermal management of the NiMH pack. To quote Toyota, "An air cooling system was adopted...because of its construction, low cost, and high reliability." (Asakura 1996) Toyota's data shows that even during the hottest months in Los Angeles, the RAV4 EV's battery temperatures are held between 30 and 40°C during charging, but there are occasions when 40°C is exceeded. This is consistent with some reports from vehicles in the field in Los Angeles and Atlanta that battery temperatures have risen above acceptable levels, and that the vehicle software has taken measures to protect the battery pack by restricting charging until the modules cool down. Toyota has acknowledged work directed toward improving the airflow distribution through the pack, and has incorporated design changes in the latest models.

Honda EV Plus

In contrast, even though the Honda EV Plus has a battery pack arrangement similar to that of the RAV4 EV and uses the same battery modules, they mount their modules on a water-cooled "cold plate" to provide additional heat removal capability. Some heat is transferred away by the water, and in addition, the air flowing through the pack is cooled. However, the cost and complexity of Honda's thermal management system is greater than that of Toyota's. But since the motor and power electronics are water-cooled, perhaps adding a "cold plate" for the battery pack to the cooling water circuit was not that big an issue. Interestingly, the earlier lead-acid version of Honda's EV Plus, the CUV-4, did not employ water cooling, and used an air cooling system similar to the RAV4. As an additional thermal control measure, Honda restricts its peak charging power (output) to 4.2 kW, while Toyota permits 6.1 kW. Even under high ambient temperature conditions, the EV Plus is able keep the temperature of its batteries under control, albeit at the expense of longer charge times.

Ford Ranger EV

The Ford Ranger EV is also a conversion of an existing ICEV platform, but unlike the Toyota RAV4 EV and the Honda EV Plus, the Ranger EV does not use an underfloor battery pack. Rather, some of the modules are stacked 2 deep in order to have a more narrow pack that will fit between the frame rails and under the cab and pick-up bed. The layout of the pack is somewhat analogous to that of the GM Impact, and forced air-cooling with ambient temperature air is apparently adequate for the thermal control of both lead-acid and NiMH battery packs.

Nissan Altra EV

The Nissan Altra EV also uses an underfloor battery pack arrangement, and the same platform is used for an ICEV version of the car in Japan. The biggest contrast with other OEM EVs in terms of thermal control of the battery pack is the Altra EV's use of a unique battery technology, lithium ion, with unique thermal characteristics. Li-ion batteries are endothermic (heat absorbing) during charging (including regenerative braking). Increases in battery temperature during discharges can be cooled during charging provided that the charging is carried out at currents within the range of endothermic reaction and depending on the amount of temperature rise during discharge. On the other hand, extreme rises in battery temperature during discharge can reduce battery life. Therefore, it is important that the pack thermal management system keep the batteries within the desired temperature range. Otherwise, the output power of the pack will be restricted by the battery pack control system to protect the pack from overheating.

The Altra EV uses twelve modules, each containing eight cells, arranged front to rear in six rows of two modules. An air intake duct admits air at ambient temperature to the lower front of the pack, and the air is forced to flow through the insides of the battery modules via openings in the bottoms and tops of each module. The heated air exits through the upper rear of the pack where a blower is located.

GM EV1 (Generation II, 1999 model year)

The upgraded battery pack thermal management system in the Generation II EV1 was the result of GM's offering two different battery packs/technologies—Panasonic lead-acid and GM Ovonic

NiMH, the latter required by GM's Memorandum of Agreement (MOA) with the California Air Resources Board (CARB) to put a required number of EVs on the road with "advanced" technology batteries.

As discussed above, NiMH batteries require more cooling than lead-acid batteries, and the Generation I EV1's thermal management system was not capable of providing the necessary cooling. Even though the new Panasonic lead-acid batteries could have been accommodated by the Generation I system, they too will benefit from the cooling capability of the new Generation II system, and the batteries can now be heated in cold ambient conditions, as well.

DaimlerChrysler EPIC

Perhaps the most highly evolved battery pack thermal management system is installed in the EPIC. The EPIC uses SAFT NiMH batteries arranged in a single-layer, rectangular array under the minivan's floor. These SAFT NiMH batteries are one generation more advanced than those employed in the other OEM EVs equipped with NiMH batteries. Not only advanced in chemistry, materials, and construction, the SAFT modules contain an integral water-cooling jacket, which permits an entire pack of modules to be connected together for effective thermal control. As a result, the pack design is much less sensitive to airflow distribution, and thermal problems with individual modules due to location within the pack should be minimized. In fact, thermal control is so good that Daimler Chrysler has made the EPIC capable of rapid charging, which is being successfully demonstrated in commercial operation by XPRESS Shuttle service, who is using a fleet of EPICs in conjunction with Aerovironment 60 kW chargers to carry customers to and from Los Angeles International Airport. NiMH battery modules with integral water cooling would be ideal for the General Motors EV1 because of its poor battery environment.

TABLE 5.11: SUMMARY OF THE CURRENT STATE-OF-THE-ART OF MOA VEHICLES BATTERY PACK THERMAL MANAGEMENT (1998 - 2000)

Increasing sophistication listed down the table.	Forced-Air System: Ambient temperature air Toyota RAV4 EV (NiMH), Ford Ranger EV (lead-acid and NiMH), Nissan Altra EV (lithium-ion), General Motors EV1 (Generation I, lead-acid and NiMH)
	Forced-Air System: Cool air from the HVAC system Chevrolet S-10 (lead-acid and NiMH), General Motors EV1 (Generation II, lead-acid and NiMH)
	Combination Forced-Air/Water-Cooled Systems Honda EV Plus (NiMH)
	Water-Cooled Systems Integrated into the Battery Pack and Module Design Daimler Chrysler EPIC (NiMH)

EV CHARGING TECHNOLOGY

One of the areas of most rapid progress and shifts in the EV paradigm is the standardization, speed, computerization, simplification, reduced costs, and increasing convenience of charging technology. As mentioned in the previous section, as EV charging technology develops further, the main barrier of single charge range (60-140 miles) may evolve into a new paradigm of "daily range" of 300-400 miles. Further, the science of computerized fast charging has been found to extend battery life.

Recharging has in fact undergone a period of rapid change since 1990, primarily due to several areas of development, including:

- evolution of multiple levels of charging for EVs;
- development of charging standards; and
- testing and development of fast charging algorithms.

Fast charging equipment and algorithms (digital instructions for the charger to control the rate and rations of pulses) have been developed for a variety of battery chemistries. Early in the production requirement era, Nissan announced their fast charging system for nickel-cadmium batteries. Now, lead-acid, NiMH, and lithium-ion batteries are charged at Level 2; lead-acid and NiMH batteries are being charged at Level 2+ and Level 3.

Prior to 1990, the refueling/recharging of electric vehicles has been measured typically in hours rather than minutes. Fortunately, electricity is available most everywhere. Recharging can take place while a vehicle is parked at home, at work or at other locations. Since vehicles are typically driven for only 1 to 2 hours per day, there is usually ample time to recharge unless the vehicle is wanted for an extended trip. Compared to the installation of refueling stations for gasoline or other fuels such as compressed natural gas, the installation of an electric charging facility can be relatively inexpensive.

Another example of the shifting paradigm of battery charging is the AC Propulsion "reductive " charging system, which allows for "Level 2 plus " charging. Their vehicle has an on-board charging system which is integral to the controller and can charge the lead-acid battery in 1 to 3 hours (depending on the state of charge of the batteries) on a simple 220 volt, 30 amp dryer outlet (AC Propulsion web site).

Charging is an arena of increased development and competition subsequent to the ZEV production requirement. Only eight patents related to recharging EVs were granted from 1980 through 1990. Since January 1991, 116 U.S. patents have been granted to EV recharging devices, systems, system components, and techniques.

Brief description of charging equipment

Energy flows into and out of batteries as direct current (dc) while the electrical distribution grid carries alternating current (ac). Therefore a primary technology in battery chargers is the inverter that converts current from ac to dc (and back from dc out of the battery to ac into the motor in ac drive trains with integrated controller/charger designs). Additionally, more sophisticated chargers monitor the condition of the batteries being charged by measuring the temperature and the state of charge of the battery modules, or in some cases individual cells.

The electricity distribution grid in the US has different types of electrical services available at different locations. Standard 110 to 120V service is provided to residences and businesses for running most appliances and lights. Additionally, a higher-powered 220 to 240V service is installed in newer residences to operate higher voltage appliances such as electric dryers and ranges.

Industrial locations have even higher-powered circuits. These three phase ac services provide 208 volts in all new parts of the grid with some residual areas of 227 and 245 volts. A few zones provide 440-480 three phase for very heavy industry.

In the past, many electric vehicles charged primarily from the ubiquitous 110-120 volt system. The advantage of this system was that while recharging was slow, plugs were everywhere. The 220-240V single phase ac circuits are also useful because they are found in most new homes and can reduce the recharge time by 75-80 percent over the time it takes to recharge from a 110-120V outlet. Even greater time savings can be realized if the 208 three phase circuit can also provide constant current. Finally, a few locations (typically industrial) can offer much faster rates of recharging because they have three phase (which offers constant power) and higher voltage (e.g., 440V) multi-phase ac electrical service. These are very attractive circuits for companies with fleets who have access to these high power levels. Also, such electrical service can be offered to the public at special public charging stations. The very fast recharge times cited for some chargers rely on these high voltage, high amperage circuits.

TABLES 5.12: OFF-BOARD LEVEL THREE CHARGING DEMONSTRATIONS

Year	Test vehicle and battery	Company	Power, kW	Recharge speeds
1994	Converted S-10, Pb-A	Hughes Magne Charge Inductive	50	3 miles per minute
1997	Transit buses, VRLA batteries	Norvik	300	na
1999	EPIC, Saft NiMH	Aerovironment	60	80% in 10 minutes
2000	GM S-10, Pb-A	GM Magne Charger	50	2.3 miles per minute

Presentation by Mickey Oros, EVI, June 2000 ARB workshop, Diamond Bar, CA.

In the past, vehicle battery chargers were designed to be compatible with only one level of electrical service. Now, many chargers can charge at least three service levels. One of the advantages of the Hughes Magne Charger is that it can communicate with virtually any electrical service and adjust the charger to match the voltage and current capabilities of the circuit. This flexibility allows a single type of charger to be placed in a variety of settings with a variety of electrical service.

TABLE 5.13: CHARGING PERFORMANCE FOR NEW PANASONIC LEAD-ACID BATTERIES

ALABC 1998 goals	50% in 3 min 80% in 10 min 100% in 30 min
1999 Panasonic Pb-A	50% in 4 min 63% in 8.5 min 80% in 36.0 min

Source: Hoshihara, 1999

On-board vs. off-board charging

In the past, vehicles either had on-board chargers (the charger is carried on the vehicle) or the charging equipment was contained in an off-board unit (the charger is not an integral part of the vehicle and typical remains at one location). The advantage of off-board chargers was the savings in vehicle weight. The advantage of on-board charging is the potential for recharging to take place wherever a parking space and an electrical plug coincide.

Thanks to advances in integrated, high voltage circuitry, newer on-board chargers are decreasing in size and weight. In 1995, we opined that these trends would insure that the charger would be re-integrated into the vehicle. So far, this has not happened with the vehicles offered by the automotive OEMs during the MOA period.

One smaller EV-specialty company, AC Propulsion, is integrating their high power recharging circuitry as part of their ac motor controller and on-board energy management systems. This design uses the same inverter for electricity flows into and out of the batteries. Such a design offer high power recharging with little added weight and simplified circuitry. Given the high power capability of their system, they are able to allow what has been approved as Level 2+ on-board charging.

Development of charging technology

There are a number of computers on board EVs and also in the charging equipment. These applications of computing has revolutionized how batteries are charged. Older, simple chargers merely apply electrical current to batteries at a slow rate so as not to overheat the battery. A slightly more sophisticated charger applies more current at the start of charging and then shifts to a lower rate near the end of charging when the battery has greater resistance and heats more easily. Even more sophisticated chargers monitor the temperature and state of charge. These chargers may have several steps in their recharging cycle rather than just two. In order to avoid damaging batteries, charging equipment must measure battery temperature, the state of charge of batteries and the current flow to the battery. While smart charging operates on these principles, the level of sophistication and complexity goes far beyond simple charging described above. Three developments are important to note:

- Sensors monitor temperatures, charge states and current flows. A computer calculates rates of change in the energy state and temperature of the battery. Sensors traditionally have been not part of the battery itself, but new projects (such as a Duracell-Intel project) aim to develop "smart" batteries which have their own internal temperature sensors.

- Additionally, some high-power chargers use a "pulse charge" technique. Electricity is applied in rapidly alternating charge and rest periods. This pulsing reduces the development of internal resistance which deforms the charge surfaces, overheats the battery, and forces the charger to slow down. Pulsing allows much faster recharging, improves battery life, and reconditions abused batteries.

- Sophisticated pulse charging depends on both algorithms and real time monitoring of the battery to tell the computer which set of instructions it should be using. These algorithms are increasingly sophisticated and recently included application of fuzzy logic. Other recent algorithm developments include specific instructions for different battery types. Each type of battery needs distinct charger algorithm.

Several companies in the United States are developing these advanced systems. They include Aerovironment, Norvik, EPTI (Electric Power Technology Inc.), and EVI (Electric Vehicle Infrastructure, Inc.). Other companies are known to be developing similar systems in Europe and Japan.

Aerovironment has received much praise for their 60 kWh charger. This unit now retails for $40,000. This has been used to recharge the water-cooled NiMH battery pack of the DaimlerChrysler EPIC EVs being used in an airport van service in LA. The vehicles are kept in service all day, while being charged multiple times.

Benefits of improved charging

A variety of benefits have been demonstrated or claimed for smart charging. These include:

- Faster charging. Aerovironment, EPTI and Norvik have provided a 50 percent recharge in 8 minutes to lead-acid batteries from about 80 percent depth of discharge.
- Increased battery cycle life. EPTI claims increased battery life of 2-3 times over conventional charging. In EV America's tests, lead-acid batteries charged by Norvik fast charge technology are at 10,000 miles and show no signs of degradation.
- Reconditioning of degraded batteries. Two charging tests, one in France and one in US have shown that batteries which have been improperly recharged or operated under conditions that result in cell reversal can be revitalized by proper fast charging. These batteries include both valve-regulated and sealed lead-acid batteries.
- Increased battery capacity (improved "formation" process). The use of smart charging may also be used in the last step of the battery manufacturing process. A battery formed in this manner can have 10 percent greater initial charge capacity than batteries "formed" by traditional means and save manufacturers up to 50 percent of their electricity costs per battery for this step.

Inductive charging systems

Given the high voltages in some of the new charging equipment, there was some initial concern that there was a danger of electrical shock due to arcing while making conductive connections. Hughes and EPRI/Walter Dorwin Teague are two North American projects who develop sophisticated, high voltage, rapid charge inductive charging apparatus. Hughes is now called GM Advanced Vehicle Technologies. Inductive charging passes current magnetically, so there are never any conductive surfaces exposed to the charging personnel, be that a fast charge station attendant or a driver charging the vehicle at home. This has the additional advantage of reduced wear on the contact points as well as no need for interlocking safety mechanisms that can malfunction, and allows for a variety of power levels. However, inductive charging requires specialized appliances at each charging location.

GM ATV now has 100 kW chargers capable of fully recharging batteries in less than 1 hour. The Hughes system has gone from prototype development in 1990 to a wide set of limited production chargers for on-board and off-board high voltage charging. The GM system is also energy efficient. It is now proven at 92 percent efficiency. Hughes chargers are have been installed in many locations. The system is employed in the General Motors Impact and has been approved by the SAE, FCC, UL, and meets the standards of the National Electrical Code. Several auto makers including Toyota, Nissan and Honda have moved to inductive charging.

The Generation 1 Level 2 Magne charger weighed 70lbs and retailed for $1995 (subsidized). The Generation 2 Magne Charger dropped to 50 lbs, was 1% less efficient, but cost 30-50% less than Generation 1. GMATV now has a Generation 3 prototype which weighs 25lbs, is targeted to be 45% of the cost of the Generation 2 ($500), and includes a new smaller paddle design which is 80 kWh compatible, has a special heat absorbing composite for fast charging and uses IR communications protocol for worldwide compatibility. Toyoda Automated Loom Company will also make small paddle chargers.

Docking systems

To make charging more convenient, several companies and designers have begun to develop and market special docking stations which don't require drivers to plug into the off-board charging system. These include floor and ceiling wand types (PowerPak) and floor post type (Power Bar) docking stations. One company, NuSun, plans to market such systems. The advantage of such systems is they make it more convenient to recharge the vehicle as the driver does not have to remember to plug the vehicle in.

Solar charging

Solar systems continue to be developed for charging electric vehicles. Some vehicles have offered on-board solar charging for many years. However, the surface area of vehicles is too small to extend range more than a few miles. Most recently, coin operated public charge stations, powered by solar cells have been developed in Switzerland. Many of these solar units are currently in service. Computer controlled solar charging units, use magnetic card have been developed for use in Meminggen Germany 1992, Additionally, solar car ports have been developed in the United States by both Southern California Edison, the Sacramento Municipal Utility District and Boston Edison. These car ports not only offer charging capabilities but shade electric vehicles during the day to offset air-conditioning loads in hot climates.

Electric vehicle interface systems

Perhaps one of the newest developments in electric vehicle technology is the Electric Vehicle Interface (EVI) System. These systems amount to a communication system between the vehicle and some off-board monitor. This monitor can be the electric utility. This gives the utility active, real time control over vehicle recharging. It also would allow them to provide a diagnostic service to EV owners. The vehicles batteries and electronics could all be tested while the vehicle is plugged in. This equipment allows the user to choose to charge during off-peak periods for lower costs. In the future, such devices will also allow users to pre-defrost, pre-heat or pre-cool their vehicle from their office or home before going to the car. Additionally, the utility will be able to monitor the charging equipment and vehicle to turn on chargers which are off or to advise EV owners of malfunctions or upcoming routine maintenance. For example, if one of the battery modules was damaged, the utility would be notified immediately by the on-board computer of the EV through the EVI system. While the on-board computer can communicate this information to the driver directly too, the additional notification of the utility may prompt quicker action to replace the damaged module.

ON-BOARD ENERGY MANAGEMENT

On-board energy management systems are differentiated from other battery related hardware and software systems in that energy management systems are designed to control battery recharge and discharge to prevent operating conditions that reduce battery life. These systems monitor battery conditions, both in real time and as stored histories of charge/discharge cycles, and incorporate this information into the function of the battery recharging and power electronics. Several systems have been developed to control the recharging side. However, most work to date on the power discharge side only warns of fault conditions, it does not incorporate this information into the function of the power electronics. In effect, these systems do not control the discharge side (with the possible exception of limiting final depth of discharge), but leave the decision of whether to continue operating in a mode that may cause irreversible battery damage to the driver.

As one example of how an energy management system might control a vehicle, the acceleration capability of a vehicle without a energy management system may be controlled entirely by the demand for power signaled by the accelerator pedal. Assuming no other component of the power electronics or drive train serves as a limit, a "foot to the floor" maximum acceleration signal will draw power from the batteries at the maximum rate the batteries can deliver, regardless of whether such high power draws will ultimately damage the battery. However, an energy management system would interpret both the demand for acceleration and the condition of the battery pack and limit power delivery to a level that is not deleterious to the life of the battery pack.

A scenario in which a battery might receive a short burst of overcharge is during regenerative braking. Depending on the batteries state of charge and recharging characteristics, it may not be possible for the battery to accept energy from a regenerative braking system at the rate set by the braking system. This case illustrates that a true energy management system must be able to dynamically control virtually all power flows on-board the vehicle in real time.

One of our interviewees compared two hypothetical vehicles, identical except one has an energy management system and the other does not: "The vehicle without energy management would likely exhibit faster acceleration initially. But within several weeks both vehicles would likely exhibit similar acceleration, and within less than a year, the vehicle with the energy management system would show superior acceleration." Of course, the vehicle with energy management would have constant acceleration performance across time. The vehicle without energy management would have declining performance as damage to the battery accumulated due to repeated high power discharges or overcharges, for example, during regenerative braking.

Overall, it appears as if less effort has been directed at developing and implementing comprehensive energy management systems, what one source calls an "operating strategy for battery packs." As recently as January, 1995 Dr. Heinz Wenzl in his review of two battery conferences held in Europe in September, 1994 commented "I feel that this area [energy management systems] was not given adequate attention." He argues for the use of not only real time battery data, including the state of charge at the beginning of the charge cycle, but also the batteries' charge/discharge history and age. He notes there has been extensive use of energy management systems in several German industrial companies using industrial trucks, but does not detail their function or their use here has been more recognition of the importance of energy management during battery recharge than during discharge. Rechargers can be designed not to overcharge batteries, while at the same time new "pulse" charging techniques appear to be able to provide rapid recharging that not only does not harm batteries, but in some cases may help maintain battery performance. However, detection of overcharging is often only made at the battery pack level, and rarely is each cell in the pack instrumented to detect overcharging. Nissan's energy management system is implemented at the battery cell level, a requirement due to potential high temperatures in lithium-ion packs and resulting fires. The system reduces the inter-cell voltage variation from 60 to 25mV.

Battery pack instrumentation and state-of-charge indicators.

On-board energy management systems may be incorporated into a vehicle's recharging technology and software, its power electronics, or may be distinct systems. But whatever the precise location on the vehicle, one important component of on-board energy management is accurate measurement of power flows into and out of each module of the batteries. Related to the measurement of power delivered to, or drawn from, a battery is the batteries' state of charge. Thus, state-of-charge indicators are another critical element of energy management systems. Simply measuring the voltage across a battery does not always give an accurate picture of the battery's state of charge. The measurement of this voltage itself is subject to the power level and temperature at which the measurement is made. Attempting to integrate this voltage information across all cells in a battery and all batteries in a pack only compounds such difficulties. The importance of precise battery instrumentation in optimizing routine battery maintenance may diminish as batteries' require less maintenance. However, the energy management systems may also reduce maintenance costs for "maintenance free" battery types. The management systems will eliminate the need for manual testing for defective or worn batteries.

Norvik Traction Inc. announced in January 1993 that it would work with Chrysler to develop what they call the Battery Energy Management System (BEMS). This system is conceptualized as controlling both recharge and discharge, but the test results reported in December 1994 referred only to the implementation of the recharging control. In contrast to several other systems discussed here, the BEMS was not designed to rely on comparisons of battery data to a battery model, but to control battery recharge and discharge based on real time diagnostics. Chrysler has gone on to develop what it considers to be the state of the art in this type of technology for its EPIC minivan.

Systems that incorporate reporting or controlling of power discharges for individual batteries.

Wavedriver LTD's energy management system constitutes advanced software, microcomputers, and power electronics to manage both energy use for driving and recharging. This system allows rapid recharging. In August 1995, Wavedriver signed an agreement with Electrosource, Inc. for the joint development of advanced power management systems for utilities. Though scaled for utilities, both companies are very active in developing products for vehicle scale applications.

A joint Chinese-Japanese-American EV, the U2001, incorporates an "energy management system" to control all energy flows through the vehicle in all modes of operation. However the sensing technology only senses battery pack voltages and currents, not individual battery information. Using a model of the battery, stored profiles of trips and real-time battery data, the unit also forecasts remaining range

Gagnol, *et al* (1994) reported on the experience of Electricité de France (EDF) with energy management systems at EVS-12, held in December 1994. Their report is in the conference proceedings. Their report is germane to the discussion in this section for three reasons. First, their efforts to develop a energy management system were made after several EVs had been put into service and many of these had experienced premature battery failure. Thus EDF's energy management system was developed in direct response to real world battery behavior. Second, their system was designed to test each battery within the pack. Third, while it monitored the batteries during both recharge and discharge, it did not provide control of battery discharge. They reported the system did correctly report failures of single batteries while the battery pack parameters were within normal.

In the same conference proceedings, Schöpe reports on the development of a energy management system for nickel-cadmium batteries. The conceptual development of a battery operating system he provides includes control of the power electronics, but it is not clear this was actually achieved in the test vehicle. It appears rather that the actual test system provided information on battery condition to the driver. The system also records and stores the temperature, voltage and current data it collects. This system allows for analysis of the cause of any fault conditions.

INSTRUMENTATION FOR EV DRIVERS.

We have commented on the relative value of accurate range information for EV drivers and gasoline vehicle drivers in other reports and articles (see for example, Turrentine and Kurani, 1995). The relative value is a function of differences between daily range, miles per charge, recharging times for EVs on one hand, and the long range per tank and rapid ubiquitous refueling opportunities afforded by the network of gasoline stations.

Despite the value of accurate range, or even state of charge, instrumentation for EV drivers, such instrumentation was quite primitive prior to the late 1990s. Examples of EVs we acquired for use at the public ride-and-drive in Pasadena in 1991 (Turrentine *et al*, 1991) and descriptions of EVs owned by private citizens early in the 1990s (Turrentine and Kurani, 1992) showed at best an amp-hour or voltage meter connected to the output of the entire battery pack. “Sophisticated instrumentation” meant the vehicle had both types of meters.

Innovation and progress have occurred on several fronts. Individual battery modules (and in some cases, individual battery cells) are instrumented. Battery management systems, state-of charge measurements, and remaining range estimates can therefore operate on much more accurate characterizations of the batteries. Adaptive range estimation algorithms attempt to base remaining driving range on past behavior of the driver and the battery. All this activity has resulted in 39 U.S. patents being granted to battery state of charge and range instrumentation inventions since January 1991; only three were granted in the previous 11years.

Proper range instrumentation can serve two main purposes:

1. Feedback on power usage or regenerative energy recovery can improve the total efficiency of the vehicle by encouraging/educating the driver as to the most efficient way to drive.
2. Precise state of charge (be it as a distance estimate or percent state of charge) is vital to a driver who may push the vehicle to near its single charge range limit on a daily basis.

Most gasoline vehicles provide little instrumentation on their instantaneous fuel consumption and the effects of instantaneous driving patterns are averaged over the course of the 300 or more miles of driving that can be accomplished with one tank of fuel. Real time instrumentation of energy consumption becomes increasingly important with a low range vehicle as the driver has a vested interest in driving the vehicle in a way that maximizes range. Simply showing power usage or recovery from regenerative braking can have dramatic effects on how people drive their cars.

Showing the driver instantaneous power usage can illustrate the need to moderate acceleration and top speed. Power loss or gain can also be used to discourage quick starts or stops that require more energy to start and recover less regenerative energy on stopping. Aside from power usage, the EV driver also needs precise information about the remaining state of charge (range) and perhaps even the battery pack's potential capacity.

The total potential charge of the battery is usually not shown to the user of an EV. In the EV1 for example, the “wake up range” or number of miles on the range meter in the morning after a full charge could have several meanings. If it is lower than usual, this could indicate the battery’s capacity to store energy is diminished. It could just as easily reflect that ambient temperature has affected the total energy that could be transferred to the battery, or even indicate how aggressively the driver drove the previous day. The battery’s true capacity is hidden from the user. Likewise on EVs such as the Toyota RAV4 and S-10, the state of charge is shown on an analog gauge that ranges between full and empty. As the scale is not incremented in meaningful units, drivers of these vehicles have no idea of what their potential range might be, other than from previous experience.

The Honda EV Plus is different. The state of charge is not shown as a remaining (or “consumed”) number of miles, but rather as a number of bars. The top bar is marked “F” for full and the bottom one “E” for empty. The battery management system of the EV Plus will eventually determine that the battery no longer has 100 percent of its capacity to store energy. At this point, it will recalibrate the display scale—the “F” indicator will light beside the 9th bar and the 10th bar will not illuminate at all. The EV Plus is the only EV that gives the driver direct feedback as to the true overall capability of his or her battery pack to store energy.

The range gauge on the Honda EV Plus is dramatically different as it gives a range of mileage. With the 10 bars as a vertical graph, the horizontal axis is labeled with miles from 0 to 100 miles. The bars themselves are triangular shaped such that at 0 bars, the bar is only long enough horizontally to reach 0 miles. At 10 bars the horizontal length reaches to 100 miles. Obviously when the pack is de-rated to 90 percent or 80 percent so is his maximum range on the display. There is a second graph within the 10 bar graph that shows a second diagonal line between 0 degrees (vertical) and 45 degrees (the normal line from the normal triangular bars). As the driver uses more power (i.e. more aggressively or going up a hill) The yellow graph within the normal green graph will shrink such that at 8 bars remaining energy (80 miles) it may only go as far as 60 or 70 miles on the horizontal graph.

This gives the user feedback not only on the potential range of the vehicle in miles (based on the SOC) but also the potential range of the vehicle if the user continues to draw power at the current rate. When the driver is drawing little power (driving efficiently) the yellow and green bars will be the same.

The EV1 also has a bar graph display. In contrast to the EV Plus, a full charge will always be indicated by the last, 11th bar regardless of the battery's potential capacity. But conversations with EV1 drivers indicate that most do not rely on the bar graph, but on the "range-o-meter" which displays the number of miles remaining on the vehicle. This display is determined by both the battery state of charge and the driver's driving habits. This single number tries to combine battery capacity and current charge all compensated by the driver's habits and ambient conditions. The EV1 presents the driver with only one number. This has the benefit of precision, presenting to the driver an estimate of remaining range down to single digits. This is an advantage over the EV Plus instrumentation which requires the driver to do some visual interpolation, but the EV1 drivers report the system's estimates can easily be confused by things like an aggressive passing maneuver, or extended uphill or downhill driving.

All EVs delivered by the automotive OEMs during the MOA period have a "reserve range" just as a gasoline car does. Even when the EV tells you that it has zero miles left (or zero bars), drivers usually have another 3 to 10 miles of normal driving before a "reduced performance" mode is engaged. In this mode, top speed and acceleration are limited. Depending on the specific manufacturer, the driver might be able to drive yet another 10 miles (albeit at a sluggish pace to avoid damage to the batteries at a low SOC).

The EV1 can give the driver instant feedback on his/her power usage from the 11 bar graph which can show power usage on an exponential scale. The graph does not however indicate regenerative energy from braking unlike the Honda Insight hybrid or S-10 electric truck with its analog power gauge. Honda EV Plus drivers must look at the difference between the green potential range graph and the current yellow range graph to see how much power they are using at the moment.

Note that many EVs do not give adequate SOC indication. Some vehicles, like theS-10, Ranger, and RAV4 merely use an analog type display that is reminiscent of a fuel gauge for a gasoline vehicle. The mileage range display on the EV1 is the most precise, but its accuracy is subject to instantaneous driving conditions. The EV Plus uses 10 bars which also does not convey enough information about the precise SOC. EV Plus drivers must watch how many odometer miles go by between bars to estimate the distance each bar represents.

All told, while significant progress has been made in range and SOC instrumentation, EV drivers report more is needed.

AUXILIARY SYSTEMS

Heating and cooling

While fewer vehicles in the rest of the world are equipped with air conditioning, 80 percent of vehicles sold in the US today are sold with air conditioning (only 25 percent in Europe). All vehicles have heating, using in most cases the waste heat of the gasoline engine. Heating and air conditioning units on conventional gasoline vehicles use significant amounts of energy. This is fine in gasoline vehicles because they carry sufficient energy and have sufficient excess power to operate heating and air conditioning. For electric vehicles, ever little bit of weight and energy counts. EPRI reports that in one EV test in the early 1990s, up to 45 percent of the on-board energy of this particular EV was consumed by an off-the-shelf automotive air conditioning unit.

Many saw this as a fatal flaw for electric vehicles. But as we see in other areas, as EV technology has improved, new and unique advantages are revealed. Gasoline vehicle air conditioning is designed to cool the interior of a vehicle that has been left in the sun (hot soak temperature), without any attention to keeping the interior of the vehicle cool in the first place. Air temperature inside a vehicle parked in the sun can reach 160°F on 90°F day. The surface temperature of the dashboard area under the windshield can exceed the boiling point of water. As a result, air conditioning units for gasoline vehicles are designed without concern for efficiency, but rather for rapid cooling in this sort of extreme condition.

EVs have the advantage to pre-heat or pre-cool the vehicle while it is plugged into an electricity source. Additionally, on a hot day, one can simply vent the vehicle with a small fan powered by solar photovoltaic cells. Reducing the interior temperature even a few degrees adds to the comfort of those getting in a vehicle after a hot soak in the sun and reduces the peak cooling demand. Thus, the design of EV units are focused on maintaining a comfort range, rather than rapid cooling.

For greater efficiency, special air conditioners for electric vehicles are needed. Such air conditioners include more efficient models of conventional air conditioners, with more efficient, brushless dc motors, controllers, fans, and compressors and new applications of technology to automotive applications. GMs heat pump heating and air conditioning system.

Similarly, with heaters there are several options. In 1993, the Ford Ecostar was equipped with a high efficiency resistance type heater as well as a gas-fired heater for cold climates. Additionally, the higher power motors and controllers in today's EVs do have some waste heat. This waste heat is captured by some heater designs and used to heat the vehicle interior, as well as now is being used to thermal manage batteries.

Several patents have been granted for EV-specific (or EV-inspired) HVAC systems. And as we have seen in most other technology areas, the vast majority of these patents that have been granted since 1980, have been granted since January 1991. While 37 EV HVAC patents have been granted since the ZEV production requirement was announced, only two were granted in the eleven years prior to that time.

Heat pumps, scroll type compressors.

GM makes use of a heat pump to air condition the EV1. Heat pumps are extremely efficient and they can both heat and cool the vehicle with the use of a heat exchanger. GM has redeveloped the HVAC for the EV1 in each generation, improving its overall comfort. Nippondenso developed a fully integrated heat pump for cooling, heating and defogging, for use across a temperature range of –10 to 40°C degrees. It uses outside air for defogging and inside for heating, and 2 separate heat exchangers-one for cooling and one for heating to reduce moisture.

TABLE 5.14: ENERGY USE OF EV HVAC SYSTEMS

HVAC systems	Type	Load, watts	Comments
Conventional ac unit	Belt driven compressor	4,000	
GM EV1 heat pump	Single Heat pump	3 power levels 2,000, 1,625, and 1,125	
GM Generation II	Heat pump and PTA resistance heater	NA	
Nippondenso	Dual heat pump. Scroll compressor	1000w	-10-40°C (assumes 50% load reduction from glass coatings)

Additionally, in place of conventional piston type compressors, Sanden Corporation, in partnership with Arthur D. Little, Ford and Chrysler has developed a variable speed scroll type compressor. In concert with other technology, this system reduced air conditioning loads to only 11 percent of battery loads at 90°F.

Hot and cold seats; fans to vent the vehicle.

Heating and cooling air is an inefficient process. Many consumers are not happy with current technologies which blow extremely cold air on occupants to achieve air conditioning, or blow very hot air for heating. Instead, as Scandinavian drivers have know for a long time, heating the seat and steering wheels is faster, cheaper and more energy efficient. The seats can also be cooled. There are many consumers who will find this a better way to cool and heat their vehicles than conventional forced air systems, which are both slow and expensive to operate. Moreover, forced air heater systems now must wait for the engine to heat up before they operate because they use waste heat.

A small innovation that has already been included on some vehicles is a small fan, powered by solar energy to vent EVs while they are parked in the sun, to reduce the temperature of the vehicle prior to use. Both the Ecostar and Impact featured such fans. At least one Japanese automobile manufacturer has incorporated this feature in a conventional (ICE-powered) car. This innovation has found its way into Audi's gasoline powered line.

Defrosters.

Another consumer plus is the defrosting systems. Because they use resistance heating, defrosters in EVs do not have to wait for engines to heat up before they are ready to defrost. Defrosting can begin almost instantaneously. (Such resistance heating systems are now used for rear windows in many conventional cars.)

However, because heat pumps contain moist air, they are subject to rapid fogging of cold glass. In 1994 Mercedes unveiled a highly efficient heating unit which recirculated 80 percent of the air in the cabin and used a zeolite air drier to reduce moisture in the system.

Compound evaporative systems.

If you live in a hot and dry climate, you know the value of cooling the air with sprinklers. Engineers have redesigned evaporative cooling systems for vehicles that take advantage of the natural cooling properties of evaporating water droplets. These new systems are now being used in buses in the American South and Southwest. At least three companies have commercially available designs that are not only effective coolers, but affordable. These systems are very cost effective, have good air feel for consumers and except for adding water, are nearly maintenance free. There are no compressors or refrigerants to replace. Additionally, there are evaporative cooling systems that effectively cool even in humid climates.

Temperature pre-set when you get in

As consumers will find out when electric vehicles get to market, one of the biggest advantages of electric vehicles is that while the vehicle is plugged in for recharging, the vehicle interior and seats can be preheated or pre-cooled and the windows pre-defrosted. The GM EV1 features pre-heating and cooling, as do Solectria vehicles and the Honda EV Plus.

This can be done simply by a delay timers or by using remote control devices being developed by CYBEX and other Electric Vehicle Interface systems developers. Also, it is not necessary to be plugged in, one has the option of pre-conditioning the interior climate of the vehicle using some portion of the battery charge. Remember, most days drivers only go about 30 miles which leaves extra energy on-board for other uses should a driver choose to do so.

As with other EV technologies, the variety of new technologies and strategies to improve the climate control of EVs may produce climate control systems that are much better than conventional vehicles. Imagine a vehicle in which you could wake up, notice that a freezing rain had come in the night. You simply used your remote control to heat the windows, interior and seat before you left your house. Or you lived in Los Angeles, looked out of your office window at your EV in hot parking lot below, and minutes before leaving work, you use your remote control to cool the seats and the air in the vehicle.

Electric steering

While it is not a new development, electro-hydraulic steering systems are certainly getting a big push from EV industry. Both the Ford Ecostar and GM Impact and many other advanced EV designs incorporated what is called variable power assist systems. This innovation uses less energy at higher speeds when less power is needed, and will find its way into most vehicles in the near future.

Future designs may use "drive by wire " systems. In drive by wire steering, the steering wheel has no steering column attached. Movements of the steering wheel are translated into digital signals that actuate steering movements at the wheels. The absence of a mechanical linkage between the steering wheel and the wheels means drive by wire systems can be lighter, less subject to wear, and safer. Drivers are less subject to injury in a collision because there is no rigid steering column (though many of these injuries are now prevented by driver-side airbags). This innovation also allows more flexible location of other components within the space under the vehicle's dashboard because the steering column is no longer in the way, as well as greater standardization of components across platforms (Sato, 1995).

LIGHT-WEIGHT MATERIALS AND AERODYNAMIC VEHICLE DESIGN

Several technological developments are not exclusive to EVs, but are valued wherever energy efficiency is important. In this group of developments we include lightweight materials and aerodynamic design features. Many of these, e.g. plastics and aluminum used to replace steel, have been incorporated into conventional vehicles. The federal Corporate Average Fleet Economy standards (CAFE) has pushed many such changes as the auto makers sought to boost the fuel efficiency of their ICE powered vehicles. The Partnership for a New Generation Vehicle (PNGV) program has further pushed the development of light-weight vehicles. But between CAFE and PNGV came California's ZEV requirements. In addition to advances in electric drive trains and batteries, vehicle platforms have become lighter and vehicle shapes more aerodynamic because of the need for efficiency in EVs.

Thus, while not strictly tied to electric vehicles, the development of materials that are stronger and lighter, shapes that are more aerodynamic, and tires that have less rolling resistance are influenced by the demand for EVs, since a high premium is placed on efficiency. GM's Impact demonstrated that a vehicle designed with efficiency as a primary goal could have an extremely low drag coefficient, a lower coefficient of rolling friction and a light, strong body and frame, The next generation of GM EVs may use plastic and aluminum on GM's Triax chassis. The predecessor to Ford's TH!NK City EV, the PIVCO City Bee, had an all aluminum frame and an all plastic body. The TH!NK vehicle will have a frame made of aluminum and steel. Honda claims the chassis for the hybrid Insight weighs 47 percent less than the similarly sized steel chassis for their ICE Civic. They use resin materials and magnesium in engine components such as valve covers, oil pans, and pulleys to reduce the weight of the ICE in this hybrid vehicle. (www.honda.com) Moreover, the panels on the EV1 are attached with glues rather than welds.

Aluminum space frames

Light, strong aluminum space frames have been relatively expensive to make because aluminum costs more than steel per unit mass, the welding of aluminum is more expensive than welding steel, and aluminum welds require heat treating after fabrication. Aluminum frames are attractive however, because they can save 200 to 300 pounds compared to a steel frame designed for the same vehicle. One pound of aluminum can replace 1.7 to 1.9 lbs. of steel in rigid frame construction (Stodolsky *et al*, 1995a). This better than one-for-one displacement is part of the reason that despite the fact aluminum can be far more energy-intensive to produce per unit mass, increased use of aluminum will result in net energy savings (and thus also net reductions of CO_2 emissions) (Stodolsky *et al*, 1995b). The claim by Honda of a 47 percent weight reduction in the chassis of the hybrid EV Insight is substantiated by results with other vehicles such as Ford's aluminum-intensive Mercury Sable project. Intentionally substituting aluminum in ways that would have minimal impact on vehicle size, shape, or manufacturing, Ford reduced the weight of the body of the Sable by 173kg—or 47 percent compared to the steel body (ibid.).

Note this effort by Ford did not involve a complete vehicle redesign around the new material, but simply an effort to use a new material in an established product and production process. In a more far reaching effort, Ford's Synthesis 2010 aluminum vehicle has the same interior dimensions as the Taurus/Sable and is designed to carry a similar payload. Yet its curb weight of 1,043kg is 386kg, or 20 percent, less than the 1,429 steel-based Taurus/Sable (ibid.).

The most direct application of aluminum to EVs is in GM's EV1. GM claims the 290lb aluminum structure of the EV1 would weigh 500lb if it had been made out of steel. The aluminum structure is extremely rigid especially at low frequencies. This helps to isolate occupants from vibration. Aluminum was stamped, extruded, and cast into a wide variety components—displaying the versatility of this light-weight metal. Finally, GM claims the aluminum structure is 100 percent recyclable. (www.gmev.com)

The recent push for electric vehicles and fuel efficiency has prompted efforts to lower the cost aluminum frames. Investments have been made in new factories and new production and fabrication processes. These processes include the use of new garnet lasers for welding and construction of frames in modular sections to reduce the size of heat treat sections. Alcoa announced recently that it was building a $70 million dollar, first-of-its-kind automobile aluminum space frame plant in Soest, Germany. Audi will be its first customer. Alcan and Reynolds also continue to move into automotive applications.

Magnesium

Magnesium alloys are finding uses in vehicles other than the Insight. One of the patents that came out of GM's development of the Impact was for magnesium seat frames. Magnesium seat frames are now used in GM's Sunfire and Cavalier ICE vehicles ((www.gmev.com). Magnesium alloys have been used for years in small, die-cast parts. Gaines *et al* (1996) report that up to the mid-1990s, these parts totaled about 3kg of the weight of cars. They describe a Volvo concept car that, among other weight savings, employed a total of about 50kg of magnesium alloy parts including wheels, chassis, and engine block. The Ford Synthesis vehicle also used magnesium alloys, in addition to aluminum. Advances are still required in forming sheets, extrusions, and production processes such as welding and bonding.

Plastic and composite materials

One method of creating light and strong bodies is to use plastic and composite materials for body panels and frames. The GM Impact is constructed largely of plastics and aluminum. In the past, the finish on such body panels was not as highly polished as the factory paint finishes on steel, but composite panel companies are increasingly able to offer excellent surface finishes. Moreover, such structures are corrosion resistant. Interest in composite materials pre-dates the ZEV production requirement; Chrysler, Ford and General Motors formed the Automotive Composite Consortium in 1998. Its goal is to promote cooperation between suppliers and auto makers to make advances in composite engineering.

For low volume vehicle production, composite panels offer cost advantages. Since they require far less capital equipment than steel shaping, far fewer panels need be made with the same molds and models before the capital investment is recovered. One process for making composite panels, a patented Resin Transfer Method used by CIBA Composites, allows low cost fabrication with better than average surface finish. The US Commerce Department has awarded a $10 million grant to CIBA, US Electricar, and Advance USA to develop an ultra-light composite body for EVs. Thermoplastics are another method of creating low cost body panels, and have been used in the design of the Ford TH!NK City. One small design company, Horlacher of Switzerland, has built a series of prototype, all composite EVs. The Horlacher vehicles' bodies and frames are made entirely of composite structures with no steel members. These composites are stronger and lighter than steel. These prototype vehicles were designed to meet some European motor vehicle safety standards.

Steel rebounds

In response the surge of interest in composite car bodies., the steel industry is developing substantially lighter frames. One steel manufacturing groups has reduced the weight of a steel automobile frame from 596 to 451 pounds. For larger vehicle manufacturers, who may choose to offer both electric and internal combustion engine vehicles built on the same frame, lighter steel frames may be competitive with light weight aluminum and composite frames. These larger manufacturers may be able to take advantage of existing economies of scale in their production facilities. However, for small production runs of purpose built EVs, the possibility of inherently lower capital costs for composite materials indicates they could take this market away from steel.

Overcoming air resistance

The drag coefficient measures the energy lost due to a body moving through air. Vehicles with lower drag coefficients expend less energy simply to overcome the resistance caused by moving through air. The theoretical lower limit for the coefficient is zero. The Impact 1 used a variety of techniques to reduce its drag coefficient to the lowest level recorded for a motor vehicle intended for general street use—0.19. Low values for conventional vehicles are approximately 0.30 and many vehicles have much higher drag coefficients. The aerodynamic design features of the Impact 1 included a body shape that minimizes flow separation of air from the body, a flat underbody, and panels that covered the rear tire wells. Run flat tires reduce the need to access the tires quickly.

Given the goal to increase fuel efficiency, we are not surprised that aerodynamic new designs are reported for PNGV concept and prototype vehicles. GM claims their Precept vehicle has a drag coefficient of 0.16; Ford's Prodigy, 0.20; and Daimler Chrysler's ESX III, 0.22 (York, 2000). We do not have sufficient details on these programs to link specific advances in aerodynamics developed for EVs to specific advances in these PNGV vehicles. On the other hand, only GM developed a sleek, new, aerodynamic platform for an EV they placed in service in response to their MOA. This raises again the question, what sort of range, efficiency, and driver satisfaction could the other automobile manufacturers attained if they had placed electric drive trains in platforms optimized for efficiency?

Overcoming rolling resistance

Energy is lost through the friction between the tires and the road. New tire designs aim to minimize this energy loss. The Impact 1 featured tires with extremely low rolling resistance—up to 40 percent less rolling resistance than conventional radial tires. The Impact 3 and other recent EVs use such tires too. These low rolling resistance tires have been improved further since 1991, but more important, the number of manufacturers has increased. Six tire manufactures—Bridgestone, Dunlop, Firestone, Goodyear, Michelin and Pirelli—are now offering low rolling resistance tires for EV and other limited production applications.

6. FUTURE IMPROVEMENTS, FUTURE DIRECTIONS FOR EVs

The rapid improvements in EV technology during the past decade have delivered vehicles for tests and practical use which are beyond what many thought possible in 1990 or were only hoping could be developed. The question now becomes what are the areas of near term improvements. Of course there are questions still about batteries: Are there design and production breakthroughs possible for lithium-based batteries? What price reductions are possible for NiMH batteries? Will the promise of long cycle life of the new Panasonic lead-acid batteries be realized? In fact for all batteries, what are the frontiers of life cycle? And what are the possibilities for rapid recharging? How much further can the price of off-board Level 3 equipment drop? Can on-board Level 2+ charging become standard? Finally, what are the myriad points of continuous improvement that will contribute to greater variety of vehicles in the market, improved daily range, longer single charge range, and competitive costs of production?

Below we rank what we believe are the areas of technical progress in the next few years that will take EVs a step further.

INCREASED VEHICLE EFFICIENCY AND MILES PER SINGLE CHARGE

- **Improved aerodynamics.** The performance of the EV1, especially in comparison to other EVs offered by the automotive OEMs to fulfill their MOA obligations, across a variety of tasks illustrates that of all the design features of EVs, the one which holds the greatest potential for improving the efficiency, and therefore range of EVs without further breakthroughs in battery technology is reduced frontal area and reduced coefficient of drag. Special areas of likely improvement to the MOA vehicles provided by the OEM in the late 1990s are smoother undersides, better tail shapes, and substitution of side mirrors with video cameras. The Ford Prodigy and DaimlerChrysler's ESXIII vehicles clearly indicate that they too can build aerodynamic vehicle platforms.

- **Thermal characteristics of NiMH batteries**. NiMH batteries have proven to be durable, and they have increased the miles per single charge of EV batteries. But the exothermic qualities of the battery limit performance in warm climates and to some extent limit rapid charging in ambient temperatures which are common in California. The water-jacketed Saft battery in the EPIC demonstrates that there are thermal management solutions—but they come at a weight and energy cost. Additionally, the current improvements in lead acid batteries offer a near term option for many applications which may be better suited to the demands of fast charging and ambient temperatures in California.

- **More efficient auxiliary loads.** Peak auxiliary loads totaling 1 to 2kW can reduce the range of EVs by 15 percent or more. Vehicles tested as part of the USDOE's FOP program showed average range reductions varying from 11 percent (Ranger EV) to 17 percent (EPIC) between no auxiliary load tests and tests in which headlights, air conditioning, and radio were on. More efficient HVAC, power steering, and other auxiliary equipment can improve range. An auxiliary load increase of 400 watts results in a 1.0mpg drop in fuel economy for a gasoline vehicle that averages 28mpg.

- **Reduced chassis and body weight**. Many of the OEM MOA vehicles were not built on lightweight vehicle platforms. In fact, some vehicles required additional reinforcement of the chassis to support the weight of batteries. There are sizable potential weight reductions for vehicles such as the RAV4 and EV Plus by moving to specialized platforms like those demonstrated by the GM Triax and Precept, DCX ESX III, Ford Prodigy, as well as the Honda Insight, and Toyota Prius and Echo vehicles already on the road in North America.

INCREASED DAILY RANGE

Reduced cost in fast charge stations: Aerovironment 60 kW charge station is currently listed at $40,000. The combination of the opportunity value of the associated space for vehicles and equipment must be reduced significantly to create a profitable public rapid charge structure (but perhaps still cheaper than a ubiquitous Level 2 off-board system).

Standardization of multi-level charging equipment across manufactures: Standardized Level 2, Level2+, and Level 3 charge connections are essential to a practical recharging infrastructure.

Adoption of Level 2+ on board charging: Level 2+ on-board charging can offset the cost of Level 2 off-board infrastructure. Further, reintegration of high power recharging on-board the vehicle reopens a technological and behavioral pathway that was blocked by the near universal adoption of off-board high power recharging systems. The initial choice by automobile manufacturers to put the charger off-board and subsequent standard setting reflect technological limits of the late 1980s. With new, lighter, more compact high power electronics, the cost and locations of away-from-home recharging opportunities may be much more numerous than the opportunities afforded by a system built around off-board recharging appliances.

FUTURE DIRECTIONS?

As we discussed in Chapter 4, nearly all manufacturers have expressed interest in continuing electric drive train development, but their goals appear to be hybrid EVs and fuel-cell vehicles. We don't list fuel-cell programs in Table 4.1, and we list only a few of the hybrid vehicle programs. We continue that discussion by continuing the quote from Hiroyuki Watanabe, (managing director and a member of the board for Toyota Motor Corporation (TMC)) in which he outlined Toyota's vision of the future in a presentation to the Society of Automotive Engineers' 2000 Future Car Congress:

> "...Toyota thinks that battery electric vehicles may potentially play a specialized role in the automotive market as part of a balanced overall clean-air strategy utilizing EV, hybrid gas/electric and ultra-low-emission internal-combustion technologies while continuing development of fuel cell technology." (Toyota Motor Company press release. May 31, 2000)

This statement represents an ironic sense of technical progress over the past ten years. Keeping in mind that the paragraph immediately prior to this one in the Toyota press release (quoted on p. 21) refers specifically to "shared usage of mini electric vehicles," and looking at Toyota's e•com, Nissan's Hypermini, and Ford's TH!NK Neighbor and City it would seem that one of the steps the automotive OEMs have taken since the ZEV production requirement went into effect is to embrace the idea of the small, light-weight, low speed EVs of the 1970s. To be sure, all the products just named are tremendous advances over the Sebring-Vanguard and the Elcar. Speeds are higher, range is longer, safety is vastly improved, and overall engineering is far more sophisticated.

But the idea that there is a role for personal mobility vehicles that are not just like the cars and trucks with which we are familiar is new since 1996 in the public rhetoric of the automobile companies. Toyota is calling for car sharing of mini-EVs; Ford is telling us to rethink personal mobility vehicles. In 1996, the auto manufacturers successfully lobbied CARB to delay implementation of the ZEV sales requirement because, they argued, they could not make EVs like conventional vehicles. Four years later, the message appears to be that they still believe they can't. They offer instead promises of hybrid and fuel cell EVs, and small light-weight "city" EVs and electric LSVs.

In April 1999, General Motors Corp. and Toyota Motor Corp. announced they would enter into a five-year collaboration to develop advanced technology vehicles. They identified more than a dozen advanced vehicle and system projects that will be researched together. Of note to EVs, the agreement calls for development of:

- A common set of electric traction and control components for future battery electric, hybrid electric and fuel cell electric vehicles.
- Batteries and battery test procedures, vehicle safety requirements, and continued work on improved inductive charging systems for battery electric vehicles.
- Power train and control systems for next generation hybrid electric vehicles.
- Future systems design, fuel selection and processing to support production of fuel cell powered vehicles.

All this "body language" from the automotive manufacturers adds up to a less than compelling argument that they will continue to offer EVs in the absence of either, or both, 1) regulatory production requirement to do so and 2) a demonstrated market demand. We note the latter is unlikely to happen in the absence of EVs from the automobile manufacturers in the first place.

And assigning causality for improvements in EVs and EV technology to the ZEV production requirement remains anathema to the automobile companies. The following exchange is from the question and answer session following a panel discussion on "Whither Tomorrow's Car?" at the 1999 Environmental Vehicle Conference:

Question:	If there is no ZEV production requirement, is that the end of the EV?
Answer:	DCX: "It would certainly give us a chance to focus on what the customer and the marketplace wants than to meet some artificial requirement."

A synopsis of the panel discussion and question and answer session may be found at:
www.evworld.com/conferences/env99/env99_blueribbon.html; and
www.evworld.com/conferences/env99/env99_Q&A.html.

The panel included representatives from Toyota, Nissan, DCX, General Motors, and EcoStar Drive (a joint venture of DCX, Ford, and Ballard Power Systems), among others. Only the representative from DCX offered the predictable response.

But the answer presumes that the customer knows whether they want EVs or not. The answer presumes that the existing marketplace already gives sufficient expression to consumer desires that car companies can judge whether people would want EVs based on purchases of conventional vehicles.

The automobile manufacturers made a measured and strategic response to their obligations under the MOAs signed with the State of California. They have for the most part supplied only as many vehicles as they were absolutely required. If they were losing money on each one, why would they offer any more? On the other hand, no one ever thought a few thousand vehicles would be all it would take to start the market for EVs.

The year 1990 marked a watershed in the development of EVs and EV technology. Advances since then have resulted in EVs that are practical, comfortable, and fun to drive. The hard work of market development remains.

7. CONCLUSIONS

We have traced several effects of the ZEV production requirement back to its root effect—it set the clock for the introduction of electric vehicles to commercial markets to the year 1998, and then reset that clock to 2003 with the MOAs with the major automotive OEMs. Since late 1990, the attention of the auto industry, electronics industry, battery industry, consumer groups, federal and state clean air programs, federal energy programs, electric utilities and a host other parties has been focused forward to 1998, and now 2003.

The effects of this attention have been dramatic. Electric vehicles have been transformed from golf carts, plant vehicles, and converted curiosities into high performance, high quality transportation tools. Old technologies have been rediscovered and improved. New technologies have been developed. Inventions and innovations have sprung out of research and development programs, some that arose directly from the ZEV production requirement and others that were revitalized by it. The advanced battery consortia were formed expressly to address perceived problems made salient by the ZEV production requirement. During the 1980s, the federal Department of Energy's Electric and Hybrid Vehicle Program had quietly moved along for over a decade before being injected with new energy and interest by the ZEV production requirement in 1990. ARPA funds may have been available even without the ZEV production requirement, but the intense focus on the commercial potential of electric transportation in every ARPA consortium can be traced to the production requirement.

Electric vehicle technologies have been improved as a direct result of California's ZEV production requirement. One important barometer of this change is the General Motors Impact. Superficially, it may appear there has not been much progress in EVs in the past ten years judging by the appearance of the EV1. Yet, the latest generation EV1 shows evolution from a show car to a practical (yet still exciting) sports car, which happens to be electric. The latest EV1 is more powerful than the first, and its components are more reliable, and less costly. It has improved electronics, more consumer amenities, and improved range instrumentation. Also, the new EV1 offers at least two types of battery packs, each much more reliable than any pack in the past. The NiMH pack allows a range well beyond previous expectations.

Many still contend that driving range, and thus battery technology, remain the same stumbling blocks to commercially viable EVs that they was perceived to be in 1990. This perception is largely a result of the misconception that electric vehicles must substitute for gasoline vehicles on a one-for-one, trip-by-trip basis. As long as one believes EVs must have driving ranges comparable to gasoline cars, one will conclude that the batteries now considered the likely candidates for use in vehicles in 2003 are inadequate. But as we have shown in other research, EVs do not have to have the range of gasoline cars.

If there is any remaining "battery problem" to the commercial viability of EVs it is likely to be cycle life—the number of times the battery can be charged and discharged while providing its rated energy and power. This problem might be solved with new batteries—new VRLA, nickel metal-hydride, and lithium-ion batteries may reliably provide cycle lives greater than 1,000. Yet even cycle life may not be a battery problem, per se. Improved charging algorithms, sophisticated monitoring of battery cell conditions, and thermal management systems all can improve battery life.

Electric vehicles, using lead-acid batteries, have advanced to the point where lightweight, efficient, sub-compact and compact designs can reliably provide up to approximately 80 miles driving range on a single charge. Further advances will extend the range and allow for increased vehicle size. But we have come far enough that we are compelled to keep moving forward. The ZEV production requirement has interwoven various strands of technological, commercial, and policy initiatives. In so doing, it has created advances in EV technologies that experts in their field believe would not have happened in its absence.

The ZEV policy setting became a good deal more complex in 1996. The 1998 ZEV sales requirement was cancelled. MOAs governing the placement of EVs in California between 1996 and 2000 were negotiated. And while the 10 percent ZEV sales requirement was nominally retained, considerable flexibility was added. In fact, should auto makers produce only EVs with single charge ranges over 100 miles, only two percent of vehicles offered in 2003 must actually be ZEVs.

The MOA period has seen the application of some advanced battery technology, though it is hard to judge whether it is what regulators expected. There has been no real competition among many competing advanced batteries. Only Nissan broke ranks and offered something other than a NiMH battery. Their lithium-ion battery looks promising. The years between now and 2003 will test whether this lithium battery proves reliable and long-lived. Battery development during the MOA period included the continued improvement of lead-acid batteries. The new Panasonic line of lead-acid EV batteries built by Matsushita do not meet the specific energy goals to be considered "advanced" battery technology according to the conditions of the MOAs. Despite this, they have made tremendous improvements in the reliability and range performance of the EV1, whose Delphi VRLA batteries they replaced.

The MOA period has not seen the release of any new, purpose-built, light-weight, aerodynamic EVs, other than GM's EV1. In many regards, GM appears to remain the technological leader among the major OEMs. The EV1 was not only offered with lead-acid batteries, and then both improved lead-acid and NiMH batteries, but the drive train was improved too. Honda's EV Plus was built on a highly modified platform, with ordinary design, weight, and aerodynamic performance. It was certainly no match for the platform built for Honda's hybrid Insight. Toyota simply converted a popular but ordinary compact SUV. Ford did much the same with their electric Ranger pickup trucks. To be fair, GM met part of its MOA obligation with an unexceptional pickup truck too.

Some of these vehicles, the pickup trucks in particular, were marked improvements over earlier conversions by other companies. But most of the range improvements of the late-1990s can be attributed the switch from lead-acid to NiMH batteries. And this switch reduced the efficiency of every single vehicle in which switch was made. In this case, longer range not only cost more money up front, it costs the driver more money for every mile driven.

Throughout the 1990s, a great deal of innovative activity was to be found in small companies. Along the way small firms such as U.S. Electricar have come and gone (and come and gone again). Unique Mobility, an early pioneer of motors and other components, recently announced they would focus solely on hybrid EVs. AC Propulsion and Solectria continue their long histories of innovation. AC Propulsion's tzero sports car is perhaps the best testament to the acceleration and speed capabilities of EVs. And along the way, they have continued to show the advantages of high-power systems for energy flows both into (recharging and regeneration) and out of the battery, as well as the importance of designing for efficiency. Their integration of Level 2+ charging capability on-board their vehicle is the latest expression of advances in charging capability.

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APPENDIX A: STATISTICAL DETAILS OF THE PATENT ANALYSIS

We are interested in the hypothesis that 1990 the year CARB announced the ZEV production requirement represented a change of "eras" in EV-related research and development activity. We expect that after 1990, EV-related research and development activity greatly increased.

As discussed in the body of this report, plots of the number of EV-related patents give a qualitative indication that the ZEV production requirement did signal a shift in inventive activity directed toward EVs. Between 1980 and 1991, there were few EV-related patents issued per year—in fact, the number of patens starts low (around 15 to 20), and then declines (4 to 6) between 1989 and 1991. Twelve patents were assigned to the federal DOE during this time period. After 1991, the number of EV-related patents climbs rapidly. By 1996, over 100 EV-related patents per year are being issued.

However, it is not enough to simply show that the annual number of EV-related patents increased after 1991. We must show that this increase is not due to any other factors that may have caused all patent activity to increase after 1991. A variety of factors may have caused the number of all patents to increase in the same time period. Changes in international agreements might have caused more foreigners to apply for U.S. patents; the advent of the rapid expansion of the World Wide Web in the early 1990s might have affected patents. The plots of all U.S. "utility" patents does show that increasing numbers of all patents were issued throughout the study period.

For statistical analysis, the null hypothesis is formulated as "no change," that is there was no difference in the number of EV-related patents issued per year before and after 1991. If P-EV_{-1991} is the measure of EV-related patent activity during and before 1991, and P-EV_{+1991} is the measure after 1991, then

1. H_{10}: $\text{P-EV}_{-1991} = \text{P-EV}_{+1991}$

We can conduct even stronger, one-tail tests since the entire analysis is driven by the idea that the ZEV increased EV-related patent activity. We form the alternative one-tail hypothesis

2. H_{1A} one -tail: $\text{P-EV}_{-1991} < \text{P-EV}_{+1991}$

Further, if P-All_{-1991} is the measure of all patent activity during the period 1980 through 1991, and if P-Al_{l+1991} is the measure after 1991, then we are interested in the null hypotheses that all patent activity was unchanged after 1991:

3. H_{20}: $\text{P-All}_{-1991} = \text{P-All}_{+1991}$

Finally, if H_{20} is rejected, we are interested in whether the change in EV-related patent activity from before to after 1991 was the same as the change in all patent activity:

4. H_{2A}: $(\text{P-EV}_{-1991} - \text{P-EV}_{+1991}) = (\text{P-All}_{-1991} - \text{P-All}_{+1991})$

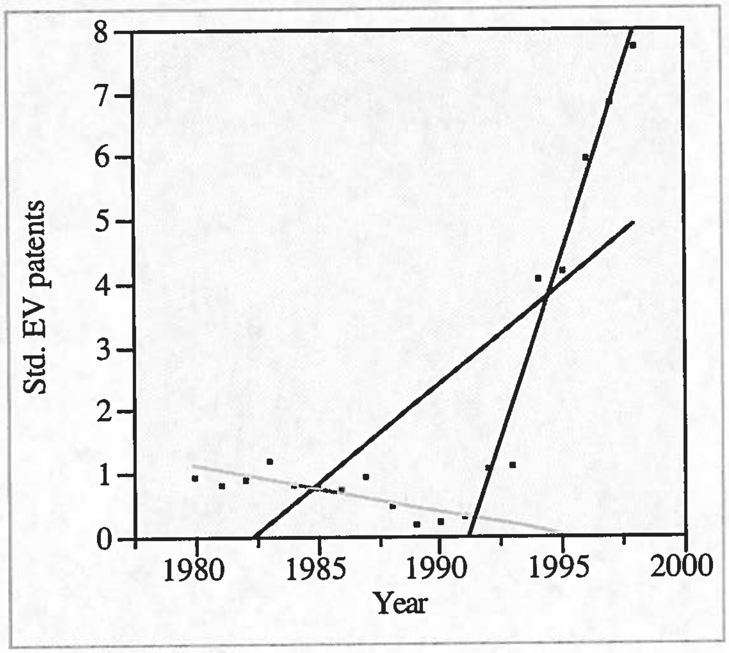
The specific measure of P that we test two is the slope of linear regression line fit to data in each of the two eras. This is equivalent to measuring 1) whether or not a linear model fits the number of patents from year to year, and if so, 2) whether or not the slopes are equal in the two eras and for the two types of patents. The analysis is shown below.

To summarize the analysis that follows, we conclude that one equation does not provide a satisfactory fit to the whole time series of data. The best fit is accomplished by fitting separate equations to two distinct eras. While we show the analysis for a dividing year of 1991, we note that similar substantive results are reached if we use 1992. During the 1980 to 1991 era, the number of EV-related patents issued per year is generally declining. After 1991, the number of patents increases each year. Further, That is, we reject H_{10} and accept H_{1A}. In addition, we show that a single equation does provide a robust fit to the data for all patents, that is, we do not reject H_{20}, and therefore do not accept H_{2A}.

EV-RELATED PATENTS

Figure A1 shows the data points of the annual number of EV patents granted per year and three lines fit by linear regression. The data have been standardized to the year 1980. This only affects the scale of the coefficients. The red line is an equation fit to all years. The green line is the fit to years 1980 through 1991. The blue line is the fit to the years 1992 to 1998.

FIGURE A1: STD. EV PATENTS BY YEAR



Equation 1: All Years (red line)

Std. EV patents = -623.93 + 0.315 Year

Summary of Fit

RSquare	0.54426
RSquare Adj	0.517452
Root Mean Square Error	1.667802
Mean of Response	2.117647
Observations (or Sum Wgts)	19

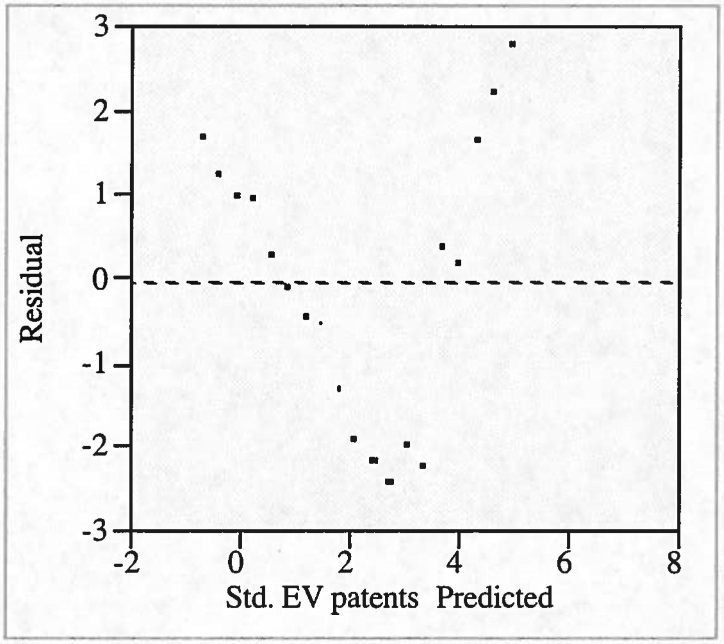
Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	1	56.471	56.471	20.302
Error	17	47.287	2.782	**Prob>F**
C Total	18	103.758		0.0003

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|	Lower 95%	Upper 95%
Intercept	-623.935	138.9452	-4.49	0.0003	-917.082	-330.788
Year	0.3147575	0.069857	4.51	0.0003	0.1673739	0.462141

FIGURE A2: RESIDUAL OF EQUATION 1 PLOTTED VERSUS PREDICTED STD. PATENTS.



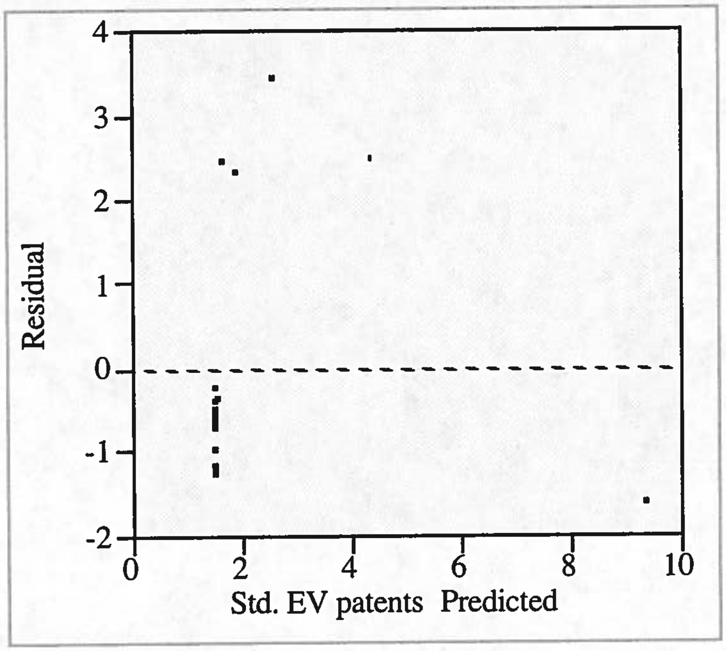
Testing of the hypothesis 1 and 2 from above is a matter of first establishing whether Equation 1 or the combination of Equations 2 and 3 are appropriate. If it is judged to be the latter, then we must compare the coefficients for the variable "Year" in Equations 2 and 3.

The Analysis of Variance table for Equation 1 tells us it is statistically better than assuming the mean value for all years is the best fit. The F-value is 20.302, and the probability of getting a larger value by chance alone is much less than one percent. The adjusted R-square value indicates that Equation 1 explains about 52 percent of the variation in the number of EV-related patents issued per year from 1980 through 1998. The coefficient for the variable "Year" is significantly different from zero at better than a 95 percent confidence level. The value of the coefficient indicates that on average the number of EV-related patents increased by 0.315 times as many such patents as were issued in 1980.

However, the plot of the residuals (the difference between the predicted and actual values) in Figure A2 reveals (in fact, simply mirrors what is obvious in Figure A1) that Equation 1 violates one of the assumptions of linear regression. Specifically, the residuals show a regular relationship with the predicted values. The residuals consistently get smaller as the predicted value increases from 1 to 3, and then consistently decline as the predicted value increases. This can be re-scaled to show that the residuals have a consistent relationship with the explanatory variable Year. This specific pattern, especially since we are dealing with time series data, is most likely a representation of violation of the assumption of no *autocorrelation*—the error term associated with one observation (the number of patents in one year) cannot correlated with the error term of any other observation. If autocorrelation is present, then the estimate of the coefficient for Year is unbiased, but the significance tests are not accurate. In general, autocorrelation tends to overstate significance, leading us to accept a coefficient is different from zero, when in fact it is not.

One commonly suggested approach to treating autocorrelation is to transform the affected independent variable. Without showing the whole analysis, we do show the residuals plot for the analysis of the number of EV-related patents regressed on the year transformed as an exponential does little to solve the problem in this case. In this case, the equation overestimates patents (residuals are negative) in 14 of 18 years.

FIGURE A3: RESIDUALS OF THE REGRESSION OF NUMBER OF EV-RELATED PATENTS PER YEAR ON $E^{\beta YEAR}$



An alternative approach to the problem is to assume that 1991 divides the data into two distinct eras. We can then estimate one linear regression during each era, and compare the coefficients for the Year variable. If the coefficient for the era from 1980 through 1991 is statistically smaller than the coefficient for the era 1992 through 1998, then we accept hypothesis H_{1A}. The statistics for these two equations are shown below as Equation 2 and Equation 3.

Equation 2: 1980 to 1991 (green line)

Std. EV patents = 143.675 – 0.07199 Year

Summary of Fit

RSquare	0.663722
RSquare Adj	0.630094
Root Mean Square Error	0.193766
Mean of Response	0.745098
Observations (or Sum Wgts)	12

Analysis of Variance

Source	**DF**	**Sum of Squares**	**Mean Square**	**F Ratio**
Model	1	0.7410410	0.741041	19.7373
Error	10	0.3754527	0.037545	**Prob>F**
C Total	11	1.1164937		0.0012

Parameter Estimates

Term	**Estimate**	**Std Error**	**t Ratio**	**Prob>|t|**	**Lower 95%**	**Upper 95%**
Intercept	143.67496	32.17215	4.47	0.0012	71.990485	215.35944
Year	-0.071987	0.016204	-4.44	0.0012	-0.108091	-0.035883

Equation 3: 1992 to 1998 (blue line)

Std. EV patents = -2363.5 + 1.18697 Year

Summary of Fit

RSquare	0.955649
RSquare Adj	0.946779
Root Mean Square Error	0.605115
Mean of Response	4.470588
Observations (or Sum Wgts)	7

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	1	39.449456	39.4495	107.7371
Error	5	1.830821	0.3662	**Prob>F**
C Total	6	41.280277		0.0001

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|	Lower 95%	Upper 95%
Intercept	-2363.544	228.1403	-10.36	0.0001	-2949.989	-1777.099
Year	1.1869748	0.114356	10.38	0.0001	0.8930177	1.4809319

Per the same criteria discussed for Equation 1, both Equation 2 and 3 provide a statistically satisfactory fit to the data for its era. We then compare the coefficients for the explanatory variable Year. From Equation 2, the coefficient indicates that the number of EV-related patents declines on average by 0.07 times as many patents as were issued in 1980. We are confident at the 95 percent level that the value of the coefficient lies between -0.108 and -0.036. From Equation 3, the coefficient indicates that on average since 1992 the number of EV-related patents has increased by 1.19 times as many such patents as were issued in 1980. The 95 percent confidence interval ranges from 0.893 to 1.481.

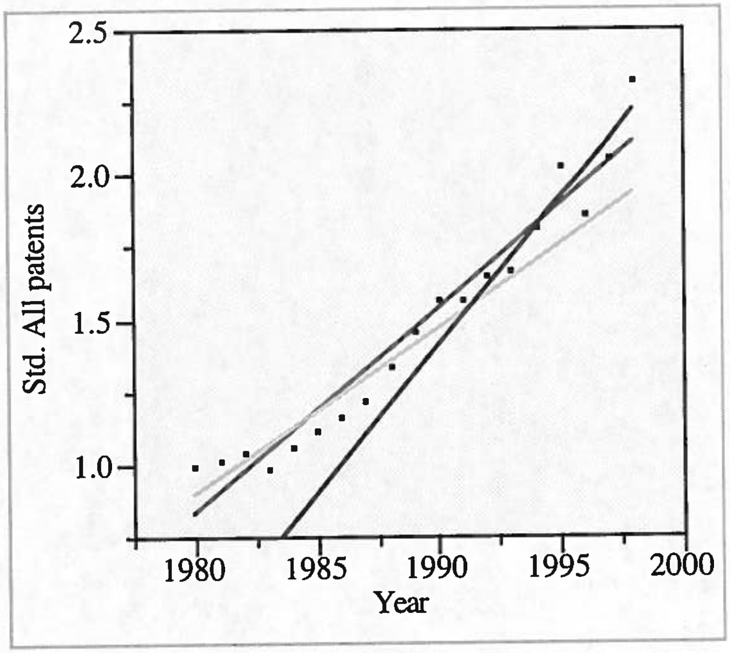
Since confidence intervals from the two estimates do not overlap, we conclude they are different. Thus, we reject H_{10}. Since the coefficient from the time period from 1980 to 1991 is unambiguously less than zero, and the since the coefficient from the time period after 1991 is unambiguously greater than zero, we accept H_{1A}. The rate of change in the annual number of patents issued per year was less during 1980 through 1991 than it was after 1991.

ALL PATENTS

The analysis of the number of all patents issued each year from 1980 to 1998 proceeds in a similar manner as that for EV-related patents above. In this case though a single equation for the entire time period provides a good fit to the data, there are no obvious problems with autocorrelation, and even if we estimate two separate equations the coefficient for the explanatory variable Year are not significantly different at the 95 percent confidence interval.

We do not reject H_{20}. We conclude there is no change in 1991 in the rate of change of growth in the number of all patents per year. Before, during, and after 1991 all patents increased by 0.07 times as many patens as were issued in 1980.

FIGURE A4: STD. ALL PATENTS BY YEAR



Equation 4: All Patents from 1980 to 1998

Std. All patents = -140.46 + 0.07136 Year

Summary of Fit

RSquare	0.946199
RSquare Adj	0.943035
Root Mean Square Error	0.09853
Mean of Response	1.476961
Observations (or Sum Wgts)	19

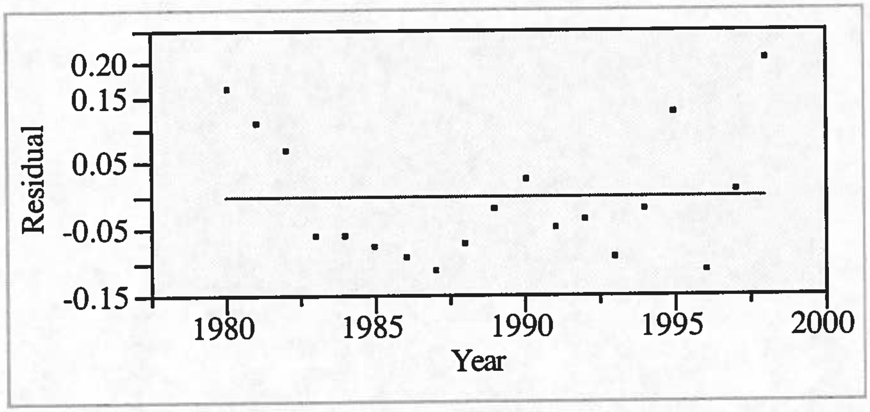
Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	1	2.9025468	2.90255	298.9813
Error	17	0.1650381	0.00971	**Prob>F**
C Total	18	3.0675848		<.0001

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|	Lower 95%	Upper 95%
Intercept	-140.4572	8.208553	-17.11	<.0001	-157.7756	-123.1388
Year	0.0713596	0.004127	17.29	<.0001	0.0626525	0.0800666

FIGURE A5: RESIDUALS OF PREDICTED ALL YEARS VERSUS YEARS



Equation 5: All Patents from 1980 to 1991

Std. All patents = -113.29 + 0.05767 Year

Summary of Fit

RSquare	0.895574
RSquare Adj	0.885132
Root Mean Square Error	0.074473
Mean of Response	1.217422
Observations (or Sum Wgts)	12

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	1	0.47564888	0.475649	85.7619
Error	10	0.05546157	0.005546	**Prob>F**
C Total	11	0.53111044		<.0001

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|	Lower 95%	Upper 95%
Intercept	-113.293	12.36513	-9.16	<.0001	-140.8444	-85.74163
Year	0.0576734	0.006228	9.26	<.0001	0.0437971	0.0715496

Equation 6: All Patents from 1992 to 1998

Std. All patents = -200.44 + 0.10144 Year

Summary of Fit

RSquare	0.841305
RSquare Adj	0.809567
Root Mean Square Error	0.104254
Mean of Response	1.921884
Observations (or Sum Wgts)	7

Analysis of Variance

Source	**DF**	**Sum of Squares**	**Mean Square**	**F Ratio**
Model	1	0.28810505	0.288105	26.5071
Error	5	0.05434493	0.010869	**Prob>F**
C Total	6	0.34244998		0.0036

Parameter Estimates

Term	**Estimate**	**Std Error**	**t Ratio**	**Prob>|t|**	**Lower 95%**	**Upper 95%**
Intercept	-200.4449	39.30598	-5.10	0.0038	-301.4827	-99.40717
Year	0.101437	0.019702	5.15	0.0036	0.0507915	0.1520825

APPENDIX B: EV1 DRIVING RANGE ON THE POMONA TEST LOOPS

Response: Range
Summary of Fit

RSquare	0.945907
RSquare Adj	0.926237
Root Mean Square Error	4.213911
Mean of Response	85
Observations (or Sum Wgts)	16

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|	Lower 95%	Upper 95%
Intercept	85	1.053478	80.69	<.0001	82.68	87.32
Battery[Delphi-Panason]	-9.325	1.053478	-8.85	<.0001	-11.64	-7.01
Payload[heavy-light]	-2.8	1.053478	-2.66	0.0223	-5.12	-0.48
Aux. Loa[no-yes]	6.6875	1.053478	6.35	<.0001	4.37	9.01
Loop[freeway-urban]	8.6	1.053478	8.16	<.0001	6.287	10.92

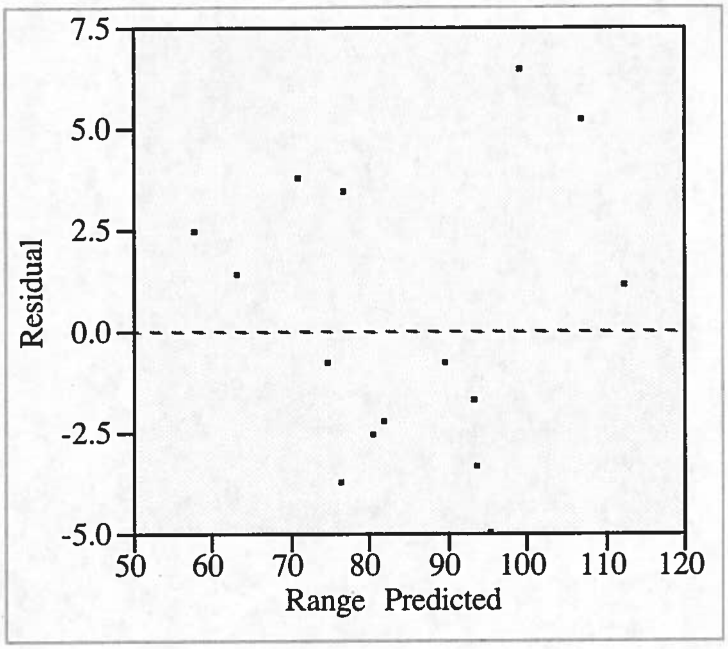
Effect Test

Source	Nparm	DF	Sum of Squares	F Ratio	Prob>F
Battery	1	1	1391.2900	78.3514	<.0001
Payload	1	1	125.4400	7.0642	0.0223
Aux. Load	1	1	715.5625	40.2974	<.0001
Loop	1	1	1183.3600	66.6417	<.0001

Whole-Model Test

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	4	3415.6525	853.913	48.0887
Error	11	195.3275	17.757	**Prob>F**
C Total	15	3610.9800		<.0001



Battery
Effect Test

Sum of Squares	F Ratio	DF	Prob>F
1391.2900	78.3514	1	<.0001

Least Squares Means

Level	Least Sq Mean	Std Error	Mean
Delphi	75.67500000	1.489842502	75.6750
Panasonic	94.32500000	1.489842502	94.3250

Payload
Effect Test

Sum of Squares	F Ratio	DF	Prob>F
125.44000	7.0642	1	0.0223

Least Squares Means

Level	Least Sq Mean	Std Error	Mean
heavy	82.20000000	1.489842502	82.2000
light	87.80000000	1.489842502	87.8000

Aux. Load
Effect Test

Sum of Squares	F Ratio	DF	Prob>F
715.56250	40.2974	1	<.0001

Least Squares Means

Level	Least Sq Mean	Std Error	Mean
no	91.68750000	1.489842502	91.6875
yes	78.31250000	1.489842502	78.3125

Loop
Effect Test

Sum of Squares	F Ratio	DF	Prob>F
1183.3600	66.6417	1	<.0001

Least Squares Means

Level	Least Sq Mean	Std Error	Mean
freeway	93.60000000	1.489842502	93.6000
urban	76.40000000	1.489842502	76.4000

APPENDIX C: RANGER, S-10, AND EV1 AC EFFICIENCY, POMONA LOOPS

Ford Ranger
AC kWh/mi
Summary of Fit

RSquare	0.823103
RSquare Adj	0.758776
Root Mean Square Error	0.018499
Mean of Response	0.450937
Observations (or Sum Wgts)	16

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	4	0.01751475	0.004379	12.7957
Error	11	0.00376419	0.000342	**Prob>F**
C Total	15	0.02127894		0.0004

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	0.4509375	0.004625	97.51	<.0001
Battery[NiMH-VRLA]	-0.001563	0.004625	-0.34	0.7418
NSpeed[freeway-urban]	0.0021875	0.004625	0.47	0.6455
Nweight[max-min]	0.0238125	0.004625	5.15	0.0003
Aux. Loa[no-yes]	-0.022812	0.004625	-4.93	0.0004

Effect Test

Source	Nparm	DF	Sum of Squares	F Ratio	Prob>F
Battery	1	1	0.00003906	0.1142	0.7418
NSpeed	1	1	0.00007656	0.2237	0.6455
Nweight	1	1	0.00907256	26.5125	0.0003
Aux. Loads	1	1	0.00832656	24.3325	0.0004

GM S-10
AC kWh/mi
Summary of Fit

RSquare	0.911998
RSquare Adj	0.893471
Root Mean Square Error	0.051913
Mean of Response	0.589875
Observations (or Sum Wgts)	24

Analysis of Variance

Source	**DF**	**Sum of Squares**	**Mean Square**	**F Ratio**
Model	4	0.53065198	0.132663	49.2259
Error	19	0.05120465	0.002695	**Prob>F**
C Total	23	0.58185662		<.0001

Lack of Fit

Source	**DF**	**Sum of Squares**	**Mean Square**	**F Ratio**
Lack of Fit	11	0.02860415	0.002600	0.9205
Pure Error	8	0.02260050	0.002825	**Prob>F**
Total Error	19	0.05120465		0.5628
Max RSq				
0.9612				

Parameter Estimates

Term	**Estimate**	**Std Error**	**t Ratio**	**Prob>|t|**
Intercept	0.6374062	0.01124	56.71	<.0001
Battery[Delco V-NiMH]	-0.142594	0.01124	-12.69	<.0001
NSpeed[freeway-urban]	-0.050875	0.010597	-4.80	0.0001
Nweight[max-min]	0.0182917	0.010597	1.73	0.1005
Aux. Loa[no-yes]	-0.033375	0.010597	-3.15	0.0053

Effect Test

Source	**Nparm**	**DF**	**Sum of Squares**	**F Ratio**	**Prob>F**
Battery	1	1	0.43377019	160.9548	<.0001
NSpeed	1	1	0.06211838	23.0496	0.0001
Nweight	1	1	0.00803004	2.9796	0.1005
Aux. Loads	1	1	0.02673338	9.9197	0.0053

GM EV1
AC kWh/mi
Summary of Fit

RSquare	0.725699
RSquare Adj	0.625953
Root Mean Square Error	0.020233
Mean of Response	0.272937
Observations (or Sum Wgts)	16

Analysis of Variance

Source	**DF**	**Sum of Squares**	**Mean Square**	**F Ratio**
Model	4	0.01191375	0.002978	7.2755
Error	11	0.00450319	0.000409	**Prob>F**
C Total	15	0.01641694		0.0041

Parameter Estimates

Term	**Estimate**	**Std Error**	**t Ratio**	**Prob>|t|**
Intercept	0.2729375	0.005058	53.96	<.0001
Battery [PanPb-A-Pb-A]	0.0063125	0.005058	1.25	0.2380
NSpeed[freeway-urban]	-0.023188	0.005058	-4.58	0.0008
Nweight[max-min]	0.0039375	0.005058	0.78	0.4527
Aux. Loa[no-yes]	-0.012313	0.005058	-2.43	0.0332

Effect Test

Source	**Nparm**	**DF**	**Sum of Squares**	**F Ratio**	**Prob>F**
Battery Type	1	1	0.00063756	1.5574	0.2380
NSpeed	1	1	0.00860256	21.0136	0.0008
Nweight	1	1	0.00024806	0.6059	0.4527
Aux. Loads	1	1	0.00242556	5.9250	0.0332

Chrysler EPIC
AC kWh/mi
Summary of Fit

RSquare	0.925058
RSquare Adj	0.897806
Root Mean Square Error	0.027678
Mean of Response	0.6555
Observations (or Sum Wgts)	16

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	4	0.10401350	0.026003	33.9450
Error	11	0.00842650	0.000766	**Prob>F**
C Total	15	0.11244000		<.0001

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|	Std Beta
Intercept	0.6555	0.006919	94.73	<.0001	0
Battery[NiMH-VRLA]	0.033	0.006919	4.77	0.0006	0.393653
NSpeed[freeway-urban]	-0.036375	0.006919	-5.26	0.0003	-0.43391
Nweight[max-min]	0.026375	0.006919	3.81	0.0029	0.314624
Aux. Loa[no-yes]	-0.05825	0.006919	-8.42	<.0001	-0.69486

Effect Test

Source	Nparm	DF	Sum of Squares	F Ratio	Prob>F
Battery	1	1	0.01742400	22.7454	0.0006
NSpeed	1	1	0.02117025	27.6358	0.0003
Nweight	1	1	0.01113025	14.5295	0.0029
Aux. Loads	1	1	0.05428900	70.8692	<.0001