3 ELECTRIC VEHICLE SYSTEMS

3.1 INTRODUCTION AND SUMMARY

An electric vehicle is propelled by an electric motor drawing power from an electric storage battery. The motor and battery take the place of the engine and fuel tank of a conventional car. The battery is rechargeable: when it runs down, after perhaps 50 to 100 miles of driving, it may be recharged by a battery charger connected to a standard electrical outlet. Recharging typically requires 4 to 12 hours.

The technology to build electric vehicles has been available for almost a century. Eighty years ago, in the early days of the automobile, electric vehicles were as numerous in the United States as gasoline and steam-powered vehicles. By the 1920's, however, electric vehicles had almost vanished from the vehicle marketplace, primarily because of limited range and higher cost than competing gasoline-powered vehicles.

Though the limited range and lengthy recharge of the electric vehicles are important drawbacks, they are offset by a major advantage: independence of the gasoline pump. Today, intense interest in electric vehicles has been reawakened by the increasing price and uncertain availability of petroleum fuel for conventional vehicles. Furthermore, programs of battery R&D initiated in response to the petroleum problem offer prospects of more competitive electric vehicles, with much longer ranges and lower costs than previously possible.

Improved batteries are plainly the key to more capable and economical electric vehicles. Throughout the history of electric highway vehicles, storage batteries have been heavy, expensive, short-lived, and limited in capability. The lead-acid storage batteries used in the typical electric car of the 1970's may be accurately likened to a gasoline tank weighing a thousand pounds, costing over $1,000, requiring replacement every 10,000 miles, and carrying only two gallons of fuel. This sort of fuel storage would add some 50 percent to the empty weight of a subcompact car, increase its operating costs by adding battery depreciation of perhaps ten cents per mile, and limit its range to around 40 miles of urban driving.

Battery R&D during the late 1970's has already increased energy storage of the lead-acid battery by over 20 percent and nearly doubled its useful life. For the future, even larger improvements seem likely, though projections are uncertain and it is impossible to predict confidently which of several competing battery types will prove best. Longer useful life is ordinarily the major problem; it is relatively easy to build batteries with increased energy storage if long life is not required.

Batteries under development for the near-term--that is, batteries which may be ready for mass production during the 1980's--include improved versions of the familiar lead-acid battery and the less-common nickel-iron battery, plus two batteries which have never before been used in commercial electric vehicles, nickel-zinc and zinc-chlorine. Depending on which of these developments is successful, energy storage per pound may be 35-100 percent greater than that of the best lead-acid batteries of 1980, and improvements in operating life may be even greater.

More advanced batteries may also be successfully developed, probably in time for mass production during the 1990's, though this is even less certain. Again, there are a number of competing systems. The best of them might provide up to 4 times the energy storage per pound of the best 1980 batteries, or last the entire life of the vehicle they power.

The 100-mile electric car, a goal stated by both DOE and GM, will become a practical possibility during the 1980's if any of the near-term battery developments are successful. The weight and cost of the car, however, will remain high. Depending on battery type, curb weight of a four-passenger 100-mile subcompact might range from 3000 to 4000 lbs, or 50 to 100 percent above that of a comparable conventional subcompact car. Projected sticker prices (in 1980 dollars) range from $8000 to $8500, or 60-75 percent above the projected price of a comparable conventional subcompact.

Life-cycle costs projected for near-term electric cars are much closer to the life-cycle cost of the comparable conventional car, but still above it. Including depreciation, maintenance and repairs, insurance, parking, electricity, and financing, life-cycle costs projected for four-passenger electric cars range from 22.0 to 26.6 cents per mile in 1980 dollars. The life-cycle cost projected for the comparable conventional car is 21.4 cents per mile. The projected electric cars benefit from longer useful life, from low costs per mile for electricity, and from relatively low maintenance and repair costs. Resultant savings are outweighed, however, by battery depreciation costs plus extra depreciation and financing costs due to the higher initial cost of the electric vehicles.

If cars with more advanced batteries become available in the 1990's, they may be substantially lighter and less expensive than the near-term cars, though still heavier and more expensive to buy than a comparable conventional car. Life-cycle costs, however, could be less than those of the conventional subcompact, even if gasoline prices are no higher than in 1980.

After battery performance, life, and cost, the biggest uncertainties in these projections are the future prices of gasoline and electricity. If electricity prices remain constant, real increases in the price of gasoline from 10 to over 100 percent, depending on the battery type, would be required to make the conventional car as expensive as the near-term electric cars.

Maximum range in actual use is also uncertain. The hundred-mile figure projected here is a nominal figure for stop-start urban driving. Depending on driving speed, battery age, frequency of stops, grades, headwinds, and use of air conditioning, actual maximum range could be more or less than the nominal by a factor of two.

The 1980 state of the art in electric car technology is best exemplified by the Electric Test Vehicle (ETV-1) built for DOE by General Electric and Chrysler. This car is shown in Fig. 3.1. It is an attractive four-passenger subcompact with sufficient speed for freeway use and a useful urban driving range which may be about 60 miles. (Testing is presently incomplete; two preliminary trials showed urban ranges of 50 and 74 miles.) The initial price of the ETV-1 in full-scale mass production is estimated by GE and Chrysler at $8500 (in 1980 dollars), 63 percent above the $5200 price of a comparable 1980 Chrysler subcompact with an internal combustion engine (ICE).

Figure 3.1 The GE/Chrysler Electric Car ETV-1

The near-term electric cars projected here might be generally similar in appearance and capability to the ETV-1. Like the ETV-1, they would carry four passengers at speeds adequate for freeway use. Their improved batteries, however, would give them much more range at little or no extra cost. Furthermore, their acceleration capability would be about 30 percent higher. On level ground they could accelerate from O to 40 mph in 10 seconds: this is comparable to the capability of many diesel automobiles, and considerably better than the ETV-1 capability for accelerating from O to 40 mph in 14 seconds.

The remainder of this chapter details projections of the performance and cost of future electric vehicles. It begins with batteries because they are the crucial problem for electric vehicles. Next, it describes electric drive technology: motors, controllers, and other components. It then devotes three sections to complete electric vehicles: design objectives and requirements, the major tradeoffs between performance and cost, and the characteristics of electric vehicles chosen to be representative of future possibilities.

3.2 BATTERIES

Background

The limited capability, high cost, and short life of the storage battery have long been the principal obstacles to electric vehicles competitive with conventional vehicles. In the early 1900's, when motor vehicles were in their infancy and there were as many electric as gasoline vehicles in use, contemporary authorities praised the cleanliness, safety, ease of operation, and reliability of electric propulsion, but bemoaned the immense weight and limited capability of the storage batteries.' In explaining the demise of the electric vehicle, historians note in addition the rapid deterioration of storage batteries with use, the high overall costs of operating the electric vehicle, and the relatively slow technological progress in storage batteries relative to that in internal-combustion engines. Even today, golf car batteries are still made in the same general configuration as that of the early 1900's by a procedure patented in 1881.

Most electric vehicles built in the 1970's are powered by lead-acid batteries designed for golf cars. These batteries physically resemble the starting-lighting ignition batteries used in conventional automobiles, but are somewhat larger, and are designed for repeated deep discharges. Four-passenger electric cars have typically required 1000-1200 pounds of golf-car batteries costing $1000-1200 to achieve perhaps 40 miles of urban driving between recharges. Since the batteries could be recharged only about 250 times, replacement was required after each 10,000 miles of driving. Thus battery depreciation alone has amounted to around ten cents per mile.

The basic cell of the lead-acid battery (and most other batteries) consists of two dissimilar materials immersed in a liquid electrolyte.

During discharge, an electrochemical reaction takes place between these materials which causes an electric current to flow through an external circuit, connected between them, such as an electric motor. As the original materials in the cell are consumed in the reaction, chemical energy is transformed into electrical energy. During recharge, the electric current through the cell is reversed by electric energy from an external source. This reverses the chemical reaction within the cell, re-forming the original chemical compounds and thus storing electrical energy in chemical form.

Recharging does not return the cell exactly to its original condition. With repeated cycles of charge and discharge, fully-charged cells depart further and further from their original state. This limits the useful life of the cell: eventually, the quantity of energy stored and the maximum power output (the rate at which energy can be released) will fall below acceptable levels, or the cumulative movement of material within the cell may develop internal short circuits.

A battery is an assemblage of interconnected cells. The standard golf-car battery comprises three cells. Electric vehicle batteries ordinarily require 48 to 72 cells. For convenience in handling and economy of manufacture, the 3-cell golf car battery rather than the single cell has usually served as the basic module from which complete vehicular batteries are assembled. By proper interconnection, the completed battery may operate at an output voltage as high as the sum of all its cell voltages, as low as the voltage of a single cell, or at various intermediate levels. For electric vehicles, all cells are usually connected in series to give battery voltages in the range of 72-144 volts.

It should be noted that many batteries are not designed for recharging. Such batteries, called primary batteries, are widely used in flashlights, transistor radios, and other devices where battery life and cost are acceptable without recharging. Batteries not designed for recharge can be light, cheap, and powerful; but replacement costs would generally be intolerable if primary batteries were used for vehicular propulsion.

In conventional batteries, all the active materials remain in the basic cell during the complete cycle of charge and discharge. In one promising new development, however, one of the active materials is stored separately and is moved to and from the cell by mechanical pumps (the zinc-chlorine system under development by Gulf and Western Industries) . The system is electrically recharged, however, without physical introduction of new active material from external sources. This is a critical distinction because it determines whether the electric utility system, or some other system, would be required to deliver energy to automotive propulsion batteries.

In this report, only electrically rechargeable batteries are considered. Thus the aluminum-air battery being investigated by

Lawrence Livermore Laboratories is omitted. It would be recharged by replacement of its aluminum plates, with periodic removal of the electrolyte containing spent aluminum. A major new chemical reprocessing industry and refueling infrastructure would be required to recycle the spent aluminum into new aluminum plates. Similarly, fuel cells are also omitted. In a fuel cell, active material such as hydrogen and oxygen are combined to release electric energy. These fuels are stored outside of the cell, however, and are not regenerated by forcing electricity in the reverse direction through the cell. Again, a new chemical industry and refueling infrastructure would be required to refuel electric vehicles using fuel cells.

To recharge the storage batteries considered in this report, electric energy from an ordinary electrical outlet is passed through a battery charger into the battery. The battery charger converts ordinary alternating currents to the direct currents required by the batteries. It provides the direct current at a voltage appropriate to the state of battery charge and to the rate of recharge desired.

The useful life of a battery, the number of times it can be fully charged and discharged, depends strongly on how it is recharged. If the battery is deeply discharged, much of its charge can be restored without harmful effects quite rapidly--50 to 75 percent in the first hour, if sufficient electricity is available and a high-power charger is available to supply it to the battery. Completing the charge, however, must generally be done slowly. For lead-acid batteries, at least 4 or 5 hours is required to reach full charge even after a shallow discharge. To avoid the expense of very high-capacity electric outlets and high-power chargers, it is customary to install equipment which requires all night (8 hours or more) to recharge a deeply discharged battery.

Measures of Performance and Cost

For evaluating the performance and cost of batteries for vehicular propulsion, 5 measures are in common use.

- Specific energy is the electrical energy in watt-hours which can be delivered by each pound or kilogram of battery. Because specific energy depends on discharge rate, it is customary to measure specific energy during a three-hour discharge, which is roughly the time required for full discharge in continuous driving of a passenger vehicle. High specific energy is vital for vehicle batteries because it determines vehicle range. If specific energy is increased, the range of the vehicle using the battery will be increased a little more than proportionately.

- Specific power is the maximum power in watts which can be delivered by each pound or kilogram of battery. Since the capability of a battery diminishes rapidly as it approaches the fully discharged condition, it is necessary to state carefully the conditions under which specific power is measured. It is customary to measure specific power when the battery is half discharged, and to make the measurement on a conservative basis which indicates about 10 percent less than the maximum which could actually then be obtained. Specific power is important because it determines the maximum electrical power available in a vehicle for acceleration or climbing hills.

- The <u>life</u> of a battery is ordinarily stated in terms of the number of deep discharge and subsequent recharge cycles the battery can withstand. Life is tested by repeated cycles of discharge and charge which each withdraw 80 percent of rated battery capacity. Rated capacity is the maximum energy which a new battery can supply in a three-hour discharge. Battery life is considered ended when the battery is no longer capable of delivering 80 percent of its rating during discharge. Cycle life depends on many factors, such as battery temperature and the manner of charging and discharging; and it slowly diminishes with the passage of time even in the absence of use. Relatively little is known about the life of batteries which are subjected to shallow rather than deep discharges, or discharges of varying depth. For lack of better information, it is customary to assume that the total energy deliverable by a battery during its life is unaffected by the depth of discharge. For vehicles, this means that the total mileage which can be driven on a set of batteries is independent of the distance driven each day. Battery life is critical for vehicular applications because it determines the frequency of battery replacement and thus affects total battery costs during the life of the vehicle.

- <u>Energy efficiency</u> is the electrical energy delivered by a battery expressed as a percentage of the electrical energy required for recharge. It is important because it determines the amount of propulsion energy the battery can deliver from a unit of recharge energy. Some batteries require electric energy from external sources for heating or refrigeration. It is customary to include this energy with energy for recharging in estimating efficiency because it affects total electricity requirements in the same way as other losses within the battery.

- <u>Specific cost</u> is the cost of each kilowatt-hour of battery capacity. It is important because it determines the initial and replacement cost of a battery of a given storage capacity. Like all other costs in this report, battery costs are measured in mid-1980 dollars and are based on mature mass production and high-volume retailing.

To compare possible future batteries and to compute their implications for electric vehicles (vehicle driving range, energy use, and cost) , it is necessary next to project specific values of these five battery measures for a representative set of future batteries.

Projections of Performance and Cost

The following projections are based on published reports which are generally the product of the DOE battery R&D program.[3] There also exist substantial independent programs of battery development, such as the GM work in lead-acid, nickel-zinc, and high-temperature lithium batteries. Published results are insufficient, however, for use of industry-supported research here.

Batteries under development by the Department of Energy are divided into two groups: "near-term" and "advanced." Near-term batteries are those considered most likely to become available for use in demonstration electric vehicles before 1985. Advanced batteries offer higher performance potential but successful development is far less certain and development schedules are speculative. It appears quite likely that at least one of the near-term batteries will be successfully mass-produced for vehicular propulsion by 1990. It is too early, however, to determine which of the batteries will succeed, so all four near-term batteries are included in the projections presented here. Advanced battery developments are far less predictable, but there is a reasonable possibility that some kind of advanced battery will follow the near-term batteries into mass production before the year 2000. To illustrate this possibility, projections are presented for batteries representative of low and high levels of advanced battery performance. The four types of near-term batteries are lead-acid, nickel-iron, nickel-zinc, and zinc-chlorine. An improved zinc-chlorine system and a high-temperature lithium-metal sulfide system were taken as representative of the lowest and highest levels of performance to be expected from advanced batteries.

Specific energies projected here for the near-term batteries are 1.6 to 2.5 times larger than those of premium golf-car batteries of the 1970's. Specific energies projected for the advanced batteries are 3 and 5 times those of premium golf-car batteries Because electric car ranges are roughly proportional to specific energy, these increases imply dramatic improvements are coming in useful range.

Major improvements in life are also expected. For the near-term batteries, cycle lives are projected to be 1.6 to 6 times longer than those of premium golf-car batteries. For the advanced batteries, projected cycle lives are 4 to 6 times longer. With these life increases, batteries might be replaced only once or twice during the life of the vehicle they power. In some cases, they might last the entire life of the vehicle. Even though the specific costs of the projected batteries equal or exceed those of golf-car batteries, the long lives projected would drastically reduce expenditures necessary for replacement batteries, and total battery cost over the life of the vehicle.

Table 3.1 summarizes the ranges of performance and cost projected for near-term and advanced batteries. It includes corresponding data for premium golf-car batteries commonly used in electric vehicles during the 1970's. It also includes data for a battery representing 1980 capability. This battery, the Globe-Union EV2-13, was developed for the DOE Electric Test Vehicle ETV--1.[4] It embodies substantial advances over the golf-car batteries of the seventies; commercial production is expected during 1981.

Tables 3.2 and 3.3 provide more detail to support Table 3.1. In Table 3.2, individual projections are advanced for the four near-term batteries. These projections are based on the development goals adopted by DOE, but include downward adjustments in specific energy and life reflecting two considerations: progress for some of the near-term batteries, notably lead-acid and zinc-chlorine, seems to be more rapid than for the others; and development goals have been set higher than probable achievements in order to pose a significant technical challenge and elicit the best possible results. In Table 3.3, the maximum performance now contemplated for advanced batteries is illustrated by a lithium-metal sulfide system. A reasonable minimum level of performance for advanced batteries is illustrated by an improved zinc-chlorine system. In general, performance goals adopted by DOE for advanced batteries, including sodium-sulfur, metal-air, and other systems in addition to lithium-metal sulfide, lie between these examples in Table 3.3. The long lives and low costs in the table are both optimistic and speculative.

The lead-acid battery projected in Table 3.2 is based on vast experience: lead-acid batteries today provide starting, lighting, and ignition for hundreds of millions of passenger cars and tens of millions of motor trucks; and they provide motive power for tens of thousands of forklift trucks. The battery sought for on-road electric vehicles would bring together the high energy, high power, and low cost of the starting-lighting-ignition battery with the extremely long service life (1500-2000 deep discharges) achieved in motive power batteries for industrial lift trucks. The construction of a battery representing the state of the art in 1980 is illustrated in Fig. 3.2, which shows the battery that was especially developed for the ETV-1 car built by GE and Chrysler. Like most other lead-acid batteries used in electric vehicles, this battery has three cells and weighs about 60 pounds. Each cell includes a set of positive and negative electrodes--in this case lead grids supporting the active materials, spongy lead and lead dioxide. The plates are immersed in a dilute solution of sulfuric acid, the electrolyte for the electrochemical reaction in which lead sulfate is formed as electric energy is delivered to an external circuit. Sixteen to twenty such batteries are usually required in a four-passenger electric car. They are typically placed on a supporting tray, connected in series, and loaded into the vehicle they are to propel from underneath. In the 1970's, it was necessary every few weeks to remove the cap for each of the 60 cells in a vehicle battery pack, add distilled

TABLE 3.1

PROJECTED IMPROVEMENTS IN PROPULSION BATTERIES

Battery Type	Availability (in quantity)	Specific Energy,[1] Wh/lb (Wh/kg)	Specific Power,[2] W/lb (W/kg)	Life, Deep Discharge Cycles[3]	Specific Cost,[4] 1980 dollars/kWh
Golf-Car	1970-1980	14 (30)	32 ○	250	55
EV2-13[5]	--	17	51 (112)	500	--
Near-Term	By 1990	23-34 (50-75)	50-54 (110-120)	400-1500	55-90
Advanced	By 2000	45-68 (100-150)	68-136 (150-300)	1000-2000	60

Source: Tables 3.2, 3.3, Ref. 3.

[1]For discharge at the three-hour rate, in Watt-hours per pound (or kilograms)

[2]For 20 seconds at 50 percent state of charge, in Watts per pound (or kilogram)

[3]For 80 percent depth of discharge during each cycle.

[4]Retail price (including markup of 30 percent added to the large-quantity factory price) for batteries in the 30-kWh class, in 1980 dollars, given mass production.

[5]This is the improved battery developed for the DOE Electric Test Vehicle ETV-1. It has not been put into production.

TABLE 3.2

ASSUMED PERFORMANCE AND COST FOR NEAR-TERM PROPULSION BATTERIES
TO BE MASS-PRODUCED BY 1990)

Battery	Specific Energy,[1]		Specific Power,[2]		Life, Deep-Discharge Cycles[3]	Energy Efficiency	Specific Cost,
	Wh/lb	Wh/kg	W/lb	W/kg		percent[4]	$/kWh[5]
Lead-Acid	23	50	54	120	800	80	55
Nickel-Iron	27	60	54	120	600	65	90
Nickel-Zinc	32	70	68	150	400	75	90
Zinc-Chlorine	34	75	50	110	1500	55[6]	90

[1]For discharge at the three-hour rate, in Watt-hours per pound (or kilogram)

[2]For 20 sec at 50 percent state of charge, in Watts per pound (or kilogram)

[3]For 80 percent depth of discharge.

[4]Electric energy output relative to energy input.

[5]Retail price (including markup of 30 percent added to the large-quantity factory price for batteries in the 30 kWh size class, in 1980 dollars.

[6]Includes charger.

TABLE 3.3

ASSUMED PERFORMANCE AND COST FOR ADVANCED PROPULSION BATTERIES

(TO BE MASS-PRODUCED BY 2000)

Battery	Specific Energy,[1]		Specific Power,[2]		Life, Deep-Discharge Cycles[3]	Energy Efficiency, percent[4]	Specific Cost, $/kWh[5]
	Wh/lb	Wh/kg	W/lb	W/kg			
Zinc-Chlorine	45	100	68	150	2000	60[6]	60
Lithium-Metal Sulfide	68	150	136	300	1000	70	60

[1]For discharge at the three-hour rate, in Watt-hours per pound (or kilogram)

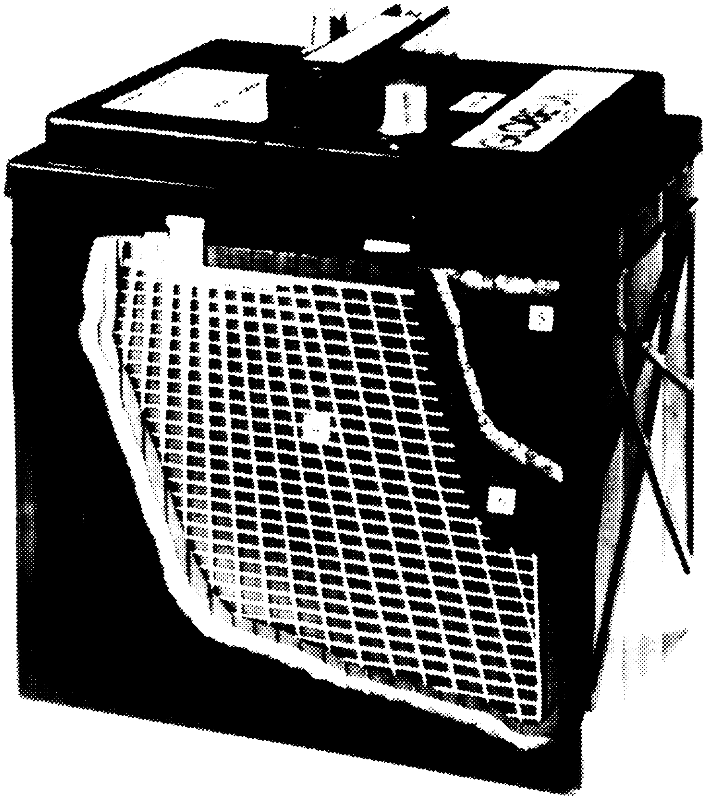
[2]For 20 sec at 50 percent state of charge, in Watts per pound (or kilogram)

[3]For 80 percent depth of discharge.

[4]Electric energy output relative to energy input.

[5]Retail price (including markup of 30 percent added to the large-quantity factory price) for batteries in the 30-50 kWh size class, in 1980 dollars.

[6]Includes charger.



GLOBE-UNION INC.

EV2-13 LEAD-ACID
ELECTRIC VEHICLE BATTERY

- 6 Volt
- 27.2 kg (60 lb)
- Unconventional, Computer-Designed Cell Geometry
- Left-Hand and Right-Hand Models

KEY

1. Thin, Lightweight, Durable Polypropylene Container and Cover Thermally Welded for a Leak-Free Assembly
2. Single-Point Watering System with Safety Venting
3. Low-Resistance, Through-the-Partition Intercell Welds
4. High-Efficiency, Computer Designed Radial Grids
5. Optimized Active Materials
6. Submicro Polyethylene Envelope Separators with Glass Mat

Figure **3.2** Current Globe-Union Lead-Acid Electric Vehicle Battery

water as necessary to each cell, replace the caps, and clean off the accumulation of acid moisture and dirt which appeared on the battery surface. Future batteries, however, will have single-point watering and venting systems which will greatly reduce the labor of maintenance. The interim state-of-the-art batteries developed for and now being tested by DOE already have such a system, and in addition appear to be close to all the projections of Table 3.2 for lead-acid batteries excepting specific energy, where they offer about 20 percent less.[5] Further development toward the DOE advanced lead-acid battery goal (27 watt-hours per pound) should bring the energy level up at least to the figure of Table 3.2 (23 watt-hours per pound) during the 1980's.

The nickel-iron battery was invented by Thomas Edison at the turn of the century. Though it failed to achieve his express intention--making electric vehicles superior to gasoline vehicles--it has found continued use in railway carriages, mine locomotives, and other applications requiring a rugged, durable, long-life battery. The development problem for on-road vehicular applications is to increase power and energy density and to lower costs, without undue sacrifice of life. The nickel-iron and nickel-zinc batteries of Table 3.2 are generally similar in arrangement to the lead-acid battery. Both the nickel-iron and nickel-zinc batteries employ multi-plate cells with an aqueous electrolyte at room temperature--though in this case the electrolyte is alkaline rather than acid (a solution of potassium hydroxide). Both batteries employ nickel positive electrodes, but the nickel-zinc battery substitutes zinc for iron negative electrodes to achieve higher energy and power output per pound of battery. A practical nickel-zinc battery has long eluded developers primarily because of problems inherent in this substitution. On repeated cycles of charge and discharge, zinc electrodes tend to change shape/ lose capacity, and grow needle-like dendrites which penetrate the separators between adjacent positive and negative plates, thus short-circuiting cells.

The zinc-chlorine battery of Table 3.2 differs substantially in construction from the other near-term batteries. One of its active materials, chlorine, is stored separately from the electrode stack, and must be conveyed to and from the stack by a system of pumps and plumbing through which the electrolyte, an aqueous solution of zinc chloride containing gaseous chlorine, is circulated. The chlorine is stored as a solid, chlorine hydrate, which forms when water containing chlorine is chilled below 50 degrees. to accomplish this, the battery charger includes a refrigerator to chill a working fluid. During charging, the chilled working fluid is pumped through a heat exchanger within the battery, where it absorbs heat from the electrolyte. The electrodes in the cells of this battery are based on graphite structures which offer very long life. During charging, zinc is plated onto the negative electrodes while chlorine is evolved at the positive electrodes. The chlorine is carried out of the cell stack by the circulating electrolyte through the heat exchanger where chlorine hydrate is formed. During discharge, the process is reversed. Because the battery may be fully discharged without harm, all the zinc may thus be periodically removed from the graphite substrates. In this way, the usual problems of zinc electrodes, cumulative shape change and dendrite buildup during cycling, may be eliminated. It appears that the pumps and plumbing, rather than the electrodes, may ultimately limit the life of the battery. It seems possible, and even likely, that sufficient life can be achieved so that the battery may be sealed in a container with terminals for input and output of electricity, and operated without servicing for the entire life of the vehicle.

The zinc-chlorine system is relatively new and may be developed well beyond the levels of performance projected in Table 3.2. Accordingly, an advanced zinc-chlorine system is projected in Table 3.3, where it is representative of the minimum performance which advanced battery developments, if successful, may bring in the 1990s.[6]

The lithium-metal sulfide system in Table 3.3 is an example of the highest performance which advanced battery systems may bring. Its characteristics are drawn from the most optimistic long-term development goals which have been published in recent years. The cells of this battery utilize lithium-aluminum negative plates and iron sulfide positive plates immersed in a molten salt electrolyte. The battery must be maintained at approximately 700 F, which means that a housing with exceptionally effective insulation is required. It is highly desirable that heat loss through the housing be low so that additional heat beyond that evolved in the cells during ordinary use will be unnecessary. If supplementary heating is necessary, it will be supplied by the battery charger, decreasing effective battery efficiency. In addition to superb insulation, the housing must also ensure safe containment of battery materials, even in crashes. The assumed specific energy in Table 3.3 includes a weight allowance f r housing, which may amount to 20 or 25 percent of total cell weight.[7] The high energy of the battery is due to the high chemical activity of lithium and sulfur. The principal difficulties in battery development are also due to this high activity, which presents serious problems of corrosion and containment, especially at the elevated temperature of operation. Extraordinary materials are needed to contain the molten electrolyte, to separate and space the plates within each cell, to collect and conduct electric currents within each cell, and to insulate the conductors where they pass through the cell container. These materials must nonetheless be inexpensive to purchase and fabricate.

In general, achieving a long operating life appears to be the major problem in battery development There is little theory to guide improvements intended to combat the gradual changes and degradation associated with charge-discharge cycling. Experimental approaches are difficult and very time-consuming, since it may take years of testing to determine the effect on battery life of a given design change. Though increases in energy density are highly desirable, it is long life which is critical to achieving acceptable depreciation costs for propulsion batteries in on-road vehicles.

Total Costs of Stored Electricity

The total costs of stored electricity include both battery depreciation and purchase of recharge electricity. For the near-term batteries projected here, depreciation costs far exceed recharge electricity costs despite assumed cycle lives well beyond those of recent years. Both costs, in cents per kilowatt-hour of battery output, are shown in Table 3.4. Since four-passenger electric cars may require roughly 0.4 kWh of battery output per mile driven, the table implies that total

TABLE 3.4

COST OF ELECTRICITY FROM PROPULSION BATTERIES

Battery Type	Battery Cost, $/kWh	Battery Life, Cycles[1]	Battery Efficiency percent[2]	Costs of Stored Electricity, cents per kilowatt-hour		
				Recharge Electricity[3]	Battery Depreciation[4]	Total
Golf-Car (1970-1980)	55	250	75	4.0	24.8	28.8
Near-Term (by 1990)						
Lead-Acid	55	800	80	3.8	7.7	11.5
Nickel-Iron	90	600	65	4.6	16.9	21.5
Nickel-Zinc	90	400	75	4.0	25.3	29.3
Zinc-Chlorine	90	1500	55[5]	5.5	6.8	12.2
Advanced by 2000)						
Zinc-Chlorine	60	2000	60[5]	5.0	3.4	8.4
Lithium-Metal Sulfide	60	1000	70	4.3	6.8	1.0

[1] 80 percent depth of discharge.

[2] Charger efficiency not included; assumed to be 90 percent.

[3] Electricity price assumed to be 3 cents per kilowatt-hour, a representative rate for off-peak recharging which is about half the average price for residential electricity in mid-1980.

[4] 10 percent salvage value assumed.

[5] Includes charger/refrigerator.

Source: General Research Corporation

costs for near-term batteries will be roughly 5 to 12 cents per mile, including depreciation, whereas costs of recharge electricity alone would be only 1.5 to 2.2 cents per mile.

Uncertainties

The battery projections and assumptions advanced here are to be viewed with caution. Such projections have usually been over-optimistic in the past. In early 1967, for example, the US Senate Committee on Commerce and Public Works held joint hearings on "Electric Vehicles and Other Alternatives to the Internal Combustion Engine."[8] At the hearings, a procession of experts spoke optimistically about metal-air and sodium-sulfur batteries, which were then in vogue:

> ". . .zinc-air rechargeable batteries should offer advantages in performance, weight, volume, and material costs...continued development. ..should lead within the next couple of years to truly economically feasible batteries for electric vehicles." Dr. Stewart M. Chodosh, Battery Manager, Leesona Moos Laboratories.

> "In our judgment the zinc-air battery project is well ahead of every other advanced project and stands a good chance of success." Charles Avila, President, Boston Edison Company.

> "We are expecting commercial availability of these zinc-air batteries in the early 1970s." Dr. Frederick de Hoffman, Vice-President, General Dynamics.

> "We believe that, within the next decade, research and development now being conducted by Ford and others will make it possible to produce marketable electrical vehicles much superior to any that can be built today.

> "Our sodium-sulfur battery is now in an advanced stage of laboratory development. Its technical feasibility and excellent performance have been demonstrated.. ." Michael Ference, Jr., Vice-President, Scientific Research, Ford Motor Company.

Now, however, thirteen years later, neither of these battery systems is commercially available. Moreover, neither is considered a near-term development by the Department of Energy. The sodium-sulfur battery remains among advanced developments which may eventually become available, while zinc-air systems have almost dropped from view, even in the research community.

3.3 DRIVE TRAIN

Background

The electric drive train converts electric power from the battery to mechanical power at the driven wheels of the electric vehicle. Its major components are ordinarily an electric motor, an electrical controller, a transmission, and a differential, as illustrated in Fig. 3.3. The motor converts electrical power to mechanical power. The controller regulates the amount of power flowing from the battery to the motor, and thus the speed and acceleration of the vehicle. The transmission and differential perform the same functions they perform in conventional vehicles: reducing the high rotation speed of the motor shaft to the low rotation speed of the driven wheels, and dividing the mechanical power between the two driven wheels.

Conventional direct-current motors have been used in the great majority of electric vehicles, past and present. Such motors have only a single moving part, a rotating set of electromagnets called the armature. The armature revolves within a stationary set of electromagnets called the field. Electric current flows to the armature through a set of carbon brushes which slide on a segmented copper cylinder called a commutator. The brushes are fixed to the frame of the motor and are motionless, while the commutator is mounted on the armature shaft and rotates with it. The commutator reverses the direction of current flow through the armature magnets at appropriate moments to obtain continuous armature rotation.

The simplicity of the electric motor leads to very high reliability and long life. Only the brushes require periodic maintenance, usually an inspection at intervals of 500 to 1000 hours of operation (a year or two in automotive use) and replacement when required.

Unlike the internal-combustion engine, the electric motor is reversible and self-starting. Furthermore, it develops high torque at zero speed, provides its full rated output with high efficiency over a wide range of speeds, and can deliver two to three times its continuous output rating for short periods of time. All this makes it so well suited to vehicular propulsion that an electric motor of 20-30 horsepower rating is the rival of internal combustion engines with much higher ratings, in the 50-75 hp class. The weight of such a motor, roughly 4-5 pounds per horsepower of short-term output capability, falls between that of gasoline engines (3-4 pounds per horsepower) and lightweight diesel engines (5-6 pounds per horsepower). Its cost in mass production would be less than that of either gasoline or diesel engines.

For vehicular use, however, the electric motor is incomplete without an electrical controller to vary its speed and power output in accord with the wishes of the driver. Depending on its design, the controller may be more expensive than the motor, and almost as bulky although lighter in weight.

Early electric vehicles employed large manually-operated rotary switches as controllers. The switches connected the cells of the propulsion battery in different arrangements to change the battery voltage

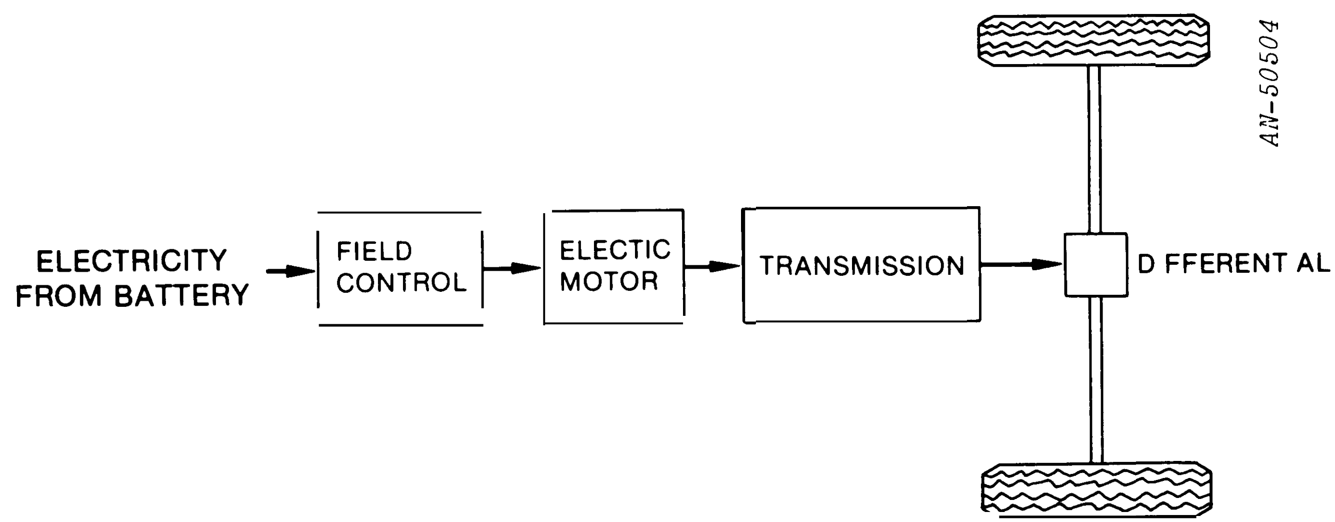


Figure 3.3 The Basic Electric Drive Train

applied to the motor, and sometimes included resistors to limit motor current, Only a few selectable levels of power and speed were thus available to the operator. With the substitution of large relays called contractors for the manually-operated switch, this type of controller can be operated by a conventional accelerator pedal. Such contactor controllers are widely used in electric lift trucks, where they have proven inexpensive and reliable.

About twenty years ago the advent of high-power semiconductor switches made a new type of controller possible, the chopper controller. The chopper interrupts the flow of electric current periodically to reduce its average value to a desired level. Semiconductor switching makes this interruption possible at such high rates, hundreds or thousands of times per second, that to the user the flow of power to the electric motor appears smooth and continuous. Choppers capable of handling the full flow of power from battery to motor are large and expensive, but give smooth control of motor speed from its maximum rated speed all the way down to zero. Choppers of much more limited capability are used to control only the current flowing in the motor field winding. They are much smaller and less expensive, but allow motor speed to be varied only through a speed range of perhaps three to one without sacrifice of efficiency. Control does not extend all the way down to zero speed.

Whether they are built with high-power choppers, field choppers, or both, controllers require a main contactor to disconnect the battery entirely when the vehicle is at rest. They ordinarily include sensors to detect overheating of the motor or excessive input currents and some means to reduce power input to the motor to protect it against damage which might otherwise result. Unless reverse movement of the vehicle is accomplished by a transmission, additional contractors may be required to reverse the rotation of the motor. Finally, modern controllers are required to provide regenerative braking, which entails additional circuitry. The conventional electric motor can operate with equal efficiency as a generator, allowing the kinetic energy of a vehicle to be converted to electricity during deceleration rather than lost as heat in ordinary friction brakes. The electricity is returned to the battery, where it is available for subsequent use.

A transmission is ordinarily required to reduce the shaft speed of the electric motor to a level compatible with the lower rotation speed of the driven wheels. Electric motors can be built to run efficiently at very low speeds, but this increases motor weight and cost so much that it is preferable to add a transmission to a higher-speed motor. Multispeed transmissions increase motor speed and efficiency during periods of low driving speed, but some designers have not considered these benefits sufficient to offset the extra expense and operating complexity involved.

A differential is usually included to distribute an even flow of power from the transmission to the two driven wheels of the vehicle. It is made necessary by vehicle turns, which cause the driven wheels to revolve at unequal speeds. A few electric vehicles have dispensed with the differential, substituting instead separate drive motors for the driven wheels. Generally, however, it appears that a single motor with differential is less expensive and equally effective overall.

The objectives of drive train design are to provide adequate propulsive power with high efficiency, high reliability, low weight, and low cost. Existing technology is already close to meeting all these objectives. Efficiency is so high, near 80 percent overall, that little is left to be gained. Motors are already highly reliable and with the experience gained from mass production, controllers will probably become equally reliable. Drivetrain weight is comparable to that of conventional internal-combustion vehicles. Drivetrain cost remains higher than that of conventional vehicles due largely to the cost of the controller, but the differential is far less than that between the costs of the gas tank and the propulsion battery.

In short, the electric drive train is not a major obstacle to successful electric vehicles. Improvements in drivetrains, especially those leading to lower cost, remain desirable, but improvements so great they would offset the drawbacks associated with the propulsion battery do not appear possible.

Examples of the State of the Art

The drive train developed by General Electric for DOE's electric test vehicle ETV-1 is built around a sophisticated chopper controller and a conventional DC motor. Its transmission is a simple chain drive which offers a fixed speed reduction, and its differential is a standard component of the front wheel drive assembly built by Chrysler for its Omni and Horizon models.

The controller employs separate choppers to control motor armature current and motor field current. The armature chopper, a device capable of handling currents as large as 400 amps, controls the motor at vehicle speeds from zero to 30 mph, which correspond to motor speeds from zero to 2500 rpm. At speeds above 30 mph, the armature chopper is bypassed and motor speed is controlled by the field chopper, a much smaller device which supplies currents of 5-10 amps to the field electromagnets. A third chopper unit with 200-amp capability is used to control battery charging current during regenerative braking. The two high-current choppers utilize special high-current transistor modules developed especially for this application. The transistors enable higher chopping frequencies and simpler control circuits than the SCR's (silicon controlled rectifiers) which have been used in most chopper controllers for electric vehicles. The low current chopper is used not only for controlling motor field current, but for controlling battery current (at levels up to 24 amps) during recharging from 120-volt outlets. Overall operation of the controller is directed by a microcomputer.

The DC motor used in the ETV-1 is a conventional design which was tailored specifically for this application (see Fig. 3.4). It is only 17 inches long and 12 inches in diameter, but can provide 20 horsepower continuously at any speed between 2500 and 5000 rpm at an efficiency of almost 90 percent. operating at this rating, the motor requires an electrical input of 96 volts at 175 amps. For short periods it can be operated at input currents up to 400 amps, with correspondingly higher power outputs. Total motor weight is about 200 pounds.

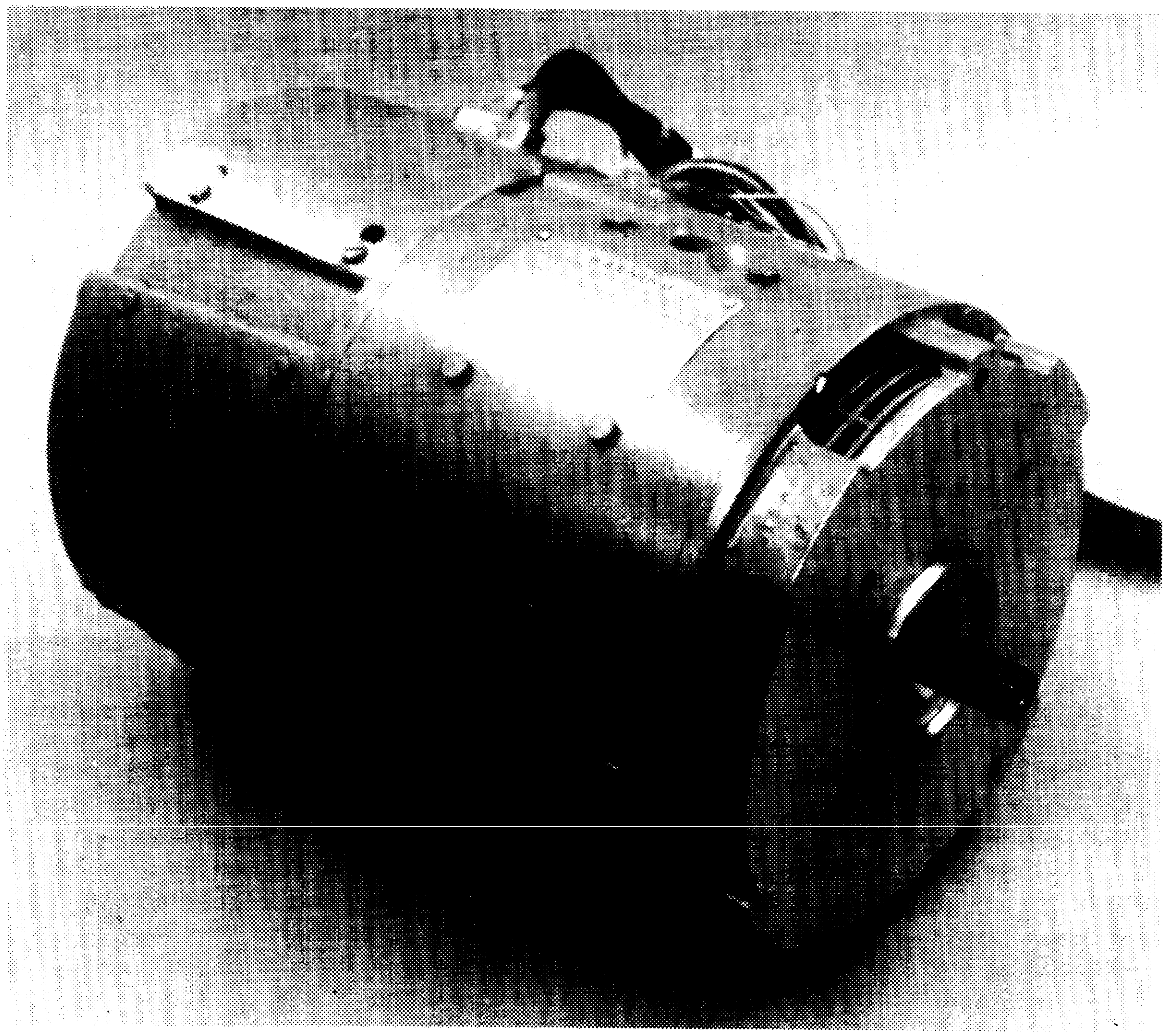


Figure 3.4 The 20-hp DC Motor Developed by General Electric for the DOE Electric Test Vehicle ETV-1

Taken together, the motor and controller would be more expensive than the conventional internal-combustion engine they would replace. In a mass-produced version of the ETV-1, their extra cost would be about $800, as compared with $1470 for the propulsion battery and a total extra co_t of about $2900 in relation to the comparable 1980 Dodge sub-compact.~ The cost of the controller would be about equal to that for the motor.

A different approach to drivetrain design is exemplified by the conversion of a conventional ICE car developed by South Coast Technology with support from the Department of Energy. The conversion is based on the Volkswagen Rabbit and utilizes the entire transaxle assembly of the basic car, including the clutch. It adds a conventional DC motor similar to that of the ETV-1, but employs a simple controller which includes only a single inexpensive chopper. The chopper controls only the field current of the motor, and thus varies motor speed only through a range of about 1800-3600 rpm.

Operation of the South Coast car is similar to that of a conventional ICE car with manual transmission. With the transmission in neutral, the operator starts the motor by turning a key similar to an ordinary ignition key. During the second or so required by the motor to reach its minimum speed, a resistor is switched into the circuit by the controller to minimize inrush current. To drive the vehicle, the operator shifts gears and engages the clutch much as in a conventional vehicle. As in the conventional vehicle, the motor “idles” during stops. Resultant loss of energy is small in ordinary driving, where stops are relatively infrequent.

Despite its simplicity, the controller provides regenerative braking. Just as weakening the field current increases power flow to the motor, field strengthening reduces it. The field control can not only reduce motor current to zero, but reverse it. Then the motor acts as a generator, decelerating the car by converting its kinetic energy to electricity flowing back into the battery. Regeneration is only possible, of course, at speeds down to the minimum speed of the motor, but by downshifting regeneration can be achieved at vehicle speeds down to about 10 mph.

The arrangement of the South Coast Rabbit's drivetrain is expeditious for a conversion because it makes maximum use of existing components within the basic car. It also illustrates, however, how effectively mechanical components--the manual multispeed transmission and clutch--may be used to reduce the complexity and cost of the electrical controller, and the cost of the overall vehicle. Despite the extra effort required for their operation, manual transmissions might be prefered by many future buyers of electric cars, just as they are now preferred by an increasing number of buyers of conventional cars.

Future Drivetrains

Drivetrain R&D for electric vehicles is concentrated on the development of improved brushless motors and their associated controllers.[3] Brushes are undesirable because they require maintenance and limit the speed at which the motor can operate. Higher operating speed generally leads to proportionate increases in maximum power output from a motor of given weight. Thus brushless motors might at once require less maintenance and weigh less than conventional designs. Brushless motors may also be substantially cheaper, partly because they weigh less, partly because they are amenable to designs which are especially suited to low-cost, high-volume production.

Brushless motors are of two general types: DC machines with external electronic circuits to replace the commutor and brushes of the conventional design; and AC machines with external electronic circuits to convert the DC output of the battery to the AC power required by the motor. In general, the number of high-power semiconductor devices required for brushless motors exceeds the number required for chopper controllers like that of the ETV-1. Unless lower-cost electronic components and designs can be developed, then, savings in the weight and cost of the brushless motors may be offset by increases in the weight and cost of the electronic controllers they require.

Transmissions for electric drivetrains are most likely to be spin-offs of developments intended primarily for conventional ICE vehicles. Innovations likely to appear soon are the continuously-variable transmission and the automatically-shifted multispeed gearbox.[11] A continuously-variable transmission would relieve the requirements placed on the electric controller for varying motor speed. So would the automatic gearbox, but with higher overall efficiency of operation. With such transmissions, cars with simple and inexpensive controllers like that of the South Coast Rabbit could be satisfactory for many more motorists, including motorists unable to use a manual transmission.

Future motors and controllers may well be no more expensive than the ICE system they supplant. It cannot confidently be predicted yet whether this will come about through improvements in high-power chopper controllers, through the advent of advanced brushless motors, or through the combination of more sophisticated transmissions with a simpler DC motor and field controller designs. It appears, however, that at least one of these developments will succeed.

3.4 VEHICLE DESIGN

Basic Considerations

The major functions of the motor vehicle are to move passengers and other payload swiftly, safely, comfortably, and conveniently, at minimum cost. The major components integrated into an electric passenger vehicle for this purpose include:

- The payload compartment, which provides comfortable seating, shelter from the elements, protection in crashes, space for parcels and luggage, convenient controls for the operator of the vehicle, and such amenities as heating and air conditioning.

- The drive train, which provides propulsive power for acceleration and cruising.

- The battery, which supplies electric energy to the drive train.

- The supporting structure and chassis, including wheels, brakes, suspension, steering, and other items necessary to carry the payload and passenger compartment, the drive train, and the battery on streets and highways.

The components of a conventional ICE vehicle differ only in that the fuel tank supplants the battery, and the drive train includes the ICE system rather than an electric motor and controller. In practice, however, the difference between the weight, bulk, and cost of the gasoline tank and the battery is so great that they become the central problem of electric vehicle design.

In every vehicle design, a basic compromise is struck between capability and cost. In conventional vehicles, extra speed and payload capacity are generally associated with higher cost. In electric vehicles this remains true, but a new dimension is added: driving range.

To increase the range of an electric vehicle with a given battery technology means that the size of the battery must be increased. Since the battery is a major contributor to vehicle weight, the power output and weight of the drive train must be simultaneously increased to avoid reductions in acceleration and top speed. With substantial weight increases in the battery and the drive train, the supporting structure and chassis must also be made heavier. All of this leads to an increased initial price for the long-range vehicle, higher energy use in operation, and increased operating costs.

In the conventional vehicle, the gasoline tank is a very small part of total car weight and cost. Increasing range, payload capacity, or propulsion power is inexpensive because it does not involve proportionate increases in a heavy and expensive propulsion battery. Furthermore, range is less important because refueling can be accomplished in minutes rather than hours.

In electric vehicles, the cost of additional payload capability, acceleration capability, and range is so high that it is worthwhile only if frequently used. Accordingly, rear seats, high acceleration, and the maximum feasible ranges with given battery technology are not always offered in electric cars, since auto occupancy is usually only one or two persons, modest acceleration suffices to keep up with almost all traffic, and daily travel by the average automobile in the United States is under 30 miles.

Electric vehicles also tend to be smaller than conventional vehicles because most auto buyers work under budgetary limitations. Buyers who could afford an $8,000 electric subcompact instead of a $5,000 conventional subcompact might not be able to afford a $12,000 standard size electric instead of a $7,500 standard size conventional car.

Because the cost of providing capability is so high in electric vehicles, extraordinary efforts are justified to maximize drive train efficiency and minimize the weight of the vehicle payload compartment, supporting structure and chassis. Expensive lightweight materials, for example, might add more to the price of a conventional car than the value of the gasoline they would save over its life, whereas those same expensive materials might result in lower overall costs for the electric vehicle.

Examples of Electric Vehicle Design

The state of the art in the design of electric passenger cars is illustrated by the electric test vehicle ETV-1 completed in late 1979 by General Electric and Chrysler for the US Department of Energy. The central feature of the ETV-1, shown in Fig. 3.5, is the large propulsion battery.[4] The battery is accommodated in an enlarged central tunnel extending from the rear luggage compartment between the four passenger seats to the front motor compartment, which houses the entire drive train(controller, motor, transmission, and front wheel drive axle) . The curb weight of the car is 3,320 pounds, while battery weight is almost 1,100 pounds. Thus the battery weighs about one-third of the total car weight without payload. Nevertheless, range in urban driving is expected to be only 50-75 miles. The ETV-1 is comparable to the Chrysler Horizon and Omni models in overall size and passenger accommodations, but offers about 40 percent less luggage space. It also offers relatively low acceleration capability: O to 30 mph in 9 seconds. A motor rated at 20 horsepower (continuous duty) suffices for this and for top speed in excess of 60 mph. TO minimize energy use and thus maximize range, the ETV-1 was carefully designed for low aerodynamic drag, which is 30 to 50 percent below that of most other passenger cars on the road. GE and Chrysler have estimated the price of the ETV-1 in mass production (3000000 units per year) would be about $8,500, about 60 percent greater than the price of the comparable 1980 Dodge Omni, $5,200.

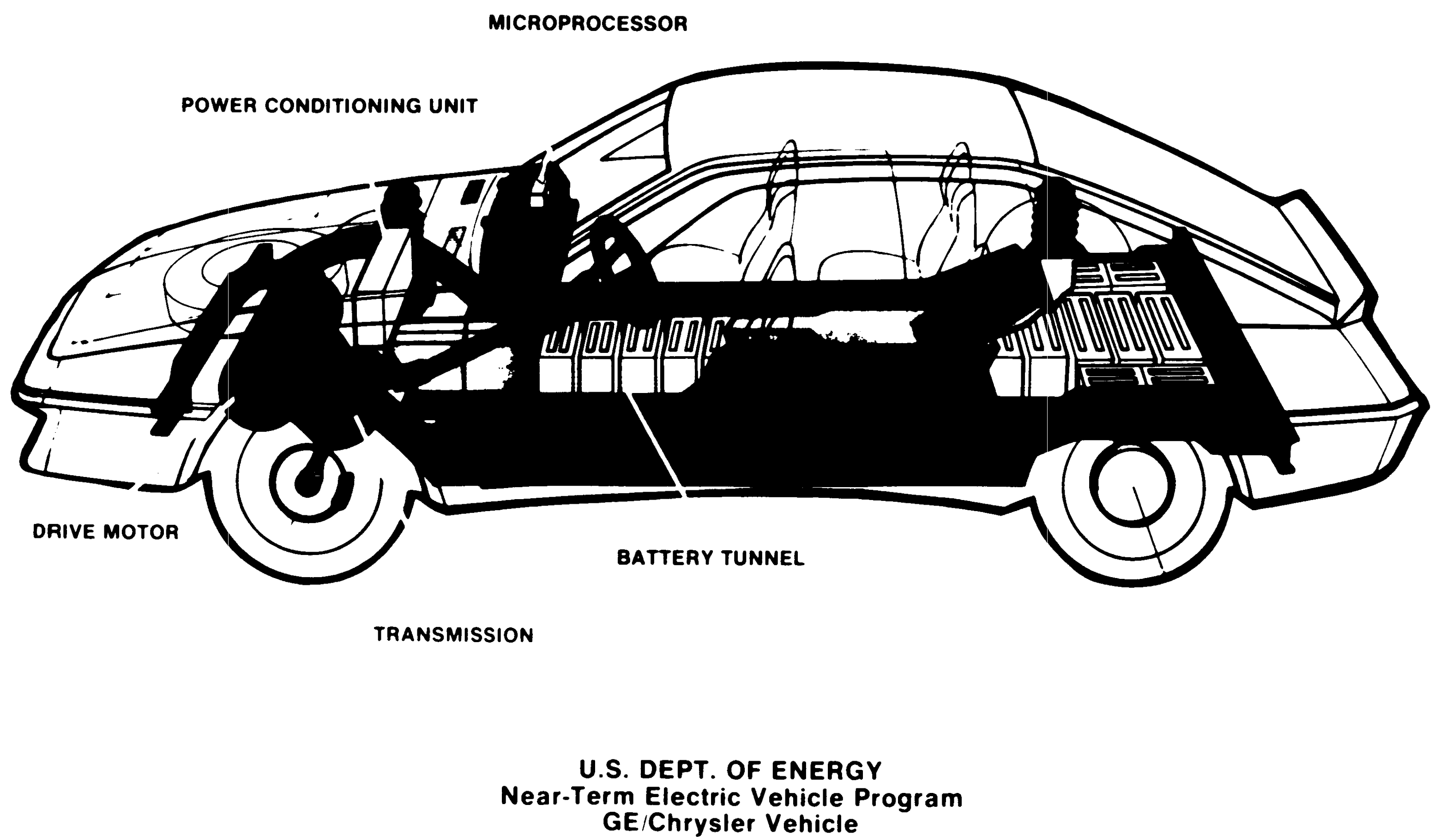


Figure 3.5 Schematic of the Electric Test Vehicle ETV-1

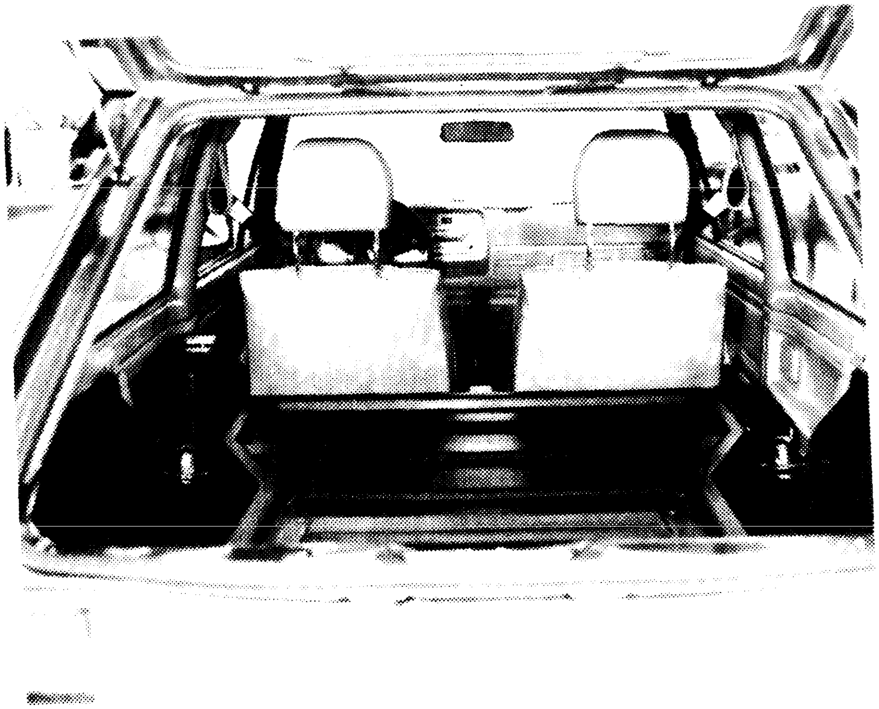
In cars designed from the ground up for electric propulsion, like the ETV-1, designers have maximum freedom in accommodating the heavy, bulky battery and in maximizing range for a given battery size through high efficiency. Most electric vehicles in operation today, however, are conversions of conventional ICE vehicles. In small quantities, conversions are far cheaper than all-new designs. They benefit to the maximum extent from the low cost and proven design built into mass-produced conventional vehicles and their components, The conversions suffer, however, in the compromise necessary to accommodate the weight and bulk of the battery. They also do not benefit from use of the lightweight materials which are not cost-effective for conventional cars (at today's fuel prices) but would be desirable in electric cars.

The state of the art in conversions is illustrated by the electric Rabbit built for the US Department of Energy by South Coast Technology, a small business located in Santa Barbara, California. The battery pack in the conversion consists of 18 golf car batteries which are the same size as the 18 special batteries included in the ETV-1.[10] To accommodate the battery pack, the rear seat of the Rabbit has been sacrificed, the rear floor modified, and the batteries placed in the area formerly occupied by the rear seat, the gasoline tank, and the spare tire. As shown in Fig. 3.6, the batteries occupy most of the floor space between the front seats and the rear wall of the car. Major modifications were made to the rear suspension of the Rabbit in order to accommodate the extra weight of the batteries, 1,170 pounds. A battery layout like that in the ETV-1 was considered, but rejected because of the much higher costs of the more extensive modifications which would have been required. As in the ETV-1, the entire drive train is in the front engine compartment. The electric motor is mounted on the standard Rabbit transaxle in place of the gasoline or diesel engine, driving the front wheels through the existing clutch and four-speed transmission. Because the motor is smaller than the engine it replaces, there is ample room above it for the controller. In Fig. 3.7, an under-hood view of the converted Rabbit, the controller is the large box slightly to the left of center.

The curb weight of the South Coast Rabbit, 3,120 pounds, is slightly less than that of the ETV-1, but it offers only half the seating capacity. Thirty-seven percent of its curb weight is battery weight. Its acceleration capability (and motor size) are comparable to those of the ETV-l; it achieves zero to 30 mph in about 10 seconds. Its aerodynamic drag is like that of efficient conventional cars now on the road, around 50 percent higher than that of the ETV-1. With golf car batteries, its urban driving range is 35 to 40 miles, whereas the more efficient ETV-1 with its specially-built batteries achieves 50-75 miles.

Method of Projection

With future batteries storing more energy per pound, the range of a car like the ETV-1 could be substantially increased. Alternatively, the car could be designed for a smaller battery at considerably reduced



a. Cover in Place

b. Cover Removed

Figure 3.6 The Battery Compartment of the Electric Rabbit Built by South Coast Technology

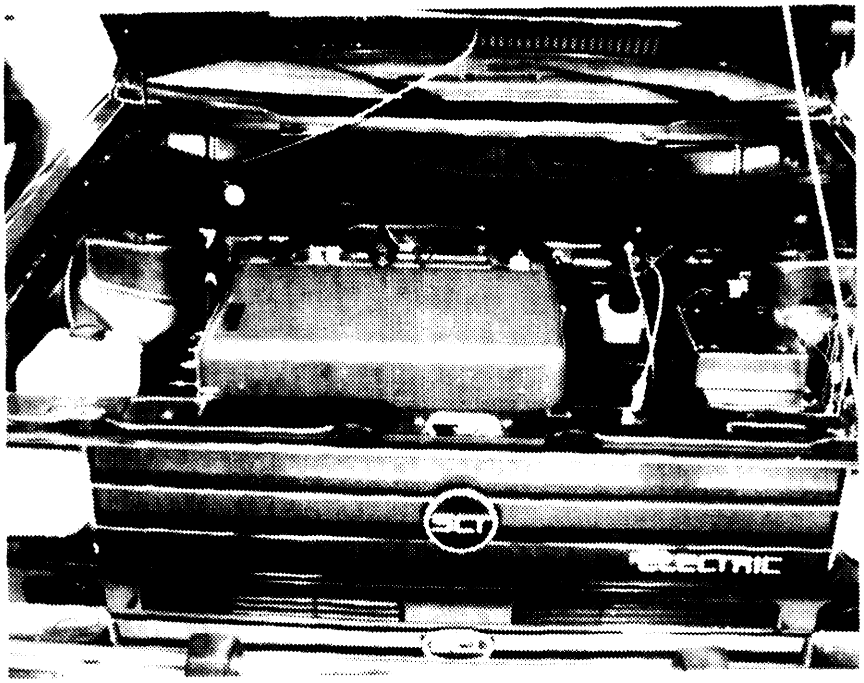


Figure 3.7 The Engine Compartment of the Electric Rabbit

Cost. As batteries improve, the spectrum of possible compromises between range and cost will widen, making explicit attention to this possibility more important.

The method of projection used for this report specifically accounts for the spectrum of possible compromises between range and cost. Its results--tradeoffs between range and cost for projected future batteries--are given in the next section. The method is based on four assumptions:

1. Payload and associated passenger compartment weight may be determined from the best current practice in the automobile industry.

2. The weight of supporting structure and chassis will be proportional to the weight of payload, passenger compartment, drive train, and battery. Again, good current practice indicates the constant of proportionality.

3. Drive train weight will be proportional to required power output. Power output, in turn, will be proportional to vehicle weight including a typical payload. Required output will be determined by acceleration requirements.

4. Battery weight will be varied over a range of practical possibility.

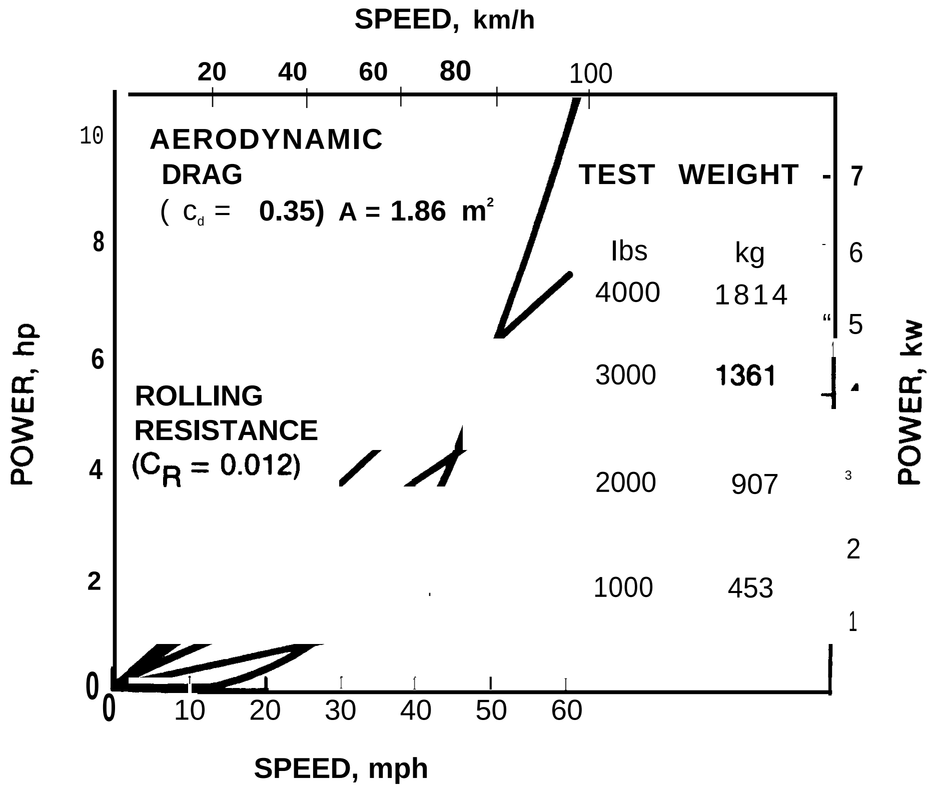
With these assumptions, the weights of the major components of the electric car may be estimated using a simple mathematical model described in the Appendix. The component weights form the basis for estimating initial vehicle price. They also determine total vehicle weight, which is essential for estimating range, energy use, and operating costs. Computer models implementing this approach have been and are being widely used for investigations of future electric vehicles. They are made available by the Cal Tech Jet Propulsion Laboratory, a DOE contractor, on a computer system which is accessible in most cities of the United States.

The third assumption above sizes the drive train of the electric vehicle, and thus its speed and acceleration capability. For projections given here, the drive train was required to produce 28 horsepower of output for each ton of vehicle weight including a standard 300-pound payload. This capability approximately suffices for acceleration of 0-40 mph in 10 seconds on level ground, a capability substantially above that of present electric vehicles such as the ETV-1 and the Rabbit conversion by South Coast Technology. Efficient cars with this capability generally offer top speeds in excess of the 55 mph limit, plus sufficient hill-climbing ability to enter freeways safely from up-hill on-ramps and to maintain safe speeds on most highway grades.

The adequacy of the 28 horsepower per ton drive train requirement follows from the "road load" of an efficient electric car. Road load is the power required to overcome the rolling resistance of a vehicle's tires and wheels, its aerodynamic drag, the force of gravity (while ascending grades), and the inertia of the vehicle during acceleration.

The power required to overcome rolling resistance and aerodynamic drag is modest at legal speeds in comparison with those for climbing grades and for acceleration. The power to overcome rolling resistance is proportional to speed and to vehicle weight. The power to overcome aerodynamic drag rises rapidly at speeds above 30-40 mph (see Fig. 3.8). Depending on vehicle weight, aerodynamic drag will equal tire rolling resistance at speeds in the vicinity of 40-50 mph. For a vehicle weight of about 3,500 pounds during cruise, like that of the ETV-l, the total power requirement at constant speed on a level road would be under 10 horsepower at 45 mph.

Ascending an up-grade at constant speed requires additional power to lift the car. Gradients are usually measured in percent, where a one percent grade corresponds to a one-foot increase in elevation for each hundred feet of travel. Highway gradients, on which safe speeds must be maintained, are usually less than 2 or 3 percent, and on interstate freeways do not exceed 6 percent. The extra power required to overcome each percent of gradient is approximately equal to the power required to overcome tire rolling resistance on level ground. Maintaining 45 mph on



Source: General Research Corporation

Figure 3.8 Road Load for Near-Term Subcompact Cars

a grade of about 3 percent would increase by a factor of 2 the power requirement for overcoming rolling resistance and aerodynamic drag alone in a typical 3,500-pound vehicle.

Overcoming inertia during acceleration adds even higher power requirements at the acceleration capability assumed here for future vehicles (0-40 mph on level ground in 10 seconds). Computer simulations have shown that this requires about 28 horsepower per ton, or a total of almost 40 horsepower for a 3,500-pound vehicle. This is to be compared with around 10 horsepower for level cruising at 45 mph, and 20 horsepower cruising at the same speed on a 2-1/2 percent gradient. The precise horsepower requirement per ton would vary a little with changes in road load for overcoming tire rolling resistance and aerodynamic drag. The changes are unimportant, however, because most of the power required for the acceleration is used to overcome inertia, not to overcome tire and aerodynamic losses.

Acceleration capability of 0-30 mph in 10 seconds, like that of the ETV-1, is usually adequate for keeping up with traffic. Figure 3.9 shows several measurements of the speed required to keep up with other vehicles in light, moderate, and heavy traffic. Even in light traffic, speed typically reaches 30 mph in about 10 seconds after a stop, and in moderate or heavy traffic even slower increases of speed suffice.

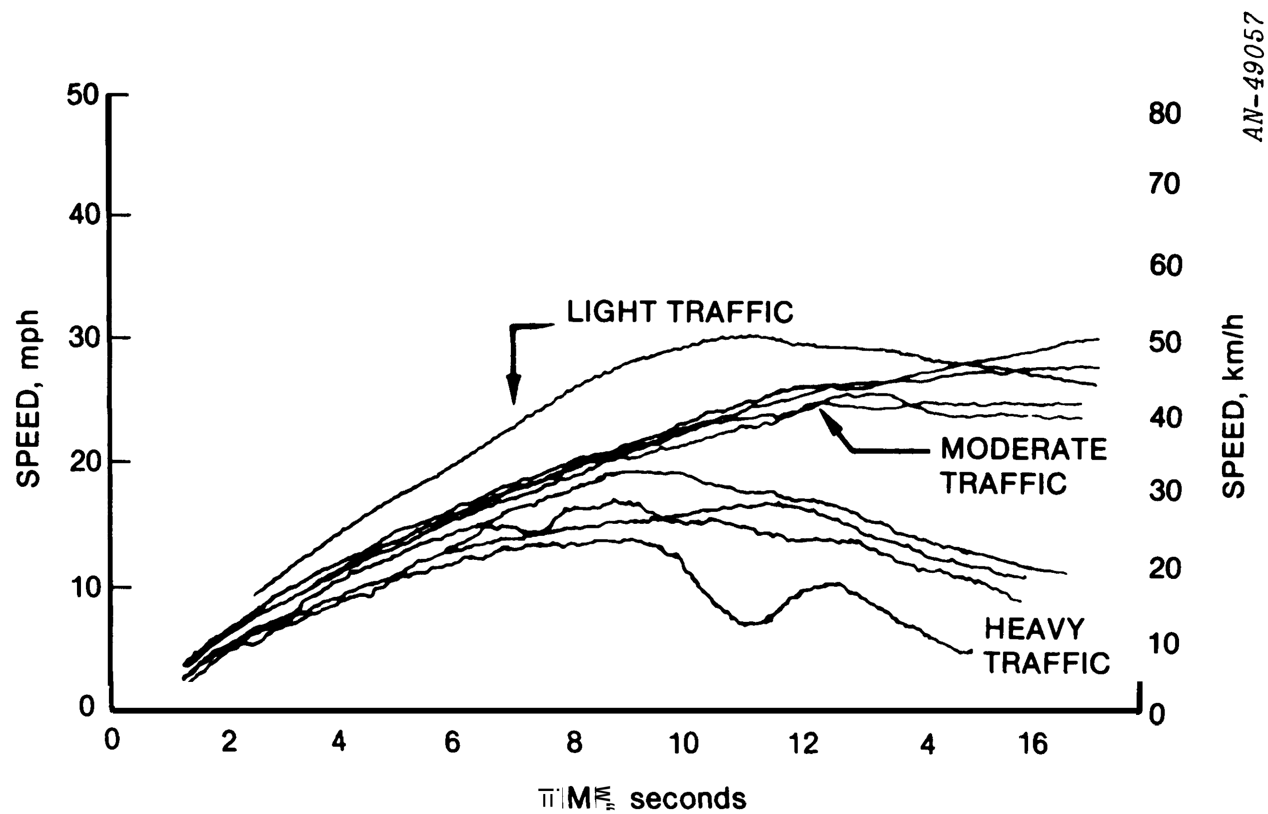
The acceleration requirement of 0-40 mph in 10 seconds used in this report is about the capability of many contemporary diesel cars and low-performance gasoline cars such as VW Beetles. It is base on a consideration of up-hill on-ramps to freeways, which are common.[13] To enter the freeway at a reasonable speed for safe merging with traffic, 40 mph or above, the power requirement for the typical up-hill on-ramp is about the same as that for the 0-40 mph acceleration on level ground in 10 seconds.

Values assumed in this report for rolling resistance and aerodynamic drag are consistent with today's tires and vehicle designs. While bias-ply tires of recent years had rolling resistances of roughly 1.5 percent of the load they carried, radial-ply tires have brought this down to 1.2 percent and below. The figures assumed here, 1.18 percent and 1.08 percent for cars with near-term and advanced batteries, respectively, are to be compared with the value of 1.11 percent for the tires selected for the ETV-1. Aerodynamic drag coefficients of US production cars have usually exceeded 0.5, though increased attention to body design has given the VW Rabbit a drag coefficient of about 0.46 and the new Chevrolet Citation about 0.42. The figure assumed here, 0.35, is better than that of almost any car now in production, but above the 0.30 reported for the ETV-1.

3.5 THE TRADEOFFS BETWEEN RANGE AND COST

The characteristics of future electric vehicles will depend strongly on resolution of a basic tradeoff between range and cost. For a vehicle with given technology, payload, and acceleration capability, both range and cost are determined by the size of battery selected. The larger the battery, the longer the range and the greater the usefulness of the electric car. But a larger battery also is more costly to buy and replace; and its extra weight necessitates increased expenses for a heavier basic vehicle with a more powerful drivetrain.

In the future, the tradeoff between range and cost will be increasingly important because improved batteries will widen the spectrum of possible choices. In the past, there was little freedom of choice about battery size because capabilities of golf-car batteries were so limited. Designers usually put as much battery as possible into their vehicles, often as much as 40 to 50 percent of curb weight, but battery power and energy output remained so low that acceleration and range were inadequate.



Source: D. Gates and M. Pocobello, Electric Van for Metropolitan Service, Paper 730249, Society of Automotive Engineers, Warrendale, Pennsylvania.

Figure 3.9 Measured Acceleration of Urban Traffic

In the future, designers will probably work with batteries providing much higher specific energy and specific power. With more energy and power per pound, the largest possible battery will no longer be required to give reasonable acceleration and range. With a large but still manageable battery, near-term vehicles might achieve twice the range attainable with the minimum battery acceptable from the standpoint of acceleration power. For vehicles with advanced batteries, the maximum design ranges might be three times the minimum, or even more.

These spectrums of future possibilities are examined by using the projection method of Sec. 3.4 to show how sticker price, life-cycle cost, curb weight, and energy use of future electric vehicles might depend on urban driving range. Generally, the projections show that with near-term batteries electric vehicles may offer ranges in excess of 100 miles, or life-cycle costs competitive with those of comparable conventional cars, but not both at once. Vehicles with advanced batteries, however, might simultaneously provide both competitive costs and ranges as great as 200 miles. Neither near-term nor advanced batteries lead to initial prices for electric vehicles competitive with those of gasoline vehicles even at the shortest possible design ranges.

Depending on battery size, projected four-passenger cars with near-term batteries could offer:

- 50-170 mile urban range
- 0.32-0.56 kilowatt-hour-per-mile energy use (input to battery charger)
- **$6,500-$11,000** sticker prices (in 1980 dollars)
- 20.2-30.8 cents per mile life-cycle costs

The initial and life-cycle costs of the comparable ICE vehicle are projected to be $4,470 and 21.4 cents per mile. The maximum battery weight assumed for these projections was 36 percent of vehicle test weight. The minimum battery fraction, depending on battery type, was in the range 20-24 percent of vehicle test weight. The lead-acid batteries gave the least range--50 to 100 miles--but also the least life-cycle cost, lower than that of the conventional vehicle for design ranges up to 70 miles. The car with the near-term zinc-chlorine battery gave life-cycle costs close to those of the conventional counterpart at its minimum design range of 95 miles, and at all other ranges up to its 170-mile maximum gave the lowest life-cycle costs of the near-term alternatives.

Depending on battery size, projected four-passenger cars with advanced batteries would offer:

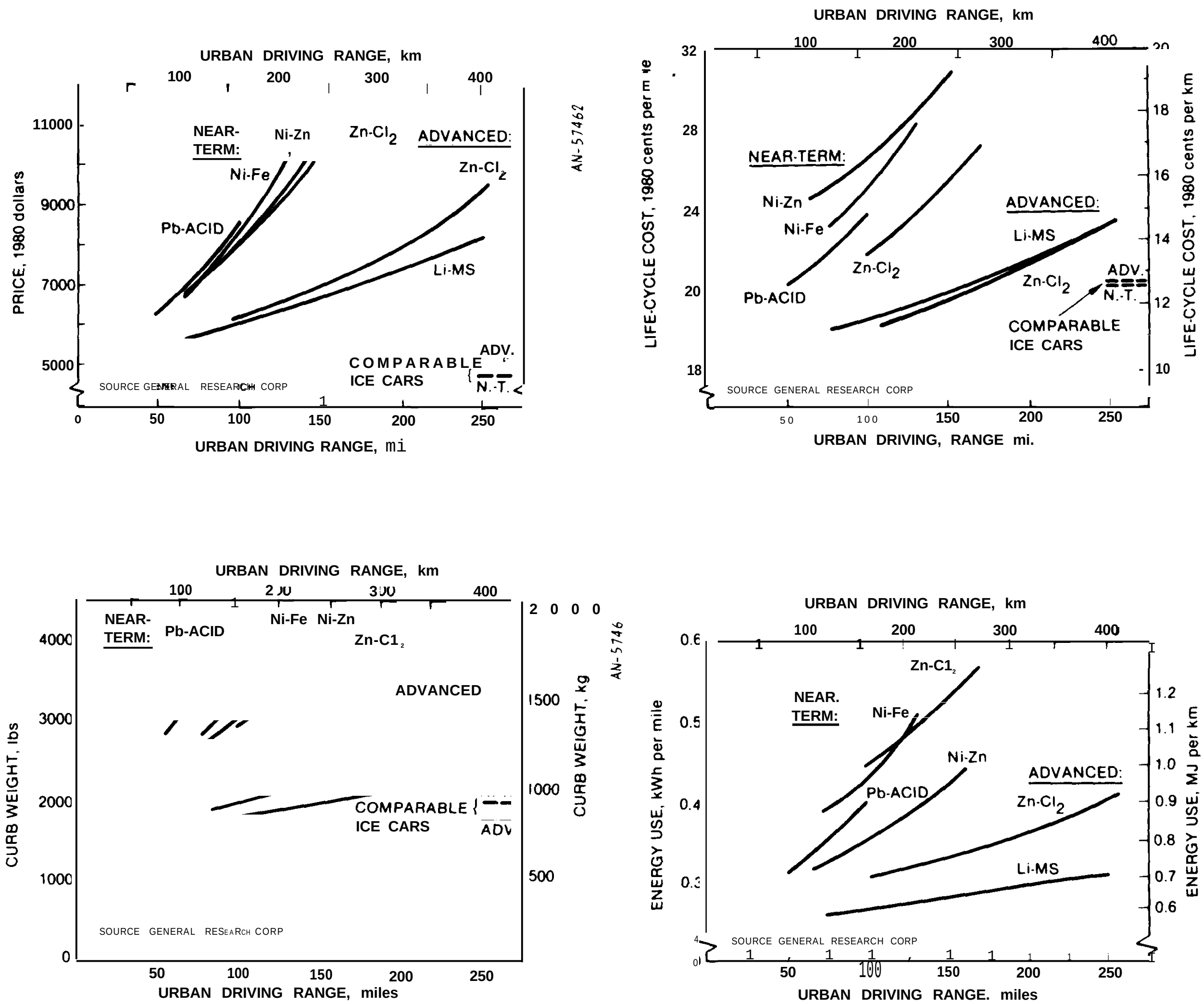
- 65-260-mile urban range
- 0.26-0.41 kilowatt-hours-per-mile energy use (input to battery charger)
- $5,700-$9,500 sticker price (in 1980 dollars)
- 17.8-23.5 cents per mile life-cycle costs

The comparable conventional car was projected to offer a sticker price of $5,140 and a life-cycle cost of 21.7 cents per mile. At all design ranges, the sticker prices of the advanced electric cars exceed this price, but their life-cycle costs are less at ranges up to roughly 200 miles. Battery sizes for the advanced zinc-chlorine car ranged from 17 to 35 percent of curb weight. For the car with the very high-power, high-energy advanced lithium-metal sulfide battery, battery fractions ranged from about 9 to 25 percent. The initial cost of the comparable advanced ICE car is higher than that of the near-term ICE car because it incorporates expensive lightweight materials. The life-cycle cost of this car is also higher than that of the near-term car; gasoline savings provided by its higher fuel economy are insufficient to offset the extra depreciation costs due to its higher-cost, lighter-weight construction (see Fig. 3.10).

The uncertainties in these projections are greatest for the cars with advanced batteries. On the one hand, advanced batteries might be developed earlier than projected here, during the 1980's; on the other, they may not be successfully developed until the next century, if ever. When they do reach mass production, they may well have lesser capabilities, higher prices, and shorter useful lifetimes than those assumed for these projections.

The projections are less uncertain for cars with near-term batteries. It appears likely that at least one of the near-term battery developments will be successful. Which one, however, is less clear; it may not be the one offering lowest cost or highest performance.

The projections for the comparable ICE vehicles are also uncertain. Projected life-cycle costs are based on 1980 gasoline prices ($1.25 per gallon) even though substantial increases in real gasoline prices are probable for the future. An increase of $1.25 in gasoline price per gallon (to a total of $2.50) would add four cents per mile to the life-cycle costs for the comparable ICE cars. Each additional $1.25 increase would add another four cents per mile. Furthermore, assumed advances in ICE car technology are very modest; they do not include turbo-charged diesel engines, engine restart systems which eliminate



Assumptions: Mid-1980 dollars

Acceleration Capability: 0-40 mph in 10 seconds

Driving Cycle: SAE J227a, Schedule D

Source: General Research Corporation

Figure **3.10** Design Tradeoffs for Four-Passenger Electric Cars idling during stops, continuously variable transmissions, Brayton or Stirling cycle engines, or any of the other innovations which may substantially reduce fuel consumption and life-cycle costs (though they generally increase sticker prices). Other advances may also be achieved, such as lower-loss tires or lighter structures, but these tend to benefit electric and conventional vehicles equally.

3.6 REPRESENTATIVE FUTURE ELECTRIC VEHICLES

Though short-range electric vehicles are cheapest to own and operate, many motorists will probably prefer the extra utility afforded by longer range, despite the extra cost. If electric vehicles are marketed in large quantities, competing models will probably offer a variety of ranges.

In this section, several representative future electric cars are selected from the spectrum of possibilities developed in Sec. 3.5, for more detailed description and for subsequent use in estimating impacts of wide scale vehicle electrification.

For near-term vehicles, 100 miles appears to be a representative future range capability. This is the adopted goal of DOE development programs for the late 1980's, and has also been stated as a goal in GM's announcements about its electric car development efforts. It is further supported by market data to be discussed in Chapter 6, which indicates that the average motorist purchasing an electric car for urban use as a second car would prefer an urban range capability of 85-95 miles, given the tradeoffs between range and price projected in Sec. 3.5. For other applications, which involve more long-distance driving, more range would probably be desired.

For near-term four-passenger cars with 100-mile range:

- Sticker price would be $8,100-8,500, 75-80 percent greater than the $4,740 price of the competitive ICE car.
- Life-cycle cost would be 22.0-26.6 cents per mile, versus 21.4 cents per mile for the comparable ICE car.
- Electricity input to the battery charger would be 0.4-0.45 kilowatt hours per mile.

For the electric vehicle with advanced batteries, more range would be appropriate because it entails less ‘expense than in the near-term car. For cars with a given range, an advanced battery can be lighter and less expensive than any of the near-term batteries. Increasing battery size (and car range) by a given amount is therefore less expensive for the advanced-battery car, because a smaller portion of its total cost is affected. One hundred-fifty miles appears to be a reasonable expectation for the representative car with advanced batteries. Preferred ranges of 125-150 miles are indicated by the market data in Chapter 6, given the range-versus-cost tradeoffs of Sec. 3.5.

For advanced four-passenger electric cars with 150-mile range:

- Sticker price would be $6,800-7,050, 32-37 percent above the $5,140 price of the comparable ICE car.
- Life-cycle cost would be 19.4-20.1 cents per mile, 8-11 percent lower than the 21.8 cents per mile projected for the comparable ICE car.
- Electricity input to the battery charger would be about 0.3 kilowatt-hours per mile.

Further details of these representative near-term and advanced cars are given in Table 3.5.

The basic factors behind the higher sticker price of the representative electric cars are the weight and cost of the battery, which far exceed the weight and cost of the gasoline tank they supplant. The contribution of battery weight to vehicle weight is illustrated in Fig. 3.11 for the lightest and heaviest of the representative near-term electric cars. For comparison, weight is also shown for the comparable ICE car. Battery weight is the major contributor to the extra weight of the electric cars. Moreover, the extra structure and chassis weight required to carry the weight of the battery also contributes significantly to the total extra weight of the electric cars. For the cars with the nickel-zinc and zinc-chlorine batteries, for example, extra structure and chassis weight is about 250 lbs. Roth battery and extra structure contribute to the extra initial costs of the electric vehicle.

More details of the projected initial and life-cycle costs of representative future cars are presented in Table 3.6. The major differences between the electric cars and the comparable ICE cars included in the tables are:

- Cost of the battery and replacements, which add far more to initial and life-cycle costs than those of the gasoline tank.
- Cost of capital, which is higher for the electric car because of the higher initial price and the higher average value of the electric car through its life.
- Costs of repairs and maintenance, which are projected to be much less for the electric vehicles.
- Costs of energy, which for the electric vehicles are about half as much per mile as for the comparable ICE vehicles.

TABLE 3.5

REPRESENTATIVE FUTURE ELECTRIC CARS

	ETV-1 (1980)	Near-Term (by 1990)					Advanced (by 2000)		
Battery Type	Pb-Acid (lead-acid)	Pb-Acid (lead-acid)	Ni-Fe (nickel-iron)	Ni-Zn (nickel-zinc)	$Zn-Cl_2$ (zinc-chlorine)	(ICE)*	$Zn-Cl_2$ (zinc-chlorine)	Li-MS (lithium-metal sulfide)	(ICE)*
Battery Specific Energy, Wh/lb+	16.9	22.7	27.2	31.8	34.0	--	45.4	68.0	--
Nominal Range (urban), mi	60	100	100	100	100	--	150	150	--
Curb Weight, lb	3260	4090	3290	3030	2960	2010	2300	2260	1810
Battery System Weight, lb	1140	1580	1050	890	840	--	600	400	--
Sticker Price, mid-1980 dollars	8480	8520	8400	8130	8120	4740	7050	6810	5140
Life-Cycle Cost, 1980 cents/mi	26.1	23.9	24.9	26.6	22.0	21.4	19.4	20.1	21.8
Electricity Use, kWh/mi	0.38	0.40	0.44	0.38	0.45	--	0.31	0.30	--
Fuel Economy, mpg (urban driving)	--	--	--	--	--	33.0	--	--	35.6

Assumptions:

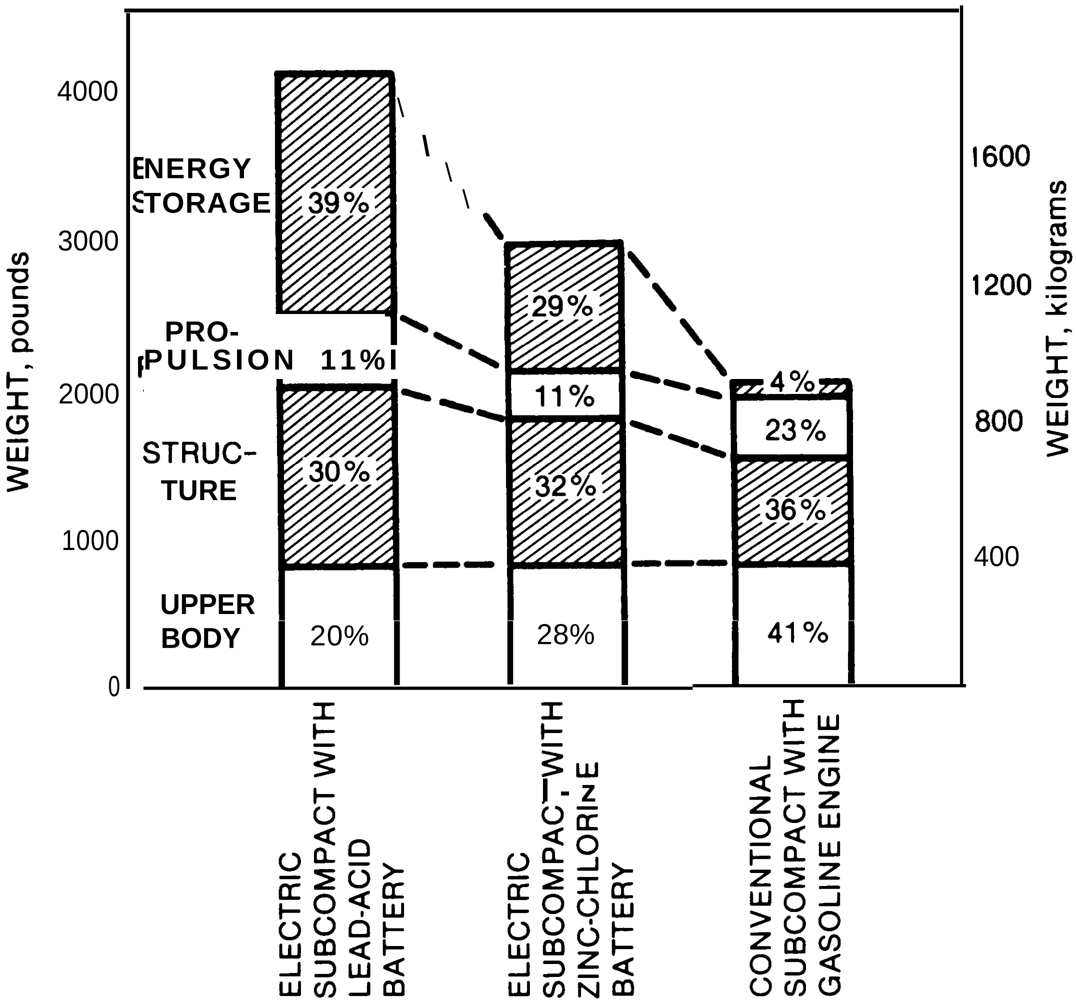
Electricity Price	$0.03 per kilowatt-hour
Gasoline Price	$1.25 per gallon
Electric Vehicle Life	12 years
ICE Vehicle Life	10 years
Annual Travel	10.000 miles
Urban Driving Cycle	SAE J227a, Schedule O, for electric cars, Federal Urban Driving Cycle for ICE cars
Acceleration Capability	0-40 mph in 10 seconds
Passenger Capacity	Four persons plus luggage

Source:

General Research Corporation. Performance and cost estimates for all vehicles were made with the ELVEC and EVWAC computer models. Costs are in mid-1980 dollars and are based on mass production of all vehicles (300,000 units or more per year).

*Internal combustion engine

+Energy delivered by the battery in a full discharge over three hours, in watt-hours per pound of battery weight



Source: General Research Corporation

Figure 3.11 Weight Breakdowns for Representative Near-Term Four-Passenger Cars

TABLE 3.6

INITIAL AND LIFE-CYCLE COSTS OF REPRESENTATIVE FOUR-PASSENGER ELECTRIC CARS

	Near-Term							
	Pb-Acid	Ni-Fe	Ni-Zn	$Zn-CL_2$	(ICE)	$Zn-CL_2$	Li-MS	(ICE)
Initial Cost, dollars	8520	8400	8130	8120	4740	7050	6810	5140
Vehicle	6660	5950	5720	5540	4740	5410	5180	5140
ery	1860	2450	2410	2580	-	1640	1630	-
Life-Cycle Cost, cents per mi	23.9	24.9	26.6	22.0	21.4	19.4	20.1	21.8
Vehicle	5.0	4.5	4.3	4.2	4.3	4.1	3.9	4.7
Battery	3.0	4.8	7.0	2.3	-	1.4	2.6	-
rs and Maintenance	1.5	1.5	1.5	1.5	3.9	1.5	1.5	3.9
Replacement Tires	0.6	0.5	0.5	0.5	0.4	0.4	0.4	0.4
Insurance	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2
Garaging, Parking, Tolls, etc.	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1
Title, License, Registration, etc.	0.7	0.6	0.6	0.6	0.6	0.5	0.5	0.5
Electricity	2.3	2.2	2.0	2.2	-	1.7	1.5	-
Fuel and Oil	-	-	-	-	4.0	-	-	3.7
of Capital	5.5	5.5	5.4	5.4	3.0	4.5	4.4	3.3

All costs are in mid-1980 dollars.

Assumptions

Electricity Price	$0.03 per kilowa[illegible]
Gasoline Price	$1.25 per gallon
Electric Vehicle Life	12 years
ICE Vehicle Life	10 years
Annual Travel	10,000 miles
Car and Battery Salvage Value	0 percent
Cost of Capital	0 percent per year

Car and battery purchases are 100 percent financed over their useful lives.

Electricity cost includes a road use tax equal to that paid by typical gasoline vehicles of equal weight via state and federal gasoline taxes.

General Research Corporation. Cost categories and many entries, such as tires, insurance, garaging, etc., are based on periodic cost analyses by the Department of Transportation (see Ref. 14). All costs shown were computed by the Electric Vehicle Weight and Cost Model (EVWAC), Ref. 15.

The savings on repair and maintenance are based on data showing that the ICE system in conventional cars has accounted for some 60 to 70 percent of all labor hours and parts sales for repair and maintenance. For electric motor-controller systems, which have many fewer moving parts and components with much longer lives, it was assumed that very little service would be required. The same assumption was extended to the propulsion battery, though there is little relevant experience. Especially for battery types which have not been in service, reliability is uncertain. It is also possible that maintenance costs for future ICE cars will be considerably reduced, despite complex pollution controls, by electronic ignition and control systems, long-life spark plugs, tamper-proof controls, and improved quality control.

The fuel prices for the projected ICE cars are 4 cents per mile at the mid-1980 price of gasoline ($1.25 per gallon). Each rise of $1.25 per gallon adds 4 cents per mile to the ICE life-cycle cost projections. Major shifts in relative attractiveness of electric and conventional cars could result from gasoline price increases. For the projected life-cycle costs of conventional cars to equal the life-cycle costs projected for the near-term representative electric cars, these price increases for gasoline would be required:[16]

- 63 percent for lead-acid battery cars (to $2.05 per gallon)
- 88 percent for nickel-iron battery cars (to $2.35 per gallon)
- 105 percent for nickel-zinc cars (to $2.55 per gallon)
- 15 percent for zinc-chlorine cars (to $1.44 per gallon)

The percentage increases required to equalize costs are very sensitive to details of projected battery life and cost. The individual figures given above are uncertain; but overall, it appears likely that price increases for gasoline of 75 to 100 percent are probably required to raise life-cycle costs of comparable ICE cars to equal those of future cars with near-tern batteries.

It is noteworthy that the advanced cars are projected to be cheaper on a life-cycle basis than the comparable ICE cars (Table 2.6) despite the assumption of low 1980 gasoline prices. This is the result of the low weight, long life, and modest cost projected for the advanced batteries. Even if these projections materialize, however, lower operating costs may seem unimportant to many motorists in relation to the 35 percent higher sticker prices and the range limitation (assuming gasoline is readily available).

If petroleum alone were used to generate recharge energy, the energy requirements of the near-term electric cars would be equivalent to those of conventional cars getting 26 to 30 mpg (miles per gallon) in urban driving. The advanced-battery cars would increase this equivalent fuel economy to 37 to 38 mpg. This is no more than competitive with the projected conventional cars offering the same passenger space and acceleration, built with the same materials, using conventional ICE drivetrains, which might get 33 to 36 mpg in urban driving. If coal alone were used to generate electricity and produce synthetic gasoline, however, the near-term electric cars would offer the equivalent of 44 to 50 mpg, and the advanced battery cars 64 to 67 mpg. This results from the inefficiencies of using coal rather than petroleum to produce gasoline. Table 3.7 summarizes these projections.

The ‘comparable ICE cars” discussed here do not necessarily exhibit the ultimate or even likely future potential of ICE propulsion, a subject beyond the scope of this analysis. Instead, they are included only to show how conventional automotive technology of the 1980's might compare with the electric vehicles projected here, assuming both offer the same passenger accommodations and acceleration capability. More advanced technology may lead to much higher fuel economies than the 33-36 mpg projected here. Some possible innovations (much improved tires, aerodynamics, and structures) would benefit both electric and ICE vehicles. Others, notably lighter, more efficient ICES and continuously variable transmissions, could improve considerably the desirability of ICE vehicles relative to electric vehicles.

In an electric vehicle, around 40 percent of the energy input to the battery charger may be used to overcome road load, as illustrated in Fig. 3.12. On the other hand, the electric energy input to the charger represents only 28 to 30 percent of the energy available from the combustion of the fossil fuels used to produce it. In an ICE vehicle the situation is reversed: petroleum is refined and delivered to the gasoline tank with high efficiency, but in the internal combustion engine which uses gasoline , efficiency in urban driving may be only 10 to 20 percent.[17,18]

Use of regenerative braking in electric vehicles can greatly reduce losses which would otherwise appear in friction brakes, even though friction braking must still be included (Fig. 3. 12). For safe and predictable braking, regeneration alone is unsatisfactory because it is effective only on the driven wheels, front or rear, rather than all four wheels. Without regeneration, the 100-mile range of the car described in Fig. 3. 12 would be reduced to about 81 miles.

So far, all ranges and energy uses which have been projected here for future electric vehicles are nominal design values: they would be achieved only with a battery in good condition (during perhaps the first two-thirds of its useful life), and only in the given urban driving schedule, on level roads without winds. Near the end of battery life,

TABLE 3.7

EQUIVALENT FUEL ECONOMIES OF FOUR-PASSENGER ELECTRIC CARS RECHARGED FROM PETROLEUM OR COAL RESOURCES

	Equivalent Miles per Gallon*	
Near-Term Cars	Oil	Coal
Lead-acid	29	50
Nickel-iron	26	45
Nickel-zinc	30	53
Zinc-chlorine	26	44
(Comparable ICE car)†	(33.0)	(33.0)
Advanced Cars		
Zinc–chlorine	37	64
Lithium-metal sulfide	38	67
(Comparable ICE car)†	(35.6)	(35.6)

Assumed Conversion Efficiencies (taken from Ref. 16):

Crude oil to gasoline	89 percent
Crude oil to electricity	28 percent
Coal to gasoline	55 percent
Coal to electricity	30 percent

Efficiencies include losses and energy inputs in extraction of the energy resource from the ground, transportation and conversion to its fixed form for vehicular use, and delivery to the vehicle.

Source: General Research Corporation

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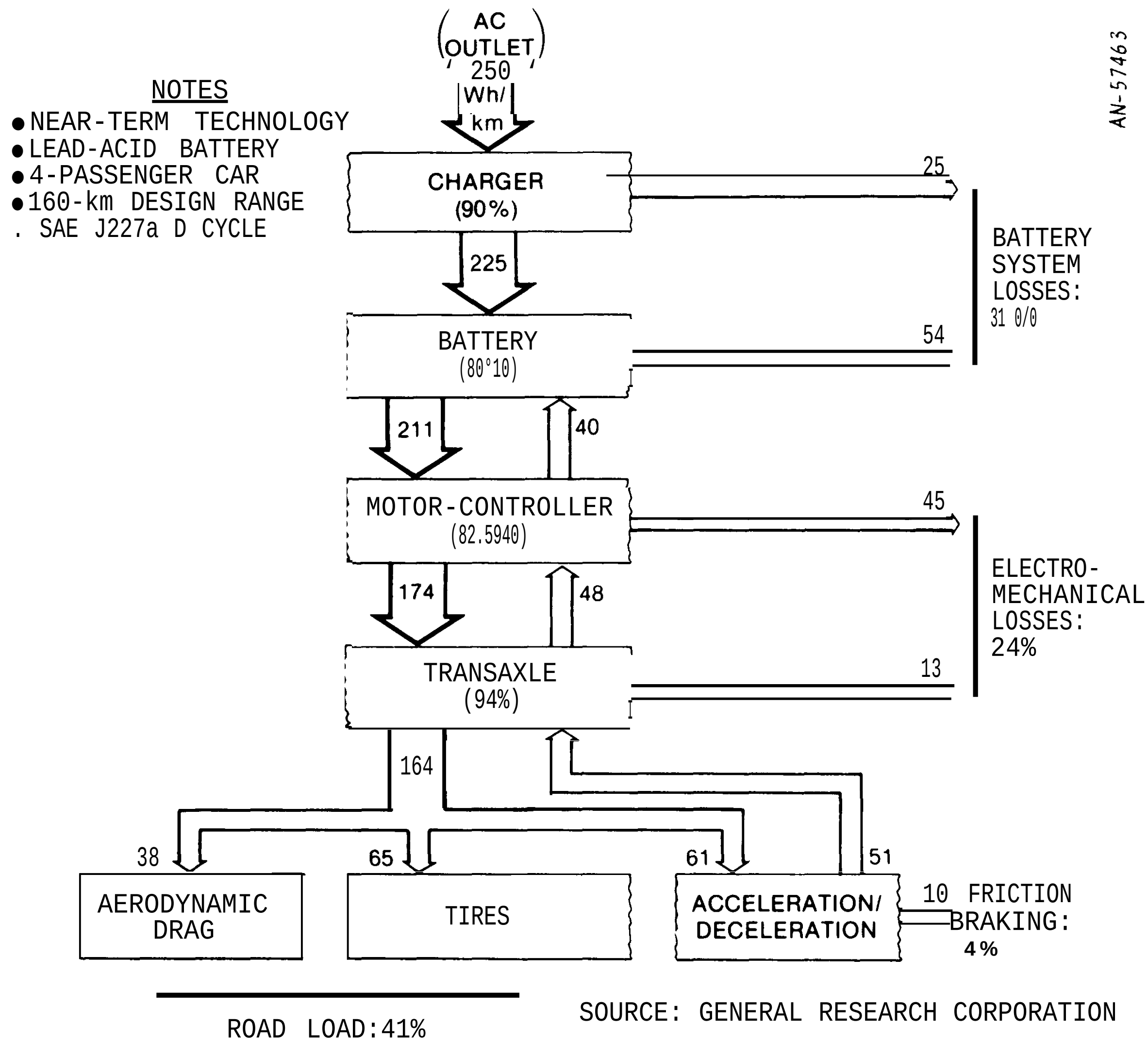
* Equivalent miles per gallon is the urban fuel economy of an ICE car requiring the same use of petroleum (for gasoline) or coal (for synthetic gasoline) as would be needed to generate recharge electricity for the electric car.

† The comparable ICE cars offer the same passenger compartments and acceleration capability as their electric counterparts, are built with the same materials, and use conventional ICE drive trains. Their fuel economies are projected for urban driving.



Source: General Research Corporation

Figure 3.12 Energy Use in Urban Driving (in Watt-Hours per Mile, with Component Efficiencies in Parentheses)

range in nominal urban driving would be reduced up to 20 percent. Non-nominal driving conditions, furthermore, can considerably affect the range and energy use. On the one hand, range in the Federal Urban Driving Cycle, range in the Federal Highway Cycle, range in the nominal urban driving cycle, and range at a constant speed of 55-60 mph are all quite close together. On the other hand, changes in battery temperature can affect range by a factor of two; low constant speeds in highway driving can more than double range; 15-mph headwinds or tailwinds in 55-mph highway driving can decrease range some 20 percent or increase it 60 percent; and on long upgrades range can be sharply reduced. Energy use varies almost as widely. This is summarized in Table 3.8.

TABLE 3.8

EFFECT ON RANGE OF CHANGED DRIVING CONDITIONS

Driving Condition	Range, mi	Energy Use, kWh/mi
Urban Driving		
SAE J227a, Schedule D	100	0.40
Federal Urban Driving Cycle	113	0.37
Battery Temperature = 32°F	65	
Battery Temperature = 10°F	123	
Highway Driving		
Federal Highway Cycle	106	0.38
Constant 60 mph	98	0.41
Constant 50 mph	133	0.34
Constant 40 mph	179	0.29
Constant 30 mph	235	0.24
Constant 55 mph	115	0.38
with 15 mph headwind	79	0.50
with 15 mph tailwind	164	0.29
on 3 percent upgrade	37	0.85

Source: General Research Corporation

All ranges estimated by the ELVEC simulation for a four-passenger car with near-term lead-acid battery and design range of 100 miles.

The nominal driving schedule used to estimate design range, Schedule D of SAE Recommended Procedure J227a, is the most demanding of four schedules recommended by the Society of Automotive Engineers for electric vehicle testing. Each cycle of the schedule requires 122 seconds and traverses about 0.95 mile. Starting from rest, the cycle requires a 28-second acceleration to 45 mpg, a 50-second constant speed cruise, a 10-second coast, and a 9-second braking to zero mph, followed by a stop. The Federal Urban Driving Cycle used for evaluating pollutant emissions and fuel economy of conventional cars is far more complex. It lasts 1372 seconds and is based on actual records of vehicle operation in an urban area, both on city streets and on a freeway. It remains to be determined which of these cycles is the better indicator of actual EV range and energy use in average urban driving.

Battery temperature can have a major effect on battery output and vehicle range. Available battery capacity may change as much as 6 percent for a 10°F change in battery temperature, depending on battery design and on initial battery temperature. The results in Table 3.8 are based on this high assumed sensitivity to temperature, and may represent upper bounds on the magnitude of likely range changes in the future. Insufficient data was available to estimate associated changes in energy use. Because of this potential sensitivity, batteries in electric vehicles for cold climates are very likely to be housed in insulated compartments, with heating available from the source of recharge power. In ordinary operation a considerable amount of energy is lost as heat in the battery. Supplemental heat from an external source will probably be necessary only for cars left idle for long periods, or in very cold weather. The electrolyte of a discharged battery freezes at temperatures well above 0°F, a condition which must be avoided to avoid battery damage. High electrolyte temperatures must also be avoided; they reduce battery life.

In highway driving near 55 mph, electric car ranges are typically like those attained in nominal urban driving. The effects of lower speeds on highway range can be dramatic, however, as can the effects of winds, A 3-percent grade affects range even more drastically. The case in Table 3.8 is extreme because a 3-percent grade 37 miles long implies a total ascent of almost 5900 feet. Though freeway grades are occasionally steeper (up to 6 percent) , they are very seldom long enough to involve so great a change of elevation.

Heating and cooling of passenger compartments pose special problems for electric vehicles. ICE vehicles utilize waste engine heat, which is sufficient for passenger comfort in all but the coldest climates, where an auxiliary gasoline heater is often added. Electric drive is so efficient, however, that relatively little waste heat is available. Wider use of auxiliary gasoline heaters would be one possible remedy. Another would be efficient use of electric heating, which might be used to heat occupied seats directly rather than the entire car interior. Alternatively, a heat pump might be employed. Since a heat pump is reversible, it could also act as an air conditioner to provide cooling on hot days. Full-time use of an air conditioner or heat pump with the capacity typical for conventional vehicles would reduce the range of an electric vehicle roughly 15 percent. On most days, of course, this would be acceptable since the full 100-mile range would be required relatively infrequently.

So far, comparisons between representative future electric and ICE vehicles have been limited to the case of four-passenger cars. Generally, however, the comparisons remain valid for larger cars and for light trucks (pickups and vans). For example, the sticker price of the four-passenger car with zinc-chlorine battery was 71 percent above the sticker price of the comparable ICE car (Table 3.5). The sticker price of the five-passenger version of this car is also 71 percent higher than that of the comparable five-passenger ICE car. Within a few percentage points, similar car comparisons also hold true for other key vehicle characteristics such as curb weight, life-cycle cost, and energy use, and for other vehicle sizes and types. A complete set of descriptors for comparable zinc-chlorine EVS and comparable ICE vehicles is given in Table 3.9. These and similar projections for EVS with other batteries demonstrate that comparisons drawn between four-passenger electric and ICE cars generally prevail for the other vehicles as well.

Under detailed examination, electric light trucks compare a little less favorably to their ICE counterparts than do electric four-passenger cars. Here, as in the four-passenger car, a 300-pound payload was assumed throughout. Had the light trucks been loaded to their maximum design payload of 1190 pounds, the electric trucks would have compared even less favorably to the ICE trucks because their range would be substantially reduced. The range of the ICE trucks is similarly reduced by loading, but shorter range is less important for ICE trucks because refueling is so much faster.

It is possible that small, low-performance two-passenger cars may play a significant role in future urban travel. At present, little more than 1 percent of cars sold in the US seat only two passengers, and most of them are sold as sport cars for high performance. Drastic changes in gasoline price and availability, far exceeding those of the 1970's, would probably be required to effect a major market shift to low-performance two-passenger cars. Should this happen, however, there is no reason to expect that electric cars built with the technology described here would gain any relative advantage in price or capability over ICE cars of this same small size. Like the larger electric cars, two-passenger electrics would be 70 to 80 percent more expensive to buy, and equally limited in range.

TABLE 3.9

CHARACTERISTICS OF LARGER VEHICLES RELATIVE TO THOSE OF REPRESENTATIVE FOUR-PASSENGER CARS

	Near-Term Vehicles With Zinc-Chloride Battery				Comparable Near-Term ICE Vehicles			
	Curb Weight, lb	Sticker Price, dollars	Life-Cycle Cost, cents/mi	Fuel Use, kWh/mi	Curb Weight, lb	Sticker Price, dollars	Life-Cycle Cost, cents/mi	Fuel Economy, mpg
4-Passenger Car	2960	8120	22.0	0.45	2010	4740	21.4	33.0
5-Passenger Car	3430	8490	24.7	0.51	2300	5540	23.7	30.0
6-Passenger Car	4270	12760	30.6	0.61	2900	7870	29.5	25.0
Compact Pickup	3360	8570	23.0	0.52	2164	4690	21.6	31.0
Compact Van	3700	9520	24.7	0.61	2330	5080	22.9	27.0

Assumptions:

- 1980 dollars
- 100-mile electric vehicle range (with 300-lb payload, in urban driving)
- Acceleration capability 0-40 mph in 10 seconds for electric and ICE vehicles

Source:

General Research Corporation

Two-passenger electric cars may nevertheless play a prominent role among the first electric cars to come to market. So long as electric cars are purchased by only a few percent of motorists, who will probably differ sharply from the average motorist, a large proportion may be two-passenger cars. The first GM electric car may well offer only two seats--but it needs to appeal to only 2 to 3 percent of new car buyers in order to succeed.

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