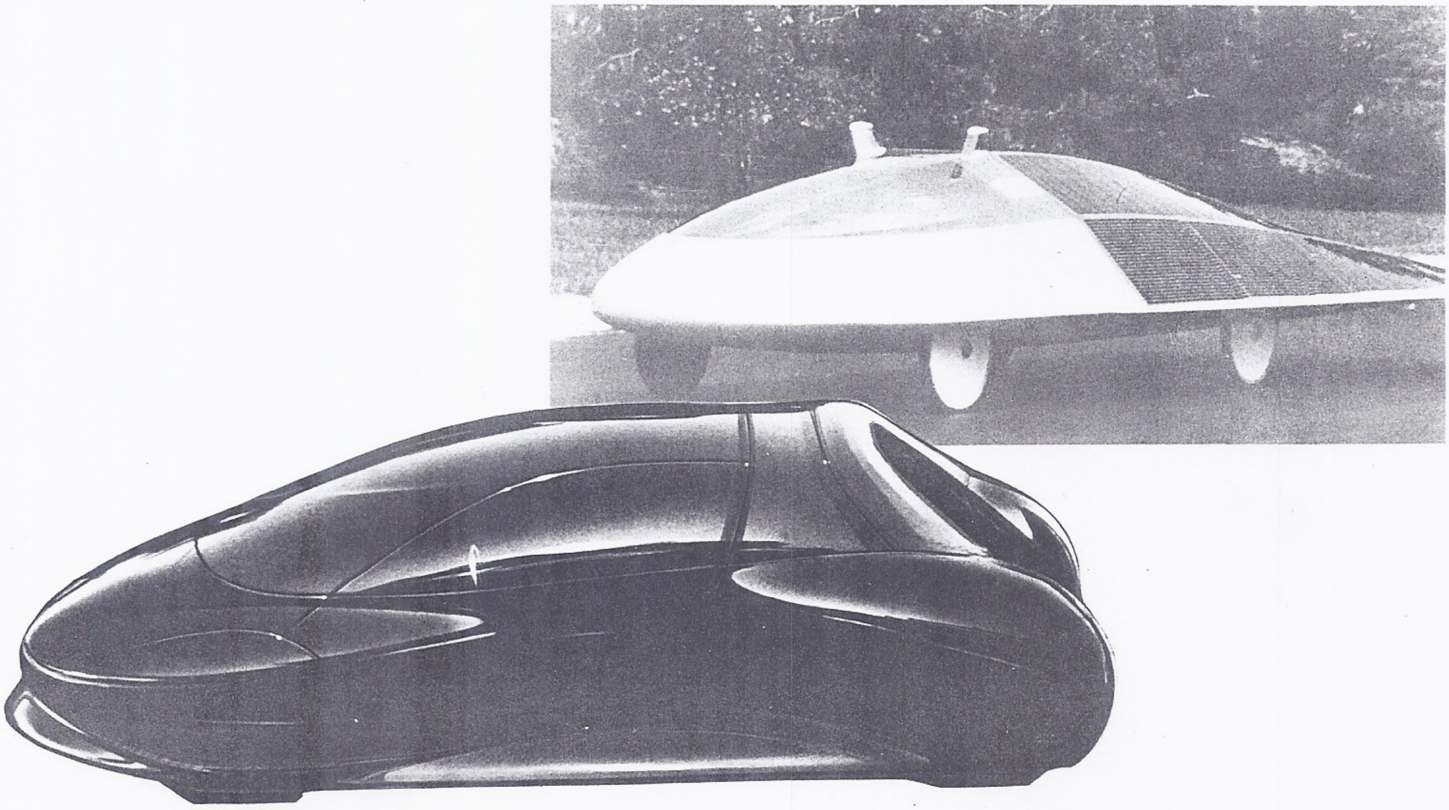
Final Study Report and Proposal

AV-FR-88

The Electric Vehicle — Time for a New Look



Submitted to:

Hughes Aircraft Company
General Motors Corp.

July 22, 1988

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Submitted to:

Hughes Aircraft Company
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By:

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Executive Summary

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Increasing concern about air pollution from automobiles, and the continuing desire to reduce dependence on petroleum-based fuels necessitates a vigorous pursuit of alternate-fueled vehicles. Electric propulsion as one form of alternate fuel has been attempted many times before and has been inadequate because of poor vehicle range and performance and high purchase and operating cost. However, it now appears that new technologies in electronics, motor design, structural materials, tires, and batteries coupled with careful attention to weight reduction and aerodynamic and rolling drag will allow the design and production of a small two-place (or two plus two) electric vehicle with more than adequate range and truly exciting performance. The range in city or highway driving will exceed 120 miles, and acceleration to 60 mph in eight seconds is predicted. Projected operating costs and purchase price will both be within the range of comparable gasoline-fueled vehicles.

This document sets forth a proposal to design and build a demonstration electric vehicle which incorporates the new technologies mentioned above. This vehicle will show that good performance can be achieved in an electric car that has been designed to meet requirements for crash safety and has the expected level of features, such as roll-down windows, air conditioning and heating, sound system, and appropriate interior finish, while incorporating materials and components that are suitable for mass production.

The anticipation of the electric vehicle era is felt worldwide. There are some twenty-four individual EV projects in Japan, with every manufacturer represented. Japan has a national program to develop battery, motor, and motor drive electronics components and technology. There is no doubt that the Japanese intend to be ready for the electric vehicle market.

Similar, but less extensive efforts exist in Europe with West Germany and Switzerland being particularly active. A major program at Brown-Boveri in West Germany is developing the high performance sodium-sulphur battery for automotive use.

In the United States, under the leadership of the EPRI, the research arm of the electric utilities, the efforts are focused on electric vans. In addition to the G-Van program, in which GM Vandura vans are fitted with electric drive train components from England's Choride Battery Company, both Chrysler and Ford are developing smaller van conversions using more advanced technology.

A careful study of all important areas of technology required for the proposed vehicle has been carried out over the past four months. Testing has been carried out on batteries, tires, electronics, and even air conditioning systems to confirm that the desired performance can be achieved.

Using this technological basis, a vehicle concept and layout have been developed. The result is a two-place sport commuter in the 2000-pound class, of which 900 pounds is a new recombinant lead-acid battery of improved performance and life. Range in city driving will exceed 120 miles, and acceleration from 0 to 60 mph in 8.0 seconds is predicted. A thermally controlled central-tunnel battery compartment avoids low temperature loss of battery performance. MOSFET electronics of over 96 percent efficiency drive two 57-horsepower motors, one for each front wheel. The same drive electronics also functions as the battery charger, inherently capable of providing a full battery charge in only 15 minutes if suitable batteries appear in the future.

The motors are 12000-rpm AC induction-type machines that maintain efficiencies of over 93% at almost all speed and power conditions, and weigh only 45 pounds each. The speed-torque characteristics allow use of a 10:1 single-ratio transmission built integrally into the motor housing. The motors and electronics accomodate regenerative braking which, because of the dual drive, can provide a measure of anti-lock braking. Traction control is easily provided with the inherent torque control for each drive wheel.

Rolling resistance of modern tires is much improved and with high inflation pressures can be as low as 0.5 percent of the vehicle weight. Body weight and strength goals will be realized through modern bonded aluminum uni-body design, an addition benefit of which is reduced tooling costs.

With this basic vehicle package, the Advanced Concepts Center of the Design Staff has developed the exterior concept that appears on the cover of this report. A key requirement of this design is that the aerodynamic drag coefficient be less that 0.2. Other recent GM designs have demonstrated that this goal is achievable.

Based on this study and analysis, a program is proposed to design and to build one or two demonstration vehicles. Their purpose will be to show that current technology allows achievement of the desired performance.

The program will be managed by Hughes Aircraft Company, with the focus of engineering and fabrication at AeroVironment Inc. Major involvement in the program will exist in all four GM technical staff organizations, the Advanced Vehicle Engineering department of CPC, and at Delco Remy. Several other GM and Hughes organizations will be involved to a lesser extent.

The program will require funding of $3.85M excluding the manpower costs in the supporting GM organizations. A second vehicle will add $311K to the funding needed. A cost contingency of $500K is also recommended. The program is scheduled to complete the first vehicle in 12 months with a subsequent test period of three months. The second car will be completed at the end of the 14th month.

The successful completion of this program will change the of image of an electric car from a slow, limited-range retirement village vehicle to that of an affordable, visually appealing, sporty performance-vehicle with good range. This will greatly accelerate the practical and widespread use of electric vehicles, providing a new market niche for General Motors. As air pollution regulation becomes more demanding, and should fuel shortages or cost increases return, the position established by development of this niche market will be of great value.

1. Introduction

1.1 Background and Discussion

In the first decade of this century, when automobiles were being introduced to the using public, the electric car occupied a prominent place in the automobile scene. The electric motor was relatively more advanced than the gasoline engine and certainly much easier to start. Further, the road systems were poor enough, and breakdowns frequent enough, that automobiles were largely urban vehicles matched to the inherent short range of battery power.

When the electric self-starter became standard equipment, cars became more reliable, the road systems improved, the gasoline engine was refined, and the gasoline-fueled internal combustion engine quickly became dominant for automobile propulsion. The requirement for inter-urban range and the small number of two-car families did not provide an opportunity for the continued development of electric propulsion components and the electric car vanished from the scene. Its attributes of clean, smooth, and reliable operation were seen as less important than range, power, and performance.

At various times during the next fifty years attempts were made to develop a practical electric car, but none succeeded. The basic difficulty was that batteries were too heavy, too expensive, and required frequent servicing. This Achilles heel was made even more limiting by the relative ineffectiveness of the other vehicle components: motors, controllers, tires, and transmissions; as well as the structural weight and poor aerodynamics of the car itself.

Now, in 1988, a new factor is becoming important. Air pollution, particularly in certain urban locations, is causing regulatory actions which will limit the use of gasoline or diesel powered vehicles in these areas. Already in Southern California the South Coast Air Quality Management District has announced a plan (Fig. 1.1) to phase out 40% of all normally-fueled cars in the Los Angeles basin over the next twenty years. The first impact of the plan will take effect in 1993 when all new commercial vehicles added to fleets of 15 or more vehicles will be required to use an alternate fuel. Similar regulation is being considered in other U.S. cities and in several cities in Europe.

At present, methanol, electricity, and natural gas are considered suitable alternate fuels. However, the GM environmental staff makes the point that the polluting effects of methanol

Part I / Saturday, January 9, 1988 ★

Los Angeles Times

FUELS: AQMD OKs Plan to Cut Use of Diesel, Gasoline

Panel OKs Plan to Cut Use of Diesel, Gasoline

AQMD Strategy Aims at Replacing 400,000 Fleet Vehicles With Those Using Clean Fuel

By LARRY B. STAMMER, *Times Staff Writer*

Signaling a "new era in air pollution control," the South Coast Air Quality Management District board Friday unanimously approved a far-reaching strategy intended to replace up to 400,000 diesel- and gasoline-powered fleet vehicles with those that run on cleaner-burning fuels or electricity beginning in 1993.

Approval of the clean fleet proposal—part of a five-year clean fuels demonstration program—came at the first meeting of the new 11-member AQMD governing board, which was sworn in Friday. The vote was 9 to 0. One member was absent, and the 11th has not been appointed.

Under the program, there will be 13 projects to test the viability of cleaner-burning fuels at industrial sites and 16 similar demonstrations in vehicular applications.

20-Year Goal

The district hopes the projects will speed the day when clean-burning fuels and electricity will be used in 40% of all passenger vehicles and 70% of all diesel-burning trucks. Officials said they believe that goal can be achieved within 20 years—by the year 2007.

The clean fuels program opens a new front in the AQMD's fight to control air pollution in the four-county South Coast Air Basin, which is the nation's smoggest. The basin includes Los Angeles, Orange, Riverside and San Bernardino counties.

Until Friday, most of the district's efforts to control air pollution have involved technological controls on smokestack and tailpipe emissions, not the fuels themselves.

The vote came after AQMD Executive Officer James M. Lents exhorted the board Friday to act decisively in cleaning the air.

"I view the seating of this board as an historic moment in the long battle that has been waged against air pollution in this basin. It is historic because it ushers in not just a new era in air pollution control but a potentially decisive one," Lents said.

AQMD board member Henry W. Wedaa, who Friday was elected vice chairman, said later, "I really think we're going to do something this year. I think the tenor of the board has changed. Some people who really weren't supportive of concerted, significant action are no longer on the board." Wedaa represents Orange County cities on the AQMD.

The board was reorganized by the state Legislature last year and vested with new authority. Its membership dropped to 11 from 14, a move that cost some incumbents their seats.

Rules Due in September

Rules for enforcing the new clean fuels edict are expected to be presented in September and cover all public and private fleets with 15 or more vehicles, including public transit bus systems and rental car agencies.

It would cover between 200,000 and 400,000 fleet vehicles in the South Coast Air Basin, including 4,500 transit district buses.

Other provisions of the program approved in principle Friday but awaiting formal rules will require service stations to sell cleaner-burning methanol by the early 1990s. Methanol is less reactive than gasoline and forms 50% to 90% less ozone, the main component of smog, one official said.

The AQMD will coordinate such a requirement with the state Air Resources Board, which is tightening vehicle emission standards that one ARB official said Friday will hasten the day when auto makers are forced to build methanol cars in order to comply.

Beginning immediately, all new electrical turbines, internal combustion engines and co-generation units must use methanol as emergency backup fuel in place of diesel. The district said it is the first in the nation to impose such a requirement.

The AQMD also plans to present a schedule by May to phase out the use of diesel fuel in all stationary boilers, turbines and other equipment.

Financing Plans

The district proposes to finance the $30.4-million clean fuels program with hefty increases in permit fees charged industrial polluters. The fees—which vary—could double, Paul Wuebben, program manager of the AQMD's Office of Technology Advancement, told reporters.

A $1 surcharge on motor vehicle registration fees, matching funds from private industry for demonstration projects and financial assistance from other government agencies will also be sought.

Lents warned Friday that the full implementation of the program will not be easy.

"I have no illusions as to what lies ahead," Lents said, reading from a prepared text. "I know that regardless of the encouraging rhetoric and even the good intentions, the regulated community [business and industry] will continually and vigorously oppose essential rules."

But, Lents declared, "This district has the mandate to take whatever initiatives are necessary, however forceful these must be, to get the job done—even if sometimes we must go it alone or tread into areas that others have considered sovereign."

Lents' tough talk drew praise from environmentalists—and a pledge from the Los Angeles County Transportation Commission.

Figure 1.1

are not yet fully understood and its acceptance as a "clean" fuel is subject to change. Other environmental factors such as concern about the "greenhouse" effect promise to become more important in the future, inhibiting the application of internal combustion vehicle powerplants.

Although the availability and cost of gasoline has faded for the moment into a non-problem, the experience of the 1970's is a reminder that the current situation could change very rapidly and at anytime. This possibility would be one element of customer interest in owning an electric vehicle. From General Motor's point of view, having an established position with a production electric vehicle would be of great value in a new fuel crisis.

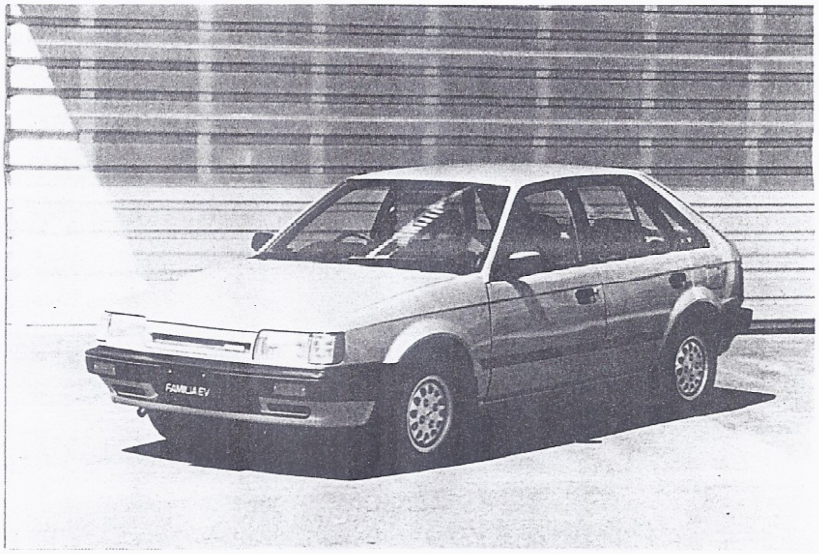
1.2 Current Electric Vehicle Programs Worldwide

The advances in technology, and the future applications of electric vehicles are understood throughout the automotive industry and nearly every manufaturer has some program in EV development. This is particularly so in Japan where the various developments exceed twenty in number. There is a national program to develop the basic components for electric vehicles; various motor types, battery systems, and control electronics are the subjects of these efforts. Figures 1.2, and 1.3 are examples of Japanese EV programs. So far, at least as reported in the public media, the Japanese vehicles are conversions of production cars. Whether this comes from not appreciating the need for a "ground-up" approach (this was the major Japanese failing in the Australian solar race) or whether they are focusing on the components only, and the visible vehicles are just development "mules" is unknown.

Efforts in Europe are more modest than in Japan, but the necessity of a total design approach seems more understood. At least one West German car and several Swiss cars are designed from scratch to be EV's, as shown in Figures 1.4 and 1.5.

One focused effort in Europe is a substantial program by the Brown-Boveri company to develop a practical, cost-effective sodium-sulphur battery. Production vehicles from Volkswagen, Mercedes, and BMW have been modified to test and demonstrate the Brown-Boveri package (Figure 1.6).

In the United States, the strongest forces in EV development are the electric utilities, who see a large market for electricity in the off-peak hours of the day when most EV charging would be done. Through the research and development arm of the utilities, EPRI (Electric Power Research Institute), work is going on at several companies and other organizations to develop batteries, controllers, motors, and complete vehicles.



Mazda Familia

Gross vehicle weight: 3130 lb.
Battery weight: 780 lb.
Range at 25 mph: 124 mi.

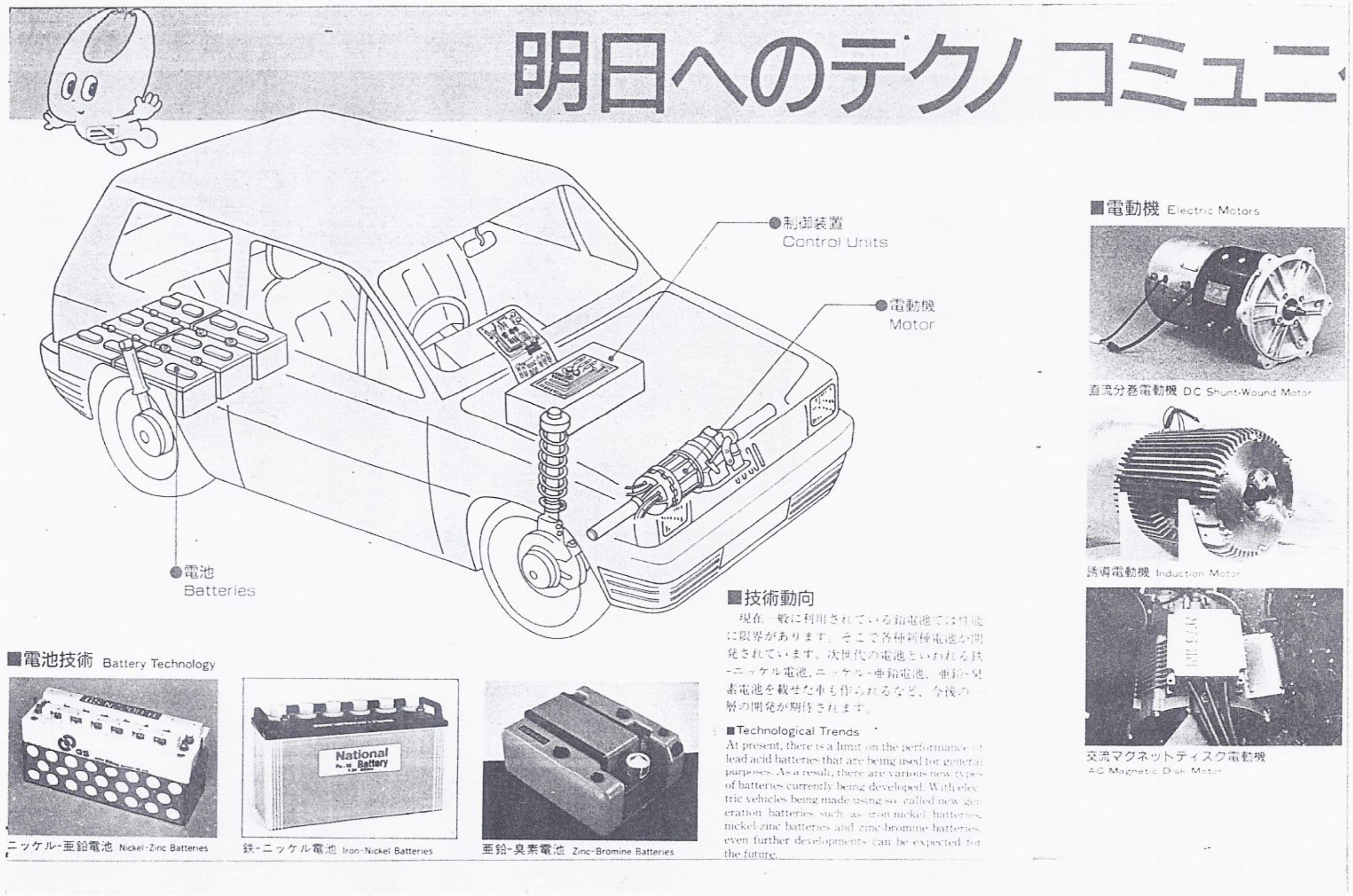
Nissan March

Gross vehicle weight: 2600 lb.
Battery weight: 1280 lb.
Range at 25 mph: 115 mi.

Suzuki Alto

Gross vehicle weight: 2270 lb.
Battery weight: 1060 lb.
Range at 25 mph: 68 mi.

Figure 1.2 Some recent Japanese electric vehicle projects. All are conversions of production cars.



明日へのテクノ コミュニ

●制御装置
Control Units

●電動機
Motor

●電池
Batteries

■電池技術 Battery Technology

ニッケル-亜鉛電池 Nickel-Zinc Batteries

鉄-ニッケル電池 Iron-Nickel Batteries

亜鉛-臭素電池 Zinc-Bromine Batteries

■技術動向

現在一般に利用されている鉛電池では性能に限界があります。そこで各種新種電池が開発されています。次世代の電池といわれる鉄-ニッケル電池、ニッケル-亜鉛電池、亜鉛-臭素電池を載せた車も作られるなど、今後の一層の開発が期待されます。

■Technological Trends

At present, there is a limit on the performance of lead acid batteries that are being used for general purposes. As a result, there are various new types of batteries currently being developed. With electric vehicles being made using so called new generation batteries such as iron-nickel batteries, nickel-zinc batteries and zinc-bromine batteries, even further developments can be expected for the future.

■電動機 Electric Motors

直流分巻電動機 DC Shunt-Wound Motor

誘導電動機 Induction Motor

交流マクネットディスク電動機
AC Magnetic Disk Motor

Figure 1.3 Some Japanese electric vehicle component developments.

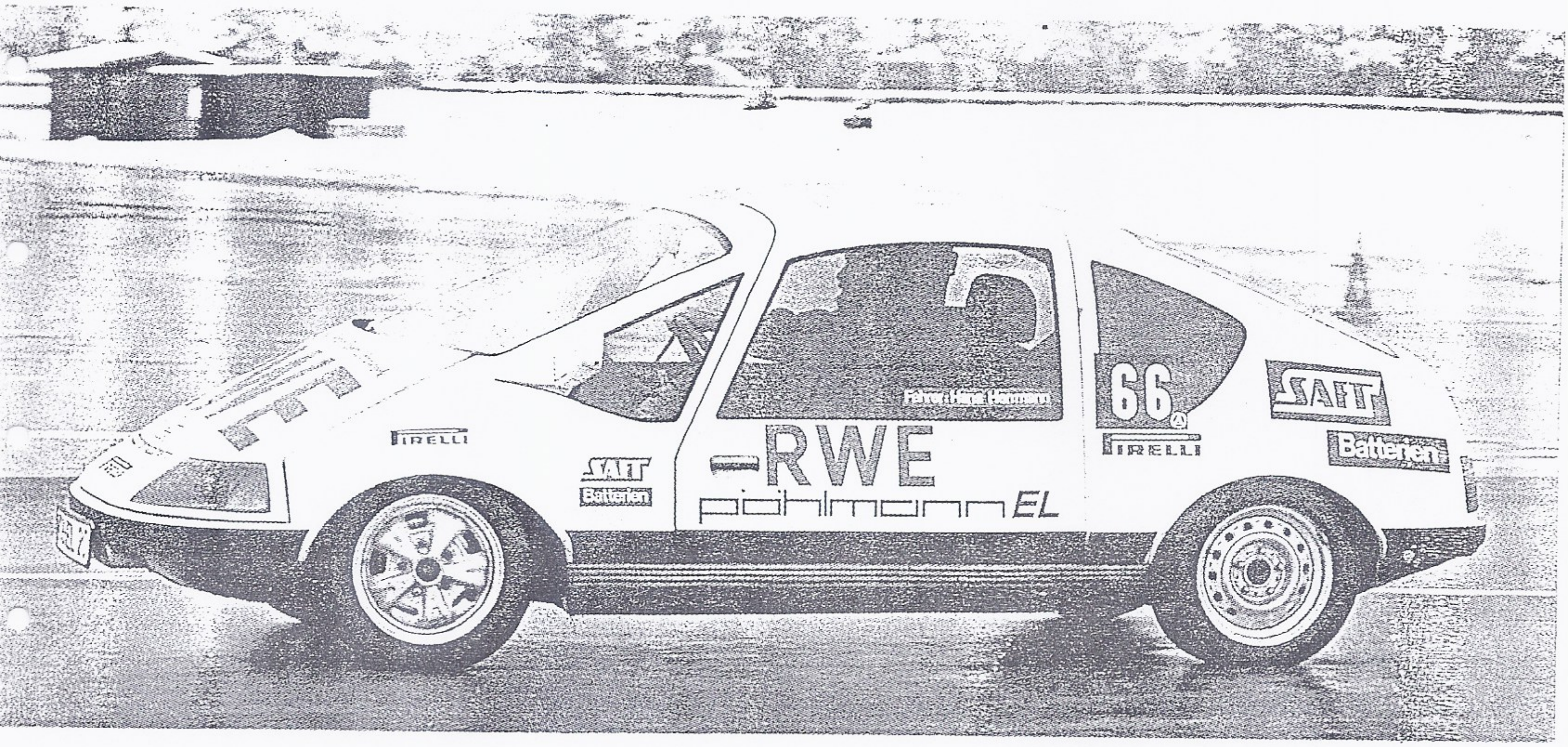


Figure 1.4 One of the electric vehicle entries in the annual Swiss "Formula E" Grand Prix race for electric vehicles.

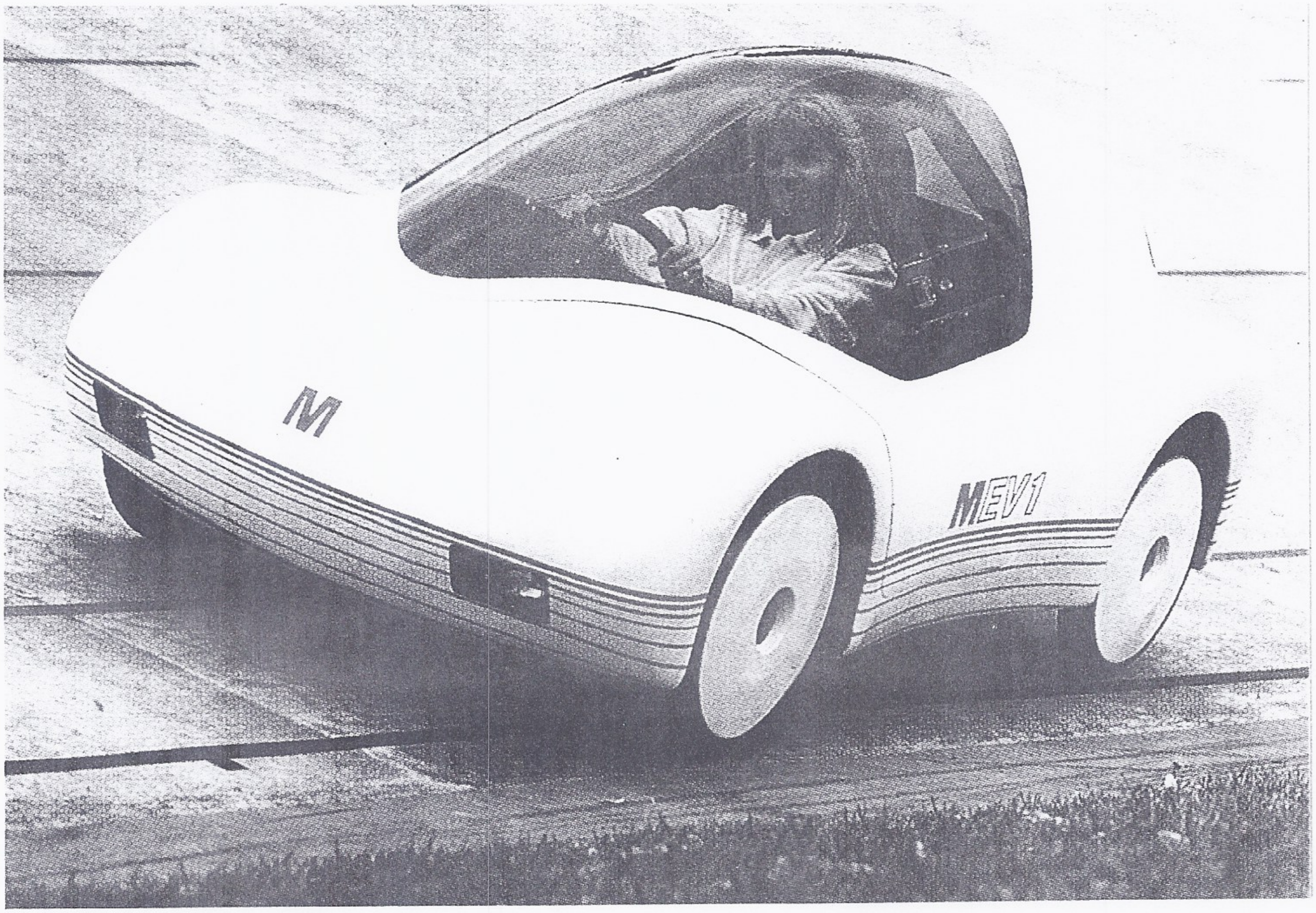


Figure 1.5 A swiss commuter vehicle designed for electric propulsion.

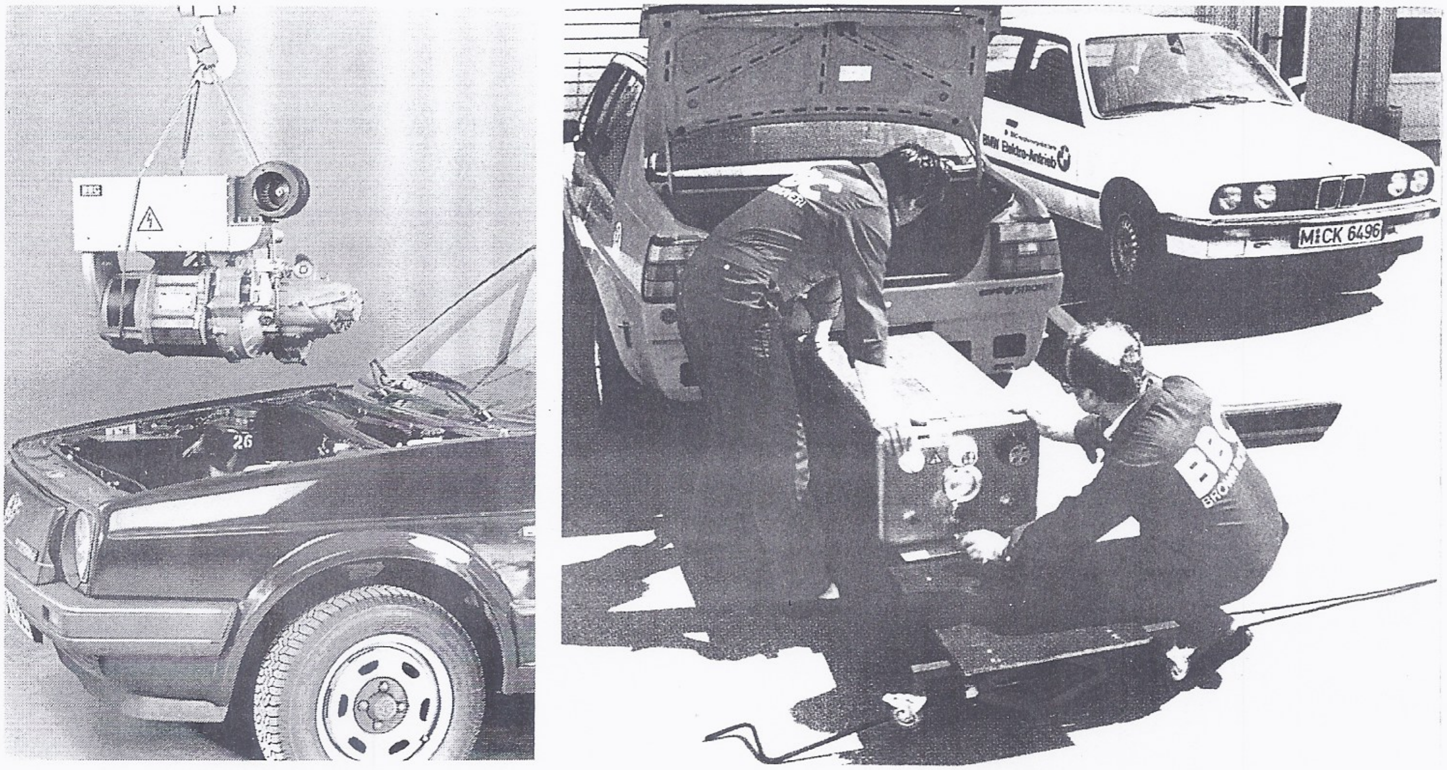


Figure 1.6   Electric vehicle developments by Brown Boveri in Germany.

The utilities and EPRI reasoned that vans would be the best initial application of electric propulsion. Many van applications do not require long range or high speed, and the vans used in fleets return to base every night where they can be recharged and receive skilled maintenance. Furthermore, the utilities themselves represent a substantial market segment.

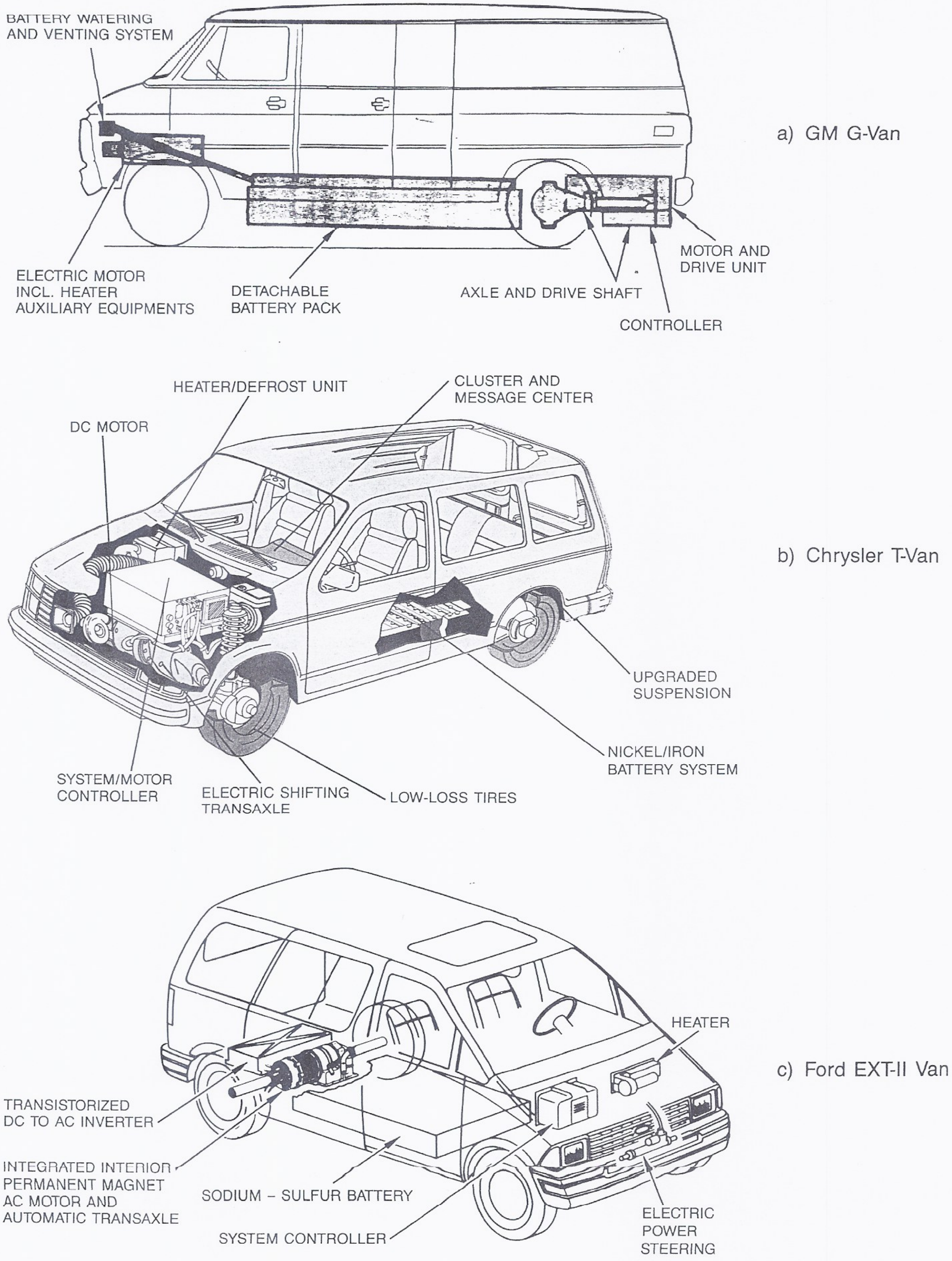
EPRI began by acquiring a few Griffon vans from England. These were Bedford vans modified to use batteries, controllers, and motors supplied by Chloride Battery Company of England. When Bedford ceased production, GMC was asked to supply Vandura vehicles without powertrain for electric conversion. A number of these "gliders" have been delivered to C&C (formerly Cars and Concepts, Inc), where the Chloride components are installed. The initial small quantity of these vans, 20 or so, will be given to a number of users for evaluation. This is the extent of current GM involvement in an EV program. Chrysler and Ford are developing smaller electric vans that will use more advanced batteries and other components, and if successful will out perform the G-Van, as the electric Vandura is called. Chrysler is supported by EPRI and Ford by DOE. The GM, Ford, and Chrysler vans are shown in Figure 1.7.

1.3 Previous GM Electric Vehicle Projects

General Motors has considerable previous experience with electric vehicles. In the early 1960's, a Corvair was converted to electric propulsion. The goal of the "Electrovair" was to match the driving performance of the standard Corvair. The drivetrain was very advanced for its time, consisting of an oil-cooled induction drive motor, an inverter to create AC power for the motor, and a high energy silver-zinc battery pack. The Electrovair did meet the performance goals, but because of the enormously-expensive battery pack, it had no hope of being a cost-effective vehicle.

Other vehicles during the 60's included the "Electrovan", a van powered by a hydrogen-oxygen fuel cell, and the "512" series of subcompact commuter cars. The van's fuel cell system was far too exotic to be practical, and the low performance of the 512's had little appeal.

The basic design approach had been to install an electric powertrain into an existing production vehicle (excepting the 512 vehicle). Because these vehicles had not been designed for electric propulsion, there were many compromises, and the vehicles were not as energy efficient as an all-new design could have been. To compensate, high energy, but costly,



a) GM G-Van

b) Chrysler T-Van

c) Ford EXT-II Van

Figure 1.7 Electric van programs in the United States.

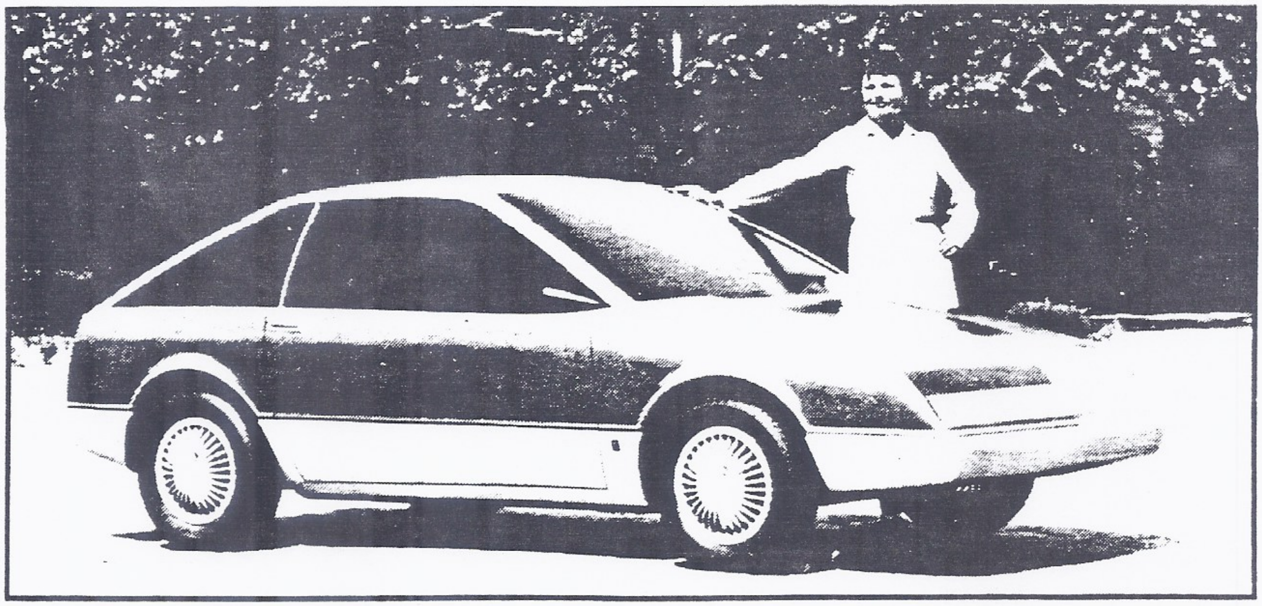
batteries were installed to show what levels of performance could be achieved in the event of a battery energy storage and cost breakthrough. It was generally thought that lead-acid batteries, while relatively cheap, just did not have the energy storage capacity for electric vehicle applications.

In 1979 Delco Remy announced a "significant breakthrough" in its program to develop a nickel-zinc battery for electric vehicles. Nickel-zinc batteries have about twice the energy storage capacity per unit weight (specific energy) as lead-acid batteries. The breakthrough was one of cycle life – from a starting point of only a few charge/discharge cycles before failure, the Delco Remy research program had found a way to make the nickel-zinc battery last for hundreds of cycles.

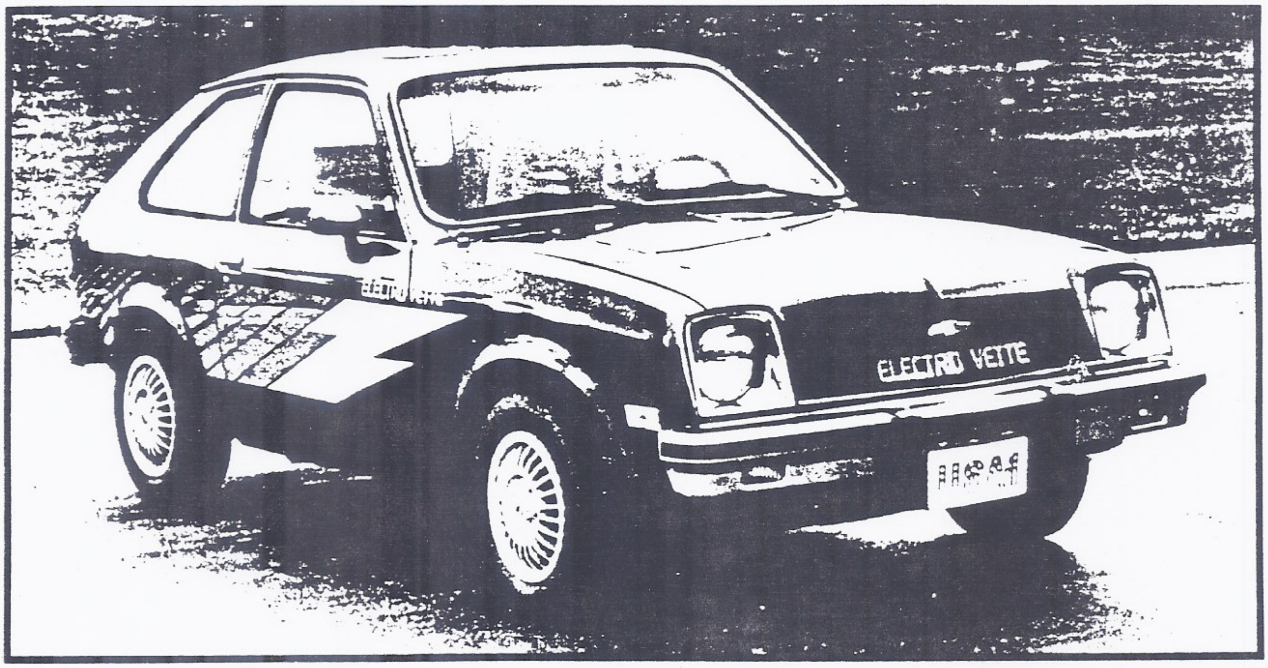
On the strength of the nickel-zinc battery developments, and projections of steadily increasing gasoline prices, GM in 1980 established an electric vehicle project center, with the goal of having a newly-designed electric car on the market by the mid 1980's. Plans called for sales of tens of thousands of vehicles the first year. As the project progressed, it was found that there were several hurdles yet to overcome with the nickel-zinc batteries. The anticipated cycle life that had been demonstrated in the laboratory on single cells was not being achieved in actual vehicle packs running on dynamometers, and the production costs for the battery were too high (about five times that of a lead acid battery of equal capacity).

At this point, the program changed direction, and the plans for an all-new car were put on hold until the battery situation was better understood. A small number of electric Chevettes (Electrovettes) were produced as powertrain test mules. As electric cars, the Electrovettes were among the best ever built, but they were inferior to standard production cars. They were generally reliable and quiet, but the driving range was limited to about 45 miles, and the acceleration was a marginal: 0 - 30 mph in 8 seconds. For interior climate control, there was an oil-fired heater that occasionally emitted fumes, and no air conditioning. The 1980 GM EV design and the Electrovette are shown in Figure 1.8.

The GM electric vehicle project office was closed in 1982 with the realization that the nickel-zinc battery would never be cost effective and that gasoline prices were not increasing as expected. Since then, GM has maintained publicly that electric vehicles cannot be practical until there is better battery.



a) Clay model of the all-new electric car designed in 1980 for 1984 production.



b) One of the fleet of "Electrovette" vehicles built for powertrain and battery testing.

Figure 1.8 The most recent GM electric vehicles.

1.4 Demonstrator Vehicle

New technologies in electronics, motor design, structural materials, tires, and batteries coupled with careful attention to weight reduction and aerodynamic and rolling drag will now allow the design and production of electric vehicles with more than adequate range for many applications and truly exciting performance. A project is proposed to design and build a demonstration electric vehicle which incorporates all appropriate new technologies.

The demonstration car will be called "Santana", after the Los Angeles area weather system and the associated hot dry winds blowing out of the Mojave desert. The significance of the name extends beyond the image of "hot" performance and a car that moves like the wind; Santa Ana winds blow the smog out of the Los Angeles basin, symbolizing the benefit of large-scale introduction of electric vehicles into the area.

After the demonstrator vehicle shows that the predicted performance is achievable, the question to be faced is: when will the market for electric vehicles, in the absence of a fuel shortage, be sufficient to support initial production and the establishment of the desired General Motors position?

It must be emphasized that the vehicle being proposed is to demonstrate that current technology coupled with careful attention to drag and weight through a system engineering approach can achieve the desired performance goals. To make the demonstration meaningful, the car must be representative of a marketable production vehicle, and not a stripped down shell. It must have a representative and crashworthy structure. Heating and air conditioning must be installed, along with roll-down windows, and sound system. The materials used must be suitable for production both in cost and manufacturing processes. Within the technological constraints required to achieve the performance and practicality goals, the demonstrator should present a styling approach that is attractive, fresh, and eye-catching.

Although the vehicle takes a specific layout, form, and style, it should be emphasized that it is not a phase-zero development. It is intended only to demonstrate what can be achieved today in EV performance. The careful assessment of particular market segments and the establishment of requirements and specifications for the phase zero development would be done following the successful completion of the demonstrator vehicle project.

Nevertheless, in chosing a vehicle type for the demonstrator vehicle, a market segment was in mind. The expected performance (0 - 60 mph in 8 seconds) takes this car out of the retirement village golf cart class. In acceleration and handling it will be comparable to a Honda CRX si, a most successful commuter vehicle.

Even though the projected driving range of the demonstrator is much improved over previous electric cars, it is not an inter-urban car. The 100 to 120 mile range is sufficient for most commuting with enough margin to be comfortable, and the acceleration and handling is good enough to make it fun to drive. With these characteristics it should be an attractive choice for a second or third car in the family as a commuter or around town vehicle.

The initial customers for a modest-production-run EV will have to pay a higher price than a bottom-cost gasoline car. These customers will include those who like to have something different, those who want independence from future fuel shortages, those who are particularly concerned with environmental issues, those who appreciate the smooth, silent and exhilarating performance, those who must meet regulatory demands, and those organizations, such as the electric power utilities, who are energetically promoting EV introduction.

Delco Remy is assessing the whole EV situation, and would like to be the supplier of batteries and motors for the G-Van if the program begins substantial production. We have been in close communication with Delco Remy preparing plans for the demonstrator commuter vehicle.

The motor and controller that would be developed for the proposed GM demonstrator vehicle program would also be suitable for van application. Also, since the Delco Remy gas-recombination lead-acid batteries to be used in the demonstrator vehicle are suitable replacements for the Cloride tubular lead-acid batteries that power the G-Van at present, the demonstrator development will put GM in a strong position to provide an upgraded or next generation power system for the van program. Delco Remy sees this as an important new product line opportunity.

2. Technology Improvements Beneficial to Electric Vehicles

2.1 Introduction

As a result of technology improvements over the past 10 years, as well as new design approaches, it now appears possible to produce an electric vehicle that is as good overall as current production cars. In some areas, such as driving range, it would not approach the convienience of a gasoline-fueled vehicle. But in other areas, the EV could offer the following distinct advantages:

- fewer moving parts, less maintenance
- less noise
- smoother and more responsive power delivery
- traction control and anti-skid regenerative braking
- flexibility to operate climate control system at any time (e.g. when parked)
- mobility unaffected by future interruptions in fuel supply
- no exhaust emissions at the vehicle

In fact, the above features of a modern electric car, without regulatory or exhaust emission considerations, could well of their own accord make it a very desirable vehicle to own and operate. Its sales appeal could be based entirely on how well it performs, even though traditional EV selling points of low-pollution, freedom from gas pumps, etc will be increasingly important in the future.

The technology improvements that allow substantial gains in electric vehicle practicality and performance are described in the following sections.

2.2 Power Electronics

"Power electronics" refers to the branch of electronics that involves solid-state control and delivery of electric power. Power electronics are the heart of any electric vehicle. Electric current from a fixed-voltage DC battery supply must be regulated and delivered in the quantity and quality required by the drive motor. If the drive motor is of the brushless or induction type, the power electronics must additionally "invert" the DC power to AC. Almost all power electronics for electric vehicles are based on rapid electronically-controlled on-off switching of the power source. The duty-cycle of the "on" compared to the "off" parts of a switching cycle determines how much current gets through on the average. Large fluctuations, or "ripple", in the current delivery is undesirable, and results in an overall loss of efficiency. If the switching is fast enough, or filtering is added, the resultant current flow can be relatively smooth. In general, it is desirable to have an electronic switch that is fast, requires very little energy to switch, has very low resistance when the switch is closed, and has low leakage when open.

Electronic switching components have advanced remarkably in these areas over the last two decades. Some of the earliest EV electronic drive systems employed Silicon Controlled Rectifiers, or SCR's, for the switching function. The switching speed of SCR's limits the overall switching frequency to about 1000 Hz. This is quite low for effective filtering of the current, hence SCR switcher-based motor controllers have high losses because of excessive current ripple. Later systems have employed bipolar transistors, which allow switching frequencies of up to about 8000 Hz. Since their switching frequencies are well within the audible range, bipolar and SCR choppers both exhibit an undesirable characteristic electronic 'whining' noise.

The breakthrough switching device for electric vehicles is the Metal-Oxide-on-Silicon Field Effect Transistor (MOSFET). MOSFET's allow extremely rapid switching frequencies, require very little energy to switch, and have very low resistance. While switching speeds of over a megahertz are possible with MOSFET's, for electric drive systems, a frequency just above the audible range (about 18 kHz) is optimum. Even after accounting for the weight of required heat sinking, MOSFET-based motor controllers show a ten-fold improvement in power-to-weight ratio over SCR controllers. This opens up a whole new range of possibilities for electric vehicle performance. The Sunraycer was one of the first electric vehicles to utilize MOSFET's as the switching device for the motor controller.

2.3 Batteries

There have been no major breakthroughs in battery technology, but steady progress is being made in several areas. There is considerable interest worldwide in the sodium-sulphur battery. Sodium-sulphur batteries must operate at high temperature - more than 600° F - and have rather poor power to weight ratio (specific power). The reason these batteries are so attractive is their outstanding specific energy level – about four times that of a lead acid battery. Development of the sodium-sulphur battery is progressing well in Germany and England, but it is still a future system. There are many development problems remaining in thermal containment, insulation, manufacturing, and durability.

Lead acid batteries have generally been passed over as electric vehicle batteries, being considered low-tech and too heavy. However, progress has been made for lead-acid batteries too, due in large part to motivations outside of the electric vehicle field. The main disadvantages of the traditional lead-acid battery are:

- low specific energy
- poor performance when cold
- need for watering
- hydrogen and oxygen evolution / explosion hazard
- corrosion of terminals
- poor cycle life due to "shedding" of active material from plates

The most significant new development for lead-acid batteries is the gas recombination design approach. In the recombinant lead-acid system, the battery is permanently sealed, and any oxygen gas evolved during charge is immediately recombined with lead within the battery. Hydrogen gas generation is prevented by carefully limiting the maximum charge voltage. The recombination process is made possible by employing a glass-fiber mat as the separator between plates in a cell. Instead of being flooded with acid electrolyte, the battery is operated in a electrolyte-"starved" condition, where the separator material captures the electrolyte like a sponge, but retains open space for the evolved gases to find their way to the plates for recombination.

The glass fiber separator mats also serve as mechanical support for the active material. The plate stacks are assembled with a small preload, so the separators push against the active material in the plates, and help to hold it in place. The shedding of active material that is inherent in all flooded-electrolyte batteries is absent in the recombinant design. Indeed, recombinant batteries have no reservoir for "mud" under the plates, resulting in a more compact battery. Additionally, there is no need for the excess battery case height that is required to store excess electrolyte above the tops of the plates of a flooded battery. Finally, since the acid electrolyte is immobilized in the glass searators, the recombinant battery should be considerably safer than the flooded battery in a severe crash.

Another significant lead-acid development that is still in its infancy is the bipolar design. Here, the lead grids and plate interconnect straps are eliminated through the use of a bi-polar plate. The bipolar plate is a non-porous and chemically stable conductive plate, with positive active material applied to one side, and negative material to the other side. To form a complete multi-celled battery, these "bi-plates" are stacked up with glass mat separators, sealed around the edges, then a measured amount of electrolyte is injected into each cell. The bipolar battery offers the possibility of about 30 percent higher specific energy and far greater specific power than standard recombinant designs.

Finally, although lead-acid batteries have usually been considered to be ambient temperature batteries for electric vehicles, with the resultant problem of severely degraded performance at low temperatures, there is no reason not to consider thermal control and management of a lead-acid battery pack. The temperature for optimum performance is quite modest when compared to the sodium-sulphur battery – only about 80 to 122° F.

2.4 Tires

The rolling resistance of tires represents a significant fraction of the overall energy consumption of a vehicle, typically accounting for about one-third of the total drag. In an electric vehicle, the rolling resistance is especially important because of the heavy battery pack.

As a result of the demand for higher-mileage vehicles, the tire manufacturers have put considerable effort into reducing rolling resistance. Tires on today's cars typically have 30% less rolling resistance than the tires of ten years ago. Improvements are due to higher inflation pressures, a move to radial-ply construction, better rubber compounds, and a better understanding of the physics of rolling drag.

The rolling resistance coefficient provides a common basis of comparison for different tires. It is defined simply as the ratio of rolling resistance to the vertical load carried by the tire. It depends on many factors such as tire construction, inflation pressure, speed, and temperature. Tires on today's cars have coefficients from 0.007 to 0.010 at normal inflation pressures and at highway speeds. The best bicycle-racing tires are about 0.0025. The 90-psi 22-in slicks on the Sunraycer were measured at 0.0034 on a smooth surface. New passenger-car tire designs under consideration by Goodyear have predicted coefficients of 0.005 to 0.006.

2.5 Vehicle Structures and Materials

Another result of the demand for higher-mileage vehicles has been substantially reduced vehicle weight. The energy efficiency in a city driving cycle depends almost entirely on weight, with energy consumed by rolling friction and repeated acceleration of the mass of the vehicle. Today's vehicles are hundreds of pounds lighter than similarly-sized vehicles of ten years ago. The weight savings is a result of better understanding of how to design efficient unibody structures, a much greater use of plastics, both cosmetic and structural, and an increased level of weight conciousness.

Current research areas in weight reduction include further plastics applications, and use of aluminum in the primary vehicle structure and body.

2.6 Systems Engineering

As vehicles become more complicated, with subsystems of components interacting more than ever before (e.g. anti-lock brake systems), systems engineering is being applied much more rigorously to vehicle design. This new attention to the overall vehicle as a system is a crucial element in the design of an electric vehicle. The Sunraycer was engineered as a system, with strong communications among the project team and careful consideration of the interations between the various systems. The 1980-1982 electric vehicle program at GM also showed considerable attention to systems engineering.

3. Description of Demonstrator Electric Vehicle

The vehicle proposed in this document is called a "demonstrator" vehicle. It is not a concept car, and this program is not intended to be "Phase 0" of a production car program. Rather, it is intended to be a vehicle that will demonstrate the best current-technology electric vehicle possible, which could be the basis of an electric vehicle produced in the near future. It is important that the vehicle has credibility; this requires the usual level of passenger comforts (roll-up windows, air conditioning, sound system, etc.), and consideration of most of the requirements for a production vehicle. These requirements include the applicable Federal and GM vehicle safety standards and the selection of realistic structural materials and configuration for the vehicle body/chassis.

Advancements in EV technology and vehicle design are applicable to a broad range of vehicle types, from vans to sedans to sports/commuter cars. The last has been selected for the proposed demonstration vehicle as it represents the largest step forward in EV technology, and is a vehicle type not previously considered suitable for electric propulsion. A sports/commuter car is primarily fun to drive and economical, and is characterized by fast acceleration, nimble handling, and often two seats. Examples include the Honda CRX si, Toyota MR2, Pontiac Fiero, and VW GTI 16V. Other desirable characteristics include usable carrying volume, and perhaps jump seats for carrying small children.

Projected acceleration performance for the demonstration vehicle and for a Honda CRX si is shown in Figure 3.1. First and second gear acceleration regimes are very distinct in the CRX data. The CRX accelerates faster in first gear that the EV, but in second gear is slower. The EV's acceleration curve is not broken by any gearshift points, as it uses a single-speed transmission. At speeds up to 50 mph, the EV will have smooth constant acceleration, and fast, smooth response to the accelerator pedal.

Although the demonstration car is not intended as an eventual production car, some attention has been given to whom the customer might be, how much it should cost, and the vehicle's feel and personality. The basic design philosophy is that the vehicle should first be a really good car, and second, the best electric car ever made. The vehicle will be a delight to drive – fast acceleration with instant response, nimble handling, and turbine-like sounds emanating from under the hood – a vehicle that a car enthusiast would want just because of the way it drives, and not just because it is electric. The first customers would most likely be enthusiasts that read the car magazines, already have one or two other cars, and have moderately high income. If the vehicle were in production on a scale similar to that of other

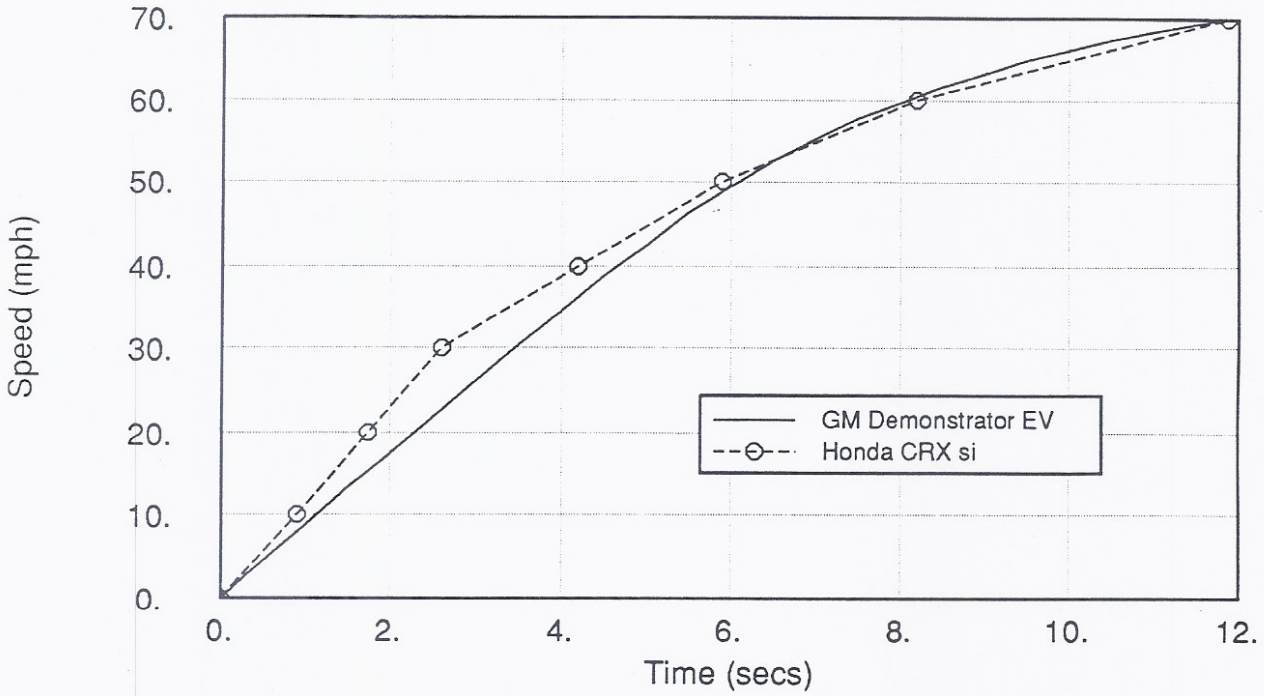


Figure 3.1 Acceleration performance of the proposed new GM demonstrator electric vehicle compared with the Honda CRX si.

unique-design cars (i.e. tens of thousands per year), the selling price should be on the order of $15,000 in 1988 dollars.

The demonstration Santana vehicle will have much better performance than the EV that GM designed in 1980, but other specifications are quite similar. The two vehicles are compared in Table 3.1.

	Santana	1980 GM EV design
Vehicle type	sport / commuter	commuter
no. seat	2	2
city driving range	133 mi.*	74 mi.
acceleration 0 - 30 mph	3.5 sec	6 sec
0 - 60 mph	8.0 sec	24 sec to 55 mph
maximum speed	76 mph	55 mph
max motor power	114 hp	34 hp
curb weight	2040 lb	1980 lb
payload	360 lb	440 lb
wheelbase	90 in	90 in
interior heating	electric heat pump	oil-burning heater
interior cooling	electric heat pump	none
battery charger	on board, integral w/ motor drive inverter 20 kW max, >90% eff.	on board, 2.9 kW max, 85% efficiency
recharge time	1/2 hr for first 50% of charge, 3 hr full charge	80% charge in 12 hr with onboard charger, 4 hr with off-board charger

* 71-mile range with air conditioning or heating operating at max power

Table 3.1 Comparison of overall specifications of proposed demonstrator vehicle with 1980 GM EV design

4. Technical Approach to Achieving Vehicle Requirements

4.1 Introduction

The specifications and performance goals set forth above are very ambitious, but are achievable with proper attention to component optimization, systems engineering, and by subordinating the vehicle styling to the functional requirements. This is the same design approach that produced the Sunraycer.

AeroVironment has been working with the Advanced Concepts Center (ACC) and the aerodynamicists of the Design Staff to design the basic look and package layout for the demonstrator vehicle. The ongoing process of defining a vehicle style that is acceptable from both styling and engineering standpoints is especially challenging. The baseline vehicle package has front wheel drive, central battery tunnel, and P165/65R14 tires on 14 by 3.5 - inch wheels. The latest ACC design and styling approach is shown in Figures 4.1 and 4.2.

Table 4.1 gives more detailed specifications for the demonstrator vehicle, and highlights some of the major differences with the 1980 GM EV. Especially noteworthy are the improvements in aerodynamic and tire drag, and lower weights of the drivetrain components.

The basic configuration of the powertrain is shown in Figure 4.3. There is a separate motor and inverter for each of the front drive wheels. The powertrain design tightly integrates the battery charging and driving functions. The neutral wires from the motor windings form the connection to outside AC power for battery charging. The motor inductance is used as part of the charging circuit. The characteristics of the charging method requires that the battery voltage be above the peak voltage of the input AC power waveform. Therefore, the nominal system voltage has been set at 320 V. This is higher than used in most previous electric vehicles, and will requre very careful attention to electrical safety. One of the advantages of high system voltage is reduced wire weight.

The charging system is inherently capable of extremely fast charge rates, a very desirable feature for an electric vehicle. Initial battery testing indicates that the first 50% of the battery charge can be added in only 30 minutes. As newer battery systems come online, even faster charging will be possible. In fact, as much as 80 kW of charge power will be possible if sufficient cooling air is provided to the electronics and motor, resulting in a 15-minute time to full charge if the battery can accept the high charge rate.

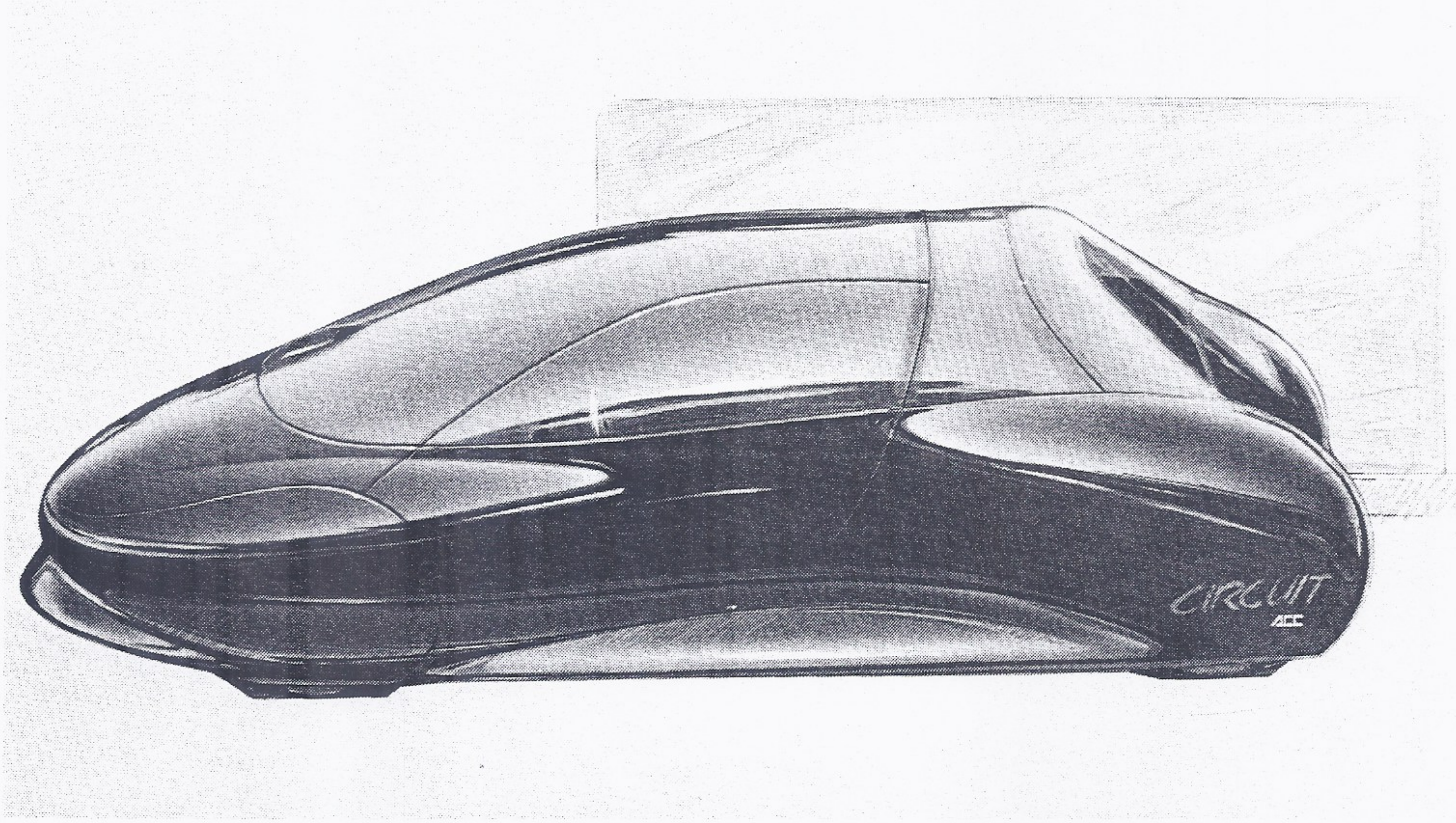


Figure 4.1

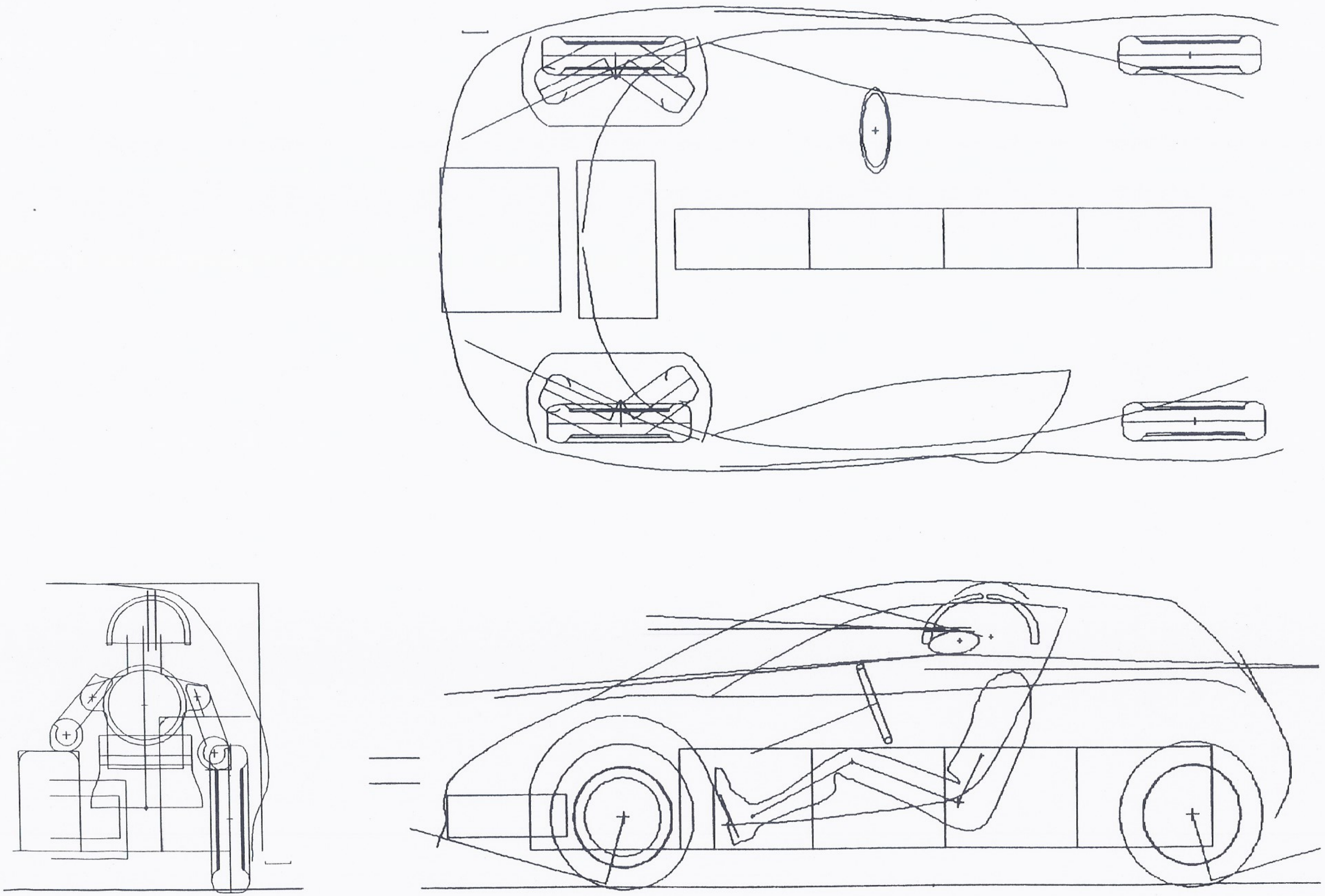


Figure 4.2

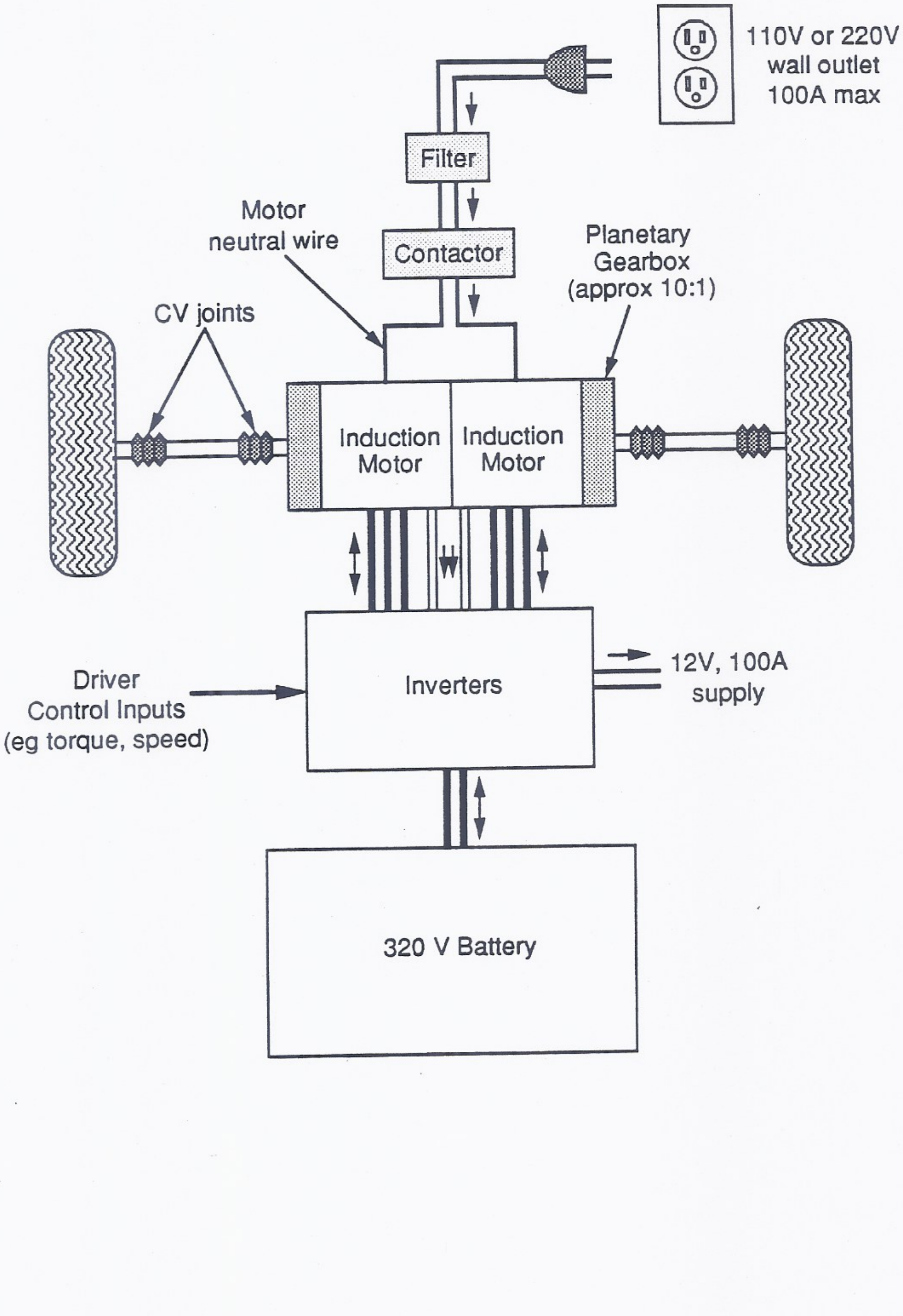


Figure 4.3 Block Diagram of the powertrain of the demonstrator vehicle.

The fundamental principles governing the design are light weight, minimum drag, and high component efficiencies. The following sections give details on the technical approaches that have been chosen for the demonstrator vehicle.

		Santana	1980 GM EV design
aero drag, Cd x A		3.5 sq ft.	5.8 sq. ft.
tire drag, Crr		0.006	0.010
tire type		65 psi, P165/65 R14	35 psi, P155/80 R13
drive configuration		fwd, two motors	rwd, one motor, differential
drive motor type		AC induction 90 - 95% eff. typical	DC separately excited 83 - 87% eff. typical
max motor speed		12000 rpm	7500 rpm
max motor power		114 hp	34 hp
max torque		90 ft-lb (both motors)	70 ft-lb
motor weight		90 lb (both motors)	195 lb
transmission		single speed	two speed, electric shift; later went to single speed
motor drive electronics		MOSFET inverter	SCR armature chopper Bipolar trans. field controller
accessory power, 12V		MOSFET supply, 100 A	transistor supply, 60 A
total electronics weight		60 lb	132 lb
battery	type	recombinant lead-acid	nickel-zinc
	specific energy	16 Wh/lb (35 Wh/kg)	23 Wh/lb (51 Wh/kg)
	weight	900 lb	683 lb
	capacity	14.3 kWh	15.8 kWh

Table 4.1 Comparison of detailed specifications of proposed demonstrator vehicle with 1980 GM EV design.

4.2 Weight

Weight is the single most important factor in the energy efficiency of a vehicle in all-around driving. Simulations of the EPA driving cycles have been made to investigate the relative importance of different design factors. A summary of the results based on the target design parameters for the demonstrator vehicle is given in Table 4.2. Regenerative braking has been assumed to be 65 percent efficient (65 percent of the kinetic energy is converted back to stored electrical energy in the battery). Note that in the urban driving cycle, the power consumed to accelerate the vehicle mass and overcome rolling resistance accounts for fully 75 percent of the total energy consumption. Even on the highway cycle, weight-related losses still account for almost 40 percent of the total.

EPA Driving Cycle:	Urban	Suburban	Highway
Range (miles)	133	131	129
Distribution of Energy Consumption (percent):			
Aerodynamic Drag	9	41	58
Rolling Resistance	31	30	30
Acceleration	44	23	8
Accessory Power	16	6	4
	100	100	100

Table 4.2 Energy utilization and range.

The high weight of previous electric vehicles has severely restricted their driving range, and also their acceleration performance. A very aggressive weight target of 2040 lb has been set for the demonstrator vehicle to help achieve the range and acceleration goals. This weight is approximately the same as that of standard I.C. engine vehicles of similar size and performance. Since electric vehicle powertrains are inherently heavier than I.C. powertrains due to the battery weight, weight will have to be saved elsewhere in the vehicle structure and systems to achieve the same overall weight as an I.C. car.

The demonstrator vehicle will be designed for bonded-aluminum unibody construction. Research by Alcan and CPC Advanced Vehicle Engineering indicates that this construction is one of the most weight-efficient approaches. Other research by the Advanced Engineering Staff indicates that inexpensive epoxy-based tooling will be suitable for aluminum stampings. To facilitate the actual construction of the demonstrator vehicle, the aluminum structure will actually be simulated with composites, principally fiberglass. The composite structural pieces will have the same shapes as the aluminum stampings would have and will be constructed using lightweight aircraft-style construction of prepreg fabric cured at high temperature in female molds. With this approach, the weight and stiffness of the aluminum structure can be closely matched. However, the composite version of the structure will not be crashworthy, but this should not be a detriment for the demonstrator vehicle.

4.3 Aerodynamic Drag

The fast acceleration capabilities of the demonstrator vehicle also gives plenty of power to cruise at freeway speeds, where aerodynamics become very important. To enable the vehicle to cruise effectively at highway speeds, the target drag coefficient has been set at a low 0.19. With an expected frontal area on the order of 18.5 sq. ft., the equivalent drag-area target is 3.5 square feet. From Table 4.2, it is seen that aerodynamic drag still represents 58 percent of the energy consumed in the highway cycle.

4.4 Tire Rolling Drag

Tire rolling drag is also an important component of a vehicle's energy consumption. For most cars, rolling drag typically accounts for about one-third of energy consumption. In order to keep rolling losses in similar proportion to the other losses for the demonstrator vehicle, lower-than-usual rolling resistance will be required. The target value for the rolling resistance (at 50 mph) has been set at 0.6 percent of the vehicle weight (coefficient of 0.006). Typical automotive tires now have values in the range of 0.75 to 1.0 percent.

4.5 Drive Configuration

Each of the two front drive wheels is driven by an induction motor through a single-speed gearbox. There is no differential or other mechanical connection between the front wheels. Each motor is driven by a transistorized inverter which is connected to the 320-Volt main battery pack.

4.6 Transmission

Automatic transmissions are not efficient enough for application in electric vehicles, and also have annoying lags for downshifting when more power is called for by the driver. Electric motors in general have high torque all the way down to zero speed, minimizing the required variation in motor/wheel gear ratios needed. For the demonstrator vehicle, a simple single speed, fixed-ratio transmission is all that is required. Response to the accelerator pedal will be smooth and progressive, unmarred by lags of manual or automatic gear shifting. Driving the demonstrator will feel like driving a moderately powerful car that remains in first gear, with the electric motors spinning smoothly and efficiently up to 12,000 rpm at the maximum speed of 76 mph.

In order to have good cruising range at highway speeds, very high efficiency is required at very light loads, a difficult combination. The efficiency goal at 60 mph cruise is 96%.

4.7 Motor Type

With a single speed transmission, the motor must be cabable of operating efficiently over a very wide range of speed and power. It has been determined that AC induction motors have characteristics that are best matched to this requirement. Induction motors have the high speed (hence high power to weight ratio) capabilities of permanent magnet brushless motors, as well as the inherent ability to optimize the magnetic field strength of the wound-field DC motor. Induction motors have lower peak efficiency than similarly sized and rated permanent magnet machines, but the efficiency stays high over a wider operating range. This is especially important for highway cruising, when the motor is operating at very high speed and less than ten percent of its rated torque.

The simple construction of the rotor and the lack of permanent magnets in the induction motor results in relatively low manufacturing costs. The disadvantage of an induction or other brushless motor is that three times as many power switching devices are needed compared to a brush-type motor.

4.8 Motor Drive Electronics

An inverter is required to generate the 3-phase AC power to drive an induction motor. The inverter consists of essentially three electronically controlled single-pole double-throw switches and logic electronics to control the switching. The two outer contacts of each switch are connected across the DC power source (the battery in this case) and each center pole is connected to one of the three leads going to the motor. By rapidly modulating the switches in the appropriate sequence, frequency, and duty cycle, AC current is generated.

MOSFET power transistors will be used as the switching devices for the inverter. MOSFET's require relatively little energy to switch on or off, have very low on-resistance, and have very rapid switching capability. These characteristics make it possible for the inverter to have very efficient operation at low power and to have very high peak power capability. This is the first known application of MOSFETs to the drive electronics for a full-sized electric vehicle (although the SunRaycer's Magnequench brushless motor did use a MOSFET inverter).

A separate inverter will be required for each of the drive motors, but both will be housed in the same physical package.

4.9 Battery

The four basic requirements for the battery are low cost, high specific energy, high specific power, and long cycle life. After review of the state of the art in battery systems, gas-recombination lead-acid batteries have been selected for the baseline approach. As detailed in section 2.3, recombinant batteries are maintenance free, evolve no gases, have immobilized electrolyte, and inherently longer cycle life than flooded lead acid batteries.

In order to achieve the desired range and acceleration performance, the 900-pound battery pack should have specific energy of 16 Wh/lb (35 Wh/kg) at a two-hour discharge rate, and specific power of 104 W/lb (230 W/kg). To avoid loss of battery performance at low temperatures and to insure uniform charge acceptance, the battery will be thermally-controlled. To facilitate thermal control, it was decided to locate the batteries all in one container, a tunnel running down the middle of the car between the seats. Heating elements and blowers will be used to maintain temperature of the batteries.

Figure 4.4 shows the battery system installation in the insulated central tunnel. The batteries are installed or removed from the vehicle from below by unbolting the bottom of the tunnel. The bottom is "U" shaped to give it enough structural rigidity to facilitate handling of the 900-lb battery pack outside of the car.

Although the recombinant lead acid battery has been judged to be the most appropriate for the

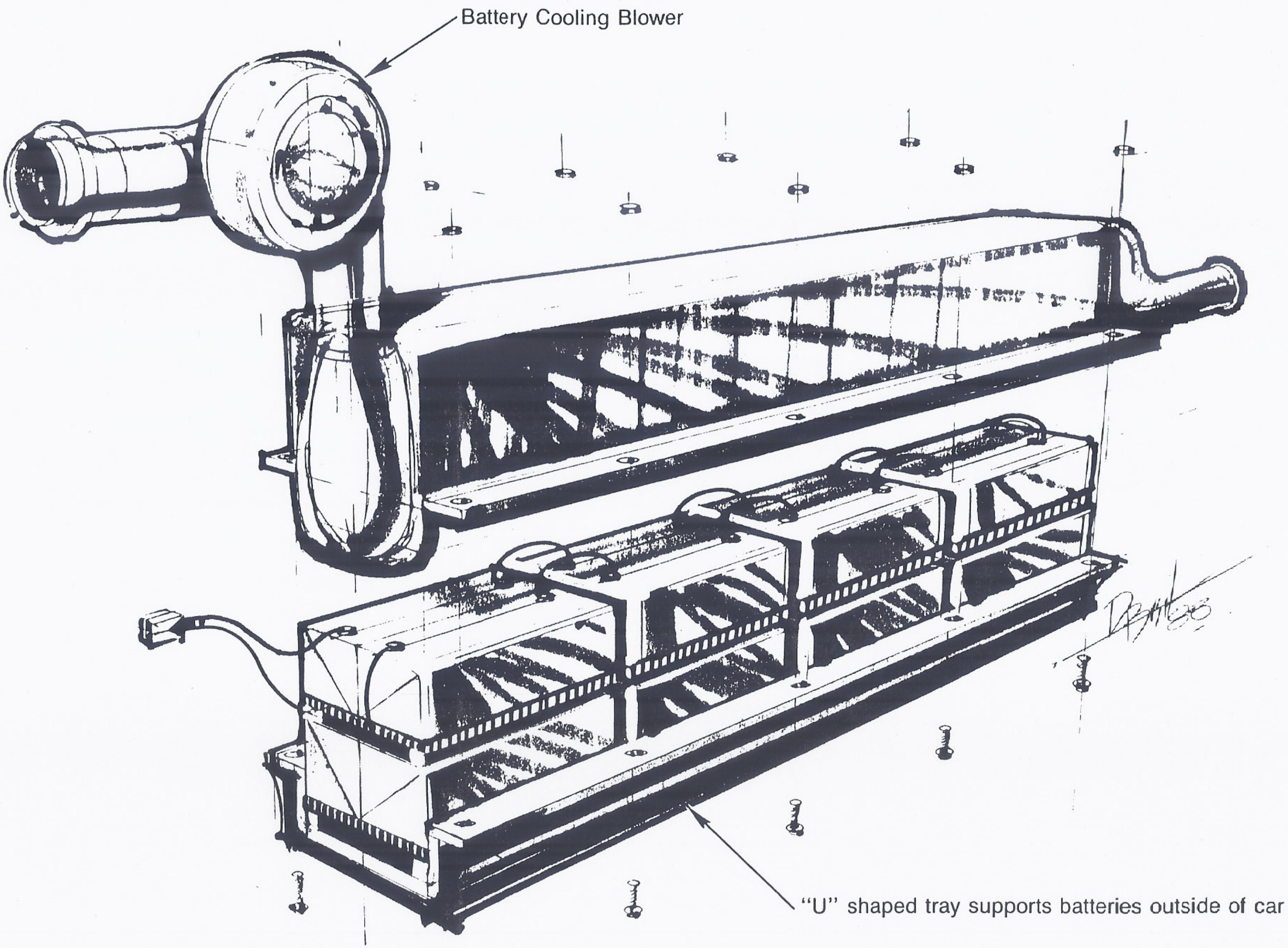


Figure 4.4 Battery Installation in central tunnel. Note cooling fins on bottom of battery cases.

demonstrator vehicle, it is also recognized that battery development remains to a large extent an art rather than a science, and that there is a possibility that the battery may not perform as expected. As a hedge against this possibility, it is planned to closely follow new battery technology, and perhaps start development of alternative battery systems. Two alternative systems appear promising: the bipolar lead acid battery, and the sodium sulphur battery. These are both described in Chapter 2.

4.10 Heating, Air Conditioning, and Thermal Management

Environmental control of an automobile interior has always been challenging, but for any modern car, it is deemed almost essential to have heating and air conditioning systems. Since batteries store so little energy compared to gasoline, the environmental control issue has never been fully addressed in previous electric vehicles. For the demonstrator vehicle, the approach will be to design in an environmental control system from the very beginning. The baseline system will be an electrically-driven heat pump, essentially an air conditioner that can pump heat in both directions. The installed cooling capacity will be about half of that of most production cars. The shortfall in capacity will be made up through careful thermal insulation and use of the best possible thermal-control window glass. The full-load power consumption of the unit will be on the order of 1500 W.

The substantial driving range of the vehicle without air conditioning means that even after considering environmental control system power drain, the resultant range is still reasonable. Table 4.3 shows the expected range in the urban, suburban, and highway driving cycles with the air conditioning operating at maximum power. Although the range in the urban cycle has dropped almost in half, at 71 miles it is still reasonable. The air conditioning consumes more than half of the total battery energy in this case.

As part of a study on automotive interior environmental control, AeroVironment developed a seating concept that would allow a reduction in the air conditioning load. Standard seats insulate much of the body area, requiring greater heat removal per unit area from the remaining exposed body area. By using an open mesh seating material, heat removal can take place around the entire body, allowing the occupant to feel comfortable at a higher ambient air temperature than with standard seats.

Figure 4.5 shows an initial design concept by ACC and AeroVironment for a ventilated Duoflex seat. Duoflex is the name of a new polymer mesh fabric material developed at GMR.

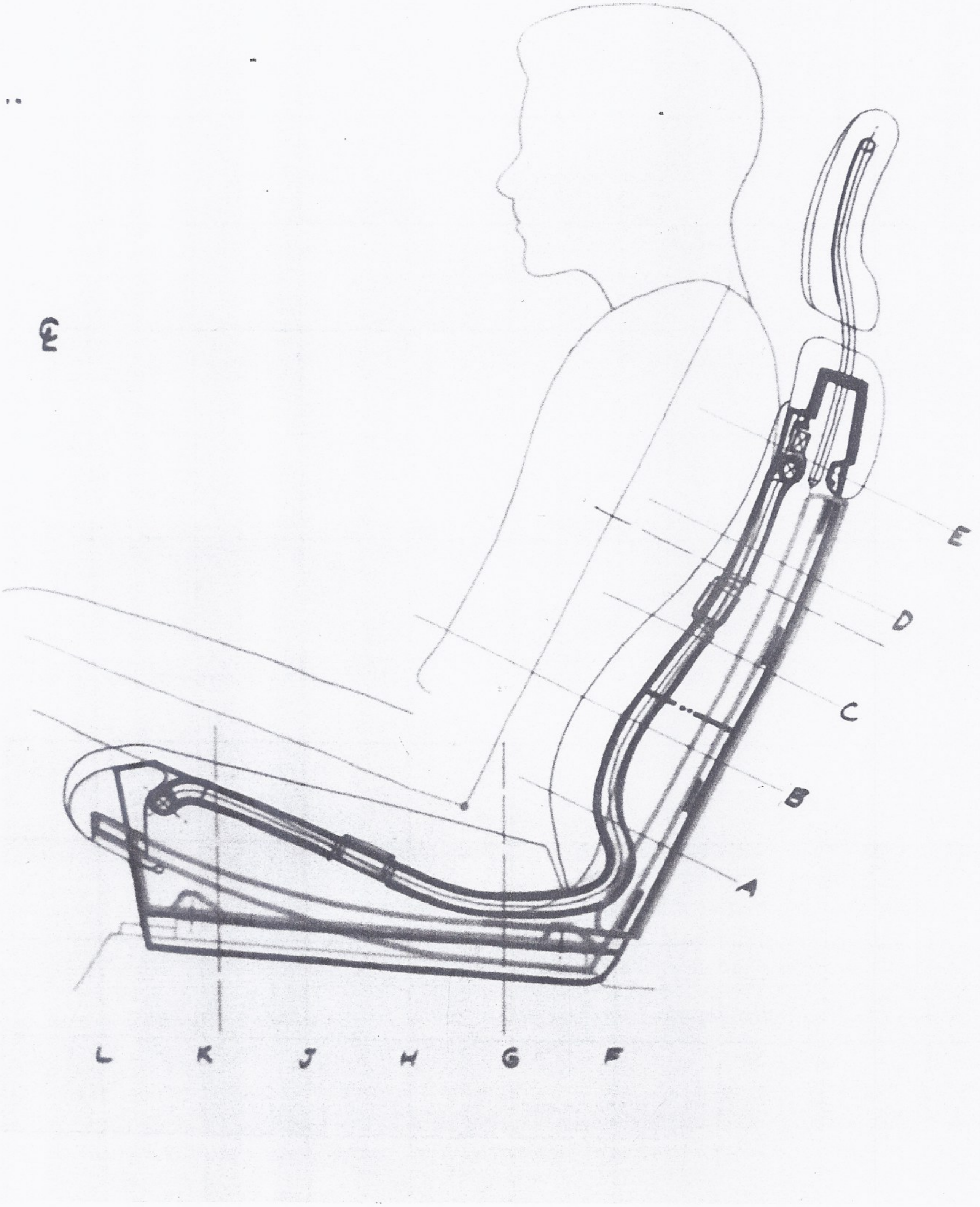


Figure 4.5 Ventilated Duoflex seat dwng.

EPA Driving Cycle:	Urban	Suburban	Highway
Range with maximum air conditioning (miles)	71	98	104
Distribution of Energy Consumption (percent):			
Aerodynamic Drag	5	31	47
Rolling Resistance	17	23	24
Acceleration	21	16	5
Accessory Power	57	30	24
	100	100	100

Table 4.3 Energy utilization and range with maximum air conditioning.

5. Basis and Support for Technical Approach

5.1 Introduction

Over the course of the present design study, there have been substantial efforts to confirm the target specifications for component performance, weights, and in general the suitability of the design approaches taken. The following sections give details of this supporting information.

5.2 Weight

The target weight of 2040 pounds will be difficult to achieve. There must be strict control of component weights, and due consideration of 'ripple' effects that the changing of one component will have on others. An example is wheel diameter. Larger wheels are desirable from a styling point of view, but the weight impact is much more than just the heavier wheels and tires. The larger diameter results in larger acceleration or braking torques, increasing the weight of the brakes, gearbox, suspension pieces, half-shafts, and motor mounts.

Table 5.1 gives an estimate of the weight buildup for the demonstrator vehicle, and for comparsion, weight data for the 1980 GM electric vehicle. The GM weights were based on considerable design and analysis, and should represent achievable weights for a production vehicle. The GM drive train component weights were available in the most detail. Major differences with the demonstrator vehicle are 217 pounds less battery weight for the GM design, 105 pounds more motor weight, and 72 pounds more elecronics weight. Overall the GM drive train, at 1210 pounds, is 50 pounds lighter than that of the demonstrator vehicle.

The 592-pound body and structure weight listed for the GM design includes windows, interior, and subsystems. These items for the demonstrator represent 580 pounds. These seem quite close, but the 580 pounds for the demonstrator vehicle must include 70 pounds for the heat pump system. The GM design did include an oil-fired heater whose weight is unknown, but is undoubtedly less than 70 pounds.

In conclusion, the target weights for the demonstrator vehicle are slightly below those of the 1980 GM design, but should be possible with very careful design and strict weight control.

	Santana	1980 GM EV Design
Structure		
body and structure	320 lb.	592 (incl.windows interior, systems)
windows	60	
suspension and steering	140	130
brakes	60	48
Drive Train		
motors	90	195
power electronics	60	132
batteries	900	683
wiring	30	30
gearing, joints, drive shafts	100	82
wheels and tires	80	88
Interior		
panelling	30	
seats	50	
restraints	20	
Systems		
lighting	10	
HVAC	70	
Radio	10	
Instruments	10	
Total	2040	1980
Payload	360	473
Gross wt	2400	2453

Table 5.1 Weight buildups for demonstrator vehicle and 1980 GM EV design.

5.3 Aerodynamic Drag

The drag coefficient target of 0.19 is 35% less than that of the best existing GM production car (Pontiac Grand Prix, 0.29), but it is well within the range of what has been achieved with one-off research vehicles, and well above the Sunraycer's 0.125. Some aspects of electric vehicles make streamlining easier. There is no requirement for large cooling airflow to a vertically standing radiator at the front of the car, and the underbody can be made quite smooth, since there is no exhaust system, catalytic converter, and fuel tank.

Figure 5.1 shows some examples of recent low-drag vehicles. Note that the Chevy 2003a and Ford Probe V both have covered front wheels, and drag coefficients well below 0.2. The Renault Vesta, with a drag coefficient of 0.19 shows that front wheel covers may not necessarily be required in order for the demonstrator to meet its target (covers would be undesirable due to added weight and mechanical complexity)

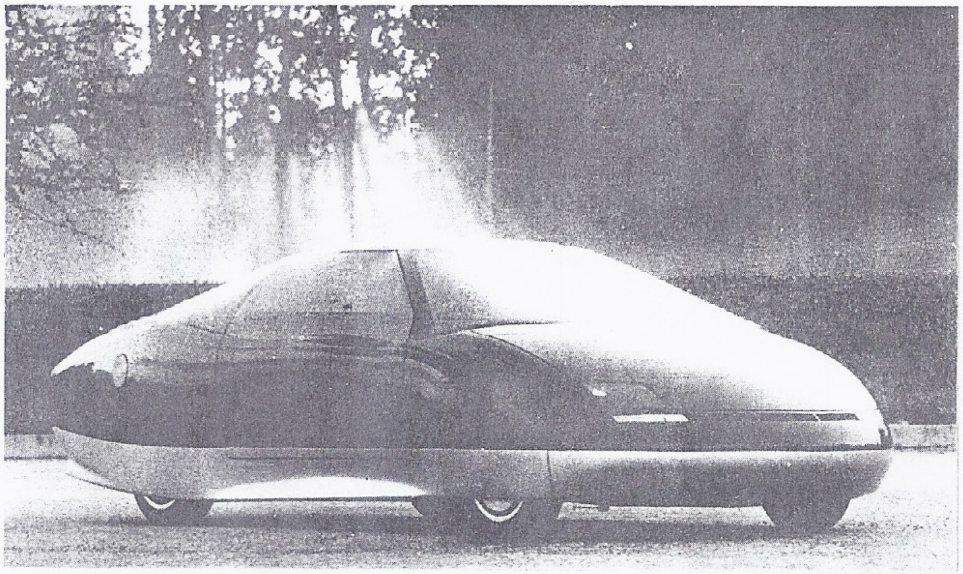
5.4 Tire Rolling Drag

The rolling resistance goal is about 25% less than that of the best current automobile tires. Discussions with the engineers at the tire and wheel lab at the Milford proving grounds resulted in investigation of high pressure compact spare tires as candidates for the demonstrator vehicle. Rolling resistance tests of a Firestone T125/70 R 15 compact spare at 60 psi indicated rolling resistance of 0.7% of the vertical load, somewhat higher than the target, but still quite good. The ride and handling qualities of these tires were known only in the one-on-a-corner mode of spare tire usage. To assess the handling qualities of a vehicle running these tires all-around, a set of four compact radial spares was mounted on a Corsica. A ride and handling engineer from the L-car development group at Milford performed the tests. The overall result was surprisingly good handling and cornering limits, with harsh but acceptable ride quality.

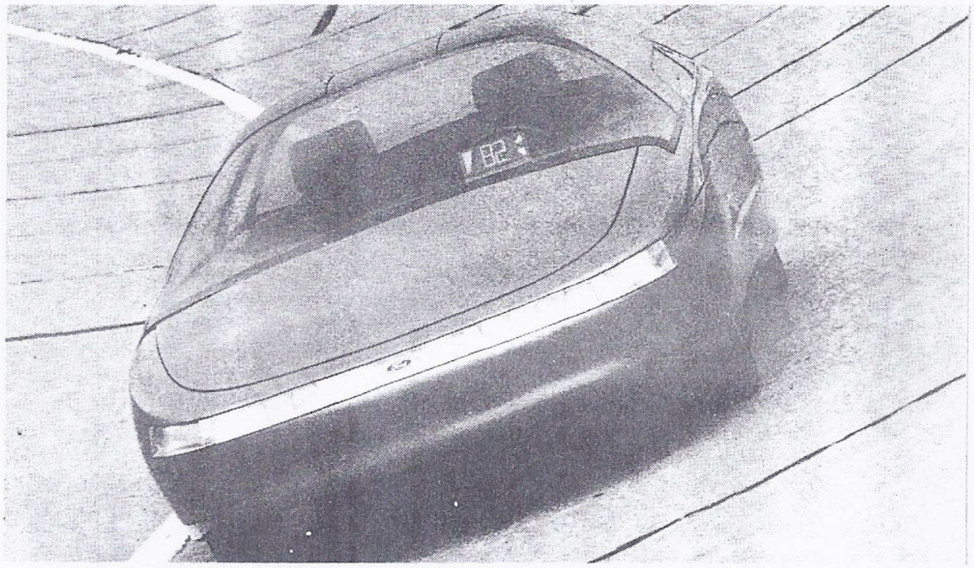
Through ACC, Goodyear has become involved in developing an all new tire for the demonstrator vehicle. Figure 5.2 shows one of the proposed 65 psi tire designs. Its projected rolling resistance is an excellent 0.6 percent of vertical load.

5.5 Drive Configuration

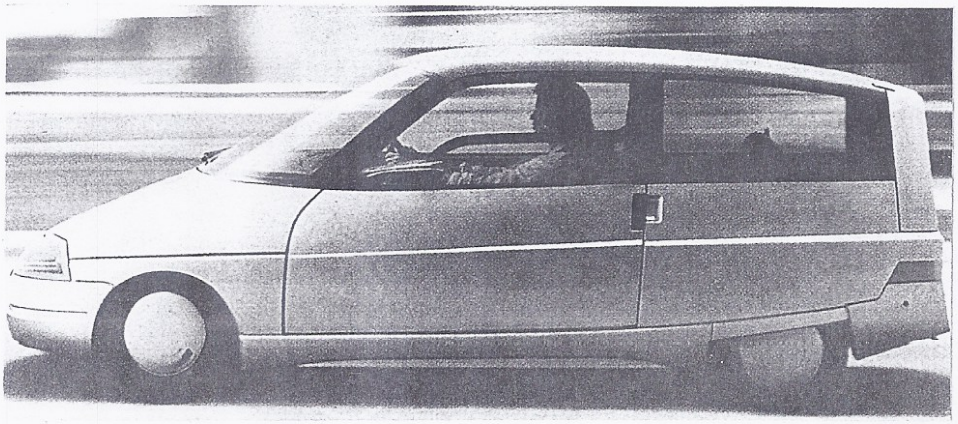
Both front and rear drive configurations were examined as part of this study, and front drive has been selected for the demonstrator vehicle. The advantages of front wheel drive configuration are good space utilization, safe handling characteristics, and good braking on slippery surfaces. Traction on dry pavement is adequate for either drive configuration for both accelerating and regenerative braking. On slippery surfaces, the front drive configuration has reduced traction for acceleration, but reasonable traction for regenerative braking. For rear drive, the situation is reversed. Since the electric drive system can be made to have traction-control in both braking and accelerating, it was deemed more appropriate to provide



a) Chevrolet 2003a
$C_d = 0.166$

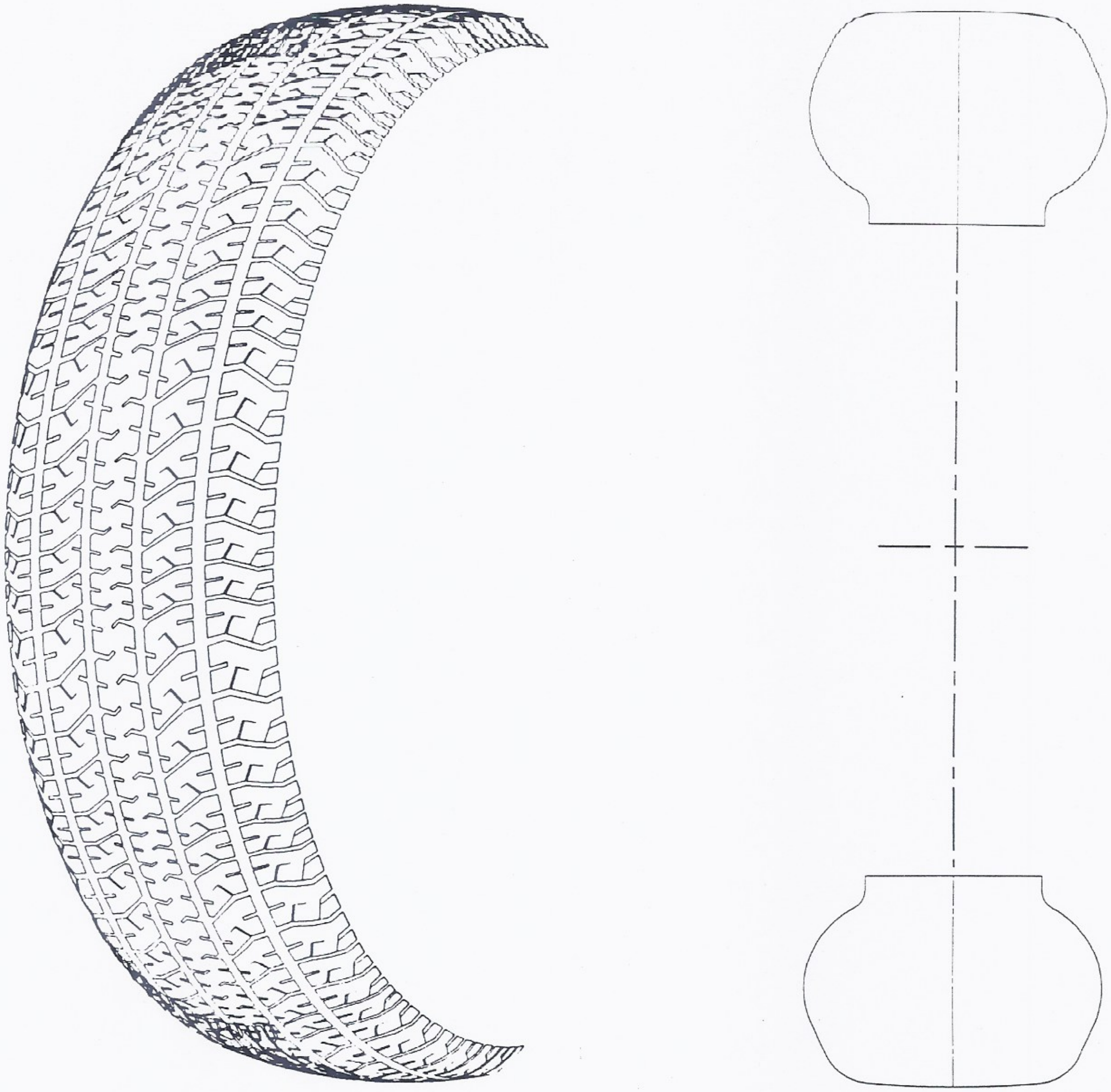


b) Ford Probe V
$C_d = 0.137$



c) Renault Vesta
$C_d = 0.19$

Figure 5.1 Recent low-drag vehicles



Tire size — P 165/65 R14

Wheel size — 14 × 3.5 in.

Load capacity — 1330 lb

Inflation pressure — 65 psi

Rolling resistance coefficient — 0.006

Weight — 11.8 lbs

Figure 5.2 One of the new Goodyear low-rolling-resistance tires proposed for the demonstrator vehicle.

for good braking rather than acceleration in slippery conditions, hence the choice of front drive. There should be no torque-steer problems due to the symmetry of the dual motor installation.

The use of two motors rather than one motor with a differential has several advantages. First, with independent control of the torque of each motor, there are numerous possibilities for tailoring the lateral torque split depending on traction, turn radius, etc. Second, having two motors gives a measure of redundancy. In the event of an electronics failure in one of the inverters, the vehicle could still be driven on the other motor. Finally, the charging mode is made simpler through having a complete motor and inverter to connect to each phase of the AC line. The switching times of all six phase modules can be staggered during charging, effectively increasing the apparant switching frequency six-fold. This allows the line filter bank to be much smaller.

5.6 Transmission

The single speed transmission will most likely by a single stage planetary gearbox. Discussions with gearbox manufacturers have indicated that our weight goal of less than 20 pounds per gearbox can easily be met, while the efficiency goal of 96 percent at 60 mph cruise will be more challenging. The approach needed to achieve high efficiency at low load is to pay very close attention to all energy loss mechanisms in the gear train. Loss terms that would not be noticed at higher torque could be very significant at low torque. The lubrication will be through a pressurized oil spray system rather than the more usual oil bath. For weight savings and elimination of several high-speed bearings, the gearbox and motor will share a common housing.

5.7 Motor Type

In addition to being used in nearly all household appliances, induction motors are used extensively in military and commercial aircraft for accessory and fan drives. These aircraft have 208-Volt 400 Hz AC power systems. The high frequency allows high motor speed, resulting in good power to weight ratio. The induction motor for the demonstrator vehicle is similar to 400 Hz aircraft motors in operating speed, but it does not have the same requirement for good starting torque at 400 Hz slip speed. It will of course need high stall torque, but since frequency is optimally controlled by the inverter, stall torque will be as high as the motor breakdown torque.

Figure 5.3 shows projected motor efficiency of the dual induction motor powertrain as well as for the Ford/GE interior permanent magnet (IPM) motor developed for the Ford electric van program. The Ford/GE motor is about twice the size of each induction motor, hence the power in the graph is vehicle power - two motors for the induction, one for the IPM. Note that the steady state power requirement is a very small fraction of the peak power. The induction motor shows much better efficiency at high speed / low torque conditions representing highway cruise power.

Contacts have been made with both General Electric and Lucas-Western (formerly Western Gear) about design and fabrication of the motors for the demonstration vehicle. Lucas Western has given the most favorable response in terms of interest and ability to meet the specified efficiencies and maximum torque. Their first design achieves 93.4 percent efficiency at the 60-mph cruise point, and 65 ft-lb of breakdown torque, in a motor package with 9-in. diameter stator, 5-in. rotor, and 2.5-in stack length. The estimated weight of each rotor and stator set is 31 pounds.

5.8 Motor Drive Electronics

The use of MOSFETs in the inverter is new for full-sized elecric vehicles. Cost has previously been the argument against using MOSFET's. There have been no cost breakthroughs, but prices continue to decline. The high switching frequency possible with MOSFET's allows the motor to have lower inductance, resulting in a higher torque to weight ratio. Other advantages of the high frequency MOSFET inverter are no audible noise, high power, and very low no-load losses. In order to reduce high frequency iron losses, it will be necessary to have the motor built with thinner stator laminations than usual, as was done for the Sunraycer motor.

The Sunraycer's MOSFET inverter had cruise-power efficiencies exceeding 97 percent, yet was able to continuously deliver peak power six times greater than cruise power. As a result, the Sunraycer did not require a variable speed transmission, and was able to climb the hills on the race course at over 50 mph.

AeroVironment consultant Alan Cocconi has developed much of the inverter during the present program. The goal of this development has been to confirm that the required efficiency and power-to-weight ratio can be achieved. Figure 5.4 shows the planned layout for the dual inverter package. For redundancy, there are two separately-fused power busses. Six phase modules (3 for each motor) are shown as well as input filter capacitors and cooling

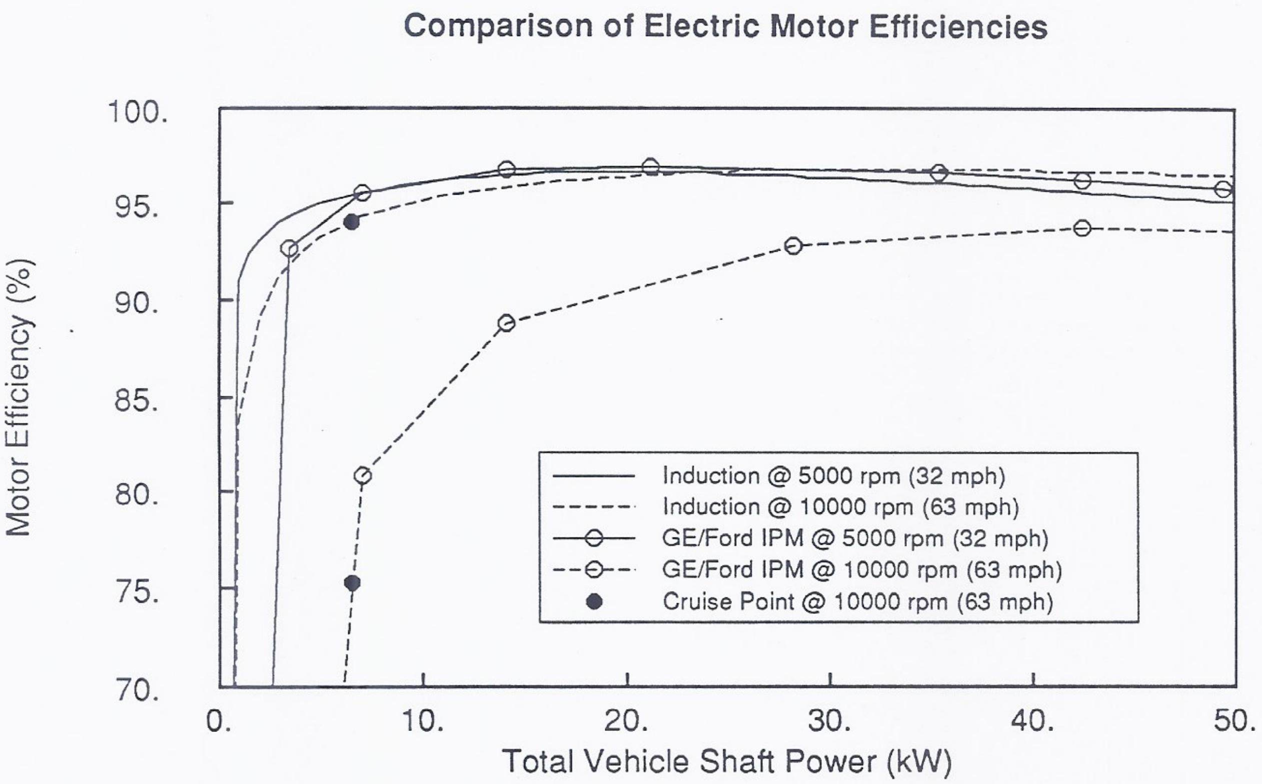


Figure 5.3 Comparison of motor efficiencies calculated for the proposed induction motor and for the Ford/GE interior permanent magnet (IPM) motor used in the ETX II Van. Note the poor efficiency of the IPM motor at high speed, low power.

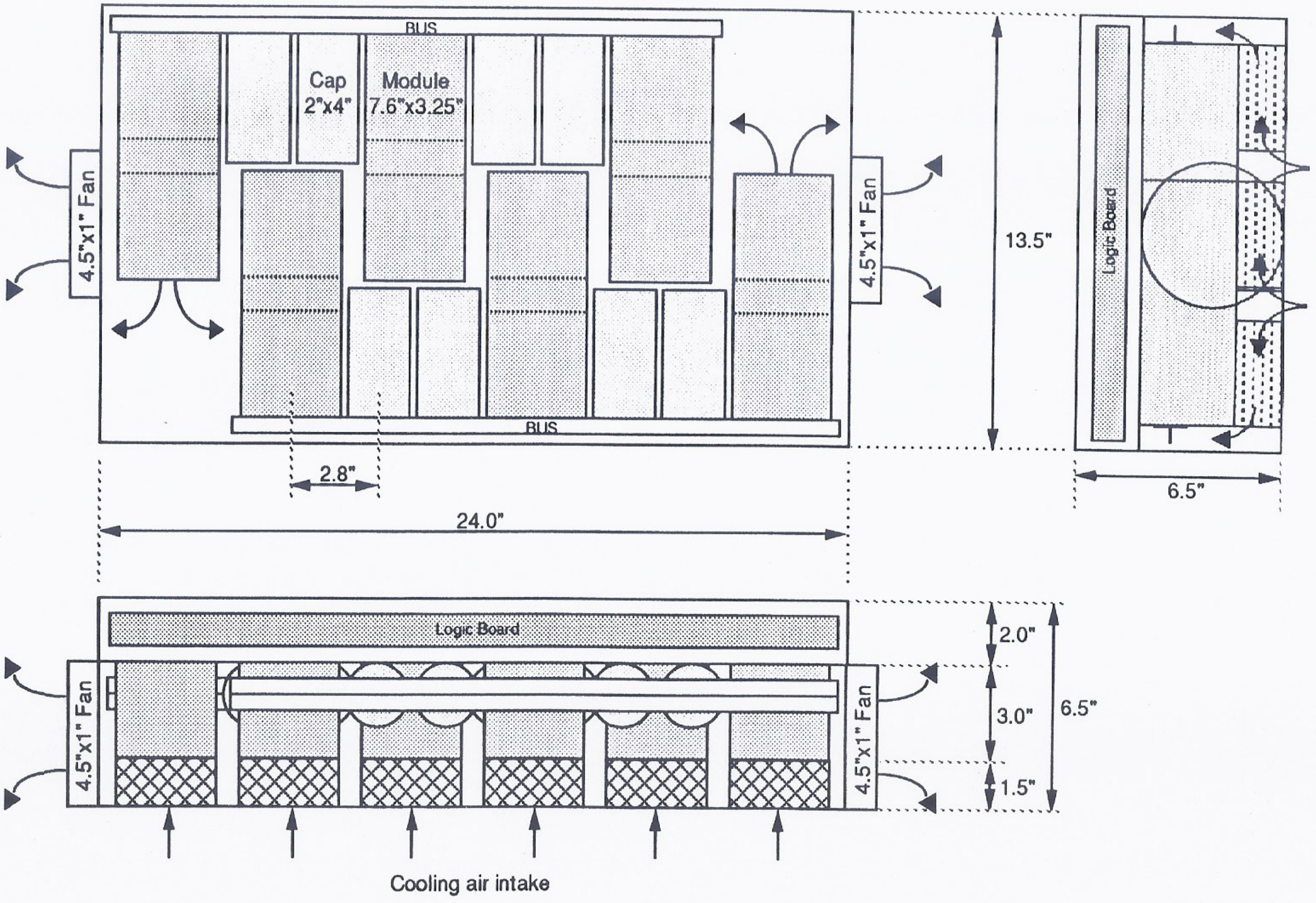


Figure 5.4 Inverter Component Layout

airflow paths. The logic-level control electronics will contain a lookup table in ROM that gives the slip speed for optimum efficiency as a function of the speed, battery voltage, and required torque. Although not shown, the inverter package will also house the 100-Amp 12-Volt auxiliary power supply.

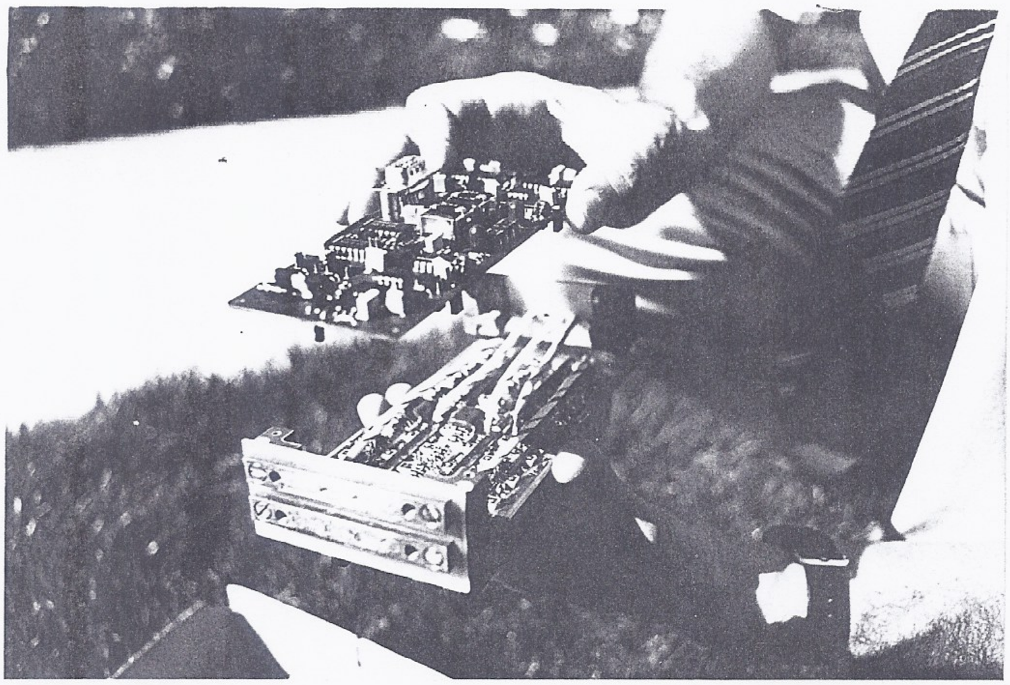
Figure 5.5 shows photographs of a prototype 'smart' phase module developed for the demonstrator vehicle by Cocconi Engineering. It includes 48 500-V MOSFET transistors, aluminum heat sink and honeycomb cooling fins, drive circuitry, and protections for overcurrent, overtemperature, and shorts. The module weighs 3.7 lb, and has been tested to 150 Amps rms at 400 V on the DC input bus. Figure 5.6 shows an exploded view of the phase module. The transistors are held in firm contact with the heat sink by two pieces of spring steel and a spacer. This arrangement greatly simplifies construction by eliminating the need for screw connections of the transistor to the heat sink.

The weight target of 60 pounds for the final inverter seems quite reasonable. All six phase modules weigh just over 22 pounds, leaving 38 pounds for chassis, case, logic circuits, capacitors, and 12V auxiliary power supply.

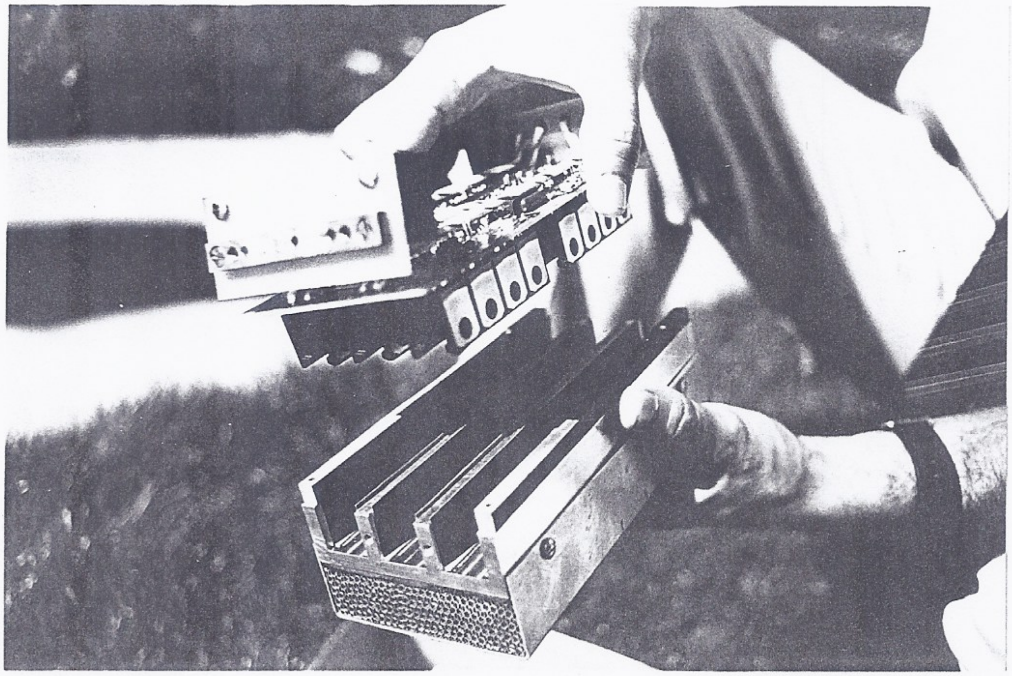
5.9 Battery

In support of the recent demonstrator vehicle design work, Delco Remy has done performance testing of two recombinant batteries. The first tests were made on a 24-Volt aircraft battery from Concorde Battery Co. This battery, denoted the RG 380E, has been designed for the high power capability needed for aircraft cranking applications. Although not intended for deep cycle service, there was reason to believe that the features of the recombinant design would result in good cycling capability.

To maximize the capacity of the battery, testing was initially carried out at 50° C. Data for some flooded lead-acid batteries had indicated that as much as 25 percent improvement in specific energy at 50° C compared to 25° C. Unfortunately, the test results showed lower capacity than expected. Further tests at varying temperature showed only 5 percent gain at 50° C. After correcting the data for removal of the heavy aluminum external case needed for aircraft use, the specific energy is at best 12 Wh/lb (27 Wh/kg), almost 25 percent below the target specific energy. The reason for the shortfall could not be explained by either Delco Remy or the battery manufacturer.

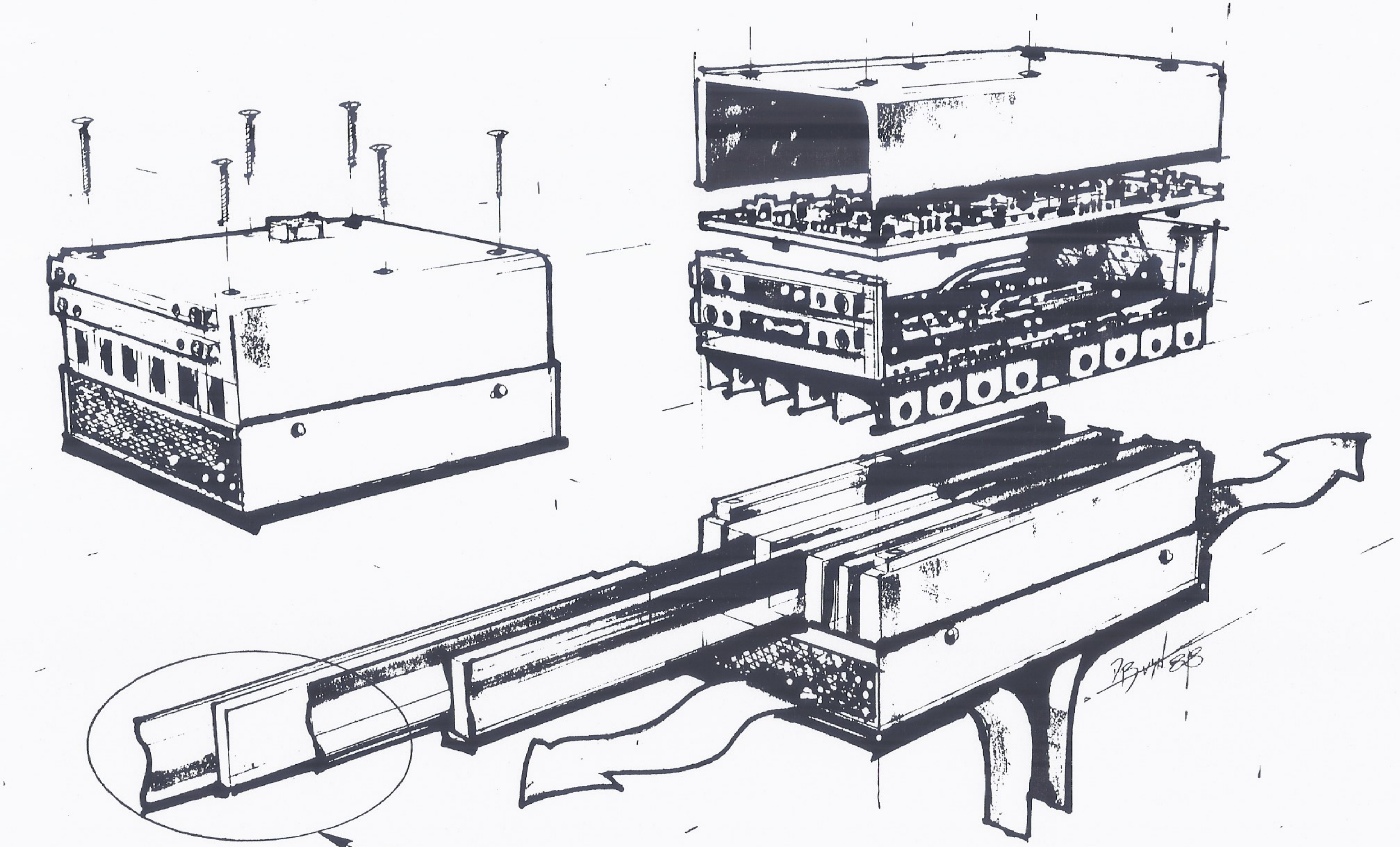


a) Logic board and power board



b) Power board and heat sink

Figure 5.5 Photographs of prototype "smart" phase module for the inverter. Weight: 3.7 lb., power handling: 150 Amps RMS continuous at up to 400V DC input. Efficiency at full rated load: 97.3%. Six modules are required for both inverters.



Spring assembly holds
transistors in firm contact
with heat sink.

Air flow path through
aluminum honeycomb heat
exchanger.

Figure 5.6 Exploded view of inverter phase module.

After some research, Delco Remy discovered that their own recombinant marine battery currently under development would probably meet the targets for both specific energy and specific power. Testing of a prototype of this battery began very recently. The specific energy at a two-hour rate at 50° C was measured at 17 Wh/lb (37.5 Wh/kg), slighty exceeding the goal. Specific power tests also proved to meet the target of 104 W/lb (230 W/kg). Based on these promising results, Delco Remy is prepared to undertake development of a new battery for the demonstrator vehicle based on the marine battery design.

Bipolar lead acid batteries are being developed by several battery companies including Delco Remy and Ensci Inc. Ensci appears to be closer to an actual production battery for electric vehicles, in part due to support they have received from Southern California Edison Company (SCE) to develop a battery suitable for electric vans. Working with Teledyne Battery Company, they have just recently completed production tooling and the first prototypes of 12-Volt batteries. Ensci predicts specific energy of 25 Wh/lb (55 Wh/kg) at the 3-hour rate, and specific power of over 360 W/lb (800 W/kg). Delco Remy has offered to assist Ensci and SCE by performing the initial testing of these batteries. If the test data looks promising, a bipolar battery sized for the demonstrator vehicle tunnel could be made by Ensci.

5.10 Heating, Air Conditioning, and Thermal Management

As a starting point in development of the heat-pump environmental control system, a review was made of currently available residential units of appropriate capacity. It was found that there are none available in the United States, but that there are many suitable units for sale in Japan. Through the Hughes Japan office, an appropriately sized Mitsubishi unit was procured. The system has an advanced electronic control system, and incorporates a variable-speed AC drive system for compressor motor. The overall efficiency is quite good (energy prices are very high in Japan).

The unit has been set up and tested, and preliminary data confirms that it performs to specification and that it is about the correct capacity for the demonstrator vehicle. The peak power consumption at full cooling is about 1200 Watts.

6. Proposal for Demonstrator Vehicle

6.1 Proposal Summary

A program is proposed to design and to build one (or two) demonstration electric vehicles. Their purpose will be to show that current technology allows achievement of performance levels much better than that of previous electric vehicles.

The program will be managed by Hughes Aircraft Company, with the focus of engineering and fabrication at AeroVironment Inc. Major involvement in the program will exist in all four GM technical staff organizations, the Advanced Vehicle Engineering department of CPC, and at Delco Remy. Several other GM and Hughes organizations will be involved to a lesser extent.

The program will require funding of $3.85 M excluding the manpower costs in the supporting GM organizations. A second vehicle will add $311K to the funding needed. A cost contingency of $500K is also recommended. The program is scheduled to complete the first vehicle in 12 months with a subsequent test period of three months. The second car will be completed at the end of the 14th month.

6.2 Program Organization and Management

The highly successful Sunraycer solar car was designed and built in a remarkably short five-month period. Two months later, after shakedown, driver training, and 4,000 miles of durability testing, it was at the starting line in Australia. Sunraycer's development cannot be compared with that of a production vehicle where government regulations, market forces, maintenance considerations and manufacturing cost are major complicating factors. Even so, the Sunraycer's "skunk works" approach, coupled with the enormous resources of skill and knowledge in GM and Hughes worked extremely well. It is the intention in the demonstrator vehicle development project to use the Sunraycer approach again. This is best suited for the project, and it may provide further insight on how GM can marshall its great capabilities more efficiently in future endeavors.

The focal point of the project will be, as it was for Sunraycer, at AeroVironment. GM will soon have a 12 percent equity position in AeroVironment, and board participation, so the linkage is becoming somewhat closer than that of a completely independent subcontractor. AeroVironment will have the overall responsibility for designing and constructing the vehicle, and performing the initial tests and evaluations.

Dr. Alec Brooks, who was the AeroVironment project manager and chief engineer for the Sunraycer, will have the same position for the demonstrator project. Dr. Paul MacCready, president of AeroVironment, will serve as overall project director for the AeroVironment effort. An important role for Hughes is to provide the overall program management, which will be done by Howard Wilson, recently retired Hughes Vice President for General Motors programs, now a consultant to Hughes. This assignment would follow the pattern of the Sunraycer Program where Mr. Wilson was Program Manager prior to his retirement. The business management and contracting functions at Hughes would support the Program Manager and manage the subcontracts to AeroVironment and certain other suppliers.

Major supporting efforts would be undertaken at various General Motors' Staff and Division organizations. Delco Remy will be responsible for the batteries, and will be involved with the motor development at an outside contractor in anticipation of a future motor product line. Both Delco Electronics and Delco Remy will follow development of the motor control electronics that will be done by Cocconi Engineering, also in anticipation of future production design and manfacturing roles.

Design Staff, through the Advanced Concepts Center in Newbury Park, California, will develop the vehicle's exterior and interior design in close cooperation with AeroVironment on the aerodynamic aspects and on the basic layout to ensure that the technological goals are not compromised. Advanced Concept Center's network of suppliers for tires, wheels, glass, small components, and fabrication will be fully utilized.

Advanced Engineering Staff will provide support in structures, manufacturing methodologies, air conditioning and heating, mechanisms, and a variety of other vehicle system components.

General Motors Research Laboratories will be consultants in motor, battery, and electronics development.

As was done on Sunraycer, Advanced Vehicle Engineering in CPC will assist in suspension design, and in addition will provide analysis for structural design, particularly for crash safety.

Current Product and Manufacturing Engineering staff will perform the test and evaluation functions and participate in vehicle testing at the Mesa and Milford proving grounds.

Regulatory concerns and communications with government agencies and electric utilities will be coordinated with the Environmental staff.

In anticipation of a possible phase zero program at a later time, Marketing and CPC will be advised on program status and accomplishments. The Truck and Bus and GMC divisions will also be informed to allow full benefits to their G-Van Program.

Other component divisions, such as Harrison, Delco Products, Delco Moraine, and New Departure will be asked for assistance when design tasks involving their areas of special capability are addressed.

Hughes Aircraft Company's involvement will be less entensive than in the Sunraycer program where the solar array and silver zinc batteries were critical components. The Hughes capabilities in systems engineering and simulation will support the program, and the Hughes participation in the GM ABS and traction control developments will be useful, as these concepts are well suited to applications in a two-motor electric drive system.

Another related but separate activity at Hughes is the design study of a sodium-sulphur battery suitable for a second generation or update of the demonstrator vehicle. Hughes has a substantial sodium-sulphur battery project funded by the government for aerospace applications and an extension of that work to automotive applications has been proposed.

Outside suppliers who will participate include Cocconi Engineering for electronics, Goodyear Tire and Rubber Company for low-rolling-resistance tires, Pittsburg Plate Glass for lightweight and heat-control glass, Alcoa for wheels and other components, and Lucas-Western for the electric motor stator and rotor development.

The organization chart of the program structure is shown in Figure 6.1.

6.3 Program Task Descriptions

The following individual tasks have been identified for the demonstrator vehicle program:

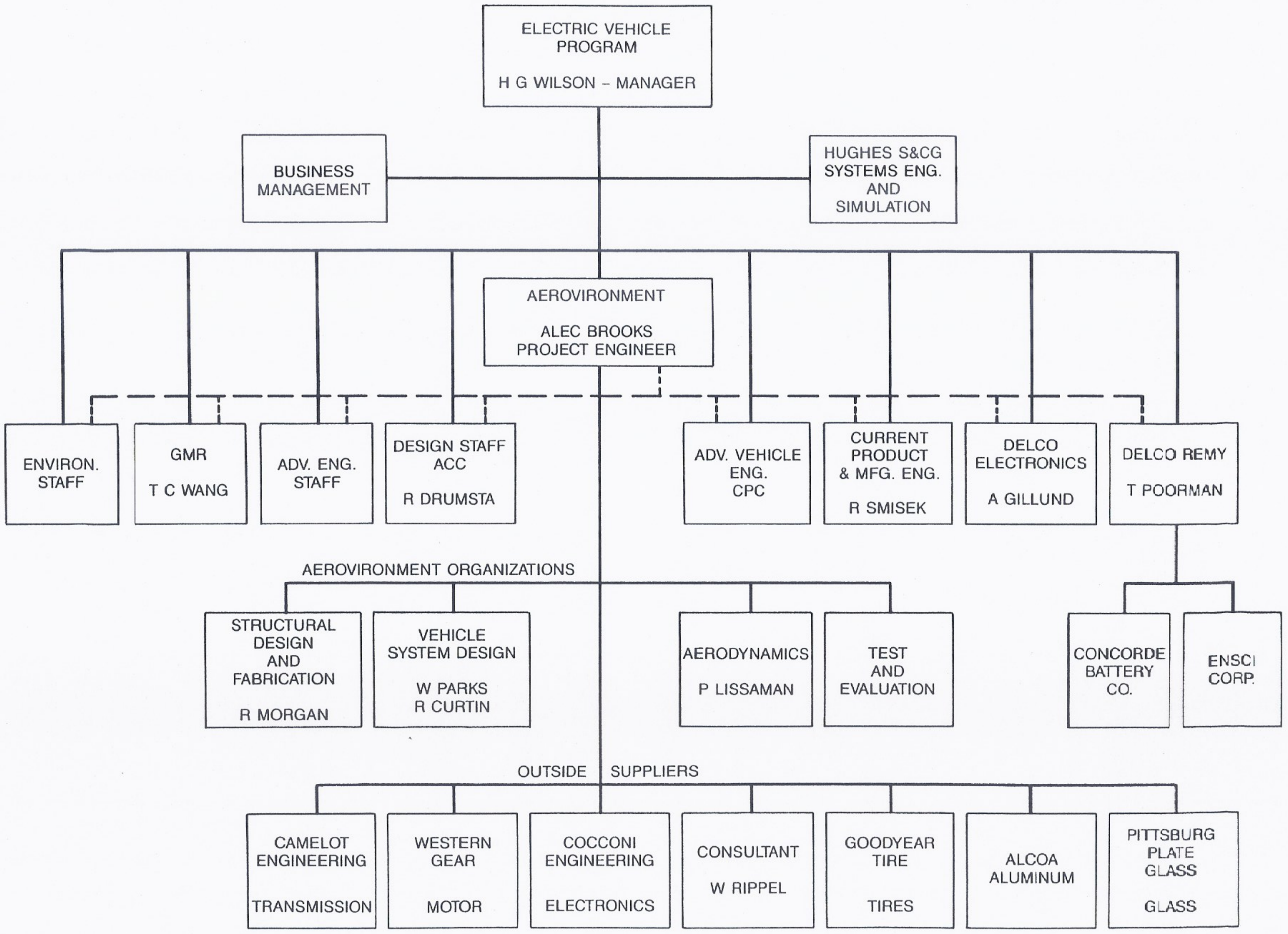

ELECTRIC VEHICLE PROGRAM
H G WILSON – MANAGER
BUSINESS MANAGEMENT
HUGHES S&CG SYSTEMS ENG. AND SIMULATION
AEROVIRONMENT
ALEC BROOKS PROJECT ENGINEER
ENVIRON. STAFF
GMR
T C WANG
ADV. ENG. STAFF
DESIGN STAFF ACC
R DRUMSTA
ADV. VEHICLE ENG. CPC
CURRENT PRODUCT & MFG. ENG.
R SMISEK
DELCO ELECTRONICS
A GILLUND
DELCO REMY
T POORMAN
AEROVIRONMENT ORGANIZATIONS
STRUCTURAL DESIGN AND FABRICATION
R MORGAN
VEHICLE SYSTEM DESIGN
W PARKS
R CURTIN
AERODYNAMICS
P LISSAMAN
TEST AND EVALUATION
CONCORDE BATTERY CO.
ENSCI CORP.
OUTSIDE SUPPLIERS
CAMELOT ENGINEERING
TRANSMISSION
WESTERN GEAR
MOTOR
COCCONI ENGINEERING
ELECTRONICS
CONSULTANT
W RIPPEL
GOODYEAR TIRE
TIRES
ALCOA ALUMINUM
PITTSBURG PLATE GLASS
GLASS

Figure 6.1

Hughes Aircraft Company

1. Manage the overall program for General Motors. This task includes top level coordination with supporting General Motors organizations, reporting of program progress and status to the GM Vice President responsible for the technical staffs, technical oversight of the program, and financial and business management.

2. Support the program in the areas of systems engineering and simulation, with a specific emphasis on traction control and anti-lock brakes.

AeroVironment Inc.

1. Project Management
   This task encompasses both project management and overall technical direction of the project. The chief engineer will monitor the technical status and progress of all tasks, and make decisions regarding overall technical direction of the program. Interface with consultants, subcontractors, and GM.

2. Vehicle Exterior Design and Styling
   Working with the GM Advanced Concept Center, design the exterior shape of the car. With GM design staff aerodynamicists, test and refine a 1/3-scale model (provided by ACC) in the Caltech wind tunnel.

3. Structural Design
   Design and analyze vehicle structure. Work with CPC AVE in analysis of crash loads.

4. Chassis and Suspension Design
   Working with CPC AVE, develop chassis configuration and suspension design. Design braking system elements with assistance from Delco Moraine.

5. Interior and Seating Design
   Working with ACC, design the interior layout, seats, and controls for the car.

6. Tire and Wheel Development
   Coordinate with Goodyear Tire and Rubber for fabrication and test of new high-pressure tires, and arrange for independent testing at GM Milford proving grounds. Work with Alcoa, or other supplier, to define requirements for prototype

wheels.

7. Power Electronics Development
Design, fabricate and test a single pole for the inverter. Evaluate component stresses and losses. Design, fabricate and test prototype inverter. Design, fabricate and test 12V accesory power supply. Design packaging for final power electronics installation, and fabricate three complete power electronics systems.

8. Motor Development
Working with Delco Remy and an outside motor manufacturer, develop preliminary design for the drive motor. Perform analysis to verify performance goals. Arrange for production of prototype motor, and interface with gearbox task as required. Test the prototype motor for efficiency, performance, and durability. Arrange for production of six motors after design and prototype testing is complete.

9. Gearbox Develpment
Develop specifications for gearbox. Select subcontractor and supervise and monitor design, fabrication, and test of prototype gearboxes.

10. Battery Development
Working with Delco Remy, define requirements for vehicle battery, and help develop test plan. Design new battery system sized and optimized for the demonstrator vehicle.

11. Subsystems Development
Identify the components for the major subsystems: lighting, defroster, sound system, instrumentation, etc. Define the packaging and power requirements, and make weight estimates. Perform necessary design, testing, and systems engineering work.

12. Heat Pump Development
Evaluate existing off-the-shelf residential heat pump units for applicability, and procure and test candidate unit(s). Define any modifications necessary for vehicle installation, and fabricate and test prototype system.

13. Body and Chassis Component Fabrication and Procurement
With help from ACC, construct plugs and molds for body and chassis components. Fabricate parts for two cars. Procure components and hardware for both cars.

14. Car #1: Assembly
Assemble the first car.

15. Car #1: Systems Integration
Install and test all systems into the first car. Perform necessary debugging and fault corrections. Verify correct operation of all systems.

16. Car #1: Testing
Conduct road tests of the first car at Mesa proving grounds. Test acceleration and range performance, and fine-tune handling, steering, ride, vehicle structure, noise, vibration, and harshness. Other testing may be done at Southern California locations.

17. Car #2: Assembly
Assemble the second car.

18. Car #2: Systems Integration
Install and test all systems into the second car. Perform necessary debugging and fault corrections. Verify correct operation of all systems.

19. Car #2: Testing
Conduct road tests of the second car at Mesa proving grounds. Test acceleration and range performance, and fine-tune handling, steering, ride, vehicle structure, noise, vibration, and harshness. Other testing may be done at Southern California locations.

Advanced Concepts Center

1. Perform the design for the exterior and interior of the demonstrator vehicle.

2. Facilitate contacts with suppliers of tires, glass, and other automotive components, materials, and services.

3. With Design Staff aerodynamicists, participate in the development of the aerodynamic shape.

Delco Remy Division

1. Evaluate batteries and battery concepts and materials to select the best battery

technology for the demonstrator vehicle.

2. Design, manufacture, and test the demonstrator batteries.

3. Participate in the specification of, and monitor development of the motor in anticipation of a future production role.

4. Monitor electronics development along with Delco Electronics in anticipation of possible future production role.

Advanced Engineering Staff

1. Provide consultation and support, and undertake specific assigned design tasks in the area of lightweight structures.

2. Provide advice and consultation on manufacturing methodologies appropriate to lightweight structures, including quick tooling.

3. Provide consultation and design assistance on various mechanisms and other components of the demonstrator vehicle. Examples include HVAC, instrumentation, door latches, and window actuators.

4. Provide support in complex subsystem development.

GM Research Laboratories

1. Provide consultation and design assistance in battery, motor, electronics, materials, and testing areas.

Advanced Vehicle Engineering – CPC

1. Assist in chassis development, especially in suspension design.

2. Participate in lightweight body/frame development, particularly in the analysis of crash response.

Current Product and Manufacturing Engineering Staff

1. Perform tire testing and evaluation to support development of low-rolling-resistance tires.

2. Participate in planning and carrying out vehicle test and evaluation program.

6.4 Program Schedule

Although this program does not have the fixed time constraint that the official race start date imposed on the Sunraycer effort, an aggressive 15 month schedule has been established. This serves to enhance a GM position of leadership in EV technology, and also provides further demonstration of program operations effectiveness. Figure 6.2 shows the overall program schedule. The time scale is labelled in quarter-years from start of the program. If the program begins Sept 1, 1988, the conclusion would be Dec. 1, 1989.

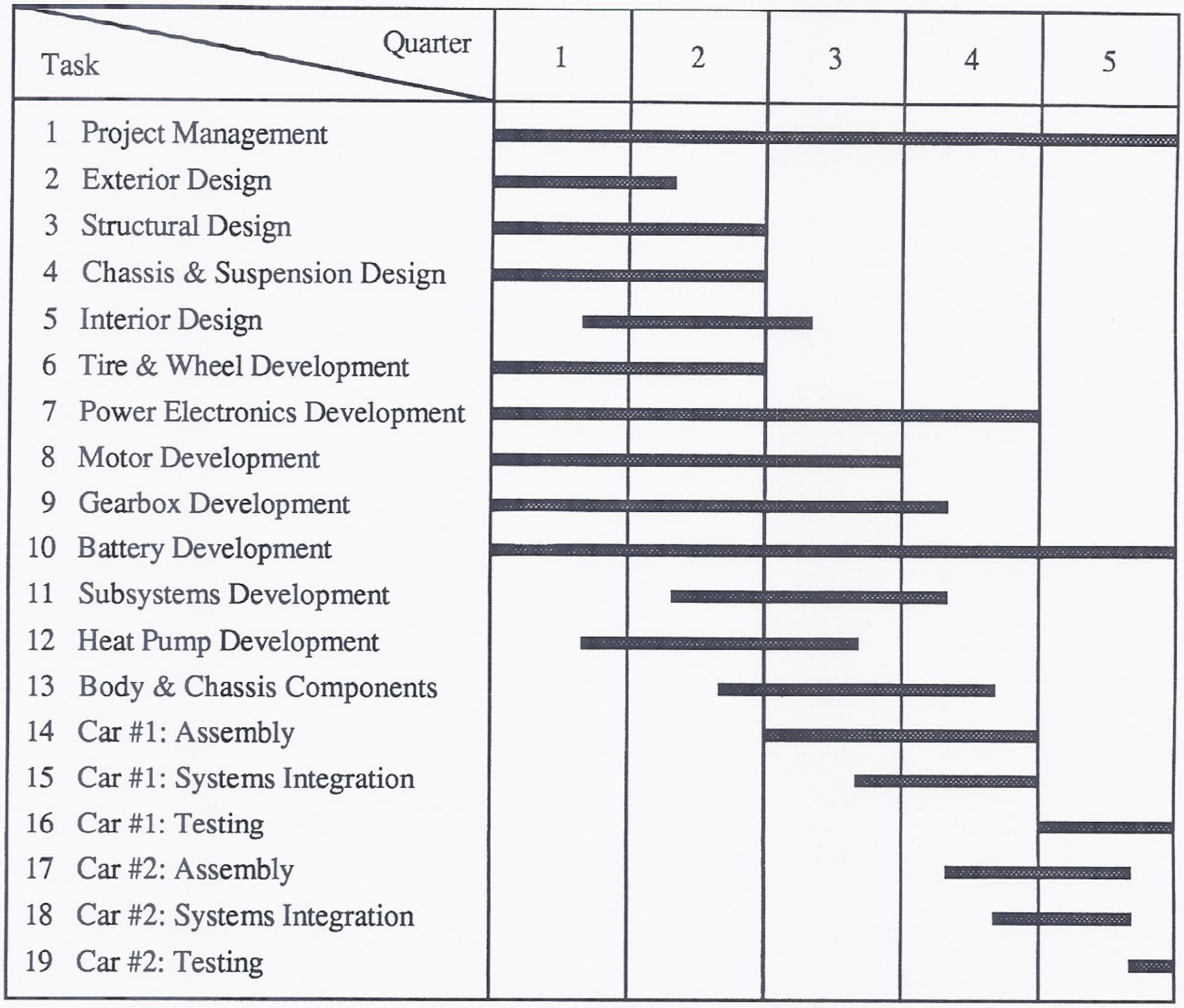


Figure 6.2 Program Schedule

6.5 Budget

The program costs have been developed on the basis that the manpower supplied by GM organizations will be absorbed by those organizations, and only major outside costs that they incur are included here. An example is the battery case mold and other tooling, costing approximately [redacted], that Delco Remy subcontracts to an outside toolmaker.

With this approach, the majority of the requested funds will go to AeroVironment for internal costs and to its subcontractors and suppliers. The estimated AeroVironment costs have been calculated using our projected FY 89 overhead and G&A rates of [redacted]% and [redacted]% respectively, and a [redacted]% fee. The approved rates from the most recent DCAA audit determination for the fiscal year ending April 30,1987 were: overhead: [redacted]%, and G&A: [redacted]%.

A summary of the budget is shown in Table 6.1. The totals are given broken down by company (AeroVironment, Hughes, Delco Remy) and by model year, assuming the project kickoff coincides with the beginning of the 1989 model year. The total AeroVironment cost of [redacted]M includes labor totalling approximately 41,700 man-hours. For comparison, the total AeroVironment labor for the Sunraycer project was about 19,700 man-hours, excluding the effort associated with participating in the race in Australia. A more detailed breakdown for the AeroVironment costs is given in Appendix 1.

TASK	AV k$		Hughes k$		Delco-Remy k$	
	Model Year		Model Year		Model Year	
	1989	1990	1989	1990	1989	1990
1 Project Management	[redacted]	[redacted]	[redacted]	[redacted]		
2 Exterior Design	[redacted]	[redacted]	[redacted]			
3 Structural Design	[redacted]	[redacted]	[redacted]			
4 Chassis & Suspension Design	[redacted]	[redacted]	[redacted]			
5 Interior Design	[redacted]	[redacted]	[redacted]			
6 Tire & Wheel Development	[redacted]	[redacted]	[redacted]			
7 Power Electronics Development	[redacted]	[redacted]	[redacted]			
8 Motor Development	[redacted]	[redacted]	[redacted]			
9 Gearbox Development	[redacted]	[redacted]	[redacted]			
10 Battery Development	[redacted]	[redacted]	[redacted]		[redacted]	
11 Subsystems Development	[redacted]	[redacted]	[redacted]			
12 Heat Pump Development	[redacted]	[redacted]	[redacted]			
13 Body & Chassis Components	[redacted]	[redacted]	[redacted]			
14 Car #1: Assembly	[redacted]	[redacted]	[redacted]			
15 Car #1: Systems Integration	[redacted]	[redacted]	[redacted]			
16 Car #1: Testing	[redacted]	[redacted]				
17 Car #2: Assembly	[redacted]	[redacted]				
18 Car #2: Systems Integration	[redacted]	[redacted]				
19 Car #2: Testing	[redacted]	[redacted]				
Sub-totals	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	

TOTAL [redacted]

Contingency [redacted]

Upper Limit [redacted]

Summary Excluding Contingency:

	1989	1990	Total
Car #1	[redacted]	[redacted]	[redacted]
Car #2	[redacted]	[redacted]	[redacted]
Total	[redacted]	[redacted]	[redacted]

Table 6.1 Cost Summary (costs in thousands of $)

Appendix 1

Detailed AeroVironment Budget