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ELECTRIC CAR DESIGN
INTERIM SUMMARY REPORT

Phase I — Deliverable Item 9
Contract No. EY-76-C-03-1294

Submitted to
U.S. ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION
SAN FRANCISCO OPERATIONS OFFICE
1333 BROADWAY
OAKLAND, CALIFORNIA 94610

Submitted by
Corporate Research and Development
General Electric Company
Schenectady, New York 12301

May 9, 1977

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ABSTRACT

The work included in this Interim Summary Report is part of the Electric Car Program undertaken by the U.S. Energy Research and Development Administration. The goal of the ERDA program is to develop by 1979 a totally new electric car with substantially improved performance over those electric cars available in 1976.

This Interim Summary Report presents the rationale used in designing a four-passenger electric car for use in an urban environment. The program reported was undertaken by the General Electric Company as prime contractor with Triad Services, Inc., as a subcontractor. The approach taken was to design an electric car utilizing current technology. On the basis of tradeoff analyses, upgrading improvements were identified which would permit the electric car to more nearly meet all of the ERDA near-term goals.

This report summarizes the electric car design, including the chassis, drive train, major components, and the control. The Phase I electric car design will meet many of the ERDA near-term goals. Upgrading development programs are identified which, when incorporated in Phase II vehicle development, will result in upgraded performance, which essentially meets ERDA's near-term goals.

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GE Electric Car

Section 1

INTRODUCTION

This interim summary report is submitted by the General Electric Company to fulfill the requirement for Deliverable Item No. 9, Interim Summary Report, on the Energy Research and Development Administration (ERDA) Contract No. EY-76-C-03-1294, Phase I. It describes the work done by the General Electric Company and its subcontractor, Triad Services, Inc., in developing the preliminary design of an electric vehicle, discusses improvements that can be made during the time frame of Public Law 94-413, and recommends specific upgrading developments in a two-year program to deliver two Integrated Electric Test Vehicles which meet ERDA's near-term goals. Related reports on this contract are listed in Appendix A.

BACKGROUND

The battery powered electric car, as it exists today and as it can be projected over the next decade, must be viewed as serving only selected portions of the nation's transportation needs. Because of its limited range and battery deep discharge cycle limitations, the electric car cannot be regarded as an equivalent or replacement for the internal combustion engine automobile.

However, as the desire to reduce this country's dependence on petroleum fuels intensifies, the electric car can emerge as an optional mode of travel for those who can make effective use of the electric car's capabilities. Using currently available technology, the electric car can provide a significant fraction of the city bound driving and commuting. Performance levels and mobility features can be developed to a suitable level to provide safe co-existence with current traffic conditions.

In the near future the electric car is viewed, then, not as a replacement for the contemporary passenger car, but as a second or third car, to be utilized for local driving and commuting.

Electric vehicles played a significant role in the development of the automobile in the early part of the 20th century. Baker and other manufacturers captured a respectable portion of the vehicle market at that time. As roads improved and people demanded increased mobility, the electric vehicle faded into history, only to be recently revived by interest in the environment and the need to overcome the high cost of petroleum fuel.

The conventional automobile has continued its development over those 60 years of the electric vehicle's absence from the scene. "Evolutionary" would describe the advances made in automobiles during the past half-century. Although the electric car can share some of the developments in automotive technology with its gasoline-powered cousin, many of the electric car systems must be engineered anew.

In late 1975, General Electric (GE) made the decision to develop a new integrated electric car and retained Triad Services, Inc., to undertake the design, fabrication, assembly, and vehicle development tests. General Electric used this development program as the basis of an alternate proposal in response to a request by the U.S. Energy Research and Development Administration (ERDA) for proposals in early 1976 for an Electric Vehicle Preliminary Design.

The electric car being designed in early 1976, initially known as the GE Baseline Vehicle, had many of the near-term features desired by ERDA. ERDA chose General Electric's proposal for an alternate to the compliant response, which would result in an electric car based on the GE Baseline Vehicle to be delivered to ERDA in late 1977. Phase I of the contract was to complete the design and tooling of the vehicle. As part of the contract, General Electric agreed to perform additional design tradeoffs and to identify development programs that would upgrade the vehicle to more fully meet the ERDA goals.

ERDA/GE ELECTRIC CAR PROGRAM

The electric car concept now under development was chosen to demonstrate the latest state-of-the-art of electric vehicle technology, to establish a baseline against which to measure the performance of alternate vehicles, and to measure improvements made through further developments.

The General Electric studies show that the performance of the electric car is quite dependent on:

- Total weight of the car
- Weight of the battery
- Drag and rolling resistance of the car
- Energy and power density of the battery
- Amount of braking energy recovered
- Peak power demands on the battery
- Efficiency of the drive train
- Ambient temperature
- Grade

The design and upgrading activities considered were done in the following sequence:

- The initial conceptual design (identified by General Electric as the Baseline Design) used commercially available drive components, namely a DC series motor, an SCR armature chopper, and golf cart lead-acid batteries.

- Detailed tradeoff studies were made using the initial conceptual design to definitize such aspects as size of battery, aerodynamics, vehicle weight, load leveling of the battery, recovery of braking energy, variable transmission and improved components. These studies considered the interrelationship of those dependent factors listed previously as they affected performance and cost.
- The preliminary design was made by modifying the conceptual design to give improved performance and to provide a drive system more amenable to upgrading in the future. The major changes were to modify the DC series motor to a separately excited configuration, to modify the armature chopper controls for armature speed control up to the base speed of the motor, and to add a field chopper for field control of speed by field forcing below the motor base speed and field weakening above the base speed. Minor changes to the vehicle and other components were made after review of the conceptual design and tradeoff studies. This became the basis of the detailed preliminary design performed during the remainder of the program. The preliminary design is identified as the Reference Electric Car and would employ the best technology commercially available in 1977.
- Additional tradeoff studies were undertaken which evaluated improvements that could be made with additional developments over the time frame of Public Law 94-413. The studies considered performance gains, cost improvements, and the time frame of availability for components and subsystems. Improvements were identified by screening a number of alternatives in two time frames that seemed meaningful, namely, a five-year period and a two-year period.

In the five-year time period, the system with the lightest weight, lowest cost, and highest performance would utilize the electronically commutated permanent magnet DC motor with regenerative transistorized power module electronics for common propulsion control and battery charging. It would use the advanced lead-acid battery from the ERDA battery program and microprocessor control for optimum vehicle system and power subsystem controls. This system would significantly reduce weight by using lighter weight, high strength vehicle materials, lighter weight components, and by eliminating the onboard battery charger.

In the two-year time frame, the preferred drive system was identified that would use an improved separately excited DC motor with regenerative transistorized power module electronics for common propulsion and battery charging. It would use the improved state-of-the-art (ISOA) battery from the ERDA battery program, microprocessor control for optimum vehicle system and power subsystem controls, and a lesser amount of weight reduction of the vehicle by using lighter weight, high strength materials, reduced component weight, and by eliminating the onboard battery charger.

Although flywheel systems showed range improvements for stop-and-go driving, their inclusion was not recommended, and emphasis was placed on improving an all-electric system utilizing regenerative braking.

- A five-year development plan was prepared which described the objective and scope of the work to be done, identified and described the work tasks, scheduled the major milestones, and estimated the level of effort for the more significant upgrading program as well as for development to the prototype production stage of the vehicles themselves.
- The two-year program was recommended for further evaluation. More detailed tradeoffs and analyses were made for the preferred two-year plan in which vehicle performance and cost improvements were compared with the 1977 Reference Vehicle Design and with the ERDA near-term goals. These results were included in the final tradeoff reports and final design review with ERDA. This system was recommended as the basis for the detailed cost proposal and program planning for a Phase II follow-on contract to develop an upgraded Integrated Test Vehicle for ERDA.

PROGRAM STATUS

The Reference Electric Car has been completely designed and initial tooling for limited fabrication has been developed. Upgrading programs have been identified and those recommended for inclusion in a 24-month program are:

- Regenerative braking
- Common power control unit/battery charger electronics
- Transistorized power module electronics
- Higher speed, wider field control speed range, higher efficiency DC separately excited motor
- Microprocessor controls
- Improved state-of-the-art battery
- Vehicle structural, safety, and weight improvements

This Interim Summary Report includes the following sections:

- Electric Car Design
- Tradeoff Results
- Tradeoff Discussions
- Recommended Upgrading Programs

- Development Plan
- Cost Data
- Conclusions and Recommendations
- Appendices

Section 2

ELECTRIC CAR DESIGN

INTRODUCTION

This section summarizes the preliminary design of the Reference Electric Vehicle. The analyses and tradeoffs that led to this specific design are discussed in Section 3, "Tradeoff Results" and Section 4, "Tradeoff Discussions." Improvements and developments which will be included in the two-year program for the upgraded Integrated Test Vehicles are discussed in Section 5, "Recommended Upgrading Programs" and Section 6, "Development Plan."

DESIGN DESCRIPTION

The electric car design was accomplished in several steps involving conceptual design, preliminary design, and finally preparation of detail drawings suitable for manufacture of a car. The following factors were considered in the conceptual design stages:

- Mobility
- Adaptability
- Utilitarian value
- Passenger comfort
- Serviceability
- Safety

An iterative process was used in balancing and compromising the hundreds of alternatives which were available in arriving at car dimensions and external shape.

The conceptual design car is shown in Figure 1. During the preliminary design, the dimensions, shape, and design details were refined and modified.

The preliminary design car is shown in Figure 2. The most apparent change is in the front end styling where the bumper and parking light arrangement was modified to meet safety standards. The side daylight openings were lowered to improve the appearance. The wheel wells were modified for appearance and to accommodate larger tires. The external shape was modified somewhat to accommodate these changes. A comparison of the dimensions for the conceptual design and the preliminary design is shown in Table 1.

In addition to the dimensional changes, some structural changes were made. The A-pillar was stiffened to improve the appearance. The B-pillar location was modified to improve occupant restraint. The front suspension was changed from the McPherson strut type to the short-long arm independent type for improved turning clearance. The new suspension features anti-dive/lift geometry and minimum kingpin offset.

Figure 1. Conceptual Design Electric Car

Table 1

SUMMARY OF CAR DIMENSIONS, WEIGHTS, AND CAPACITY

Parameter	Conceptual Design	Preliminary Design
Wheelbase	92 in.	92 in.
Overall Width	64 in.	66.1 in.
Overall Length	157 in.	160 in.
Track - Front	54 in.	54.5 in.
Track - Rear	55 in.	58.0 in.
Overall Height	56 in.	53.6 in.
Ground Clearance	6 in.	6 in.
Curb Weight	2942 lb	2942 lb
Gross Vehicle Weight	3692 lb	3692 lb
Weight Distribution	56% front (2 pass.)	56% front (2 pass.)
Cargo Volume	45 ft ³	45 ft ³
Frontal Area	19 ft ²	19 ft ²
Estimated Drag Coefficient	0.269*	0.294†

*Wind tunnel data adjusted for yaw

†Adjusted for "on-road" conditions

Figure 2. Preliminary Design Electric Car

During the conceptual design drive train selection, General Electric analyzed five combinations: (1) DC series motor/DC chopper, (2) DC shunt motor/switched batteries/switched resistors field control, (3) DC shunt motor/shifting transmission/field control, and (4) secondary energy storage of braking energy. The conceptual design system finally chosen was the DC series motor/DC chopper utilizing commercially available components. In the preliminary design, the motor and drive were reevaluated, and on the basis of control characteristics in the motoring and generating modes, the separately excited DC machine (5) was selected utilizing modified commercially available components.

Signal level electronic controls make it possible to maximize the utility of an electrically powered vehicle by measuring, processing and controlling a relatively large number of variables. The functions in an electric vehicle may be implemented by digital and analog control integrated circuitry or by a purely digital approach employing a microprocessor system. The electric car designed uses commercially available components to the greatest extent possible. Since most of these commercially available components have control circuits already developed as part of the equipment, only a minimal amount of hardware has to be developed to interface with the equipment. If a microprocessor

control were developed to perform this function, it would be underutilized. The approach recommended was to use the control circuits already developed and to implement the necessary vehicle interfaces by using off-the-shelf digital and analog integrated circuits.

The design project was divided into the following major phases:

- General arrangement
- Body structure
- Chassis components
- Drive system
- Hardware and accessories
- Tooling

Layout and detail drawings for fabrication of components are listed in Appendix B.

GENERAL ARRANGEMENT

Figure 3 shows the general arrangement of the major components in the vehicle. Some of the features of the arrangement begin with the position of

Figure 3. Side View -- General Arrangement

the driver. Note that the front wheelhouse does not intrude at all into the passenger compartment; the result is easier entry and egress and a more comfortable seating position. This feature is not generally found in small vehicles. Headroom is a very generous 40 in., allowing adequate clearance for the 6 ft-2 in. males shown. Rear seat passengers sit in two rearward-facing fold-down jump seats, which are accessible through the rear of the vehicle. These seats fold down when not in use, offering a flat, shopping-cart level loading platform for easy loadability. The cargo volume available is large, approaching that found in contemporary compact wagons. The forward location of the drive components was selected, as opposed to rear drive. Figure 4 is an artist's concept of the preliminary design electric car with the major components indicated.

Figure 4. Locations of Main Components

BODY AND STRUCTURE

An early step in body and structural engineering was to determine the body panel breakup, inner reinforcement location and fabrication technique. This process resulted in the generation of a set of drawings called "Typical Section Sheets." These sheets represent the basic construction of most of

the vehicle body structure. At this stage, consideration was given to the manufacturing technique to be employed (welding, bonding, forming, etc.) as well as the structural requirements of each section. Weather sealing, flanging, water runoff, and trim requirements were also explored.

Following the development of the typical section information, body cut lines were established by checking clearance for all movable panels. Latching and hinging mechanisms were located and integrated in the design. Standard parts were selected where possible. Utilizing the general arrangement drawing and the typical section sheets, full-size body layouts were made with sufficient detail to allow fabrication. Interior panel surface development, as well as bracketry for mounting suspension, drive, and body hardware components, was included in the workout.

The primary structural element in the body substructure is the battery-enclosing tunnel, which accommodates a battery tray holding 18 golf cart type batteries (Figure 5). This member provides the primary bending and torsional stiffness of the vehicle. The loads are distributed to the tunnel through two main cross-car members, one at the toe board, and one aft of the driver's seat. Lateral

Figure 5. Battery Pack Service

impact protection is afforded by a door beam overlapping both bulkheads. The lower underbody, along with its bulkheads, provides a rigid, driveable chassis containing all power elements. The upper body structure, specifically the roof and A-pillar, is relieved of much of its structural responsibility, a feature which provides a great level of latitude in the selection of body style and construction. Front end structural rails project from the forward cross-car member through a torque box at the toe board. Bumper loads in front are taken through these rails, while the tunnel is directly loaded at the rear. The underbody is a fully welded assembly fabricated primarily from 0.029 in. thick stainless steel with local, thicker reinforcements where required.

The front end of the vehicle consists of integrally welded front outer fender panels with firm tie at the hinge pillar and to the front fender inner. The hood is front hinged and double latched at the cowl to comply with Federal Motor Vehicle Safety Standard (FMVSS) 219 "Windshield Zone Intrusion." The hood outer and inner panels are fabricated from fiberglass reinforced plastic.

The passenger doors (Figure 6) swing forward on a pair of links in parallelogram fashion. Primary hinging is attached to the integral door reinforcement beam. This beam is adequate to meet FMVSS 214 "Side Door Strength." These doors have two latches: one at the front for anti-rattle, and one at the rear for positive latching. Both latches are standard hardware. The rear hatch lifts upward via twin gas struts concealed in the C-pillar. Hinging is at the roof rail. Upper inner panels are steel, while lower inner panels are fiberglass reinforced plastic.

Figure 6. Door Arrangement

Side door sealing is door mounted. Seals are located at the door cut line which results in a clean shut face and a minimum of wind-generated noise.

Rear hatch seals are surrounded by a large water runoff channel to reduce the static head on them.

The driver and passenger seats are fabricated from fiberglass reinforced plastic. The seat adjusting mechanism allows fore-aft adjustment of 8 in., and a back angle adjustment of 10 degrees. Integral head restraints meet FMVSS 207 requirements. The rear occupant seats are in two sections: the lower section is integral with the underbody, while the upper back section may be "plugged" into the underbody. These backs are made from fiberglass reinforced plastic with steel tubing.

Bumpers are mounted to the vehicle via hydraulic energy absorber cylinders. The stroke of these units is approximately 2 in. Bumpers are aluminum with integral rub strip, and bumperettes are standard equipment. The system has been designed to pass FMVSS 215, "Exterior Protection."

Front seat passengers are passively restrained via a torso belt and an integral knee restraint. The torso belt consists of a door pillar mounted latch with an inertial retractor attached to the tunnel. Upon closing the door, the torso belt is automatically draped over the occupant. Submarining is controlled by an integral knee restraint fabricated from steel. The system was aimed at complying with FMVSS 208, "Occupant Crash Protection." Rear seat occupants have lap belt protection.

All body lamps are 12 V production automotive components positioned so as to comply with FMVSS 108, "Lighting." Front headlights are of the rectangular type and are covered for daylight operation. Covers are manually operated through a driver's compartment lever.

The front compartment doors feature sliding windows. The forward section of the glass slides rearward, resulting in a large body opening for ventilation. The glass is tempered and 0.156 in. thick. The rear quarter and backlight glass is fixed and bonded flush with the exterior body panels. The material is 0.156 in. thick tempered glass. A laminated windshield with an integral radio antenna and a shade band is bonded into the front opening. The overall thickness of the glass is 0.210 in. All glass conforms to FMVSS 205, "Glazing Materials."

The motor and drive are resiliently mounted to the front underbody structure. Two rubber bushings are placed under the center of gravity of the package, while torque reactions are handled through a link terminating at the front cross-body member.

CHASSIS COMPONENTS

Suspension and steering design efforts began with the establishment of the ride and handling targets. These targets were expressed in terms of

suspension instant center locations. A suspension geometry was developed which attempted to simultaneously achieve the desired goals while blending with the basic structural and packaging concept. Suspension parameters, such as roll camber, roll steer, deflection steer, and deflection camber coefficients were checked utilizing computer models of the suspension geometry and stiffness. Vehicle handling character was also predicted through the use of a rolling, linear computer simulation. Brake dynamic and thermodynamic characteristics were also checked through the use of computer simulations. Brake fade properties were compared to the requirements of FMVSS 105-75.

Suspension geometry layouts were utilized to finalize the location of all suspension and steering components. Hardware layouts were developed to permit fabrication. Stress analyses of suspension and brake components were conducted to ensure adequate durability of the components.

SUSPENSION SYSTEM

The suspension system chosen for the front wheels is of the short-long arm independent type. It features anti-dive/lift geometry and minimum kingpin offset in an effort to minimize steering moments caused by biased braking and drive torques. The steering linkage is positioned to provide good Ackerman characteristics as well as lateral force deflection understeer. Coil springs are mounted on the upper control arm.

The rear suspension system posed some unique problems: the location of the batteries eliminated the possibility of a cross-car suspension member at the rear wheel centerline. These packaging and structural considerations, along with the desire to minimize the rear wheelhouse intrusion into the cargo area, led to the decision to utilize a fully independent suspension at each rear wheel, as opposed to a solid axle. The particular suspension selected combines these packaging features without compromising vehicle ride and handling properties associated with side view swing center location and deflection steer characteristics.

The base wheels and tires are AR78-13 tires mounted on 4.5 in. rims. Optional tires can increase in size to CR-70-13 for tire testing and evaluation.

BRAKES

Because of the lack of auxiliary power for assisted application, a brake employing some mechanical servo action is desirable. Additionally, a brake system that has little or no drag in the released position will improve the range. The duo-servo drum brake which was selected incorporates these features, as well as some additional advantages in the reduction of fluid displacement requirements during actuation, as compared with the contemporary disk brake.

Inboard brakes are utilized for the front wheels as a further refinement. An advantage of this scheme is the constant turning moment about the kingpin axis as the vehicle deceleration torque is shared between regenerative and friction brake torques; with inboard brakes, both torques are transmitted through the drive axles. Positioning the front brakes inboard has the additional feature of reducing the front unsprung weight, an important factor in ride harshness reduction. The front brakes are 9.5 in. dia., duo-servo drum brakes. Steel backing plates bolt to the aluminum drive housing. The drum mounting is through the axle companion flange. The drum material is chromium copper in order to take advantage of its superior heat dissipation characteristics within the confined space available.

The rear brakes are outboard mounted 7 in. dia., leading-trailing drum brakes. The rear drums are cast iron and are integral with the hub. The parking brake is pedal actuated through cables. The front brakes are used for parking. The service brakes are actuated through a tandem master cylinder located at floor level. There is no proportioning valve in the system.

STEERING SYSTEM

During the design, rack and pinion steering was replaced for packaging and serviceability reasons with a recirculating ball type steering gear mounted on the front rail. Linkage to the wheels is through the idler arm, relay rod, and tie rods. The overall ratio is 23:1. Steering control is through two universal joints with collapsing intermediate shaft. The steering column is not energy absorbing since it does not become involved in the crash event. Some energy absorption is built into the steering wheel. The steering control system will pass FMVSS 204, "Steering Control Rearward Displacement." It does not have to pass FMVSS 203, "Impact Protection for the Driver From the Steering Control System," since the restraint system is passively applied.

FRONT WHEEL DRIVE

A front drive line was selected over a rear drive arrangement for the following reasons:

- Rear area clear for loading
- More efficient utilization of floor space
- Vehicle handling and performance
- Improved serviceability of drive components
- Favorable weight distribution

Servicing of all drive components is easily accomplished through the large hood (Figure 7). The complete drive can be removed without removal of any structural element or crossmember.

The basic drive consists of a longitudinally positioned drive motor connected to a spiral bevel final drive gear through transfer cases containing Hy-Vo chains. Torque is transmitted through constant velocity universal joints to the front wheels. The design of the drive housing is unique since it will allow the adjustment of chain center distance

Figure 7. Drive Serviceability

to permit changes in the overall gear ratio. This feature will be important during drive development. The drive housing is an aluminum casting carrying the final drive gearset and differential, the chain drive, and the motor. Provisions have been made for electronic speedometer pickup. Design features include common sump oiling for both the chain and gearset. This casting was designed specifically for this application.

Final drive shafts are double-jointed, with a Rzeppa joint outboard, and a constant velocity joint inboard. The nominal axle shaft operating angle is 0°. Final drive gearing is through a 7 in. dia. spiral bevel gearset having a ratio of 4.125:1. A conventional cross gear differential is employed. These components are available automotive parts. Primary reduction is through a Morse Hy-Vo chain 2.0 in. wide. The torque capability of this drive is 300 lb-ft input. Sprockets are made from alloy steel and are custom fabrications.

HARDWARE AND ACCESSORIES

Body hardware and accessory design relied heavily on existing components where their utilization would not adversely effect the performance of the vehicle. For example, items like door latches, windshield wiper motor, seat adjusting mechanisms, etc., were not specifically designed for this program. The best available hardware was utilized where possible.

Heating is accomplished via a gasoline burning heater mounted on the right-hand front inner fender panel. A system of logic doors and a blower provide warm air delivery for passenger compartment heating, defrosting, and defogging, complying with FMVSS 103, "Windshield Defrosting and Defogging." The heater unit may be bypassed for delivery of fresh, cool air which enters the ventilation system through an integral duct in the hood reinforcement.

TOOLING

The purpose of the tooling program was to develop tooling suitable for the fabrication of the steel exterior body panels. The program scope was confined to the exterior surfaces. Following the external aerodynamic development, the resulting scale (0.393:1) clay model (see Figure 8) was scanned at the Chrysler Design Center. This scan was digitized and, with the aid of a computer controlled drafting machine, drawn full size. Utilizing the body scan from the scale model, a body surface layout was developed. This large drawing consists of developed sections taken through the body at grid stations nominally 5 in. apart. These sections are cross-checked in all three views to make sure that the body surface flows continuously from section to section without waves or discontinuities. This involves some "smoothing" from the scan data.

Based on the full-size body surface drawings, a full-size clay model was constructed on a surface plate. The model was positioned at curb height in order to get a good feel for the overall appearance. The clay model was built over a wooden armature (Figure 9), which was made approximately 2 in. smaller than the actual outside surface of the vehicle. Templates were made of the sections on the surface drawings. Clay was added to the buck until the section templates were matched (Figure 10). Surface between the sections was established by splining, a technique of body surface development. The model was then covered with painted "Dynoc" in order to provide a more accurate representation of the exterior appearance (Figure 11). All body cut lines (doors, hood, etc.) were delineated on the surface of the model. Day-light openings and glass edge lines were also scribed on the model surface.

Fiberglass reinforced epoxy molds were made of the exterior surface of the clay model. These molds were constructed in seven sections to facilitate

Figure 8. Scale Clay Model

Figure 9. Wooden Armature

Figure 10. Model Buildup

Figure 11. Painted Clay and Wood Model

removal and handling (Figure 12). These molds were reinforced with plywood and bolted together through flanges. The molds are to be retained as the master body contour and will be used later in the assembly stage. Each panel was fenced off with wax and wood to represent flanges and depressions surrounding the part. Window mounting depressions were added for the windshield, quarter windows, backlight and sunroof. After fencing, a tool development plaster cast was made of each panel. These male models were made utilizing expansion plaster to match the shrink in the final zinc alloy punch (Figure 13).

Figure 12. Exterior Surface Mold

A tooling plaster was pulled from each expansion plaster after providing an adequate runoff surface with foam and wood (Figure 14). The 1:1 sized tooling plaster was utilized as the mold to cast the final zinc alloy tools (Figure 15). The tooling plasters were used as patterns for the green sand cast zinc alloy punches. These punches have machined bases to facilitate mounting in the press. Parts will be made using these punches against urethane blocks to form the majority of the part. Flanging and trimming will be done by hand. Full-size (1:1) plasters with hemp reinforcement were made of all glass surfaces. These plasters will be utilized by the glass fabricator to make edge molds from which prototype glass parts will be made.

Figure 13. Tool Development Plaster Cast

Figure 14. Tooling Plaster

Figure 15. Zinc Alloy Tool

DRIVE PROPULSION SYSTEM

The drive propulsion system uses a DC separately excited motor and is controlled by a thyristor chopper in the armature circuit and a high frequency transistor chopper in the field circuit. The power converter circuit is shown in Figure 16. The thyristor chopper uses the Jones commutation technique for pulse-width modulated voltage control which also incorporates a bypass contactor (1A) to impress the battery voltage directly across the armature when the chopper voltage approaches the supply voltage V_B . The motor speed is reversed by a reversing field contactor.

Figure 17 shows the block diagram of the control system. It is a torque controlled system where armature and field currents, which are related to developed torque, are controlled in a closed loop manner by the driver actuated command pot. The armature current (I_a) and field current (I_f) are controlled in such a manner that the following operating modes are obtained:

- (A) Mode I. This is an equivalent series motor operation and holds true in the initial high acceleration mode. The armature current command (I_a^*) and field current command (I_f^*) signals are independent but are tracked together to get maximum developed torque of the drive system. In this mode, the switch S_1 remains closed and the switches S_2 and S_3 remain closed at position 1.

Figure 16. Power Converter for Separately Excited DC Motor

(B) Mode II. This is a shunt motor operation mode and can be considered as a special case of Mode I. This mode of operation holds true at lower torque commands and at below base speed of the motor. The field current is maintained at the rated value and the armature current is controlled by the chopper to regulate the developed torque.

(C) Mode III. This is a field weakening mode of the motor and holds true at higher than base speed. In this mode, the switch S_1 is open, but S_2 and S_3 remain closed in position 2. The armature chopper is bypassed and the armature current is regulated by controlling the field current.

The transition from Mode I to Mode II is controlled by the magnitude of torque command as well as armature and field temperature overriding controls as shown in Figure 17. The circuit details are given in Figures 18a and 18b. The temperature overriding controls become effective only in the high acceleration mode when more than rated armature and field currents are demanded. Armature temperature is approximated using an RC circuit impressed with the armature current signal, whereas the field temperature signal is obtained directly from a thermistor sensor. As high I_a is demanded, armature temperature T_a rises, and when it crosses the rated value T_{aR} , the I_a^* command

Figure 17. Control Circuit Block Diagram

is brought down to the rated value by the overriding control. The field temperature overriding control is similar in nature, except that if less than rated field current is demanded, I_f remains clamped at the rated torque as demanded in the urban driving cycle and permits smooth torque during mode transition.

Figure 19 shows the steady state performance curves of the drive system related to the vehicle speed. As previously explained, in Mode II armature current is controlled by the chopper to control the vehicle speed, whereas in Mode III, armature current is controlled by the regulation of field current. The developed torque (proportional to the product of air gap flux and armature current) increases with speed to match the load torque. At the end of Mode II, as the armature chopper reaches saturation (95% on), the bypass contact closes and the control is transferred to Mode III.

Figures 18a and 18b show the detailed schematic of the signal level control circuits. The circuit has been designed such that the mode transitions occur smoothly without any jerk of the vehicle or any possible maloperation in the system. For less power consumption and higher noise immunity, 12 V CMOS logic has been used. Also multiple operational amplifier integrated circuits are used to keep a low hardware count for the system. The total control hardware is accommodated in two cards and their layouts are shown in each diagram. Figure 20 is a photograph of the breadboard control cards.

Figure 19. Steady State Characteristics

The essential operating modes of the control system have been previously explained. There are, in addition, some logic and timing circuits which provide various logical and interlocking operations during the mode transitions. The operation sequence and performance in the Mode II to Mode III transition are summarized below:

1. As the output voltage of the chopper reaches the saturation value (0.95) and persists for a given time interval, closing of the bypass contactor is requested.
2. This event opens the I_a control switch S_{11} and closes S_{12} to introduce bias voltage such that the chopper is locked to the saturation value (0.95). The switch S_{21} is opened and S_{22} is closed to transfer to I_f control within the armature control loop.

Figure 20. Breadboard Control Cards

3. Now the armature current is controlled by the field current I_f and as the field current goes below the rated value, the 1A contactor is closed.
4. This causes an inrush of I_a , and I_f increases to control it. However, this tends to open 1A (explained below), which is locked closed for a fixed time until I_a returns to the normal value. This completes the mode transition.

The transition from Mode III to Mode II will follow if I_a^* is stepped down to a low value, or if the vehicle meets an upward slope. The operation sequence in the former case can be explained as follows:

1. As I_a^* is reduced, the large positive loop error tends to increase I_f , which eventually goes above the rated value.
2. This increases field temperature and I_f is brought down to the rated value by the field temperature overriding control.
3. This results in high I_a , and the contactor 1A is tripped open. 1A is tripped open whenever I_a cannot follow the commanded value I_a^* .
4. When 1A opens, the I_f command is locked to zero and the I_a control switch is locked open for a fixed time. I_f decays to zero in this interval which permits the commutation capacitor to charge up before the chopper is enabled.
5. I_a and I_f control switches are enabled after the time delay, permitting satisfactory chopper operation. This ends the mode transition.

DRIVE SYSTEM SIMULATION

Once the control circuit had been developed, analyzed, and designed in detail, the whole system including the motor and the power conditioner was simulated on the General Electric EAI 681 hybrid computer. For the sake of simplicity, the battery was simulated as a fixed voltage source with fixed internal resistance. The chopper was simulated as a programmed on-off switch with bypass contactor and free-wheeling diode, but the commutation circuit was disregarded. The dynamic model of the motor with the coupled vehicle load was simulated in detail taking into consideration the field and armature inductance nonlinearities.

The control and logic circuit of the system, including the compensators and timers, were simulated with one-to-one correspondence.

The drive system performance in static and dynamic conditions under all the modes and the mode transitions was tested on the hybrid computer, and the system operation agreed well with the predicted performance. Figure 21 shows the steady state performance of the drive system under the chopping condition. Since the field current remains constant, the ripple in torque follows the armature current ripple. Figure 22 shows waveforms for the chopping mode at a fixed vehicle speed. Figure 23 shows waveforms for transition from the chopping (Mode II) to field control mode (Mode III) and also the transient response in Mode III. It is evident that the loop is slightly underdamped in both the Mode II and Mode III operation.

Figure 21. Steady State Chopping Mode -- 300 Hz

Figure 22. Transient Response -- Chopping Mode

Figure 23. Transient Response -- Field Control

Table 2
MAJOR ELECTRICAL COMPONENTS
REFERENCE DESIGN

Component	Description	Rating
DC Motor	GE Model BT2364 EV motor with shunt wound field	25 hp at 3500 rpm and weak field (1 hour rating)
Batteries	Eighteen EV-106 lead-acid batteries	75 A for 106 min. 10.8 Wh/# @ 1 hour rate
Armature Chopper	GE Model EV-1C SCR chopper	750 A - motor stall current (50% voltage output) 850 A commutating ability
Onboard Battery Charger	GE developmental ambient temperature compensated constant voltage charger with current limit	120 V, input current limited to 15 A maxi- mum, 14-18 hour charge time
Offboard Battery Charger	GE developmental ambient temperature compensated constant voltage charger with current limit	220 V input, 6-8 hour charge time
Accessory Power Supply	GE developmental 108 V to 12 V transistor converter	20 A at 12 V
Field Chopper	GE developmental transistor chopper	30 A maximum rating

MAJOR ELECTRICAL COMPONENTS

Table 2 lists the major electrical components for the Reference Electric Vehicle. Except for the field chopper, the drive power components are all commercially available proven designs. The transistor field chopper, battery chargers, and 12 V power supply are General Electric developmental units designed for electric vehicle application. The major components are discussed below. The transistor field chopper is discussed in Appendix C.

MOTOR

The electric vehicle drive motor for the reference vehicle is a General Electric Model BT2364 DC separately excited motor. The one-hour rating of this open, fan-cooled motor at weak field, 3500 rpm, is 25 hp. This machine weighs 230 lbs. A brochure depicting the motor is included in the Appendix.

BATTERIES

Eighteen EV-106 lead-acid batteries were selected as the 108 V power source for the Reference Electric Vehicle. These batteries are manufactured by ESB, Inc., and are commercially available. They weigh 1182 lb and have an energy density of 10.8 Whr/# at the 1-hour rate.

ARMATURE CHOPPER

The armature chopper for the reference vehicle is a commercially available GE thyristor chopper model EV-1C. This chopper is rated to supply a motor stall current of 750 A (motor current with chopper 50% on time) and is rated to commutate 850 A at 30% on time. Figure 24 shows a typical EV-1 chopper panel. A brochure on the EV-1 SCR control is included in the Appendix.

Figure 24. Typical EV-1 Chopper Panel

BATTERY CHARGERS

Two battery chargers were designed for the reference vehicle: an onboard charger and a heavier full rated offboard charger. Both chargers operate as current limited constant voltage chargers. The charger circuit employs a ferroresonant transformer to obtain electrical isolation (for safety) and a high power factor (to minimize line current). The output voltage of the ferroresonant transformer is controlled using the feedback control technique proposed by Kakalec.* The constant voltage at which the batteries are charged is ambient temperature compensated. Figure 25 shows the charging current and battery voltage vs. time for the offboard charger, and it is seen that a fully discharged battery is charged in 6 to 8 hours. The onboard charger results in a charging time of 14 to 18 hours.

Figure 25. Laboratory Charging Data

Table 3 gives efficiency and power factor data for the offboard charger. It is noted that the efficiency and power factor are high, facts which serve to minimize current drawn from the AC source.

*R. J. Kakalec, "A Feedback-Controlled Ferroresonant Voltage Regulator," IEEE Transactions on Magnetics, Vol. MAG-6, No. 1, March 1970.

Table 3
OFFBOARD BATTERY CHARGER TEST DATA

I_{DC} (amps)	Efficiency (%)	Power Factor	I_{AC} (amps from 240 volts)
2	35	0.43	1
4	79	0.95	3.3
6	89	0.91	4.6
8	89	0.90	6.2
10	93	0.86	7.7
12	94	0.87	9.0
14	95	0.85	10.6
16	94	0.86	12.2
18	94	0.84	13.8
20	93	0.85	15.2

ACCESSORY POWER

A developmental DC-DC converter steps the voltage from the main traction battery down to "float" a separate 12 V accessory battery. The accessory battery supplies sufficient energy to run critical loads (e.g., headlights) if the DC-DC converter fails.

FIELD CHOPPER

Field current for the separately excited DC drive motor must be controlled over a range of 5 to 30 A and must be supplied by the 108 V main battery. To accomplish this function, a prototype transistorized DC-DC converter has been developed. The design and operation of the chopper is described in detail in Appendix C.

SUMMARY OF ELECTRIC CAR DETAILS

Details of the GE 1977 electric car are summarized in the following tables. Table 4 presents the four-person car dimensions and weights. Table 5 presents the car interior dimensions. Table 6 defines the estimated component weights.

Table 4

SUMMARY OF CAR DIMENSIONS, WEIGHTS, AND CAPACITY

Parameter	Conceptual Design	Preliminary Design
Wheelbase	92 in.	92 in.
Overall Width	64 in.	66.1 in.
Overall Length	157 in.	160 in.
Track -- Front	54 in.	54.5 in.
Track -- Rear	55 in.	58.0 in.
Overall Height	56 in.	53.6 in.
Ground Clearance	6 in.	6 in.
Curb Weight	2942 lb	2942 lb
Gross Vehicle Weight	3692 lb	3692 lb
Weight Distribution	56% front (2 pass)	56% front (2 pass.)
Cargo Volume	45 ft ³	45 ft ³
Frontal Area	19 ft ²	19 ft ²
Estimated Drag Coefficient	0.269*	0.294†

*Wind tunnel data adjusted for yaw

† Adjusted for "on-road" conditions

Note: Table 4 is identical to Table 1 and is repeated here for the reader's convenience.

Table 5

ELECTRIC CAR INTERIOR DIMENSIONS

Parameters	Measurements
Shoulder Room -- Front (W3)	54.2 in.
Hip Room -- Front (W5)	53.2 in.
Steering Wheel to Center Line of Car (W7)	15.0 in.
Lateral Head Clearance -- Front (W19)	4.72 in.
H Point to Bottom Daylight Opening (DLO), (H6)	16.9 in.
Effective Head Room -- Front (H61)	38.3 in.
H Point to Heel Hard (H73)	14.7 in.
Back Angle -- Front (L40)	25°
Hip Angle -- Front (L42)	102°
Knee Angle -- Front (L44)	125°
Foot Angle -- Front (L46)	90°
Maximum Effective Leg Room -- Accelerator (L34)	41.9 in.
Effective Head Room -- Rear (H86)	37.2 in.
H Point to Heel Hard -- Rear (H86)	12.50 in.
H Point Couple Distance (L85)	26.75 in.
Effective Leg Room -- Rear (L86)	36.56 in.
Knee Room -- Rear (L87)	18.5 in.
Back Angle -- Rear (L88)	20°
Hip Angle -- Rear (L89)	83.5°
Knee Angle -- Rear (L90)	95°
Foot Angle -- Rear (L91)	112.5°
Side View Sight Lines -- Up (95 Percentile)	15°30'
-- Down	8°30'

NOTE: Numbers in parentheses refer to the Society
of Automotive Engineers standard dimensions.

Table 6
ESTIMATED COMPONENT WEIGHTS

Component	Estimated Weight (lb)	Percent of Curb Weight
Body and Structure	666	23
Suspension, Steering and Brakes	243	8
Wheels and Tires (5)	160	5
Seats, Trim, and Insulation	136	4
Instruments and Accessories	35	1
Motor and Drive	286	10
Controls and Electrical	145	5
Tools and Miscellaneous	12	1
Bumpers	77	3
Batteries	1182	40
<u>Totals:</u>	2942	100

Section 3

TRADEOFF RESULTS

GENERAL TRADEOFF DISCUSSION

The requirements for the electric car, the mission, and its environment were defined by ERDA. In order to convert these requirements into a set of hardware specifications for an optimized system with optimized subsystems and components, it was necessary to conduct system tradeoff studies.

The near-term requirements allow a variety of solutions. A unique vehicle, while it might be optimized for the mission, may preclude the possibility of large-scale manufacture. Therefore, it is essential that the mission characteristics be evaluated in such a way that the requirements that dictate component size are given prime consideration from the start.

For electric vehicle applications, it is not meaningful to calculate efficiency of range for a single operating condition. Electric vehicles, as any type of commuter vehicle, are not constrained to operate over a predetermined mission. General Electric had previously developed a computer simulation of the vehicle, battery, power conditioner, motor, and mechanical drive train which allows the overall effects of variations of components to be evaluated over an entire mission. This simulation was made available for use in this program.

This simulation initially calculates the actual acceleration profile to determine the discharge level that can be reached while maintaining the capability to meet a prescribed mission. The vehicle simulation is cycled through the mission until the batteries reach this minimal acceptable level of discharge. The results are then integrated and averaged to determine range, efficiency and losses. Detailed models of the batteries, motor, power drive train, cabling, and vehicle dynamics are included.

Important considerations are such factors as grades, top speeds, road conditions, and temperature. Other factors include:

VEHICLE CHARACTERISTICS

- Curb weight
- Frontal area
- Aerodynamic drag coefficient
- Ratio of wheel rpm to vehicle speed

VEHICLE MISSION

- Time to accelerate
- Time at constant speed (cruise)

- Time to decelerate
- Time vehicle stopped
- Cruise speed
- Grade
- Passenger load

SOLID-STATE POWER CONDITIONING AND CONTROL

- Power semiconductor rating
- Voltage rating
- Charging time

TRACTION MOTOR-GENERATOR

- Windage and iron loss characteristics
- Torque and voltage constants
- Field current
- Armature and field resistance
- Brush voltage drop

DRIVE TRAIN

- Gear ratios
- Speed at which shifting occurs (if shifting transmission is used)
- Power loss characteristics
- Rolling resistance

AUXILIARIES

- Air conditioning
- Heating
- Lighting
- Other

After a technical solution to the various requirements has been achieved, a life cycle and cost/benefit analysis can be performed. Initial equipment costs, estimated operating costs, and other cost data will be used to determine life cycle costs.

MISSION AND DESIGN CONSIDERATIONS

MISSION

The electric vehicle, as it exists today and as it can be projected into the foreseeable future, must be viewed as providing only a select portion of individual transportation functions. Because of its range and recharge limitations, the battery-powered vehicle cannot be regarded as a 1:1 equivalent or replacement for the internal combustion engined automobile.

However, the electric vehicle, utilizing currently available technology, can provide a significant fraction of city-bound driving and commuting. In addition, performance levels and mobility features can be developed to a suitable level to provide safe coexistence with present-day traffic.

If the electric vehicle is to coexist with current traffic, certain performance goals are apparent. For example, a maximum cruising speed of 55 mph is commensurate with the natural speed limit. Acceleration capability under normal circumstances must be sufficient to avoid creating traffic delays. Average acceleration levels presented in the Federal urban driving cycle of 4.1 ft/s^2 appear to represent an acceptable target. This is equivalent to accelerating to 30 mph in 9 seconds, a value better than the ERDA near-term goal of 10 seconds.

Additionally, the vehicle must demonstrate at least minimal gradeability, being able to negotiate a 30 percent grade and hold a sustained speed on a grade.

Other mobility factors that require consideration are ground clearance, ramp and departure angles, and adverse road conditions such as snow.

Coexistence with internal combustion engined vehicles not only imposes performance goals, but also implies requirements on the vehicle control as it relates to driver adaptability. The electric vehicle should not require any special training or driver skill improvements over those already needed. Acceleration and direction control must be simple, smooth, and comparable to present automotive practice. Control sensitivities (steering, braking, and acceleration) should not deviate widely from current practices. The vehicle handling character, in terms of its linear range stability and its limit of control performance, should match contemporary automotive practice. No sacrifice should be made in maneuverability.

DESIGN FACTORS

Many factors influenced the shape and proportion of the exterior. Some of these were functional; others were simply related to appearance. The first priority in this design was given to functional elements such as:

- Aerodynamics
- Visibility
- Legal considerations
- Ventilation
- Weight

Aerodynamics

Aerodynamic drag, even in a vehicle with a restricted speed, is a large portion of the total vehicle drag. At 40 mph, approximately 50 percent of the total vehicle drag is aerodynamic.

In an attempt to combine low drag with a pleasing style and a practical package, two scale clay models were constructed and wind-tunnel-tested for objective design tradeoffs between styling and aerodynamic drag. The model program began with the construction of two wooden bucks representing the minimum interior package. Two 0.393:1 scale clay models were constructed over these bucks (Figure 26). One model, the "aero car" was used to minimize aerodynamic drag without regard to styling compromises; the other model was more contemporary in style, having more angular lines. The "engineering model" incorporated such features as a full rounded nose and full front and rear fender skirts.

Figure 26. Clay Model Bucks

A third model, financed by the Copper Development Association, Inc., was constructed in the same scale, to represent the "Copper Electric town car." This vehicle has been under development for some time. Considerable road test data were available, providing a good baseline and a correlation with actual road experience.

Wind tunnel tests were conducted during December 1975, at the University of Maryland. The objectives of the tests were:

- To evaluate the design concept relative to the baseline vehicle.
- To determine the effect of features that represented major styling or engineering compromises (e.g., wheel skirts).
- To develop the shape of the final vehicle through flow visualization and drag measurement.
- To verify the estimates made for vehicle drag, which were used in making range and performance estimates.

To explain the testing technique and data reduction methods employed, some discussion of the effect of yaw attitude is required. The average wind velocity in this country is approximately 10 mph. If the assumption is made that the average vehicle speed is 35 mph, it can be demonstrated that the maximum average aerodynamic yaw angle is 15.94 degrees. This implies that the flow over the vehicle at yaw angles up to 16 degrees is important. Drag was measured at discreet yaw angles of +15, +9, +6, +3, and 0 degrees. A yaw-weighted drag coefficient was calculated as the mean drag for the total 30 degree sweep. Typically, the vehicle axis drag increases with yaw angle in the range tested.

Several basic design elements were evaluated in the wind tunnel to determine their influence on the total vehicle drag. As each feature was evaluated, the model was modified on the spot by a clay sculptor. Minimal turnaround time was possible with this method. The availability of two models ensured maximum utilization of wind tunnel time while modifications were performed. The elements investigated were:

- Wheel skirts and flares
- Nose radius
- Roof angles
- Tail radius
- Spoilers
- Windshield wiper treatments

Figure 27 is a summary of the test results. The top bar on the chart represents the drag coefficient of a 1976 Vega not weighted for yaw. The Vega is relatively clean as compared with most contemporary cars. The third bar is the drag coefficient of

Figure 27. Wind Tunnel Results

the Copper Electric town car model, which was tested along with the GE models to provide baseline information. A comparison of the second and third bars provides some insight into tunnel data and road data. Correlation is within 8 percent. Most of this variation can be explained by the differences between the model and the actual car, such as door cuts and bumper clearances.

As the importance of the various modifications was determined, they were incorporated into the style car. Some items, such as rear radii, were incorporated for their effect on the yaw performance of the vehicle rather than their straightahead drag. The final configuration of the style car, which is the one planned for construction, has a drag coefficient of 0.269 weighted for yaw. The zero yaw-angle drag coefficient was 0.243. When adjusted for actual "on-road" conditions the drag coefficient weighted for yaw is 0.294.

The basic difference between the style car and the aero car was skirted wheels, the feature that accounted for the 6 percent lower total drag of the aero car. It was judged that this difference did not warrant the compromises required in mechanical complexity.

Some factors contributing to the low aerodynamic drag were:

- Full flat underbody

- Flush glass
- Covered headlamps
- Covered windshield wipers
- Rounded nose
- Sloping hood
- Smooth transition between roof and windshield
- Rounded fenders
- Optimum roof slope
- Rounded rear corners
- Flush, radiused A pillar

Visibility

Minimum acceptable visibility angles were used to establish restrictions on windshield and backlight openings. As the design progressed, the shape lent itself to an improvement of these angles to what can be considered good-to-excellent. Upward vision is 15° 30' minimum; downward visibility is 8° 30' minimum.

Glass sizes were restricted as much as practicable consistent with the desire to maintain adequate visibility and reasonable styling, because of the extra weight and sun load associated with large glass areas. All side and backlight glass is tempered safety glass 0.125 inch thick. The sliding sunroof above the driver's head is also tempered glass, 0.180 inch thick. Windshield glass is of laminated construction (0.265 inch thick) with an integral radio antenna.

Legal Considerations

Once the basic shape had been established, care was taken to provide for those features required by law. For example, MVSS 108 specifies the height, size, color, and intensity of all vehicle lighting elements.

MVSS 215 establishes bumper performance specifications which effectively determine the height and the energy absorption (and consequently the minimum size) of the front and rear bumpers.

It is not planned to program all of the tests required by the law, particularly since many are distinctive in nature and only two are planned at this time. The intent is to design to meet the legal requirements.

Ventilation

Door glass has sliding half sections for accessibility. Side glass is fixed rather than opening, following the lead of the engineering safety vehicles built for the Federal government a few

years ago. The primary motivation for this feature is safety. Fixed glass ensures occupant containment during impact situations. The lack of window channels and other glass-dropping mechanisms paves the way for stronger, stiffer doors, which are able to better cope with lateral impacts. Additional features resulting from the fixed glass are lighter weight and better passenger compartment sealing.

Ventilation is provided by internal ducting, sliding front windows, and the sliding sunroof above the driver's head. Communication to persons outside of the vehicle for such purposes as paying tolls is accomplished through sliding half-section segments of both door glasses.

Winter heating and defrosting is handled by a gasoline-burning heater through the internal duct work.

Weight Analysis

Analysis of the vehicle weight included consideration of materials for construction, requirements for sound and thermal insulation, vehicle durability, and crashworthiness. Although the vehicle weight estimate is a relatively light 1760 pounds, less batteries, a lighter vehicle could probably be built by employing aircraft or race car materials and construction techniques. It is felt, however, that a vehicle constructed of materials commonly utilized in the manufacture of production automobiles would lend more impact to the vehicle as a concept and more closely represent the electric automobile of the future.

The weight breakdown presented previously in Table 6 is represented in Table 7 and is based on an actual tear-down weight analysis of a vehicle of similar size, combined with engineering judgment developed from earlier projects.

Table 7

WEIGHT BREAKDOWN

Component	Weight (lbs)	% of Curb Wt.
Body and Structure	664	23
Suspension, Steering, and Brakes	243	8
Wheels and Tires (5)	160	5
Seats, Trim & Insulation	136	4
Instruments & Accessories	35	1
Motor and Drive	286	10
Controls & Electrical	145	5
Tools and Misc.	12	1
Bumpers	77	3
Batteries	1182	40
Totals	2942	100

TRADEOFF RESULTS

The electric battery-powered vehicle, by reason of its restricted operating range, has been used to a very limited extent in the United States. Its disappearance from American streets and highways about 50 years ago resulted primarily from the limited capacity of the battery package. The internal combustion engine, with its essentially unlimited energy supply, was better able to meet the requirements for increased speed, acceleration, and primarily increased range.

Not a great deal has changed in this regard over the past 50 years. Batteries, although they have been improved, are still the primary limitation. The lead-acid battery is the only type likely to be commercially available for electric vehicle use in this decade. It, too, however, is limited in both capacity and peak power.

The effects of changing various parameters such as efficiencies, weights, duty cycles, speeds and accelerations, and grades are displayed and discussed, both singly and in combination, in the subsections which follow. In many cases, the effect on range is considered, inasmuch as achievable range has a high weighting factor in evaluation.

EFFECT OF STOP-AND-GO DRIVING

Range is greatly dependent on the number of starts and stops and their severity, primarily due to effects on the battery, discussed later. Secondary effects are the increased electrical losses due to high currents. The SAE J227A Schedule D urban cycle is used as a measure of performance on this contract.

Performance on SAE J227A Schedule D

A computer program using actual motor speeds, efficiencies, volts, and amperes has been prepared for calculating vehicle velocity and power consumption. Tables 8 and 9 tabulate the results for the GE reference vehicle for the SAE J227A Schedule D driving cycle. From this data the range, the peak power, the average power, and the kWh/mile may be determined. The urban range of the reference vehicle as designed with two 150-lb occupants is 39.3 miles on the level, with no wind, and with fully charged seasoned batteries at 80°F ambient. Performance off this design point for a variety of parameters will be covered later in this section. Table 8 shows the performance for a series motor drive; Table 9 shows that for a shunt motor drive.

Acceleration Performance (0 to 30 Mph and 25 to 55 Mph)

Table 10 shows the results of a computer run of the acceleration from 0 to 30 mph. The time required for this acceleration is about 11 seconds. Table 11 presents the results of a merging condition into highway traffic. Here the acceleration is from 25

Table 8

SERIES MOTOR SAE J227A SCHEDULE D COMPUTER RUN

Wheels

Motor

SEC	VAV	KWAV	VOLTS	AMPS	RPM	TORQUE	EFF
1	2.41	3.72	35.926	673.57	141.	190.0	0.157
2	6.89	9.29	43.560	601.87	403.	165.8	0.362
3	10.79	12.82	49.867	542.63	630.	146.2	0.483
4	14.20	15.01	55.116	493.32	829.	130.0	0.563
5	17.21	16.33	59.519	451.97	1005.	116.7	0.619
6	19.88	17.07	63.239	417.03	1161.	105.6	0.660
7	22.27	17.43	66.405	387.30	1301.	96.3	0.692
8	24.43	17.55	69.118	361.82	1426.	88.4	0.716
9	26.37	17.50	71.458	339.83	1540.	81.6	0.735
10	28.14	17.35	73.490	320.75	1643.	75.8	0.751
11	29.76	17.14	75.263	304.10	1738.	70.8	0.764
12	31.24	16.88	76.819	289.49	1824.	66.5	0.775
13	32.60	16.61	78.191	276.60	1904.	62.7	0.784
14	33.86	16.33	79.407	265.18	1977.	59.3	0.792
15	35.02	16.06	80.489	255.02	2045.	56.4	0.798
16	36.11	15.79	81.447	246.01	2109.	53.8	0.804
17	37.12	15.54	82.299	238.01	2168.	51.5	0.809
18	38.06	15.29	83.068	230.79	2223.	49.4	0.814
19	38.95	15.06	83.764	224.25	2275.	47.6	0.818
20	39.78	14.83	84.396	218.32	2323.	45.9	0.822
21	40.56	14.62	84.971	212.91	2369.	44.3	0.825
22	41.30	14.42	85.497	207.97	2412.	43.0	0.828
23	41.99	14.23	85.979	203.45	2452.	41.7	0.830
24	42.62	13.24	88.321	181.45	2489.	38.2	0.843
25	43.18	13.15	88.505	179.72	2522.	37.5	0.844
26	43.73	13.10	88.600	178.82	2554.	36.9	0.844
27	44.25	13.07	88.666	178.21	2584.	36.3	0.844
28	44.75	13.04	88.721	177.69	2614.	35.8	0.844
29	45.00	6.33	67.667	113.34	2628.	17.3	0.842
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77							
78	45.00	6.33	67.669	113.34	2628.	17.3	0.842
79	44.75	0.	0.	0.	2613.	0.	0.
80	44.25	0.	0.	0.	2584.	0.	0.
81	43.75	0.	0.	0.	2555.	0.	0.
82	43.25	0.	0.	0.	2526.	0.	0.
83	42.75	0.	0.	0.	2497.	0.	0.
84	42.25	0.	0.	0.	2467.	0.	0.
85	41.75	0.	0.	0.	2438.	0.	0.
86	41.25	0.	0.	0.	2409.	0.	0.
87	40.75	0.	0.	0.	2380.	0.	0.
88	40.25	0.	0.	0.	2351.	0.	0.
89	39.78	0.	0.	0.	2323.	0.	0.
90	39.33	0.	0.	0.	2296.	0.	0.
91	38.89	0.	0.	0.	2270.	0.	0.
92	38.44	0.	0.	0.	2245.	0.	0.
93	38.00	0.	0.	0.	2220.	0.	0.
94	37.56	0.	0.	0.	2196.	0.	0.
95	37.11	0.	0.	0.	2172.	0.	0.
96	36.67	0.	0.	0.	2149.	0.	0.
97	36.22	0.	0.	0.	2126.	0.	0.

Table 9

SHUNT MOTOR SAE J227A SCHEDULE D COMPUTER RUN

<u>SEC</u>	<u>ARMATURE CURRENT</u>	<u>FIELD CURRENT</u>	<u>RPM</u>	<u>TORQUE</u>	<u>MPH</u>
0	299.29	11.36	16.52	55.91	0.19
1	289.03	11.36	166.06	53.99	1.97
2	289.04	11.36	315.48	53.99	3.75
3	289.05	11.36	464.72	54.00	5.53
4	289.07	11.36	613.71	54.00	7.30
5	289.09	11.36	762.42	54.00	9.07
6	289.12	11.36	910.78	54.01	10.83
7	289.15	11.36	1058.77	54.01	12.59
8	289.18	11.36	1206.31	54.02	14.35
9	289.22	11.36	1353.38	54.03	16.10
10	289.26	11.36	1499.92	54.04	17.84
11	289.30	11.36	1645.89	54.04	19.58
12	289.35	11.36	1791.24	54.05	21.31
13	289.40	11.36	1935.93	54.06	23.03
14	289.45	11.36	2079.91	54.07	24.75
15	289.51	11.36	2223.14	54.08	26.45
16	289.57	11.36	2365.58	54.09	28.14
17	289.63	11.36	2507.19	54.10	29.83
18	299.68	10.56	2648.94	54.57	31.52
19	299.93	9.20	2785.17	51.87	33.14
20	301.85	8.34	2912.83	49.84	34.66
21	300.97	7.69	3032.68	47.55	36.08
22	299.40	7.27	3145.88	45.76	37.43
23	301.49	6.87	3253.37	44.50	38.71
24	299.71	6.54	3355.47	42.89	39.92
25	299.64	6.27	3452.58	41.67	41.08
26	299.66	6.03	3545.17	40.57	42.18
27	301.19	5.81	3633.71	39.75	43.23
28	300.66	5.62	3718.67	38.74	44.25
29	72.88	8.22	3718.03	11.94	44.24
30	73.64	8.22	3718.07	12.06	44.24
78	0.	0.	3713.44	0.	44.18
79	0.	0.	3675.88	0.	43.74
80	0.	0.	3638.67	0.	43.29
81	0.	0.	3601.79	0.	42.85
82	0.	0.	3565.24	0.	42.42
83	0.	0.	3529.02	0.	41.99
84	0.	0.	3493.11	0.	41.56
85	0.	0.	3457.52	0.	41.14
86	0.	0.	3422.24	0.	40.72
87	0.	0.	3387.25	0.	40.30
88	0.	0.	3311.87	0.	39.40
89	0.	0.	2872.34	0.	34.17
90	0.	0.	2436.04	0.	28.98
91	0.	0.	2002.48	0.	23.82
92	0.	0.	1571.24	0.	18.69
93	0.	0.	1141.85	0.	13.58
94	0.	0.	713.88	0.	8.49
95	0.	0.	286.91	0.	3.41
96	0.	0.	0.	0.	0.
97	0.	0.	0.	0.	0.

Table 10

PERFORMANCE PREDICTION WITH REFERENCE CAR DRIVE

(Acceleration from 0 to 30 Mph)

SEC	VAV	KWAV	VOLTS	AMPS	RPM	TORQUE	EFF
1	2.53	3.75	35.171	649.63	143.	181.9	0.167
2	7.24	9.29	43.215	577.52	423.	157.7	0.380
3	11.31	12.71	49.798	518.51	660.	138.2	0.502
4	14.85	14.78	55.231	469.80	867.	122.4	0.581
5	17.96	15.98	59.753	429.27	1049.	109.5	0.636
6	20.71	16.62	63.547	395.26	1209.	98.8	0.675
7	23.16	16.91	66.756	366.50	1352.	89.8	0.705
8	25.36	16.96	69.490	341.98	1481.	82.3	0.728
9	27.34	16.87	71.837	320.95	1597.	75.9	0.747
10	29.14	16.69	73.864	302.77	1702.	70.4	0.761
11	30.14	5.45	52.488	130.11	1760.		
STOP							

Table 11

PERFORMANCE PREDICTION WITH REFERENCE CAR DRIVE

(Acceleration from 25 to 55 Mph;
Minimum Acceleration Time - 30 Seconds)

SEC	VAV	KWAV	VOLTS	AMPS	RPM	TORQUE	EFF
1	26.68	27.50	83.282	483.29	1558.	126.8	0.697
2	29.78	26.36	86.098	427.42	1739.	109.9	0.731
3	32.40	25.11	88.273	384.27	1892.	95.3	0.755
4	34.65	23.89	89.988	350.24	2024.	84.8	0.774
5	36.61	22.77	91.366	322.90	2138.	76.5	0.787
6	38.34	21.75	92.490	300.58	2239.	69.8	0.798
7	39.87	20.85	93.421	282.12	2329.	64.3	0.807
8	41.25	20.04	94.201	266.65	2409.	59.8	0.814
9	42.49	19.33	94.861	253.55	2481.	56.0	0.820
10	43.61	18.71	95.417	242.51	2547.	52.8	0.825
11	44.64	18.17	95.895	233.03	2607.	50.1	0.830
12	45.59	17.68	96.312	224.76	2662.	47.7	0.833
13	46.46	17.24	96.678	217.50	2713.	45.6	0.836
14	47.26	16.84	97.002	211.08	2760.	43.8	0.839
15	48.01	16.48	97.289	205.37	2804.	42.2	0.842
16	48.66	14.80	98.585	179.66	2842.	37.4	0.853
17	49.22	14.74	98.628	178.80	2874.	36.8	0.853
18	49.76	14.70	98.659	178.21	2906.	36.3	0.853
19	50.28	14.66	98.683	177.72	2936.	35.9	0.853
20	50.78	14.63	98.707	177.24	2965.	35.4	0.853
21	51.26	14.59	98.734	176.72	2994.	35.0	0.853
22	51.72	14.55	98.762	176.15	3021.	34.6	0.853
23	52.17	14.50	98.795	175.50	3047.	34.2	0.853
24	52.60	14.45	98.833	174.75	3072.	33.8	0.854
25	53.01	14.39	98.876	173.90	3096.	33.4	0.854
26	53.41	14.32	98.924	172.93	3119.	33.0	0.854
27	53.79	14.24	98.979	171.85	3141.	32.6	0.854
28	54.16	14.16	99.040	170.63	3163.	32.2	0.855
29	54.50	14.06	99.107	169.30	3183.	31.7	0.855
30	54.83	13.96	99.180	167.84	3202.	31.3	0.856

to 55 mpg. The computer run indicates that this acceleration will require 30 seconds.

EFFECT OF STATE OF CHARGE ON BATTERY CURRENT DURING ACCELERATION

The battery current drawn during acceleration is quite sensitive to the state of charge of the battery. Figure 28 shows the current drawn from the battery on the Schedule D acceleration for the case of a freshly charged battery and after 30 driving cycles.

Figure 28. Battery Current Acceleration to 45 Mph

EFFECT OF EFFICIENCY

One of the important factors influencing range is the efficiencies of the components, both electrical and mechanical. The prime components of interest are battery, controls, and drive motor. There is little room for improvement in efficiency of controls, and battery improvements will require long-range developments. The motor pays a penalty in having to operate over a wide speed range and deliver maximum torque at low speed and voltage. Possibilities of motor efficiency improvements are discussed later in this section and in Section 4.

Calculations have been made on the effect of increased overall efficiency on urban range. An increase of 1 percent in efficiency of the motor and controller with other efficiencies unchanged yields an increase in urban range of 2 percent. Thus a 10 percent increase in efficiency would increase the urban range 20 percent.

Figure 29 presents the effect of constant vehicle speed on vehicle range for the GE reference vehicle with the EV-106 battery. It is clear from Figure 29 that the range of the vehicle is not fixed for a given battery capacity. Range is dependent on many factors. Initial charge of the battery, prior history of use, and ambient temperature are important factors. A number of additional factors which influence range include the total vehicle weight, number of starts, vehicle acceleration, wind velocity, road surface, and grades. Figure 30 presents the effect of ambient temperature on urban range. The revised battery data for 80 °F were used to calculate the urban range and are indicated on Figure 30. The revised data resulted from modifying calculations from constant current at the one hour rate to actual dynamic conditions during driving.

Figure 29. EV-106 Battery Performance Prediction with Reference Drive -- Range vs Speed; Solid-State Level

Figure 30. EV-106 Battery Performance Predictions
with Reference Drive -- Range vs
Temperature

EFFECT OF BATTERY ENERGY DENSITY

The prime factor in increasing the range of an electric car is to use batteries of high energy density. Today only the lead-acid battery is commercially available and there are programs underway to improve it. Figure 31 shows the effect of energy density on urban range at constant vehicle weight, with the EV-106 point indicated.

Figure 31.

Effect of Battery Energy Density on Reference Vehicle Urban Range (Energy Density Associated with Driving Urban Cycle)

EFFECT OF BATTERY ON TOTAL VEHICLE WEIGHT

The approach normally used to improve performance has been to increase the ratio of battery weight to total vehicle weight, taking advantage of the "mass compounding effect" whereby the added structural weight of the vehicle increases at less than one-half the added battery weight. This has two effects on range:

- Battery capacity per unit weight has a net increase.
- Current and power demands are reduced, thereby increasing the energy available from the battery.

The effect of increasing the number of EV-106 batteries in the GE reference car is shown in Figure 32. Although the increase in urban range from an increase in batteries is significant the space originally allocated to passengers would have to be used for batteries.

EFFECT OF DRAG

Figure 33 indicates the effect of drag reduction on increase of the baseline vehicle range. The curve is relatively flat, indicating that further effort on drag reduction would not be very productive in increasing range.

Figure 32. Predicted Performance with Reference Drive -- Effect of Increasing Battery Weight

Figure 33. Predicted Performance with Reference Drive -- Effect of Reducing Drag Coefficient

EFFECT OF PAYLOAD

Figure 34 indicates the effect of payload on reference car range. The reference curve "Based on the Vehicle Test Model" (shown by dashed line) is based on full discharge of the battery. The revised battery model calculations (shown solid) use an 80 percent discharge limit.

Figure 34. Predicted Performance with Reference Drive --
Effect of Payload on Range

EFFECT OF SUSTAINED SPEED ON GRADE

With a sustained speed a steady-state power consumption results. Figure 35 shows the typical energy consumption per mile at various speeds and grades. The data of Table 12 are based on a preliminary battery model. The maximum available energy from the battery will be the limiting factor in sustaining a given

Figure 35. Performance Prediction with Reference Drive -- Energy Consumption vs Speed; Steady-State Grade

Table 12
CONSTANT SPEED ON GRADE

Speed (mph)	Percent Grade		
	0	2	5
	Range (Miles)	Range (Miles)	Range (Miles)
20	163.2	54.4	22.6
40	97.6	39.6	13.2
43	--	--	5.4
50	--	23.2	--
55	62.1	--	--

Notes:

1. Maximum speed on 5% grade is 43 mph.
2. Maximum grade for sustained 50 mph is 2.3%.
3. In computing vehicle range on a grade, the attainable percent discharge of the battery varies with variable current demands.
4. Thermal limitations of the traction motor are not considered.
5. Revised battery model used.
6. Battery fully charged at start.

speed on a particular grade. For the reference car with the EV-106 battery, this speed limit is about 43 mph on a 5 percent grade. To sustain 50 mph on a 5 percent grade would require a battery with a higher permissible drain rate. In Table 12, which gives gradeability and range data for the latest battery model, the maximum grade at 50 mph is 2.3 percent. All data are based on battery limitations and do not consider thermal limitations on the motor.

RECOVERY OF KINETIC ENERGY BY REGENERATION

A key to improving range is to recover braking energy when the vehicle stops. The approach most frequently proposed is to use the main propulsion lead-acid battery to store the kinetic energy recovered by regeneration when the vehicle is braking.

It is estimated that the battery can receive by regeneration from 10 to 20 percent of the total cycle energy in the Schedule D urban cycle. Each percent of energy regeneration adds 0.6 percent to the range. Thus regeneration with today's battery is expected to improve urban range from 6 to 12 percent.

LOAD LEVELING

In addition to recovering the braking energy, a significant improvement can be made by reducing the power peaks to and from the battery. Ideally, the battery prefers to deliver its energy at a constant discharge rate. By means of a secondary energy storage device such as a hybrid battery or flywheel system, the accelerating peaks and braking energy absorption duties can be removed from the lead-acid main battery. By proper programming or load leveling, the load on the main battery can be kept essentially constant.

Load Leveling With Hybrid Batteries

An investigation of a hybrid battery for load leveling was conducted for comparison with the flywheel system. The systems studies had an open circuit voltage at 108 volts to operate in parallel with the main lead-acid battery. The hybrids were sized to deliver 200 watthours in one acceleration cycle of 28 seconds, with a peak power of 20 kW. Only commercially available systems were considered.

The three most viable candidates selected were the lead-acid, the nickel-cadmium, and the silver-zinc systems. Nickel-iron was not considered, because of its poor specific power capability. Comments on each system follow:

- Lead-Acid. The power delivery rate of lead-acid is the limiting factor. About 1000 pounds of traction batteries are required to deliver the 20 kW peak. To date, batteries have been designed for energy storage rather than for higher discharge rates. It is felt that even if designed to the limit of power delivery, the batteries would still

be too heavy and would have short life, since each acceleration would be essentially one discharge cycle.

- Nickel-Cadmium. The nickel-cadmium battery has performance characteristics well suited to this duty cycle. A 100 to 150 lb, 11 Ah battery with 108 volts open circuit would be required to meet performance with reasonable cycle life. However, the availability of materials for high volume utilization may be questionable, and the OEM price of this supplementary battery projected in large volume is in the order of \$2500 for the size estimated. It is very unlikely that cost reduction programs can make this system economically viable.
- Silver-Zinc. The silver-zinc battery is very well suited for high power discharge rates and is accompanied by good energy storage capability. However, the cycle life is quite limited, silver is a rare material, and the cost of the battery is prohibitive.

It was concluded that the hybrid battery system was not a viable system when both performance and cost were considered. It was felt that the flywheel system, with its almost infinite life, would be a much better candidate for load-leveling the main battery.

Load Leveling by Flywheel

One of the most significant ways to increase vehicle range with a fixed battery is to load-level the battery by the use of a flywheel to supply power for acceleration and to absorb and store energy during deceleration. This is illustrated in Figure 36. Figure 37 is a schematic diagram of an electric vehicle propulsion system with a flywheel for load-leveling the battery. In operation, a constant power is drawn from the battery. If more power than the amount supplied by the battery is needed, this additional power is taken from the flywheel. When the vehicle stops, the braking energy is returned to the flywheel; power is taken from the battery at a constant rate to bring the flywheel up to the planned speed.

The effect of load leveling on range is dramatic. Using the latest battery model, the latest motor model, and a prototype flywheel and control weighing 175 pounds, and with a payload (people) of 300 pounds, the upgraded GE vehicle urban range would be 53.5 miles compared with the reference car urban range of 39.3 miles, or an increase of 35 percent. The reduction in weight by removing the battery charger and using the electronically commutated motor and power module would increase this range to 56 miles, or an increase of 42 percent over the original drive.

Figure 36. Performance Prediction with Reference Drive Range vs Payload Comparison For Battery Alone and Battery with Flywheel Load Leveling

Figure 37. Propulsion System with Flywheel for Load Leveling

ADVANCED AC VS DC DRIVES

Using conventional state-of-the-art motors and controls favors the DC drive, primarily because of the much higher cost of the AC control even though the AC motor is smaller, lighter, and less costly.

A tradeoff study was made on the projected size, weight, cost, and efficiency of both DC and AC drives utilizing advances in technology over the next five years. Power transistors rather than thyristors and power module controls were considered for both DC and AC drives. The current fed, permanent-magnet rotor, synchronous AC motor (an electronically commutated motor - ECM) was found to have the greatest potential for low cost, size, weight, and high efficiency.

The ECM with transistorized power module control offers the potential of reducing the cost of DC drives of today by 75 percent if built in very high volume, being slightly less costly than a DC drive of the future utilizing the same power control technology. The AC system of the future will be about 25 percent lighter than the DC drive and will have from 7 to 10 percent higher efficiency.

MOTOR SELECTION TRADEOFFS

The drive selected for the reference vehicle is based on the separately excited DC machine with an SCR armature chopper and a transistorized field chopper. The armature chopper is used for lower-speed operation to match the battery voltage to the lower motor voltage in an efficient manner. As the motor speed increases, the armature chopper is no longer needed and can be taken out of the circuit (bypassed) when the machine counter emf matches the battery voltage. The motor is then connected directly across the battery and is controlled by the low power field chopper.

Compared to the series motor drive this drive has the advantage of higher motor speed capability; efficient field weakening can be attained which in turn results in the ability to use a higher axle ratio. The higher axle ratio, in turn, allows higher torque multiplication and, hence, lower armature current for a given torque. Since the machine speeds up relatively fast (because of the higher axle ratio) it enters its high efficiency region sooner than an equivalent series machine.

Because a high-frequency transistor chopper is used to supply the high inductance field, there is negligible field ripple current. This reduces the eddy current and hysteresis loss of the machine stator as compared with the series motor case, which has high series field ripple current. For the same reason, the torque pulsations of the separately excited machine (proportional to armature ripple current) are less than those of the series machine (proportional to ripple current squared).

In the bypass mode, the chopper is out of the circuit and the motor current and battery current are ripple-free, resulting in a highly efficient drive.

From the above advantages, it was concluded that by employing the separately excited machine, a more efficient, higher performance drive would result.

DC MOTOR UPGRADING

It is possible to improve both the field control speed range and the efficiency of DC motors in the two-year time frame. Tradeoffs indicate that it should be possible to increase the field control speed range to at least 3 to 1 and increase the speed to 6000 rpm maximum for increased system efficiency and no increase in weight. Motor efficiency can be increased to 90 percent with some increase in weight and cost unless this can be traded off against motor speed. The tradeoffs in motor design are discussed in Section 4.

POWER ELECTRONICS TRADEOFFS

It is possible to substantially improve the power electronics in two years. Tradeoffs indicate that transistorized power electronics as discussed under advanced AC vs DC drives using power module technology would reduce the size and weight and cost of the electronics by 50 percent. The efficiency would be increased to 97 percent. This circuitry would provide the regenerative braking and the onboard battery charging functions. It may be preferable to utilize the field chopper for battery charging by increasing the current from 30 to 40 amperes rather than operate the main armature chopper at less than 10 percent of its normal rating.

Section 4

TRADEOFF DISCUSSIONS

The major onboard electric car subsystems have been defined to include:

- Battery and its associated charging equipment.
- Propulsion subsystem, comprising the power conditioning unit, the traction motor, and the drive train.
- Vehicle control subsystem.
- Accessory subsystem.

Each of the above subsystems is discussed here from the point of view of existing near-term technology.

BATTERY**BATTERY TRADEOFFS**

In the two-year time frame of interest, the electromechanical energy source most likely to meet the electric vehicle performance requirements at a reasonable cost is the lead-acid battery. A battery specifically optimized for an on-the-road electric vehicle has yet to be designed. In this program, a lead-acid battery, such as the EV-106 golf car battery manufactured by ESB, was planned for use. Although the EV-140 battery has a higher power output, it has higher cost, lower cycle life, longer delivery time, and is available only in special order.

Battery Candidates in Electric Vehicle Usage

In the beginning of the modern on-the-road electric vehicle industry, analytical studies disclosed that no off-the-shelf lead-acid battery was thoroughly suitable for urban stop-and-go traction service. However, the studies revealed two candidates worthy of trial and evaluation: the "deep discharge" version of the automobile starting battery, commonly called the "golf car" battery, and the industrial truck battery. Each of these products has attributes that appear desirable to the electric vehicle designer:

- High-rate specific energy of the automotive product, 30 to 50 percent greater than that of the conventional industrial product, assures adequate acceleration.
- Cycle life of the industrial product, 3 to 5 times that of the automotive product, assures satisfactory service life.

- Cost per pound of the automotive product, one-fourth to one-third that of the conventional industrial product, shows prospects for acceptable operating costs.

As they are currently manufactured, however, neither product is completely satisfactory. A single product containing a favorable ratio of specific energy to cycle life cost has not been designed and built. The state-of-the-art of lead-acid batteries for electric vehicle propulsion is listed in Table 13 in terms of the two most useful parameters: specific energy and cycle life.

Table 13

ENERGY AND LIFE CYCLE PARAMETERS OF LEAD-ACID BATTERIES

Battery Type	Specific Energy (Wh/lb)		Cycle Life (Laboratory)
	5-Hour Rate	1-Hour Rate	
Flat Plate (Automotive)	14.6	10.3	400-450
Tubular Plate	13.0	7.5	1500-2000

Figure 38 shows the relation between specific energy and specific power of the EV-106 battery, which was selected for electric vehicle application. A similar curve for the revised battery model is shown in Figure 39.

Figure 38. EV-106 Battery Performance Data

Figure 39. Specific Energy vs Specific Power
EV-106 Battery, Revised Model (12-11-76)

Battery Capacity and Driving Cycle

The most commonly used method of rating battery capacity is by ampere-hours, for the specified rate of discharge and for the specified end voltage. Figure 40 shows the typical variation in ampere-hour capacity of EV-106 battery as a function of discharge rate. Since the battery is an electromechanical storage device, the capacity also varies with temperature, as shown in the same figure. Similar performance for the revised battery model (December 1976) is given in Table 14.

Table 14

TYPICAL REVISED BATTERY DISCHARGE CHARACTERISTICS		
Temperature (°C)	Time (min)	Current (A)
+27	20	300
+27	9	500
-29	6	300

As the battery discharges, the voltage at the terminals falls gradually from its open-circuit value until the end of the discharge is approached, when it begins to fall much more rapidly. This point indicates that the exhaustion of the cell is near. Figure 41 shows the typical discharge curves for EV-106 battery

Figure 40. EV-106 Battery Discharge Rate vs Discharge Time at Various Temperatures

Figure 41. Effect of Discharge Current on Battery Voltage vs Time

at 80°F temperature. Figure 42 shows similar curves at 300 A and 500 A discharge rates. These data were obtained from special tests by ESB Incorporated, and account for the revision in range calculations referred to throughout this report.

Assuming the logical use for an electric car is as a second or third family car in a metropolitan area, it follows that the logical standards for real-life performance are stop-and-go driving cycles rather than a series of range-at-constant-speed tests. Figure 43 shows the typical current drawn from the EV-106 battery for a 3000 pound vehicle accelerating to 45 mph. The current drain becomes higher when the battery is partially discharged after 30 cycles of operation as a result of the drop in voltage as the cells discharge.

Figure 42. Effect of Discharge Current on Battery Voltage

Figure 43. Battery Current Acceleration to 45 Mph

BATTERY COLD SOAK

One of the more severe operating conditions for battery-powered vehicles is a cold ambient after a cold soak. The cold soak goal of ERDA is operation of the vehicle after the ambient temperature has been at -20°F for seven days. An unmodified, unprotected lead-acid battery will not operate a vehicle after a seven-day cold soak at -20°F . Several alternatives are available to meet such a cold soak condition.

One is to heat the battery with external power. A second is to insulate the battery and to maintain a given temperature with its own energy, but to be effective a very thick insulation is required. A third method, which is preferred, is to insulate the battery with a thin layer of insulation, allow it to cool to ambient, and then warm the battery with its own stored energy.

These conclusions are summarized in Table 15.

Table 15

COLD SOAK CONCLUSIONS

- Insulate - 2 in.
- Best performance by allowing to cool, then preheating just prior to use.
- Preferred final battery temperature depends upon subsequent duty cycle.
- Disadvantage is time to preheat:
- ~ 120 minutes to 80°F for 30 A heating
- ~ 12 minutes to 80°F for 300 A heating

The following paragraphs describe the results of an analysis of the battery capacity available after a period of seven days at an ambient temperature of -20°F for the specific case of a lead-acid battery pack applicable to an electric car. It includes consideration of various methods aimed at increasing available capacity, including use of a portion of the battery energy to maintain battery temperature at a higher level than the ambient or to raise the battery temperature just prior to use. The cold soak analysis is given in Appendix D.

Certain notes regarding the energy balance within a battery are included. These are useful in analyzing self-heating of a battery during discharge or charge.

Configuration

The configuration considered consists of 18 lead-acid batteries of the automotive variety, designated EV-106, as manufactured by

ESB, Incorporated. They are arranged in a rectangular box approximately 17 inches wide, 12 inches high, and 94 inches long, mounted in the bottom center of the vehicle.

Cold Soak Results

The following information is presented herein:

- Rated battery capacity as a function of battery temperature
- Battery capacity remaining at the end of a seven-day soak at -20°F ambient temperature when some of the battery energy is used to maintain the battery at a temperature higher than the ambient. This information is presented as a function of battery temperature for various amounts of thermal insulation.
- Battery capacity at the end of the seven-day soak period when the battery is heated to a higher temperature just prior to use by utilizing a portion of its own energy. This is done for battery temperatures prior to heating of -20°F and 0°F , respectively, for different values of thermal insulation. In the case of the 0°F temperature prior to heating, a portion of the battery energy is used to maintain the battery temperature at 0°F prior to heating it up.

Results are presented in two forms: 1) Ampere-hours capacity available at the final battery temperature for the limiting case of battery current approaching zero, and 2) ampere-hours used up in controlling or maintaining battery temperature. The first format graphically illustrates which of the various approaches yields the maximum available capacity. The second format, in connection with the basic battery capacity curves, gives quick insight into the capacity available for various amounts of subsequent current drain.

Figure 44 gives the capacity of each of the 18 batteries as a function of current and battery temperature. Data were obtained from typical battery performance curves for an EV-106 battery. These capacities are based upon a semiarbitrary definition of cutoff voltages:

- 1.75 V/cell for 10 to 75 A current
- 1.00 V/cell for currents greater than 75 A

In electric vehicle system calculations, a less arbitrary cutoff voltage definition, consistent with the characteristics of the electrical circuit to be utilized, would be preferred and should be used.

Figure 44. Battery Capacity (6 Volt Battery)

Capacities for currents less than 30 A in Figure 44 were obtained by extrapolation.

Figure 45 gives remaining battery capacity for various temperature control techniques, also showing rated capacity, as current approaches zero, for a fully charged battery (obtained from Figure 44) for reference purposes.

Figure 45. Remaining Battery Capacity (6 Volt Battery)

In preparing Figure 45 remaining battery capacity after a period of variable current and/or temperature discharge was determined according to the ampere-hour additivity procedure. Briefly, that procedure states that a good estimate of remaining battery capacity is obtained simply by totaling the ampere-hours discharged, regardless of the currents or temperatures at which this was done, and subtracting that total from the basic capacity given in Figure 44 at whatever combination of current and temperature is of interest.

The solid lines of Figure 45 show the results of allowing the battery to cool to a given temperature, and then actuating the battery by the use of heaters to maintain itself at that temperature. This is done for various temperatures and amounts of thermal insulation. Vehicle configuration effects were ignored, and the battery package was treated as a rectangular box suspended in still air. The effective values of thermal conductivity of the insulation were assumed to be 0.03 Btu/hr-ft-°F. This is approximately equal to or slightly greater than the thermal conductivity of a number of potential insulating materials such as styrofoam or fiberglass.

It is seen from Figure 45 that a considerable amount of insulation is needed to avoid excessive energy drain from the battery when it is used to maintain its temperature above ambient.

The dotted lines of Figure 45 depict the case in which the battery is allowed to drop in temperature to either 0 or -20°F and then is heated just prior to use; current during heating of 30 amperes was arbitrarily assumed. From a performance standpoint this is definitely the best approach, the preferred method for maximum remaining capacity at temperature being to allow the battery to cool down to -20°F and then heat it up to 80°F prior to use. An additional advantage of this approach is that it is relatively insensitive to the amount of thermal insulation used, provided the method of heating does not create hot areas on the outer surface of the battery package. If a heating "blanket" were used around the battery package and around each battery, higher surface temperatures would exist, and some thermal insulation would probably be desirable. The preferred method of heating from a performance standpoint would, of course, be internal heating of the electrolyte and plates, but this would add considerable complexity.

Figure 46 shows the actual ampere-hours of discharge taken from each battery for the various temperature control approaches used in Figure 45. Overlaid on the figure are curves of rated battery capacity for various constant current discharge conditions, taken from Figure 44, giving a somewhat better insight than does Figure 45 into the practicable capability remaining in the battery.

Figure 46. Effect of Battery Temperature on Ampere-Hours of Discharge (per Battery)

For example, Figure 45 indicates that the maximum remaining battery capability, provided currents are to be very low (approaching zero), is obtained by letting the battery cool to -20°F and then heating it to 80°F . Suppose, however, a 600 A current drain is required of the battery upon startup with the use of the ampere-hour additivity procedure.* Figure 46 indicates that the battery at 80°F is just barely capable of meeting this current drain, and that it would have more capability for this amount of drain if it were not heated to so high a temperature.

From this illustration, the preferred battery procedure for handling the seven-day, -20°F soak condition depends upon the subsequent duty cycle required of the battery, although, generally speaking, allowing the battery to cool to ambient and then preheating it prior to use appears to be preferable.

Use of a 30 A current for this preheating was arbitrary and required roughly 2 hours to heat the battery package from -20°F to 80°F . By using higher currents, this warmup time could be reduced. A current of 300 A, for example, with proper heater design could reduce the warmup time by a factor of about 10. This, in turn, might eliminate the need for a preset timer and result in a waiting time that would be reasonable for all but the most impatient motorist.

*Kerr, D., "A Suggested Procedure for Estimating Lead-Acid Battery Capacity Under Varying Discharge Conditions," General Electric Company internal memorandum, September 13, 1976.

BATTERY CHARGER AND FUEL GAUGE

Charging Requirements

From the standpoint of the battery, the basic requirements of the charger are:

- Providing a safe value of charging current throughout the charge.
- Completion of the charge in a time period compatible with the service involved.
- Accurate termination of the charge when complete.
- Prevention of excessive battery temperature and gassing.

Accurate termination of the charge has proved to be the most difficult requirement to satisfy. The end-of-charge voltage of a lead-acid battery depends on the temperature of the electrolyte of the cells and on the history of the battery.

Difficulty in accurately terminating the charge results in excessive cost of charging and, perhaps more importantly, short service life of the battery. Overcharging produces corrosion of the positive grids and excessive gassing, which loosens the active material in the positive plates. Excessive gassing also results in needless loss of water, requiring more than normal attention.

Compounding this problem is the requirement to provide for a periodic "equalizing" charge to correct any inequalities among the cells of a battery that may develop in service. It is essentially a prolonged charge at a rate not exceeding the finishing rate. The charge is terminated when all of the cells are gassing gently but not excessively. A battery in daily service should receive a periodic equalizing charge.

Charging Methods

There are basically three generally accepted methods by which a partially or fully discharged battery may be recharged: constant current, constant voltage, and taper charging. Most chargers today use one of these methods alone or one in combination with another.

In practice, a charger can use a combination of the above methods. For example, to limit the charger size, weight, and cost, a fixed current can be delivered to the battery followed by a taper charge or constant voltage charge as the battery begins to gas freely.

In two-step charging, the first step is constant current, continuing until a predetermined battery voltage is reached. At

that time, the second step is initiated, consisting of a constant voltage charge for the remainder of the cycle. Three-step charging is another example. In this method, a constant current charge is followed by a constant voltage charge. The constant voltage charge continues until the current has decreased to a predetermined value, at which time a constant current is delivered as the third step.

The characteristics of a 168 Ah cell (6 hour rate) have been investigated to determine the effects of various parameters on watthour efficiency. The results were derived by using known curves of cell voltage vs time, with charging current as a parameter, and integrating the appropriate curves. The watthour efficiencies are given for the battery only, unless otherwise indicated:

$$\text{watthour efficiency} = \frac{\text{watthours discharged from battery}}{\text{watthours needed to charge battery}} \times 1000$$

To compute most of the curves, a two-step charging method was assumed.

Comparison of Charging Methods

Table 16 compares three different methods which are commonly used to charge lead-acid batteries: the modified constant potential method (MCP) which is essentially a taper charge, two-step charging using series resistors which results in some current taper as the cell voltage changes, and two-step charging with regulated current. The method of charging does not have a major effect on the watt-hour efficiency although it may affect the battery life.

Table 16

COMPARISON OF CHARGING METHODS FOR A DISCHARGED 168 AMPERE-HOUR CELL (6 HOUR RATE)

Charging Method	Watthours per Cell	Watthours Efficiency (%)
MCP*	414	79
Two-Step Semi-Taper**	429	76
Two-Step, No Taper***	418	78.4

* 2.63 volts/cell, 0.013 normal ohm/cell, 0.018 maximum ohm/cell.

** Series resistor decreases current from 38 A to 21 A in 5 hours; 8.4 A for 3 hours finishes charge.

*** 5 hours at 31.9 A followed by 3 hours at 8.4 A.

Required Recharge Energy

Figure 47 allows the calculation of the amount of recharge energy needed, knowing the ampere-hours removed from the battery based on two-step charging.

Figure 47. Required Recharge Energy
for Partially Discharged
Cell (Two-Step Charging)

If the consumed watthours and ampere-hours are known for any particular driving cycle, the energy needed to recharge the battery can be determined for that particular driving cycle.

Effect of Charging Time

Figure 48 shows that the watthour efficiency decreases slightly as the charging time decreases, because of the decreasing ability of the battery to accept all the charge as the charging current increases. The decrease in efficiency going from eight to six hours charging time (3%) is slight.

Cycle life is not materially reduced by charging the battery in six hours compared with eight hours. However, charging in shorter times may result in degradation caused by heating effects. For rapid charges (e.g., 4 hours), the means of heat transfer to the environment is critical and must be considered in the overall design. Additional gassing may result which in turn would require more frequent maintenance of the electrolyte level. Also, the rating, and hence cost, of the battery charger will increase as the charging time decreases.

Figure 48. Effect of Charging Time on Watthour Efficiency for Two-Step Charging (Finishing Rate = 8.4 A for 3 Hours in All Cases)

Effect of Discharge Rate

Figure 49 shows that if the battery is discharged at a higher current rate the watthour efficiency decreases slightly. The average efficiency is approximately 76 percent and varies only ± 3 percent over a very wide current range.

Figure 49. Effect of Discharge Rate on Watthour Efficiency for Two-Step Charging (Starting Current = 32 A; Finishing Current = 8.4 A for 3 Hours in All Cases)

Effect of Efficiency

Since the analysis shows only slight variations in watthour efficiency for wide ranges of parameters, it is concluded that, with the use of conventional charging methods and available traction batteries, the watthour efficiency can be taken approximately as a constant 76 percent for most conditions. Based on that assumption, the efficiency of the battery-charger combination is taken as $0.76N_c$, where N_c is the average battery charger efficiency. It is possible to design a charger with average efficiencies from 65 to 95 percent. Table 17 lists the resulting overall energy efficiency for various battery charger efficiencies.

Table 17

BATTERY CHARGER ENERGY EFFICIENCIES

<u>Average Battery Charger Efficiency</u>	<u>Charger-Battery Watthour Efficiency</u>
0.9	68.4
0.8	60.1
0.7	53.2

The efficiency of the battery charger should be as high as possible within economic, weight, and volume constraints.

Required Recharge Energy

Calculations show that the vehicle will require 0.278 kWh/mi when operated on the SAE J227A Schedule D cycle. Assuming a battery charging, battery watthour efficiency of 60.1, the required recharge energy is then 0.463 kWh/mi.

Charger for Reference Vehicle

For the reference vehicle a current limited, constant voltage charger would be used. This method is a proven technique which will charge the batteries in minimum time for a given charger rating. The constant voltage portion of the charging cycle will be automatically temperature-compensated.

An onboard charger will accept 120 volts AC, will limit the current drawn from the line to 15 A, and will also provide transformer isolation to allow the battery to be changed from a conventional outlet in a safe manner in 14 to 18 hours (limited by the capability of the outlet). An offboard charger of higher rating operating from a 220 volt household circuit will charge the vehicle in 6 to 8 hours.

As an upgrading option, a full rated, lightweight, solid-state design based on power module technology can be developed.

Charger Arrangements

Figure 50 illustrates three possible configurations for charging the batteries of an electric vehicle. The proper choice will depend on charger size, weight, reliability, and cost traded off against effect on battery life, charging time, and convenience of use.

An onboard charger must be capable of accepting the remote 100 volt, AC source while limiting the current drawn from the source to 15 A. This allows the vehicle to be charged at unknown locations where the only power available is from a 110 volt source.

Depending on the overall system configuration selected, the same power electronics used for driving the car may be used to obtain the battery charging function. This configuration is shown in Figure 50(c). With the drive machine disconnected and the external ac source connected, the batteries can be charged by operating the power conditioning equipment as a charger.

(a) Dedicated On Board Charger

(b) Small On Board Charger to Obtain Boost Charge or Slow Full Charge

(c) Drive Electronics Used for Battery Charging

Figure 50. Alternate Battery Charger Arrangements

Battery Charger Circuits

Figure 51 shows several standard circuits used for battery charging. The half-controlled bridge circuit provides higher displacement power factor and less rms line current for a given dc voltage and current than the fully controlled bridges do. However, in the half-controlled circuit, the line current is more distorted when the voltage is considerably reduced by phase control. The high-frequency chopper circuit uses a diode rectifier at the input, and therefore draws square-wave unity displacement factor current irrespective of output voltage. In addition, the filter inductances are reduced substantially because of high chopping frequency.

Fuel Gauge

A required function unique to electric cars is the determination of battery state-of-charge: a "fuel gauge" feature. A basic way to perform the fuel gauge function is to measure the ampere-hours removed from the battery, subtract them from the rated capacity of the battery, and display the remainder. This method requires two knowns that may vary from time to time and thus dictate an adjustment for the fuel gauge:

- The capacity of an electric vehicle battery depends on the driving cycle of the vehicle. For example, the gauge would read differently in flat, than in hilly country.
- In the case of an in-and-out meter, the requirement of a lead-acid battery for overcharge must be taken into account.

Another method of performing the fuel gauge function is to measure the battery terminal voltage under known conditions. A proprietary "fuel gauge" such as this has been developed by General Electric and is planned for use in the baseline vehicle.

(a)

(b)

Full-Wave Half-Controlled Rectifiers

(c)

Full-Wave Phase-Controlled Rectifier Midtap Connection

(d)

Rectifier with High-Frequency Chopper

Figure 51. Battery Charging Circuits

PROPULSION

INTRODUCTION

Propulsion System Alternatives and Tradeoffs

The function of the propulsion system is to convert the battery energy to vehicle tractive effort. The main elements involved in the propulsion system are:

- Traction motor
- Power conditioning unit
- Drive train

The technical options available for each of these elements are discussed below and several sample propulsion systems for a 3000 pound electric vehicle are described.

Table 18 lists a number of possible propulsion system configurations. They are presented for the purpose of forming a framework on which to discuss the application of the system elements: motors, transmissions, electrical power conversion units, transient energy storage features, and control intelligence. The systems are not meant to be optimum nor does the list include all of the possible systems. Rather, it is intended to include all of the likely system elements and to show them in at least one practical system connection.

Propulsion Systems Using a DC Motor

Systems D1 through D4, shown in Table 18, use a dc motor. The basic incompatibility in these systems is that a motor directly geared to the wheels is subjected to a wide speed range. Thus, it requires a wide range of motor voltage and current for efficient operation. The battery is a source of fixed voltage and limited current. The solution to this incompatibility is to provide a means of either varying the battery voltage or restricting the motor speed range.

The chopper in System D1 or the battery switching arrangement in System D2 provides a means for varying the battery voltage and furnishing a motor current much higher than the battery cell current. The shifting transmission in System D3 and the IVT (infinitely variable transmission) in System D4 provide a means for limiting the motor speed range. These same elements can be arranged in other combinations.

All of these systems have been installed in vehicles and shown to be practical but not necessarily optimum.

Table 18
PROPULSION SYSTEMS

Propulsion Systems	Motor	Armature Control	Field	Mechanical Drive	Motor Speed Range
<p>SYSTEM D1</p>	DC Series	Chopper	Series	---	Wide
<p>SYSTEM D2</p>	DC Separately Excited	Battery Switching Starting Resistor or Chopper	Separate, Controlled	---	Wide
<p>SYSTEM D3, D4</p>	DC Separately Excited	Start Resistor	Separate, Controlled	IVT Shifting Transmission	Narrow
<p>or PERMANENT-MAGNET SYNCHRONOUS MOTOR (ECM) SYSTEM D5</p>	AC Induction	Force Commutated Inverter	Induction	---	Wide
	ECM		Permanent Magnet		Wide
<p>SYSTEM D6, D7</p>	AC Synchronous	Line Commutated Inverter Rectifier	Separate, Controlled	IVT Shifting Transmission	Narrow

Propulsion Systems Using an AC Motor

Systems D5, D6, and D7, shown in Table 18, use an AC motor. This provides savings in costs and motor maintenance by eliminating the commutator, but it introduces a new incompatibility: the DC voltage of the battery vs the AC requirement of the motors. Therefore, these systems include a solid-state power inverter or power conditioning unit.

System D5 in one case uses an induction motor -- the simplest, most rugged AC motor -- for traction applications. As in System D1, the motor is operated over the full vehicle speed range. Thus, it requires an inverter that provides variable output voltage and current as well as a variable output frequency. Instead of an induction motor a permanent-magnet synchronous motor may be used which, when controlled properly by synchronizing the AC line currents with the rotor positioning, has the characteristics of a DC motor. Such a system is often called an electronically commutated motor (ECM), since commutation is accomplished by the use of power semiconductors rather than the mechanical commutator of a DC machine. The advantage of the ECM is the higher efficiency (up to 10 points) compared to the DC machine as explained below.

The inverter selected to accomplish this will have the broadest performance requirements of any of the solid-state converters considered. The force-commutated inverter shown for System D5 could take several forms, but all of them are at present relatively expensive to build. The system has been used in on-the-road vehicles with good performance, but with a cost penalty in the inverter because of the broad requirements imposed on it. By employing high-current power transistors in power module form the cost of the inverter can be brought down so that the motor-inverter combination cost can be competitive with the DC drive system. It is felt that power module technology is the key to making an AC drive economically competitive with DC drives.

Systems D6 and D7 are similar to Systems D3 and D4 in that they provide a variable-ratio mechanical transmission to restrict the speed range of the motor. This allows the motor to operate at a more nearly constant voltage. Thus, the inverter does not have to produce a variable voltage and can be of the less complex line-commutated type.

Candidate Systems for the Reference Vehicle

System D1, which uses an inline chopper and a series DC motor, is by far the most predominant system in use today (e.g., in electric fork-lift trucks). System D3 or D4 is presently drawing considerable interest because of the rating reduction (and hence cost reduction) in the chopper. The chopper needs to control only the smaller field current rather than the full armature current. At present, AC systems are more costly than DC systems. Consequently, considerable development work is required before the AC systems

can match the DC systems in cost and performance. Although experimental AC systems have been built, they should be considered advanced systems.

On the other hand, DC propulsion systems are well developed and economically practical. Therefore, they are well suited for the reference vehicle. The components involved in the systems in Table 18 are discussed below, with emphasis on the DC traction motor and the DC-DC converter.

CANDIDATE MOTORS FOR ELECTRIC VEHICLES

Vehicle speed and gear ratio normally set the motor speed range at 0 to 5000 rpm. The motor candidates are (Figure 52):

- Series DC motor
- Separately excited DC motor
- Induction AC motor
- Synchronous-type AC motor

Figure 52. Motor Candidates

DC Series Motor

To date, the majority of the propulsion applications utilize the series DC machine for three basic reasons:

- No separate excitation source is required; the field is connected in series with the armature.
- Its torque-speed characteristic automatically results in high torque values in the low-speed, and low torque values in the high-speed range.

- The field strengthening at overload conditions counteracts the demagnetizing effects of the armature reaction.

These advantages are accompanied by several disadvantages:

- Field control (field weakening) is accomplished by shunting some of the armature current that involves high current values. This becomes significant in modern drive systems, where this type of control is to be performed through semiconductor switches. In the old form, with variable resistors parallel to the field winding, it was less efficient and required heavy-current resistors, which are usually large.
- Regeneration requires reversal of the field windings. This results in the interruption of the armature electrical circuit by means of breakers or static power devices when changing from motoring to braking. This interruption may, in some cases, be at higher current levels. If the energy generated during the braking process is to be utilized for other purposes than heating, voltage and torque control of the series-wound machine becomes very difficult.
- In most applications involving series-wound machines where regeneration is desired, the field winding is connected to a separate power supply during the regeneration operation, and thereby effectively converted into a separately excited generator. In this case, the field power supply has to provide large current at extremely low voltages. This is difficult to obtain efficiently with either a mechanical (variable resistors and breakers) or a semiconductor-controlled power supply.

DC Separately Excited Motors

Regeneration has been shown to be advantageous for multi-stop vehicles reaching peak speeds above 30 mph. The standard, separately excited, DC rotating machine has control characteristics in the motoring and generating modes that are extremely desirable for a drive motor in a regenerative system. Armature voltage control combined with field control will give the same extended operational speed range as for a series-type machine. However, a separately excited machine will allow smooth transition from the motoring mode to the generating mode without switching the windings. The low field current level will result in a highly efficient field control. The power conditioner, for use with a DC machine, is relatively inexpensive. The existence of a mechanical commutator inside the machine results in a machine that is slightly ($\sim 20\%$) heavier than a comparable AC induction motor.

Tradeoffs against improvements in overall system performance, size, weight, and cost may justify modifications in the motor. Wider field controlled speed range is desirable, but will require more iron in the motor to achieve full armature voltage at a lower

speed. Compensating windings need to be provided for stable operation at weaker fields. These may be minimized by increasing motor speed to reduce weight.

Motor manufacturers presently have the capabilities of increasing efficiency by making the following modifications:

- Increasing the copper content in the rotor to reduce armature $I_a^2 R_a$ (resistance heating) losses
- Increasing the copper content in the field structure (or using permanent magnet excitation) to reduce (or eliminate) $I_f^2 R_f$ (resistance heating) losses
- Reducing lamination thickness to reduce iron losses
- Switching from common silicon iron to a lower loss iron and/or increasing core length ("stacking out" the motor) to reduce iron losses
- Improving the bearing, fan, and brushes to reduce mechanical losses (windage and friction)
- Reducing the air gap to minimize excitation requirements

All these changes result in increased costs, and most result in increased motor weight. In DC machines, the motor frame is used as part of the field's magnetic circuitry, so that the increased weight cannot be compensated for by employing cast aluminum frames as has been done in new induction motor designs. But the end shields, mounting feet, and brush assemblies can be weight-reduced by the use of aluminum and engineering plastics.

Typically, an electric vehicle will operate under peak torque conditions only during acceleration when the needed peak motor shaft torque can be 5 to 10 times the torque needed to cruise at 45 mph. For high speed motor drives, the mechanical losses associated with the motor and gearbox predominate during high speed and low or moderate torque conditions, which makes it difficult to obtain good overall electric vehicle system efficiency. Many recent designs tend to match propulsion motor speed to the drive shaft speed as closely as possible (2500 to 4500 rpm).

Typically, the losses in an EV traction motor operating at rated conditions can be approximately broken down into the following categories:

- Armature copper loss - 40 percent (including brush loss)
- Field copper losses - 15 percent
- Core losses - 25 percent
- Mechanical losses - 20 percent

The winding losses (field plus armature) are dominant especially during low speed, high armature current accelerating conditions when they can account for up to 75 percent of the total.

AC Induction Motor

The induction motor has the advantage of low cost (industrial speeds), inherent ruggedness, low losses, and no brush friction. The most important features for this application are cost and weight. The motor's main drawback relates to the expense of the PCU (power conditioning unit). The PCU must be a force-commutated inverter that provides excitation energy for the induction motor in both the motoring and generating modes. Either of these PCU's is significantly more expensive than the PCU for a DC motor or a synchronous AC motor.

AC Synchronous Motor

A synchronous AC machine would be more attractive than an induction motor because of the system flexibility provided by separate field control. With separate field control, a traction motor can provide commutation for a power inverter, thereby allowing the less expensive inverter to be used as the PCU. However, a synchronous motor is about equal in cost and weight to a DC motor.

Electronically Commutated Motor

The electronically commutated motor has its field supplied by a permanent magnet or magnets on the rotor. The machine size is reduced, compared with the DC, wound-rotor synchronous and induction motors because of the absence of brushes, slip rings, and windings on the rotor. Since there is no field winding loss, the efficiency of this machine can be up to 10 points greater than the above-mentioned motors. Since the PCU for a DC motor is the least expensive of all, it seems that a DC motor with shunt excitation is the best candidate with respect to total system cost, assuming a regenerative system. The characteristics and relative costs of various PCU's will be considered later in this section.

Multiple Motor Vs Single Motor Approaches

The question of the use of multiple motors or single motors was considered from several viewpoints. The most pertinent points are discussed below.

OEM Price and Weight Considerations

Motors in the 10 to 25 hp range were evaluated for cost and weight of motors in production. It was found that the AC severe-duty polyphase induction motors, DC industrial traction motors, and estimated electronically commutated motors the OEM price of two 10 hp motors was from 10 to 15 percent greater than the OEM price of one 20 hp motor. The weight of the two 10 hp motors was from 15 to 25 percent greater than that of the single 20 hp motor. The fact that both OEM prices and weights were taken from a rather limited range of incrementally structured product lines indicates there is no significant advantage one way or the other.

One would expect that manufacturing for high volume would favor the smaller motors with higher volume.

Drive Train Considerations

The use of multiple motors would give more flexibility in body design because the transverse axle would be eliminated. However, suspending and/or springing the motors is more complicated since the inherent cross-body support and the fully sprung motor support is lost. The single motor requires a single high-speed gear reduction and a low-speed differential that is inactive except when the wheels are operating at different speeds. This is less expensive and more efficient than multiple high-speed spur gear reductions with multiple motors. The concept of mounting the motors in the wheels is often suggested. Experience with heavy, earth-moving trucks utilizing this concept shows that large tires (or other shock absorbing means) have to be used to prevent shock damage to the motors. Even with precautions taken, the fatigue stresses are very severe. The problem of sealing the wheel against road dirt and corrosive spray is also very difficult. When this approach was considered, it was concluded that it would require a great deal of development to become practical.

Control Considerations

The single motor with mechanical differential is the simplest to control with a single power controller. Signal electronics can provide the antislip function. Should the rating of the power controller be such that it favors modular construction, then the multiple motor configuration would only replace a simpler signal electronic control.

Other Considerations

Since the total weight of the motors did not vary significantly, it follows that the volumes are nearly the same. The multiple motors should have more surface area, and therefore have better cooling. Probably this would prove a second order effort.

The use of two motors was not chosen for the vehicle designed in this contract because a single motor and a single control were commercially available that were adequate to propel the vehicle. However, the two-motor approach should be considered for each new vehicle, and the decision as to which drive should be used should fit the merits of the case. One cannot take the position that one drive will always be superior to the other for all applications.

CANDIDATE POWER CONDITIONING UNITS

The functions of a PCU (power conditioning unit) in an electric vehicle are to:

- Mate the propulsion motor to the available voltage source.
- Control the torque and speed of the propulsion motor by controlling the current, voltage, and frequency applied to the motor.

Several types of PCUs that have been considered are listed in Table 19. A circuit diagram and a few characteristics of the PCUs are shown for different conversion categories. Some of the general characteristics of each type of PCU are presented below.

Table 19

CHARACTERISTICS OF POWER CONTROL CIRCUITS

EXAMPLE	CONVERSION CATEGORY	OUTPUT VOLTAGE RANGE	RMS CURRENT GAIN ($I_{out} > I_{in}$)	EFFECT ON SOURCE	CIRCUIT DIAGRAM
CHOPPER	DC-DC	0-Input Volts	Yes	Draws high ripple current
LOAD COMMUTATED INVERTER	DC-AC	Must be greater than DC Input	No	Draws lagging VA from AC load
FORCE COMMUTATED INVERTER WITH VOLTAGE CONTROL	DC-AC	0-Input Volts	Yes	Draws small ripple current

Starting Torque

In order to start a motor at high torque, the PCU must deliver high current to the motor when it has no back-emf. Table 19 shows that two of the converter types can be operated at zero output voltage and the third one has current gain. The chopper and the force-commutated inverter can deliver high-torque starting performance.

The line-commutated inverter cannot start the motor at all, and accessory features must be provided if these circuits are to be used. (For example, temporary commutation can be obtained by using a single commutating capacitor at low speed.)

Bidirectional Power Flow

A second important characteristic of the PCU is its ability to handle power bidirectionally; e.g., in accelerating and regeneratively in braking. Only the force-commutated inverter has

this inherent characteristic when used with a battery. Bidirectional operation in the other circuits can be achieved by either providing switching contacts to reverse the function of a simple converter or duplicating the converter circuits in the opposite polarity to provide both a propulsion and a regenerative converter. The line-commutated inverter and phase-controlled rectifier are duplicate complementary converters. As such, they are normally combined to form a bidirectional line-commutated inverter-rectifier.

Power Semiconductors

All of the power converters shown in Table 19 employ SCR's (silicon controlled rectifiers) as the power switching devices. At the power levels required for a 3000 pound vehicle, the SCR is at present the most economical and practical choice, except for the field controller that may use power transistors (discussed later in this section).

The drive selected for the reference vehicle is based on the separately excited dc machine with an SCR armature chopper and a transistorized field chopper. The armature chopper is used for lower speed operation, to match the battery voltage to the lower motor voltage in an efficient manner. As the motor speed increases, the armature chopper is no longer needed and can be taken out of the circuit (bypassed) when the machine counter-emf equals the battery voltage. The motor is then connected directly across the battery and is controlled by the low power field chopper.

The drive described above was selected on the basis of the following advantages.

Higher Axle Ratio

Since the field is separately excited it can be weakened at higher motor speed to match the battery and counter-emf voltages. Thus, a given motor can be operated at considerably higher speed than the series motor, and a higher axle ratio can be used. With the higher axle ratio, there is more torque multiplication, with the result that less motor torque, and hence current, is needed to obtain low-speed tractive effort.

Also, since the machine speeds up faster than the series motor, it enters its more efficient region of operation sooner than the series motor.

Lower Field Current Ripple

Because the field is driven from a high-frequency transistor chopper and because the field inductance of a separately excited machine is considerably more than that of a series field, negligible current ripple (and hence field flux ripple) results. In a series machine, the field ripple is high. This is due to the decreased inductance and switching frequency of an armature

chopper. The separately excited machine thus results in lower hysteresis and idling current loss in the stator (obviating the need for a laminated stator). It also reduces torque pulsations, because the torque is proportional to armature current in the separately excited machine (for a given field current) but in a series machine is proportional to the motor current squared.

No Ripple Current in the Bypass Mode

When the armature chopper is bypassed the motor armature is connected directly to the battery, and ripple-free current results in both the battery and motor. Thus, losses due to armature chopping in both motor and chopper are eliminated.

From the above advantages, it was concluded that a more efficient, higher-performance drive would result from employing the separately excited machine.

Relative Costs of Power Conditioning Units

The presentday costs of the PCUs are compared in Table 20, together with the relative costs of the various units for a fully regenerative system. When considered as a part of the cost of the propulsion system, the PCU cost is similar to the motor cost.

Table 20

RELATIVE COSTS OF VARIOUS POWER CONDITIONING UNITS

Type	Relative Cost
Fully Regenerative Chopper	1.00
Line-Commutated Inverter-Rectifier	1.40
Force-Commutated Inverter	2.40

Motor Field Controls

The field controller will have an output power rating approximately 20:1 smaller than the PCU. It will take the form of a chopper and will be implemented with power transistors rather than SCR's because of the lower power rating.

Although the cost, weight, and losses of the field controller must not be neglected in the analysis, their impact on total system cost and performance is small.

CANDIDATE TRANSMISSIONS

The function of the transmission is to match the speed and torque of the motor to that required at the wheels. The simplest and most efficient arrangement is with no transmission at all; the electric motor is directly mounted at the axle.

For most types of motors the motor weight can be reduced if a transmission is used. In its simplest form, this would be a fixed gear ratio, incorporated in the differential housing of the axle. The next step in complication is a shifting transmission, of perhaps three or four gear ratios, that matches the vehicle torque-speed requirements to the optimum motor torque-speed performance area over a broad range of vehicle speeds, accelerations, and grades. The most complex is the IVT (infinitely variable transmission), where the transmission is required to do a substantial portion of the power control in both the acceleration and braking modes.

Shifting Transmissions

Incorporation of a shifting transmission with the electrical propulsion system reduces the period during which the traction motor must deliver high torque at low speed. This has two beneficial effects: 1) the physical size and cost of the motor can be reduced, and 2) the motor/battery system can be operated in a more efficient region of its performance map.

Size reduction comes about because, for a typical vehicle velocity profile, the highest wheel torque is required during the initial portion of an acceleration, when the power requirement is still relatively low. If the motor is sized to produce this torque without a gear shift, it will be capable of producing much higher power near the cruising speed than is needed in the vehicle. On the other hand, if the motor is sized to produce only the required power, and low-speed torque is produced with a lower gear ratio, a smaller motor can be used.

Concurrently with the use of a higher gear ratio at low vehicle speed, the motor/battery current will be reduced, thus increasing the energy utilization efficiency during the acceleration period in comparison with a single ratio drive, as shown in Figure 53. The efficiency of a shifting transmission is well over 90 percent at rated design. Developmental problems entailing their use would be minimal.

Figure 53.
Energy Utilization
Efficiency During
Acceleration

Infinitely Variable Transmission

The IVT can be used as the ultimate example of a shifting transmission. The use of a mechanical IVT in automotive vehicles has had obvious merits for many years. As a result, a substantial amount of development work has been carried out on both stationary and automotive applications. Applicable approaches to vehicles of the size under consideration fit into two general categories: traction and hydrostatic. Neither of these is available in practical form and will require substantial development.

PROPULSION TRAIN SELECTION FOR THE BASELINE VEHICLE

General Electric analyzed five propulsion train systems to select a sound approach for a baseline vehicle. The systems were updated and reviewed with Triad Services on an iterative basis. The five systems were evaluated as follows:

- DC Series Motor/DC Chopper

This system met the established performance goals and was favored because a significant infrastructure which supports this type of drive is on the industrial market. The system offered smooth, flexible, and continuous control capabilities.

- DC Shunt Motor/Switched Batteries/Switched Resistors/Field Control

This system also met the performance goals, and its controllability was almost continuous and smooth. The system offered a potentially lower first cost, but the supporting infrastructure was not as good as for the DC series motor/DC chopper system. The need for further experimentation was indicated.

- DC Shunt Motor/Shifting Transmission/Field Control

This system has much to offer in reducing the size of the drive motor, but it requires a clutching system that is smooth, efficient, and low-cost. The system was deferred for further development.

- DC Shunt Motor/DC Chopper/Field Control

This system results in the most efficient DC drive, because the armature chopper is used only for starting and low-speed operation. For cruising, the armature chopper is bypassed and vehicle control is accomplished by field control. This system also allows operation over a wider speed range than the series motor, since the field can be weakened efficiently to obtain high speed, and smooth efficient operation with no shifting transmission is possible. The capability of regener-

ation can be added more easily than with the series motor drive.

- Secondary Energy Storage of Braking Energy

Flywheel and secondary battery systems were evaluated for recovering braking energy. These systems offered increased urban cycle range. However, the flywheel system is in the development stage, and the lead-acid battery's ability to charge and discharge rapidly is a subject of continued discussion. This system was also deferred for further experiments and developments.

The DC shunt motor/DC chopper/field control was selected as the best system. The lead-acid battery was the only type of battery available for immediate application. Therefore it was the obvious choice. The major components are:

- 18 ESB Model EV-106 electric vehicle batteries -- nominal voltage 108 volts.
- 1 General Electric Model BT-2364 DC shunt-wound motor -- nominal one-hour rating at weak field, 3500 rpm, open fan cooled, 25 hp.
- 1 General Electric Model EV-1 DC SCR chopper controller (modified) -- nominal voltage 108 V, nominal battery current 350 A, nominal motor current 850 A.
- 1 DC transistor chopper field controller developed by GE to control field power.

All these components are commercially available, except the developmental transistor field chopper.

ADVANCED AC VS DC DRIVES

Using conventional state-of-the-art motors and controls favors the DC drive primarily because of the much more costly AC control, even though the AC motor is smaller, lighter, and less costly.

A tradeoff study was made on the projected size, weight, cost, and efficiency of both DC and AC drives utilizing advancements in technology over the next five years. Power transistors, rather than thyristors, and power module controls were considered for both DC and AC drives. The current-fed permanent-magnet rotor synchronous AC motor (an electronically commutated motor (ECM)) was found to have the greatest potential for low cost, size, and weight, and high efficiency (see Table 21).

Table 21

COMPARISON OF SYSTEM OEM PRICES

<u>DC Motor And Control</u>	<u>Motor</u>	<u>Control</u>	<u>System</u>
State-of-the-Art low volume	\$1370	\$ 817	\$2187
State-of-the-Art high volume	675	624	1299
Transistors and Power Modules - (low volume)	675	220	895
Transistors and Power Modules - (high volume)	675	110	785
<u>ECM Motor and AC Control</u>			
ECM and Transistors and Power Modules - (low volume)	240	740	980
ECM and Transistors and Power Modules - (high volume)	240	370	610

Electronically Commutated Motor (ECM)

General Electric has demonstrated an ECM that utilizes conventional induction motor stator punchings, modified but similar stator windings, and a relatively simple rotor construction containing rare-earth permanent magnets. This configuration utilizes much of the proven low-cost, high-volume induction motor manufacturing techniques. The motor uses essentially the same amount of stator materials, with the manufacturing complexity essentially the same or perhaps simplified. The rare-earth magnets increase the cost of the rotor materials while decreasing the rotor manufacturing complexity.

The overall effect should be essentially an equal tradeoff, or with only a nominal adder for the ECM motor compared to the induction motor. The advantage is that for the same physical size, the ECM has essentially twice the power rating of a conventional ac induction motor. The ECM will weigh approximately 50 percent as much as the equivalent dc propulsion motor and will operate at 10 percent higher efficiencies.

OEM Price Projections

The OEM price for the induction motor is \$20/hp at the 7.5 hp rating. The ECM motor of the same size is \$10-12/hp at the 15 hp rating. This may be the largest size that could be manufactured easily in high volume and at low cost. For greater horsepower, multiple motors could be mounted in the same frame or could be operated individually, on a common shaft or driving separate wheels. \$10-12/hp is used as the OEM price for ratings through 30 hp.

OEM Price Comparisons (at 24 Hp Nominal)

The OEM price is \$55/hp for industrial forklift truck dc motors when built in low volume. Projections show this decreases to \$28/hp when motors are built in volumes of 100,000 per year. Polyphase ac induction motors of the same rating manufactured in high volume vary from \$24/hp, for the severe-duty type, to \$16/hp for the standard duty type.

The OEM price for a nonregenerative DC-DC chopper with associated controls is \$34/hp. Projections for 100,000 units per year show this decreases to \$26/hp.

Comparison of Power Control Circuits

Analysis of several types of power circuits amenable to electric vehicles indicates that the nonregenerative chopper has the lowest OEM price; the regenerative chopper has an OEM that is 1.4 times the nonregenerative chopper; and the force-commutated inverter (as well as the circuit for the electronically commutated motor) has an OEM that is 2.4 times the regenerative chopper. The weight of the ac control is about twice that of the DC, and the efficiency is about 5 percent less.

Device and Assembly Comparisons

Development of transistors suitable for electric vehicle power circuits should reduce the complexity, size, weight, and cost over thyristor-controlled circuits by 30 percent. The development of power modules with improved heat transfer, the elimination of clamping devices, and module techniques that enhance high-yield, high-volume production should reduce the basic circuit size, weight, and cost by 50 percent. Specially tooled high-volume production offers the opportunity to reduce the cost another factor of 50 percent.

Comparison of System OEM Prices

Table 21 and Figure 54 show the comparison of system OEM prices for DC and AC (ECM) drives.

System Weight and Efficiency

The ECM drive system should weigh 25 percent less than the DC system and the efficiency should be from 7 to 10 percent higher.

COST TO VEHICLE
MANUFACTURER

- A: CONVENTIONAL DC TRACTION MOTOR WITH
CONVENTIONAL POWER CONDITIONING UNIT
- B: CONVENTIONAL DC TRACTION MOTOR WITH
INTEGRATED POWER MODULE
- C: ELECTRONICALLY COMMUTATED MOTOR
WITH INTEGRATED POWER MODULE

Figure 54. Projected Relative Drive System Costs
(1.0 = Low Volume Present-Day Chopper-
DC Drive)

ELECTRICAL ACCESSORIES AND SIGNAL LEVEL CONTROLS

Although not usually highlighted in discussions of electrical vehicles, accessories and controls play an extremely important role. This will be particularly true as vehicle control systems become more complicated with energy saving schemes requiring optimized control over a range of missions. Some of the major elements are discussed in this subsection.

ACCESSORIES AND ACCESSORY POWER

The accessories consist of a complete automotive lighting set, heater, defroster, rear-window defogger, radio, and a suitable instrument cluster to clearly display the appropriate parameters. Use of a 12 volt accessory power system allows the use of standard automotive components in the reference car. Methods of obtaining this voltage from propulsion system voltage are discussed below.

Methods of Obtaining Low-Voltage Accessory Power

Simply tapping into a 12 volt segment of the propulsion system cell for 12 volts is not practical, because of the unequal loading that would result in the cells. Therefore, a DC-to-DC converter to stepdown the higher propulsion system voltage to a 12 volt level will be used to supply the auxiliary power. A small, 12 volt battery will provide stability and power for hazard flashers. A DC-to-DC chopper circuit such as that discussed earlier could be used. However, the stepdown ratio is high, resulting in a relatively short "on" time for the semiconductor switch as compared with the total switching period. Because of the lower power levels required, more sophisticated PCU circuits can be used.

A more suitable approach, shown in Figure 55, uses the same high-frequency switching principle but employs a high-frequency transformer to better match the high voltage source at the desired accessory voltage level. Since the switching frequency is high (approximately 20 kHz), the size and weight of the transformer is greatly reduced over a conventional 60 Hz transformer. Figure 56 shows the reduction in transformer size possible for a 600 VA transformer.

The approach is based on maximum utilization of the power transistors and the power transformer. The higher propulsion system's DC voltage is inverted in a two-transistor inverter run at 20 kHz, quasi-squarewave, variable duty cycle; the two power transistors provide both inversion and control of the voltage and the current. The secondary of the transformer is rectified by fast turnoff diodes. The output inductor, L1, is effective in smoothing the 40 kHz current ripple.

Figure 55. High-Frequency Power Converter with Transformer Isolation to Obtain Accessory Power

Figure 56. Comparison of 600 VA Transformer at 60 Hz and 20 kHz

The mode of operation of the circuit is shown in the waveforms in Figure 57. The inverter normally operates at a constant frequency of 20 kHz. The pulsewidth, or duty cycle, is controlled to maintain constant peak flux in the power transformer, resulting in optimum utilization of the transformer. Another result is a constant open-circuit secondary voltage on the power transformer that makes the output DC voltage independent of the input voltage and constant, except for a defined droop with load caused by losses of the transformer secondary, rectifier, and inductor.

Figure 57. Operating Waveforms for the High-Frequency Converter

If the collector current in the power transistors exceeds the rated load, the inverter pulsewidth or duty cycle is controlled to maintain constant peak current to the transistors. This results in a more or less constant output current into loads heavier than rated. Frequency is also depressed in the constant-current operating mode; hence the very low duty cycle will not result in very short conduction time.

While the above discussion has centered around one particular method of control, variations are possible to obtain the most efficient design suitable for an electric vehicle application.

Accessory Power Requirements

Table 22 lists the power requirements of the typical automotive components. The heating and air conditioning loads would be the most significant contributors to decreasing the vehicle range, if their power were obtained from the electrical propulsion source.

Passenger heating and cooling cannot be overstressed in the design of an electric vehicle. Since there is little waste heat available from the motor and control system, alternate methods must be found to heat the passenger compartment for cold weather operation. Emphasis must also be placed on thorough thermal insulation of the passenger compartment.

Summer cooling also provides a challenge. Conventional air conditioning systems drain considerable power from the propulsion system, as seen in Table 22. Defogging and defrosting pose additional practical and legal problems.

Table 22
TYPICAL ACCESSORY LOADS
FOR A FOUR-PASSENGER SUBCOMPACT VEHICLE

Device	Watts	Amperes @ 12 Volts
Radio	19.2	1.6
Headlamps, Low	93.6	7.8
Side Marker Lights	84	7.0
Parking Lights		
Interior Lights		
Windshield Wiper, High	21.6	1.8
Rear-Window Defogger	240	20
Hazard Flasher	106.8	8.9
Heater Blower Motor, High	96	8.0
Heating and Defrosting (25,000 Btu/hr)	5848	58.48 @ 100 volts
Cooling (13,500 Btu/hr)	3947	39.47 @ 100 volts

Extracting heat from the battery source will significantly decrease vehicle range. Alternately, a fuel-burning heater can handle winter heating and defrosting. Ventilation can be accomplished through internal duct work and a sunroof.

A tradeoff study encompassing vehicle range, performance, and passenger convenience and comfort must be made to determine the best method of accomplishing the heating and cooling tasks.

VEHICLE CONTROL

Signal-level electronic controls make it possible to maximize the utility of an electrically powered vehicle by measuring, processing, and controlling a relatively large number of variables. Fortunately, much of this variable manipulation can be accomplished with a negligible weight penalty, at low power levels. Examples of electric vehicle systems in which signal-level electronic control can be used are:

- Operating the vehicle under optimum energy utilization conditions.
- Optimizing charging of the battery.
- Determining diagnostic and predictive information for display and control.
- Maintaining occupant safety, comfort, and convenience.
- Integrating special safety functions, such as skid control.

Examples of functions that will be included in the reference car are:

- Control of battery charge and discharge rates.
- Conversion of operator-requested functions to appropriate device activation and malfunction alarm indications.
- Monitor and display of remaining battery capacity.

Assuming a dc shunt motor driving through discrete ratio mechanical transmission, the electronic control interfaces with the system are shown in Figure 58.

Figure 58. Electronic Control Interface with the Propulsion System

In this system, the basic vehicle control system is required to:

- Control the armature current and the motor field in the "throttle" position, and control the armature current as modified by actual and projected motor temperature.
- Control the recharging rate of the battery (assuming a partially regenerative braking system), to avoid damage and to maximize battery life and availability on the basis of measurements of the battery voltage, current, and temperature.
- Provide appropriate operator alarms of impending energy exhaustion, component failures, or abusive practices.

The control functions in an electric vehicle may be implemented by digital and analog integrated circuitry or by a purely digital approach employing a microcomputer system. The decision on which approach to use depends on the complexity of control and the required performance. Most microcomputer systems at present require a number of integrated circuit chips in addition to the microprocessor itself. For example, the 8080 PCU typically requires a clock generator and driver, system controller, read-only memory (ROM), and random access memory (RAM) as well as interface circuits to allow communication with the "outside world." The microcomputer system has the capability of controlling the vehicle drive system as well as controlling the battery charging and providing diagnostic functions.

For the reference electric car drive, commercially available components are to be used to the greatest extent possible. Since most of these components have control circuits already developed as part of the equipment (such as the EV-1 armature chopper), only a minimal amount of hardware has to be developed to interface with the equipment. If a microprocessor control were developed to perform this function it would be underutilized. To be viable, most of the vehicle and battery charging control should be done with microprocessor control.

Since the reference car drive is making use of existing components, it was decided that the soundest approach would be to use the control circuits already developed and implement the necessary vehicle interfaces by using off-the-shelf digital and analog integrated circuits.

Longer-range developments of advanced drive systems will determine the proper role of microprocessor systems.

REGENERATION AND SUPPLEMENTAL ENERGY STORAGE

Figure 59 shows a plot of propulsion power vs time for a typical 3000 pound battery electric car. The upper curve shows the instantaneous power drawn from the battery by the motor. A portion of this power is dissipated as electrical losses. The portion available as power to the drive train is shown as the intermediate curve. Part of this power is then lost as tire rolling resistance, friction and windage, bearing losses, and transmission losses. The lowest curve shows the power converted to kinetic energy. The area under the curve is equal to the energy stored in the vehicle.

Figure 59. Electric Drive Power Profiles

Once the vehicle has reached its maximum speed, the power drain from the battery is reduced to typically a third of the peak value. At this point in the driving cycle, if vehicle velocity is held constant, the power drained from the battery is consumed as losses in the motor, aerodynamic drag of the body, rolling resistance of the tires, and the mechanical inefficiencies of the drive train.

A key to improving range is to recover braking energy when by regeneration the vehicle stops. The portion shown under the curve (Figure 59) as "Vehicle Kinetic Energy" is now available to be recovered in a regenerative braking system. Normally this energy is dissipated as heat in the friction braking system. A portion of this available vehicle kinetic energy is lost as a result of the rolling resistance and vehicle drag as the vehicle comes to rest.

If the traction motors are used as generators, a further portion is lost to electrical losses in the generator. What remains is that portion of the available kinetic energy indicated as "Braking Energy for Potential Recovery." Depending upon component efficiencies, this energy can amount to approximately 50 to 75 percent of the total vehicle kinetic energy. The "Braking Energy for Potential Recovery" is available for recovery in a secondary battery, a flywheel, or by recovering a portion of the energy in the lead-acid system. It is important that this recovery system have a high efficiency. This can have a significant effect on range for a multistop-per-mile application.

If the energy is not recovered, the effect on vehicle performance is shown in Figure 60. The number of starts and stops in the mission is extremely important to vehicle range. Each time a vehicle stops, the brakes thermalize the accumulated kinetic energy during the stopping process. This energy must again be accumulated in the moving vehicle as it accelerates to speed. Observations of the range of electric cars in sustained driving without repeated stops gives no real insight into the range to be expected in normal traffic patterns. In city traffic, with perhaps four to six stops per mile, the range may be reduced to a third of that which would be obtained in constant-speed driving. Typical urban cycles in the United States for a subcompact car are about four stops per mile. Mail delivery trucks may have as many as twenty stops per mile. Delivery vans average between seven and ten stops per mile. The SAE J227A metropolitan driving cycle has one stop per mile.

Figure 60. Battery Electric Car Range vs Number of Stops per Mile

In addition to recovering the making energy, a significant improvement can be made by making the peak power peaks from the battery. Ideally the battery prefers to deliver its energy at a constant discharge rate. By means of a secondary energy storage device such as a hybrid battery or flywheel system the accelerating peaks and making-energy absorption entries can be removed from the lead and main battery. By proper programming, the load on the main battery can be kept essentially constant.

REGENERATION TO THE MAIN BATTERY

The energy recovery approach most frequently proposed is the use of the main propulsion lead-acid battery package. Unfortunately, the lead-acid battery as it is designed today cannot accept the high rate of charge unless the battery bank is in a low-discharge condition. Typically, when the battery pack nears its full-charge condition, battery charging currents must be limited to avoid excessive gas generation. Even then, the charging efficiency is only about 70 percent. With regeneration back into the battery only a nominal improvement in range results, because of the inefficiency of the fast charging rates on the lead-acid battery plus the inefficiency of energy conversion from mechanical to electrical and back again.

LOAD LEVELING WITH HYBRID BATTERIES

An investigation of a hybrid battery for load leveling was conducted for comparison with the flywheel system. The systems studied had an open-circuit voltage at 108 volts to operate in parallel with the main lead-acid battery. The hybrids were sized to deliver 200 watthours in one acceleration cycle of 28 seconds with a peak power of 20 kW. Only commercially available systems were considered.

The three most viable candidates selected were the lead-acid, the nickel-cadmium, and the silver-zinc systems. Nickel-iron was not considered because of its poor specific power capability. Comments on each system follow:

- Lead-Acid. The power delivery rate of lead-acid is the limiting factor. About 1000 pounds of traction batteries are required to deliver the 20 kW peak. To date, batteries have not been designed for higher discharge rates rather than energy storage. It is felt that even if designed to the limit of power delivery, the batteries would still be too heavy and would have short life, since each acceleration would essentially be one discharge cycle.
- Nickel-Cadmium. The nickel-cadmium battery has performance characteristics well suited to this duty cycle. A 100 to 150 pound, 11 ampere-hour battery with 108 volts open circuit would be required to meet performance with reasonable cycle life. However, the availability of materials for high-volume utilization may be questionable,

and the OEM price of this battery projected in large volume is in the order of \$2500. It is very unlikely that cost reduction programs can make this system economically viable.

- Silver-Zinc. The silver-zinc battery is very well suited for high power discharge rates and is accompanied by good energy storage capability. However, the cycle life is quite limited, silver is a rare material, and the cost of the battery is prohibitive.

It was concluded that the hybrid battery system was not a viable system when both performance and cost were considered. It was felt that the flywheel system with its almost infinite life would be a much better candidate for load-leveling the main battery.

LOAD LEVELING BY FLYWHEEL

One of the most significant ways to increase vehicle range with a fixed battery is to load-level the battery by using a flywheel to supply power for acceleration and to absorb and store energy during deceleration. Figure 61 is a schematic diagram of an electric car propulsion system with a flywheel for load-leveling the battery. In operation a constant power is drawn from the battery. If more power (than the amount supplied by the battery) is needed, this additional power is taken from the flywheel. When the vehicle stops, the braking energy is returned to the flywheel. If the vehicle is stopped, power is taken from the battery at a constant rate to bring the flywheel up to the required speed.

Figure 61. Propulsion System with Flywheel for Load Leveling

As indicated in Figure 62, the effect of load leveling on range is dramatic. Using the latest battery model, the latest motor model, and a prototype flywheel and control weighing 275 pounds, and with a payload of 300 pounds, the upgraded GE electric car range would be 51.6 miles, as compared with the reference car range of 39.3 miles. A redesigned flywheel and control would reduce the weight by 100 pounds and increase the range approximately 2 miles. Elimination of the battery charger and weight reduction of the vehicle propulsion control by using electronically commutated motor and power module controls would reduce the weight another 175 pounds, with an additional range minimal of almost 2 miles. The vehicle total weight would remain constant.

Figure 62. Range vs Payload Comparison for Battery Alone and Battery with Flywheel Load Leveling

Section 5

RECOMMENDED UPGRADING PROGRAMS

INTRODUCTION

Based on the results of the tradeoff studies and a review of the program, it was recommended that the two-year time frame of vehicle development best suited ERDA's requirements. Additional analyses and tradeoffs were made (adjusted to a 600 lb payload rather than 300 lb as used previously) on those developments which deemed to offer the most improvement and which could be accomplished in two years. Upgraded performance and cost predictions using these improvements were made and compared to ERDA goals. These became the basis for the recommended program to develop the upgraded Integrated Electric Test Vehicle.

UPGRADING PROGRAM

The all-electric drive proposed in the reference design is highly desirable in light of the improvements promised in transistor and power module developments. Expected cost reductions in high volume production should make this approach highly competitive with other drive systems. The all electric, when made cost competitive, has proven to be a simple, efficient, reliable, and truly continuously variable speed drive in related applications such as forklift trucks, transit cars, and electric locomotives.

The DC drive was selected since it can be upgraded in two years. The separately excited motor with armature and field choppers was preferred over the series motor with armature chopper since it reduced peak demand on the battery and increased efficiency by removing the armature chopper when switching to the lower power level field chopper control. It also greatly simplifies the control in regeneration.

The upgrading programs recommended are:

- Power electronics
 - Transistorized power module electronics
 - Regeneration
 - Combined power control/battery charger
- Improved DC separately excited motor
- Microprocessor control
- Improved state-of-the-art (ISOA) battery
- Vehicle safety and weight

A discussion of these improvements follows.

POWER ELECTRONICS

A program to identify or develop suitable power transistors and to incorporate them in the power circuitry would make substantial improvements possible. The two most important improvements are: reduced size, weight, and cost by elimination of the commutating circuit required by SCR controls; and elimination of or reduction in size, weight, and cost of the reactor required in series with the armature resulting from the higher frequency capability.

The use of power module technology would have several major advantages. The first is its adaptability to the use of manufacturing techniques that offer higher production yields, improved quality, increased reliability and lower cost. The second is its ability to provide improved packaging with smaller size and weight. The third is its reduced thermal and electrical losses in mounting and connecting to the semiconductors and components which increases efficiency and also reduces size and weight.

The requirement to provide power control of regeneration would add some complexity and additional cost to the controls. However, the gain in range and in stop-and-go driving offered by regeneration would be enough to more than offset this additional complication.

The onboard battery charging function could be incorporated with minimum additional effect in the power electronics controls since these circuits have not yet been developed. This would add some complexity to the circuits and would possibly reduce reliability of both functions slightly. However, the gain offered in reduced cost, size, and weight by eliminating a major component would more than compensate. It is yet to be determined whether it would be better to combine this function with the armature chopper or the field chopper. The rating of the field chopper would have to be increased slightly if it is preferred. The armature chopper is basically designed for currents an order of magnitude higher than the charging requirements and might not operate efficiently nor control as well at this light load condition.

IMPROVED DC SEPARATELY EXCITED MOTOR

Present motors of this type are based on designs developed for industrial material handling. Improvements are possible in increasing efficiency, the field controlled speed range, and the motor speed. Increasing efficiency and field control speed range imply increased cost, size, and weight, but this can be partially offset by speed increase. The design will also be affected by (and will in turn affect) the chopping frequency selected for the armature chopper. Many of the overall system gains are made possible by these motor improvements.

MICROPROCESSOR CONTROLS

The reference design used power electronic components that contained control circuits not developed to operate with microprocessor controls. The new design for the power electronics would make possible the optimum use of microprocessors in determining and executing circuit and control strategy. The high level of control offered by microprocessors is required to operate limited energy electric vehicles with maximum performance over varying missions and battery conditions.

IMPROVED STATE-OF-THE-ART (ISOA) BATTERIES

Battery improvements may have the greatest impact of all on electric vehicle performance. The final system design and performance would be based on using the ERDA ISOA battery which is expected to be available at the end of the two-year period. During the course of the program, batteries with improved performance over the EV-106 would be sought and utilized in the Integrated Electric Test Vehicle.

VEHICLE STRUCTURE, SAFETY, AND WEIGHT

An additional review of tradeoffs of vehicle features such as rearward facing seats, hinging of the doors, and front wheel drive would be made before commencing final vehicle development programs. Detailed structure and crashworthiness programs would be conducted (as well as heating and ventilating) to determine if the reference design is in accordance with FMVSS and make appropriate changes. The program would not undertake certification testing that the vehicle fully complies with these standards. Finally, lightweight structural materials would be considered to improve vehicle weight provided they are available in the time frame and cost and producibility goals can be met.

The major electrical components recommended for development and inclusion in the Integrated Electric Test Vehicle were compared with those selected for the Reference Electric Car and are summarized in Table 23.

CALCULATION OF UPGRADED PERFORMANCE

Performance calculations were made based on the expected improvements made during the two-year period. The more pertinent effects included were:

- Payload adjusted from 300 to 600 lb. The predicted reference and integrated vehicle performances are based on this new weight. (The initial tradeoffs were not repeated and are based on 300 lb.)
- The ISOA battery is predicted to have 18.15 Whr/lb (40 Whr/kg) at the three-hour rate, which is equivalent to 14.3 Whr/lb at the one-hour rate. This compares with 13.8 and 10.8 respectively

Table 23
COMPARISON OF MAJOR ELECTRICAL COMPONENTS

Component	Reference Design	Upgraded Integrated Test Vehicle
DC Motor	Modified GE Model BT 2364 DC separately excited motor, 25 hp @ 3500 and weak field 230 lb, 2 to 1 field control range max. Max. efficiency 87%.	Redesigned DC separately excited motor. Goals--Field control range 3 to 1 min., max. efficiency 90%, max. speed 6000 rpm, 230 lb, 25 hp at 5000 rpm and weak field.
Power Electronics	<p>Modified GE EV-1C SCR armature chopper control, 600 A max. Nonregenerative discrete part construction.</p> <p>GE developmental transistorized field chopper--30 A max. Discrete part construction.</p> <p>GE developmental ambient temperature compensated constant voltage onboard charger with current limit. 120 V input, 15 A max., 14-18 hour charge time. Discrete part construction.</p> <p>GE developmental ambient temperature compensated constant voltage offboard charges with current limit. 6-8 hour charge time. Discrete part construction.</p> <p>GE developmental 108 V to 12 V transistorized converter accessory power supply--20 A at 12 V. Discrete part construction.</p>	<p>New transistorized regenerative armature chopper control, 600 A max., power module construction. Goals--97% efficiency, 50% size, weight, and cost in high volume power module construction.</p> <p>New transistorized field chopper/temperature compensated taper controlled onboard battery with current limit. Goals--120 V AC or 108 DC input, 40 A max., 6-8 hours charge. Power module construction.</p> <p>New developmental 108 V to 12 V transistorized converter accessory power supply. Goals--20 A at 12 V. Power module construction.</p>
Batteries	18 ESB, Inc., EV-106 lead-acid batteries, 108 V nominal, 1182 lb, 10.8 Wh/lb at one-hour rate, 75 A for 106 minutes.	18 ISOA lead-acid batteries, 108 V nominal, 1182 lb, 14.3 Wh/lbs at one hour rate; 75 A for 140 minutes.

for the EV-106, or an improvement of 32%. The power capability should be adequate for hill climbing and passing, since the EV-106 is almost adequate without factoring in improved motor and drive efficiency as well as weight reductions.

- Major improvements in efficiency are hard to accomplish since they are already in the range of the high eighties to mid-nineties. Power circuit efficiency can be increased from 95 to perhaps 97%. Maximum motor efficiency can be increased from 87 to 90%. Improved field control speed range and higher speed should increase the low speed/high acceleration region efficiency by an additional 3% overall.
- Regeneration calculations had indicated an increase in range on the SAE J227A - Schedule D Urban Cycle of 13 to 15%. Independent

tests by Triad Services, Inc., on the copper development town car, verified this.

- Weight reduction affects the range of the urban cycle by approximately 5% per 100 lb over the range considered. Overall weight reductions predicted were modest, considering a weight reduction tradeoff in increased motor weight vs. reduction in series reactor weight and power electronics. Elimination of the battery charger was estimated at 50 lb. Conservatively, no weight reduction was allotted to the vehicle, though improvements are expected.

PREDICTED UPGRADED PERFORMANCE

All of the individual upgraded improvements were included in an overall calculation; the results are shown in Table 24. These results are compared to those calculated for the Reference Electric Vehicle and to the ERDA near-term goals. It is expected that the improvements in vehicle weight will be sufficient to achieve the urban range goal of 75 miles.

Table 24

COMPARISON OF GOALS AND CALCULATED PERFORMANCE

Parameters	ERDA Near-Term Goals	GE 1977 Reference Electric Car	Upgraded 1979 Integrated Electric Test Vehicle
Min. Passenger Capacity	4 Adults	4 Adults	4 Adults
Max. Curb Weight (lb)	Open	2942	2892
Min. Urban Range (miles)	75	34.7	66.4
Max. Initial Cost Project (1975\$)	5000	4667	3892
Min. Life (miles)	100,000	100,000	100,000
Max. Life Cycle Cost Project (1975\$/mile)	0.15	0.217	0.1644
Max. Electric Recharge Energy in Urban Driving (kWh/mile)	0.8	0.524	0.406
Max. Recharge Time (hr)	6	6 to 8	5
Min. Top Speed (mph)	55	60	60
Min. Accessories	Heater/Defroster	Same	Same
Min. Unserved Park Duration (days)	7	7	7
Min. Acceleration (sec for 0-30 mph)	10	10	9
Min Merging Time (sec for 25-55 mph)	25	30	25
Sustained Speed on 5% Grade (mph)	50	41.5	50
Battery Type	Open	EV-106 Lead-Acid	ISOA Lead-Acid
Min. Ambient Temperature Range	-20° to 125°F	-20° to 125°F	-20° to 125°F

Blank

Section 6

DEVELOPMENT PLAN

This section summarizes the development plans recommended by Corporate Research and Development at General Electric and its subcontractor Triad Services, Inc. The general objective of the programs outlined in the development plan is to enhance the acceptance of electric cars in the United States in order to lessen the use of oil-based fuels. The scope of the development plan includes all-battery electric cars as well as hybrid electric cars.

GENERAL PLAN

The general plan for the development of an improved electric car is presented in condensed form in Figure 63. This plan, as developed by the General Electric Company and its subcontractor Triad Services, Inc., covers a 55-month period from September 1976 through March 1981. The condensed schedule in Figure 63 shows the major work efforts by which this program, in conjunction with other specific battery developments, would enable upgrading of a state-of-the-art electric car by achieving the following major goals:

- A reference electric car would be available for ERDA evaluation in late 1977.
- Additional cars would be provided at prescribed intervals for ERDA evaluation of all improved battery types and all drive train and vehicle developments.
- Coordinated developments for all power train and energy storage developments would proceed at a rapid but economic pace.
- Vehicle developments would proceed in parallel with key component development to assure an electric car structure that meets current and planned standards.
- Marketing and manufacturing studies would be undertaken to assure that marketable products are developed which are feasible to manufacture.

FLYWHEEL ENERGY STORAGE PACKAGE

An alternate method of recovering the vehicle's kinetic energy during braking is by the use of a flywheel energy storage package. The flywheel system can absorb and deliver power at higher peak rates with a higher system efficiency than can a battery. The development work for the flywheel energy storage package should include the designing, building, and laboratory testing of a unit and the installation of that unit in a reference electric car allocated for the purpose.

Figure 63. Condensed Development Schedule -- Electric Car Project

The objective of this program is to provide a means of increasing vehicle range by recovering vehicle kinetic energy during braking and storing of this energy in a flywheel energy storage package. A secondary benefit requiring evaluation is related to softening the input/output surges to and from the main battery.

REGENERATION AND BRAKING PACKAGES

The reference electric car intended for ERDA would not have electrical braking capability. Probably the simplest scheme for electrical braking is that of modifying the DC power conditioner so that the braking energy can be absorbed by the battery as a partial recharge, hence, the term "regeneration." Computer simulation studies made to date indicate that the benefit from a regenerative power supply would amount to approximately 13 to 15% extension in vehicle range using the standard SAE J227A schedule driving cycle.

The existence of two braking systems, one electric and the other the normal automotive-type hydraulic system, would require some additional investigation to determine the proper means for operator control along with assurance that all applicable safety standards have been met. The blending of the two systems, the operation of either system without the other, as well as the energy savings are all items that must be studied.

The objective of this activity is to provide an increase in range through regeneration of vehicle kinetic energy into the main traction battery or hybrid battery system during braking. The optimum circuit configuration and control method for a DC drive system using a separately excited DC machine would be determined. This program is recommended for the two-year program.

BATTERY DEVELOPMENT

One of the key items in electric car development is the battery development necessary to increase the energy and power densities of battery systems over the present widely used lead-acid batteries. In general, these programs are being conducted as separate ERDA and manufacturer-sponsored programs. Although these battery development programs are not contractually a part of this electric car project, the battery development activity and the timing of expected output from this activity is shown because of the obvious tight coupling of the two programs.

It is proposed that all of the new battery types being developed receive periodic audits and that evaluations be made both at the manufacturer's laboratories and in an electric car specifically designed for battery testing. To keep the number of variables at a minimum, all other components of the car would be similar to the reference electric cars, the difference being in any special requirements (size, weight, charging) dictated by the specific battery.

The batteries currently visualized that would be suitable for electric cars with their approximate timing are:

- Improved state-of-the-art lead acid battery -- available for evaluation early in 1979. This is recommended for the two-year program.
- Zinc-chlorine battery -- expected to be available in a preliminary configuration early in 1978.
- Nickel-iron battery -- expected to be available for evaluation in mid-1978.
- Nickel-zinc battery -- expected to be available early in 1979.
- Advanced lead-acid battery -- expected to be available by early 1980.

The objective of this program is to conduct evaluations of advanced batteries as they become available.

ONBOARD CHARGER AND POWER CONDITIONER

For maximum utility, the electric car must have an onboard battery charger that is capable of recharging the batteries in approximately 6 hours or less. The reference electric car would provide two chargers--one an onboard unit with a charging rate established by the normal 15 A, 115 V distribution circuit with a full recharge time of approximately 18 hours; the other a heavy-duty stationary unit operating from 220 V, with a recharge time of approximately 6 hours.

A development would have to be initiated for a lightweight, onboard full-rated charger, one that can be plugged into either a 110 or a 220 V circuit. The investigation will include the use of high-frequency switching techniques as a means of reducing transformer weight and will investigate the possibility of sharing components with the propulsion power converter. This development activity will include a prototype unit, to be laboratory tested and then installed in a reference electric car for evaluation.

The objective of this activity is to develop a battery charging concept that results in optimum battery charging while minimizing the size and weight of the charger. A single full-rated (6 hour charge time), lightweight, onboard charger will be the goal of this development. The use of both onboard drive system components and power module technology to implement the charger is desirable and this development is recommended for the two-year program.

POWER TRANSISTORS AND POWER MODULES

There are two major areas where recent developments in power electronics set the stage for the electric car performance goals to be met within the desired cost goals for high volume production. These areas are the power switching devices themselves and the circuit assembly technology.

Advances in power transistor technology have so increased the power rating that it appears feasible to apply transistors to the power electronics in the electric car. The transistor allows the power circuit designer much greater flexibility in the design of the circuit, resulting in simplification, lower cost, and added function. Further development of transistors to reduce the switching losses and to match the circuit parameters to the electric car application will increase the advantages.

A power conditioner utilizing the developed power transistors and power module packaging techniques would be developed, tested in the laboratory, and installed in a reference vehicle allocated for this evaluation.

The objectives of this activity are to:

- Upgrade the electronic configurations of the vehicle drive system from the standpoints of cost, weight, and reliability.
- Demonstrate technology to efficiently produce low-cost, compact, lightweight, and reliable assemblies for the power electronics in the vehicle drive system.

This work is recommended for inclusion in the development of an advanced DC drive in the two-year program.

ADVANCED ELECTRONICALLY COMMUTATED DRIVE

For optimum performance, the electric car needs the highest efficiency and lightest-weight drive train possible. A development program to produce an advanced, lightweight, high-efficiency drive for the electric car should be undertaken.

Traditionally, DC drive systems have been employed in electric vehicles because the simple power conditioning requirements give an easy interface with the battery power supply along with a near ideal speed-torque curve. However, a DC motor has a larger weight and cost than an AC motor, and because of the commutator and brushes, requires more frequent maintenance. AC motors, however, require a more complex power conditioning in order to interface the DC of the battery with the AC of the motor. Advances in power electronics have reduced the cost so that the advantages of AC drives can now be exploited for electric cars. The permanent-magnet synchronous motor has the additional advantage of having the highest inherent efficiency of AC motors and is a strong candidate for electric cars. This development program would make an in-depth study of the many alternate drive types, with specific reference to the electric vehicle applications and drive cycles.

The object of this program is to formulate an optimum AC drive system for the vehicle which will provide better performance characteristics but at the same time will have higher efficiency, lower cost and weight, be more rugged and reliable, and have fewer maintenance problems compared with

an equivalent DC drive system. A preliminary study and evaluation of AC drives has already been made, and at this point the electronically commutated, permanent-magnet synchronous machine drive system seems to be the most viable candidate. This should be considered for the five-year program.

ADVANCED DC DRIVE

Significant improvements in DC drives can be made by modifying the motor at some expense in size, weight, and cost to obtain better overall system improvements. Increased motor efficiency, wider field controlled speed range, and higher speed, when coupled with transistorized regenerative power module controls, will provide a drive almost comparable with the advanced electronically commutated drive.

The objective of this activity is to develop an advanced DC drive system for evaluation in comparison with other advanced drives. The DC drive will employ improved DC separately excited motors and transistorized power circuitry utilizing power module implementation. Inclusion of a full-rated, onboard battery charger through dual use of certain power module components will be considered in the overall design, resulting in an optimized DC drive/battery charger system. This is recommended for the two-year program.

STRUCTURES AND PACKAGING

An electric car presents a new set of problems in the development of structures and occupant restraint to meet standards similar to those imposed on internal combustion vehicles. To meet acceptable levels of crashworthiness within the weight, cost, and flexibility goals requires a development program.

The objective of the structures and packaging activity is to design and develop an electric vehicle structure capable of meeting the requirements imposed by the Federal motor vehicle safety standards as well as the durability and performance goals established in the general objectives of the program. This is recommended for the two-year program.

HEATING AND VENTILATING SYSTEM

The electric car requires new thinking on the subject of heating for passenger comfort and defrosting and defogging to meet Federal standards. There is no large source of waste heat available as with the internal combustion vehicle; hence, new concepts must be developed that are energy- and weight-efficient.

A development program would be undertaken to establish the heat requirements to maintain reasonable temperature levels in passenger compartments and to meet the Federal standards. Investigation must then be made of the various alternate sources of heating, and a design concept selected to minimize operating and manufacturing costs while maintaining high efficiency.

The selected approach would be evaluated by building hardware for both laboratory and vehicle evaluation.

The objective of this phase of the program is the design and development of a heating/ventilating system for electric vehicle use. This program is recommended.

LOW ROLLING RESISTANCE TIRES

The electric vehicle, with its relatively small amount of stored energy, is much more sensitive to changes in rolling resistance of the tires than is the normal, internal combustion engine car. A development aimed at the reduction of rolling resistance is proposed specifically for the electric car market, with all of the design tradeoffs affecting the tires optimized for the electric vehicle class of service.

A series of tests of existing tires is proposed to determine the most suitable tires for the reference vehicles and to establish a data base for relating the tire rolling resistance to the construction, size, and compound. Following this, a series of developmental tires would be proposed for fabrication and test. The final optimized design would be installed on a reference electric car.

The objective of this activity is to select the best available tire for early electric vehicle testing and to develop a new tire for improved rolling resistance.

LOW AERODYNAMIC DRAG CAR

Aerodynamic drag is an important factor for electric vehicles, particularly as it influences the selection of motor size and gear ratio. A continuing development program for the reduction of aerodynamic drag would be undertaken to verify the earlier model studies and to provide correlation factors so that other designs can be made. The effect of drag reduction modifications would be investigated and incorporated into a reference electric car allocated for this program.

The objective of this phase of the program is to improve the aerodynamic drag characteristics of the reference vehicle, and to provide shape information for future vehicle programs.

ALTERNATE VEHICLE AND CHASSIS CONCEPTS

In an effort to improve the flexibility of the electric vehicle in an unknown marketplace, the development of a driveable chassis as an approach to the manufacture of a family of electrics is recommended. This chassis would be the foundation for a number of different vehicle configurations sharing common battery, motor, drive, suspension, steering, and structural components. One significant advantage of this approach would be to provide an engineered and developed chassis and drive for many different body building companies.

The specific objective of this program would be to generate a driveable chassis, usable or modifiable, for a family of electric vehicles. An additional objective would be to provide a basis on which many manufacturers could participate in the final assembly and marketing of a variety of vehicle types based on the same chassis. Figures 64, 65 and 66 depict the modular construction and several vehicles.

Figure 64. Vehicle Body Modular Construction

Figure 65. Sketches and Line Diagrams of Pickup Truck and Utility Van (97 In. Wheelbase) Built on the Basic Chassis

Figure 66. Artist's Conceptions and Line Diagrams of Passenger Vehicle Bodies: (Top to Bottom) Two Passenger Shopper, Two Passenger Sports Car, and Four Passenger Wagon

INTEGRATED ELECTRIC TEST VEHICLE

Based on incorporating the basic design of the Reference Electric Vehicle and the upgrading developments completed during the two-year program, an Integrated Electric Test Vehicle is proposed for development.

This vehicle will incorporate tested components and subsystems, and should meet all of ERDA's near-term goals for electric vehicles.

The objective of this activity is to design, build, and evaluate two or more Integrated Test Vehicles that would contain as many of the upgrading possibilities as feasible. This activity is recommended for the two-year program.

PRODUCTION PROTOTYPE ELECTRIC CAR

Based on considerable developmental testing and on marketing inputs, a production prototype electric automobile would be proposed for development. Hardware perfected in the fleet of reference electric cars would be utilized in the production prototypes in order to maximize the chances for success.

This advanced vehicle would feature tested componentry in the areas of regenerative braking, power conditioning, drive systems, and heating and ventilation systems. It would reflect the best available thinking in the area of aerodynamics consistent with pleasant styling and basic mission.

The objective of this activity is to design, build, and evaluate one or more production prototype electric cars that would contain as many of the upgrading possibilities as are feasible in the five year time frame.

MARKETING STUDY

Concurrently with the technical development, a marketing study is proposed to assure that the electric car, as developed, meets the needs of a defined market segment. The electric car is a unique product without a backlog of marketing data, yet it will be competing with a well-established internal combustion automobile whose characteristics are well known to the entire population.

The advanced electric car to be developed under this program would be introduced in a much different marketing environment from today's, for example, in the area of governmental regulation and other constraints on the traditional passenger car, as well as uncertain fuel costs. The marketing effort would describe the potential buyer groups, would assist in defining the car for the largest appeal, and would estimate the market demands so that realistic manufacturing plans could be made.

MANUFACTURING STUDY

After the basic vehicle development programs have been completed and vehicle redesigns have been made, the manufacturing plan for the production of electric vehicles would be undertaken. As currently visualized, this plan would have two major subdivisions: one for the low-volume type of production, and a second for high-volume production similar to that currently used for today's automobiles. Only a moderate effort would be made for the Integrated Electric Test Vehicle during the two-year program to determine cost and manufacturing tradeoffs in choosing preferred approaches in hardware development.

Section 7

COST DATA

Life cycle costing for an electric car takes into account the first cost of the car plus those costs that are incurred during the life of the car, such as maintenance, power used, insurance and registration.

The first cost of early-production electric cars is likely to equal or exceed the first cost of conventional gasoline-powered automobiles because of the great difference in production quantities between the two types. For example, the cost of an electric traction motor that is built at a rate of about 70/month should not be directly compared to the cost of a gasoline engine built at a rate of 70/hr. The design duty cycle of the propulsion system must also be considered. Gasoline engines are designed for intermittent duty at rated power, whereas electric motors are designed for continuous duty at rated power. A compromise in the design duty cycle should reduce electric motor cost.

The assumptions used in estimating vehicle costs are a production of 100,000 vehicles/yr, a 10-year vehicle life, 10,000 vehicle miles/yr, an electricity cost of 5¢/kWh, and interest at 10%.

An approach to electric car costing is to consider the subsystem or component costs such as the chassis, motor, and controller. A summary of a cost breakdown is given in Table 25. The chassis is estimated to weigh 1327 lbs at a cost of \$1.25/lb. OEM prices are used with a multiplying factor of 1.4 to estimate selling prices. The traction motor for the reference electric car is estimated at \$675 OEM, or \$959 retail cost. The controller, which consists of a chopper and contactors, is estimated at \$624 OEM and \$879 retail. Various accessories are estimated at \$200 retail. The battery has an OEM price of \$485 or a retail cost of \$970 with a multiplying factor of 2.

Operating costs include maintenance, battery replacement, and fuel. Batteries are assumed to have a trade-in or salvage value, which reduces the retail cost of a replacement battery to \$945. Battery life is assumed at 400 deep-discharge cycles (urban cycle driving). Over the 10-year life of the vehicle, 5.25 battery sets would be needed in addition to the first battery set. The total battery replacement cost is then \$4963.

Repairs and maintenance are taken as \$0.0109/mile, or \$1090 for 100,000 miles. Seven replacement tires are assumed at a cost of \$61.42 each, or \$430 total.

Power requirements are based on an 80% charger efficiency and a 77% battery efficiency. The power required to operate the car is estimated at

Table 25

ESTIMATED ELECTRIC VEHICLE COSTS
FOR REFERENCE VEHICLE*

SAE J227A Schedule D Urban Driving Cycle

Components and Operation	Retail Cost	
	(\$)	(\$/mile)
<u>Vehicle Component</u>		
Chassis	1659	0.0166
Motor	959	0.0096
Controller	879	0.0088
Accessories	<u>200</u>	<u>0.0020</u>
Subtotal	3697	0.0370
Battery	<u>970</u>	<u>0.0097</u>
Subtotal Vehicle Cost	4667	0.0467
<u>Operating Costs</u>		
Battery replacement	5750	0.0575
Maintenance	1090	0.0109
Tire replacement	430	0.0043
Electricity	2388	0.0239
Insurance	1530	0.0153
Parking and tolls	1960	0.0196
Registration and title	218	0.0022
Finance charges	<u>3627</u>	<u>0.0363</u>
Subtotal Operating Cost	<u>16993</u>	<u>0.1700</u>
GRAND TOTAL VEHICLE AND OPERATING LIFE CYCLE COSTS	\$21660	\$0.2167/mile

*Separately excited DC shunt motor

EV-106 lead-acid battery

EV-1 power conditioning unit

600 lb payload

No regeneration

0.26 kWh/mile. Factoring in the charger and battery efficiencies gives 0.42 kWh/mile. At a power cost of \$0.051/kWh, the power cost is \$0.0211/mile, or \$2110 for 100,000 miles.

Insurance is estimated at \$0.0153/mile and parking and road tolls at \$0.0196/mile. Registration and title are estimated at 4% of the retail price, or \$218. Financing costs are based on an interest rate of 10% and are applied to the initial retail cost of the vehicle and to the battery replacements.

A summary of these cost estimates is presented in Tables 25 and 26. These costs may be used as a first approximation in a cost comparison of electric vehicles and gasoline-powered automobiles.

Table 26
ESTIMATED ELECTRIC VEHICLE COSTS
FOR UPGRADED VEHICLE*

SAE J227A Schedule D Urban Driving Cycle

Components and Operation	Retail Cost	
	(\$)	(\$/mile)
<u>Vehicle Component</u>		
Chassis	1659	0.0166
Motor	959	0.0096
Controller	154	0.0015
Accessories	150	0.0015
Subtotal	2922	0.0292
Battery	970	0.0097
Subtotal Vehicle Cost	3892	0.0389
<u>Operating Costs</u>		
Battery replacement	2549	0.0255
Maintenance	1090	0.0109
Tire replacement	430	0.0043
Electricity	1850	0.0185
Insurance	1530	0.0153
Parking and tolls	1960	0.0196
Registration and title	218	0.0022
Finance charges	2922	0.0292
Subtotal Operating Cost	12549	0.1255
GRAND TOTAL VEHICLE AND OPERATING LIFE CYCLE COST	\$16441	\$0.1644/mile

*Separately excited DC shunt motor
Transistorized power module
Improved state-of-the-art lead-acid battery
600 lb payload
Regeneration

Section 8

CONCLUSIONS AND RECOMMENDATIONS

Based on the results of the Phase I electric car design work, the following conclusions were drawn:

- To achieve ERDA's goals, a highly integrated program is required which treats the vehicle and its components as a total system.
- The electric car which was designed in Phase I will meet most of the ERDA near-term goals on an early delivery time scale.
- The electric car may be upgraded to meet almost all of the ERDA near-term goals, including safety and reliability, while at the same time offering an opportunity for cost reduction.
- The urban range and the sustained electric car speed on a 5% grade are limited.

Based on the work done and the conclusions drawn, the following recommendations are made:

- Continue into Phase II and build the electric car.
- Authorize upgrading development programs such as load leveling and also the development of power transistors, power hybrid circuits, and the electronically commutated motor.
- Test and evaluate new batteries in the electric car.
- Undertake electric car weight reduction upgrading programs for application to an advanced electric car.
- The ISOA lead-acid battery should be built in a golf cart case as an EV-106 replacement to upgrade the electric car.
- Emphasize programs to make new technology and advanced vehicles available for the second buy under Public Law 94-413.
- Utilize marketing, manufacturing and engineering inputs to specify an advanced electric car.
- Develop advanced electric car concepts.
- Develop power modules and traction motors for major reductions in size, weight, and cost and for improved efficiency.

Appendix A
RELATED REFERENCES
Contract EY-76-C-03-1294

1. Electric Vehicle Conceptual Design Report, SRD-76-103, General Electric Company, Schenectady, N. Y., September 10, 1976.
2. Electric Car Design Tradeoff Studies Report, SRD-77-013, Phase I - Deliverable Item # 3, General Electric Company, Schenectady, N. Y., February 10, 1977.
3. Conceptual Design Review Report, Phase I - Deliverable Item #4, General Electric Company, Schenectady, N. Y., October 4, 1976.
4. Preliminary Design Review Report, Phase I - Deliverable Item #5, General Electric Company, Schenectady, N. Y., October 4, 1976.
5. Electric Car Design Development Plan Report, SRD-77-012, Phase I - Deliverable Item #6, General Electric Company, Schenectady, N. Y., February 10, 1977.

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Appendix B

LAYOUT AND DETAIL DRAWINGS

<u>Drawing No.</u>	<u>Drawing Name</u>
GE-1	Package Drawings
GE-2	Surface Layout
GE-3, Sheet 1	Underbody Layout (side view)
GE-3, Sheet 2	Underbody Layout (plan view)
GE-4	Panel -- Tunnel Side
GE-5	Panel -- Tunnel Top
GE-6	Panel -- Tunnel Top
GE-7	Panel -- Tunnel Floor
GE-8	Track -- Battery Tray
GE-9	Plate -- RR Energy Abs. Mounting
GE-10	Reinf. -- RR Energy Abs. Mounting
GE-11	Plate -- RR Energy Abs. Mounting Plate
GE-13	Panel -- Front Floor
GE-14	Panel -- Sill
GE-17	Panel -- Seat Riser Side
GE-18	Reinf. -- Center Cross Car
GE-19	Plate -- Cross Car Reinf.
GE-20	Panel -- B-Pillar Lower Inner
GE-21	Panel -- Seat Riser Center
GE-22	Panel -- Rocker Inner Rear
GE-23	Reinf. -- Rocker Inner Rear
GE-24	Closure -- Rocker Rear
GE-28	Panel -- Door Beam
GE-29	BRKT -- Door Hinge on Door
GE-30	BRKT -- Door Hinge on Body
GE-31	BRKT -- Door Hinge Secondary Link
GE-33	Bushing -- Door Hinge (Body)
GE-34	Bushing -- Door Hinge (Door)

<u>Drawing No.</u>	<u>Drawing Name</u>
GE-35	Spacer -- Door Hinge
GE-37	Bushing -- Door Hinge Secondary Link
GE-39	Retainer -- Door Seal
GE-40	Block -- Battery Tray Retaining
GE-41	Panel -- Tunnel Front
GE-42	Layout -- Rear End Structure
GE-43	Hatch -- Battery Compt.
GE-44	Rail -- Roof Rear - Upper Transverse
GE-45	Rail -- Roof Rear - LWR Transverse
GE-48	Retainer -- Door RR Striker Plate
GE-49	Tapping Plate -- Door RR Striker Plate
GE-50	BRKT -- Door Rear Latch
GE-51	Reinf. -- B-Pillar Lock Striker
GE-52	Layout -- Side Door
GE-53	BRKT -- Door Front Latch
GE-54	Extension -- Door Beam
GE-55	Reinf. -- A-Pillar Lock Striker
GE-56	Layout -- Windshield Wipe Pattern Areas
GE-58	Gusset -- Roof Side
GE-78	Filler -- Drain Through Corner
GE-81	Trough -- Qtr. Panel Drain - Upper - L. H.
GE-82	Reinf. -- Qtr. Panel to Drain Trough
GE-92	Trough -- Qtr. Panel Drain Lower
GE-93	Cap -- Qtr. PNL Drain Through Lower
GE-107	Panel -- RR Door Inner Upper
GE-146	Layout -- Seat - Driver and Passenger
GE-159	Layout -- Rear Floor
GE-164	Layout -- Side Door Sliding Glass
GE-188	Layout -- Heater Assembly
GE-189	Layout -- Wiper System

<u>Drawing No.</u>	<u>Drawing Name</u>
GE-203	Layout -- Frt. Suspension Lwr. Control Arm
GE-204	Layout -- Steering & Frt. Susp. (Sht. 1)
GE-204	Layout -- Steering & Frt. Susp. (Sht. 2)
GE-205	Layout -- Rear Suspension
GE-206	Layout -- Final Drive Case
GE-207	Scan -- Body Surface
GE-208	Study -- Seating Package
GE-209	Structural Workout -- Preliminary
GE-210	Battery Tray Assembly

<u>Drawing No.</u>	<u>Typical Sections</u>
GE-T-01	Section -- A-Pillar Upper
GE-T-02	Section -- 55 in. - Front View
GE-T-03	Section -- 70 in. - Rear View
GE-T-04	Section -- C.L. Windshield Header
GE-T-05	Section -- Frt. Fender Thru Rocker
GE-T-06	Section -- Rear Door Header @ C.L.
GE-T-07	Section -- Rear Bumper @ C.L.
GE-T-08	Section -- Frt. Fender & Valance
GE-T-09	Section -- Rear Door Upper @ C.L.
GE-T-10	Section -- Frt. Fender at Windshield
GE-T-11	Section -- Rear Door at Belt @ C.L.
GE-T-12	Section -- Rear Qtr. & Floor

<u>Drawing No.</u>	<u>Typical Sections</u>
GE-T-13	Section -- C.L. Rear Wheel at Belt
GE-T-14	Section -- Rocker & Door @ 60.00
GE-T-15	Section -- B-Pillar Lower (P.V.)
GE-T-16	Section -- Frt. Bumper (P.V.)
GE-T-17	Section -- Headlamp Door (P.V.)
GE-T-18	Section -- Door Hinge Lower (P.V.)

<u>Drawing No.</u>	<u>Typical Sections</u>
GE-T-19	Section -- Rear Door Hinge @ 15.00
GE-T-20	Section -- Roof Rail @ 80.00 (R. V.)
GE-T-21	Section -- Hood & W/Shield @ C. L.
GE-T-22	Section -- Roof Rail @ 100.00 (R. V.)
GE-T-23	Section -- Rear Pillar @ 30.00 (P. V.)
GE-T-24	Section -- B-Pillar Upper (P. V.)
GE-T-25	Section -- Side Door Glass @ 60.00 (P. V.)
GE-T-26	Section -- Roof Bow @ C. L. (S. V.)
GE-T-27	Section -- Side Door @ 35.00
GE-T-28	Section -- Headlamp Door
GE-T-29	Section -- Frt. Bumper Energy Absorber
GE-T-30	Section -- Frt. Bumper @ C. L.
GE-T-31	Section -- Hood & Headlamps
GE-T-32	Section -- Frt. Fender at 0.00

Appendix C

FIELD CHOPPER

Field current for the separately excited DC drive motor must be controlled over a range of 5 to 30 A and must be supplied by the 108 V main battery. These current and voltage levels are within the range of commercially available power transistors.

CIRCUIT DESCRIPTION

The circuit schematic diagram is shown in Figure C.1. The first comparator compares the input reference voltage with the voltage developed across the current sensing resistor (40 m Ω). As long as the reference signal is higher than the feedback signal, the output of the comparator will be positive. This positive signal is applied to the second comparator and to the transistor base current amplifiers (2N2222A and D44C3) which supply +1 A to each base of the power transistors holding them in forward conduction saturation.

The circuit continues in this mode until the current feedback signal exceeds the reference signal and comparator number 1 goes negative. This pulls comparator 2 negative and applies the negative base bias to the power transistors, shutting them off.

As soon as the transistors shut off, the feedback signal at comparator 1 returns to zero, and the comparator will return positive. To obtain the off time, the input to comparator 2 is connected to a 0.01 μ F capacitor which charges through a 47 k Ω resistor. This delay time is the constant off time of the circuit. When comparator 1 goes negative, any positive charge on the 0.01 capacitor is drained through the diode.

During the time that the power transistors are shut off, motor field current circulates through the free wheeling diode connected across the fields. Since the feedback control signal is derived from the ground side of the power transistor, no comparisons of the actual field current versus the desired field current (command signal) can be made until the transistor is turned on again.

Figure C.2 shows elementary voltage and current waveforms generated during circuit operation. The power taken from the battery will be equal to the I^2R power loss in the fields and the transistor switching losses.

CIRCUIT TEST DATA

The circuit shown in Figure C.1 was assembled in a compact form as shown in Figure C.3. The circuit was powered from a 110 V, 30 A DC

Figure C.1. Schematic Diagram--30 A Field Chopper Circuit

Figure C. 2. Chopper Control System Waveforms

laboratory power supply and connected to a $170 \mu\text{h}$ inductor in series with a 3.3 ohm resistor to simulate the motor fields and battery bank.

Figure C. 4 shows power transistor current and voltage waveforms with 10 A average current in the field windings.

Figure C. 5 shows current sharing in the two power transistors at transistor turn on and turn off. Both transistors are turned full on in less than $0.5 \mu\text{s}$ and share very well. Both transistors are off in less than $4 \mu\text{s}$ with one turning off about $0.5 \mu\text{s}$ sooner than the other. Field current was 20 A for both oscillograms.

Circuit response to ramp and square wave command signals are shown in Figure C. 6. Figures C. 6a and b show transistor current response to a square wave input and a ramp input. Figure C. 6c shows field current response to the ramp input command. Since the ramp command signal required a field current ramp response which was less than the maximum field current ramp attainable, transistor chopping occurred.

Measurements of field current (at a constant reference voltage) were made while the supply voltage was varied over a 50 to 110 V range. The field current remained constant until V_s/R_f limits were reached.

Command signal linearity tests indicated that linearity was within $\pm 2\%$ (double reference signal gives double the field current, etc.), from 3 to 30 A of field current.

Figure C. 3. Breadboard 30 A Field Chopper

Figure C. 4. Power Transistor Voltage
and Current Waveforms

a. Transistor Turn On
 10 A/div
 50 V/div
 1 μ s/div sweep
 $I_f = 20$ A

b. Transistor Turn Off
 10 A/div
 50 V/div
 1 μ s/div sweep
 $I_f = 20$ A

Figure C.5. Power Transistor Current Sharing

- a. Square Wave Command
 4 A/div
 1 V/div
 2 μ s/div
 Transistor Current

- b. Ramp Wave Command
 4 A/div
 1 V/div
 0.1 s/div
 Transistor Current

- c. Ramp Wave Command
 4 A/div
 1 V/div
 0.1 s/div
 Field Current

Figure C.6. Field Chopper Circuit Response Tests

Appendix D

COLD SOAK ANALYSIS

OUTLINE OF ANALYSIS

GENERAL

The time required for the battery package to cool down or heat up was determined by calculating rates of heat loss by free convection in air, utilizing an average specific heat for the battery package, assuming uniform temperature throughout the battery, assuming that thermal input to the battery, when present, is uniformly distributed, and performing a transient integration.

Average specific heat of the battery was estimated by applying specific heat values to typical battery compositions, as indicated in Table D-1. Total battery weight was taken as 1182 pounds.

Table D-1

BATTERY SPECIFIC HEAT

Material	Percent By Weight ⁽¹⁾	Specific Heat (Btu/lb-°F)	Weighted Specific Heat (Btu/lb-°F)
Lead	65	0.03	0.0195
H ₂ SO ₄	20	0.72 ⁽²⁾	0.144
Rubber/Metal/ Wood	15	0.10	0.015
Average Specific Heat =			0.1785

1. Vinal, G., Storage Batteries, 4th ed., John Wiley & Sons, Inc., New York, 1955, p. 210.
2. For 35% H₂SO₄ in water, a typical composition.

THERMAL INPUT TO BATTERY DURING DISCHARGE

When battery energy itself is used to maintain or increase the temperature of the battery, it was assumed that resistive heating elements were placed within the battery package. The heat input to the battery package during discharge then consists of the I²R heating in these resistive elements plus the heat generated within the battery itself as a result of internal I²R losses and electrochemical reactions.

Applying an energy balance to a cell (see Vinal*, for example);

$$Q = W + q \quad (D-1)$$

when: Q = Heat of reaction and is equal to the difference between the heat content of the reacting substances and the products of the reaction

W = Available energy, or work done external to the cell

q = Heat evolved in the electrochemical reaction

For the case considered here, Q is equal to the thermal input to the battery during discharge. Vinal* shows (pp. 187 through 190) that Equation D-1 can be developed into:

$$\frac{Q}{23,070 n} = E - T \frac{\partial E}{\partial T} \quad (D-2)$$

where: Q = Heat of reaction (calories)

E = Cell voltage (open circuit) (volts)

T = Absolute temperature

n = Number of Faradays involved in the reaction
(1 Faraday = 96,500 coulombs)

Comparing Equations D-1 and D-2, the external work, W , is:

$$W = (23,070 n) E \text{ (calories)} \quad (D-3)$$

and the heat evolved in the electrochemical reaction, q , is:

$$q = -(23,070 n) T \frac{\partial E}{\partial T} \text{ (calories)} \quad (D-4)$$

For a lead-acid battery, $(\partial E / \partial T)$ is positive for acid concentrations of interest; q is negative during discharge, and the battery tends to absorb heat from its surroundings during discharge.

Converting Equation D-2 to watt-seconds by noting that

$$1 \text{ Faraday} = 96,500 \text{ Asec}$$

$$1 \text{ calorie} = 4.184 \text{ Wsec}$$

$$Q = It [E - T \frac{\partial E}{\partial T}] \quad (D-5)$$

*Vinal, G., Storage Batteries, 4th ed., John Wiley and Sons, Inc., New York, 1955.

where: Q = Heat of reaction (Wsec)

I = Current (A)

t = Time (sec)

Vinal (p. 193) indicates that for a given acid concentration, $\partial E / \partial T$ is constant, or very nearly so, with temperature.

Thus, for a given acid concentration:

$$E = E_O + (T - T_O) \frac{\partial E}{\partial T} \quad (D-6)$$

where subscript o refers to any reference temperature.

Therefore:

$$E - T \frac{\partial E}{\partial T} = E_O - T_O \frac{\partial E}{\partial T} \quad (D-7)$$

from which it is seen that the quantity Q in Equation D-5 is, for practical purposes, a function only of acid concentration and not of temperature.

From Vinal (p. 192), a value of $E_O = 2.006$ V/cell at 25°C, and 21 percent acid concentration by weight was selected as typical. This gives an open-circuit voltage consistent with the battery data supplied by ESB. At this concentration, Vinal (p. 194) indicates $\frac{\partial E}{\partial T} = +0.28 \times 10^{-3}$ V/°K

So:

$$\begin{aligned} E_O - T_O \frac{\partial E}{\partial T} &= 2.006 - 298 (0.28 \times 10^{-3}) \\ &= 1.92 \text{ V/cell} \end{aligned}$$

For a three-cell battery, Equation D-5 thus yields:

$$Q = It \quad (5.75) \quad (D-8)$$

or the thermal power input, P_T , per battery during self-heating is:

$$P_T = 5.75 I \quad (W) \quad (D-9)$$

This is the relation that was used for battery self-heating calculations.

Since acid concentration in the cell reaction zone decreases as current increases and as the battery is discharged, Equation D-9 is an approximation, but is a fairly good one.

For example, taking two extremely low acid concentrations from Vinal (pp. 192 - 193) as follows:

Acid by Weight (%)	E (volts)	$\frac{\partial E}{\partial T}$ (mV/°C)	T (°C)	$3[E - T \frac{\partial E}{\partial T}]$ (volts)
4.55	1.878	+ 0.02	25	5.61
7.44	1.907	+ 0.10	25	5.62

This indicates minor variations from Equation D-9 over the range of interest for a battery having an open circuit voltage ≤ 6 volts.

BATTERY CURRENT FOR ISOTHERMAL OPERATION

Of interest is an estimate of battery current at which the internal I^2R loss in the battery just matches the heat, q , absorbed during discharge.

From comparison of Equations D-5 and D-6:

$$\frac{q}{I t} = - T \frac{\partial E}{\partial T} \quad (D-10)$$

while

$$I^2 R_i = I (E - E_t) \quad (D-11)$$

when: R_i = Internal resistance

E = Generated cell voltage

E_t = Terminal voltage per cell

It is assumed that E under open-circuit conditions is equal to E with current flow; i.e., changes of electrolyte concentration and of cell temperature between open circuit and current flow are neglected.

Equating $\frac{q}{I t}$ from Equation 10 with $\frac{I^2 R_i}{I}$ from Equation D-11 in magnitude:

$$E - E_T = T \frac{\partial E}{\partial T} \text{ at the balance point.} \quad (D-12)$$

For typical $(\partial E)/(\partial T) = 0.28 \times 10^{-3}$ V/°C, and noting the constancy of $(\partial E)/(\partial T)$ with temperature:

$$E_O - E_T = 0.25 \text{ V for a 3-cell battery} \quad (D-13)$$

when: E_O = Open-circuit voltage, at a reference temperature of 27°C (80°F) in this case

E_T = Terminal voltage at any temperature

For typical battery data supplied by ESB, the corresponding match point currents are about 20, 35, and 100 A at -20°F , 0°F , and 80°F battery temperatures, respectively. Currents higher than these values are needed to cause the battery to heat up from its internal I^2R losses during discharge and chemical reactions.

Fifteen copies of this report contain the following brochures: Electric Vehicle Motors (GEP-356); New EV-1 SCR Control, (GEA-10107).