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# PRELIMINARY POWER TRAIN DESIGN FOR A STATE-OF-THE-ART ELECTRIC VEHICLE

Phillip Mighdoll and  
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Design and Development Division  
BOOZ, ALLEN & HAMILTON Inc.

April, 1978

Prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION  
Lewis Research Center  
Under Contract NAS 3-20595

for

U.S. DEPARTMENT OF ENERGY  
Electric and Hybrid Vehicle Systems Program  
Division of Transportation Energy Conservation



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## PREFACE

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## GLOSSARY

AC	Alternating Current
AMG	AM General Corporation
CVT	Continuously Variable Transmission
DC	Direct current
DOE	U.S. Department of Energy
ERDA	Energy Research and Development Administration
EV	Electric Vehicle
EVA	Electric Vehicle Associates, Inc.
GE	The General Electric Company
GRC	General Research Corporation
HB	HB Electrical Manufacturing Company
ICE	Internal Combustion Engine
MG	MG Motor Division, British Leyland, Ltd.
NASA-LERC	National Aeronautics and Space Administration, Lewis Research Center
SAE	Society of Automotive Engineers
SCR	Silicon Controlled Rectifier
SOA	State-of-the-Art
VW	Volkswagen

## 1.0 SUMMARY

As part of the national effort to stimulate the use of electrically powered vehicles for transportation, the design of urban passenger electric vehicles has been reviewed. This study considers automotive and electric vehicle technologies with specific emphasis on the power train. Its purpose is to objectively identify an "optimum" power train system which can be assembled with state-of-the-art components, to predict the performance of such a system, and to identify and evaluate improvements which might benefit vehicle performance.

In the past, power trains consisting of controller, motor, transmission, running gear, wheels, brakes and tires have been incorporated into a wide variety of vehicle designs. Most of the designs are based on conventional chassis, but superior performance has been demonstrated in complete designs, such as the Copper Development Association town car. In this program several configurations and combinations of off-the-shelf components were suggested by a study of existing electric vehicles, a review of related technology and an application of engineering judgment. These candidate electric vehicle power trains were evaluated quantitatively and by computer simulation to identify the system which can achieve maximum range over the SAE J227a Schedule D driving cycle. This state-of-the-art power train employs regenerative braking and consists of a series wound DC motor, SCR chopper controller, electrically controlled V-belt continuously variable transmission, radial tires, and drum brakes. Analysis predicts that a vehicle weighing 1,587 kg (3500 lbs.), using 16 EV-106 lead-acid batteries and employing this power train would achieve a range of about 50 km (31.2 miles) over the Schedule D cycle.

The electric vehicle literature, technical judgment and interviews with a broad spectrum of persons within the industry, provided suggestions for potential near term technical advances, which could be applied to improve the state-of-the-art power train design. These include means to extend vehicle range, as well as features to enhance the commercial success of electrically powered passenger vehicles. Several systems involving shunt wound DC motors were considered in detail. An improved power train was selected which employs a high speed separately excited motor with armature and field control. A single ratio speed reducer replaces the multi-ratio transmission. On the Schedule D cycle, a vehicle with this power train can achieve a range benefit of approximately 20 percent when compared with a power train of similar weight which uses state-of-the-art components.

## 2.0 INTRODUCTION

By the turn of the century, automobiles powered by the internal combustion engine (ICE) and battery powered electrics were competing to replace the horse in urban centers. At their peak acceptance, around 1912, it has been estimated that several hundred thousand electric vehicles were in use throughout the world (Ref.1).

The features of the present gasoline powered ICE vehicle have developed over a long period of refinement. These include:

- Favorable initial cost,
- Good performance,
- Inexpensive fuel, and
- Long range.

England has continued to build and favor electrically powered vans (milk floats), but the electric vehicle has virtually disappeared from the American market. In the U.S.A., a small group of independent experimenters have continued to build electrically powered road vehicles, and several commercial ventures to build and market electric road vehicles, such as Sebring-Vanguard, were established throughout the years. Battery powered propulsion has been well suited to various off-the-highway vehicles such as industrial fork lift trucks, golf carts and underground mining machinery. Lower maintenance costs and longevity are well documented benefits of the electrics, but their higher initial cost and lower overall performance have been drawbacks.

Within the current decade, we have been faced with both an energy crisis and an environmental crisis. It has been recognized that the earth's fossil fuel reserves are finite and we must take increasing advantage of other energy sources. These include, for example, hydroelectric, nuclear, wind and solar power. Moreover, the recent oil embargo has stimulated the use of domestically produced coal and the establishment of minimum fuel economy standards for vehicles.

A significant portion of air pollution results directly from the use of gasoline powered vehicles. This problem is particularly severe in urban areas. As a result, a significant effort is being made to reduce exhaust emissions. The use of electric vehicles allows the energy conversion process to take place at a central power plant where

pollution is easier to control. It also offers the opportunity to make a major shift in the transportation sector energy-base from foreign petroleum to other sources.

Due to the low energy density of currently available batteries, electrically powered vehicles are not presently capable of both the acceleration performance and range of ICE vehicles. There is significant federal support for battery technology programs and for hybrid systems which combine the range benefit of the internal combustion engine with the pollution-free operation of electric power. However, it is possible to fulfill a portion of the transportation needs with state-of-the-art electric vehicles. Studies have shown that an electric vehicle with a range of 129-161 km (80-100 miles) would meet the second-car requirements of a significant portion of the population (Ref. 2) if a minimal level of performance were acceptable. Programs to improve batteries, vehicle designs and propulsion system components are underway.

There is a rather voluminous literature on electric vehicles (see the Bibliography) and much of this information was reviewed in the course of the present study. Vehicles have been built in a wide range of configurations. Some use existing ICE chassis and others are designed from the "ground up". The criteria for selecting power train systems and components has not, however, been clearly established. Judgment indicates that component efficiency is significant. Since most devices have efficiencies which vary with load, speed and environment, no particular set of components clearly offers optimum performance for all driving conditions.

This study considers automotive and electric vehicle technologies with specific emphasis on the power train. Its purpose is to objectively identify an "optimum" power train system which can be assembled with state-of-the-art components, to predict the performance of such a vehicle, and to identify and evaluate improvements which might benefit vehicle performance.

An electric vehicle power train begins at the battery terminals and ends at the road. Battery technology and overall vehicle design are beyond the scope of the present study. Typically, an electric vehicle power train consists of a controller, a motor, running gear, four wheels and tires, and four brakes. As defined in the contract statement of work, state-of-the-art components are those that are available off-the-shelf as standard items or can be manufactured by special order involving limited design modifications such as special mountings. Components that require developmental engineering are not considered to be state-of-the-art.



The urban passenger vehicle is the focus of this investigation. The statement of work defined basic vehicle characteristics, such as weight, aerodynamic drag and battery parameters and specified that the vehicle must perform over the SAE J227a Schedule D\* cycle, at a constant 72 km/h (55 mph) and also climb a 10 percent grade at 49 km/h (30 mph). A design objective was to maximize range over the SAE\* cycle with a power train capable of meeting the speed and grade requirements.

This program does not specifically address the issue of cost effective design for a state-of-the-art power train. It has been assumed that the commercial availability of components implies reasonable cost. Actual cost will depend upon market demand and appropriate manufacturing techniques.

Information was obtained by literature search, by in-person and telephone interviews and by mailings to manufacturers of vehicles and components. A number of vehicles were examined at NASA-LERC and at the Electric Vehicle Exposition in Chicago in the spring of 1977. From this data base and by applying engineering judgment, various power train design approaches were identified and studied. Computer-aided analysis was one tool employed to select the state-of-the-art power train and to evaluate range increases achievable with various improvements.

The review and assessment of state-of-the-art electric vehicles and power train components is presented in Chapter 3.0. A preliminary design of a power train based on these components is developed in Chapter 4.0 and improvements are evaluated in the last chapter.

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\* Throughout this report, reference to "the SAE cycle" implies the SAE J227a Schedule D driving cycle.

### 3.0 ASSESSMENT OF THE STATE-OF-THE-ART IN ELECTRIC VEHICLE POWER TRAIN TECHNOLOGY

The conversion of electrical power into mechanical motion is basic to our industrialized society. Machinery, powered by electricity, finds significant application in most industries. Within the transportation field the most common types of electrically powered vehicles are:

- Golf carts
- Railroad locomotives and subway cars
- Industrial forklift trucks
- Delivery vans ("milk floats" in England)
- Mine vehicles
- Motorized wheels for earth moving equipment
- Highway passenger vehicles.

For each type of vehicle, mission goals, environmental constraints and economic considerations establish requirements which result in specific configurations and component selections. Vehicles and machinery used in underground coal mines are electrically powered because of both the fire hazard associated with internal combustion engines and the air pollution (ventilation) requirements. Dynamic (or regenerative) braking is employed in large earth moving equipment primarily to minimize the servicing of conventional brakes rather than to conserve energy. Contactor controllers are cost effective for delivery vans but the smoothness of control desired for passenger vehicles generally leads to the pulse (i.e., chopper) type of motor controllers.

Many electric passenger vehicles have employed the same DC series wound motors and SCR controllers originally developed for the forklift truck industry. However, due to the difference in mission, this approach can lead to a less than optimum propulsion system design.

This chapter presents a review of power train technology for electrically powered highway vehicles. The first section summarizes the various design approaches taken in the recent past. Electric motors and their related controllers are reviewed from a generic point of view in the second section and mechanical power transfer devices such as transmissions and tires are reviewed in the third section.

### 3.1 EXISTING ELECTRIC VEHICLES

The design of electric vehicle power trains are reviewed in this section with particular emphasis on:

- The architecture of the power train ,
- The type of components employed ,
- System optimization and tradeoffs, as well as,
- Implementation.

A basic electric vehicle power train is shown in Figure 3-1. The configuration is that of the conventional "Detroit" drive where the electric motor replaces the conventional internal combustion engine. The battery is shown dashed since the present contract does not include battery technology.

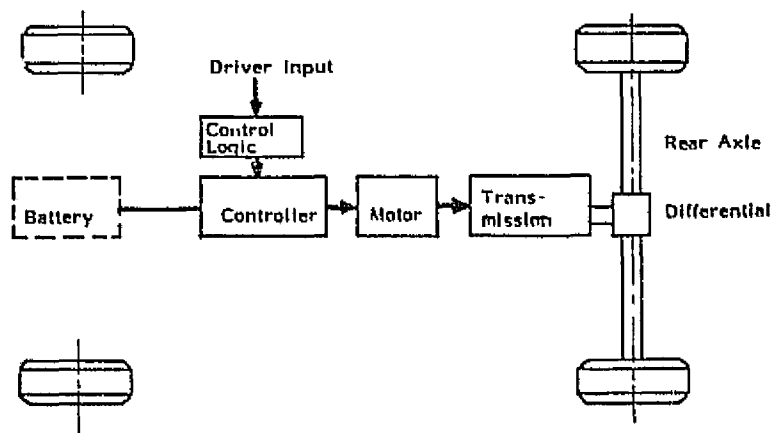


Figure 3-1 Basic electric vehicle power train.

Many electric vehicle designs attempted to match the performance of conventional internal combustion vehicles. The GM Electrovalr (Ref. 3) and the Ford Cortina Estate Wagon (Ref. 4) are examples. The need for improved batteries was apparent and some of these vehicles used high temperature prototype batteries.

Analytic studies indicate that lighter vehicles with higher battery mass fractions (ratio of battery weight to total weight) should have superior performance. Several studies (i.e., Ref. 5) have attempted to compare electric vehicle performance by normalizing performance data with respect to battery mass fraction or overall weight. Unfortunately the number of well documented vehicles is small and test conditions vary. Therefore, a statistical approach to assessing the state-of-the-art for power train features would not appear to be fruitful. However, the commonality of several features and the trends in recent power train designs can be observed in the data.

### 3.1.1 Electric Vehicles Designed by The Enthusiast

A significant population of independent electric vehicle experimenters have for several years, been building, testing and using electric highway vehicles. There are several regional clubs which serve the members by providing a means to share experience. Such organizations include the Electric Vehicle Association of Ohio, which claims to have over 50 active members. Not unlike the "hot-rodder" who modifies a vehicle for greater performance, their approach has been to convert existing compact cars, such as VW, Renault and Austin, to electric power. Table 3-1 lists the basic characteristics of several such designs (Ref. 6). Objective test data is generally not available.

The selection of components for these vehicles has necessarily been dictated by economics and availability. The fundamental objective has been to package the hardware and "make the system work". It is not uncommon to see used forklift truck or golf cart motors and aircraft generators in these vehicles. Engineering tradeoffs in the design are quite rare. The technology employed in the golf cart and forklift truck industry finds application in these designs because these industries are virtually the only sources for relatively inexpensive components.

TABLE 3-1 SOME ENTHUSIAST BUILT ELECTRIC VEHICLES\*

BUILDER	CHASSIS	MOTOR	CONTROLLER
F. Rienecker Livermore, CA.	1960 NSU Prinz	GE, DC series , 36 volt, 9.4 hp	Contactor
G.M. Hughes San Leandro, CA	1960 NSU Prinz	GE, DC shunt, 30 volt	Battery switching, starting resistor
H.H. Arnold Lewisville, N.C.	1961 Renault Dauphine	Delco, DC shunt , 96 volt, 19 hp	Battery switching, starting resistor, solid state field control
D. Wiegner Winston-Salem, N.C.	1966 VW	Delco, DC shunt , 96 volt, 19 hp	Battery switching, solid state control
H.W. Barber Bakersfield, CA	1970 Fiat 850 Sedan	Mercury, DC series , 72/96 volt, 12 hp	Chopper
T. Frizzell Charlestown, N.H.	VW Bug	Delco, DC series , 36 volt, 7.5 hp	Resistance Steps
J. O'Connor Greenfield, IN	MG - 1100	Hertner, DC series , 72 volt, 13 hp	Transistor chopper
R.R. Bassett Al., N.M.	1963 Renault	Aircraft generator , 23 volt	Resistance steps
J. Wilson Fairhaven, NJ	1963 Renault Dauphine	Delco, DC shunt , 84 volt, 15 hp	Transistor chopper
C. Kenney/ J. Wasylinz Oakland, CA	1961 Renault Gordini	GE, aircraft generator, 28 volt, 9.8 hp	Battery switching and field weakening
P.C. Wergin/ D.M. Yates Reynoldsburg, OH	1966 Sunbeam	Aircraft generator, 30 volt, 15/30 hp	Transistor chopper
K.V. Kordesch Lakewood, OH	Austin A 40	Baker, DC series, 72 volt, 8/20 hp	Battery switching
A. St. Amant Walnut Creek, CA	VW	Westinghouse, DC series, 72 volt, 31 hp	Battery switching

\*In this table, and in several other instances throughout this report, where particular component suppliers are identified in the literature, they are reported. The omission of any individual manufacturer is regretted. No endorsement is implied.

A major virtue of these conversions is practicality. Vehicles which are built using existing automotive and industrial components easily fit into the existing infrastructure. Repairs and service are obtainable, or within the reach of the "do-it-yourselfer", and the hardware is well developed, safe and rugged.

Interest has been large enough to encourage the formation of several commercial ventures to produce and market electric vehicles. Firms such as Electric Vehicle Associates, Inc. (EVA) have their roots in the enthusiast sector.

### 3.1.2 Domestic Commercial Electric Vehicle Conversions

A summary of the characteristics of several domestic, commercially produced electric vehicle conversions is presented in Table 3-2. Data was not available for all parameters.

Most domestic and foreign electric vehicle programs have included the conversion of a conventional vehicle as a first generation test bed. Expediency and overall project emphasis are the rationale for this choice. In several cases the primary focus of the project seems to be the demonstration of an advanced battery concept. For example, the GM Electrovair II employed experimental silver-zinc batteries and an AC motor drive was designed to match the acceleration and speed performance of its internal combustion engine counterpart. The major portion of the engineering design effort was centered around the AC motor controller.

EVA and Waterman designs are conversions of compact conventional vehicles. Both retain the original transmission, and, in the case of the Waterman DAF-based design, this is a V-belt continuously variable ratio system. Battronic, and AM General have concentrated on the commercial market by using the conversion approach. The Battronic motor and controller are typical industrial designs whereas the AM General Jeep employs a compound wound motor and two phase DC chopper.

### 3.1.3 Domestic Electric Vehicles Designed From the Ground Up

It is generally recognized that the ideal electric vehicle should be designed from the ground up. In this manner, the limited energy storage capacity of electrochemical batteries can be used most efficiently for vehicle range and performance. Analytical studies have shown the

TABLE 3-2 DOMESTIC COMMERCIAL ELECTRIC VEHICLES

VEHICLE (Date)	TYPE/ CURB WEIGHT	BATTERIES	MOTOR	CONTROLLER	TRANSMISSION
GM Electrovair II (1967)	Corvair, 5 passenger 3400 lbs.	Silver-zinc 530 V, 60Ah	Delco, 4 pole, 3 phase AC induction, 120 lbs., 115 HP at 13,000 RPM, oil cooled.	Three Phase SCR, Oil Cooled.	Fixed gear reduction.
GM XEP Opel (1970)	4 passenger 3000 lbs.	Zinc-air and Lead-acid	Two DC series in parallel, rear mount. 128 lbs., 28 HP each. Blower cooled.	Two synchronized SCR.	Dual input gearbox.
Ford Cortina Estate Wagon	5 passenger 3036 lbs.	Nickel-cadmium 110 V., 900 lbs.	GE DC series, 150 lbs., 40 HP, 100 V., 26 ft. lbs., 8000 rpm. Fan cooled (60 watt)	SCR and bypass contactor	Front wheel drive, standard manual, 3.12.1 in second.
Boeing LRV	Rail 62,000 lbs.	Pantograph	2 in series, DC separately excited, 210 HP. Blower cooled.	SCR armature chopper	Fixed gear reduction
EVA Metro	Renault R-12 4 passenger 3150 lbs.	Lead-acid, EV-106 96 V., 1040 lbs.	DC series 13.4 HP 4500 RPM Fan Cooled	SCR, no bypass, 340 amp limit.	Torque converter and 3 speed Renault automatic.
EVA Contactor (1977)	4 passenger AMC Pacer		DC shunt 8 HP	HB contactor	Automatic
Batronic Minivan (1973)	Van 5800 lbs.	Lead-acid 112 V 330 Ah.	GE DC series 94 V., 52 HP. 6000 rpm.	GE SCR chopper, field weakening bypass contactor, current limit.	2 speed, helical gear rear axle 1.96, 1.0.1
Waterman CHW-886	4 passenger 2480 lbs.	Lead-acid, 48V	Prestolite, DC series 12 HP	Contactor, 3-speed	Continuously variable belt transmission
Jel Industries Electra-Van	Subaru Van 2500 lbs.	Lead-acid, EV-106 96 V., 910 lbs.	Baldor, DC series, 10 HP, 3500 rpm, 168 lbs. Blower cooled.	Cableform SCR	Standard
Dana Electric Van	Van 8080 lbs.	Lead-acid 144 V. 329 Ah/5 hr.	Reliance, DC shunt, 120 V, 53 HP at 4250 rpm, 830 lbs.	Reliance, SCR chopper, 300 lbs.	3-speed, clutch standard manual 3.03, 1.75, 1.0.1
AM General Electruck DJ-5E (1975)	Van/Jeep 3640 lbs.	Lead-acid 54 V., 1250 lbs.	DC compound, 283 lbs.	SCR blower cooled 110 lbs.	No transmission, conventional shaft with universals
Otis P-500	Van 3900 lbs.	Lead-acid, 96 V, EV-106, 1040 lbs.	Otis, DC series 30 HP, 4000 rpm Blower cooled.	GE pulse type, SCR, 96 V blower cooled	None, conventional shaft with universals
Sebring/Van- guard Citicar (1974)	2 passenger 1300 lbs.	Lead-acid, 48	GE, DC series rear mounted, 6 HP, 4100 rpm.	Contactor and starting resistor	No transmission
GE Delta (1971)		Lead-acid and nickel-cadmium			
Linear Alpha (1974)	Dodge Van 8950 lbs.	Lead-acid (24) 220 Ah, 144 V, 7433 lbs.	3-phase AC induction, 36 HP.		Direct 1.6.1
EFP Mars II (1966)	4 passenger Renault R-10 4100 lbs.	Lead-acid 120 V 1840 lbs.	DC series	Contactor	

TABLE 3-2 DOMESTIC COMMERCIAL ELECTRIC VEHICLES (Continued)

DIFFERENTIAL	TIRES	BRAKES	PERFORMANCE	REFERENCE
Standard			80 mph max.; 8-60/17 sec. 40 - 70 mi. range	(3)
Standard 3.23:1			60 mph max. 8-30/10 sec. 7, 80 mi. range	(8)
3.9:1	Radial		77 mph max. (3rd gear), 80 mi. at 25 mph	(4)
		Dynamic (re- generative optional) and hydraulic disc.		(9)
2.34:1	Radial 155 R-13 32 psi		50 mph max., 56 mi. at 25 mph. 27 mi. during urban cycle	(10), (11), (12)
				(13)
Hypoid 3.07:1	6.70 x 15	Hydraulic	60 mph max., 50 mi. at 20 mph.	(14)
		Regenerative available	45 mph max. 60 mi. at 30 mph	(15)
Standard	Bridgestone K663, bias ply 40 psi.	Hydraulic	45 mph max. 40 mi. at 40 mph	(10)
Dana 7.17:1		Regenerative and hydraulic	50 mph max., 200 mi. at 25 mph	(16)
5.89:1	CR 78-15 (Range C)	Regenerative over 15 mph and hydraulic drum	45 mi. at 30 mph, 8-30/26 sec., 30 mi. on cycle	(17), (18)
Standard 5.17:1	Uniroyal Rally 180, 6 ply radial, 175-SR 13, 32 psi.	Hydraulic	8-30/12 sec., 21 mi. on cycle	(18), (10)
6.83:1	Goodyear, 2 ply nylon 4.80x12, 30 psi.	Disc/drum hydraulic	35 mph max. 36 mi. at 25 mph, 20 mi. on cycle	(19), (20)
			180 mi at 20 mph 80 mi at 40 mph	(21)
Standard		Regenerative and hydraulic		(22)
	Goodyear radial	Regenerative, 4-wheel disc.	125 mi. at 30 mph 22 mi. on cycle	(23)



need for vehicle designs which:

- Minimize overall weight,
- Minimize aerodynamic drag,
- Minimize tire and other rolling element friction,
- Incorporate highly efficient components, and
- Maximize battery mass fraction.

Although the majority of existing electric vehicles are based on converting an internal combustion engine chassis, the more significant innovations are found in those vehicles designed from the "ground up." These are generally lightweight, low drag designs and are typified by:

- The Copper Development Association (CDA) Van and Town Car,
- The Sundancer,
- The EXAR I, and
- The Anderson Electric.

The characteristics of this class of vehicles are found in Table 3-3. These vehicles employ many conventional industrial and automotive components, but the major factors contributing to their improved performance are their low overall weight, low aerodynamic drag, and low rolling-resistance tires.

#### 3.1.4 Foreign Electric Vehicles

Europe, England and Japan have been petroleum importers for some time and are concerned about air pollution. As a result a significant effort has been expended in developing electric vehicles (Ref. 7). The battery powered "milk float" has, for example, been used in England for many years and has proven to be a reliable and cost effective delivery van. Lucas has designed a small taxicab, from the ground up, for specialized urban service.

Japan has an active electric vehicle program supported by the Ministry of Technology. Toyota and Daihatsu have developed several small electric cars and trucks. These projects have included both DC series wound and shunt wound motors with separate field excitation.

TABLE 3-3 DOMESTIC PROTOTYPE ELECTRIC VEHICLES

VEHICLE (Date)	TYPE/ CURB WEIGHT	BATTERIES	MOTOR	CONTROLLER	TRANSMISSION
GM 512 (1969)	2 passenger	Lead-acid, 84 V, 326 lbs.	DC series, 50 lbs., 8.5 HP., 4000 rpm, Blower cooled	SCR	Coaxial motor, planetary gear and differential at rear axle.
Copper Development Association Van III (1970)	Van 5100 lbs.	Lead-acid, 108 V	GE, DC series & Interpoles, 12 HP. at 4725 rpm, 231 lbs.	SCR, 500 amp and bypass contactor	Chrysler 3-speed automatic. 15.14, 9.33, 6.30: 1 overall ratios. No torque converter
Copper Development Association Town Car (1976)	2 passenger 2952 lbs.	Lead-acid, 108 V.	DC separately excited, 40 HP. max.	4.6:1 field variation by transistor chopper. Armature resistance switching.	Front wheel drive, standard toothed belt and spiral bevel gear.
ESB/McKee Sundancer - 2 (1972)	2 Passenger 1600 lbs.	Lead-acid, 72 V., 750 lbs.	Tork link, DC series, 8 HP	SCR chopper, 400 amp	Rear transaxle and motor. McKee 2-speed 6.08, 3.14: 1, manual
Ametrax EXAR-1	4 Passenger 2800 lbs.	Lead-acid	DC	Solid state	Fixed
Anderson Third Generation	Utility Van 2500 lbs.	Lead-acid 72 V	DC series, 20 HP (35 HP. peak), 240 amp, 4000 rpm., 170 lb. Blower cooled.	SCR	2-speed automatic, planetary gear, mechanical shift on speed and torque, FWD
TSL - T/3 Van (1974)	Van 3000 lbs.	Lead-acid 84 V, 900 lbs.	DC series 20 HP. (35 HP. peak)	SCR, 600 amp	Fixed
Lunar Rover (1971)	500 lbs.		Four DC series, brush type, or four permanent magnet brush- less.	Electronic plus four power contacts for reversing.	80:1 harmonic drive and planetary- spur gear.

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TABLE 3-3 DOMESTIC PROTOTYPE ELECTRIC VEHICLES (Continued)

DIFFERENTIAL	TIRES	BRAKES	PERFORMANCE	REFERENCE
5.0:1 overall ratio.			45 mph max. 0-30/12 sec. 100 mi. at 34 mph.	(38)
Front wheel drive. Morse Hy-Vo chain to differential.	Firestone radial	Hydraulic		(39)
4.95:1	AR 70-13 radial.		60 mph max. 0 - 20/11.2 sec.	(40), (41), (10)
Dana EG-20	Goodyear low rolling resistance 6.05 x 8, 30 psi.	Disc/drum hydraulic	100 mi. at 30 mph, 45 mi. at 60 mph	(42)
11.81:1	Goodyear, Run Flat.	Disc Brakes.	65 mph max. 100 mi. at 55 mph	(43)
	Radial, 165 x 15.	Dis/drum hydraulic	55 mph max. 60 mi. at 45 mph	(44), (45)
7.83:1	Radial, 165 x 15	Disc/drum	40 mph max. 0 - 30/16 sec. 30 mi. on cycle	(46)
	32 in. diameter wire mesh.	4 wheel regen- erative brakes	10 mph 74 mi. range	(47)

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The trend to the separately excited DC motor and regenerative braking is apparent both in Japan and in Europe. Chopper type controllers are also quite common.

A summary of the characteristics of many foreign electric vehicles is presented in Table 3-4.

### 3.1.5 Summary and Design Trends

A major objective of efficient electric vehicle design is to minimize overall weight while maximizing the battery mass. The packaging of passengers, battery pack, motor and controls is a task requiring care and ingenuity. Generally the overall vehicle body design presents constraints on the power train configuration. For example, the front mounted motor/rear wheel drive is incompatible with the central "battery tunnel" frequently suggested for state-of-the-art electrics. Also, the modern "hatchback" design may preclude the use of a rear mounted motor/transaxle. Individual wheel mounted motors are an interesting configuration which eliminates the differential and may allow a simple form of redundancy. A review of the data presented in Tables 3-1 through 3-4 as well as related studies and technical literature (see the Bibliography) suggests the following list of power train architecture:

- Front mounted motor/rear wheel drive,
- Rear mounted motor/rear wheel drive,
- Front mounted motor/front wheel drive,
- Rear mounted dual output shaft motor, and
- Individual wheel motors (2 or 4).

The concept of "load levelling" has received attention in the electric vehicle literature because present lead-acid batteries are unable to efficiently deliver the surges of power needed for acceleration or to efficiently accept regenerated energy. Much of this work has been theoretical and has proposed the use of:

- Flywheels,
- Liquid or gas accumulators, and
- Supplemental batteries.

TABLE 3-4 FOREIGN ELECTRIC VEHICLES

VEHICLE (Date)	TYPE/ CURB WEIGHT	BATTERIES	MOTOR	CONTROLLER	TRANSMISSION
Thev II Taiwan	4 passenger 2654 lbs.	Lead-acid 132 V. 1102 lbs.	Tongyuan, DC series, rear mount 176 lbs., 34 HP, 6000 rpm. Blower cooled.	SCR chopper	Fixed reduction 1.5:1
Lucas Taxi (1976)	8851 lbs.	Lead-acid 216 V.	DC series, front mount transverse, CAV, 50 HP.	Lucas SCR chopper	Double reduction, Morse Hy Vo chain, transverse to differential.
Daihatsu Kogyo Lightweight car (1972)	4 passenger 2010 lbs.	Lead-acid, 98 V, 220 Ah/5 hr.	Two rear wheel, DC series, 7.5 HP, each, 45 V.	SCR chopper	Rear mounted, automatic, 2-speed
Toyota Compact car (1972)	5 passenger 3054 lbs.	Lead-acid, 192 V. 153.5 Ah/5 hr.	DC separately excited 27 HP. (20 kw) rated 54 hp. (40 kw) max. Blower cooled.	SCR chopper, automatic field weakening	Rear transverse mount, automatic, torsional damper, no fluid coupling, 2-speed hydraulic from electric pump
Toyota Small Truck	2 passenger + 770 lbs. load	Lead-acid, 86 V., 135 Ah/5 hr., 723 lbs.	DC separately excited 13 HP. rated, 18 HP. max.	SCR	Fixed gear reduction
Enfield 8000 (1976)	2 passenger + 2 children 2100 lbs.		DC series, 48 V, Mawdsley, 8 HP., 175 lbs. Blower cooled.	6 step contractor, field weakening	Optional
Bedford Van ERC England	Van 6000 lbs.	120 V	DC series, 50 HP.	5 step contactor (patented)	Torque converter, Variable Kinetic Drive, 4.5 at stall, 90% cruise efficiency
Ford Comuta England (1968)	2 passenger + 2 children 1200 lbs.	Lead-acid (A) 12 V 120 Ah/5 hr. 384 lbs.	CAV type TM 55, DC series (2), 24 V., 5 HP. Blower cooled.	Thyristor pulse controller, Sevcon Mk VI, bypass contactor.	Rear transverse mount fixed gear reduction
VW Electric Transporter	Van 3000 lbs. approx.	Lead-acid 144 V. 150 Ah/5 hr. 1896 lbs.	DC separately excited, Bosch and Siemens, 21 HP. (42 peak), 6700 rpm max. Separate fan.	Electronic, pulse width and frequency modulation.	Fixed gear, Vn Standard transaxle
Daimler Benz LE 306	Van 6500 lbs. approx.	Lead-acid 180 V. 180 Ah/5 hr. 1234 lbs.	DC Separately excited, 42 HP (70 peak), 6000 rpm max.	Electronic, 2 position variable pulse width and frequency	Fixed gear reduction
Elcar Model 5000 (1975)	4 passenger 1500 lbs.	Lead-acid 48 V, 300 Ah.	DC series, OE, 3.5 HP., Rear mount.	SCR chopper with contactors and resistor.	Fixed reduction
SRE Combi-Truck Israel	2 passenger van 2800 kg.	Varta, MD 750-V3 144 V.	DC separately excited, 25 HP, continuous at 8500 rpm., CE.	No armature control, field weakening	Front wheel drive, continuously variable transmission, flywheel

TABLE 3-4 FOREIGN ELECTRIC VEHICLES (Continued)

DIFFERENTIAL	TIRES	BRAKES	PERFORMANCE	REFERENCE
Standard differential 4.1:1			56 mph max. 8-37/12 sec 200 mi. at 30 mph.	(24)
5.63:1		Regenerative and Cirling servo hydraulic brakes.	60 mph max. 200 mi. at 30 mph	(25)
		Regenerative and hydraulic.	55 mph max., 8-20/3 sec 175 mi. at 25 mph.	(26), (27)
	Special	Regenerative and hydraulic.	58 mph max., 8-20/2.5 sec 180 mi. at 25 mph	(26), (27), (28)
		Regenerative and hydraulic.	38 mph max., 24 mi. over urban cycle	(27), (28)
3.55:1	Radial, 35 psi		8-30/12 sec 40 mph max	(29)
			8-30/14 sec 47 mph max 33 mi. over cycle	(30)
Overall ratio 4.0:1, helical pinion.	4.4 x 10	Hydraulic drums, all wheels	60 mph max. 40 mi. at 25 mph 8-30/12 sec	(31)
	Radial	Regenerative and hydraulic.		(32), (33)
Standard		Regenerative and hydraulic	47 mph max	(34), (35)
	Steel Radial SR-145x10	Hydraulic.	45 mi at 35 mph 40 mi at 40 mph 8-30/14 sec.	(36)
			43 mph max	(37)

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Flywheel systems have yet to be reduced to practice in electrically powered vehicles. No known passenger vehicle has demonstrated such a system and at least one study (Ref. 5) indicates that a similar improvement in range is obtainable solely with regenerative braking. However, the predicted benefits of flywheel energy storage are encouraging.

In order to ensure safety, the accumulator storage concept requires excessive structural weight to contain high pressure fluids. Additional energy and pumping hardware is needed to transfer the stored fluid.

The approach of using a supplemental battery (i.e., Ni-Cad) has been demonstrated in the GE Delta vehicle (Ref. 21). This design approach allows for the implementation of improved batteries as they become available. More study of the impact of this concept on range over the driving cycle is needed to determine its effectiveness.

Although battery development is beyond the scope of the present study, it was necessary to obtain parameters and discharge characteristics of lead-acid batteries for use in range computations. Discharge characteristics of lead-acid batteries in electric vehicle applications are not well understood. No model of the EV-106 battery (which was specified in the contract) that can be absolutely accepted is available. Performance models under conditions of pulsed loading, typical of use with chopper controllers, are needed. Even under steady discharge, the available predictions (Ref. 48, 49, and 50) are not in agreement. Jayne (Ref. 51) identifies and describes test results indicating increased effective capacity using pulsed discharge techniques as compared to steady state discharge of the same average current. Current work at NASA-LERC is aimed at investigating this apparent anomaly.

Analysis indicates that no single power train can simultaneously maximize range at various constant speeds and range over various stop and go driving cycles. In addition, a system that maximizes range for one set of conditions may be totally unsatisfactory for another cycle. For example, where a design is optimized for maximum range at constant cruising speed and the vehicle is subjected to stop and go cycling or grade climbing, the motor may overheat. A less extreme example is a vehicle designed for efficient high speed cruise which may have poor acceleration and gradeability.

The vehicle characteristics presented in Table 3-1 through 3-4 show significant variation in configurations, motor types, controller types, transmissions and tires. There does not, however, appear to be any correlation between these variations and the performance data. This is due to the more significant manner in which battery

characteristics and total vehicle weight affect performance. Detailed dynamometer testing of power trains has generally been bypassed and vehicle performance has been reported for various, and sometimes arbitrary, driving cycles. The recently established SAE J227 test procedure promotes uniform testing. Unfortunately, much of the information published concerning particular vehicles is promotional in nature. Moreover, many firms consider their design approach and detailed performance data to be proprietary. Objective verification of the many performance claims is needed.

The frequency of occurrence of power train design approaches for those vehicles reviewed in Tables 3-1 through 3-4 was obtained and is summarized in Table 3-5. With this information, and the literature reviewed, notable trends and common practice include:

- The most common motor type is the DC series wound motor with an SCR controller. Significant interest has been found in the separately excited, shunt wound motor.
- Blower cooling of motors is common.
- Most transmissions are fixed speed reducers.
- The use of low rolling resistance tires, roller type bearings and efficient (i.e., not hypoid) gearing is desired.
- A single motor transversely mounted near the driven wheels (front or rear) appears most consistent with the overall vehicle package design.
- An objective systems tradeoff study is required to optimize power train design for a particular mission.



TABLE 3-5 FREQUENCY OF ELECTRIC VEHICLE DESIGN APPROACH

Feature	Number*
Total number of vehicles reviewed	37
Motor Types	
DC Series wound	23
DC Separately Excited	7
AC polyphase induction	2
Blower Cooling of Motor	13
Controller Types	
Battery Switching (Contactor)	6
Solid State (AC or DC)	27
Transmission Types	
Fixed Gear Reduction	20
Manual Gear Change	4
Automatic Gear Change	6
Continuously Variable	3
Power Train Configuration	
Rear Motor and Drive	8
Front Motor and Drive	3
Conventional	11

\* Complete data not available for all vehicles.

In summary it appears that since battery type and weight directly determine the amount of energy, and since the total mass to be propelled is proportional to vehicle weight, battery type and weight are the two main factors in determining vehicle performance. A power train which can efficiently convert battery energy into mechanical energy over the driving cycle is essential to optimize the use of the limited energy.

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### 3.2 MOTOR AND CONTROLLERS

The subject of electric motors for vehicle traction applications has a long and varied history. The first electric drive system to gain prominence was the Ward-Leonard system patented in the early 1890's. Since then, complex electronic controls have been developed utilizing sophisticated solid state technology and motor control techniques.

#### 3.2.1 Alternating Current (AC) Motors

AC Motors are extensively used in constant speed applications. The most popular type of integral horsepower alternating current motor is the polyphase induction motor. Induction motors may be either squirrel cage or wound rotor types.

Compared to a direct current machine of comparable performance, a "squirrel cage" induction machine has the following advantages:

- Lower cost,
- Greater ruggedness,
- Brushless,
- Lower weight, and
- Lower maintenance.

Features of the wound-rotor motor include:

- Use of slip rings in the rotor circuit to provide a means of varying the effective rotor resistance.
- Rotor control circuitry isolated from the high power stator supply.

Figure 3-2 illustrates the torque-speed characteristics of a typical induction motor at constant voltage and frequency. Two values of rotor resistance are illustrated. Induction motors with high resistance rotors are less efficient than motors with low resistance rotors.

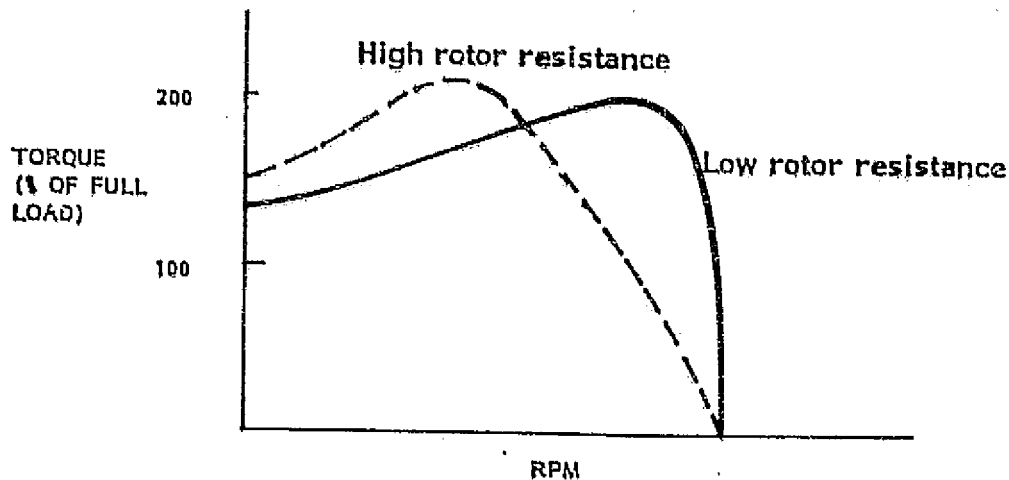


Figure 3-2 Induction motor characteristic

### 3.2.2 AC Motor Controllers

Since induction motors with low rotor resistance always operate near synchronous speed, the only effective method of controlling speed is by varying the synchronous speed which is proportional to line frequency. To avoid magnetic saturation of the iron, as frequency is reduced, the applied voltage must also be proportionally reduced. A block diagram of a typical variable voltage, variable frequency inverter is shown in Figure 3-3. Because the hardware is generally large and costly, these systems have a limited range of practical applications.

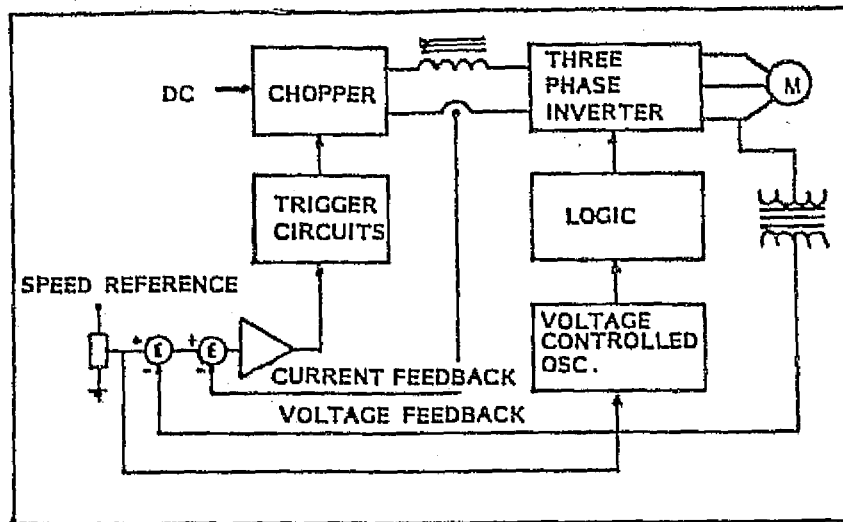


Figure 3-3 Variable voltage, variable frequency inverter

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Wound rotor motors may be similarly controlled. However, for this type of motor, speed control is typically achieved by varying the effective rotor resistance. As shown in Figure 3-2, a constant frequency, constant voltage power source may be used to drive the motor primary coils and speed control is obtained by varying the effective rotor resistance. Usually this control technique uses series resistors which result in relatively high power dissipation in the rotor circuit and adversely affects overall machine efficiency. There are other techniques which feed the excess power back to the source and are useful for limited applications.

Further technical improvements are necessary before AC induction motor controllers can be a practical part of an electric vehicle power train.

### 3.2.3 Direct Current (DC) Motors

Most existing battery powered vehicles consist of industrial vehicles, such as forklift trucks, tractors, and golf carts. These market areas utilize DC (direct current) motors almost exclusively. The characteristics of direct current motors that are attractive for traction applications include, high torque at low speed and ease of speed control.

In addition, several motors are available off-the-shelf in the performance range required for on-the-road electric vehicles. Suppliers include:

- |                    |                |
|--------------------|----------------|
| • Baldor           | • Prestolite   |
| • General Electric | • Reliance     |
| • Gould            | • Westinghouse |
| • Lawnel           | • Century      |

In general, direct current machines are classified by the method of energizing the field. The most common types are:

- Series,
- Shunt, and
- Permanent magnet.

Characteristics for a typical series motor are shown in Figure 3-4.

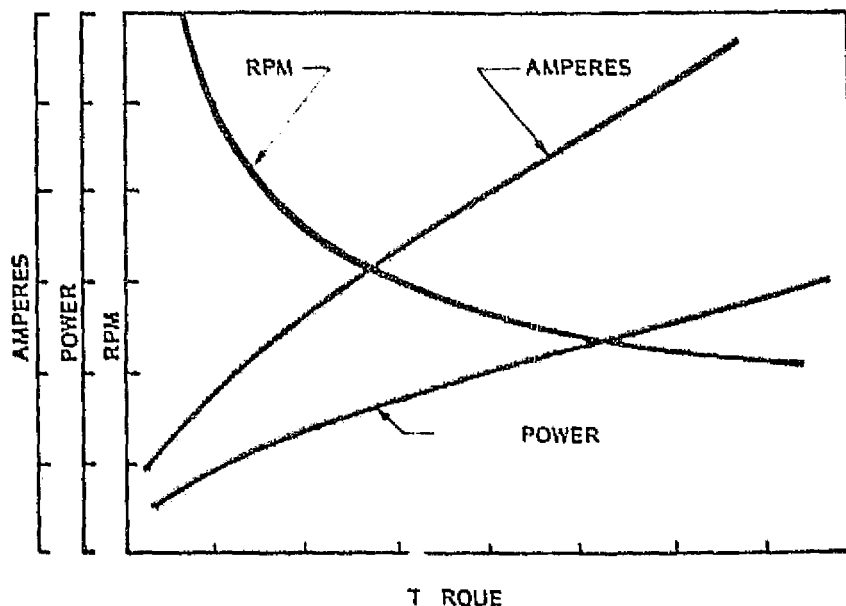


Figure 3-4 DC series motor characteristics with constant applied voltage.

Shunt wound motors are typically used where speed control is desired. This type of motor readily lends itself to controlled braking and regenerative applications since the power in the field circuit is much lower than the power in the armature circuit.

Permanent magnet motors are inherently more efficient due to the fact that no external field supply is required. Speed is directly proportional to armature voltage and the speed-torque curve and the current-torque curve are quite linear. Permanent magnet motors are available in fractional horsepower and very low integral horsepower sizes only.

Direct current machines using wound fields have been generally constructed for specific configurations. Series field motors are generally applied in torque demand situations where precise speed control is not required. Shunt wound motors are generally utilized with constant load, variable speed applications where precise speed control is required. Both configurations have been utilized in experimental electric passenger type vehicles with varied success.

#### 3.2.4 DC Motor Controllers

Speed control of direct current motors may be obtained by field control, armature voltage control, or a combination of both. These methods result in varying motor speed/torque characteristics. Field control of a shunt motor can be obtained with a small rheostat in the circuit with little loss as the field current is low. Armature voltage control can be performed in a similar manner. Armature currents, however, are high, up to 25 times greater than the field current, so this method involves bulky components and is less efficient.

Battery switching is a straight forward method of direct current motor control. Using this method, the armature voltage is varied by stepping the motor connections across fixed increments of the composite battery. Specific characteristics of this technique are:

- Controls require only contactors and/or diodes.
- Without current limiting step changes in voltage result in jerky operation.
- High starting currents are shared by several batteries in parallel.
- Without care in balancing the battery system loading, uneven discharging and premature battery failure may result.

A typical four step controller using six balanced battery sections is shown with a series motor in Figure 3-5. Operation may be improved by adding a series resistor in the armature circuit. Unless the resistance is removed from the circuit once speed is attained, speed regulation will be poor due to the resultant voltage drop across the resistance as the motor is loaded. The series resistance must also be capable of very high power dissipation at reduced motor speeds.

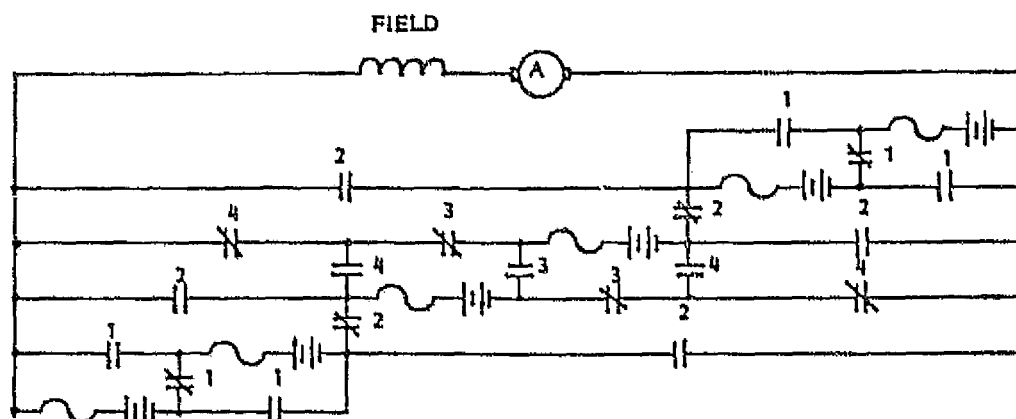


Figure 3-5 Six step controller. The contactors are energized in the following sequence: 1 & 2 (IV), 2 & 3 (2V), none (3V), 1 & 3 (4V), 4 (5V), 3 (6V). V is the individual battery voltage.

Another method of direct current motor speed control is obtained by "chopping". A chopper control applies an effective variable voltage across the motor through the use of the well known switching technique shown in Figure 3-6. The duty cycle may be proportioned by controlling the "on" time pulse width, the pulse repetition rate, or both. This method of control is extensively used in industrial vehicles such as forklift trucks. Characteristics of this type of control include:

- Effective motor voltage is proportional to the battery voltage times the switching duty cycle,
- Power transfer is: smooth,
- Electronic package has established reliability,
- Technique is considerably more complex than the battery switching technique, and
- Control is attained with low power components but actual power switching components are large and expensive.

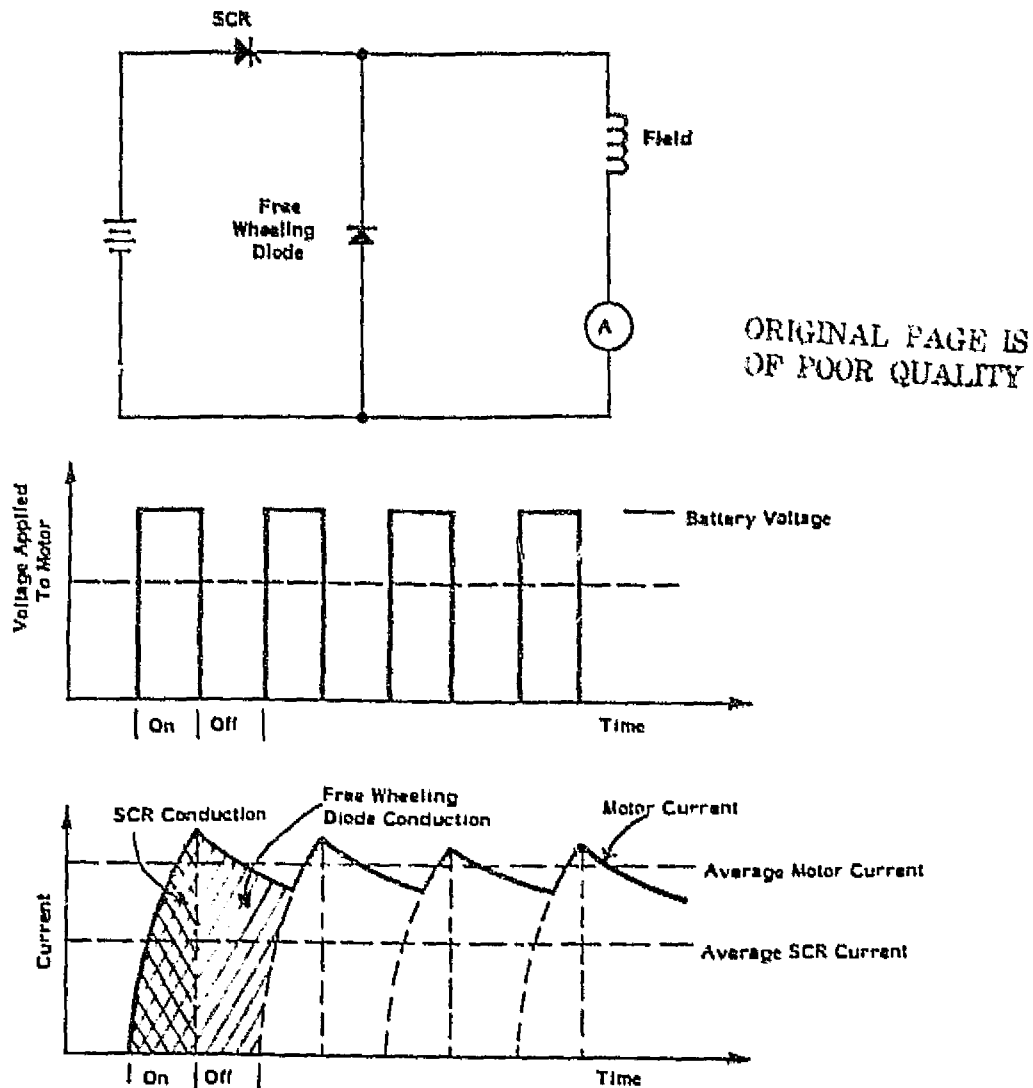


Figure 3-6 Chopper Control Waveforms.

There are a number of manufacturers currently manufacturing chopper controls for series wound motors. They include:

- Cableform
- Reliance Electric
- General Electric
- Sevcon

Sevcon and Cableform offer traction motor controllers with integral regeneration capability. Since most chopper type controls utilize thyristors or silicon controlled rectifiers (SCR) they are generally referred to as SCR controllers.

The direct current motor control techniques described above are applicable to the electric vehicle and have been utilized with most configurations of DC motors.



### 3.2.5 Vehicle Control Requirements and Summary

An integrated traction control system for an electric vehicle is still an unfilled need. Many have been developed utilizing sophisticated logic packages incorporating both analog and digital techniques to integrate vehicle controls. A general purpose system is, however, not available.

Experimental vehicle designs vary extensively in the complexity of the electronics utilized for the controller. The least complex is a simple transistor gating circuit utilizing discrete components. The most complex involves a 16 bit microcomputer providing complete real-time control of all vehicle dynamic parameters. To date no complete specifications have been identified, nor total package developed, for an integrated traction control system. The requirements for a total electronic control system needs definition within such areas as:

- Accelerator - If an objective is to duplicate conventional vehicle behavior, the accelerator position should be a torque demand control input. However, it is possible to provide other schemes such as speed control. Also, the electronic control of transmission gear ratios has not been significantly addressed.
- Brakes - Definition of requirements for blending of electrical (dynamic or regenerative) brakes with friction brakes is needed. For example "coasting" could result when releasing pressure from the accelerator or at an intermediate position so that the "feel" of engine braking is obtained.
- Operator Override - There are no specifications to require a means for an operator to disconnect the vehicle in an emergency. This may be a desirable feature in a practical electric automobile.
- Battery Monitoring - The existing criteria most commonly used for determination of battery condition is battery voltage. A specification for state-of-charge as a function of charge depletion and charge replenishment due to regeneration should be developed.

As a summary, Table 3-6 presents an overview of the motor/controller assessment for electric vehicle traction applications.

TABLE 3-6 MOTOR/CONTROLLER SUMMARY

	AC INDUCTION	DC SERIES WOUND	DC SHUNT WOUND, SEPARATELY EXCITED
Primary Application	Constant speed	Variable speed torque control	Variable speed; speed control
Motor Size	Compact, light weight	Moderate	Moderate
Motor Cost	Low	Moderate	Moderate
Motor Reliability	High, brushless	Moderate	Moderate
Torque/Speed Characteristic	Low starting torque, maximum at higher speed	High starting torque, decreases with speed	High low-speed torque, decreases with speed
Controller For Variable Speed	Complex, multiphase variable voltage and frequency	Proven SCR chopper, excellent torque regulation	An extension of series motor techniques, armature and field control, excellent speed regulation
Controllable Speed Range	As much as 8:1 is feasible, limited by synchronous speed of the motor	Limited by maximum speed of motor, loss of load results in overspeed	Limited by maximum speed of motor, loss of field results in overspeed
Reverse and Regeneration	Complex, part of control electronics function	Difficult but state of the art, switching in armature circuit	Simple, switching and control of low current field circuit

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### 3.3 MECHANICAL ELEMENTS OF AN ELECTRIC VEHICLE POWER TRAIN

In addition to the motor and controller, an electric vehicle power train typically consists of:

- A transmission to transform the high speed, low torque characteristics of the motor to the low speed, high torque road load;
- A differential to allow power transfer as the vehicle negotiates curves ;
- Bearings, drive shafts, universals and related mechanical hardware;
- Tires and brakes.

The nature of these components in the conventional automobile is reasonably well known. However, since little attention to fuel economy (efficiency) was required as this hardware evolved, a review of the state-of-the-art was undertaken to identify systems appropriate for the electric vehicle application.

#### 3.3.1 Transmissions

A simple calculation illustrates the need for rotational speed reduction in an electric vehicle power train. For the case of 0.61 m (24 inch) diameter tires on a vehicle travelling at 88 km/h (55 mph) the rotational speed of the tire is 770 RPM. Electric motors typically are designed to operate at several thousand (say 2) RPM. Thus an overall speed reduction in the order of 3:1 is required. In addition, empirical motor data shows higher efficiency in the high speed, low torque region.

Transmissions can generally be classified according to:

- Type of shift
  - None (fixed ratio reduction)
  - Manual
  - Automatic

- Ratio Incrementation
  - Discrete
  - Continuous
- Principle elements
  - Gear
  - Belt or Chain
  - Rolling traction
  - Hydrodynamic
  - Hydrostatic
  - Clutches
  - Combinations of the above

Table 3-7 lists several sources of transmission components and systems identified during the present study. The list is not, by necessity, all inclusive.

Fixed ratio reducers are numerous and are available in many packaged forms as well as on a build-to-suit basis. They can be classified somewhat by the type of gearing, belt or chain elements used. For example,

- Gear types include
  - Spur
  - Helical
  - Worm
  - Bevel
- Belt types include
  - V-belt
  - Toothed (timing) belts
  - Flat belts
- Chain types include
  - Standard roller type
  - Special

TABLE 3-7 MANUFACTURERS OF CANDIDATE TRANSMISSIONS

COMPANY	TYPE
American-Standard Dearborn, Michigan	CVT - fluid drive
Arter and Co. Mannedorf, Switzerland	CVT - traction type
Emil Beeklege Willowick, Ohio	Multiratio planetary - automatic shift
Chrysler Corp East Syracuse, New York, N.Y.	Standard automotive manual & automatic transmissions
Chrysler Marine Marysville, Michigan	Standard automotive manual & automatic transmissions
Dana Corporation Auburn, Indiana	Manual shift, hydrostatic and fixed ratio gear type
Eaton Corp. Marshall, Michigan	Fixed ratio gear reducers
Excelsomatic Austin, Texas	CVT - traction type
Fafnir Bearing Co New Britain, Connecticut	CVT - traction type
Floyd Drives Co. Denver, Colorado	CVT - traction type
Fluid Drive Engineering Co Wilmette, Illinois	Fluid torque converter & variable speed "V" belt
Ford Motor Co. Livonia, Michigan	Standard automotive manual & automatic transmissions
Gates Rubber Co. Denver, Colorado	Belts for variable speed belt drives
Graham Transmissions, Inc Menomonee Falls, Wisconsin	CVT - traction type
Hans Heynau GmbH Germany	CVT - traction and "V" belt types
Industrial Teclonics, Inc. Ann Arbor, Michigan	CVT - traction type
McKee Engineering Corp. Palatine, Illinois	Modified STD automotive automatic transmissions
Marathon - USA Inc. Stanford, Connecticut	CVT-hydrostatic type
Morse Chain Div Ithaca, New York	Fixed ratio chain & belt types

TABLE 3-7 MANUFACTURERS OF CANDIDATE TRANSMISSIONS (Cont'd)

COMPANY	TYPE
Nauwag GmbH Wuert, West Germany	CVT-traction type
SRF Jerusalem, Israel	CVT-hydrostatic
Sumitomo Machinery Co. Ltd. Carlstadt, New Jersey	CVT-various traction element types
Walter Chery Meadville, Pennsylvania	CVT
Warner Gear Div. Muncie, Indiana	Fixed ratio gear reducers
Electromatic Incorporated Cleveland, Ohio	CVT - variable slip fluid drive
Electromatic Drive Corp. Fort Worth, Texas	CVT - variable ratio "V" belt
Holton Axle & Transmission Juneau, Wisconsin	Fixed ratio transmissions
Fairfield Manufacturing Co., Inc. Lafayette, Indiana	Fixed ratio gear reducers
Winsmith Springfield, New York	CVT - traction type and fixed ratio gear reducers
SEK - Eurodrive Bruchsal, West Germany	CVT - traction and self types, fixed ratio gear reducers
AVS Ltd. England	High efficiency Hobbs torque converter
Sis Rite -	CVT hydrostatic type
Rydraco -	CVT hydrostatic type
Ernodrive Inc. Troy, Ohio	CVT traction type
Lewellen Mfg. Co. Columbus, Ohio	CVT pulley type
Reliance Electric Co. Cleveland, Ohio	CVT - pulley type
Lovajoy Inc. Downers Grove, Illinois	CVT - "V" belt type

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The efficiency of gear reducers can vary widely but spur gear sets have efficiencies that typically exceed 98%. Special gear systems offer high reduction ratios in small compact packages. These include:

- Planetary
- Harmonic
- Planocentric

The planetary system is quite common in transmissions and is attractive due to an inherently high power to weight ratio.

Belt or chain type reducers are candidates for fixed ratio electric transmissions as they, also, can be very efficient. A special chain type produced by Borg Warner, the Morse HI-VO chain bears special attention. Power transmission efficiencies for this chain used in actual drives, within rated limits, are claimed to be as high as 99.5%. This chain has been used as a drive train component in the CDA Van III (Ref. 39) as well as the Lucas Taxi (Ref. 25). Chains have been proven, by their extensive use in motorcycles, as an effective vehicle drive train component.

Multiratio transmissions of the type currently used in conventional automobiles have distinct compatibility and availability advantages. As such they have found application in many of the conversions discussed previously. These transmissions include:

- Current automotive manual and automatic shifting transmissions,
- Standard and automatic transmissions used on other vehicles such as motorcycles, small tractors and other specialty vehicles, and
- Standard transaxle assemblies.

Several conversions have used standard manual transmissions more for the readily available fixed-ratio reducer than for the multi-speed feature. In those cases, little effort was made to select multiple gear ratios, but rather the transmission was left in a single, "best overall", gear. In general consumer trends within the automotive market clearly discourage the use of a manually shifted transmission. The successful search for an efficient, automatic transmission will, therefore, enhance acceptance of the electric vehicle.

Standard automobile automatic transmissions that have been applied to electric vehicles include:

- The Chrysler 3-speed automatic (without torque converter) as applied to the CDA Van (Ref. 39) and
- The Renault transaxle as applied to the EVA Metro sedan (Ref. 12).

The use of these transmissions in electric vehicles involves consideration of several factors:

- The shift control needs modification to properly interface with electric controls,
- A power drain 0.75 - 2.2 kw (1 - 3 hp) is typical due to the internal hydraulic circuit, and
- Although the torque converter is a source of inefficiency it serves to provide some degree of shock isolation within the power train.

Advanced Systems Ltd. of England has developed a transmission which is claimed to be as much as 25% more efficient than conventional units. It employs a Hobbs torque converter coupled to a Borg-Warner automatic transmission (Ref. 52 and 53). This system has been demonstrated in a delivery van (Ref. 30).

Figure 3-7 presents efficiency data for a typical "Detroit" automatic transmission with a torque converter. This data serves to illustrate typical transmission behavior. Efficiency data for the Hobbs torque converter is given in Figure 3-8. In general, a torque converter in series with the transmission gives poor low speed efficiency and depresses the overall efficiency throughout the speed range.

There has been a good deal of interest and activity in the area of continuously variable transmissions (CVT) within the past several years. In essence, the torque converter itself is a form of CVT. Such mechanical power transmission equipment has long been available for industrial applications and scaled designs are being offered for vehicle use. A summary of the state-of-the-art in industrial traction drives is presented in Table 3-8. The high weight per horsepower rating is, generally, due to the fact that these units are packaged for industrial, rather than vehicular, use. However, the basic drive concepts may be applicable to the electric vehicle.



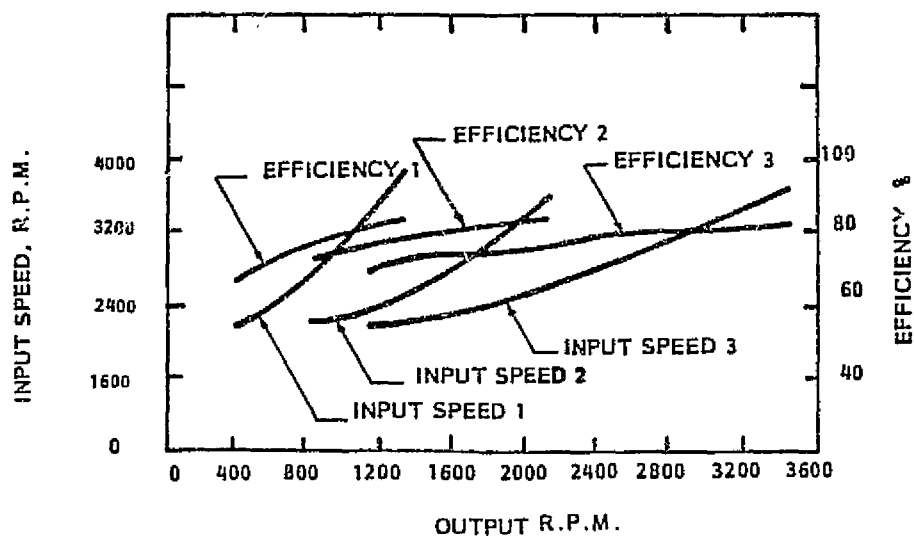


Figure 3-7 Efficiency and speed ratio of a typical "Detroit" automotive transmission with a torque converter. 1, 2 and 3 refer to speed ratios. This data was taken at the "wide open throttle" condition.

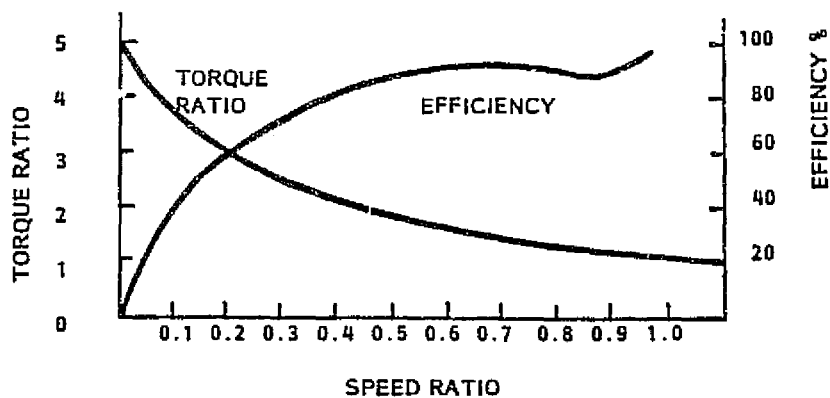


Figure 3-8 Performance characteristics of "Hobbs" torque converter built by Advanced Vehicle Systems.

TABLE 3-8 INPUT/OUTPUT CHARACTERISTICS OF TRACTION DRIVES

TYPE	SUPPLIER	RATING HP	RATIO RANGE	OUTPUT SPEED 1750-RPM INPUT	WEIGHT, LB. WITHOUT MOTOR		EFFICIENCY %
					10 HP	100 HP	
<u>Ring-Cone</u>							
With planetary	Graham	1/15-5	3:1	0-500	--	--	85-90
	Graham-Shimpo SCM	1/8-5	4:1	112-450	--	--	82
dual with planetary	Graham-Shimpo OM	1/8-5	10:1	300-0-360	--	--	60
single cone	Graham-Shimpo NT	1/16-2	10:1	5-500	--	--	60
<u>Varlator</u>							
ball	Eaton	1/2-16	8:1	600-5400	600	--	75-93
	Winemith-Allspeed	1/4-15	8:1	600-5200	375	--	75-90
roller	Koppers-Kopp	1-100	12:1	250-3000	265	1275	83-84
	Parker-Unicum	1/4-20	8:1	300-2500	480	--	77-82
<u>Free Ball</u>							
	Floyd	1/3-1 1/2	1:0:1	to $\pm$ 1750	--	--	80
	TEK-Contraves	1-25	40:1	80-3500	180	--	85-90
<u>Disc planetary</u>	ITI Disco-Lenze	1/3-15	8:1	200-1200	230	--	75-84
Beier	Sumitomo	1/4-220	4:1	360-1440	400	4200	80-87
<u>Toroidal</u>	David Brown-Sadi	1/3-5.5	7:1	600-4200	--	--	80
<u>Metal Belt</u>	FMC-PIV	7.5-75	6:1	715-4200	310	1280 (75HP)	85-90

Source: Power Transmission Design, November, 1975.

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Some of the more promising CVT's which were identified during the search for components are discussed in the following paragraphs.

- The basic automotive torque converter is, essentially, a CVT with slip. The Hobbs (Ref.52) design offers an efficiency of about 90% at speed ratios from 0.6 to 0.95. See Figure 3-8.
- Excelermatic, Inc. of Austin, Texas, offers a cone roller type CVT which has been demonstrated in an internal combustion engine vehicle (Ref. 54). Efficiencies of about 90% have been obtained above 20 mph. An illustration of this transmission is given in Figure 3-9.
- A hydrostatic - gear - flywheel hybrid transmission has been demonstrated by SRF, Jerusalem, Israel. Efficiencies of 86 to 91% over a speed ratio of 16:1 are claimed.
- Hans Heynau GmbH, Germany offers a line of infinitely variable drives with optional electric control.
  - One, based on a ring cone traction system, is available in sizes to 5 hp and speed ratios of 9:1. Figure 3- 10 illustrates the mechanical portion. Power is transmitted from the steel ring which, under tension, connects each pair of steel cones on the input and output shafts. The ring rides on the surface of the cones. Variable output speeds are provided by an axial movement of the cones which are rigidly connected by the rods.
  - Another is a variable pitch V-belt drive which is typical of a generic type available from several other suppliers. It is rated up to 20 hp and has an adjustable speed range of 6:1. Figure 3-11 illustrates the system. The output speed is varied by axial displacement of the movable side of the input pulley. The spring loaded output pulley automatically follows the altered effective radius. Similar systems are available from such domestic manufacturers as Reliance Electric of Cleveland and Lewellen Manufacturing of Columbus, Indiana.

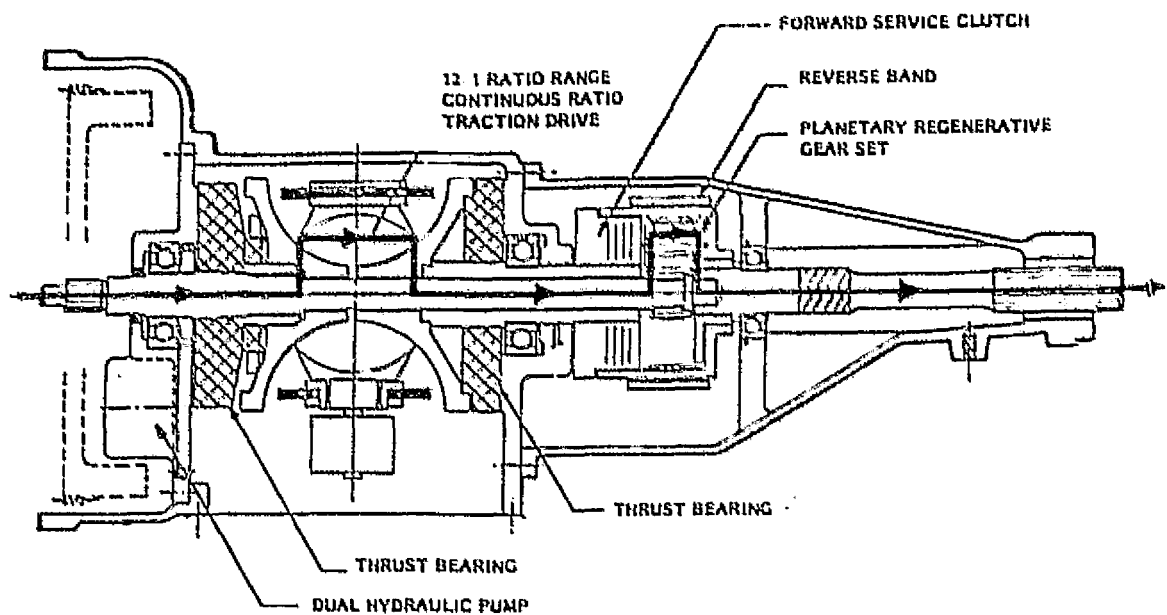


Figure 3-9 Excelermatic Transmission. A continuously variable ratio of 100:1 is achieved by coupling a traction drive to a regenerative gear set.

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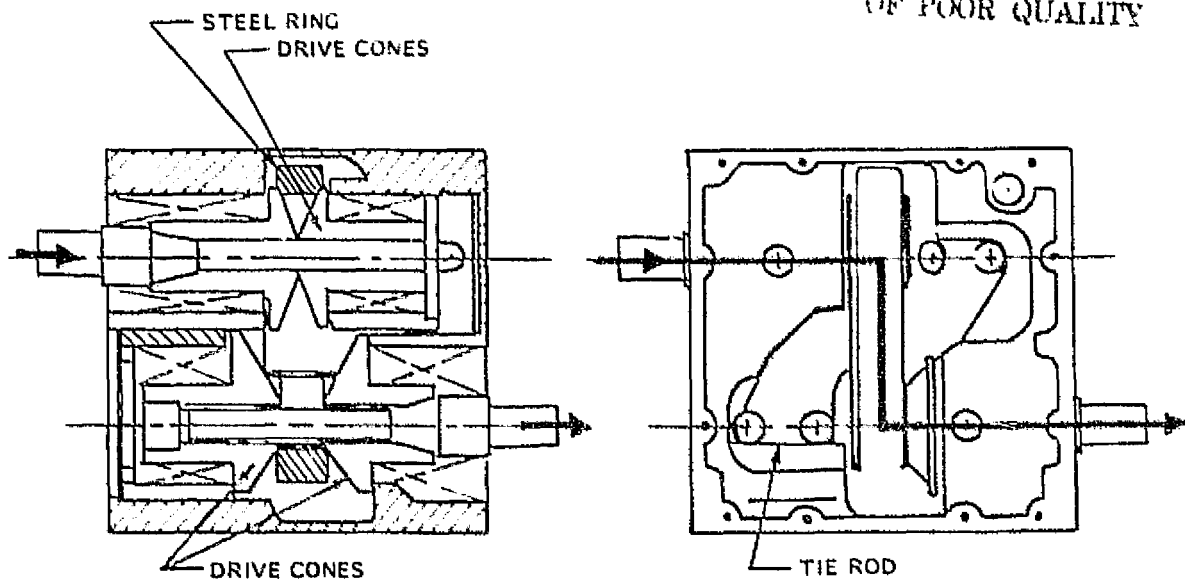


Figure 3-10 Cone/ring traction drive. The tie rod moves the drive cones to affect a ratio change of 9:1.

- Fafnir Bearing of New Britain, Conn., supplies a manually controlled traction drive which is used in lawn and garden tractors. It is available in sizes up to 20 hp with a 2.6:1 ratio change. Figure 3-12 illustrates the system. The traction-drive races and regenerative sun gear are both driven by the input shaft. The traction-drive and regenerative gears have a common carrier. The traction-drive carrier ratio is changed by adjusting the outer race spacing which changes the rolling contact angles. The output ring gear speed is determined by the summation of the sun gear and traction-drive carrier speeds. As the traction-drive is reduced the output shaft goes to neutral and, on further reduction, into reverse.
- One of the few CVT's available with electrical controls is offered by Electromatic Drive Corporation. This transmission is a variable pitch V-belt drive (based upon Salisbury Corp. components). The pitch diameter of the drive pulley is changed by driving a ball nut on a lead screw by means of a hysteresis brake. The driven pulley is spring loaded. An illustration of the CVT is given in Figure 3-13. The Electromatic weighs 30-40 pounds, and consumes about 5 watts of electrical power to shift. Mechanical efficiencies above 90% are claimed and this system has been demonstrated in the URBA car (Ref. 55). A similar electrically controlled CVT is manufactured by Lovejoy, of Downers Grove, Illinois for industrial applications. In addition, the DAF division of Volvo has had a V-belt system in the field for several years.

Hydrostatic transmissions are finding increasing application in industrial and agricultural machinery. They offer continuous ratio change by varying the coupling between a hydraulic pump on the input shaft and a hydraulic motor on the output shaft. Due to the multiple transfer of power between mechanical and hydraulic circuits the overall efficiency of hydrostatic drives are limited and not considered adequate for the electric vehicle application.

The transmission plays an interacting role with the motor and control system within a power train. Because of the large time spent in speed and torque change (accelerating) the relative performance of transmissions cannot be evaluated without an analysis over a driving cycle. Size and weight, efficiency, power capability, range of ratio change, controllability and reliability are some of the general selection criteria.

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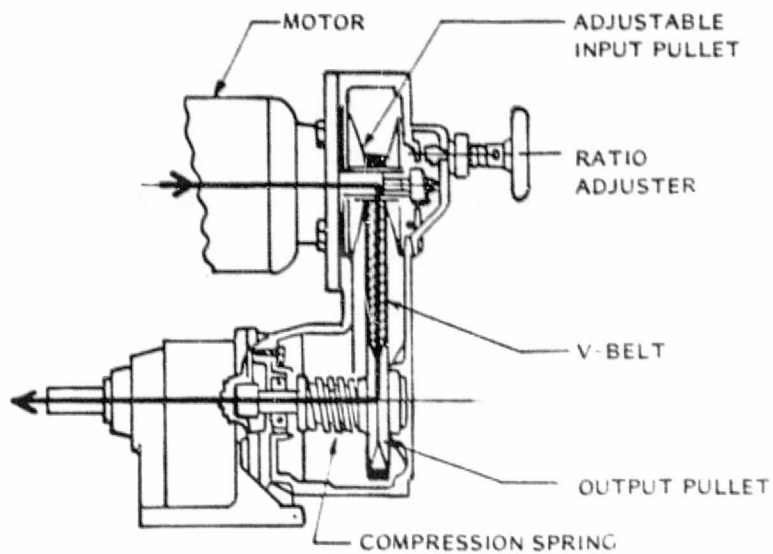


Figure 3-11 Hans Heynau belt type transmission

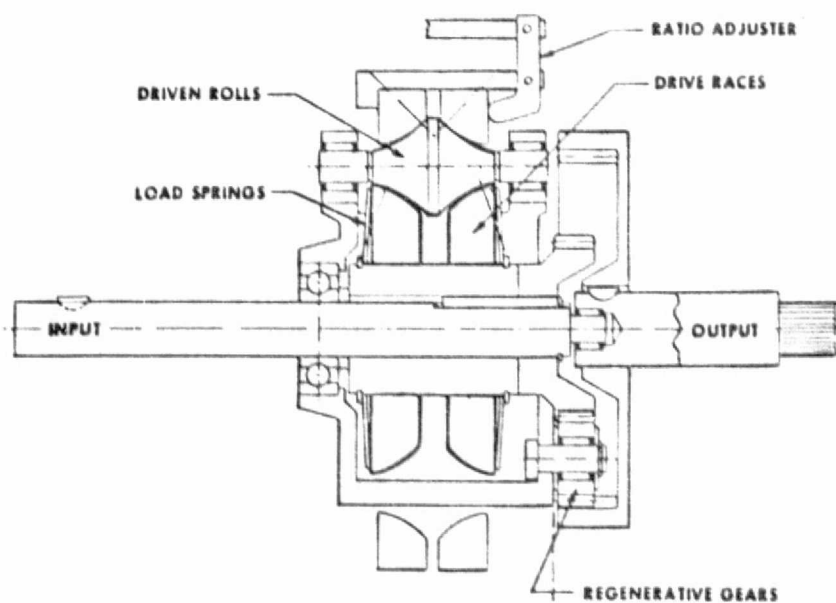


Figure 3-12 Fafnir continuously variable drive.

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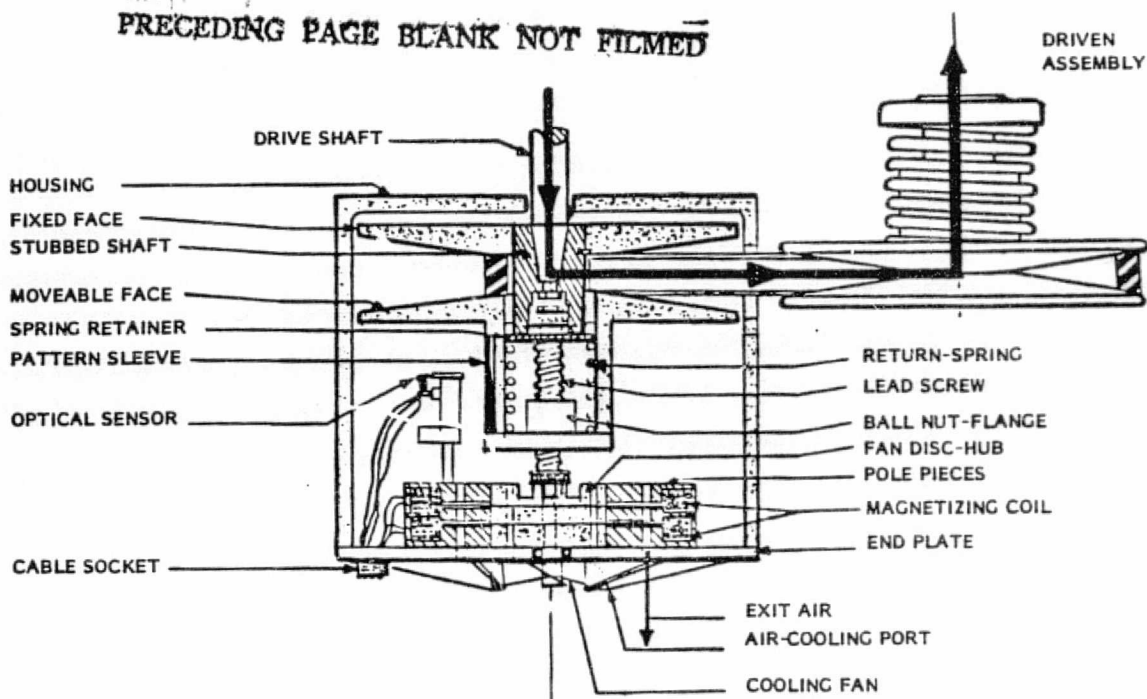


Figure 3-13 Electromatic V-Belt drive transmission

### 3.3.2 Differentials and Axles

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The purpose of a differential as used in a vehicle is to allow relative motion of the drive wheels to occur during cornering. A cross section of a typical automotive differential is shown in Figure 3-14.

Variations of this standard type of differential, which are within the state-of-the-art and applicable to electric vehicles, include the following:

- Replacement of the power input bevel gear pair with a belt drive, chain drive or spur gear pair, and
- Insertion of the differential within a transaxle housing as is typically done in some compact vehicles.

When the vehicle is not cornering, the efficiency of the mating bevel gears is irrelevant since they are not rotating relative to each other. The major energy losses in a typical differential occur at the power input gear pair and because of lubricant viscosity and splash effects. When the input gear is of the hypoid type, typical overall efficiency of a differential/axle assembly at rated capacity is 92%. Chain drive or spur gear inputs yield 98% efficiencies.

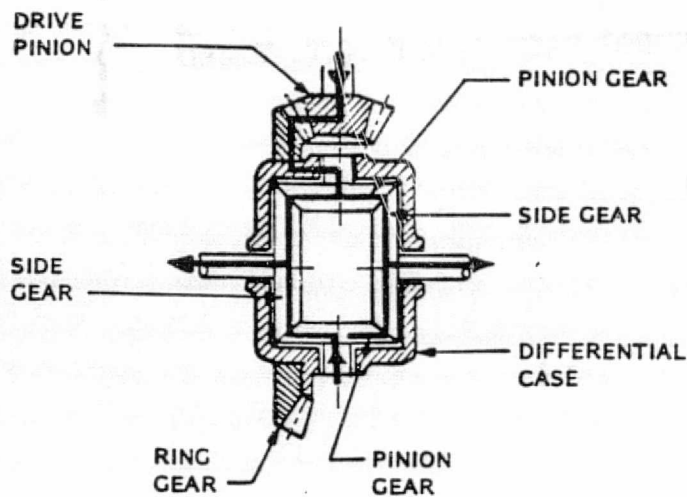


Figure 3-14 Typical automotive differential

Some sources of differential gearing, differentials, and total differential axle assemblies are listed in Table 3-9. There are few standard assemblies in this category but many firms are able to build production versions of special designs.

### 3.3.3 Brakes

Disc and drum brakes are commonly used on automotive vehicles with the disc offering superior stopping capability and fade resistance. For the electric vehicle application, regenerative braking appears attractive and if implemented, hydraulic brakes will experience a reduced thermal load. When comparing disc with drum brakes, major considerations are:

- Disc brakes weigh more than drum brakes with the weight penalty for a set of four approximately 6.8 - 20 kg (15 - 45 lb).
- Drag losses of 2.6 - 4 N-m (2 - 3 ft-lb) are typical with disc brakes and are essentially zero with drum brakes.
- Since drum brakes can be designed to be self-energizing, pedal pressures are lower than with disc brakes.

Therefore, the state-of-the-art power train should incorporate drum brakes, without power assist, based on the benefits of low weight and low residual drag.

Table 3-10 lists potential sources for electric vehicle hydraulic brake systems.



TABLE 3-9 MANUFACTURERS OF DIFFERENTIALS AND AXLES

Chrysler Corporation, East Syracuse, New York	K-B Axle Co., Inc. Los Angeles, California
Dana Corporation, Auburn, Indiana	Lear Siegler, Inc. Detroit, Michigan
Eaton Corporation, Cleveland, Ohio	Napco Industries Hopkins, Minnesota
Fairfield Manufacturing Co. Lafayette, Indiana	Rockwell International, Troy, Michigan
Hanaur Machine Works, Inc. Avon, Minnesota	Saginaw Steering Gear Division Saginaw, Michigan
Holtan Axle and Transmission Co. Juneau, Wisconsin	The United Mfg. Co. Cleveland, Ohio

TABLE 3-10 BRAKE MANUFACTURERS

Bendix Corporation, South Bend, Indiana	Goodyear Industrial Brakes Berea, Kentucky
B. F. Goodrich, Akron, Ohio	Gould Inc. St. Louis, Missouri
Delco Moraine, Dayton, Ohio	Hurst/Airheart Products Inc. Chatsworth, California
Eaton Corporation, Cleveland, Ohio	Mercury, Division of Apro Inc. Canton, Ohio
Electrold Company, Union, New Jersey	Midland Ross Owosso, Michigan
Friction Products, Medina, Ohio	Minnesota Automotive Inc. North Mankato, Minnesota
Gerdes Products Company, Vandalia, Ohio	Tool-O-Matic Minneapolis, Minnesota
Girling Troy, Michigan	Warner Electric Brake & Clutch Company Beloit, Wisconsin

### 3.3.4 Tires

Important parameters pertaining to tire selection for the electric vehicle include:

- Rolling resistance
- Wheel and tire weight and size
- Stopping performance
- Ride and handling quality
- Wet weather performance

For the preliminary design of the power train, rolling resistance, size and weight are most significant. The other factors are strongly related to the overall vehicle and suspension system design.

Wheel and tire weight should, obviously, be minimized for an efficient vehicle design. One way to minimize weight is to eliminate the spare tire. Firestone's ACT radial tire, with its "run-flat" capability, accomplishes this although each tire is somewhat heavier than a standard radial. Generally, weight is related to size and it would appear that smaller tires and wheels are optimum. However, the behavior of rolling resistance tends to cloud this choice.

Tire rolling resistance is generally defined as the force resisting vehicle motion due to tire hysteresis and the interaction of the tire with the road surface. It is usually expressed as resisting force per unit of tire load. Typical values are .098 to .196 N/kg (.01 to .02 lb/lb) although data as low as .059 N/kg (.006 lb/lb) have been reported (Ref.39 ). Tire companies obtain rolling resistance data by means of drum tests under "free rolling" or "coasting" conditions. Although most of our knowledge of tire behavior is based on such data, there is some question (Ref. 56 ) as to the validity of applying these results to the real case when torque is transmitted through the tire to the road. Figure 3-15, for example, illustrates that the use of the "free rolling" data may be significantly in error when calculating power losses over a driving cycle.

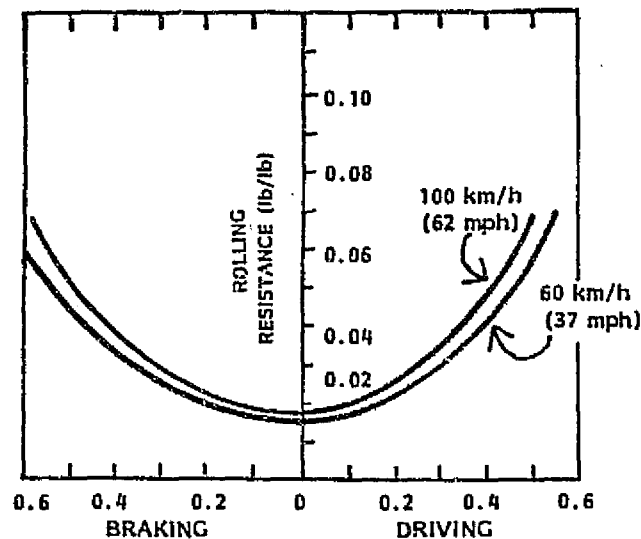


Figure 3-15 Apparent rolling resistance of cross-ply tires during braking and driving. Both ordinate and abscissa are normalized with respect to the supported load per tire.

Tire rolling resistance has received a good deal of attention recently (Refs. 56, 57, 58 & 59). Investigators have attempted to ascertain the dependence of rolling resistance on such factors as:

- Inflation pressure
- Load
- Cord design (belt, bias, radial)
- Cord and tread material
- Tire wear
- Vehicle speed
- Operating time
- Size

Figures 3-16 through 3-20 present the results of some of this research. It should be noted from this data that tire rolling resistance:

- Decreases with increased inflation pressure (Figure 3-16),
- Increases with load independently of rated capacity (Figure 3-17),
- Is lowest with radial construction (Figure 3-18),
- Decreases as wear increases (Figure 3-18),
- Increases with vehicle speed in a nonlinear manner (Figure 3-18),
- Decreases asymptotically to an equilibrium value as operation time increases (Figure 3-19),
- Is independent of tire size (Figure 3-20), and
- Is independent of cord material (Ref. 59).

Goodyear has recently announced the development of an "elliptic" tire (Ref. 60 ) which features.

- An elliptical sidewall profile
- Of steel belted, polyester carcass, radial construction
- A relatively low, 65, aspect ratio
- A high inflation pressure (typically 35 psi).
- Rolling resistance as much as 34 percent lower than standard radials.

This tire may be applied to 1980 model automobiles.

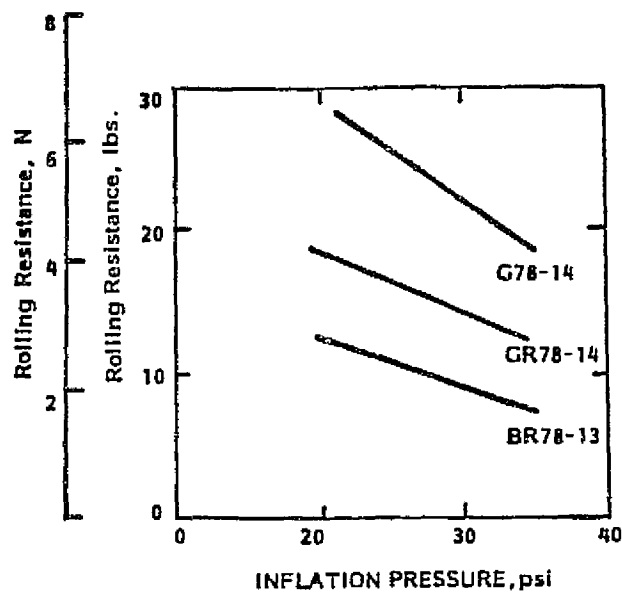


Figure 3-16 Effect of inflation pressure on rolling resistance.

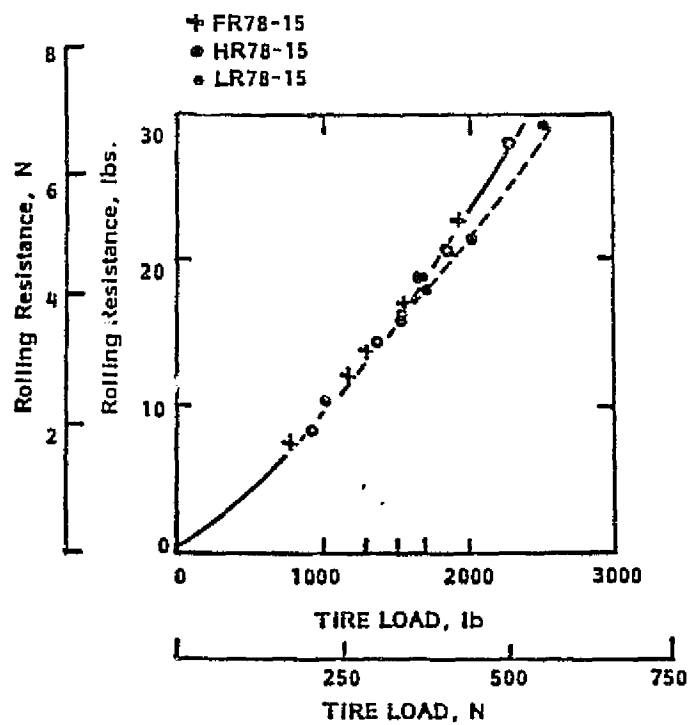


Figure 3-17 Effect of load on rolling resistance.

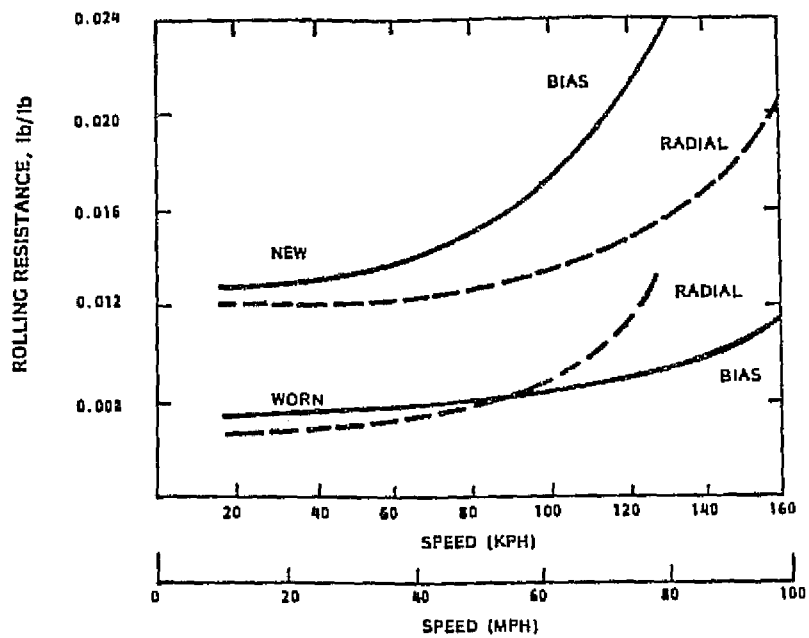


Figure 3-18 Rolling resistance versus speed for several tire types.

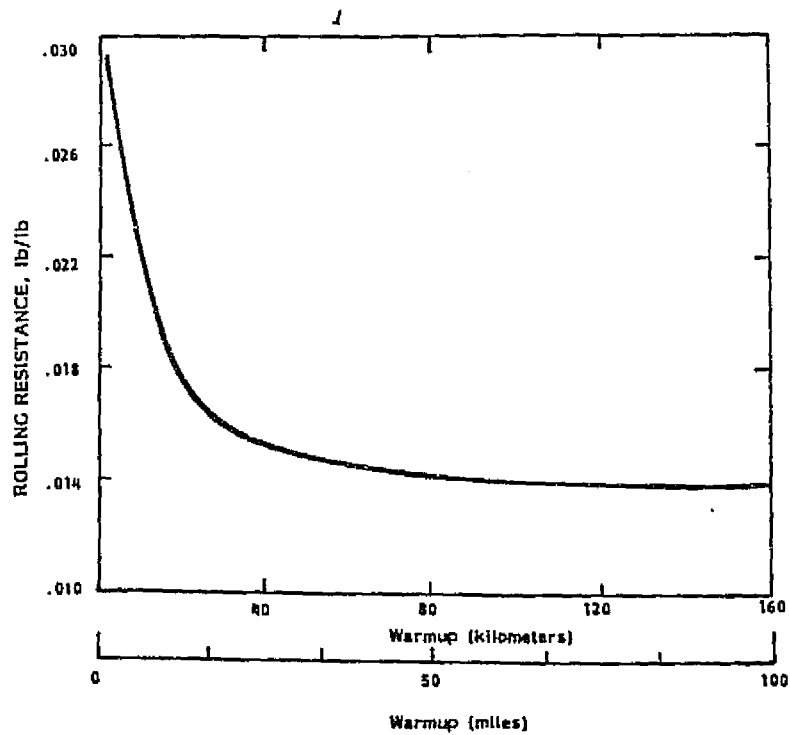


Figure 3-19 Effect of warmup distance on rolling resistance of a tire.

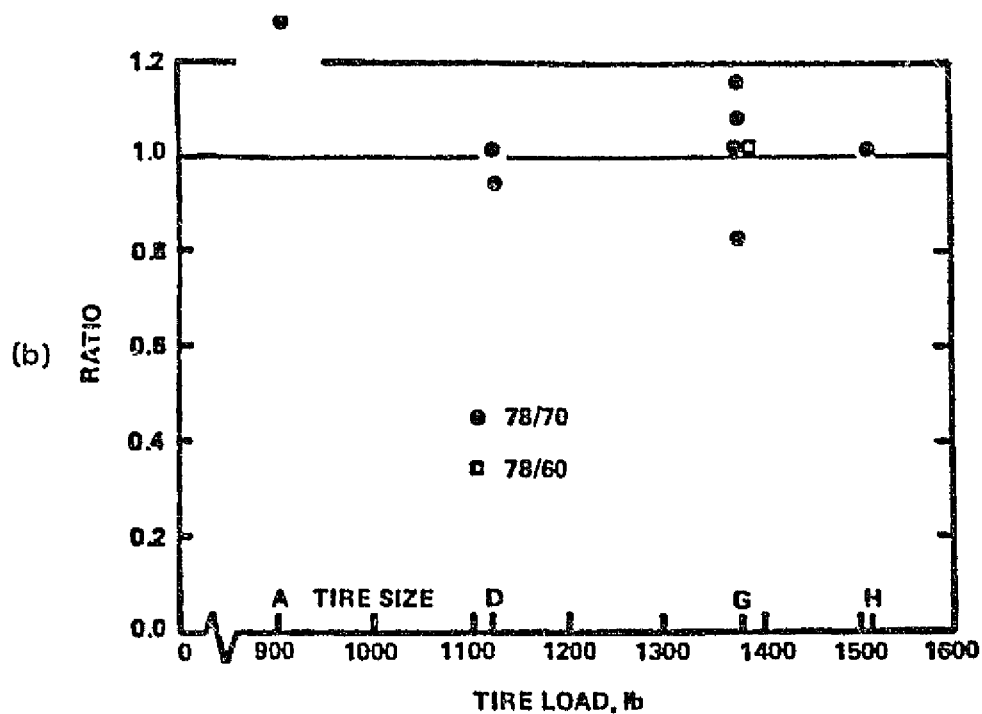
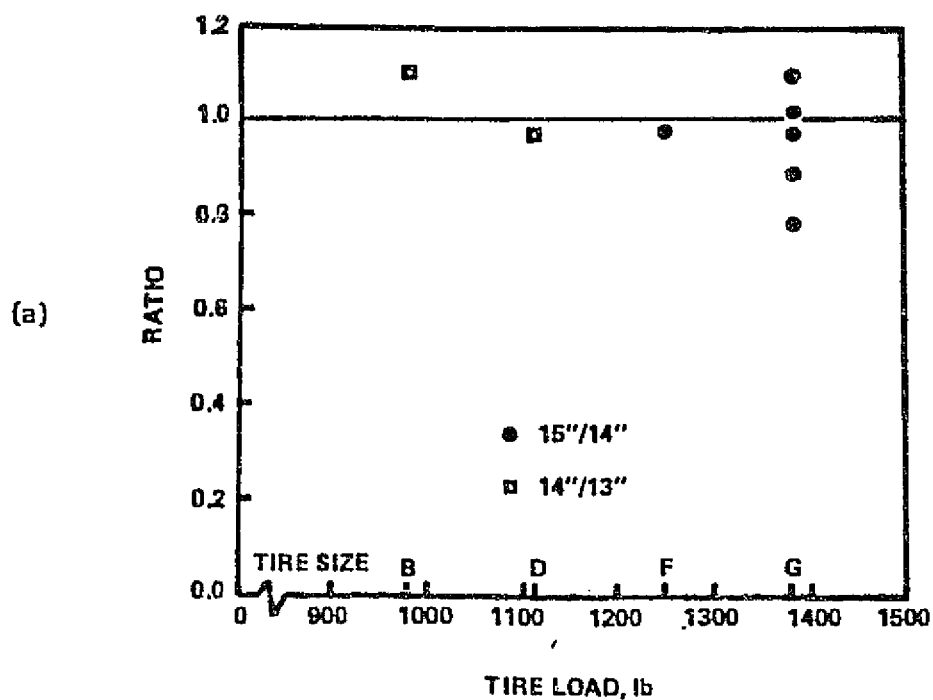


Figure 3-20 Ratio of rolling resistances for (a) different wheel diameters, and for (b) different aspect ratio tires.

Some potential sources for tires are listed in Table 3-11. Representative rolling resistance values are presented in Table 3-12. Analysis of the data indicates that a value of .098 N/kg (0.01 lb/lb) is a reasonable value for a state-of-the-art radial tire. In general, tires for the electric vehicle should be:

- Of radial construction,
- With load capacity well in excess of that required to support the vehicle, and
- Inflated to the maximum safe pressure.

### 3.3.5 Bearings

Standard engineering practice is to use rolling element bearings to support the wheels, axles and shafts which are part of a vehicle power train. Experience has shown that compared to bushings, which, involve relative surface-to-surface motion and fluid film bearings (hydrodynamic or hydrostatic), the lubricated rolling element bearing offers a good compromise between:

- Load capacity,
- Friction,
- Lubricant supply power,
- Size,
- Wear, and
- Cost

Typical overall values of friction coefficients (ratio of friction force per pound of load) for rolling element bearings are:

• Self aligning ball bearings	-	.0010
• Thrust ball bearings	-	.0013
• Single row ball bearings	-	.0015
• Tapered roller bearings	-	.0018



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TABLE 3-11 TIRE SUPPLIERS

Armstrong Rubber Company New Haven, Conn.	Lee Tire & Rubber Company Conshohocken, Pa.
B. F. Goodrich Tire Company Akron, Ohio	Mansfield Tire Corporation Mansfield, Ohio
Cooper Tire Company Findlay, Ohio	Michelin Tire Corporation New Hyde Park, New York
Dayton Tire & Rubber Company Dayton, Ohio	Mohawk Rubber Corporation Hudson, Ohio
Dunlop Tire & Rubber Corporation Buffalo, New York	Reynolds Tire & Rubber Corporation Brooklyn, New York
Firestone Tire & Rubber Company Akron, Ohio	The Goodyear Tire & Rubber Company Findlay, Ohio
General Tire and Rubber Company Akron, Ohio	Uniroyal Inc. New York, New York
Hercules Tire & Rubber Company Findlay, Ohio	

TABLE 3-12 REPRESENTATIVE TIRE ROLLING RESISTANCE DATA

MANUFACTURER	MODEL	LOAD (lb.)	INFLATION PRESSURE (psi)	ROLLING RESISTANCE (lb/lb)
Firestone	ACT (P185/65R14)	940	24	.014
Firestone	GR7815 GR7815	700 1000	--- ---	.0097 .0102
Goodyear	BR7813 HR7815	980 1510	24 24	.010 .008

Even with tapered roller bearings, at each of the four wheels of a 1633 kg (3600 lb) electric vehicle travelling at about 72 km/h (45 mph), the power loss is only 0.045 kw (0.06 hp).

Typically oils and greases increase in viscosity by more than an order of magnitude as the temperature drops 56°C (100°F). However, viscous forces are only a fraction of the total bearing friction. For lubrication of gear systems in differentials or transmissions, viscosity affects are significant and their variation with temperature will be noticeable.

Since seal power losses can be several times bearing power losses, low friction seals such as teflon, should be used wherever practical. In general, reasonable engineering practice will suffice to keep bearing losses at a minimum.

Table 3-13 presents a list of possible sources for automotive bearings systems.

TABLE 3-13 BEARING MANUFACTURERS

American Roller Bearing Company Pittsburgh, Pa.	INA Bearing Company Cheraw, S.C.
Fafnir Bearing Company New Britain, Conn.	Muller Georg of America, Inc. Schaumburg, Ill.
FAG Bearings Corp. Stamford, Conn.	New Departure-Hyatt Bearings Div., GMC. Sandusky, Ohio
FMC Corporation Indianapolis, Ind.	SKF Industries, Inc. King of Prussia, Pa.
Garlock Bearings, Thorofare, N.J.	The Timken Company Canton, Ohio
	The Torrington Company Torrington, Conn.

#### 4.0 STATE-OF-THE-ART POWER TRAIN DESIGN

Having reviewed the state-of-the-art in electric vehicle power train design, this chapter presents a preliminary design based upon that technology. Several candidate power train configurations are discussed and are evaluated using a computer simulation. Finally, a power train which represents the state-of-the-art is described and its performance is predicted.

##### 4.1 REQUIREMENTS

The terms of the contract required that a "state-of-the-art" power train should consist of components which:

- Are available off-the-shelf or by special order without requiring developmental engineering, but
- May involve design changes to facilitate mounting without affecting the intended basic function.

In addition to employing "state-of-the-art" hardware, as defined above, the electric vehicle power train design must also fulfill a set of performance specifications, which were also defined in the contract. These are considered representative of typical urban passenger vehicle usage and are stated as follows:

- The SAE J227a Schedule D driving cycle (See Ref. 61 ).
- A top speed of at least 88 km/h (55 mph).
- The ability to climb a 10% grade at a constant 48 km/h (30 mph) speed.

The design approach taken was to maximize range over the SAE driving cycle. A selected power train must be capable of the top speed and the hill climb, but range over the cycle was used as the overall measure of power train efficiency.

The SAE procedure specifies a cycle of  $122 \pm 2$  seconds which includes:

- Acceleration to  $72 \pm 1.5$  km/h ( $45 \pm 1$  mph) in  $28 \pm 2$  seconds.
- Cruise for  $50 \pm 2$  seconds
- Coast for  $10 \pm 1$  second
- Brake to a stop for  $9 \pm 1$  seconds
- Remain stopped for  $25 \pm 2$  seconds

Figure 4-1 depicts the velocity-time profile of this cycle. The shaded areas are drawn to illustrate that only the end points of each portion of the cycle are specified. Therefore, the shape of the accelerating portion of the curve is arbitrary and the speed at the end of the coast period depends upon the vehicle drag characteristics.

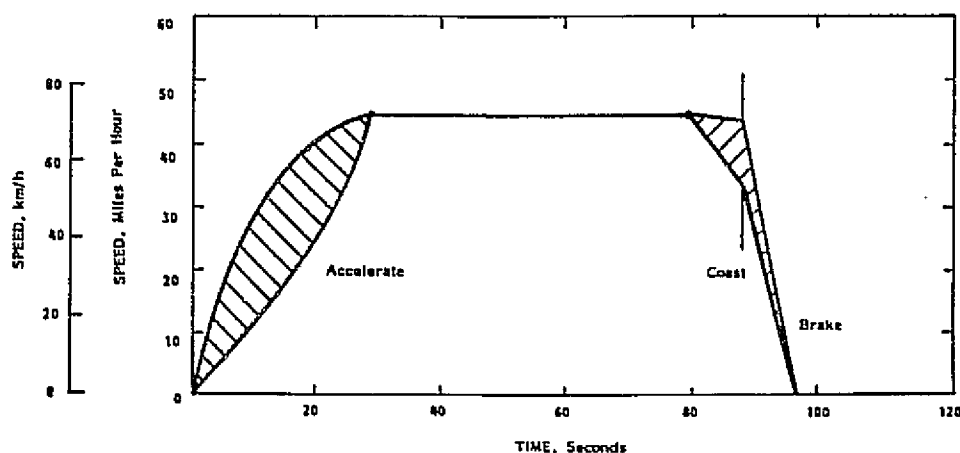


Figure 4-1 SAE J227a Schedule D driving cycle

The following vehicle characteristics were specified for the present study:

- Four passenger, urban type vehicle. \*
- Vehicle test weight including chassis, support systems, batteries and four passengers but excluding the weight of the power train is (1293 kg) 2,850 lbs.

- 16 EV - 106 batteries
  - 11.7 w-h/lb., 65 lb./battery \*
  - 1.04 w-h/in<sup>3</sup>, 734 in<sup>3</sup>/battery \*
  - 96 volts DC system
- Operating temperature =  $70 \pm 10^{\circ}$  F. \*
- Vehicle frontal area x drag coefficient =  $0.56 \text{ m}^2$  (6 ft.<sup>2</sup>)\*

The power train consists of the motor, controller, transmission, differential, axles, couplings, brakes, wheels and tires for four wheels, and any associated cooling equipment.

#### 4.2 PRELIMINARY COMPONENT SELECTION

On the basis of the definition of "state-of-the-art" (SOA) hardware and the review of electric vehicle power trains (Chapter 3.0) many elements of the SOA system can be selected. The following paragraphs identify those components generically and outline a methodology for completing the preliminary design.

The series wound DC motor and chopper type controller are well suited to electric vehicle (EV) power trains. The technology of DC motors and SCR type controllers is mature and has been successfully applied to many electrically powered vehicles. An industrial infrastructure exists to service these systems which are relatively simple to understand. The motor can be designed to meet a large variety of specialized requirements using well known techniques and hardware. In addition, the solid state controller is inherently capable of high reliability and low cost. Motors are available in the range of power rating which can fulfill the electric vehicle requirements. An analysis will be presented in a later section to size the motor.

Although shunt wound DC motors and AC motors are available in the basic rating needed for an electric vehicle, there are no off-the-shelf controllers for these motors. Hence they cannot be applied to a state-of-the-art design as defined herein.

Several mechanical transmissions are potentially suitable for electric vehicles. In general, recent consumer buying trends preclude consideration of manual gear change units. However, fixed ratio reducers, automatic gear change transmissions or continuously variable transmissions (CVT) are candidates. Versions of each of these types have been demonstrated in electric vehicles.

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\* Per specification in contract statement of work.

Mechanical elements such as gearing, differentials and tires are available which offer improved efficiency over those which have been used in conventional vehicles. In general, these utilize rolling element bearings and high efficiency gearing. Tires of radial construction, sized with high overload capacity and with high inflation pressures, offer the lowest rolling resistance.

The rear mounted motor/transaxle or the front wheel drive are preferred power train architectures. The most common, and practical approach to packaging the propulsion batteries has been to employ a central tunnel. Thus a central drive shaft is not feasible. The front wheel drive package, which is popular on many foreign internal combustion engine vehicles, and the rear motor/transaxle, typified by the Corvair, are two practical alternates. The selection of either approach has little bearing on the efficiency of the power train design and should be made by the vehicle designer.

The combination of motor, controller and transmission forms a very interactive system. The characteristics and efficiencies of these components vary significantly over a typical driving cycle. Even a basic design approach such as whether to use a fixed or changeable transmission ratio cannot be decided on the basis of simple efficiency considerations or intuitive engineering judgement.

Consider, for example, the extreme case of a CVT versus a fixed ratio reduction. The CVT will allow motor operation in its high efficiency range, will require less control range of the motor, and hence a simpler controller, but it is not clear whether the added weight penalty of the CVT can be offset through performance gain. The goal is to maximize the range over the driving cycle. The battery and motor sizing enters into this analysis due to the high current draw typical of grade climbing and acceleration at low motor speeds.

Further implications of the need for a careful, and objective trade-off analysis can be seen when considering the concept of individual wheel motors. At first it appears that such an approach is not desirable on the basis of efficiency because motor losses (i.e., end turn losses) and transmission losses will be greater for the multiple motor design. However, if fixed ratio reduction is feasible, then lightweight, high speed, wheel mounted motors, which are individually controlled may become viable.

The selection of an optimum power train requires a systems analysis of the hardware operating over the driving cycle. Therefore, the next section describes the analytical model to be used for this study.

### 4.3 ANALYTICAL MODEL

As part of work performed for the Environmental Protection Agency under Contract No. EPA-460-3-74-020 and for ERDA under Contract No. E(04-3)-1180, the General Research Corporation (GRC) of Santa Barbara, California developed a computer program for analyzing the performance of electrically powered vehicles. This GRC software was employed in the present study.

#### 4.3.1 Component Mathematical Models

The propulsion system must provide the tractive effort to overcome the total "road load" on the vehicle and the losses associated with the power train. For a pure electric vehicle the energy required is supplied by the storage batteries. The calculation of range proceeds by accounting for this energy consumption as the vehicle operates repeatedly over a driving cycle until the batteries can no longer deliver the required power. The power calculation proceeds from the road load to the battery as depicted in Figure 4-2. The following paragraphs summarize the algorithms used in the GRC model.

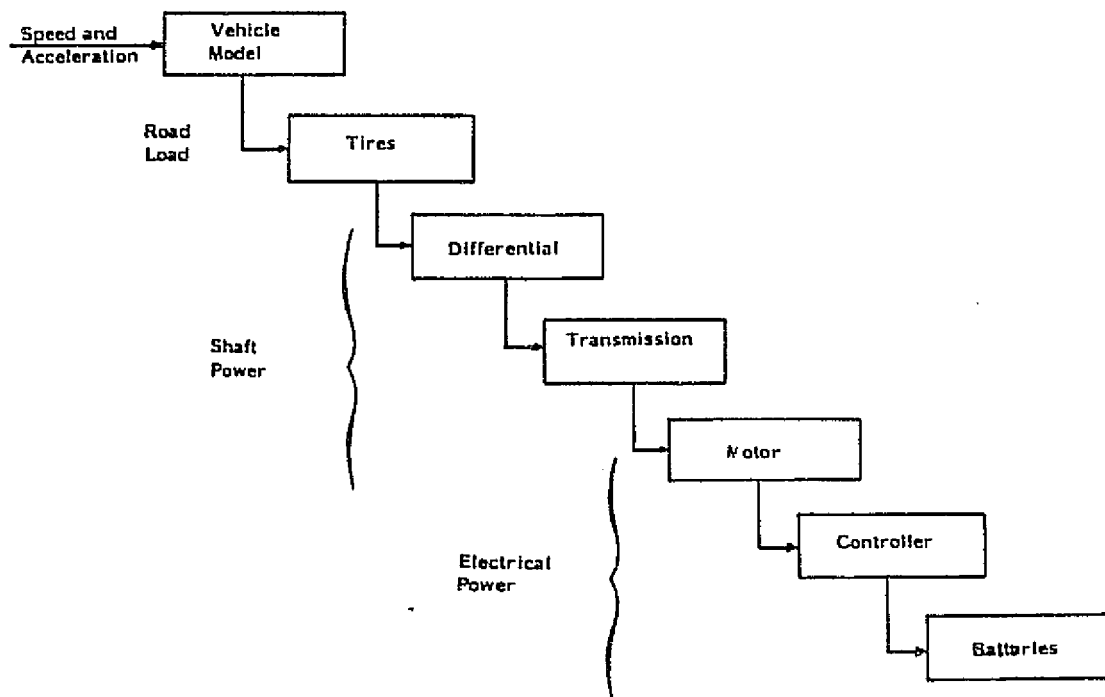


Figure 4-2 Sequence for calculating power required.

Vehicle road load is defined as the sum of aerodynamic drag and inertia forces. The aerodynamic force  $F_A$  is given by

$$F_A = 500 \rho C_D A V^2, \text{ N} \quad (4-1)$$

where:

$\rho$  = air density,  $\text{gm/cm}^3$

$C_D$  = aerodynamic drag coefficient

$A$  = vehicle frontal area,  $\text{m}^2$

$V$  = vehicle velocity,  $\text{m/s}$

and the force due to acceleration,  $F_I$  is given by

$$F_I = \left\{ \frac{W}{g} + \sum_i I_i \right\} dV/dt \quad (4-2)$$

where:  $W/g$  = vehicle mass,  $\text{kg}$ .

$I_i$  = inertia of the  $i$ th rotating component  
(i.e., wheels, motor armature, etc.) reflected to the road,  $\text{kg}$ .

$dV/dt$  = vehicle acceleration,  $\text{m/s}^2$

The vehicle road load is then,

$$\text{Road Load} = 500 \rho C_D A V^2 + \left\{ \frac{W}{g} + \sum_i I_i \right\} dV/dt \quad (4-3)$$

The term in brackets is an effective mass, since it is the sum of the vehicle and component inertia. The force due to acceleration frequently dominates. For example, assume a vehicle whose total effective mass is 1633 kg (3600 lb) with a product of frontal area and aerodynamic drag coefficient,

$$C_D A = 0.56 \text{ m}^2 \text{ (6 ft}^2\text{)}$$

moving at 72 km/h (45 mph) and accelerating at  $0.71 \text{ m/sec}^2$  (0 to 72 km/h in 28 seconds). The road load, in this case would be 1296 N (291 lb) but for steady motion at 72 km/h, it would be only 136 N (31 lb).



A practical approximation for tire rolling resistance is

$$F_R = W (a_1 + a_2 V), N \quad (4-4)$$

where:

$W$  = vehicle weight, kg

$V$  = vehicle velocity, m/s

$a_1$  and  $a_2$  are coefficients which can be extracted from data such as Figure 3-18.

$F_R/W$  is usually referred to as the rolling resistance coefficient.

The torque required at the drive wheels is given by

$$T_D = (F_R + F_A + F_I) R \quad (4-5)$$

where:

$R$  = tire radius, m

$T_D$  = torque, N-m

With known values for efficiency and gear ratios for the differential and transmission, the motor output torque and speed can be calculated.

The motor model is semi-empirical and assumes a DC series wound machine with current a function of torque only. Losses are modeled as an equivalent resistance to account for field and armature ohmic resistance, windage losses and hysteresis losses. The equivalent resistance is extrapolated from a set of motor characteristic data. The motor equations are:

$$\text{Power loss} = I^2 R_c \quad (4-6)$$

$$R_c = b_1 + \omega b_2 + b_3 (\omega/I)^2 \quad (4-7)$$

$$I = C_1 + C_2 T + C_3 T^2 \quad (4-8)$$

where:

$I$  = armature current, amps

$R_c$  = equivalent resistance, ohms

$\omega$  = motor speed, RPM

$T$  = motor torque, N-m

$b_1, b_2, b_3, C_1, C_2, C_3$ , are curve-fit coefficients

Although this model is not particularly sophisticated, it is not intended for motor design. Its utility is in estimating vehicle performance when the motor has been specified and when characteristics are available. It does account for the varying efficiency as a function of operating point which is crucial to a driving cycle analysis.

Figure 4-3 depicts a model of the static controller. Losses are assumed to occur as a voltage drop across the SCR when it is conducting and as a voltage drop across the free-wheeling diode during the "off" time.

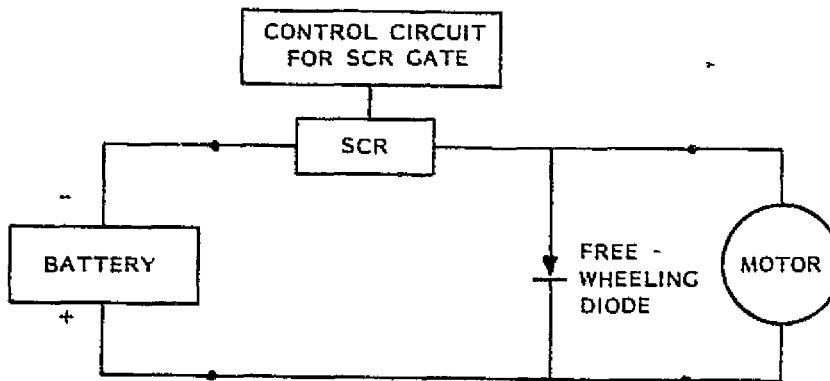


Figure 4-3 Basic SCR controller

Range is calculated by depleting the energy stored in the batteries until the vehicle cannot operate over the driving cycle. There are several battery models available. For example:

- The Kleckner algorithm based on Peukert's equation (Ref. 48),
- The Hoxie algorithm based on work conducted by Taylor and Sinek which allows for recuperation effects (Ref. 49 ), and
- The fractional utilization algorithm based on the Ragone plot (i.e., plot of specific energy density versus specific power density) (Ref. 62 ).

The fractional utilization model, which is a simple battery depletion algorithm, agreed well with test data (Ref. 62) and was employed for the present study. It has been reported (Ref. 5 ) that the apparent capacity of a battery may increase when regeneration is included. Polarization and sulphation are suspected to be responsible for this enhanced regeneration. A recent investigation into the pulsed discharge characteristics of lead-acid batteries (Ref. 51) suggests that similar "recovery" between pulses may account for an increase in capacity in some cases. Experiments presently underway at NASA-LERC may help to increase our understanding of battery behavior. The present investigation includes an enhanced regeneration utilization factor of 1.99 (Ref 5 ) as an upper bound on range over the driving cycle. A lower bound is given by ignoring this enhancement and accounting only for the energy regenerated with a 75% efficiency.

#### 4.3.2 Computer Program Description

The computer program simulates the operation of an electrically driven vehicle by a sequence of time-velocity pairs. For each time step specified by the user, the model determines the torque required from the motor to move the vehicle which in turn determines the power required from the battery to produce this torque. The distance traveled by the vehicle and the quantity of energy removed from the battery during the time step are computed and added to the distance traveled and energy used in the previous time steps. When the driving cycle is completed, the distance traveled by the vehicle over the one cycle and the amount of energy removed from the battery is used to estimate the total range of the vehicle.

As shown in Figure 4-4 the program consists of several sub-routines which are described below:

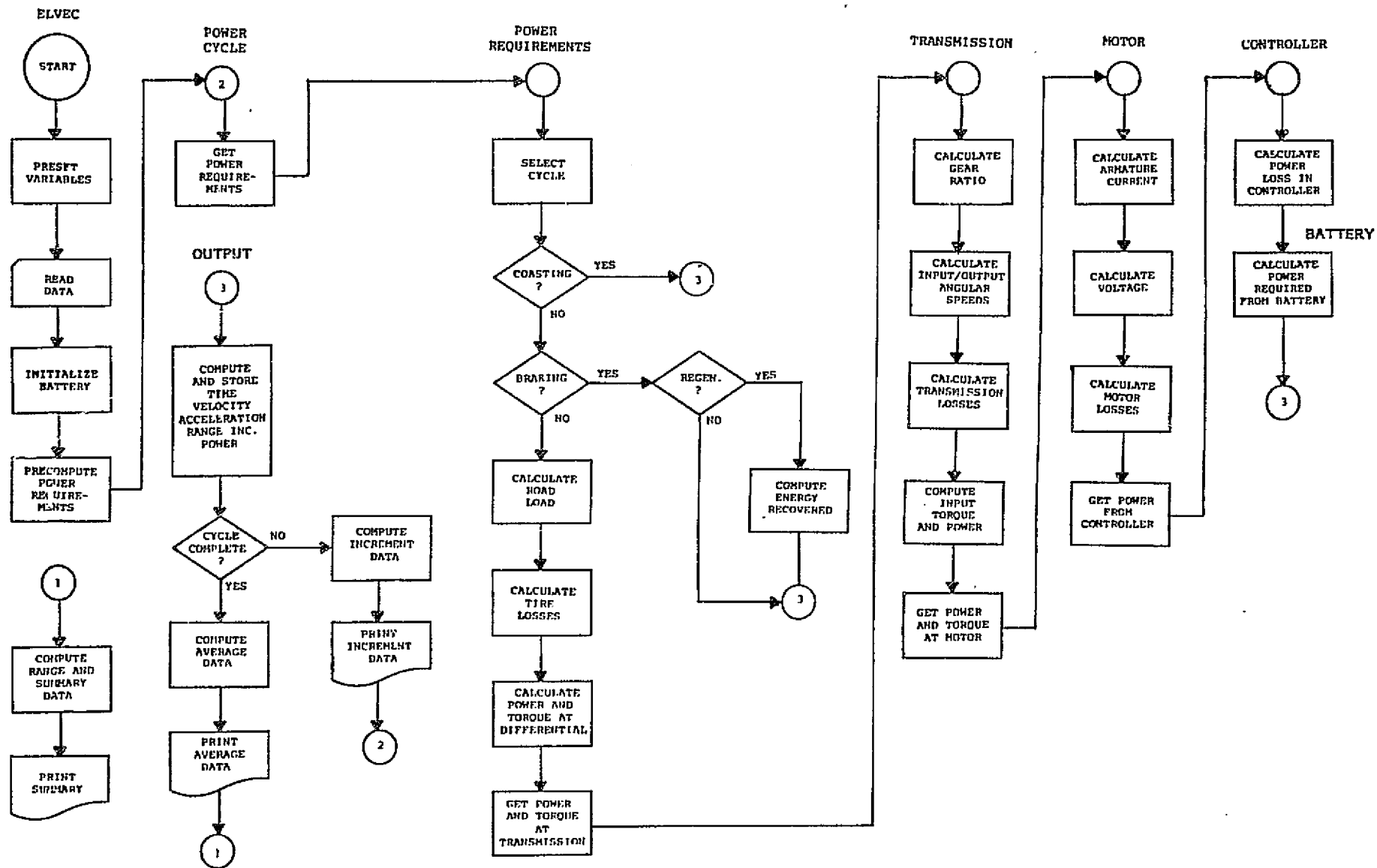


Figure 4-4 Computer simulation block diagram

- The input routine (ELVEC) reads in the data required to run the model and initializes calculations. In addition, this routine also checks the validity of the data. Input data requirements include:
  - Vehicle characteristic data, such as vehicle weight, aerodynamic drag, transmission/differential efficiency, number of gears and gear ratios, motor data and controller data;
  - Battery data, such as battery weight, battery power and energy density, number of batteries, number of cells per battery and battery cell voltage;
  - Mission profile data, such as the speed of the vehicle and the grade for "constant speed" runs or the driving cycle the vehicle is to be simulated on for non-constant speed runs.
- The load routine (POWER REQUIREMENTS) serves to calculate the torque required to drive the vehicle. Using data on the efficiency of the driveline, the model accomplishes this by computing:
  - The forces exerted on the vehicle due to aerodynamic drag, tire rolling resistance and acceleration;
  - The torque and speed required to drive the wheels;
  - The torque and speed required at the input to the differential and transmission.

The forces exerted on the vehicle, and the power required at the wheels and transmission, are based on standard engineering relationships as described in the previous sections.

- The MOTOR and CONTROLLER routines model the electric motor and solid state controller. The basic functions of the routine are:
  - To calculate the armature current, equivalent resistance and applied terminal voltage required to match the power input to the transmission;
  - To calculate the motor and controller losses;

- To calculate the required battery output based on the above two factors plus motor speed and the torque required to drive the vehicle (i.e., the output of the load routine).

The electric motor is modeled as a direct-current series wound machine and the solid state controller as a "chopper" type controller.

- The BATTERY discharge routine simulates the depletion of energy from the vehicle's battery. The basic outputs of this routine are the power discharged from the battery and quantity of energy consumed. In addition, this routine also simulates battery recharge during vehicle braking (i.e., regenerative braking) if desired.
- The OUTPUT routine compiles and prints out statistics regarding the performance of the vehicle. Primary outputs of the model include:
  - The distance traveled (range) by the vehicle during the driving cycle selected and the projected range of the vehicle assuming the vehicle was operated repeatedly over the driving cycle until total battery depletion;
  - A summary of aerodynamic road load, transmission and motor/controller losses;
  - A summary of vehicle speed, road load, motor speed, current and voltage, transmission efficiency, motor/controller efficiency, overall efficiency and battery power used, with respect to time;
  - The energy efficiency of the vehicle.

The GRC model was applied to calculate the range of an ideal vehicle, to perform a sensitivity analysis, to aid in sizing the motor and to evaluate candidate power train configurations.

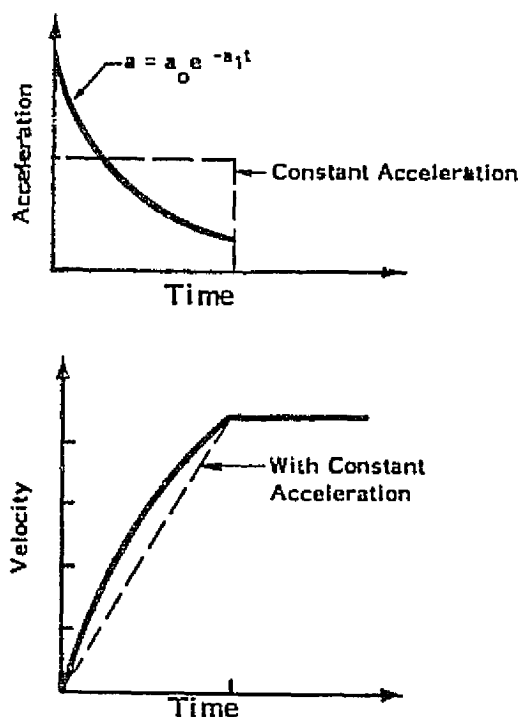
### 4.3.3 Acceleration Profile

Since the computer model requires a set of velocity-time pairs, and since the SAE driving cycle only specifies the end points of the accelerating portion (0 to 72 km/h in 28 seconds), some choice for the velocity profile must be made.

One choice is to use a constant acceleration of:

$$\frac{72 \text{ km/h}}{28\text{s}} = 0.71 \text{ m/s}^2$$

Alternatively the 28 second period could be divided into several time intervals each with its own constant acceleration. Using this method, a continuous function was selected which represents reasonable driver action. Such a profile is illustrated in Figure 4-5.



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Figure 4-5 - Exponentially decreasing acceleration profile for SAE driving cycle.

The coefficients for this profile are set by the following conditions:

- The area under all acceleration profiles must be the same since a given velocity must be reached in the same time.
- The final acceleration is selected, arbitrarily, at 50% of the constant acceleration of  $0.71 \text{ m/s}^2$ .

For the SAE cycle the initial acceleration is approximately 0.125 G and at 72 km/h the acceleration drops to 0.037 G.

With the exponential profile the power drain from the battery is more nearly constant when compared to the constant acceleration case. Figure 4-6 illustrates this point for a typical simulation run.

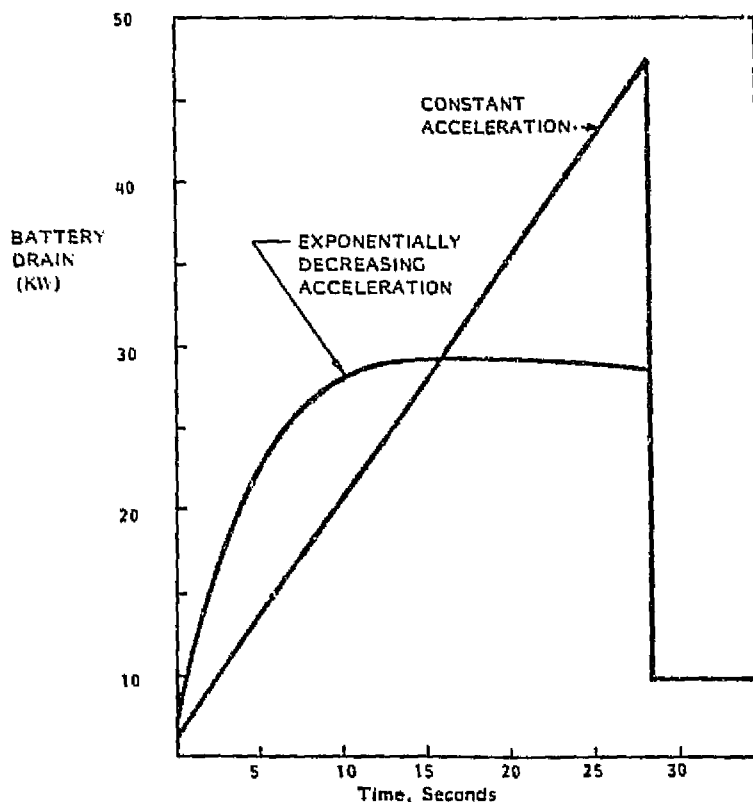


Figure 4-6 - Battery drain with different acceleration profiles.

The area under these two curves is approximately equal since it represents energy consumed. The acceleration profile would not affect energy drain directly but since higher speeds are associated with greater motor windage and aerodynamic friction one might anticipate a small difference in favor of the constant acceleration profile. However,



since the vehicle travels farther with the exponential profile and because of the desirability of using the battery at constant power drain, the exponential profile is preferred. Simulations have shown that the exponential profile improves range over the SAE cycle by about 5%.

#### 4.3.4 Range of an Ideal Vehicle

The total energy contained in the 16 EV-106 batteries is (16 batteries)  $\times$  (65 lb/battery)  $\times$  (11.7 watt-hr/lb) or 12.168 kwh. By assuming that the power train weighs 340 kg (750 lb), the total test weight is 1633 kg (3600 lbs). If the rolling resistance is 0.098 N/kg (0.01 lb/lb) and the product of the aerodynamic drag coefficient and the frontal area is  $0.56 \text{ m}^2$  (per Section 4.1) the tractive power necessary to propel a vehicle over the SAE cycle is shown in Figure 4-7. The power required for the 88 km/h (55 mph) cruise and the hill climb is also indicated in Figure 4-7.

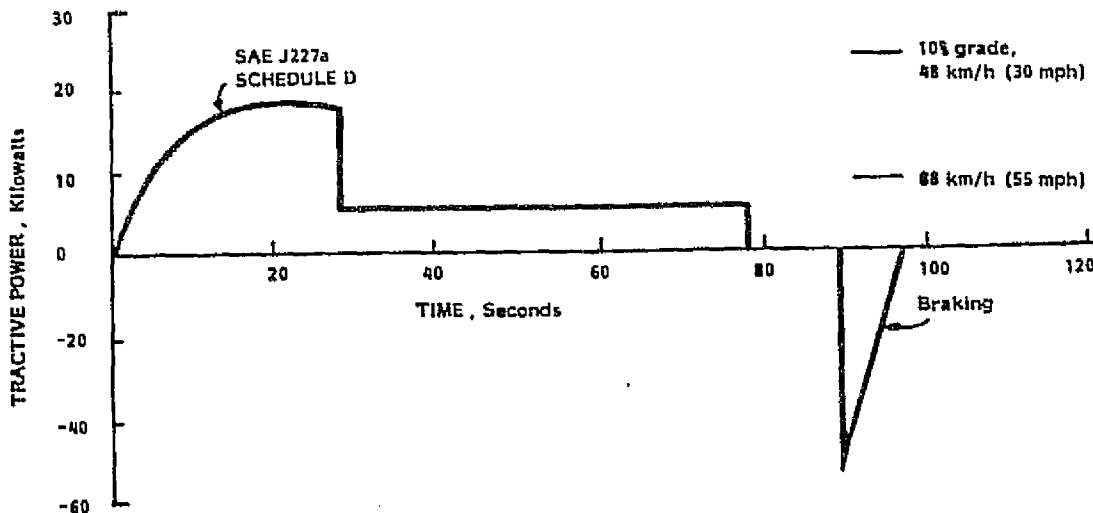


Figure 4-7 Tractive power required for a 1633 kg (3600 lb) vehicle.

If we assume, further, that all other drive line elements (such as motor, transmission, differential, etc.) are perfectly efficient the range achievable with a fully charged set of batteries can be estimated. Table 4-1 presents the results of such a calculation.

TABLE 4-1 COMPUTED RANGE OF IDEAL 3600 POUND VEHICLE

CYCLE	RANGE km (miles)
SAE J227a, schedule D	82/96* (51/60*)
55 mph constant speed	120 (75)
30 mph, 10% grade	24 (15)

\* Without regeneration/with regeneration but no enhancement.

#### 4.3.5 Sensitivity Analysis

In order to develop a feel for the relative importance of the basic power train features a sensitivity analysis was performed. The parameters studied were:

- Vehicle weight
- Transmission efficiency
- Tire rolling resistance
- Regenerative braking

Variations in aerodynamic drag were not investigated since the product of aerodynamic drag coefficient and frontal area ( $0.56 \text{ m}^2$ ) was a given vehicle parameter and is not part of the power train. The results of these simulation runs are presented in Figure 4-8. The height of each bar represents the improvement in range as the particular factor varies from minimum to maximum. In moving from left to right (case to case) the mean value of the previous parameter was maintained. Since the vehicle used in the simulation was arbitrary, the absolute values of range are not significant.

This analysis serves to illustrate that different features impact different portions of the driving pattern. For example:

- Regenerative braking improves range over the SAE cycle. (Figure 4-8 (a)).
- Tire rolling resistance is the major factor affecting range at top speed. (Figure 4-8 (b)).
- Vehicle weight strongly affects gradeability. (Figure 4-8 (c)).

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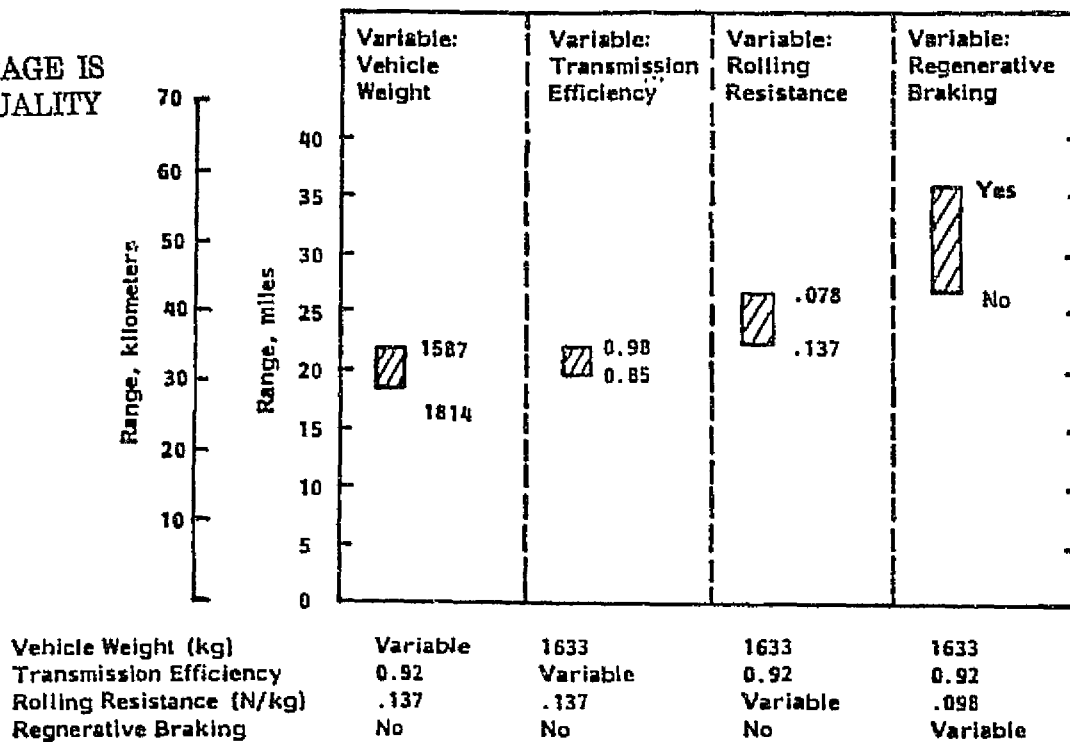


Figure 4-8 (a) Sensitivity of range over SAE cycle. Regenerative braking includes enhancement.

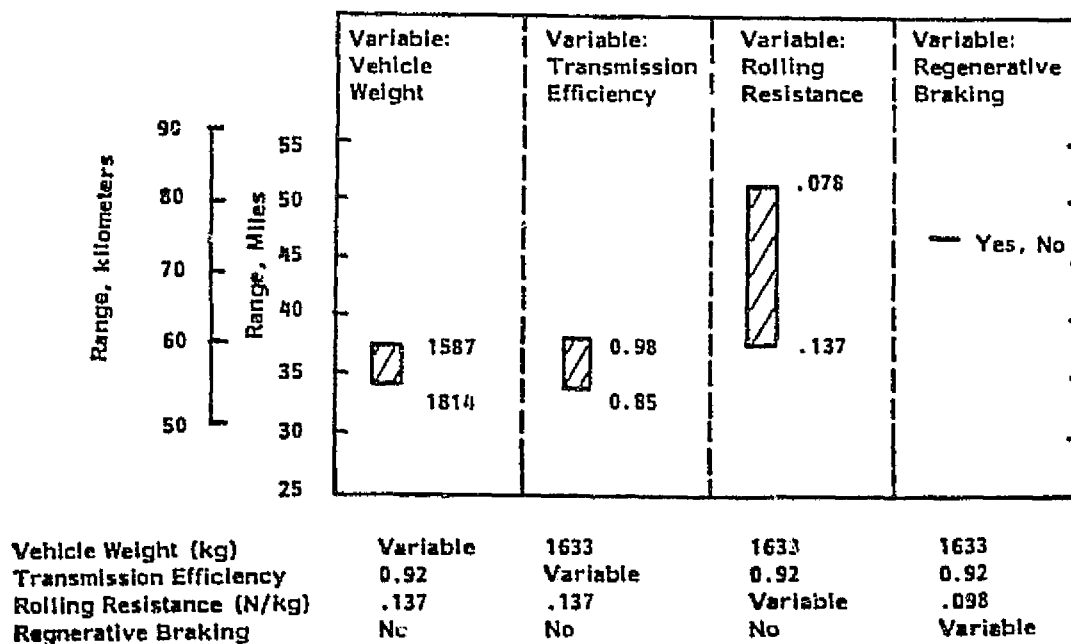


Figure 4-8 (b) Sensitivity of range at 88km/h (55mph)

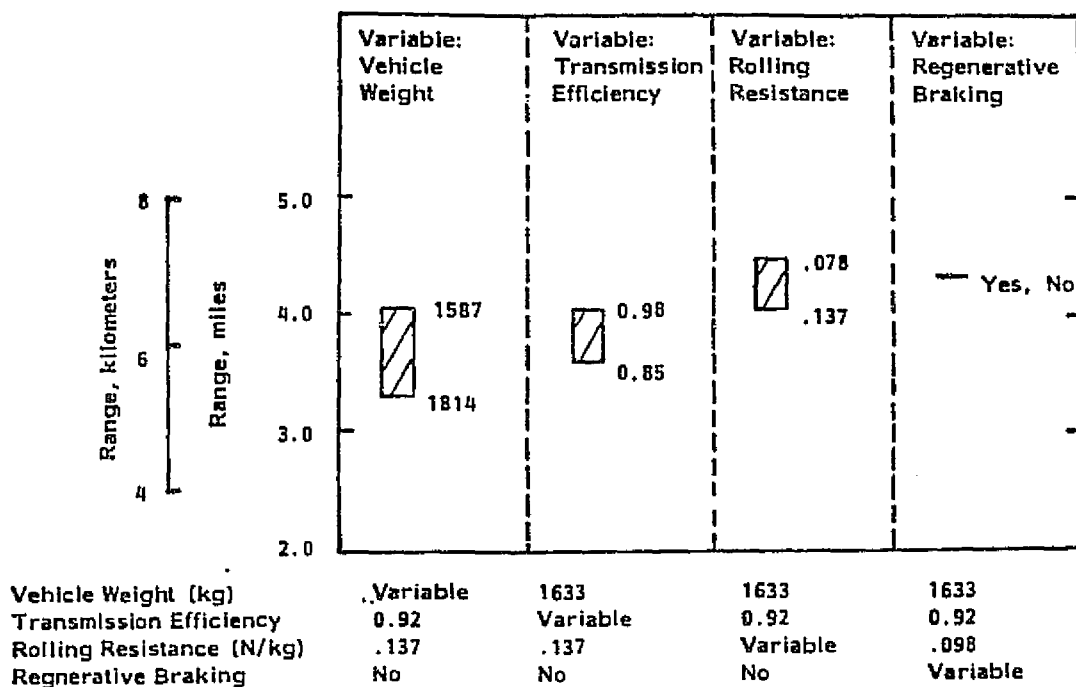


Figure 4-8 (c) Sensitivity of range up a 10% grade at 48 km/h (30 mph)

In addition, the analysis is useful as a method to approximately scale calculated range as parameters vary. For example, the sensitivity of range up a 10% grade at 30 mph to vehicle weight is approximately  $4/(20 \times 500) = 0.0004$  mi/mi/lb., so that if a vehicle weighing 1633 kg (3600 lb) achieved a range of 2.5 miles up this grade, a similar one weighing 1542 kg (3400 lb) should achieve about 2.7 miles ( $0.0004 \times 200 \times 2.5 + 2.5$ ).

#### 4.3.6 Motor Sizing

The tractive power data presented in Figure 4-7 can be used to approximately size a motor for the power train. This curve is based on a set of vehicle characteristics which include a maximum vehicle weight and reasonable tire performance. It should, therefore, represent a worst case requirement.

To arrive at a motor size note that the 88 km/h (55 mph) top speed requires that the motor deliver about 9 kw to the road. By conservatively assuming an overall driveline efficiency of 50%, a motor rated at 18 kw (24 HP) can be expected to provide the 25 kw needed for the gradeability.

#### 4.4 POWER TRAIN DESIGN

The selection of an optimum power train is based on engineering judgement as well as the computer simulation and is representative of what can be achieved with off-the-shelf, state-of-the-art hardware. As discussed in Section 4.2, the assessment of the state-of-the-art identified those components which are available for the electric vehicle application. In the following sections, specific hardware is selected for the major elements of the power train. The simulation study was employed to select a motor/transmission system.

##### 4.4.1 Power Train Components

The DC series wound motor is the most common machine used in traction applications and is recommended by most motor manufacturers for electric vehicle use. Since suitable state-of-the-art (as defined for this contract) controllers for either separately excited shunt wound or AC motors are not commercially available, these types of motors were precluded from consideration.

The Prestolite EO-26747 motor was selected as a representative SOA motor. Detailed performance data is available and a shunt wound version may be ordered in the same frame size. Table 4-2 summarizes its features and Figure 4-9 gives calculated characteristic data for several fixed voltages. This information was used in the computer simulation.

TABLE 4-2 MOTOR SPECIFICATION

Type	Series wound DC with interpoles
Manufacturer	Prestolite
Model	EO-26747
Weight	93 kg (205 lb)
Size	28.6 cm OD x 43 cm L (11 $\frac{1}{4}$ " OD x 17" L)
Power Rating	18 kw (24 hp) continuous
Voltage	100 volt nominal
Maximum Speed	4000 RPM

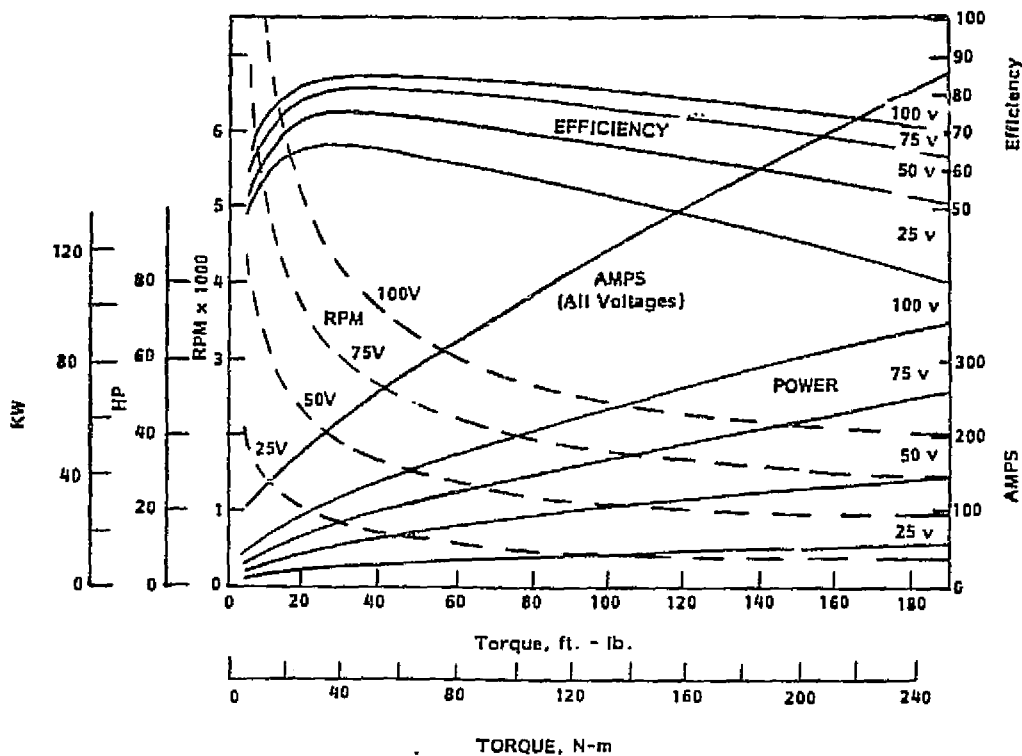


Figure 4-9 Prestolite EO-26747 motor characteristics.

A solid state chopper with integral regeneration circuitry was selected. A suitable unit is manufactured by Sevcon and Table 4-3 summarizes its features.

TABLE 4-3 CONTROLLER SPECIFICATION

Type	SCR chopper, logic unit, coil and capacitors
Manufacturer	Sevcon
Model	7650-4
Rated Voltage	80-130 volts
Rated Current	750 amps max, 400 amps continuous
Weight	27 kg (60 lb)
Size	Chopper: 36 cm x 25 cm x 18 cm (14" x 10" x 7") Logic: 8 cm x 28 cm x 15 cm (3" x 11" x 6") Coil: 15 cm x 10 cm x 13 cm (6" x 4" x 5") Capacitors: 25 cm x 13 cm x 15 cm (10" x 5" x 6")

Table 4-4 lists a typical set of line and directional contactors and Table 4-5 lists typical mechanical driveline components other than the transmission. With these elements an overall value of 0.98 N/kg (.01 lb/lb) conservatively accounts for both tire rolling resistance and mechanical friction within the bearings and axles. (See Section 3.3.4 and 3.3.5).

**TABLE 4-4 CONTACTOR SPECIFICATION**

TYPE	DIRECTIONAL CONTACTOR PAIR	LINE CONTACTOR
Manufacturer	HB Electric	HB Electric
Coil Voltage	12 Volts	12 Volts
Weight	4.5 kg (10 lb)	2.3 kg (5 lb)
Model	HB 33BA123LIB	HB 39BD122LIB

**TABLE 4-5 MECHANICAL DRIVELINE COMPONENTS**

COMPONENT	SUPPLIER	UNIT WEIGHT kg (lb)
Modified Differential	Dana Spicer	15.9 (35)
Chain Drive	Morse	6.8 (15)
Drive Shaft and Universals (2)	Dana Spicer	6.8 (15)
Wheel (4)	Kelsey-Hayes	9.1 (20)
Drum Brake (4)	Delco-Moraine	9.1 (20)
Radial Tire (4)	Goodyear	9.1 (20)
Miscellaneous		4.5 (10)

#### 4.4.2 Motor/Transmission Selection

The characteristics, features and performance of ten power train configurations are described in this section. Each system described was simulated in operation over the SAE cycle, at a constant 88 km/h (55 mph) speed and while climbing a 10% grade. These quantitative results are augmented by several qualitative considerations leading to an objective choice for the optimum state-of-the-art power train design.

In each case simulated:

- The motor was the Prestolite EO-26747 DC series motor,
- The tires were of 0.32 m (12.6 in) radius,
- The rolling resistance assumed was 0.98 N/kg (0.01 lb/lb),
- The transmission and differential efficiencies were estimated from manufacturer's data,
- A weight penalty (or benefit) was assigned with respect to a baseline of 1633 kg (3600 lbs),
- Preliminary computer runs were made to determine the best gear/transmission ratio, and
- Regenerative braking was included both with and without "enhancement" (See Section 4.3.1).

Figures 4-10 through 4-19 depict the configurations and list the simulation conditions.



Case 1: DC motor directly coupled to a hypoid differential.  
 (Figure 4-10) . This is the most common arrangement found on existing conversions where the internal combustion engine and transmission is replaced by an electric motor. Construction is simple and rugged. However, little concern for matching motor efficiency to the load is apparent in this approach. Hypoid gearing is inefficient and efficiency is sensitive to lubricant temperature.

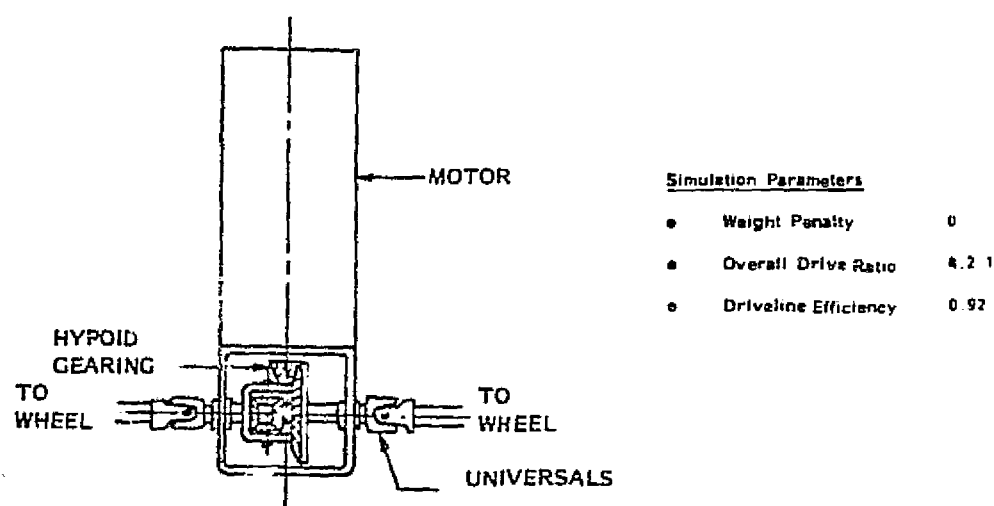
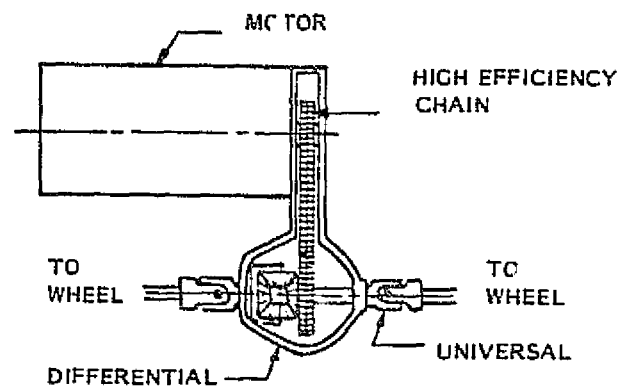


Figure 4-10 DC motor directly coupled to a hypoid differential.

Case 2: Fixed ratio reduction with a high efficiency chain.  
 (Figure 4-11) This example serves to illustrate the benefit of replacing the inefficient hypoid gearing with a chain drive such as Morse Hy-Vo. Construction is simple and lightweight. Efficiency of the chain drive is high and relatively insensitive to temperature. Motor characteristics are poorly matched over most of the driving range.

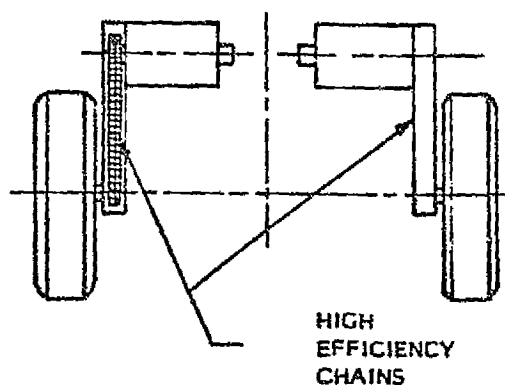


Simulation Parameters

•	Weight Penalty	0
•	Overall Drive Ratio	4.2 1
•	Driveline Efficiency	0.98

Figure 4-11 Fixed ratio reduction with a high efficiency chain.

**Case 3:** Dual Motor drive with fixed reduction chains. (Figure 4-12)  
 This configuration, or an alternate using coaxial gearing, offers a weight advantage. The chain drive version should result in the more desirable condition of lower unsprung weight. To compute the range for this case the motor model was that of a single Prestolite unit but the power train weight was reduced by 45 kg (100 lbs). It can be expected that since smaller motors are generally less efficient than a single large motor, the predicted range is optimistic. In addition the technique best suited to control this pair of motors has not been defined. A series connection from a single controller offers an inherent differential action but may result in unbalanced driving forces. Dual controllers, on the other hand, subtract from the apparent weight benefit. The chain drive approach offers high efficiency but the use of fixed reduction results in poor matching of the motor to the variable load.



#### Simulation Parameters

• Weight Penalty	-45 kg (100 lb.)
• Overall Drive Ratio	4.2 : 1
• Driveline Efficiency	0.88

Figure 4-12 Dual motor drive with fixed reduction chains

Case 4: Standard 3-speed automatic transmission with a torque converter. (Figure 4-13) This power train configuration utilizes a standard "Detroit" transmission. This is an example of an off-the-shelf, multi-ratio system with automatic ratio change. Due to the internal hydraulic pump circuit, losses are of the order of 0.75 kw (1 hp) to 2.2 kw (3 hp) depending on vehicle speed. The torque converter adds significant loss to the drive train during both acceleration and constant velocity operation. The lubricant in both units causes efficiency to vary with temperature. The efficiency was modeled by using discrete values for each gear ratio which are probably optimistic.

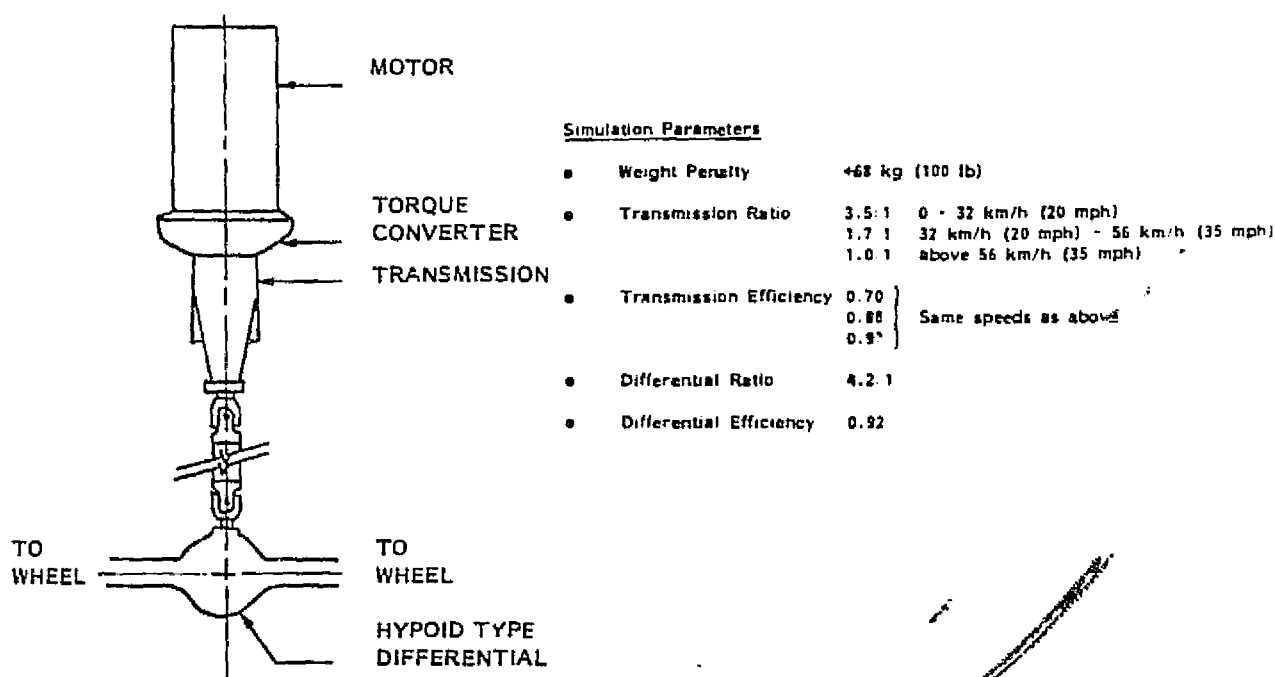
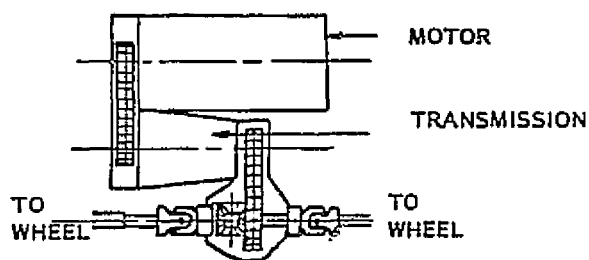


Figure 4-13 Standard 3-speed automatic transmission with a torque converter

Case 5: Standard 3-speed automatic transmission without torque converter, chain coupled to the differential. (Figure 4-14)  
 This example combines the "Detroit" automatic with the high efficiency chain coupling. Although this approach eliminates the torque converter loss, field experience with such configurations indicates that shock loading can reduce transmission reliability. The transmission efficiencies used in the calculation are realistic, discrete values at each gear ratio.



#### Simulation Parameters

- Weight Penalty 45 kg (100 lb)
- Transmission Ratio
 

2.74 : 1	0 - 32 km/h (20 mph)
1.57 : 1	32 km/h (20 mph) - 56 km/h (35 mph)
1.0 : 1	above 56 km/h (35 mph)
- Transmission Efficiency
 

0.76	Same speeds as above
0.80	
0.82	
- Differential Ratio 5.0 : 1
- Differential Efficiency 0.98

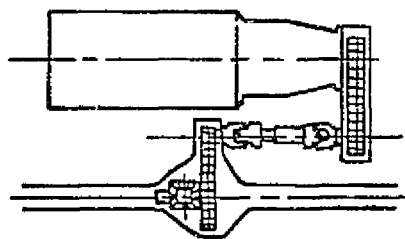
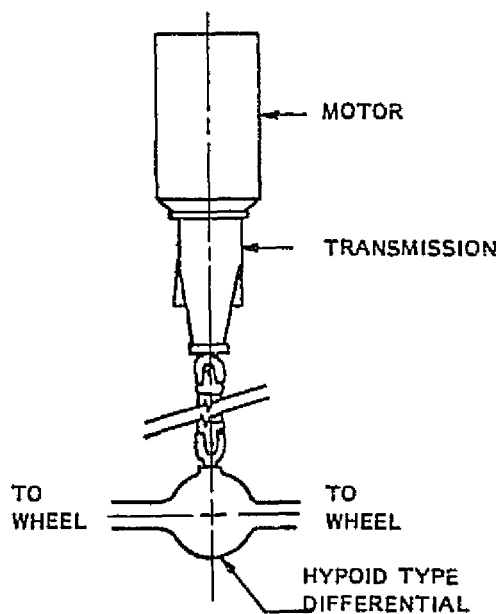


Figure 4-14 Standard 3-speed automatic transmission without torque converter, chain coupled to the differential.

Case 6: Standard 2-speed automatic transmission without a torque converter. (Figure 4-15) This case illustrates what can be achieved with a simpler "Detroit" automatic. The efficiency used in the calculation is optimistic, therefore, the absolute values of computed range are probably high.



Simulation Parameters

- Weight Penalty +34 kg (75 lb)
- Transmission Ratio 2.74:1 0 - 32 km/h (20 mph)  
1.0:1 above 32 km/h (20 mph)
- Transmission Efficiency 0.90
- Differential Ratio 4.2:1
- Differential Efficiency 0.92

Figure 4-15 Standard 2-speed automatic transmission without a torque converter.

Case 7: Torque converter alone directly coupled to the differential (Figure 4-16) The torque converter is a form of variable ratio transmission. Although the motor can operate at higher, more efficient speed at low vehicle speeds, the absolute value of torque converter efficiency is quite low since it achieves variable ratio by a dissipative process (fluid coupling). The continuous ratio and efficiency change were modeled as four discrete levels.

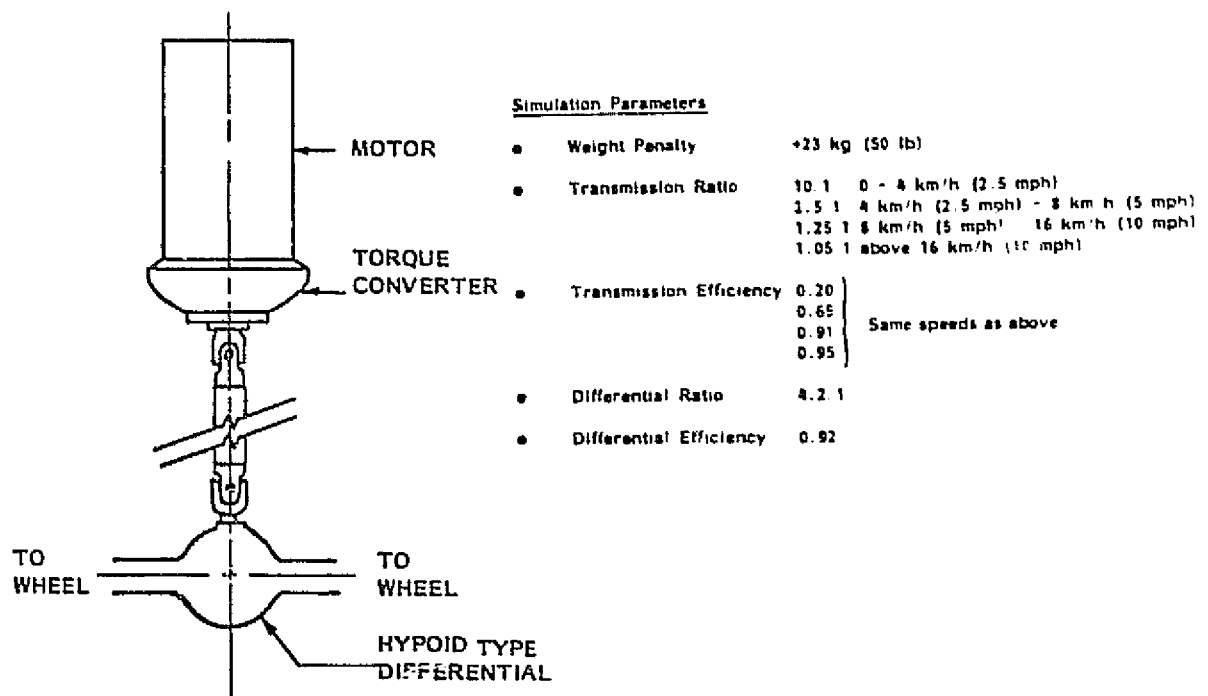


Figure 4-16 Torque converter alone directly coupled to the differential

Case 8: Hypothetical infinitely variable speed transmission of the rolling element type. (Figure 4-17) This case uses the industrial type of rolling element CVT. The drive train can be well matched with the motor characteristics to offer high efficiency over a wide range of torque and speed. Such transmissions are not available off-the-shelf for vehicle use and would probably be relatively heavy. The continuous ratio and efficiency variation were modeled as six discrete levels.

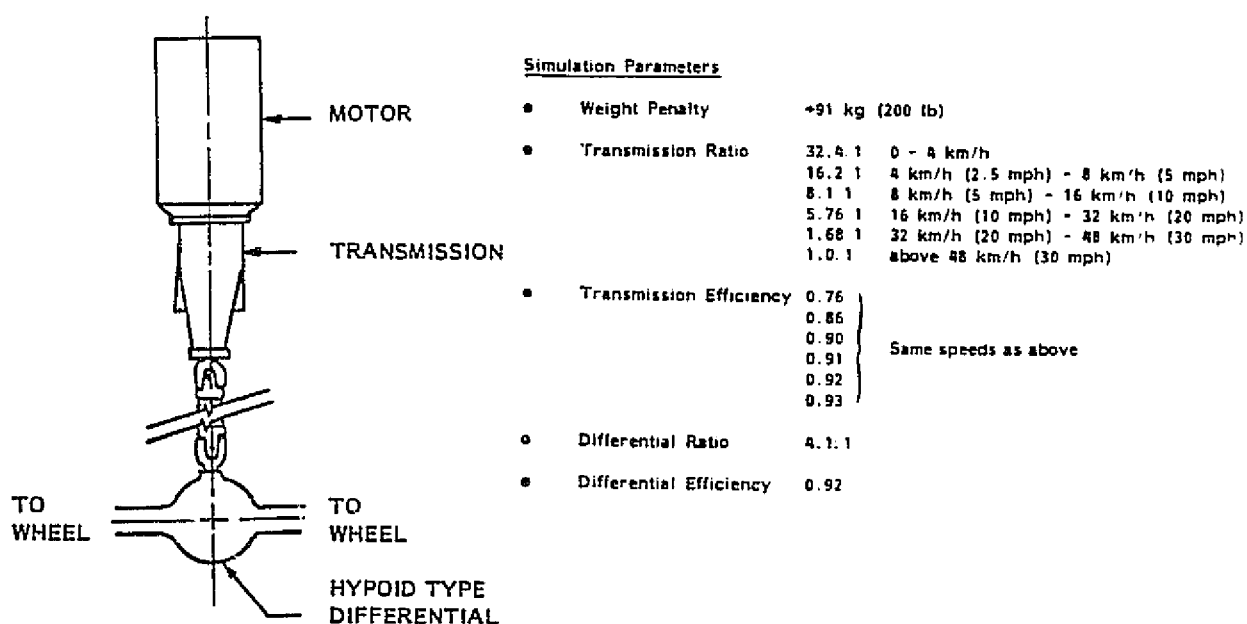


Figure 4-17 Hypothetical infinitely variable speed transmission of the rolling element type.

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Case 9: Variable speed V-belt transmission. (Figure 4-18)  
 The Electromatic Drive variable speed V-belt transmission has been designed for electrical actuation and hence is compatible with the control system of an electric vehicle. As a variable ratio transmission it offers all the benefits of motor/load matching. Efficiencies in the range of 86-94% are claimed and these would be relatively insensitive to temperature since the unit is "dry". The device has been produced in limited quantity and so field reliability has not been documented. The transmission ratio was modeled at five discrete values for the simulation.

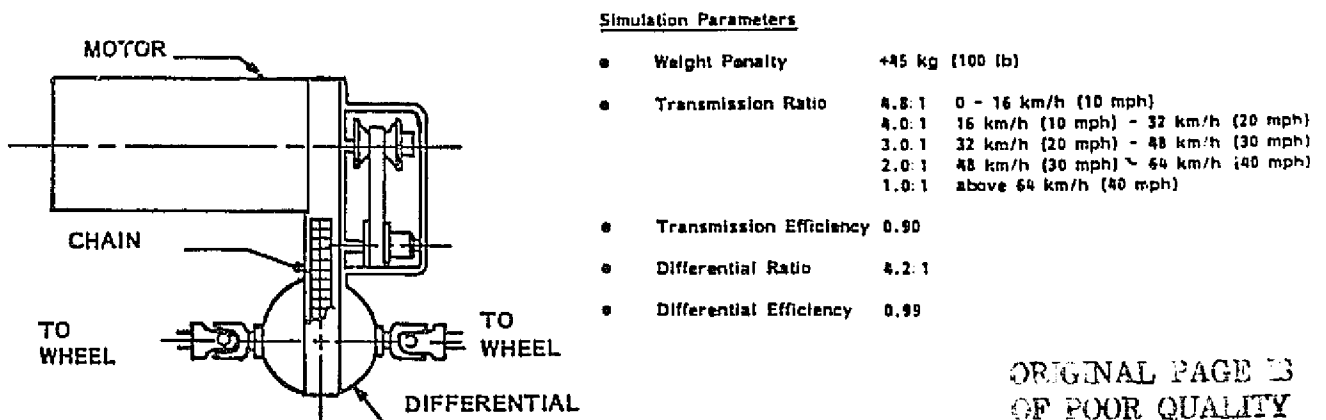
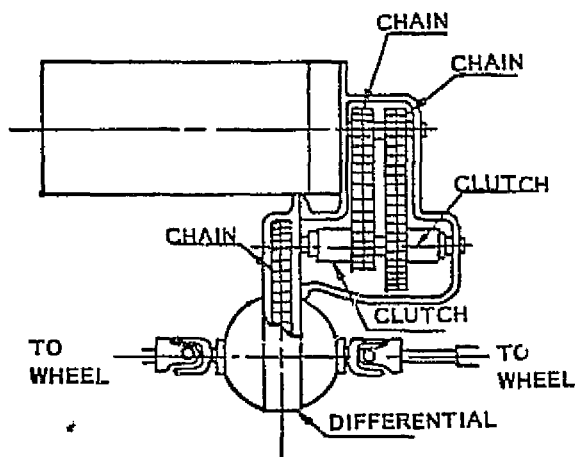


Figure 4-18 Variable speed V-belt transmission.

Case 10: Two-speed transmission using electrically actuated clutches.  
 (Figure 4-19) This power train combines the desirable multi-ratio gear change with efficient chain drives or helical gearing, and electrical actuation. It is comprised of standard industrial components arranged in a special package. Although this system is not off-the-shelf it promises to be reasonably efficient. The case simulated had two speeds but more are feasible depending on available space and weight.



ALTERNATE: HELICAL GEARING IN PLACE OF CHAINS

#### Simulation Parameters

- Weight Penalty +45 kg (100 lb)
- Transmission Ratio 4.0:1 0 - 32 km/h (20 mph)  
1.0:1 above 32 km/h (20 mph)
- Transmission Efficiency 0.92
- Differential Ratio 4.5:1
- Differential Efficiency 0.98

Figure 4-19 Two-speed transmission using electrically actuated clutches.

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Table 4-6 presents a summary of the simulation results for these ten cases. The greatest range over the SAE cycle and up the grade was predicted for the power train with the variable speed V-belt transmission (Case 9). The high efficiency fixed reduction power train (Case 2) gave the greatest range at a constant 88 km/h (55 mph).

TABLE 4-6 CALCULATED RANGE FOR TEN POWER TRAIN CONFIGURATIONS

CASE	
1.	DC motor directly coupled to a hypoid differential.
2.	Fixed ratio reduction, high efficiency chain drive.
3.	Dual motor drive, fixed reduction.
4.	Standard 3-speed automatic transmission with a torque converter.
5.	3-speed automatic transmission chain coupled to the differential without torque converter.
6.	Standard 2-speed automatic transmission without a torque converter.
7.	Torque converter coupled directly to the differential.
8.	Hypothetical, infinitely variable speed transmission, rolling element type.
9.	Variable speed V-belt transmission.
10.	2-speed transmission using electrically operated clutches.

TABLE 4-6 CALCULATED RANGE FOR TEN POWER TRAIN CONFIGURATIONS  
(cont'd)

RANGE OVER SAE J227a/D		RANGE AT CONSTANT 88 km/h (55 mph)	RANGE UP 10% GRADE AT CONSTANT 48 km/h (30 mph)
WITH REGENERATION	WITH ENHANCED REGENERATION		
km (mi)	km (mi)	km (mi)	km (mi)
48 (30)	58 (36)	76 (47)	6.9 (4.3)
50 (31)	66 (41)	82 (51)	7.4 (4.6)
51 (32)	68 (42)	82 (51)	7.7 (4.8)
40 (25)	63 (39)	71 (44)	7.9 (4.9)
45 (28)	68 (42)	68 (42)	6.4 (4.0)
50 (31)	64 (40)	74 (46)	6.8 (4.2)
48 (30)	58 (36)	77 (48)	7.1 (4.4)
47 (29)	56 (35)	72 (45)	8.4 (5.2)
53 (33)	74 (46)	72 (45)	9.2 (5.7)
52 (32.5)	72 (45)	79 (49)	7.2 (4.5)

#### 4.4.3 Recommended State-of-the-Art Power Train

Since the variation from greatest to shortest calculated range over the SAE cycle was only about 30%, the selection of Case 9 as the optimum state-of-the-art power train configuration needs further support.

In Table 4-7 those cases with the greatest range are tabulated as well as the peak battery current drawn during the SAE cycle. The two values tabulated for range are with regenerative braking and enhanced regeneration respectively. (See Section 4.3.1). The significance of the peak current lies in the fact that the available energy from a lead-acid battery decreases when large bursts of power are drawn. The Kleckner battery model (Ref. 48) accounts for this effect and, although not included in the present study, it is anticipated that greater range will result from those cases requiring lower peak currents.

TABLE 4.7 RANKING OF CALCULATED PERFORMANCE

Range over SAE cycle		Peak Battery Current		Range at 88 km/h		Range Up 10% grade, 48 km/h	
Case	km	Case	amps	Case	km	Case	km
9	53-74	9	375	2,3	82	9	9.2
10	52-72	5	400	10	79	8	8.4
3	51-68	4	425	7	77	4	7.9
2	50-66	10	450	1	76	3	7.7

The variable speed V-belt transmission with the DC series motor forms the basis for a state-of-the-art power train which offers:

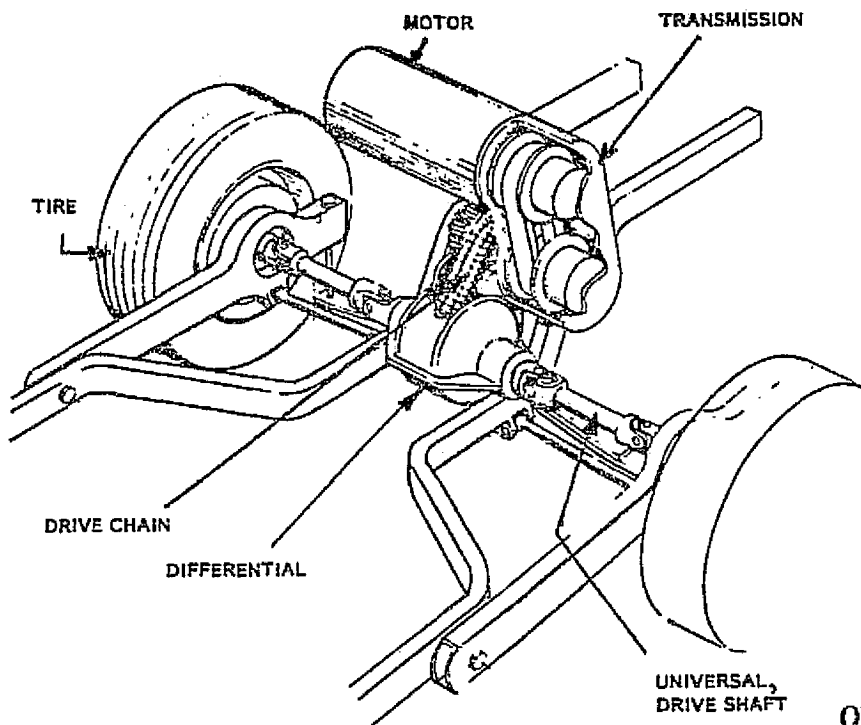
- High calculated range ,
- Good efficiency ,

- Compact and lightweight transmission, 18 kg (40 lbs),
- Electric controllability,
- Design based on proven components, and
- Mounting arrangement well suited to transaxle configuration.

The state-of-the-art power train is illustrated in Figure 4-20 and a typical vehicle installation is shown in Figure 4-21. The major components described earlier as representative of the state-of-the-art, are listed in Table 4-8.

TABLE 4-8 PARTS LIST FOR THE STATE-OF-THE-ART POWER TRAIN

Motor	Prestolite model EO-26747
Transmission	Electromatic Drive Corporation variable ratio V-belt transmission with automatic ratio control system.
Drive Chain	Morse Hy-Vo
Differential	Dana Spicer IS-18, modified for chain drive input
Drive Shaft (2)	Dana Spicer universals and torque tubes
Wheels (4)	Kelsey-Hayes
Brakes (4)	Delco-Moraine drum type
Tires (4)	Goodyear HR-78-15
Controller	Sevcon model 7650-4
Contactors	HB Electric, model HB33BA123L1B (directional pair) and HB39BD122L1B (line)



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Figure 4-20 State-of-the-art power train.

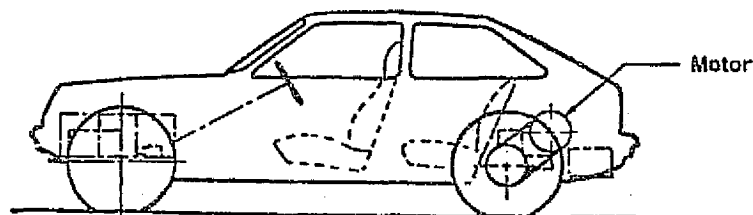
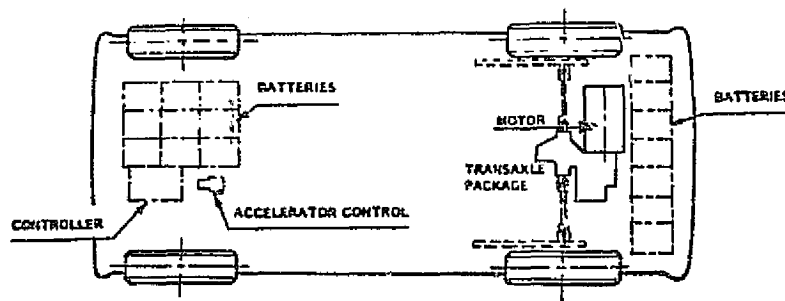


Figure 4-21 Typical installation of a power train in a vehicle.

#### 4.4.4

#### Predicted Range of the State-of-the-Art power train

The total weight of the state-of-the-art power train is estimated to be 295 kg (650 lb). Since this configuration was analyzed in the previous section (Case 9) at a weight of 385 kg (850 lb), the sensitivity values of Figure 4-8 can be used to approximately scale the predicted range for the lower weight case.

Table 4-9 summarizes the predicted range for a vehicle with the state-of-the-art power train. The total vehicle weight is 1587 kg (3500 lb). Absolute values for range are quite sensitive to component modelling and control strategy. The control assumption here is that the power train instantaneously provides needed tractive effort and that all braking is regenerative. The results given here (Chapter 4.0) are self-consistent and primarily intended for relative comparison. In Section 5.3.2 the state-of-the-art power train is subject to another analysis based on a different set of component models and with a constant current control scheme. The range predicted there is only 50 km (31.2 mi) over the SAE cycle. In general, caution should be taken to review the conditions and assumptions underlying absolute range predictions when diverse sources are compared.

TABLE 4-9 VEHICLE RANGE WITH STATE-OF-THE-ART POWER TRAIN

CYCLE	RANGE, km (mi)
SAE J227 s/D	58 (36) - 80 (50)*
88 km/h (55 mph)	76 (47)
10% grade, 48 km/h (30 mph)	10 (6.2)

\* With regeneration - With enhanced regeneration.



## 5.0 IMPROVED POWER TRAIN DESIGNS

In the previous chapter a preliminary design was presented for a state-of-the-art electric vehicle power train. This chapter identifies several areas which have the potential to improve that design. These are reviewed and several are subjected to a more detailed evaluation.

Two classes of improvements are considered. One class will improve the range and performance of the vehicle and the other class encompasses features which can enhance the commercial success of an electric vehicle. Such features include smooth, safe operation within a comfortable driving package. Sections 5.1 thru 5.3 are concerned with the former class. The latter are discussed in subsequent sections.

### 5.1 PERSPECTIVE ON RANGE IMPROVEMENTS

In order to put the subject of improved range into perspective, Table 5-1 compares the performance predicted for a vehicle based on state-of-the-art components with that of the ideal vehicle described in Section 4.3.4. For the ideal case, aerodynamic drag was based on an effective frontal area of  $0.56 \text{ m}^2$  ( $6 \text{ ft}^2$ ) and the assumed rolling resistance was  $0.098 \text{ N/kg}$  ( $0.01 \text{ lb/lb}$ ). With a motor, controller, transmission and differential which have 100% efficiency, the range of a  $1633 \text{ kg}$  ( $3600 \text{ lb}$ ) vehicle is only  $96 \text{ km}$  ( $60 \text{ mi}$ ) over the SAE cycle. The range penalty due to actual component efficiencies is about 45%. However, the absolute range achievable even with an ideal system is limited due to battery energy density and total vehicle weight.

TABLE 5-1 CALCULATED RANGE OF IDEAL AND STATE-OF-THE-ART VEHICLES.

CYCLE	RANGE, km (miles)		
	Ideal	State-of-the-art Design	
	1633 kg (3600 lb)	1633 kg	1587 kg (3500 lb)
SAE J227 a/D*	96 (60)	53 (33)	58 (36)
88 km/h (55 mph)	120 (75)	72 (45)	76 (47)
48 km/h (30 mph), 10% grade	24 (15)	9.2 (5.7)	10 (6.2)

\* With Regenerative Braking

In addition to the energy required to accelerate the vehicle, losses are due to:

- Aerodynamic drag
- Tire rolling resistance
- Transmission/gearing losses
- Motor/controller losses

For each of the three driving schedules the major losses tend to occur in different parts of the system. For the state-of-the-art design, presented in Chapter 4.0, these can be ranked in "major loss first order".

- Over the SAE cycle the major losses are due to:
  - Motor/controller
  - Tires
  - Aerodynamics
- During the 88 km/h (55 mph) cruise the major losses are due to:
  - Aerodynamics
  - Tires
- When climbing a 10% grade at 48 km/h (30 mph) the major losses are due to:
  - Motor/controller
  - Tires
  - Transmisssion/gearing

Although aerodynamic drag is a significant factor at higher speeds, the effective frontal area (area x drag coefficient) of  $0.56 \text{ m}^2$  ( $6 \text{ ft}^2$ ) represents a value typical of the most streamlined body shapes. As such it will be difficult to affect aerodynamic improvements. Motor/controller, transmission and tire efficiency gains are, however, achievable and will result in increased vehicle range.

## 5.2 NEAR TERM TECHNICAL IMPROVEMENTS

In the course of reviewing electric vehicle technology and developing a preliminary state-of-the-art design, several potential improvements were identified. The following paragraphs describe those near-term technical advances which could increase vehicle range.

- The separately excited \* DC motor with the Electromatic CVT represents a combination of two recent trends. There has been significant interest in the separately excited motor, which appeared as a trend in the state-of-the-art assessment. The separation of field and armature controls should offer advantages in reducing controller complexity since the low current field circuit can be used to implement vehicle reverse speed and to control regenerative braking. The Electromatic CVT is a derivative of a reliable snowmobile transmission and has been built into the Mechanics Illustrated "URBA" car (Ref. 55). By combining a separately excited shunt wound motor with this V-belt type of transmission, a more efficient and driveable power train may result.
- Since decreasing weight directly improves vehicle performance, light weight power train components are desirable. Candidate materials include plastics, composites, and other high strength to weight ratio materials.
- Several manufacturers have noted that it is feasible to achieve lower rolling resistance in a tire designed especially for electric vehicles. Parameters to be optimized include:
  - Aspect ratio
  - Sizing
  - Inflation pressure
  - Cord angle
  - Compound selection
  - Tread contour
  - Rim width
- A greater range can be achieved for a vehicle with a greater ratio of battery mass to overall vehicle mass. This ratio is referred to as the "battery mass fraction."
- Since the size of most electrical components is proportional to current, higher voltage batteries should result in a smaller system which is lighter and more compact.

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\* In this report "separately excited" refers to a shunt wound motor with separate armature and field controls.

- Several studies (i.e., Ref. 63, 64 and 65 ) indicate that an AC motor and controller package will offer weight and cost benefits over the DC systems. The weight reduction alone can increase vehicle range if efficiency is not sacrificed.
- A trade-off analysis should be performed to ascertain the potential for using a dual set of batteries. One set would be capable of fast charge and discharge to provide power for acceleration and to accept regenerated power. The other set would be suited for steady charge and discharge and would be relied upon during cruise operation. This approach was attempted with the GE Delta vehicle (Ref. 21 ) and in some recent Japanese vehicles.
- Battery development has been recognized as a key to the success of the electric vehicle program. Efforts to improve the energy storage capacity should be encouraged.
- Mechanical storage of energy in high density, composite flywheel structures can provide effective battery load levelling. Power needed in surges for acceleration or generated during deceleration can be transferred from, or to, the flywheel.

In order to evaluate any of these potential improvements, more detailed study is required. Due to limited funds and time on the present contract, only the most "important" area(s) could be analyzed. Therefore a set of preliminary evaluation criteria were established to rank the improvements by priority. Improvements were sought which:

- Represent near-term state-of-the-art rather than advanced technology,
- Offer some potential for range improvement which has not been fully evaluated (For example, since tire improvements have already been shown to increase range, there is little to add to our understanding in this area short of a prototype electric vehicle tire development program),
- Present minimal risk to the immediate objectives of the electric vehicle program.
- Are technically feasible, and
- Represent a reasonable level of evaluation effort.

A matrix is presented in Table 5-2 which compares the areas of potential improvement. The separately excited DC motor was selected for further study on the basis of this comparison since it represents a near-term, feasible advance of moderate risk and unquantified range improvement.

TABLE 5-2 COMPARISON OF POTENTIAL IMPROVEMENT AREAS

Evaluation Task Area	State-of-the-Art	Improved Range	Development Risk	Technical Feasibility	Commercialization Potential	Estimated Effort To Assess
1. Separately excited DC motor	Near	?	Moderate	Yes	Yes	Moderate
2. Component weight reduction	Current	Yes	Low	Yes	Yes	Moderate
3. Electric vehicle tires	Near	Yes	Low	Yes	Yes	High
4. Increase battery mass fraction	Now	Yes	?	?	Yes	---
5. Battery voltage change	Near	?	Moderate	?	?	Moderate
6. AC motor system	Near	?	High	?	?	High
7. Supplemental load leveling batteries	Advanced	?	Low	?	?	High
8. Improved batteries	Advanced	Yes	High	Yes	Yes	High
9. Flywheels for load-leveling	Advanced	Yes	High	Yes	?	High

### 5.3 SEPARATELY EXCITED MOTOR SYSTEMS

In this section several power train configurations employing separately excited, shunt wound DC motors are described. These were simulated with a computer program to estimate the range over the SAE driving cycle. The added flexibility provided by separate control of the motor field, either with or without a transmission, allows a better match between the motor and the load and, as a result, vehicle range is improved by approximately 20% over a comparable power train using a series motor.

### 5.3.1 Computer Simulation Model

An iterative simulation with empirically adjusted component models was used to investigate the performance of the separately excited motor systems. This computer program is proprietary to TRIAD Services, Inc. of Dearborn, Michigan. The state-of-the-art power train design using the series DC motor (Case 9 of Chapter 4.0) was also simulated with this program to provide a direct comparison between the series and separately excited, shunt wound motor systems with the same analytical tool.

The computer program simulates a given vehicle, drive train and control strategy using an iterative process based on current feedback. The accelerator pedal position controls motor current. Since the most efficient manner of extracting a given amount of energy from a battery is to do so at constant current, motor current is held constant during the accelerating portion of the cycle. The sequence of program execution is, generally, as follows:

- The speed range (i.e., 0-72 km/h for the SAE cycle) is divided into 1% velocity steps;
- A first "guess" is made for motor current and the motor torque is calculated;
- By looking "ahead" 1/2 of a velocity step an average road load is computed from the vehicle model and the motor speed is calculated from the drive train ratio;
- The motor torque is reflected through the power train and a net vehicle acceleration is obtained (acceleration = (tractive effort - road load) ÷ vehicle mass);
- From the acceleration, the time to reach the end of the velocity step can be calculated;
- At each step vehicle speed and drive ratio is used to compute motor speed and, since current is known, the motor voltage is calculated from the motor model;
- If an armature chopper is employed, the duty cycle is calculated from the ratio of motor voltage and battery voltage (at the battery current).
- The battery discharge characteristics, and the time at discharge, are used to compute the percentage energy drawn;

- The process is continued until the "cruise" speed 72 km/h (45 mph) is reached;
- The time to reach the cruise speed is compared to the specification (28 sec), the motor current is then adjusted, up or down, and the process is iterated until the time to reach cruise is as required.
- Range at constant speed is calculated by working from the road load "backwards", through the drive train, to the battery.

For each of the power trains with separately excited motors, and for the series motor design (Case 9), several simulation runs were made to select the best final drive ratio. Common parameters for these studies were:

- Vehicle test weight was 1633 kg (3600 lbs.)
- The vehicle dynamic model included:
  - An effective frontal area of  $0.56 \text{ m}^2$  ( $6 \text{ ft}^2$ ).
  - A tire radius of 0.32 m (12.6 in.)
  - A rolling resistance of 0.98 N/kg (0.01 lb./lb.).
- The efficiency of the armature chopper controller was assumed to be 96%.
- A motor mathematical model was developed from the Prestolite EO-26747 data (shown earlier in Figure 4-9), and included:
  - Armature resistance = 0.012 ohms.
  - Maximum torque constant = 0.292 ft./lb. per amp.
  - Minimum torque constant = 0.097 ft./lb. per amp.
  - Field strength variation = 3:1.
- The Electromatic CVT was shifted over a range from 3.41 : 1.0 to 0.68 : 1.0. Its assumed efficiency is shown in Figure 5-1.
- For regenerative braking the current was limited to 150 amps. Based on tests performed with the CDA town car, the regeneration efficiency used was 83%. Due to the current limit, some kinetic energy was dissipated in the friction brakes to achieve the braking requirement of the SAE cycle.

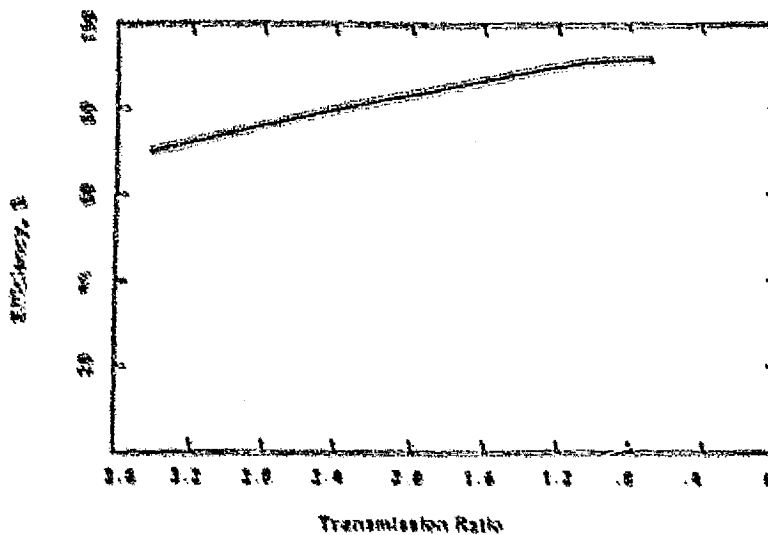


Figure 5-1 Electromatic CVT efficiency

### 5.3.2 Description and Performance Calculations

The power trains studied in this section are distinguished by armature control, field control or the incorporation of the Electromatic CVT. Four cases employing shunt wound motors were considered.

Figure 5-2 is a block diagram of the power train with the series motor and CVT (Case 9). The battery current and motor speed for this case is shown in Figure 5-3. A possible control scenario begins with the transmission ratio at 3.41:1 when the vehicle is at rest. Armature chopping is used to accelerate the vehicle until the duty cycle reaches 100% (motor voltage = battery voltage) and further acceleration, above about 18 km/h (11 mph), is accomplished by upshifting the transmission at a constant motor speed. Since the road load is approximately constant during this part of the driving cycle (see Figure 4-7) the battery current is constant. Since the vehicle is no longer accelerating, there is a reduced load demand for cruising at 72 km/h (45 mph), the transmission is downshifted, the motor speed increases to a "base" speed limited to 4000 RPM and the current drops substantially. With the motor at this speed the transmission ratio is 1.55:1. Further decreases in demanded torque (operator controlled through pedal position) are accommodated by chopping the armature voltage. Basically, the control logic responds to accelerator pedal (torque) demand by a hierarchy of armature chopping and transmission control with the motor speed defining an additional decision path. If motor speed is at its peak (4000 RPM) increased torque demand is met by upshifting and decreased load is achieved by chopping in the armature circuit.



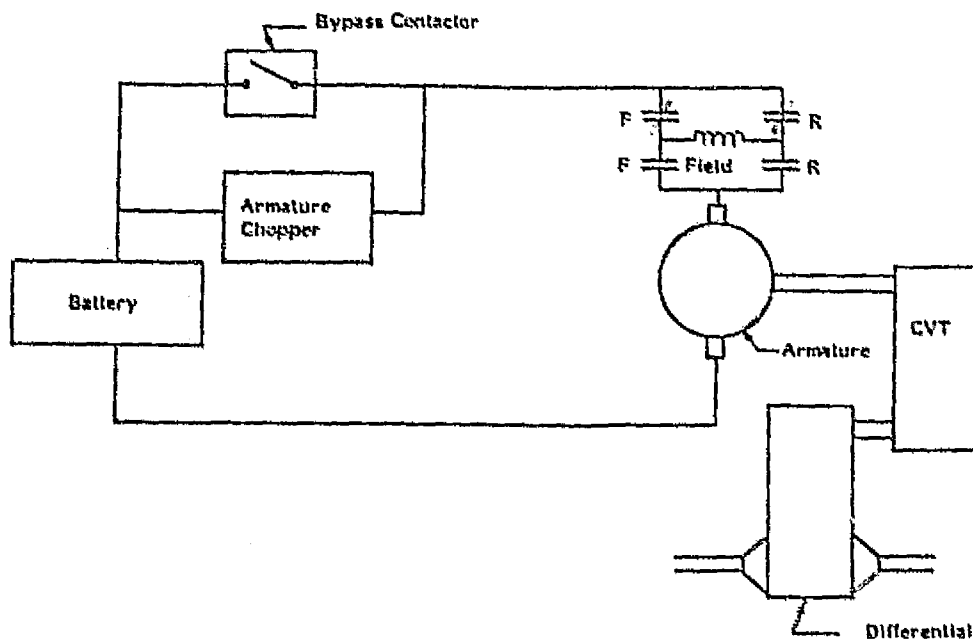


Figure 5-2 Power train with series motor and CVT (Case 9).  
The "F" contactors are activated for forward, etc.

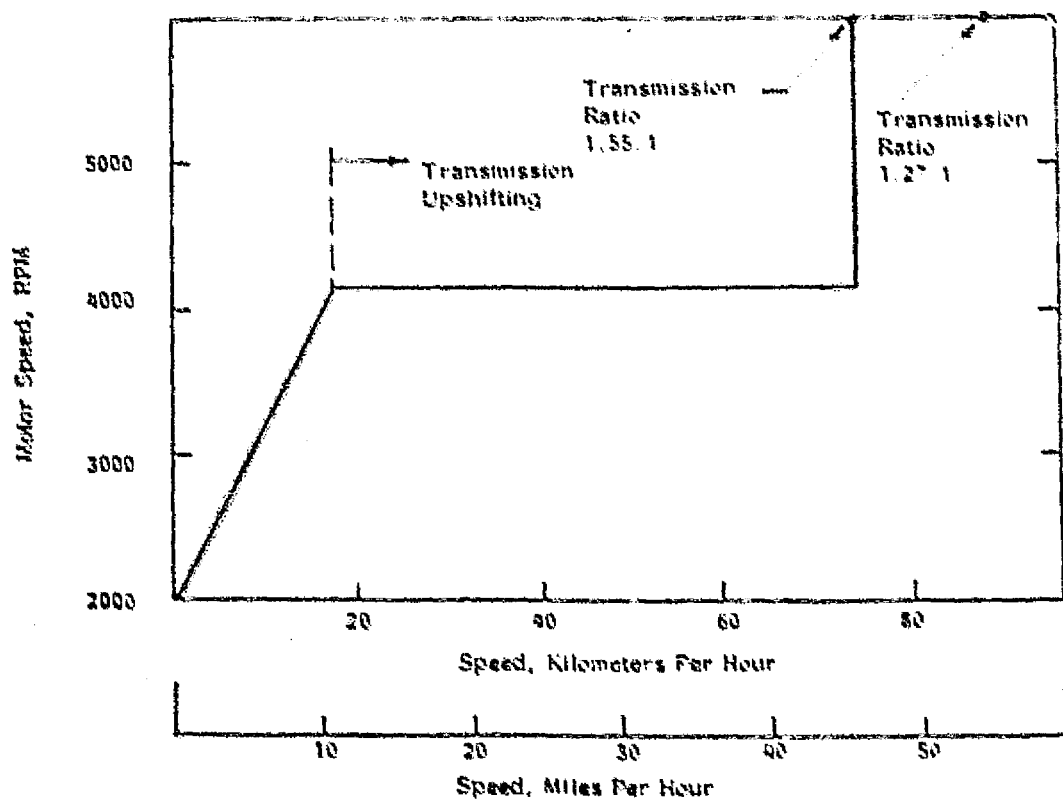
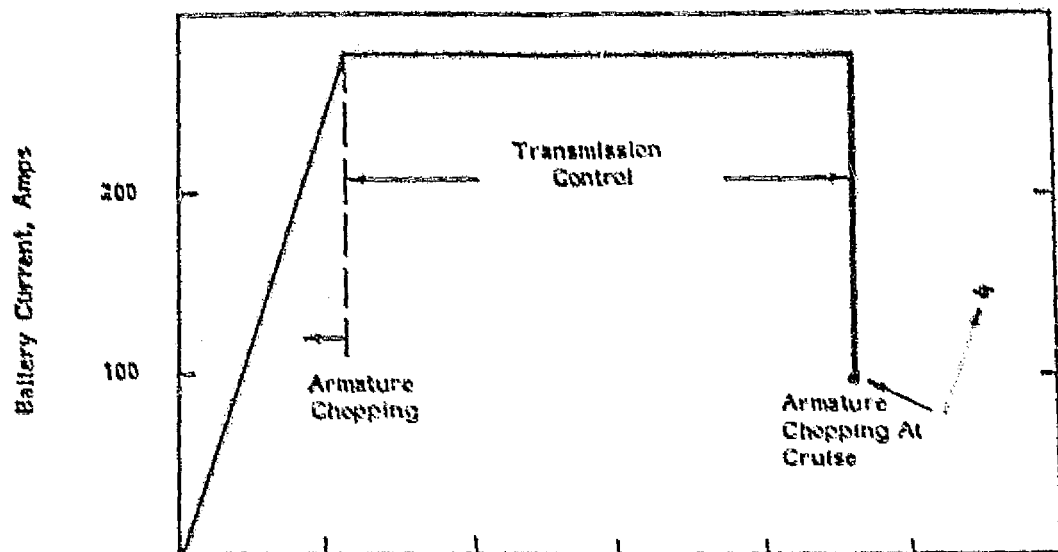


Figure 5-3 Battery current and motor speed for power train with series motor, armature chopper and CVT (Case 9).

Figure 5-4 is a block diagram of a power train with both armature and field chopping and the Electromatic CVT. Figure 5-5 shows the battery current and motor speed for this case. In operation the system starts with the battery voltage across the field and the transmission at its highest numerical ratio (3.41:1). Armature chopping is used to accelerate the vehicle to about 8 km/h (5 mph). At this speed the duty cycle is 100%. Further demands for speed are met by upshifting the CVT until about 45 km/h (28 mph) is reached. At this speed the transmission ratio is 0.68:1 and field weakening, by the field chopper, provides additional speed. The control strategy is a hierarchy in order of armature chopping, shifting and field weakening.

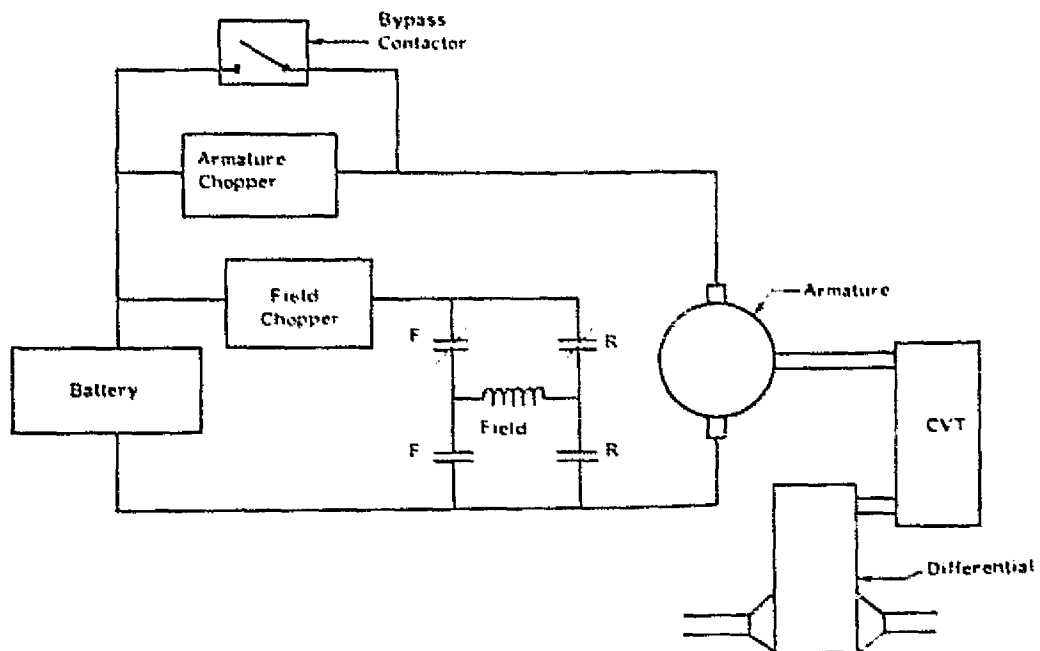


Figure 5-4 Power train with both armature and field control and the CVT (Case 11). The armature chopper would use SCR's whereas the field chopper, since it is in a low power circuit, could be implemented with transistors.

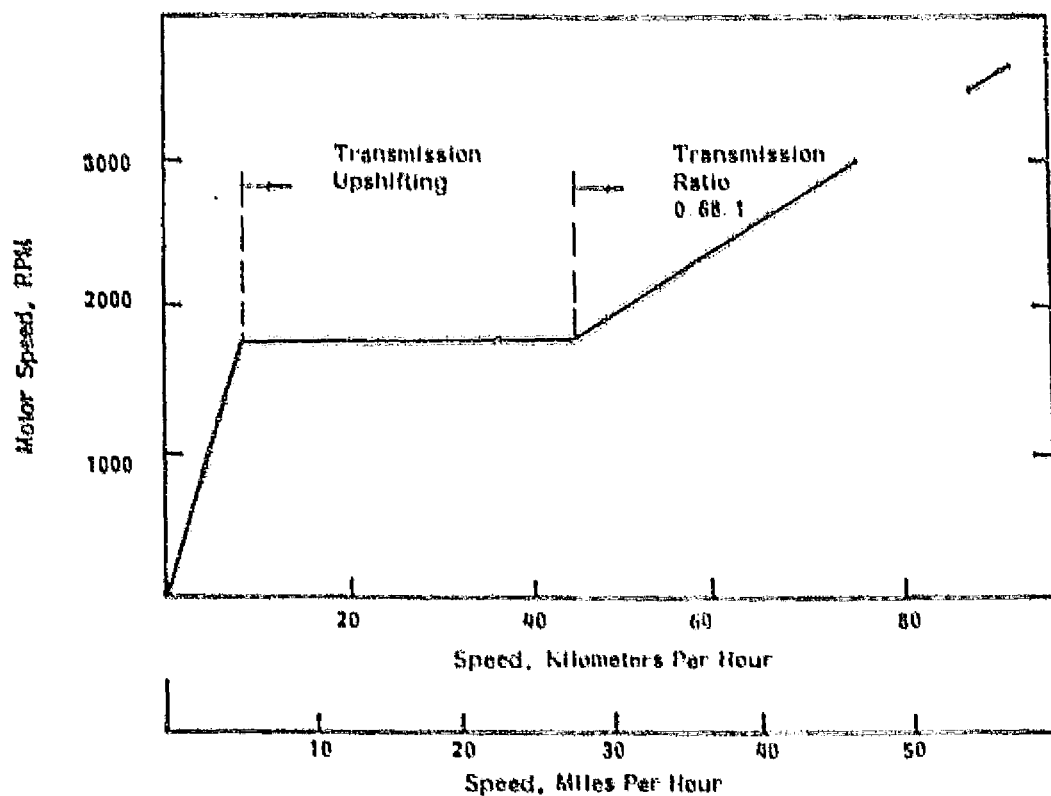
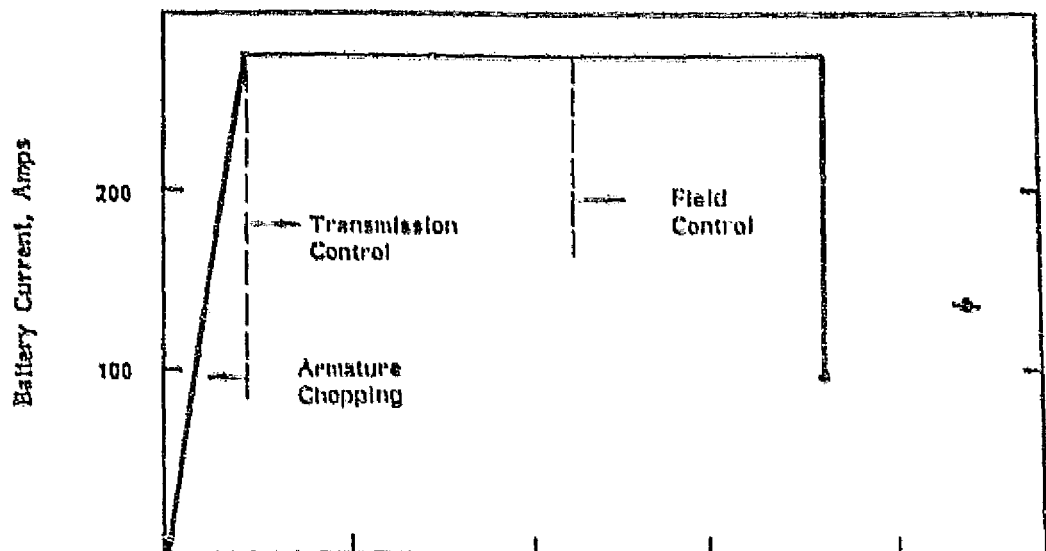


Figure 5-5 - Battery current and motor speed for power train with separately excited motor, armature and field chopper and CVT (Case 11).

Figure 5-6 shows a block diagram of a power train which eliminates the armature chopper. The calculated results for battery current and motor speed for this case are given in Figure 5-7. The system starts with the battery voltage across both the armature and the field of the motor and the transmission ratio at 3.0:1. Some degree of belt slipping must occur when starting and current limiting is also needed. The Mechanix Illustrated URBA car (Ref. 55) employed a similar control method but the high starting speed of the motor was disturbing and the clutching action of the Electromatic was rough. Above about 8 km/h (5 mph) this system operates similarly to that of Case 11.

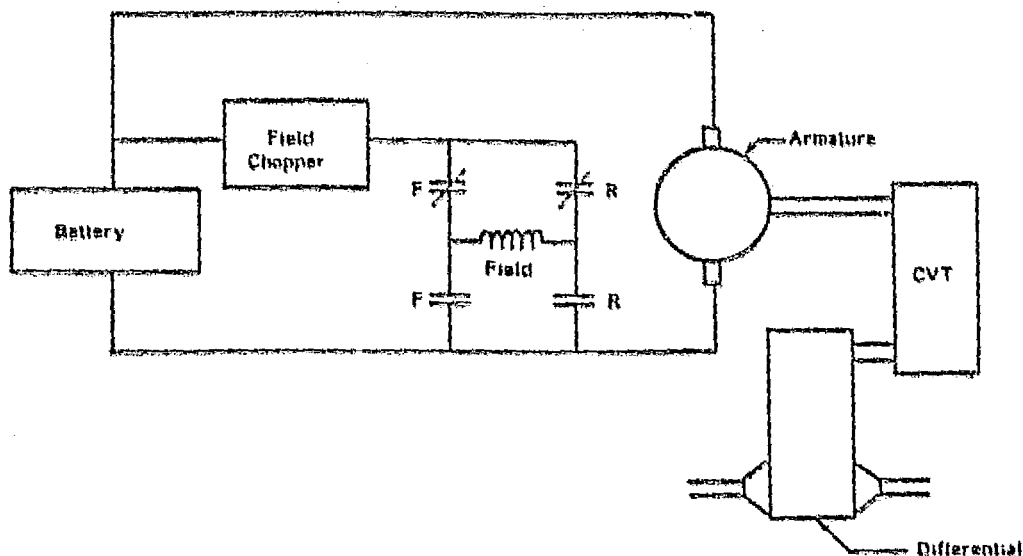


Figure 5-6 - Power train with field control and CVT. Case 12, is similar to Case 11 but eliminates the armature chopper and connects the battery directly to the armature.

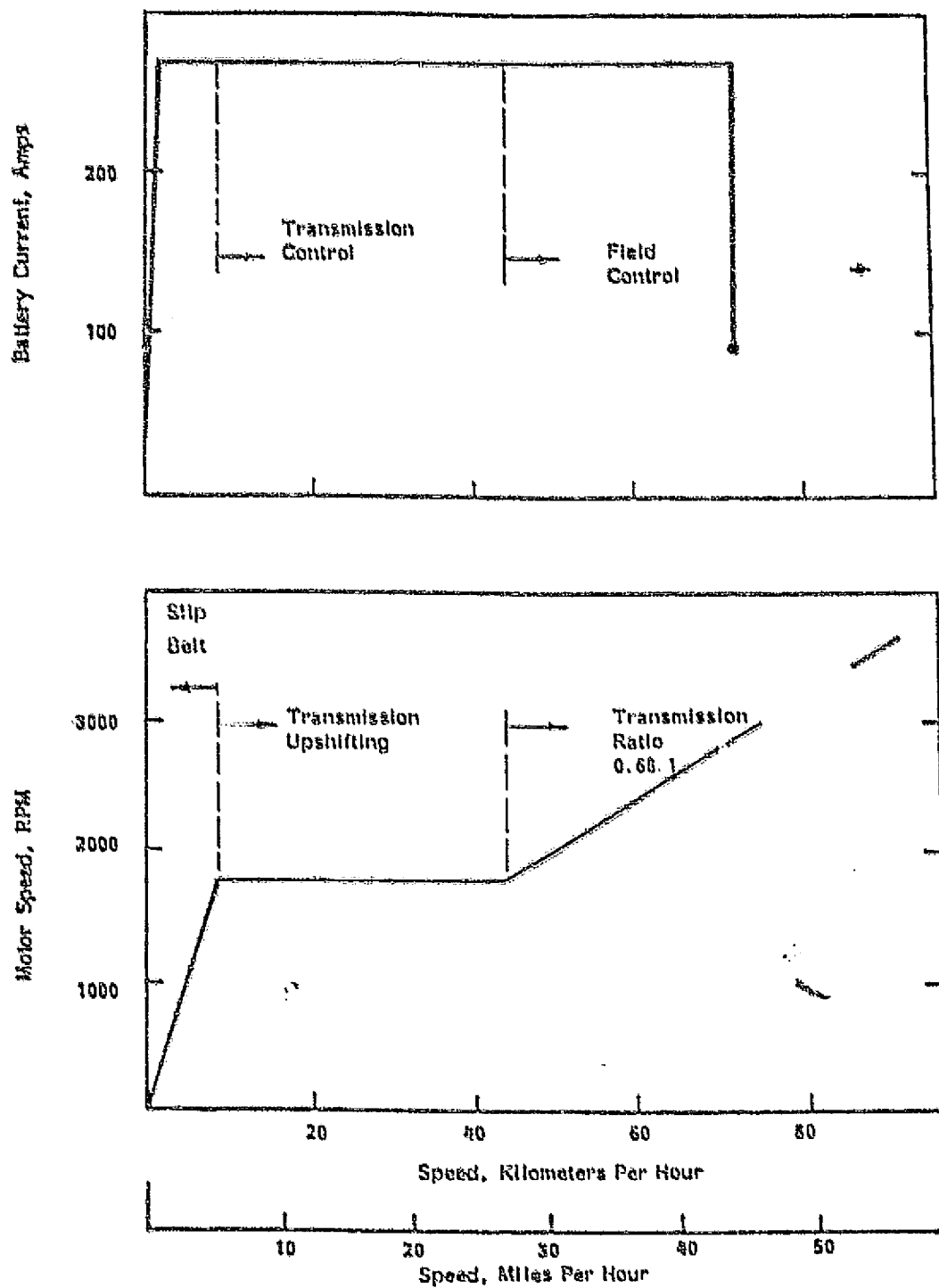


Figure 5-7 - Battery current and motor speed for power train with separately excited motor, field chopper and CVT (Case 12).

Figure 5-8 depicts a block diagram of a power train which features an armature chopper, fixed field voltage and the Electromatic CVT. The battery current and motor speed for this case is shown in Figure 5-9.

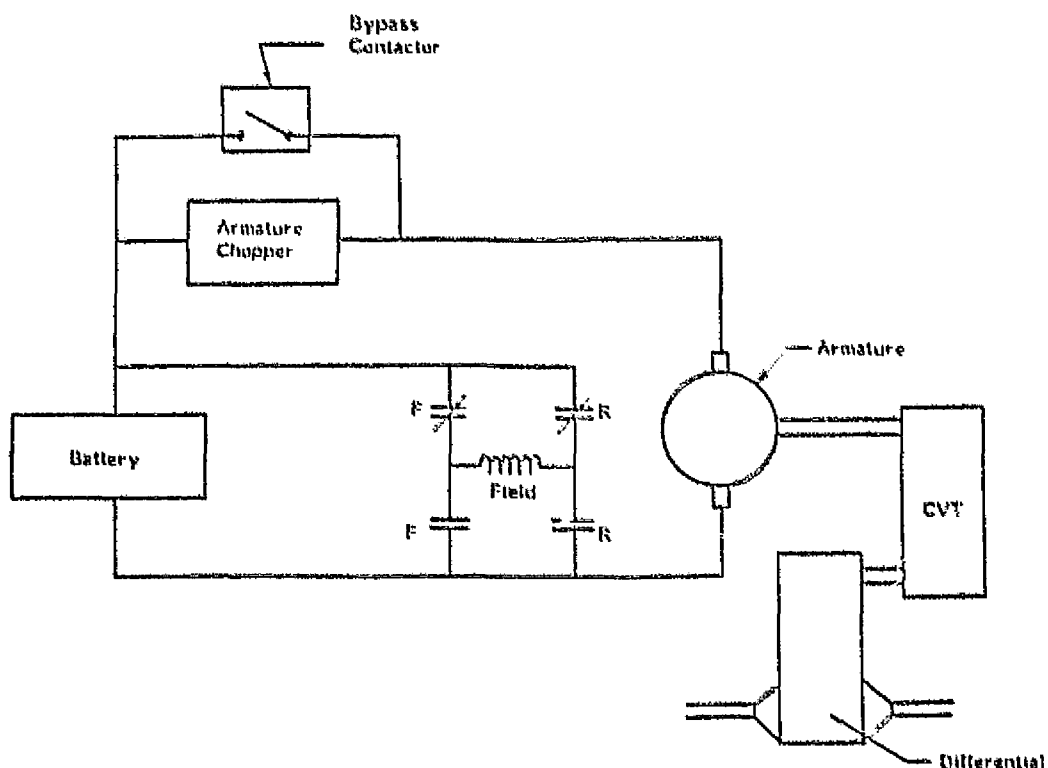


Figure 5-8 Power train with armature control and CVT. Case 13 features an armature chopper, fixed field voltage and the Electromatic CVT.

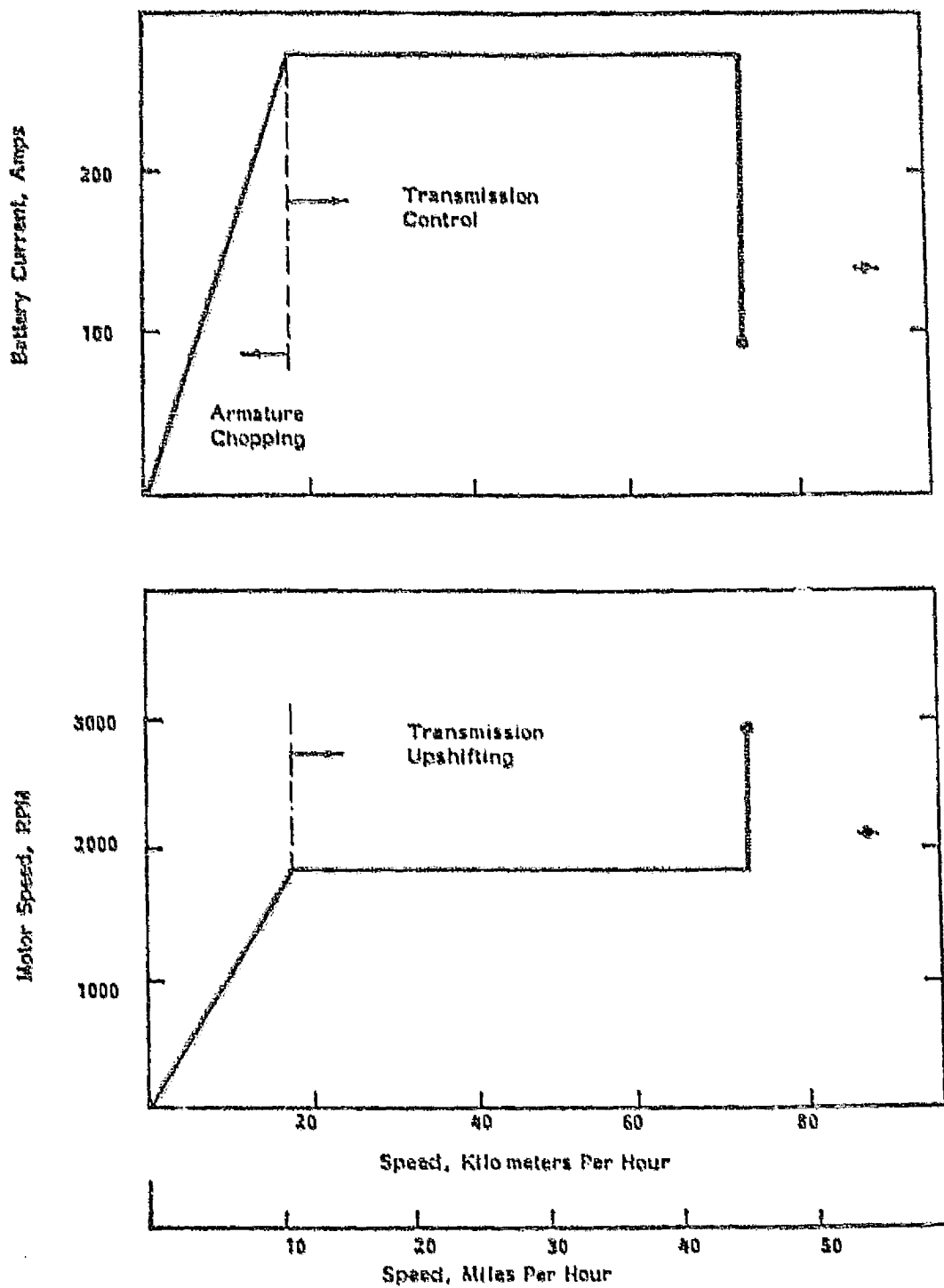


Figure 5-9 - Battery current and motor speed for power train with separately excited motor, armature chopper and CVT (Case 13).



In this configuration the motor has a linear torque-speed characteristic similar to a permanent magnet field motor. Reverse can be implemented by switching the low current field circuit. The control hierarchy consists of armature chopping to about 18 km/h (11 mph) and transmission control at higher speeds.

Figure 5-10 is a block diagram of a power train which performs all control electrically and features a fixed gear reduction. The battery current and motor speed for this case is given in Figure 5-11. For this "all electric" power train the maximum field voltage and armature chopping is employed until the battery voltage is impressed on the armature. Further control range is achieved by field weakening.

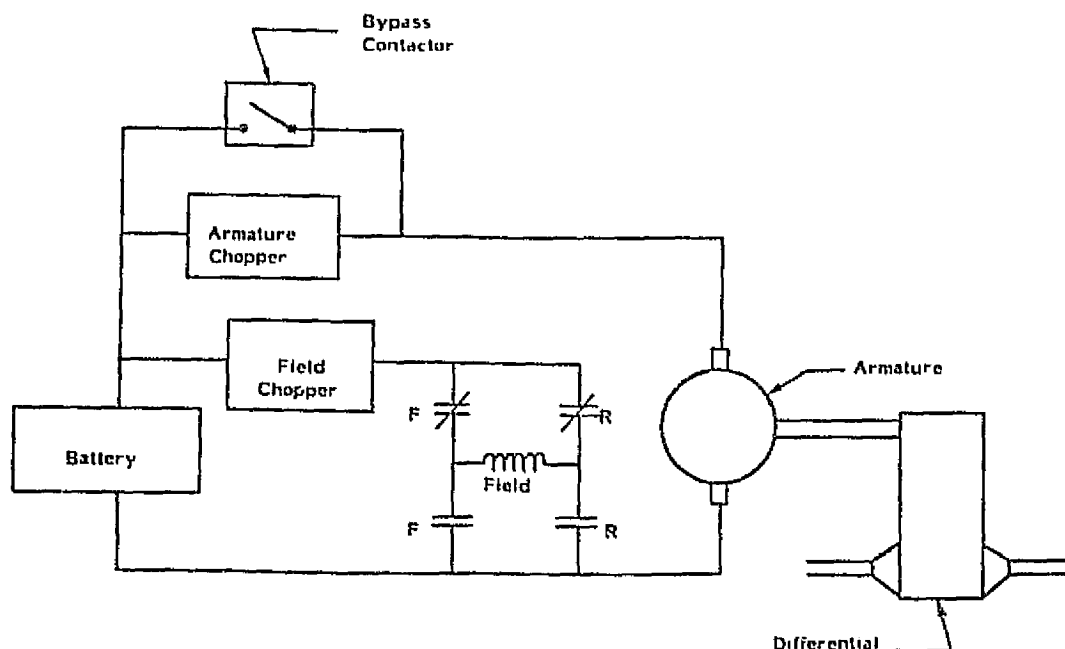


Figure 5-10 - Power train with all electric control. Case 14, is similar to Case 11, but eliminates the CVT and does all control electrically.

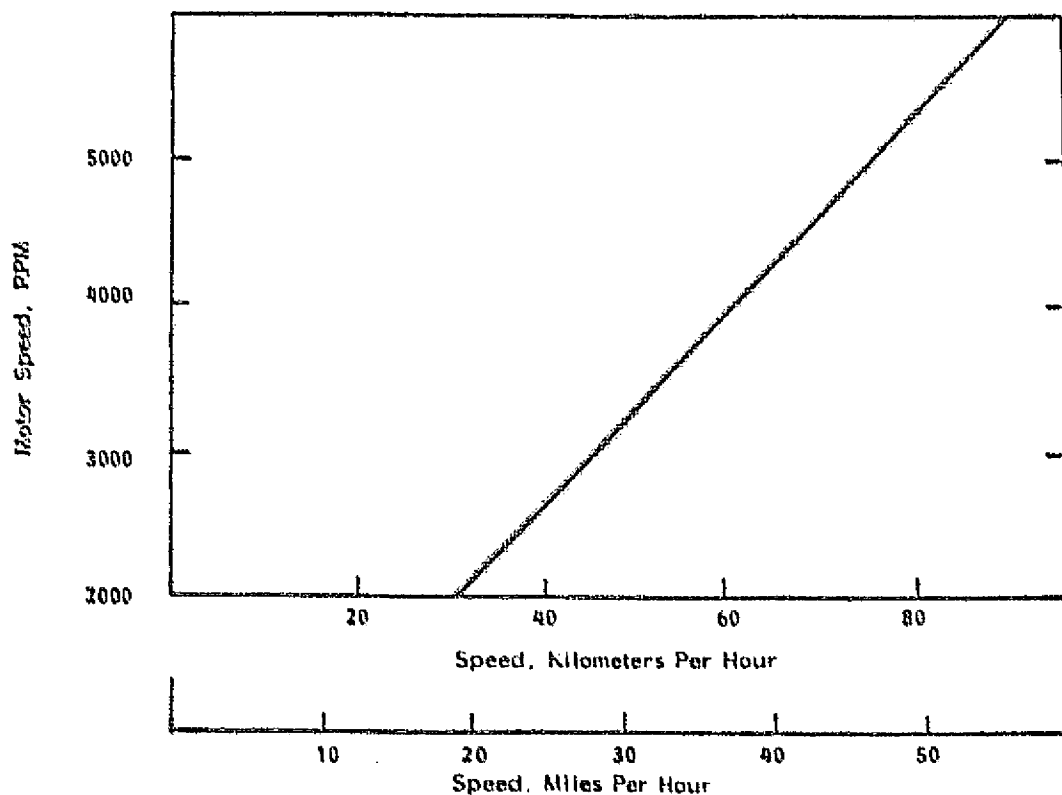
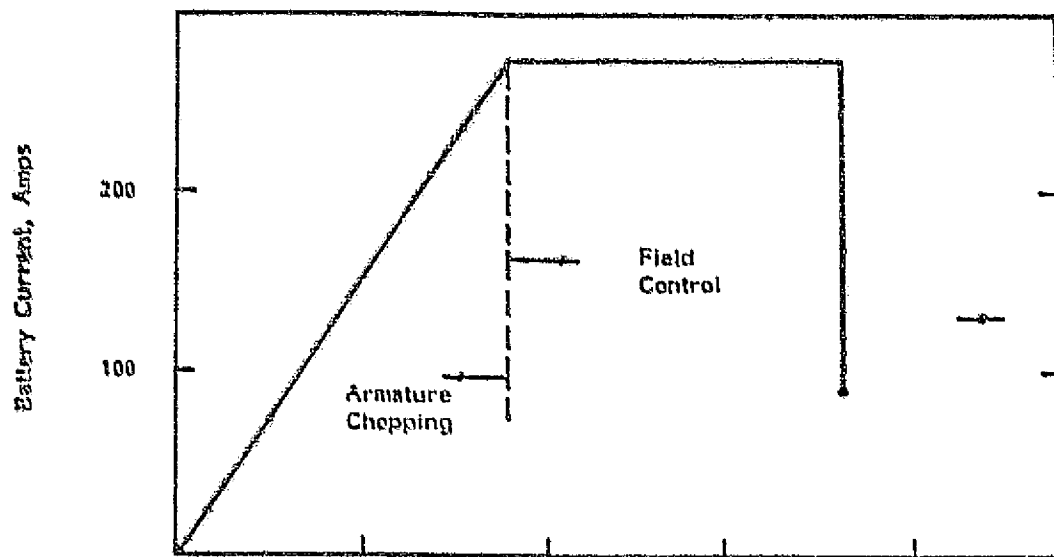


Figure 5-11 - Battery current and motor speed for power train with separately excited motor, armature and field choppers and fixed gear reduction (Case 14).

The results of range calculations for these five cases are summarized in Table 5-3 for the SAE J227 a/D driving schedule. The primary objective of this comparison was to identify relative improvements in range over the SAE cycle.

TABLE 5-3 - COMPARISON OF CALCULATED RANGE OVER THE SAE CYCLE FOR SEPARATELY EXCITED AND SERIES MOTOR SYSTEMS.

CASE	9	11	12	13	14
Motor Type	Series	Shunt wound, Separately excited			
Armature Control	Chop	Chop	Fixed	Chop	Chop
Field Control	---	Chop	Chop	Fixed	Chop
Transmission Type	EM CVT	EM CVT	EM CVT	EM CVT	---
Differential Ratio	4.3:1	7:1	7:1	4.2:1	8:1
Range Over SAE J227a/D, 1635 kg (3,600 lb) vehicle	48 km (30 mi)	55 km (34 mi)	54 km (33.5 mi)	56 km (34.5 mi)	58 km (36.1 mi)
Motor Speed at 88 km/h (55 mph)	4000 RPM	3491 RPM	3491 RPM	2094 RPM	5870 RPM

There is a difference in the calculated range for the series motor design shown here and that presented as Case 9 in Chapter 4.0. This is primarily the result of assumed efficiencies and transmission shifting range as follows:

- The shifting range of the Electromatic used here is narrower (3.41 to 0.66 vs 4.8 to 1.0) and the overall drive ratio is lower (2.9:1 vs 4.2:1).
- A lower transmission efficiency was assumed here (see Figure 5-1), particularly at higher ratios.
- Regenerative braking was limited to 150 amperes. Less energy, therefore, was recovered during deceleration.

For the state-of-the-art power train which weighs 295 kg (650 lbs) scaling the present results predicts a range of 50 km (31.2 mi) over the SAE cycle. The results shown in Table 5-3 are consistent since

they are based on the same component models and computer analysis, and illustrate that the use of a separately excited, shunt wound motor offers a definite benefit in range over the SAE cycle. This is reasonable on physical grounds as discussed below.

Consider an electric vehicle which must operate both over the SAE cycle and at a steady top speed of, for example, 88 km/h (55 mph). For a power train consisting of a fixed ratio reducer and a series wound motor, the top speed of the vehicle will correspond to the maximum motor speed and, with armature voltage control, will be reached at full battery voltage. This top speed establishes the overall drive ratio. Since the efficiency of a series motor is maximum in the region of high speed and high voltage, the power train is well matched to the load for steady high speed operation. However, in order to deliver the power peaks of the accelerating portion of a stop-and-go driving cycle, the motor must be controlled to operate at reduced armature voltage and speed for a significant part of its duty cycle. This is a region of lower motor efficiency. Thus, the requirement to reach a top speed sets parameters in the series motor power train which are in conflict with achieving optimum range over the SAE cycle. One cannot, for example, match the motor efficiency to the peak power demanded during acceleration.

The separately excited, shunt wound motor and control system, provide the flexibility to match motor characteristics to the diverse requirements of both top speed and stop-and-go operation. Typically a shunt wound motor achieves maximum efficiency at "base speed" when full armature and field voltage are applied. The controller can be designed to deliver the power peaks while the motor is at its maximum efficiency. This more effectively (although perhaps not optimally) matches the load and results in improved range over the SAE cycle. Top speed operation is achieved by weakening the field, which decreases the generated voltage (back EMF) and allows higher motor speeds.

The advantage of the separately excited, shunt wound motor system over the series wound motor is the result of the motor/controller system flexibility, and not inherent to the machines alone.

In addition to absolute predictions of range, several qualitative factors merit consideration in an electric vehicle power train design. Key among these are reliability, maintainability and development risk.

The absence of an armature chopper in Case 12 requires that the V-belt slip in order to start the vehicle from rest. Excessive wear and poor driveability can be expected from the Electromatic transmission under these conditions. This case is therefore, rejected for the electric vehicle application.

The tradeoff considerations between Cases 11, 13 and 14 are more subtle. All of the range predictions shown in Table 5-3 were made assuming a 1633 kg (3600 lb) vehicle which implies a power train weight of 340 kg (750 lb). Since the CVT weighs about 18 kg (40 lb) and the field chopper about 2.3 kg (5 lb), the Case 14 power train will weigh 279 kg (615 lb). This should result in a range over the SAE cycle of 61 km (38 mi). Moreover, one can expect greater reliability and lower maintenance costs to be associated with this "all electric" drive. However, the high motor speed presents an offsetting consideration. Traction motors are not normally built for operation much above 4000 RPM. Special designs are available which incorporate high strength armature construction and high speed bearings, but these tend to be more costly and field experience is limited. A low speed motor for Case 14 is feasible but it will, necessarily, be larger and heavier. Cases 11 and 13 are attractive due to the lower motor speed; however, there still remains some development risk associated with refining the Electromatic CVT.

Separately excited motors can provide a range advantage over comparable power trains with series machines. The motors are available, at least by special order. These systems require tailored controller designs which are within the near term state-of-the-art. In view of a rapidly advancing electronics technology, the all electric system with a high speed motor (Case 14) is the most viable design approach. Development of the Electromatic transmission should continue and as positive experience is obtained, the power train with fixed field voltage (Case 13) may be a good alternate.

The continued development of high speed DC shunt motors and electronic control packages will enhance the potential success of the "all electric" drive concept. In this context, the dual motor drive (Case 3 of Chapter 4.0) with separately excited machines and a single controller warrants some reconsideration. In addition to these power train developments, further research is needed to provide better batteries, expanded use of lightweight materials and low rolling resistance tires, since these have the major potential for improving range.

#### 5.4 MISCELLANEOUS IMPROVEMENTS

Several other improvements will lead to features which should enhance the commercial success of the electric vehicle. These may not increase range but are desirable in order to satisfy the general expectations of the potential electric vehicle buyer. The following paragraphs describe these miscellaneous improvements:

- Smooth stopping of an electric vehicle utilizing electrical dynamic or regenerative brakes in conjunction with hydraulic brakes requires a brake blending control system. Consistent with safety, such a system would blend the electrical and hydraulic brakes in response to driver input.
- The reliability of electric vehicle power train components should be carefully assessed. Areas of weakness should be identified and improved.
- The issue of safety needs to be carefully addressed to ensure compliance with applicable standards. Current designs, that have primarily been vehicle conversions, generally meet applicable DOT and SAE vehicle requirements. Other vehicles, especially those that are based on golf cart and similar technology, are not viewed as favorably. Compliance with the National Electrical Code may also be a requirement.
- In order to achieve the maximum weight and volumetric economy for the vehicle package, the motor and transmission (or gear reduction) should be designed as a single mechanical unit.
- The state-of-the-art assessment presented in Chapter 3.0 indicated the need for off-the-shelf, efficient and reliable automatic transmissions for electric vehicle use. The Electromatic CVT, when used in conjunction with a variable speed electric drive (as in Case 9) promises to fulfill this need. Efforts to refine the development and prove the field reliability of this type of unit should be pursued.

Another system based on off-the-shelf electromagnetic clutches, (used in Case 10 of Chapter 3.0) also shows promise as an efficient and reliable automatic transmission. A preliminary description of this latter concept is presented in the next section.

## 5.5 DISCRETE GEAR CHANGE AUTOMATIC TRANSMISSION

A two speed, discrete gear change automatic transmission, based on Formsprag dry electromagnetic clutches, is shown in Figure 5-12. The disc clutches couple alternate gear trains to the drive motor. Low gear is 4:1 and high is 1.03:1. The transmission output gear is coupled to a standard Dana differential with a modified housing through a ring gear of 4.5:1 ratio. The differential outputs are coupled through two universal shafts typical of the Corvette and VW transaxle approach.

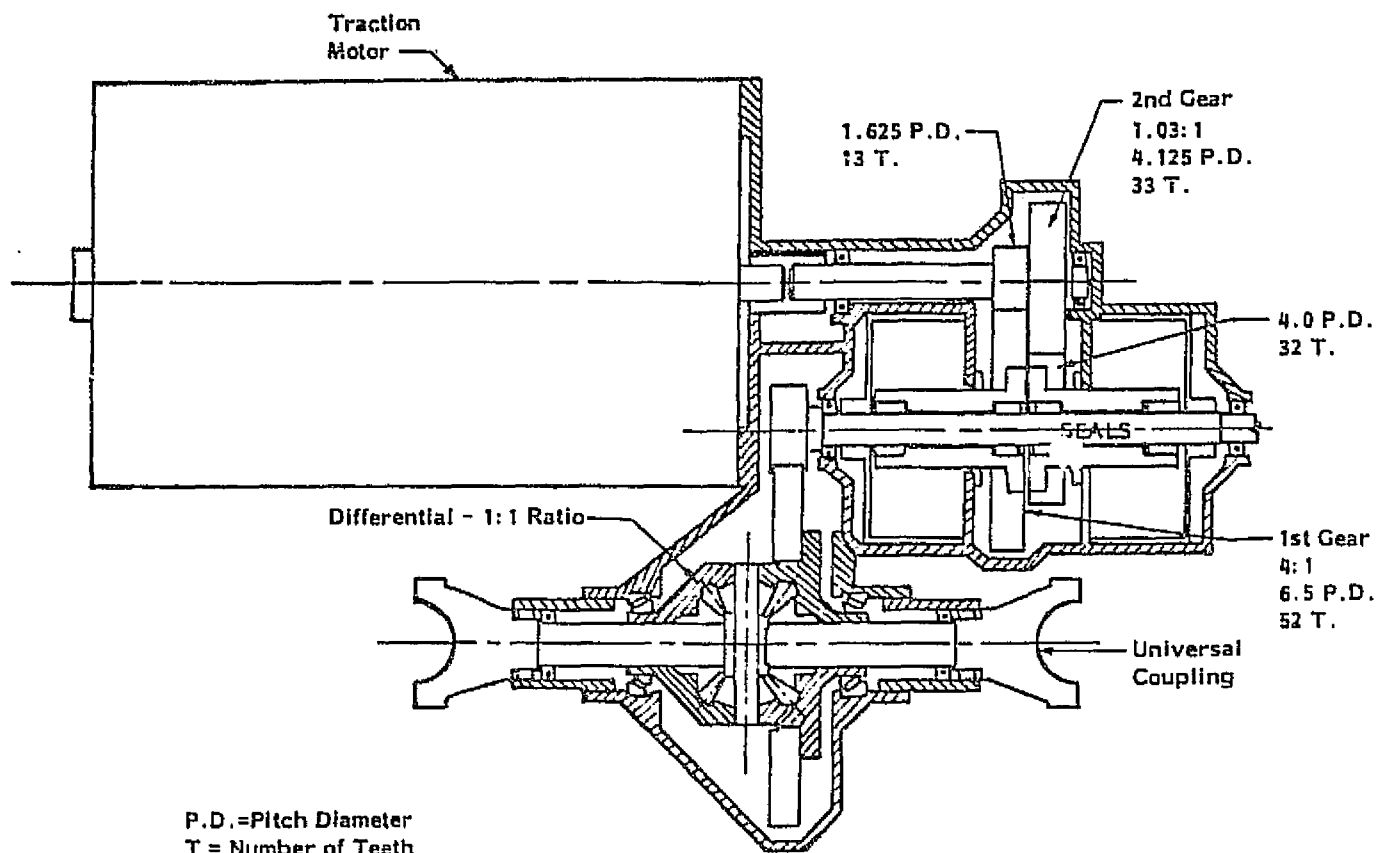


Figure 5-12 Layout of a two-speed electromagnetic transmission.

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Power flow in the two gears is shown in Figure 5-13 and a typical vehicle mounting is shown in Figure 5.14.

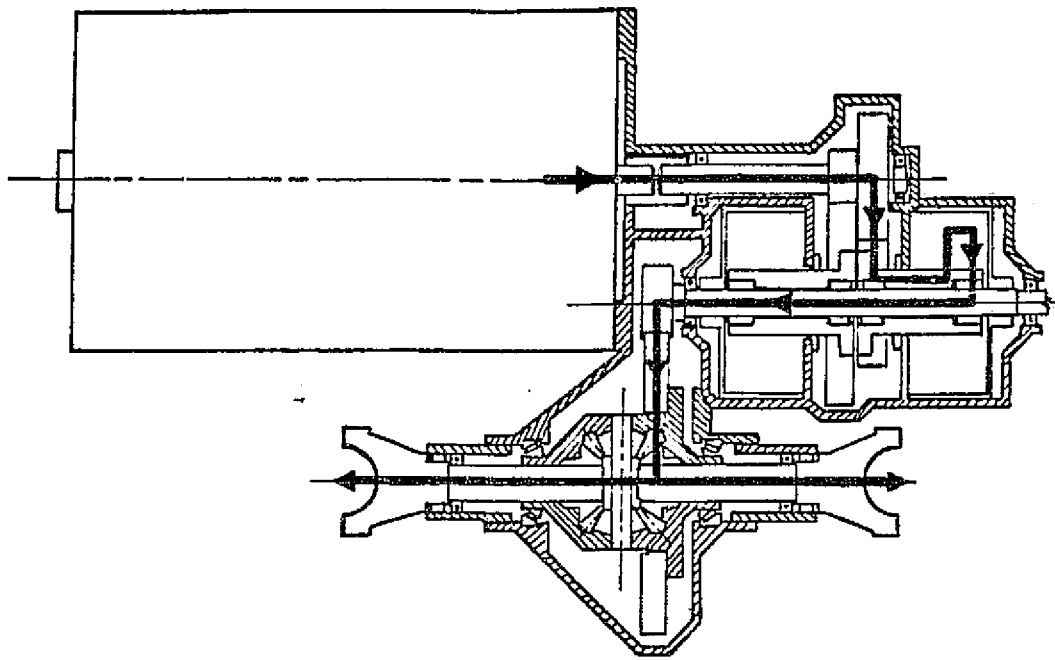
Some of the features of the electromagnetically shifted, discrete gear change, automatic transmission are listed here.

- The design is based on off-the-shelf hardware. Formsprag electromagnetic clutches are shown.
- The unit is compact and is estimated to weigh less than 100 pounds.
- Low electrical power is required to activate or maintain the clutches. Only 31 watts (.04 hp) is required as compared to 0.75 - 2.2 kw (1-3 hp) loss of conventional hydraulically actuated automatics.
- Low drag loss, dry clutches are employed. Slip friction losses are 0.2 N-m (0.15 lb-ft) or 75 w (0.1 hp) at 88 km/hr (55 mph). This loss can occur only during shifting.
- The gear design is conservative, stress levels and life expectancy is consistent with standard automotive practice. The gear sets are lubricated.
- Motor synchronization with the shift function is required to maximize reliability and smoothness. Each clutch can dissipate 360,000 N-m (282,000 lb-ft). Under a worst case assumption of 120 shifts per hour, the change in motor rotor inertia requires that 1,240,000 N-m (950,000 lb-ft) per hour be dissipated. Motor speed control during shifting is, therefore, desirable. The details of such a control system need to be evaluated although they do not appear to be conceptually difficult.

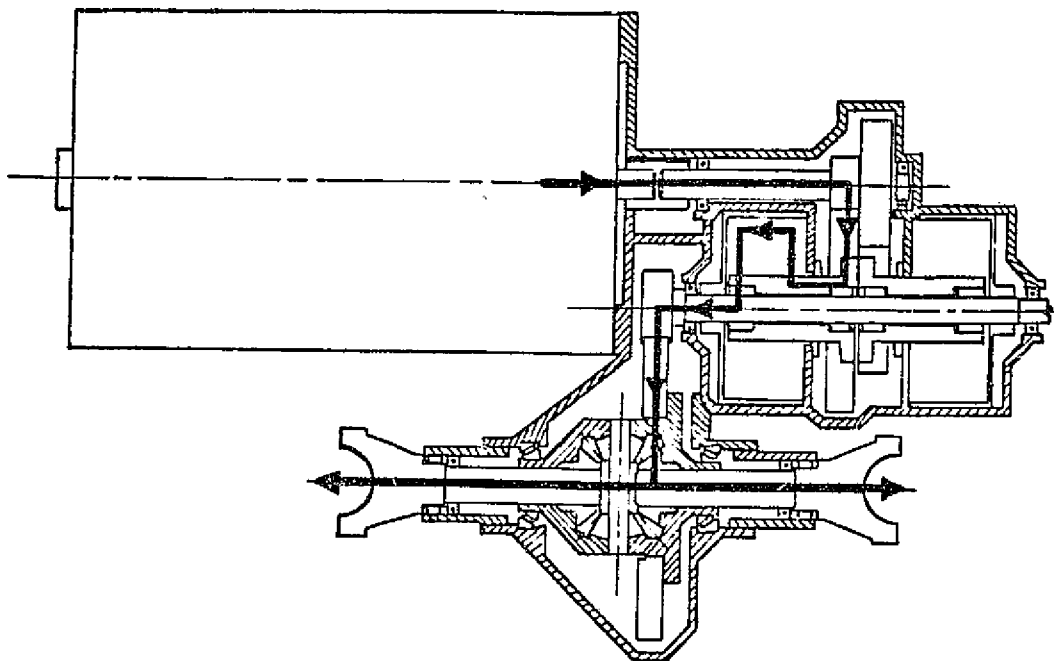
Further development and testing of the electromagnetically shifted design appears warranted.

If the electronic synchronization during shifting can be achieved with a high degree of accuracy, the slip type disc clutches can be replaced by positive engagement tooth type clutches, such as manufactured by Bendix. These are significantly smaller and less expensive than the disc type clutches and their use would permit 2,3 or 4 speeds to be designed in a relatively small package. They can be operated wet (in oil) and therefore, need not be isolated from the gearing. The efficiency of such a transmission would be comparable to the disc clutch design. A 3-speed transmission concept using this design approach is depicted in Figure 5-15.





LOW GEAR



HIGH GEAR

Figure 5-13 Power flow in the electromagnetic transmission.

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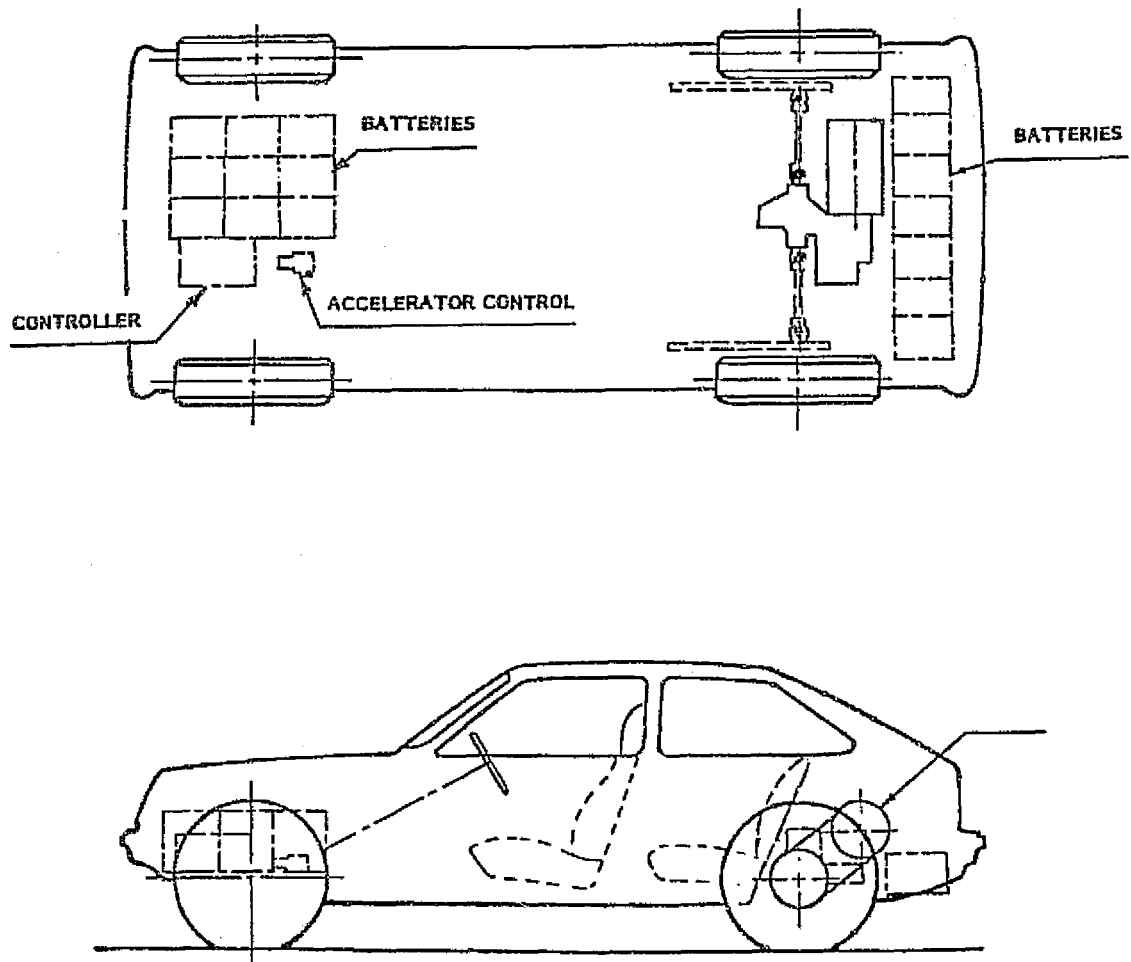


Figure 5-14 Typical installation of power train in a vehicle.

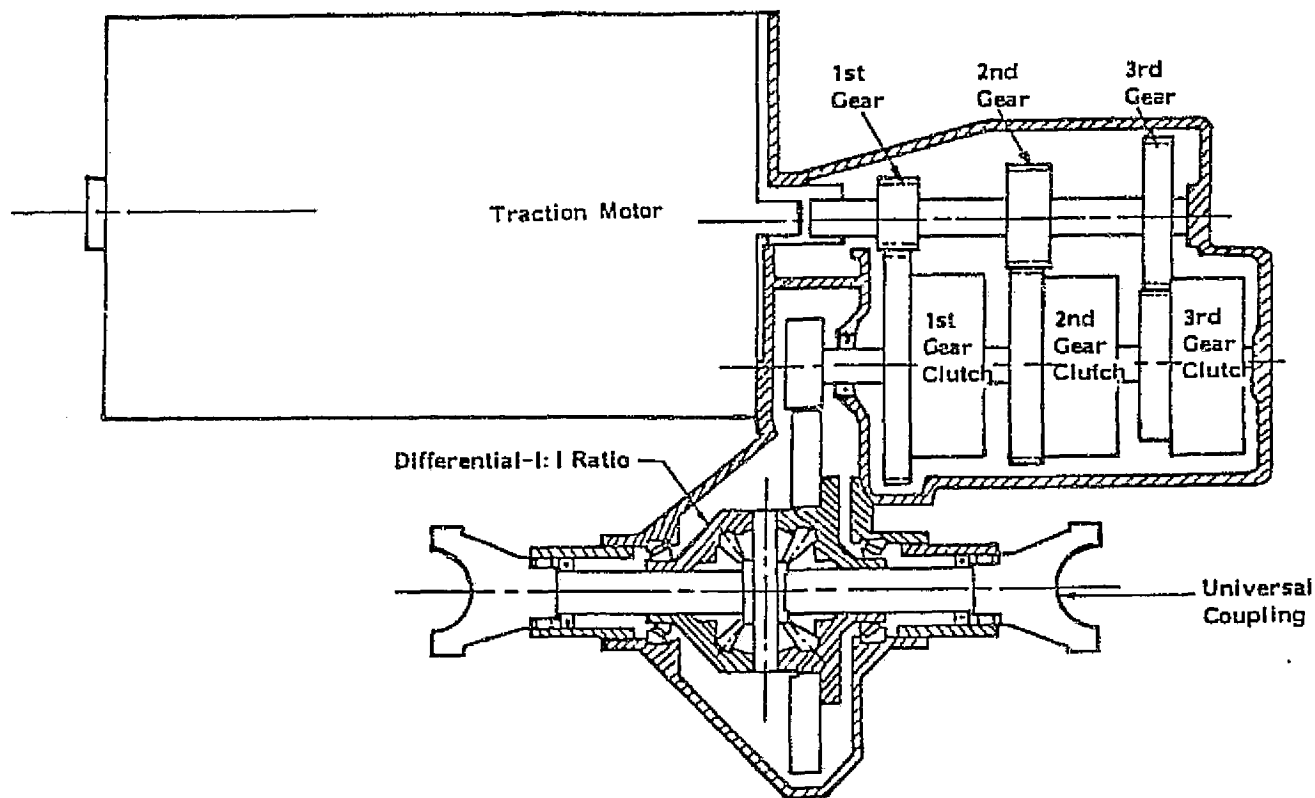


Figure 5-15 Tooth type electromagnetic 3-speed transmission.

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## 6.0 CONCLUSIONS

This report has presented a preliminary design of an electric vehicle power train based on an objective assessment of the state-of-the-art, and has identified and evaluated technical advances which can improve vehicle performance. The primary standard of performance was range over the SAE J227a schedule D driving cycle.

Most state-of-the-art electric vehicles are conversions of conventional highway vehicles. Very few completely original designs exist. Prototypes such as the Copper Development Association town car and the McKee Sundancer, however demonstrate that carefully designed, lightweight vehicles can achieve superior performance.

Several state-of-the-art AC and DC motors are available in the size and power range required. However, the only state-of-the-art controllers commercially available are for DC series wound motors.

One technique of optimizing the range of an electric vehicle over a stop and go driving cycle is to match the motor characteristics to the load through an efficient, lightweight multiratio automatic transmission. The number of useable components is quite limited and include modified conventional transmissions and an electrically controlled, V-belt, continuously variable system. A promising alternate design is based on off-the-shelf, electrically activated clutches.

The recommended state-of-the-art power train design employs an 18 kw (24 hp) DC series wound motor, SCR controller, V-belt CVT, drum brakes, radial-ply tires and regenerative braking. A power train based on a separately excited shunt wound DC motor will achieve about 20% greater range over the SAE cycle than one with a series wound motor. In order to implement this system, technical development is needed in the areas of higher speed, shunt wound motors and electrical controllers featuring both armature and field control.

Even with power train components which are perfectly efficient, a highly streamlined 1633 kg (3600 lb) electric vehicle, with state-of-the-art tires, would have a range of only 96 km (60 mi) over the SAE cycle. In order to significantly extend range, improved batteries, expanded use of lightweight materials and low rolling resistance tires are needed.

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16. Abstract  <p>Power train designs which can be implemented within the current state-of-the-art were identified by means of a review of existing electric vehicles and suitable off-the-shelf components. The affect of various motor/transmission combinations on vehicle range over the SAE J227a schedule D cycle was evaluated. The selected, state-of-the-art power train employs a DC series wound motor, SCR controller, variable speed transmission, regenerative braking, drum brakes and radial ply tires. Vehicle range over the SAE cycle can be extended by approximately 20% by the further development of separately excited, shunt wound DC motors and electrical controllers. Approaches which could improve overall power train efficiency, such as AC motor systems, are identified. However, future emphasis should remain on batteries, tires and lightweight structures if substantial range improvements are to be achieved.</p>					
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