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THE ELECTRIC CHOREMASTER:
DEVELOPMENT AND PERFORMANCE OF AN AGRICULTURAL ELECTRIC TRACTOR

by

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1985

THE ELECTRIC CHOREMASTER:
DEVELOPMENT AND PERFORMANCE OF AN AGRICULTURAL ELECTRIC TRACTOR

This thesis is approved as a creditable and independent investigation by a candidate for the degree, Master of Science, and is acceptable as meeting the thesis requirements for this degree. Acceptance of this thesis does not imply that the conclusions reached by the candidate are necessarily the conclusions of the major department.

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INTRODUCTION

Electric vehicles designed for agricultural applications are one means for the United States and for United States agriculture to reduce dependence on petroleum fuels. Electric vehicles can be used to complement the petroleum powered vehicles already in use by adding energy flexibility to a farm operation, while reducing dependence upon and use of petroleum. Electric farm vehicles may also improve agricultural energy efficiency, reduce farm operating costs, and improve farm operator convenience.

Electric vehicles are technically and economically proven for many specialized applications, and research is continuing to develop electric vehicles suitable for other applications. Battery energy density, which restricts operating range, and the higher initial cost of electric vehicles, which requires intensive year-round usage to justify investment costs, have limited electric vehicle applications. However, industries throughout the world have been using electric vehicles for several decades in applications where these limitations are offset by one or more of the following advantages of electric vehicles: lower

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Note: Reference to a manufacturer does not imply any endorsement of that company or its products by the author or by the Agricultural Engineering Department of South Dakota State University.

life cycle costs due to lower operating costs and longer vehicle life, fewer noise and exhaust pollution problems, and improved mechanical simplicity and durability. Electric vehicles are in widespread use for materials handling, delivery, mining, personnel transport, lawn and garden care, recreation, and aircraft towing applications.

The Electric and Hybrid Vehicle Act of 1976 mandated that the United States Department of Energy implement a research, development and demonstration program for electric vehicles. This act was intended to stimulate the electric vehicle industry to make electric vehicles a practical transportation alternative. Electric road vehicles have found only limited acceptance, due mainly to inadequate traveling range between battery charges. However, the research supported by the Department of Energy has improved electric vehicle technology, which may lead to increasing acceptance of electric transportation vehicles.

The United States Department of Agriculture in 1979 conducted a study of the feasibility of electric vehicles in agriculture, as part of the Department of Energy electric vehicle program. Researchers from six universities, including South Dakota State University, concluded that electric vehicle technology was at the stage where electric vehicles were commercially feasible for selected farm applications (Christianson, et al., 1981). These researchers also recommended the development of a prototype electric tractor for testing and demonstration.

The National Rural Electric Cooperative Association partially funded a project at South Dakota State University for development of an electric tractor in 1983. The goals of this project were to build, demonstrate and evaluate a battery-powered farmstead chore tractor which would lead to a commercially produced and widely accepted vehicle. Three major results were expected from the work: 1) test results and analyses to verify the feasibility of farmstead electric vehicles and to indicate some of the problems and limitations encountered during actual use, 2) a vehicle to demonstrate the concept of electric vehicles to farmers and to farm equipment manufacturers, and 3) design information for an electric vehicle prototype which could be used to aid the commercial development of electric farm vehicles.

Design of this tractor, the Electric Choremaster, was a team endeavor. As a member of the design group, this author's responsibilities were to: contribute to the vehicle design criteria; review and evaluate power train components; size, select, and supervise the installation of motors and drive train components; and perform the first phase of testing and evaluating the completed prototype.

This thesis reports on the development of the Electric Choremaster and can serve as a guide for future developments of agricultural electric vehicles. Specific objectives of the research reported in this thesis were to:

1) describe the design process used for development of the Electric Choremaster,

2) detail the power train design for the Electric Choremaster,

3) evaluate the performance of the Electric Choremaster as compared to a conventional diesel tractor, and

4) investigate the effects of battery temperature and state of battery charge on vehicle performance.

REVIEW OF LITERATURE

Feasibility of electric vehicles in agriculture:

Throughout this century, the United States has become increasingly dependent upon petroleum fuels. By 1970, approximately 75% of the energy used in the United States was obtained from petroleum fuel. The Arab oil embargo of 1973 and the oil shortages in 1979 provide examples of the consequences of dependence upon petroleum. Agriculture in the United States has become particularly dependent upon petroleum fuels. American agriculture uses only three percent of the national total energy consumption, but the majority of the energy used in agriculture is obtained from petroleum fuels. A shortage of petroleum at a critical time in the crop growing season could be devastating to farm production. It is critical that the energy required in agriculture is received at the time it is needed, if production efficiency and product quality are to be maintained (Parker, 1981).

The oil shortages of the 1970's seriously affected transportation businesses, which account for one-fourth of United States oil consumption. This spurred efforts to develop more efficient vehicles, and to develop vehicles powered by alternative energies such as electrical energy. At the turn of the century electric vehicles dominated the self-propelled vehicle market. By 1912 nearly 34,000 electric cars were registered in the United States, and scores of electric trucks and commercial vehicles were in use (Shacket, 1979). However, as petroleum fuels became readily available, gasoline-powered vehicles became more popular and electric vehicles were gradually phased out. As petroleum reserves are becoming limited, electric vehicles are once again receiving public attention for transportation purposes.

The Electric and Hybrid Vehicle Research, Development and Demonstration Act of 1976 mandated that the United States Department of Energy conduct a program to support the electric vehicle industry (USDOE, 1983). This program was intended to help develop electric vehicle technology so that electric vehicles would be accepted as a practical means of transportation. This program has contributed substantially to the development of electric vehicle technology, but electric road vehicles have found only limited acceptance, due to limited range, sluggish performance, and high purchase prices. The main performance limitations are inadequate energy density, power density and life of batteries, accentuated by the high costs of batteries, motors, controls and other components (Secunde, et al., 1983).

The battery pack is the most limiting component of the electric vehicle power train, due to the low energy density. Energy densities and conversion efficiencies of petroleum fuels and electric vehicle batteries are compared in Table 1. Despite the better energy conversion efficiency of the electric vehicle, a large battery mass is required to provide the operating time and range of an equivalent size, petroleum-powered tractor. Nearly 8500 kg of industrial lead-acid batteries are needed to provide the energy available in one tankful (100 L) of gasoline. The electric vehicle is further limited because a gasoline tractor may be re-fueled in a matter of minutes, whereas battery charging takes several hours.

TABLE 1. Comparison of fuel energy densities (Alcock, 1985).

Fuel Source	Energy Density (MJ/kg)	Conversion Efficiency	Equivalent Mass (1) (kg)
Gasoline	44.2	0.20	1
Diesel	43.0	0.26	0.79
Industrial Lead-Acid Battery	0.108	0.72 (2)	114
Advanced Lead-Acid Battery	0.148	0.72 (2)	83

(1): Mass necessary to supply energy in 1 kg of gasoline.
(2): Assumes controller efficiency=0.95, motor eff.= 0.80, (Edie, 1981) and gear reduction eff. = 0.95.

Despite these limitations, electric vehicles do offer several advantages over conventional petroleum-powered vehicles. The principal advantages are: 1) electricity can be produced from many energy sources, some more abundant than oil, and hence could prove to be a more reliable and economical energy supply, and 2) electric vehicles more efficiently convert energy to work than conventional vehicles, thereby providing operating cost savings (Resen, et al., 1981). Other advantages of electric vehicles include quick and easy starting, minimal noise, no poisonous gasses or polluting by-products at the point of use, mechanical simplicity and durability, and the ability to handle short-duration overloads which would stall a comparably-sized internal combustion engine (Resen, et al., 1981, Obert, 1972).

These advantages have helped electric vehicles find wide acceptance for certain applications. Industrial materials handling is one popular application, as illustrated by the wide range of electric lift trucks available. One manufacturer (Caterpillar, 1984) markets 16 models of electric fork lifts, and in sales literature compares each model to similar models offered by five competitors. The forklift industry (electric, propane, gasoline and diesel) generates nearly $10 billion in annual worldwide revenue, and electric lift trucks account for more than 50% of the 225,000 units sold annually (Christianson, et al., 1985). Underground mining is another popular application for electric vehicles. Conventional vehicles are conventional internal combustion engines, 4) the technical and mechanical proficiency of most farm operators, which makes them particularly capable of adopting new technologies, 5) the availability of more than one vehicle on nearly all farm operations, which makes it non-essential that an electric vehicle be well-suited for all tasks, and 6) the vulnerability of farm operations to energy supply interruptions.

The United States Department of Agriculture in 1979 selected six institutions, including South Dakota State University, to study the technical and economic potential of substituting electric for petroleum-powered vehicles in agricultural applications (Calkins, et al., 1981). The group used a sequence of five steps to assess the feasibility of electric farm vehicles. These were to: 1) determine vehicle requirements for performing agricultural tasks, 2) develop hypothetical electric vehicle designs based on current (1980) and projected (1990) technology, 3) analyze the technical feasibility for performing agricultural tasks with electric vehicles, 4) assess the economic feasibility of electric vehicles in agriculture for 1980 and 1990, and 5) identify specific factors which could hasten or hinder adoption of agricultural electric vehicles (Christianson, et al., 1981).

Resen (1981) used two methods to determine the power, time and energy requirements of agricultural restricted in mines because of poisonous exhaust gases and sparks which cause explosion hazards. The motors and controls in electric mining vehicles are totally enclosed and spark-free, and therefore safer than conventional vehicles.

Electric vehicles are also gaining acceptance in delivery and other commercial fleets. In a survey of commercial fleet operators, Berg, et al. (1984) found that, depending upon required vehicle performance, between one-fourth and three-fourths of the approximately 13 million vehicles in United States commercial fleets could be replaced by electric vehicles, thus providing a substantial reduction in the dependence on petroleum fuels. The United States Postal Service has used a large number of electric vehicles in the mail delivery fleet for several years, and their feasibility has been firmly established (Cole, 1983).

Agricultural chore and utility work could be another specialized application for electric vehicles. Christianson, et al. (1981) list several characteristics of light-duty agricultural tasks which enhance the potential for utilizing electric vehicles on the farm. These include: 1) the regularity of many farm tasks which must be performed daily, year-round and for short durations, 2) the local nature of farm tasks, most of which are performed on the farm unit, 3) the start-and-stop characteristic of many farm tasks, analogous to city driving, which inefficiently utilize vehicles: 1) review of literature, and 2) in-depth farm surveys and farm operator interviews. Farm tasks were divided into five groups and farm sizes were divided into three categories. Results for both methods were similar, although a wider range of values was obtained by the survey and interview approach. The results of the review of literature method are summarized in Table 2. This information was not only important for assessment of electric farm vehicle potential, but also defined the range of power and energy capacities necessary for design of a prototype electric farm vehicle.

Hypothetical electric vehicle designs were established with cooperation from the Department of Energy (Christianson, 1980). Vehicle sizes of 11, 19 and 30 kW were used for 1980, and 19, 30 and 45 kW for 1990, as preliminary analysis had suggested that these sizes would be the most practical. The hypothetical vehicle designs are summarized in Table 3.

The technical feasibility of agricultural electric vehicles was determined by comparing hypothetical electric vehicle capabilities with agricultural task requirements (Resen, et al., 1981). Table 4 indicates the percentages of Eastern South Dakota farm tasks, calculated on an energy not hourly basis, which could be performed by 11 to 45 kW electric vehicles with no management changes other than the utilization of an electric vehicle to replace conventional

Table 2. Principal vehicle performance requirements for tasks typical of farms in Eastern South Dakota (Resen, 1981).

	Heavy Tillage (1)	Medium Field Work(2)	Light Field Work(3)	Livestock Production (4)	General Utility (5)
Drawbar Power (kW)	45-130	30-63	15-30	19-41	8-15
Speed (km/h)	5- 10	5-24	3-24	2-24	2-10
Draft (kN)	17- 80	4-50	1-20	3-45	1- 7
PTO Torque (N-m)		230-712	185-395	185-1058	198-305
Loader Lift (kN)			7	4-11	4- 7
Operation Duration (h)	8- 12	5-12	2-12	1- 8	3- 8
Energy (kW-h)	436-126	252-507	112-209	78-186	56-62
Annual Operating Time (h)	98-475	174-680	195-535	300-1000	45-70
Annual Energy (kW-h)	4750-60215	5839-40566	3635-13963	7271-31692	503-783

(1) Tasks include molboard plowing, chisel plowing and field cultivating.
(2) Tasks include disking, fertilizing, silage chopping, combining, baling and hauling heavy loads.
(3) Tasks include seeding, windrowing, light hauling, mowing, raking, dragging, spraying, stalk chopping, row cultivating, planting and corn picking.
(4) Tasks include grinding, loader work, sewage handling, livestock moving and snow moving.
(5) Tasks include operating augers and elevators, digging post holes, moving machinery and hauling rock.

Table 3. Hypothetical electric vehicle designs for 1980 and 1990 (Christianson, et al., 1981).

1980 Technology: Vehicle power (kW)		11.2	18.6	29.8
Vehicle mass (kg)		3175	4763	8074
Battery:	type		lead - acid	
	specific energy		42 Wh/kg	
	capacity (kW-h)	97	162	259
	life (cycles)	500	500	500
Efficiency (%)		33	33	33

1990 Technology: Vehicle power (kW)		18.6	29.8	44.7
Vehicle mass (kg)		3175	5216	7711
Battery:	type		nickel - zinc	
	specific energy		70 Wh/kg	
	capacity (kW-h)	133	202	302
	life (cycles)	2000	2000	2000
Efficiency (%)		52	52	52

Table 4. Percentages of farm tasks which could be performed by 11 to 45 kW electric vehicles in typical Eastern South Dakota farms (Christianson, et. al., 1981).

Vehicle Size:	11.2 kW					18.6 kW				
Task Type:	Heavy Field	Medium Field	Light Field	Live-stock	General Utility	Heavy Field	Medium Field	Light Field	Live-stock	General Utility
Medium farms:	7	13	27	43	89	11	22	45	71	100
Large farms:	6	8	19	18	89	10	14	32	29	100

Vehicle Size:	29.8 kW					44.7 kW				
Task Type:	Heavy Field	Medium Field	Light Field	Live-stock	General Utility	Heavy Field	Medium Field	Light Field	Live-stock	General Utility
Medium farms:	18	34	72	100	100	27	52	100	100	100
Large farms:	16	22	51	47	100	25	34	77	71	100

Notes:

(1) Based on actual field practice records for 17 farms during two growing seasons, and assumes that the electric vehicle will produce rated power for four hours per charge, and that only one battery charge will be used per day. Percentages are calculated as the portion of internal combustion tractor energy use which can be replaced.

(2) Tasks are as defined in Table 2.

(3) Medium farms are from 200 to 999 acres, large farms are over 1000 acres.

farm tractors. This assumes one electric vehicle per farm with one battery charge per day. This is a conservative estimate of the potential to replace oil-derived fuel consumption in Eastern South Dakota agriculture with electricity because farm operators could adjust their work schedules to accomodate electric vehicles. Electric vehicles are probably not practical for heavy field work, but are technically capable of replacing petroleum-powered tractors in nearly all the livestock and utility work, and can be used for a portion of the light and medium field work (Table 4). These percentages could be doubled (up to 100%) if two electric vehicles of that size were operated daily, or if a battery replacement during the day was allowed.

Buck and Hughes (1981) divided agricultural tasks into four categories for assessment of electric vehicle feasibility: 1) heavy field work, 2) light field work, 3) hauling tasks, and 4) utility tasks. They found that existing petroleum-powered vehicles perform heavy field tasks with an efficiency of 24%, but are less efficient with light field tasks at 17%, and are only 11% efficient at hauling and utility tasks. Buck and Hughes (1981) also found that most farm operations use more than one tractor, so it is not essential that electric vehicles be well-suited to perform all tasks. They concluded that electric tractors could be used to more efficiently perform the light duty utility tasks, while the heavy field work should be performed by conventional tractors.

Christianson, et al. (1981) list the following factors which affect the economic feasibility of replacing conventional petroleum-powered farm vehicles with electric vehicles: 1) relative purchase prices, 2) vehicle efficiencies, 3) comparative energy prices, 4) vehicle and component lives, 5) relative maintenance costs, 6) comparative ease of operation, 7) chemical or physical pollution, 8) the importance of reducing energy vulnerability on a local level, and 9) the effects of direct or indirect government policy.

Electric vehicle manufacturers have indicated that the purchase price for an electric farm vehicle would be approximately 10 to 15% more than the purchase price of an equivalent diesel tractor, not including the cost of the battery pack and the charger (Christianson, et al., 1985). This initial cost difference is more a function of achieving economies-of-scale than of inherent extra labor or materials cost. However, the higher initial cost of the electric vehicle could be offset by lower operating and maintenance costs, longer vehicle and component lives, and better reliability of electric vehicles. Using life-cycles, costing techniques and data from the electric forklift industry, Christianson, et al. (1985) provides an estimated life-cycle cost comparison between electric and diesel farm tractors (Table 5). This comparison shows that, due to lower operating and maintenance costs and longer vehicle life, the electric vehicle could save approximately 11% of annual diesel vehicle costs.

Table 5. Life-cycle cost analysis of electric versus conventional farm tractors (Christianson, et al., 1985).

	Battery-powered <u>Electric Tractor</u>	Diesel <u>Tractor</u>
Initial costs of a 60 kW, 4 WD equivalent tractor (1984 in United States)	$50,000	$40,000
Expected vehicle life	10 years	7 years
Annual ownership costs at 10% interest	$ 8,150	$ 8,290
Energy cost / unit	$.05/kW-h	$.30/L
Annual energy costs with 7500 kW-h energy available at axles	$ 1,875	$ 2,100
Annual maintenance and repair costs	$ 4,500	$ 6,000
TOTAL ANNUAL COSTS	$14,525	$16,390

Ease of operation is an important advantage of electric vehicles. They start immediately, are simple and easy to use, and respond quickly. Electric vehicles also have important advantages in terms of pollution, especially for in-building work common with farm chores. The noise and chemical emissions of electric vehicles are negligible compared to those of gasoline- or diesel-powered vehicles.

Government policy can be designed to favor diesel or electric vehicles. Rationality suggests that government policy favors the goal of energy independence which, in most countries, could be achieved through increased utilization of electric energy. Income tax credits, reduced interest rates for purchase of electric vehicles, and oil depletion allowances are examples of government policies that can affect consumer choices (Christianson, et al., 1985).

Christianson, et al. (1981) defined other events which could also enhance the economic potential of electric farm vehicles, as the last step in the United States Department of Agriculture study. These were: interruptions of diesel or gasoline supplies, technological breakthroughs in the electric vehicle industry, especially in battery design, and encouragement of electric vehicles by electric utility companies through special off-peak electric rates for electric vehicle users.

Electric vehicles for agricultural applications:

Sporadic attention had been given to the use of electric vehicles in agriculture before the United States Department of Agriculture and Department of Energy feasibility study. Allis Chalmers built an experimental electric tractor powered by fuel cells (Ihrig, 1960). It had a 15-kW electric motor and could develop a drawbar pull of approximately 13 kN. Hard dry ground with about 30 cm of alfalfa on it was plowed with a double-bottom plow without difficulty. Initial tests indicated efficiencies of 50 to 60%, which were much better than could be attained with diesel or gasoline engines.

The Farm Electrification Council and Lead Industries Association in 1969 introduced the Electric Experimental Tractor (EXT) to demonstrate the capability and feasibility of small, battery-powered vehicles (Turrel, 1969). This tractor was described as a four-wheeled, riding-type tractor, equivalent in capabilities to a 9-kW gasoline-powered unit. It was designed to mow, blow snow, clean free-stall dairy barns and move various materials around the farmstead. The EXT was powered by six, 6-volt lead-acid batteries, and could be fully recharged within 12 hours on a 110-volt ac charger. It had a solid state control which allowed for reversing and for speed variation without loss of power. Two, 0.75-kW dc series traction motors drove the EXT. Three, 1-kW permanent magnet motors powered the mower, and one, 3-kW permanent magnet motor powered the snowblower. The EXT also had an electric power lift for attachments (Turrel, 1969).

Field tests showed that the EXT could operate for approximately two hours between charges, depending upon how it was used. The tests also showed that the EXT was more economical to operate than engine-type units. Turrel (1969) noted keen interest from several manufacturers, who indicated that an electric tractor comparable to a 5-kW gasoline tractor could be competitively produced and marketed. The EXT was the forerunner of the electric riding mowers and garden tractors later produced by John Deere, General Electric and Wheelhorse.

The development and wide acceptance of the electric garden tractor and riding mower prompted Obert (1972) to investigate the feasibility of electric vehicles for farm use. Obert (1972) examined the duty requirements for farm tasks, and found vehicle applications which could be electrically powered. Obert (1972) concluded that electric vehicles would be limited by the battery, but that some specific electric farm vehicle applications were feasible, and that the tools and technical support were available for further feasibility studies and for electric tractor development.

Elamin (1981) compared the performance of an electric lawn and garden tractor with that of a similar gasoline-powered unit. Three tasks (mowing, disking and plowing) were used to compare operating speeds, energy usage and energy costs of the two tractors. Highly significant savings in energy use and cost were reported for the electric tractor at similar operating speeds for both tractors. This work cannot be extrapolated to predict the performance of larger battery-powered tractors because of the large difference in scale between garden and farm tractors. Elamin (1981) suggested repeating this type of work with larger vehicles, such as fork-lift trucks, to verify his results on a larger scale.

TEMA (a company in the Italian National Hydrocarbon Agency) in 1983 conducted a feasibility study for an electrically powered agricultural tractor (Gervasio, et al., 1984). This study led to the development of a prototype battery-powered tractor which was completed in May, 1984. The prototype was powered by two groups of lead-acid batteries, connected in series to supply 140 volts, with an energy capacity of approximately 50 kW-h. Vehicle mass was approximately 4500 kg, with one-third of this due to the batteries. The tractor had four-wheel drive, achieved by using four, 5-kW permanent magnet motors, one at each wheel. A 15-kW motor drove an independent pto which could be operated at either 540 or 1000 r/min. The tractor had a hydraulic hoist powered by a 3-kW motor, but did not have a loader. Direction of operation was reversible by rotating the operator console around a vertical shaft. The tractor was steered by one axle, normally the front axle (opposite the drawbar).

Field tests were conducted to determine the performance of the TEMA tractor for powering three types of machinery: 1) that requiring only drawbar power, 2) that requiring only pto power, and 3) that requiring both drawbar and pto power. Initial results indicated that the tractor performed best for tasks requiring moderate drawbar and pto power. When coupled to a trailer which required high drawbar pull, the tractor was limited by the excessive current needed by the motors to produce the necessary torque. When coupled to a scythe bar mower, the tractor was underutilized in terms of power required, and created compaction problems due to its excessive weight. TEMA plans to continue research in this area, mainly to try to reduce the weight of electric tractors.

ELECTRIC CHOREMASTER DEVELOPMENT PROCESS

Overview of vehicle design:

The goal of this process was to develop an electric tractor for testing and demonstration within one year. The philosophy of the design process was to design and build a useful vehicle within the specified time constraints, and then make necessary design improvements to optimize vehicle performance. Commercially available and technically proven components were to be used so that the design team could concentrate on applying electric vehicle technology to agriculture rather than designing new components and to enhance future manufacturing potential. A decision was made to modify an existing vehicle rather than attempt to develop an entirely new prototype because many components are similar to those currently used on petroleum-fueled tractors.

The first step in the design process was to define the requirements of an electric vehicle in agriculture. Relying on previous research (Resen, 1981, Buck and Hughes, 1981) and on the experience of individuals in the design group, a list of tasks which the vehicle should be capable of performing was compiled (Table 6). The review of literature indicated that electric vehicles would not be feasible for extensive field work, due to insufficient battery capacity, therefore the list concentrates on farmstead and utility tasks. Loader tasks represent more than 50% of the anticipated use time, therefore a primary consideration in development of this tractor was optimization for loader use.

Table 6. Anticipated uses for an electric tractor.

Loader Tasks: estimated as 50% of tractor use
- Feed handling
- Silage loading
- Round bale moving and feeding
- Manure handling
- Snow moving
- Rock hauling from fields
- Land scraping/leveling

Other uses:
- Feedlot wagon towing and operating
- Farmstead-to-field hauling
- Manure hauling
- Grain hauling
- Grain augering
- Farmstead mowing
- Spraying
- Short duration seeding, mowing and raking
- Post-hole digging
- Irrigation pumping
- Irrigation pipe transporting
- Log splitting / firewood hauling
- Standby power source
- Portable power source
- Field repair

The next step in the design process was to decide upon general drive and steering options. The drive options were: rear-axle, two-wheel drive; front-axle, two-wheel drive; rear-axle drive with front wheel assist; and four-wheel drive. Many of the tasks the vehicle would be required to perform are on soft, muddy ground or snow. Four-wheel drive provides better traction and can develop more thrust in adverse soil conditions, therefore four-wheel drive was selected for the prototype.

Several methods of steering were available with four-wheel drive. These included: skid-steering, front-axle, rear-axle, both front- and rear-axle steering, and articulated steering. Skid-steering and front-axle steering were both eliminated due to concerns about the loss of mobility on soft soils. Double axle steer was eliminated in favor of rear-axle steering because double axle steering was more expensive and did not appear to offer improved performance. Rear-axle steering was a promising alternative for this tractor because it would provide for good maneuverability with the loader attached. With a reversible cab, the rear-axle steered tractor would perform like a front-axle steered vehicle for drawbar loads. However, articulated steering was generally considered to be the simplest and least expensive steering method. An articulate steered vehicle would also be very mobile, as it can maintain full power through turns, and would provide good maneuverability and loader control. Therefore, articulated steering was chosen for this vehicle.

Several farm and construction vehicles currently on the market were examined and compared with the design criteria outlined above. From these comparisons the

Versatile 160 tractor was selected as the basis for the electric tractor, and a prototype of the 160 was purchased. This was a four-wheel drive, articulated frame vehicle with a reversible operator console to facilitate its use as either a loader/utility tractor or as a field tractor.

Power train design:

The main difference between a conventional tractor and an electric tractor is the power train. Therefore, it is the power train design which merits the most attention. The power train of a vehicle can be defined as the integrated set of components that convert input energy to usable power. The power output is usually a mechanical driving force at the vehicle wheels, but with agricultural tractors power is also available from the power-take-off (pto) shaft and from the auxiliary hydraulics system. An additional option of the electric power train could be the provision of an electrical outlet, so the tractor can be used as a portable power source.

The power train of a gasoline or diesel tractor typically includes: 1) a fuel tank for energy storage, 2) an internal combustion engine to convert the energy in the fuel to mechanical energy, 3) a fuel pump and throttle to regulate the engine speed, 4) a clutch, multi-ratio transmission and additional gear reductions to match the mechanical output characteristics of the engine to the propulsion needs of the vehicle, and 5) systems to drive the pto and auxiliary hydraulics from the engine. A comparable electric tractor power train would include: 1) a battery pack for energy storage, 2) an electric motor or motors to convert electrical energy to mechanical energy, 3) a controller system to condition the electrical energy from the battery and control motor operation, 4) a transmission and gear reduction system, and 5) motors and controls to drive the pto and auxiliary hydraulics system. The electric vehicle also requires a battery charger to supply energy to the tractor, analogous to the petroleum fuel bulk tank.

One advantage of an electric tractor is the ability to separate the traction, pto and hydraulic systems. With a conventional tractor all the power is supplied by one internal combustion engine so operation of each of the three power output systems is dependent upon engine speed. The cost and complexity of internal combustion engines make it impractical to use more than one engine on conventional farm tractors. In the electric tractor, a separate motor and control system can be used for each of the power outputs without substantially increasing cost or complexity. Separate electric motors allow the operator to independently control travel speed, pto speed and hydraulic system response.

The ideal performance of the power train for vehicle drives is constant power output over the full speed range (Taborek, 1957). To produce constant power, the torque output must vary inversely with speed (Figure 1). This will provide the vehicle with high tractive effort at low speeds where demands for acceleration, drawbar pull or grade climbing capability are high. High speeds can be attained when there is low torque demand, such as for road traveling. There are power plants that have power-torque-speed characteristics similar to those which are ideal for vehicle propulsion, such as series-wound electric motors (Figure 2) and steam engines. The internal combustion engine has less favorable characteristics (Figure 3) and can only be used with a suitable transmission which helps it approximate the ideal curve (Figure 4). The more gear ratios available in the transmission, the better the internal combustion power train can approximate the ideal power characteristics. An internal combustion engine coupled to an infinitely variable transmission, such as a hydrostatic transmission, can be designed to closely match the ideal power plant characteristics (Figure 5). However, infinitely variable transmissions are generally inefficient (Figure 6) and expensive.

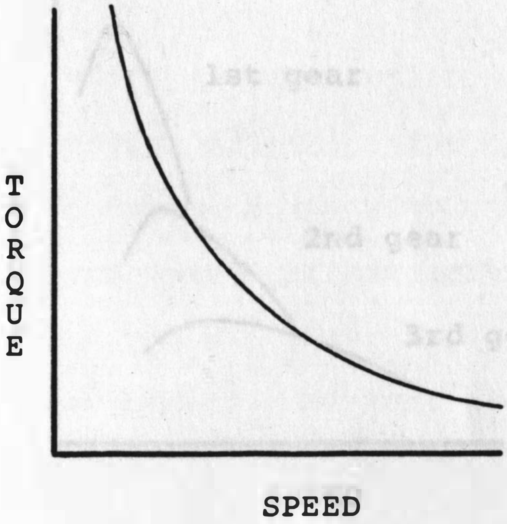


Figure 1. Ideal power characteristics for vehicle propulsion (Taborek, 1957).

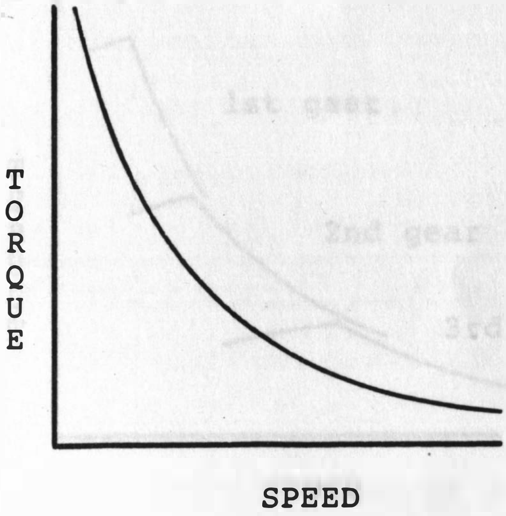


Figure 2. Torque-speed characteristics typical of a dc series motor (Richardson, 1980).

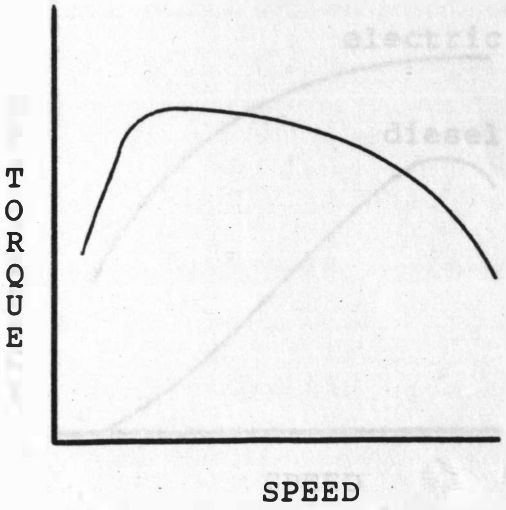


Figure 3. Torque-speed characteristics typical of an internal combustion engine (Wong, 1978).

Figure 4. Thrust characteristics typical of a vehicle driven by an internal combustion engine with a three-speed transmission (Wong, 1978).

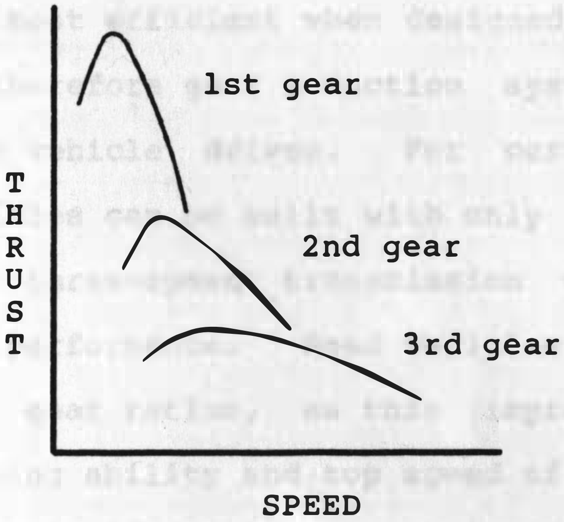


Figure 5. Thrust characteristics typical of a vehicle driven by an internal combustion engine and hydrostatic transmission (Hull, 1981).

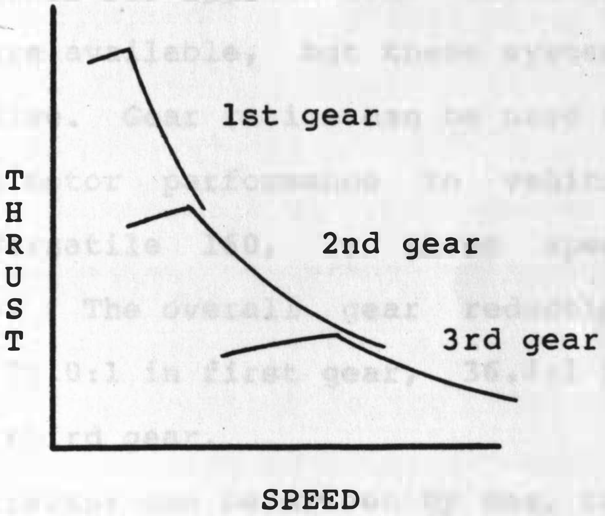
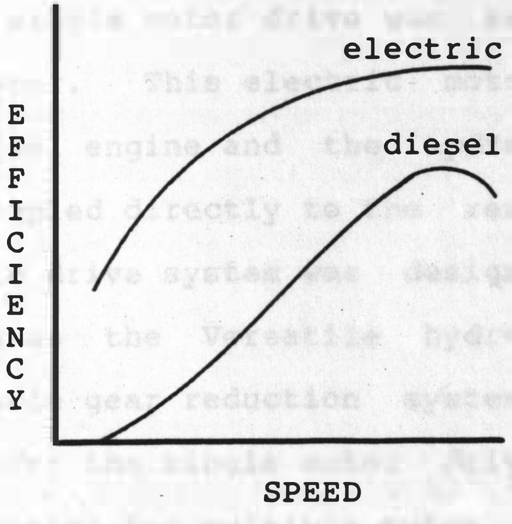


Figure 6. Comparison of efficiencies of a diesel / hydrostatic power train versus an electric power train (Christianson, et al., 1985).



Electric motors are most efficient when designed for high-speed applications, therefore gear reduction systems are necessary for electric vehicle drives. For certain applications electric vehicles can be built with only one gear ratio, but a two- or three-speed transmission will greatly enhance the vehicle performance. Road vehicles are generally built with several gear ratios, as this improves the acceleration, hill climbing ability and top speed of the vehicle. Motors and controls for applications involving single ratio transmissions are available, but these systems are large, heavy and expensive. Gear ratios can be used to more effectively match the motor performance to vehicle requirements. In the Versatile 160, a three speed transmission was available. The overall gear reduction ratios for the vehicle were 72.0:1 in first gear, 36.4:1 in second gear, and 17.67:1 in third gear.

A four-wheel drive tractor can be driven by one, two or four traction motors. A single motor drive was selected for the Electric Choremaster. This electric motor was designed to replace the diesel engine and the hydrostatic transmission, and then coupled directly to the remaining drive system. The electric drive system was designed to operate at the same speeds as the Versatile hydrostatic motor to utilize the available gear reduction system. The electronic control system for the single motor drive was simpler and less expensive than for multiple motor drives since two and four motor systems require complicated controls to coordinate motor operation. Also, the controller for the single motor drive was commercially available, but equivalent controls for multiple motor drives were not.

The ideal performance of the pto is to provide constant speed, according to throttle setting, for the full range of power. Electric motors are well-suited to constant-speed applications. The inherent characteristics of a dc shunt motor are nearly constant speed for the full range of output power, and controls can be built to provide constant speed from other types of electric motors. Additionally, electric motors can provide a wider range of constant-speed power outputs than can equivalent internal combustion engines.

The most important consideration in the design of the hydraulic system is the availability of power on demand. This is especially critical for applications such as power steering, where system response time directly affects operator safety. A wide selection of available hydraulic components allows many types of power sources to be used to drive the hydraulics package. Hydraulic system components can be matched to the power source characteristics to provide power on demand.

A system with one motor to operate both the pto and hydraulics was used for the prototype electric tractor. The preliminary design specified that two motor and control systems be used, one to drive the pto and one to drive the hydraulics. However, the higher cost of this design prompted a decision to combine the two systems. The pto was driven by the motor through the 4:1 gear reduction system of the original vehicle. The hydraulics system was powered from the motor by a high-torque belt drive system. A priority valve with load sensing was used to direct the hydraulic power to steering as first priority. This system was intended as the first step in the design process of the pto and hydraulics. The performance of this system was to be analyzed and modifications made to optimize system performance and cost.

<u>Power train component selection:</u>

Batteries:

The primary considerations for electric vehicle batteries are a high energy density, high power density, long life expectancy, and low cost per charge-discharge cycle. The batteries best able to meet these criteria are classified as "near-term" electric vehicle batteries (USDOE, 1981). Batteries are developed to where 30 to 40 Wh/kg and 1500 to 2000 cycle lives are practical from lead-acid batteries (Table 7).

Table 7. Battery developmental state (Vincent, 1984).

Battery type:	Specific Energy (Wh/kg)	Specific Power (W/kg)	Cycle Life
Lead-acid	30	80	2000
Advanced lead-acid	40	100	1500
Nickel-iron	40	100	1500
Advanced nickel-iron	60	110	1000
Nickel-zinc	60	90	250
Advanced nickel-zinc	80	120	500
Zinc-chlorine	80	120	1000

The most technologically proven and widely used battery for electric vehicles is the lead-acid battery. It is also the most economical in terms of cost per cycle of use. Other battery systems have exhibited better energy and power characteristics than those of the lead-acid systems, but reduced cycle life, charging difficulties, complexity and high cost have limited their use in electric vehicles. It is expected that at least one of these new systems may soon be competitive with lead-acid batteries, but the lead-acid battery presently represents the state-of-the-art in electric vehicle batteries (Collie, 1979).

A lead-acid battery pack similar to those commercially available for use in industrial lift trucks and mining vehicles was selected to provide power to the electric tractor prototype. This battery was chosen because it represents the most economical battery presently available, and would be the most likely choice for future manufacturing potential. The higher weight of the standard lead-acid battery pack was offset by its lower cost and longer lifetime, as compared to an advanced lead-acid battery pack. The nickel-iron and nickel-zinc batteries were not commercially proven, and therefore did not meet the design criteria for this project.

Motors and controls:

Electric vehicle motors are presently at an advanced state of development and show many characteristics desirable for vehicle propulsion. The wide range of commercially available motor characteristics offers a great deal of flexibility in vehicle design. After the power train requirements of a vehicle have been determined, the vehicle designer can choose the motor with characteristics best suited to the requirements. A review of electric vehicle motor characteristics (Appendix B) suggests that a dc series motor was the best choice for a traction motor.

A dc series motor was chosen for the drive of the Electric Choremaster because of the high torque it can provide for starting heavy loads and because the torque-speed characteristics of the series motor can approximate the ideal power curve. A dc series motor was also used to drive the pto and hydraulics system because the series motor can provide high torque for driving heavy pto loads at low speeds, and because controllers were technologically proven for only the series wound motor. Controllers for compound and separately excited motors were available, but these were relatively new, unproven and more expensive than the series motor controllers.

The most effective means of controlling dc motors is with a silicon-controlled rectifier (SCR) chopper (Secunde, et al., 1983). SCR controllers were used for both motors in the Electric Choremaster. These controllers operate by switching battery power on and off at a frequency high enough that the motor responds to the average value of the switched voltage. For instance, if the "on" time and "off" times are equal, the average voltage applied to the motor is about one-half battery voltage. By adjusting the ratio of "on" and "off" times, the average voltage applied to the motor can be varied from zero to near full battery voltage.

System voltage:

Three important factors to consider when selecting a vehicle voltage are safety, efficiency and cost. Typical battery voltages used for small electric vehicles are 36 volts and 48 volts, with higher voltages used for larger machines. Increasing voltage decreases the current draw for a given power output, which decreases the cost of wiring, the resistive energy losses, and the cost and size of motors and controllers. However, increasing the voltage also increases the manufacturing and maintenance costs for the battery, the probability of battery failure, the battery size and the potential hazard from electrical shock.

The National Safety Council (1969) has indicated that a 500-volt dc system will produce about the same biological effects as the commercial 115-volt, 60-Hz ac system. Both systems should be considered extremely dangerous. For identical conditions of body contact and grounding, a low-voltage dc system can be considered less dangerous than a high-voltage system. However, even a 50-volt dc system has the potential to cause a fatality and must be considered dangerous.

Forbes (1981) found that battery performance and cost were optimized for the lowest system voltage considered, 54 volts. However, with the low voltage, electrical losses were high, heavy cables were required for the high currents, and high-current components were necessary throughout the entire system. Forbes (1981) suggested increasing system voltage to around 100 volts. This provides a large improvement in electrical system performance with a relatively small increase in system cost. A commonly recommended voltage is 96 volts, as it is a convenient multiple of standard 6- and 12-volt battery modules, and is close to the suggested 100 volts.

System voltage for the Electric Choremaster was set at 128 volts. Initially, 72 volts was considered, but the advantages of lower cost, lower current flow, higher efficiency and better component availability prompted the decision to use a voltage over 100 volts. Industrial grade lead acid batteries were available in 2-volt cells, so there was no concern relative to maintaining 6- or 12-volt modules.

Component efficiencies:

Propulsion system efficiency has a direct effect on the battery requirements and operating range of an electric vehicle. With increased efficiency, vehicle range can be increased, or less battery is required for the desired performance and range. Predictions are that electric vehicle technology will advance dramatically before the end of the century, resulting in improved component performance and 67% better overall efficiency than presently available (Table 8).

Table 8. Efficiencies of electric vehicle propulsion system components (Christianson, et al., 1981).

	Current Technology	Advanced Technology
Charger	81%	90%
Battery (charging)	71%	82%
Battery (discharging)	71%	82%
Motor	90%	95%
Controller	90%	95%
OVERALL EFFICIENCY	33%	55%

The battery tends to be most efficient at light loads, whereas a motor is most efficient when it is operated near rated power. In electric vehicles, where the motor is powered from a battery, this tends to flatten the overall system efficiency curve. Most of the reduced efficiency of a battery operated at a high discharge rate takes the form of reduced voltage at the terminals rather than reduced ampere-hour capacity. The reduced voltage causes the motor to draw more current to compensate, which reduces the voltage still further and forces the current still higher. Since the energy losses in a motor are directly proportional to the square of the current, this can substantially reduce the efficiency of a system. (Buck and Hughes, 1981).

Power train sizing:

Two methods were used to size the power train components of the Electric Choremaster. Initially, power and energy requirements were estimated for the tasks listed in Table 6. Feed wagon operation and the towing of implements to and from the field were seen as the tasks requiring the highest power output, the first at low speed and high tractive effort, and the latter at high speed and low tractive effort. For these calculations the weight of the electric chore tractor was assumed to be 50 kN. Also, extreme values for the coefficient of rolling resistance were used to estimate the performance of the tractor in a worst-case scenario. Power requirements for the chore tractor were estimated with the following equations (ASAE, 1984):

Power, kW = (Rolling Resistance, kN)x(Speed, km/h)/3.6,

Rolling Resistance, kN =

(Weight, kN)x(Coefficient of Rolling Resistance).

Energy requirements of the tractor were calculated by:

Energy, kW-h = (Power, kW) x (Time of Operation, hours).

The power requirements of the feedlot operation were estimated assuming a loaded wagon weight of 80 kN, a forward speed of 5 km/h, and a coefficient of rolling resistance of 0.25.

Rolling Resistance = (50 kN + 80 kN) x (0.25) = 32.5 kN,

Power required = (32.5 kN) x (5 km/h) / 3.6 = 45 kW.

The power requirement for the travel to the field and back was estimated assuming an implement weight of 10 kN, a forward speed of 30 km/h, and a coefficient of rolling resistance of 0.05.

Rolling Resistance = (50 kN + 10 kN) x (0.05) = 5 kN,

Power required = (5 kN) x (30 km/h) / 3.6 = 42 kW.

The second method of power train sizing was by comparison with the hydrostatic power train of the Versatile 160. This power train was designed to match the ideal power source characteristics shown in Figure 7. This figure shows the inverse relationship between vehicle speed and tractive effort required to produce a constant drawbar power of 40 kW. The dc series motor drive was sized to closely match the ideal curve. The hydrostatic transmission (Figure 8) provided an excellent approximation of the ideal curve up to about 60 kN tractive effort. The electric drive (Figure 9) does not approximate the ideal curve as well as the hydrostatic, but it can provide approximately 67% more low-speed torque. This large torque "back-up", coupled with the added weight of the battery pack, could give an electric chore tractor an important advantage in traction and mobility over a conventional tractor.

The battery pack was sized to provide energy for one full day of light-duty work on a single charge. The design duty cycle was defined as three, 15-minute feeding trips with the feed wagon and 30 minutes of road travel, and resulted in an initial estimated requirement of 55 kW-h. However, the physical size of such a battery was more than could be accommodated on the prototype frame. Therefore, the requirements were re-estimated using only two feeding trips instead of three, and this provided an estimate of 43.5 kW-h. This estimate was deemed acceptable because the calculations represent a worst-case situation for the tractor in a muddy feedlot. More typical figures for the coefficient of rolling resistance are 0.12 for soft, sandy soils and 0.08 for firm soils (ASAE, 1984). These values would lower the power and energy requirements of the vehicle by approximately 50 to 70%. Therefore, under normal conditions the tractor would be capable of performing more than indicated by the battery-sizing duty cycle.

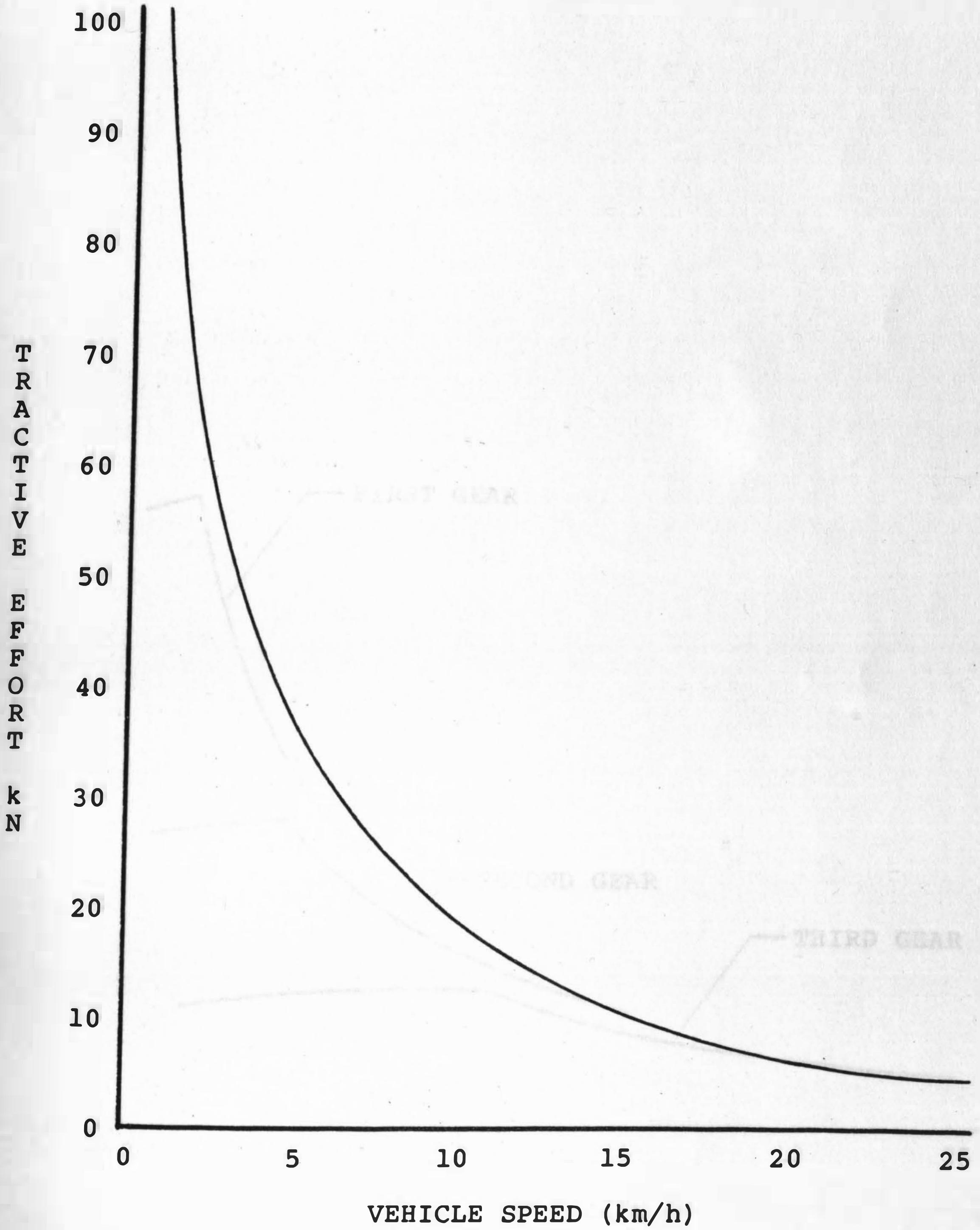


Figure 7. Ideal vehicle propulsion performance curve, 40 kW constant power.

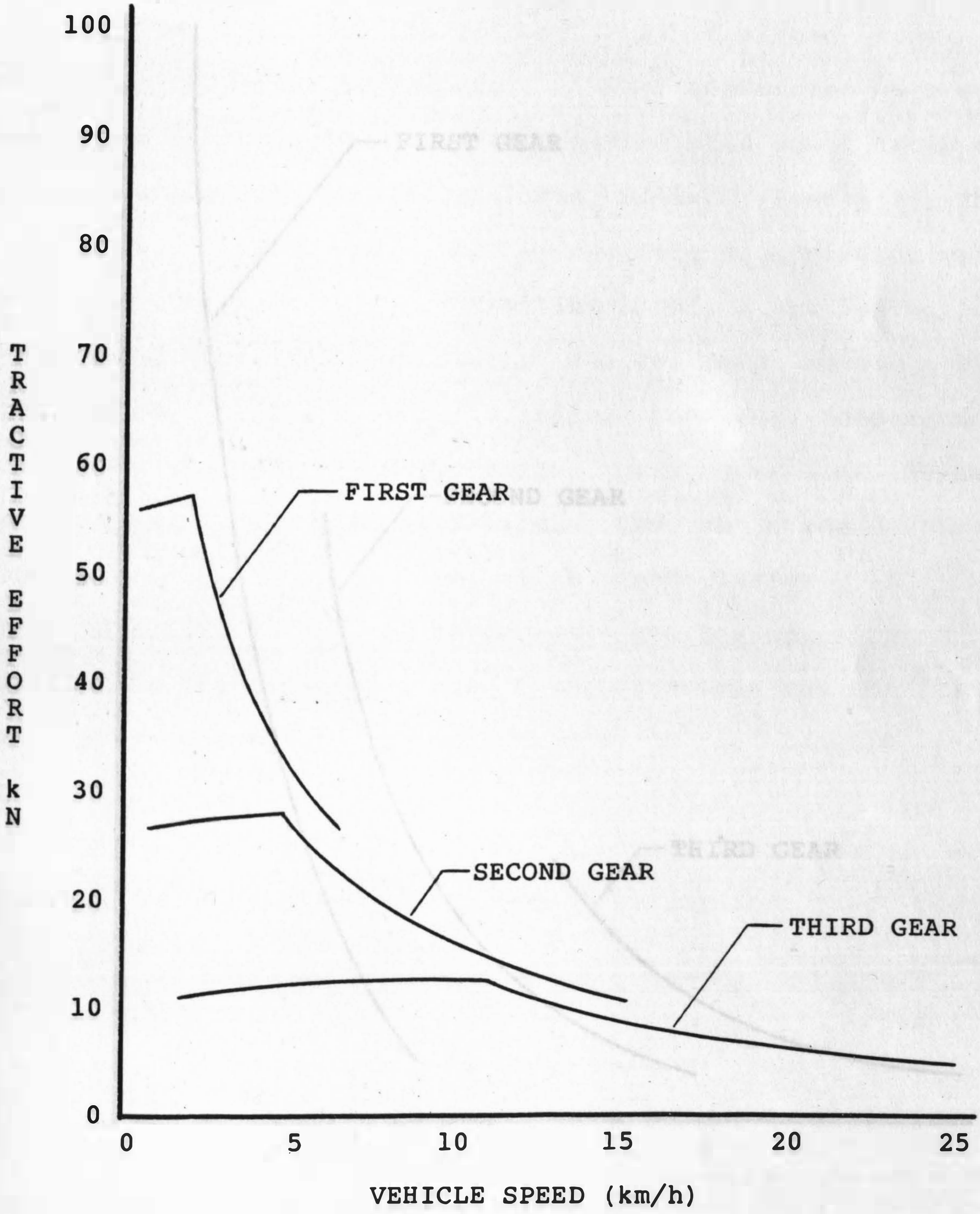


Figure 8. Versatile 160 diesel engine / hydrostatic transmission output characteristics.

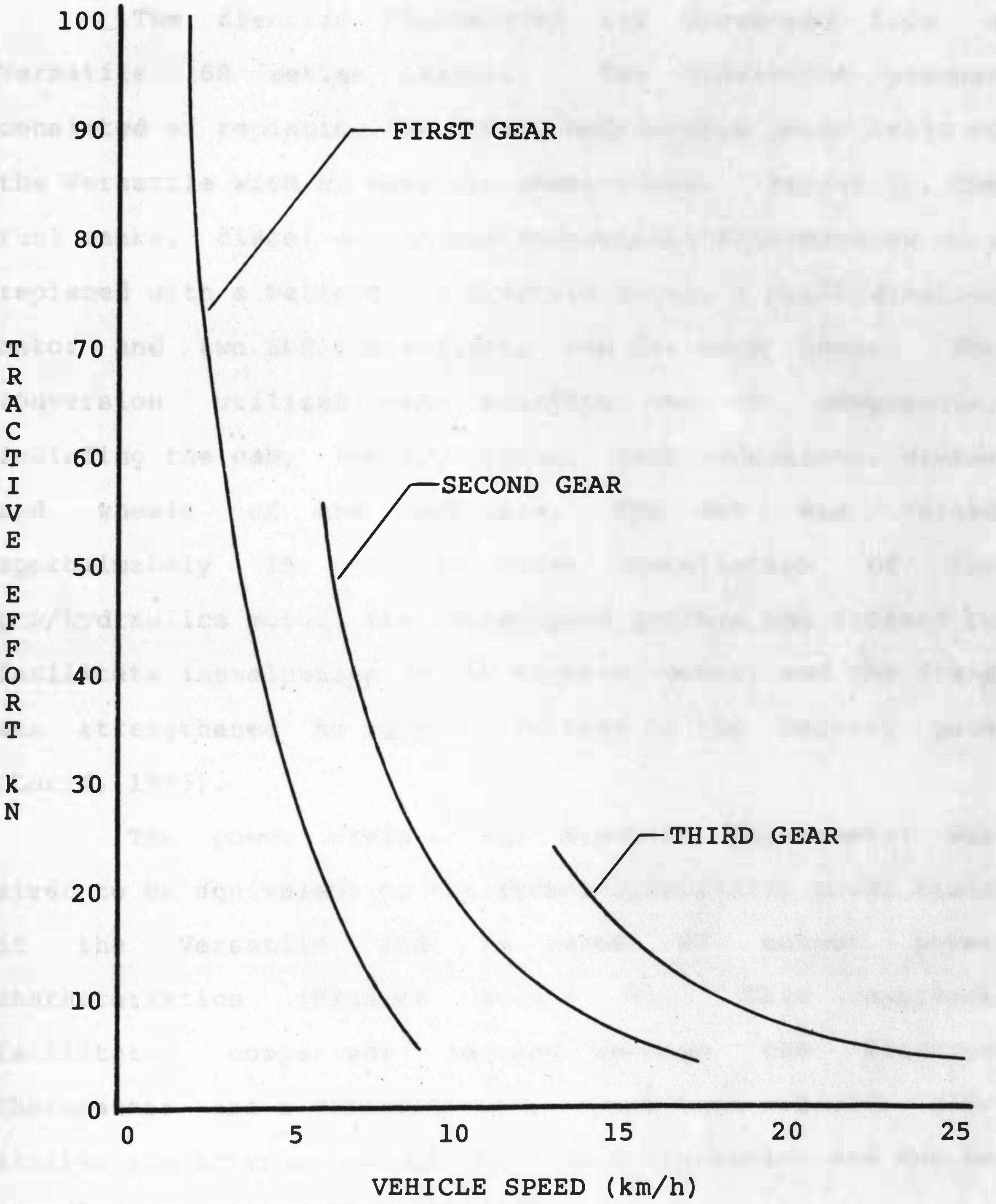


Figure 9. Electric Choremaster electric drive output characteristics.

Electric Choremaster configuration:

The Electric Choremaster was developed from a Versatile 160 series tractor. The conversion process consisted of replacing the diesel/hydrostatic power train of the Versatile with an electric power train. Basically, the fuel tanks, diesel engine and hydrostatic transmission were replaced with a battery, a traction motor, a pto/hydraulics motor and two SCR controllers, one for each motor. The conversion utilized many existing vehicle components, including the cab, loader, frame, gear reductions, brakes and wheels of the Versatile. The cab was raised approximately 15 cm to allow installation of the pto/hydraulics motor, the three-speed gearbox was rotated to facilitate installation of the traction motor, and the frame was strengthened to support the mass of the battery pack (Latif, 1985).

The power train of the Electric Choremaster was sized to be equivalent to the diesel/hydrostatic power train of the Versatile 160 in terms of output power characteristics (Figures 8 and 9). This approach facilitated comparison testing between the Electric Choremaster and a Versatile 160, since both vehicles have similar characteristics and short-term capacities and can be expected to perform the same tasks.

Industrial grade lead-acid batteries were used to power the Electric Choremaster. The pack consisted of two, 32-cell blocks, with a total nominal operating voltage of 128 volts. They provided a total battery capacity of 340 A-h at the six hour discharge rate, or 43.5 kW-h. The expected life of the battery pack was 1500 cycles, or approximately 4 years of daily usage. Each battery block was 0.89 m in length, 0.5 m in width, and 0.59 m in depth. The total battery mass was 1850 kg, and the effective energy density was approximately 24 Wh/kg. The battery pack was sized to provide energy for approximately four to six hours of light duty work on a single charge.

Battery charge level was measured by electrolyte specific gravity. The specific gravity in two pilot cells, one in each battery block, was observed on a daily basis, and the specific gravity of the electrolyte in all of the cells was measured once per month. The battery was recharged when the specific gravity indicated that the battery charge had been reduced to approximately 20% of its nominal rating. The batteries were recharged with a 220-volt, 50-amp, 60-Hz ac charger. This charger automatically tapered the charge rate as the battery neared full charge. Recharging could take up to ten hours, depending on the final discharge state of the battery prior to recharging.

Instrumentation and auxiliary power for the tractor was supplied by a 12-volt, deep-cycle lead-acid battery. This battery was completely separated from the main battery pack and serviced and charged independently. Normally this power would be supplied by a 128- to 12-volt converter, but the cost and complexity of these devices prevented their use on the electric tractor prototype.

The traction motor selected was a series-wound motor with a one-hour rating of 36 kW. Because the electric motor is rated according to its ability to dissipate heat, it can provide substantially more power for short periods of time (Figure 10). This electric motor has a five-minute rating of 71 kW, and a one-minute rating of 102 kW. Traction motor characteristic curves are shown in Figure 11 for comparison with the hydrostatic output curves shown in Figure 12.

The pto and hydraulic pump are driven by another series wound motor. This motor has a one-hour rating of 17.5 kW (Figure 13), and was chosen for the low-speed torque and power it can provide for starting heavy pto loads (Figure 14). Mechanical power is transmitted through a belt driven pulley to the hydraulics system, which is unchanged from that provided on the Versatile 160.

A 12-volt dc blower was connected to each motor to cool the motor which increases the length of time it can operate at a given load. These blowers were powered by the 12-volt auxiliary battery and can supply approximately 0.05 cubic meters per second of cooling air to the motors. Both motors used thermal switches to control winding temperatures. A normally-open switch closed when the motor temperature reached 60 degrees Celsius to turn on the blower. A normally-closed switch opened at 140 degrees Celsius to open the motor control circuit and stop motor operation, which prevents high temperature damage to the motor.

Two SCR controllers were used to regulate the speed of the two motors. These controllers regulate the average voltage supplied to the motors by a combination of frequency and pulse width modulation. The pto/hydraulic motor controller was separate from the traction motor controller, which provides the operator independent control of pto and vehicle speed.

The controller for the traction motor had the additional features of a reversing switch and a bypass contactor. The reversing switch allows stepless speed control in either direction and provides for "plugged" braking of the vehicle. The bypass contactor is used to provide maximum power after the SCR controller has reached 100 percent of its capacity. The bypass contactor is automatically operated and can improve efficiency and total power output by eliminating the inherent inefficiency associated with providing power through the SCR.

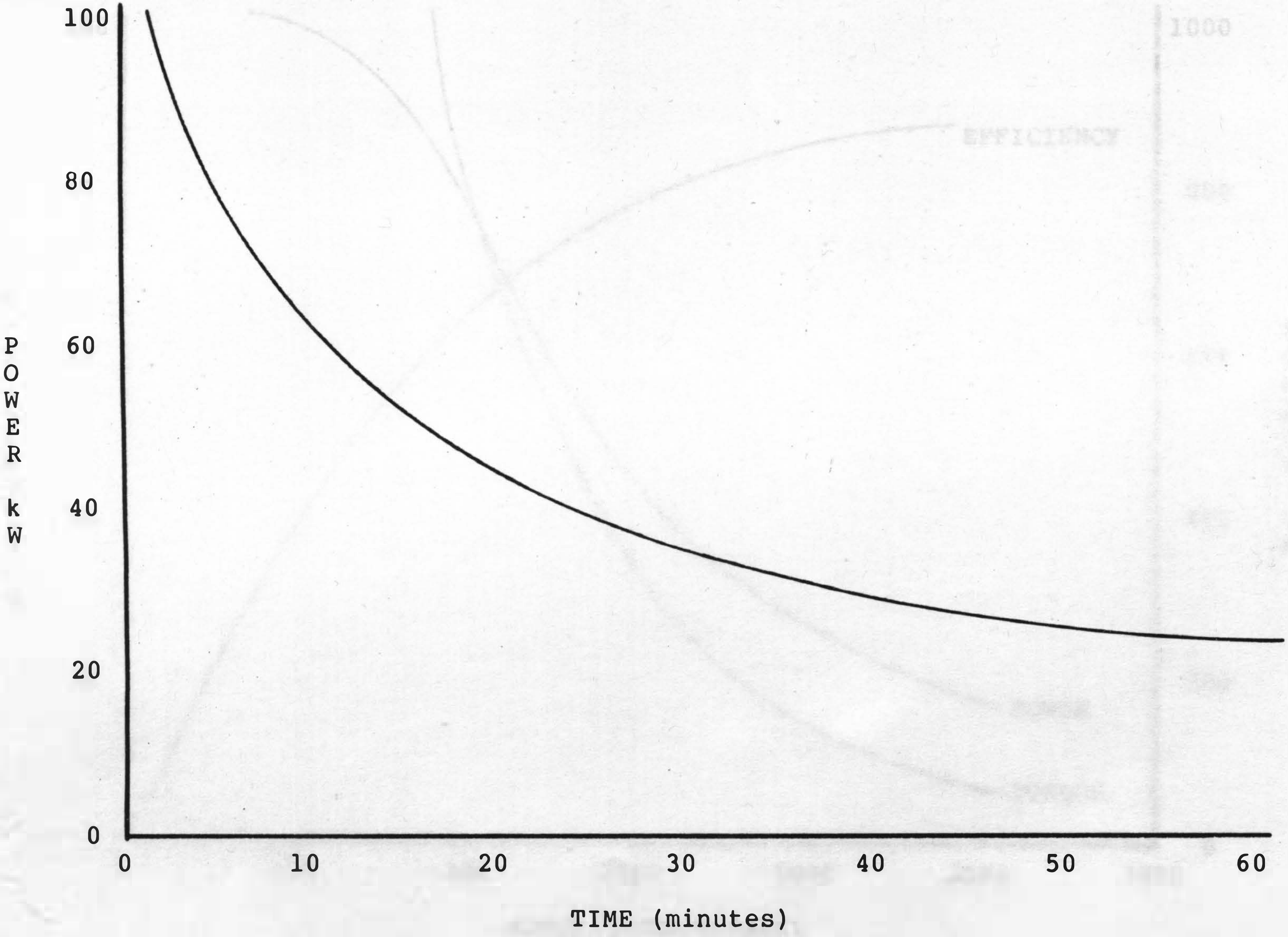


Figure 10: Thermal rating of Electric Choremaster traction motor.

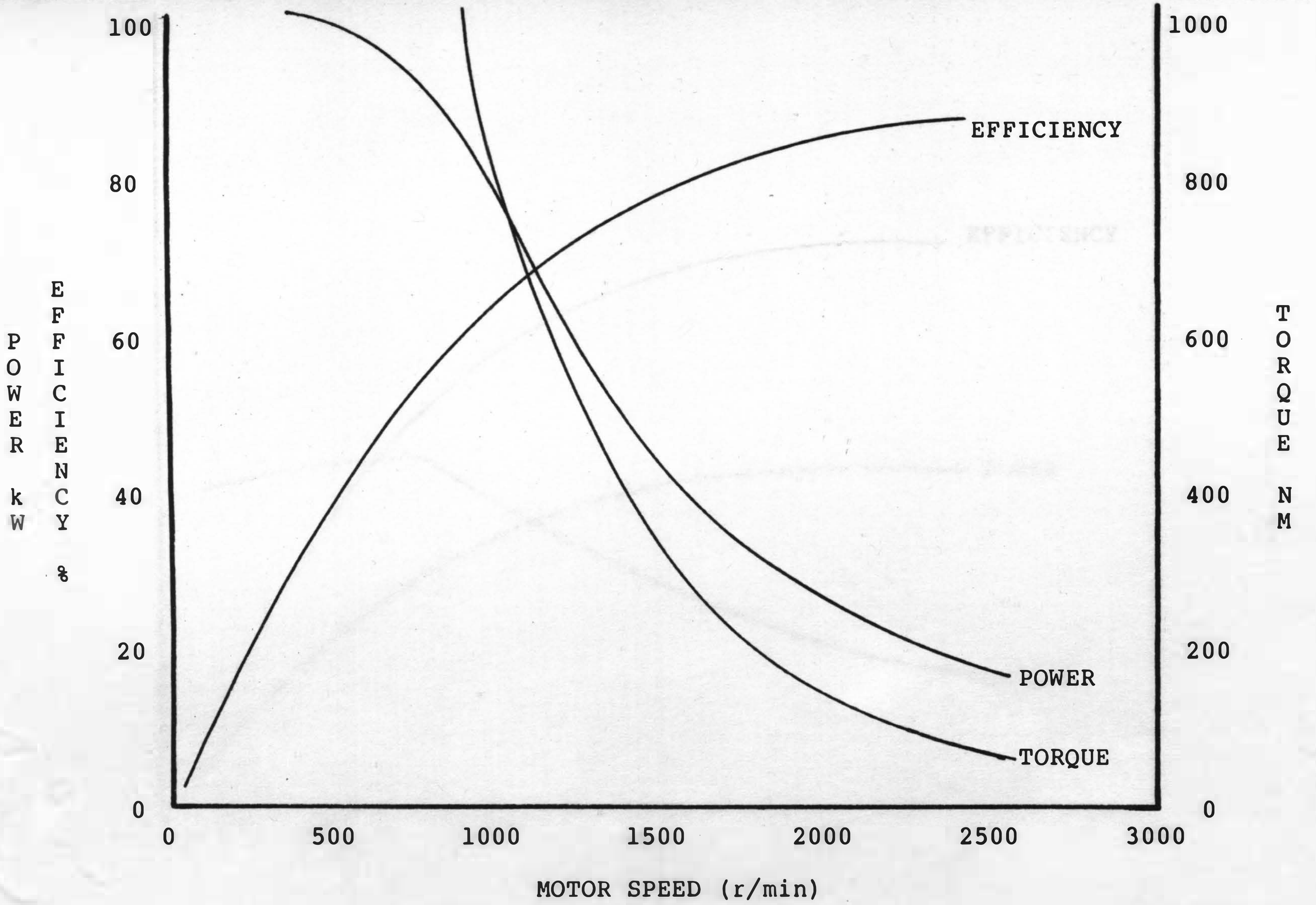


Figure 11: Electric Choremaster traction motor output characteristics.

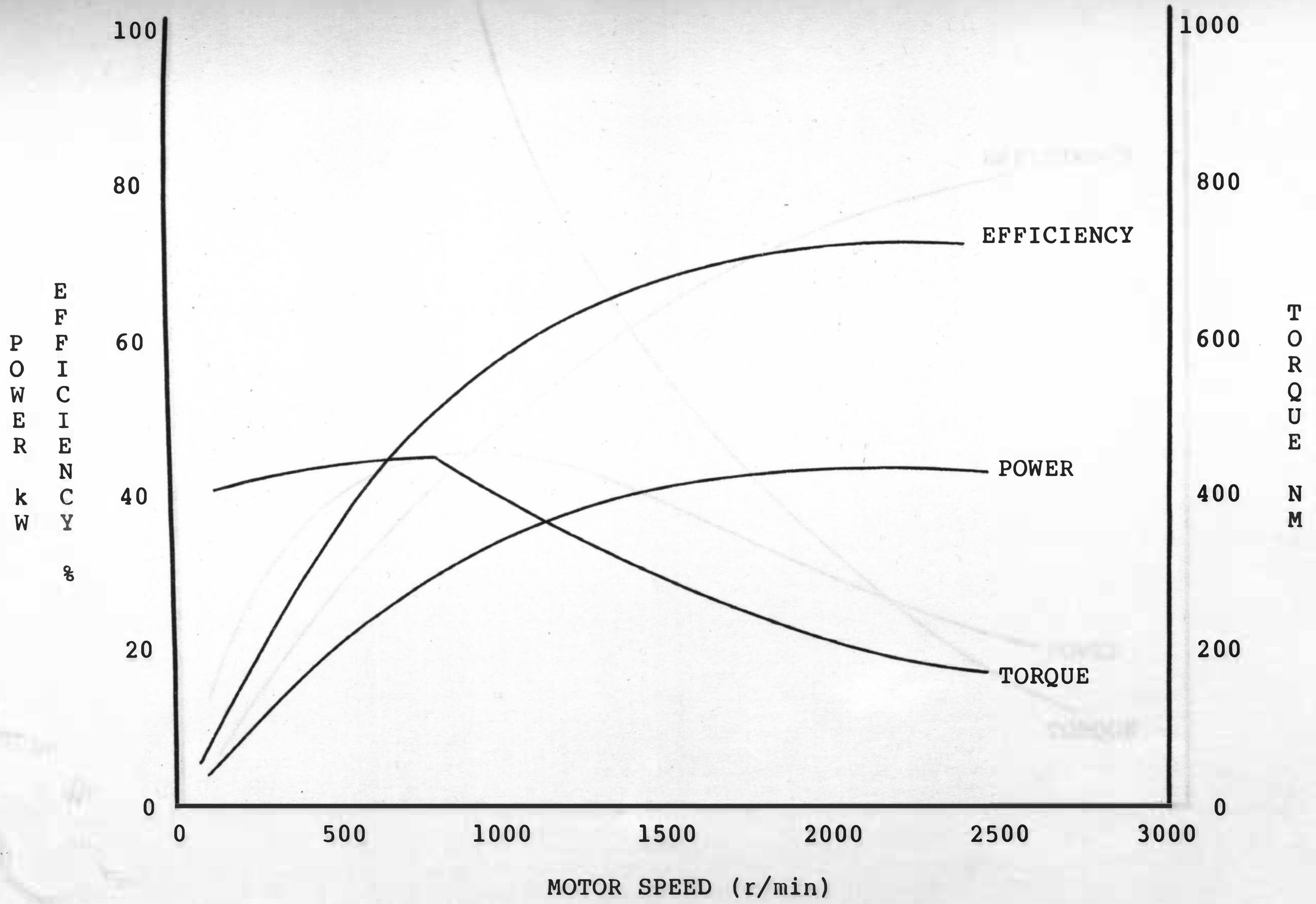


Figure 12: Versatile 160 hydrostatic drive motor output characteristics.

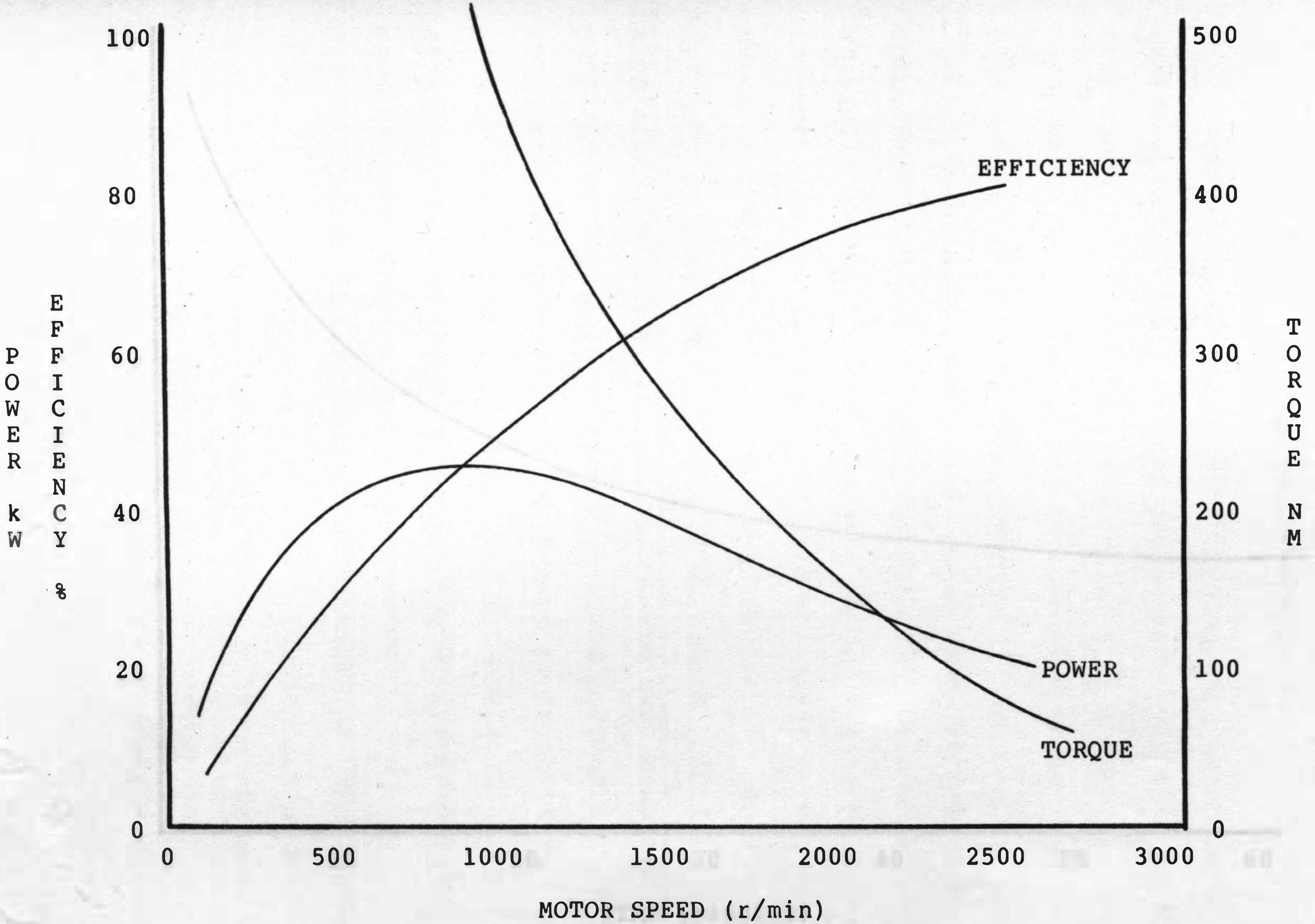


Figure 13: Electric Choremaster pto/hydraulics motor output characteristics.

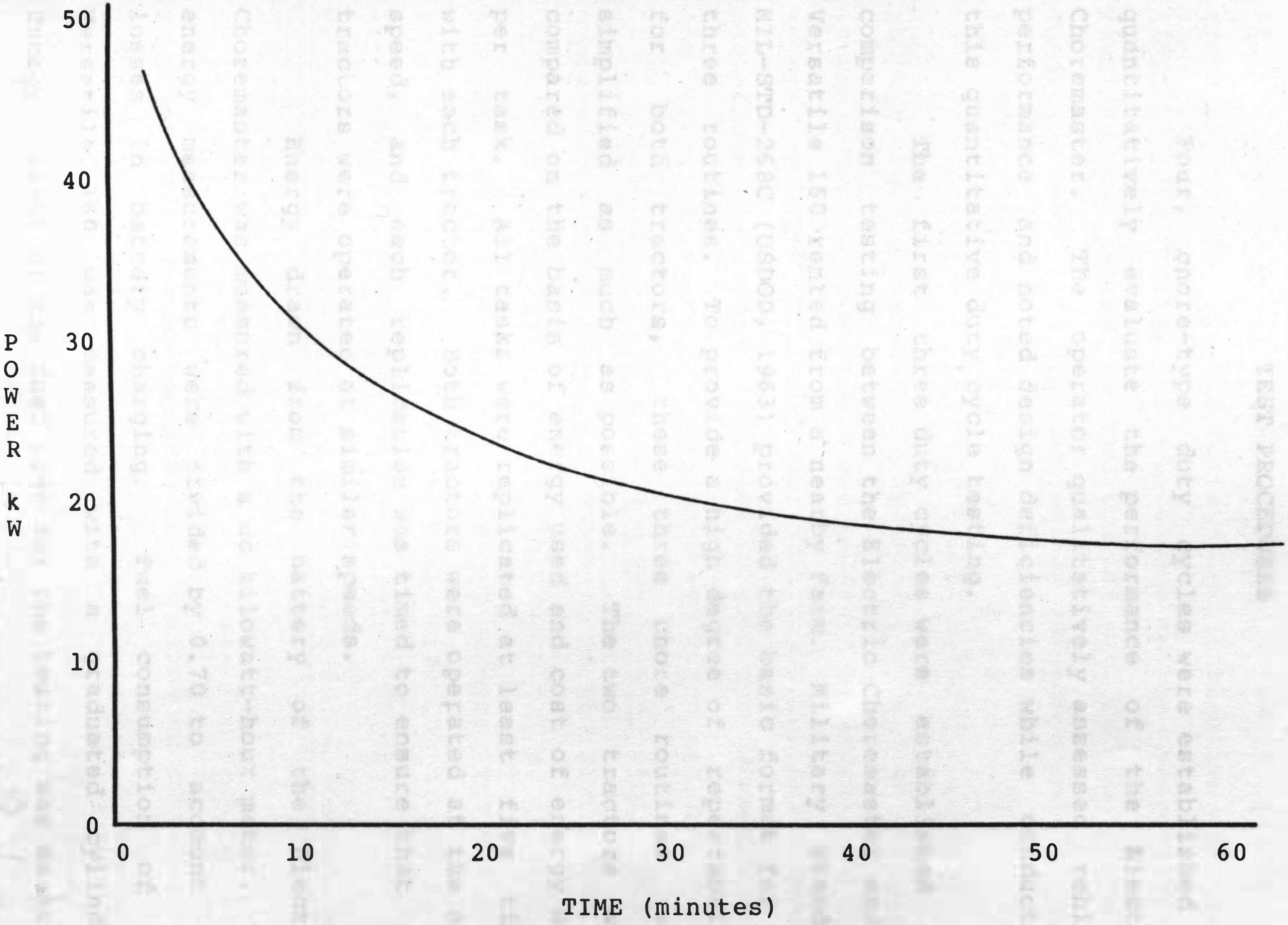


Figure 14: Thermal rating of Electric Choremaster pto/hydraulics motor.

TEST PROCEDURES

Four, chore-type duty cycles were established to quantitatively evaluate the performance of the Electric Choremaster. The operator qualitatively assessed vehicle performance and noted design deficiencies while conducting this quantitative duty cycle testing.

The first three duty cycles were established for comparison testing between the Electric Choremaster and a Versatile 160 rented from a nearby farm. Military Standard MIL-STD-268C (USDOD, 1963) provided the basic format for the three routines. To provide a high degree of repeatability for both tractors, these three chore routines were simplified as much as possible. The two tractors were compared on the basis of energy used and cost of energy used per task. All tasks were replicated at least five times with each tractor. Both tractors were operated at the same speed, and each replication was timed to ensure that the tractors were operated at similar speeds.

Energy drawn from the battery of the Electric Choremaster was measured with a dc kilowatt-hour meter. The energy measurements were divided by 0.70 to account for losses in battery charging. Fuel consumption of the Versatile 160 was measured with a graduated cylinder. Energy content of the fuel used for the testing was measured using a bomb calorimeter, and the energy content was found to be approximately 45,250 kJ / kg, which is within the range specified by the Society of Automotive Engineers (1985). The output of the engine on the Versatile was measured to ensure that the tractor was in good running condition and that its performance was comparable to that reported by the manufacturer.

The first duty cycle was a loader-use routine for which a steel plate weighing approximately 7.8 kN was placed in the loader. The weight was raised to a height of three meters and then lowered, ten times per routine. Several engine speeds, ranging from 1200 to 2000 rpm, were tried for the Versatile 160 to find the most efficient setting.

The second chore routine was a stop-start driving cycle with the 7.8 kN weight remaining in the loader and the loader height fixed. Both tractors were driven through an 800 meter course with four stop/start points, two obstacles to steer between, a segment of grade with 10% slope, and a short segment of very rough terrain (Figure 15). The terrain and manuvering restricted top speed to second gear for both tractors.

The third routine was a light hauling task in which a 100-bushel grain wagon loaded with 2540 kg of corn was pulled around a 1200-meter roadway. Various road surfaces, slopes and turns were included (Figure 16). This task was performed in third gear at full power train loading, and

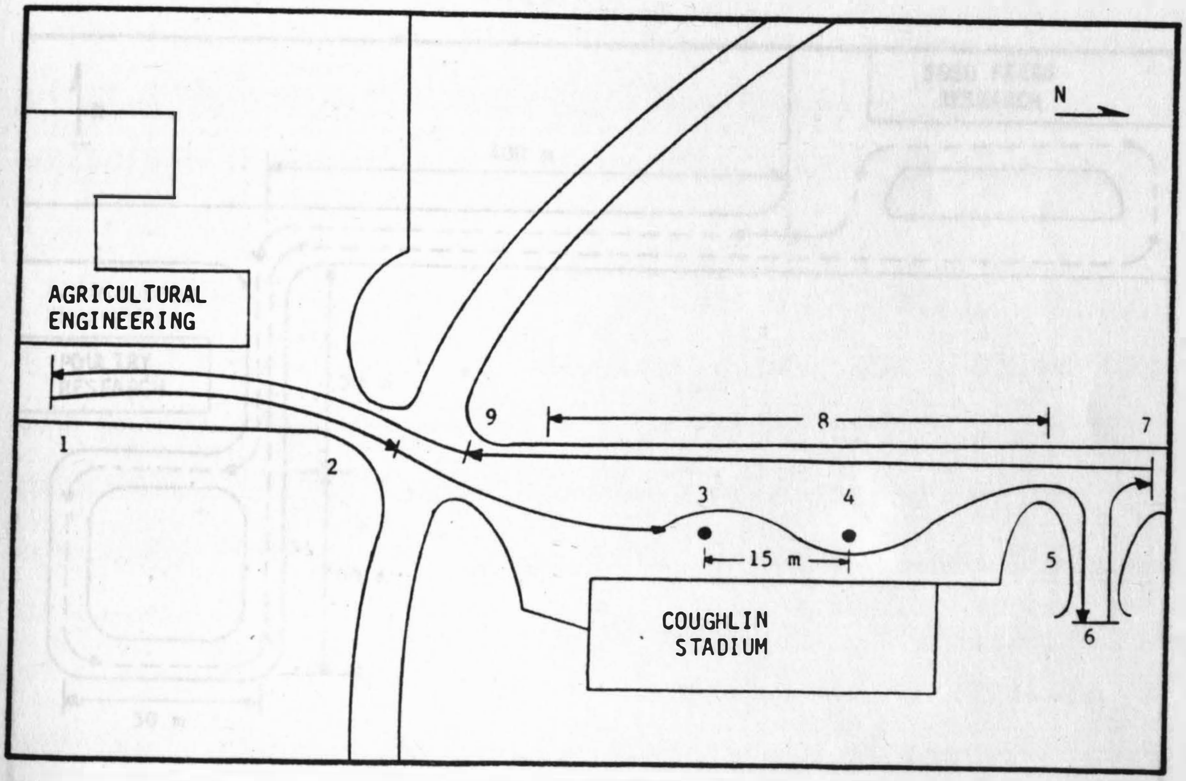


Figure 15. Stop-start driving duty cycle.

1. Start and end point.
2. First stop.
3. First obstacle.
4. Second obstacle.
5. Ten meter incline, 10% slope.
6. Stop and reverse.
7. Stop and proceed forward.
8. Approximately 100 m rough gravel road.
9. Fourth stop.

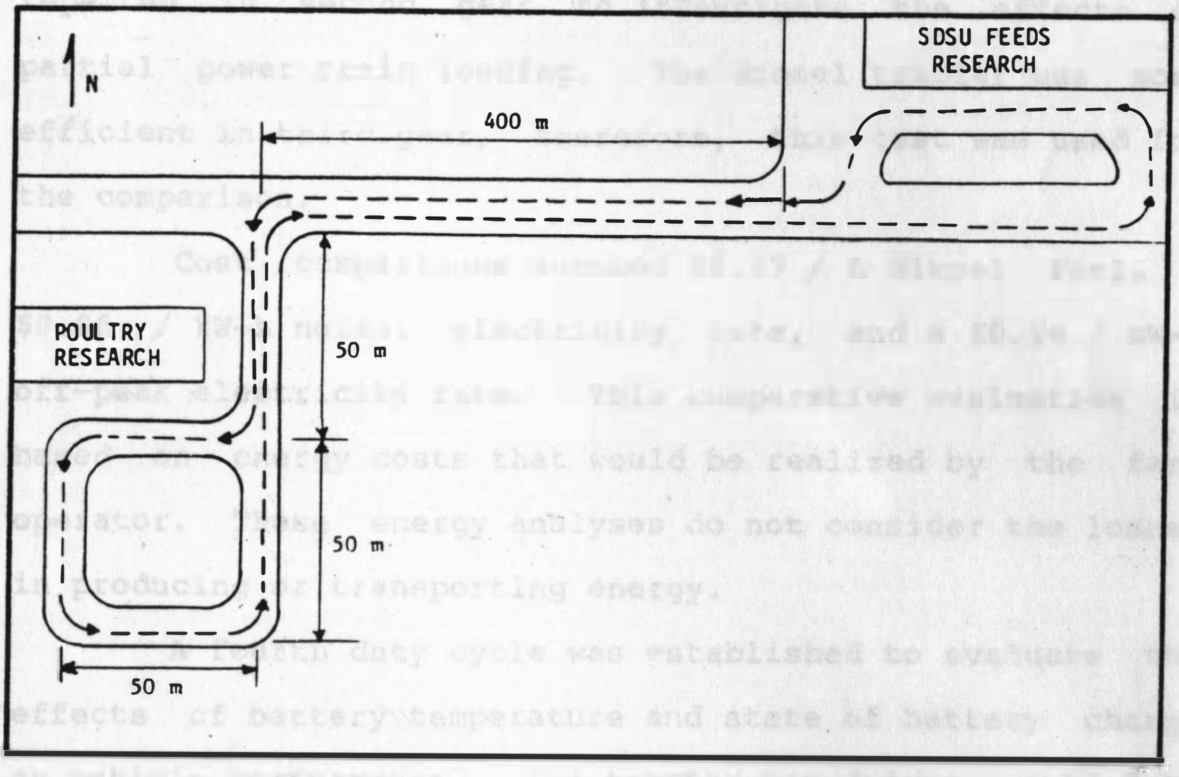


Figure 16. Grain hauling duty cycle.

repeated in second gear to investigate the effects of partial power train loading. The diesel tractor was most efficient in third gear, therefore, this test was used for the comparison.

Cost comparisons assumed $0.37 / L diesel fuel, a $0.06 / kW-h normal electricity rate, and a $0.04 / kW-h off-peak electricity rate. This comparative evaluation is based on energy costs that would be realized by the farm operator. These energy analyses do not consider the losses in producing or transporting energy.

A fourth duty cycle was established to evaluate the effects of battery temperature and state of battery charge on vehicle performance. The tractor was driven around 5 km of paved roadway once a day through two charge-discharge cycles. The data recorded included: initial battery temperature and electrolyte specific gravity, energy drawn from the battery, and time taken to complete the 5-km course. Specific gravity of the battery electrolyte was used to determine the level of charge in the battery. Through the first charge cycle, the tractor was parked inside a building maintained at a temperature of about 20 degrees Celsius. For the second charge cycle, the tractor was left outside, and the initial battery temperature for this cycle ranged from -3 to 10 degrees Celsius. Multiple regression analysis-of-variance was used to statistically evaluate the effects of battery temperature and charge level on the time taken to complete the duty cycle and on the percentage of battery capacity used to complete the cycle.

RESULTS AND DISCUSSION

Quantitative duty cycle results:

The Electric Choremaster used 57 to 76 % less energy and demonstrated 13 to 67 % lower on-farm energy costs than the Versatile 160 in the comparison testing (Table 9 and Table 10). These results were compared statistically using the Student's t-test, and were found to be significantly different at the 0.01 probability level. Five replications were performed, and the complete data are listed in Appendix A.

Table 9. Electric Choremaster versus Versatile 160 diesel, energy use comparisons.

Task	Mean Energy Use Per Replication		On-Farm Energy Savings
	Diesel	Electric	
Loader-Use Routine	4.79 MJ	2.05 MJ	57%
Stop-Start Driving Cycle	14.13 MJ	3.38 MJ	76%
Grain Hauling Routine	16.50 MJ	6.75 MJ	59%

Table 10. Electric Choremaster versus Versatile 160 diesel, energy cost comparisons.

Task	Mean Energy Cost Per Replication Diesel	Electric Normal Rate	Electric Off-Peak	On-Farm Cost Savings
Loader-Use Routine	$.0390	$.0341	$.0227	13-42%
Stop-Start Driving Cycle	$.1151	$.0564	$.0376	51-67%
Grain Hauling Routine	$.1344	$.1125	$.0750	16-44%

In the loader use and grain hauling test cycles the diesel tractor was operated at the highest efficiency practical by gear selection and by adjusting the throttle setting. The savings provided by the electric tractor are similar in these tasks, suggesting that the diesel tractor efficiency was also similar. In the stop-start duty cycle the throttle setting and gear choice were essentially dictated by the test course. The operator could not be expected to shift gears alternately between high torque and low torque situations over a duty cycle lasting approximately 3 to 4 minutes in typical farm operations. Highest savings for the electric tractor relative to the diesel are reported for the stop-start cycle, indicating that the efficiency of the diesel tractor was considerably lower than in the other two cycles. The results from the stop-start cycle may provide a better estimate of the savings provided by an electric tractor, because in actual farm work the diesel tractor will not always be operated within the narrow speed band where top efficiency is achieved.

The grain hauling test cycle was performed in second and third gear with both tractors. The diesel tractor was most efficient in third gear, therefore, this was the test used for the energy and cost comparison. In second gear the efficiency of the diesel tractor was considerably lower, as indicated by a 45% increase in energy use (Table 11). However, the change in electric tractor energy use between second and third gear was less than 1%. This indicates that the level of power train loading affected the performance of the diesel tractor, but was negligible for the electric vehicle. The implication is that the electric tractor has a relatively high efficiency over a wider operating range, when compared to the diesel unit, as initially suggested in Figure 6.

Table 11. Effects of power train loading level on energy use of Electric Choremaster versus Versatile 160 diesel.

	Mean Energy Use per Replication		
	Second Gear	Third Gear	Percent Change
Diesel	23.93 MJ	16.59 MJ	45%
Electric	6.78 MJ	6.75 MJ	0.4%

The analysis-of-variance performed on the data collected in the fourth duty cycle (the battery performance evaluation cycle) shows that as battery electrolyte temperature decreased, the time required and the percentage of battery capacity used to complete the duty cycle increased significantly at the 0.01 probability level. These results demonstrate that for cold weather operation improved performance can be expected by protecting the vehicle from cold temperatures. However, it is not known whether this improvement was due to a higher battery discharge efficiency or to lower drive train losses at warmer temperatures. More detailed tests are needed to determine the effects of cold temperature on individual power train components.

This test also showed that as battery charge level was reduced, neither the time required nor the percentage of battery capacity used to complete the duty cycle increased significantly at the 0.05 probability level. However, the time required to complete the duty cycle did increase as charge level was reduced (significant at the 0.06 probability level). These results show that as battery charge level decreases, vehicle speed also decreases but the amount of battery energy required for a particular task does not change. The results of the analysis-of-variance are summarized in Appendix A.

Qualitative observations:

During the testing process, the Electric Choremaster proved effective at performing the specified duty cycles, and battery capacity was not a limitation for these tests. Operating time per battery charge was the principal limitation expected for using electric vehicles in agriculture. Four design deficiencies were noted, which pertain uniquely to this prototype and are not necessarily indicative of electric vehicle capabilities.

The first problem was the high center-of-gravity of the vehicle. This resulted from placing the battery pack 25 cm above the vehicle axles, which raised the center-of-gravity approximately 13 cm from that of the original vehicle (Latif, 1985). Battery mass could be used as an advantage for stability and traction if properly located. Therefore, for future developments it is proposed that the battery mass be placed as near to the ground as possible without excessively restricting the vehicle ground clearance.

The second problem was caused by using the series-wound motor to power the hydraulics. Electric motor speed decreased and increased dramatically in response to changing hydraulic system demand. When hydraulic and pto power were not needed, the operator would reduce the power available to the SCR to limit the motor speed. Then, when hydraulic power was needed for steering, the SCR control lever had to be adjusted so that steering could be accomplished efficiently and safely. This problem has been countered by installing a feedback system to maintain a set motor speed (Helder, 1985).

The third problem resulted from driving the pto and hydraulic systems from the same motor. Operator control is needed for the pto, but the hydraulic system requires power availability on demand. The recommended modification for this would be to separate the two systems and install a third motor to provide power for the hydraulic pump. This motor could be controlled with a hydraulic pressure sensing system to provide hydraulic power on demand.

The fourth problem noted was the coasting effect encountered, when traveling with the control lever left in the neutral position. In order to stop the tractor the operator must either reverse the traction motor to provide plugged braking or use the transmission brake. Operating experience has shown that coasting is an undesirable and potentially dangerous feature, but that the operator can learn to compensate by careful control adjustments. Further work is needed to develop controls which limit unwanted coasting.

One further observation stemming from experience with this vehicle is a concern for safety with the electrical components. Despite the precautions taken by the design group, inadvertant contact with high voltage components did occur. Although none of these incidents were serious, the potential for serious injury was present. Safety and liability must be important considerations for any future development of an electric vehicle for the agricultural market.

CONCLUSIONS

A battery-powered tractor suitable for agricultural chore and utility routines has been constructed and is currently under evaluation. This vehicle was converted from a conventional Versatile 160 tractor using technologically proven and commercially available components. Four simplified steps used in the design process for this vehicle were: 1) define the requirements of an agricultural electric vehicle, 2) specify general frame, drive and steering options, 3) size and select power train components, and 4) integrate power train components into a prototype frame.

The Electric Choremaster is a four-wheel drive, articulation-steered vehicle with a reversible operator console. A 36-kW rated dc series motor drives the Electric Choremaster, and energy is supplied by a 64-cell, 128-volt industrial lead-acid battery pack sized to provide 43.5 kW-h of energy. The power train of the Electric Choremaster was designed to closely match the hydrostatic power train output of the Versatile 160 in terms of tractive effort and speed.

The first phase of vehicle testing has been completed. Comparison tests between the Electric Choremaster and a Versatile 160 documented that the electric vehicle used significantly less energy and had lower on-farm energy costs than the diesel unit. The Electric Choremaster required 57 to 59% less energy and cost 13 to 16% less to operate compared to the diesel, for the tasks in which the diesel tractor performance was optimized, assuming diesel costs $0.37 / L and electricity $0.06 / kW-h. The energy and cost savings were 76% and 51%, respectively, for the task in which the load was not well-matched to the power available from the tractors. The electric vehicle was shown to have higher efficiencies over a wider range of speeds and torques as compared to the diesel tractor. Four design deficiencies of the Electric Choremaster were noted and suggestions were made to correct these.

Battery performance testing showed that as battery temperature decreased, the time required and the amount of energy used to complete a specified task increased significantly. As battery charge level decreased, the time required to perform the task increased and the amount of energy used did not change significantly.

REFERENCES

REFERENCES

Alcock, R. 1983. Battery powered vehicles for field work. Transactions of the ASAE 26(1):10-13.

Alcock, R. 1985. A battery powered tractor. Accepted for publication in: The Agricultural Engineer 40(2). The Institution of Agricultural Engineers, Silsoe, England.

ASAE. 1984. Agricultural Machinery Management Data. ASAE D 230.3. American Society of Agricultural Engineers Yearbook. ASAE, St. Joseph, Michigan.

Berg, M.R., M.J. Converse and D.H. Hill. 1984. Electric vehicles in commercial sector applications. Electric Power Research Institute project 1569-3. Institute for Social Research. The University of Michigan.

Buck, N.L. and H.A. Hughes. 1981. Final report: the feasibility of electric farm vehicles. Agricultural Engineering Dept. Virginia Polytechnic Institute and State University, Blacksburg, Virginia.

Calkins, P.H., B.A. Quasmir, N.L. Buck, L.L. Christianson and R. Alcock. 1981. The economic feasibility of electric vehicles on U.S. farms. ASAE Paper No. 81-1549. ASAE, St. Joseph, Michigan.

Carlson, B.A. and D.G. Gisser. 1981. Electrical engineering concepts and applications. Addison-Wesley Publishing Co. Reading, Massachusetts.

Caterpillar Tractor Co. 1984. Sales literature Nos. CECB0104 and CEGD0018. Caterpillar Tractor Co. Peoria, Illinois.

Christianson, L.L. 1980. Minutes of the electric vehicles principal investigators meeting. October 1, 1980. Radison Muehlbach Hotel. Kansas City, Missouri.

Christianson, L.L., M.M. Resen and T. Chisolm. 1981. Electric vehicles for U.S. agriculture - assessment of potential. Procedings of the EV Expo 81, EVC Paper No. 8125, Electric Vehicle Development Council Washington, D.C.

Christianson, L.L., R. Alcock, G. Jahns and K.L. Seshasai. 1985. Electric vehicles in agriculture. Vol. V, Ch. XI, Energy in Agriculture Handbook. Farm Electrification and Electricity Use Sysems (in editing).

Cole, G.H. and L.S. Gerlach. 1983. USPS state-of-art electric delivery vehicles. Procedings of the EV Expo 83, EVC Paper No. 8314, Electric Vehicle Development Council, Washington, D.C.

Collie, M.J. (ed.) 1979. Electric and hybrid vehicles. Noyes Data Corporation, Park Ridge, New Jersey.

Edie, P.C. 1981. Straight and chopped performance data for a General Electric 5BT 2366C10 motor and an EV-1 controller. DOE/NASA/0123-1. Eaton Corporation, Southfield, Michigan.

Elamin, M.A. 1981. A comparative evaluation of electric and gasoline powered garden tractors. Unpublished M.S. Thesis, Iowa State University, Ames, Iowa.

Forbes, F.E. 1980. Advanced electric propulsion system concept for electric vehicles. National Aeronautics and Space Administration, Washington, D.C.

Gervasio, V., P. Verrechia, R. Carli and P. Piccarolo. 1984. Prototype battery powered electric tractor. Unpublished report, TEMA, Italy.

Helder, D. 1985. Control and instrumentation of an electric farm tractor. Unpublished M.S. Thesis, South Dakota State University, Brookings, South Dakota.

Hull, W.E. 1981. Transmissions to meet agricultures energy challenge today. ASAE Paper No. 81-1053. ASAE, St. Joseph, Michigan.

Ihrig, H.K. 1960. An electric powered tractor. Agricultural Engineering, 4:232-233, 240.

Latif, M.N. 1985. Vehicle configuration design for a battery-powered chore tractor including human factors consideration. Unpublished M.S. Thesis, South Dakota State University, Brookings, South Dakota.

National Safety Council. 1969. Accident prevention manual for industrial operations, eighth edition. National Safety Council, Chicago, Illinois.

Obert, M.J. 1972. Electric farm vehicles - are they feasible? Agricultural Engineering 8:26,27.

Parker, B.F. and B.L. Clary. 1980. Agricultural energy. Selected papers from the 1980 ASAE National Energy Symposium, Vol. 1 preface, ASAE, St. Joseph, Mich.

Resen, M.M. 1981. Electric vehicle feasibility for farms in eastern South Dakota. Unpublished M.S. Thesis, South Dakota State University, Brookings, South Dakota.

Resen, M.M., P. Calkins and L.L. Christianson. 1981. Electric vehicles - assessment of potential for North Central region farm operations. ASAE Paper No. 81-1547. ASAE, St. Joseph, Missouri.

Richardson, D.V. 1980. Handbook of rotating electric machinery. Reston Publishing Co., Reston, Virginia.

Secunde, R.R., R.M. Schuh and R.F. Beach. 1983. Electric vehicle propulsion alternatives. National Aeronautics and Space Administration, Lewis Research Center, Cleveland, Ohio.

Shacket, S.R. 1979. The complete book of electric vehicles. Domus Books, Chicago, Illinois.

SAE. 1985. Standard SAE J313 - Diesel fuels. SAE Handbook 3:23.41. Society of Automotive Engineers, Inc. Warrendale, Pennsylvania.

Taborek, J.J. 1957. Powerplant characteristics. Ch. 13, Mechanics of vehicles. Penton Publishing, Cleveland, Ohio.

Turrel, J.D. 1969. Battery powered tractor developed for suburban and farm needs. Electrical World, May 19, 1969.

USDOD. 1963. Test and inspection of trucks, lift, fork. Military Standard MIL-STD-268C. Department of Defense, Washington, D.C.

USDOE. 1981. Fourth annual report to Congress of electric and hybrid vehicle program. DOE/CS-0/30/4. Department of Energy, Washington, D.C.

USDOE. 1982. Fifth annual report to Congress of electric and hybrid vehicle program. DOE/CE-0028. Department of Energy, Washington, D.C.

USDOE. 1983. Sixth annual report to Congress of electric and hybrid vehicle program. DOE/CE-0028/1. Department of Energy, Washington, D.C.

Vincent, C.A. 1984. Modern batteries - an introduction to electrochemical power sources. Edward Arnold Publishing, Baltimore, Maryland.

Wong, J.Y. 1978. Theory of ground vehicles. John Wiley and sons, New York, New York.

APPENDICES

APPENDIX A:

Test Data

Table 12. Electric Choremaster versus Versatile 160 diesel, data taken in comparison testing for task no. 1, loader use routine.

Versatile 160:

Replication	Fuel Used	Time
1	120 mL	2' 45"
2	125 mL	2' 36"
3	120 mL	2' 41"
4	125 mL	2' 34"
5	125 mL	2' 38"
mean	123 mL	2' 39"
s.d.	2.74	

Electric Choremaster:

Replication	Energy Used	Time
1	0.40 kW-h	2' 32"
2	0.39 kW-h	2' 28"
3	0.41 kW-h	2' 30"
4	0.40 kW-h	2' 26"
5	0.39 kW-h	2' 25"
mean	0.398 kW-h	2' 28"
s.d.	.00837	

Table 13. Electric Choremaster versus Versatile 160 diesel, data taken in comparison testing for task no. 2, stop-start driving cycle.

Versatile 160:

Replication	Fuel Used	Time
1	365 mL	3' 35"
2	360 mL	3' 34"
3	360 mL	3' 31"
4	365 mL	3' 32"
5	365 mL	3' 26"
mean	363 mL	3' 32"
s.d.	2.74	

Electric Choremaster:

Replication	Energy Used	Time
1	0.66 kW-h	3' 20"
2	0.66 kW-h	3' 25"
3	0.65 kW-h	3' 18"
4	0.67 kW-h	3' 28"
5	0.65 kW-h	3' 26"
mean	0.658 kW-h	3' 23"
s.d.	.00837	

Table 14. Electric Choremaster versus Versatile 160 diesel, data taken in comparison testing for task no. 3, grain hauling routine, second gear.

Versatile 160:

Replication	Fuel Used	Time
1	615 mL	6' 24"
2	605 mL	6' 10"
3	610 mL	6' 08"
4	630 mL	6' 03"
5	615 mL	---
mean	615 mL	6' 11"
s.d.	2.74	

Electric Choremaster:

Replication	Energy Used	Time
1	1.39 kW-h	5' 57"
2	1.30 kW-h	5' 56"
3	1.31 kW-h	5' 51"
4	1.28 kW-h	5' 50"
5	1.31 kW-h	5' 48"
mean	1.318 kW-h	5' 52"
s.d.	.0421	

Table 15. Electric Choremaster versus Versatile 160 diesel, data taken in comparison testing for task no. 3, grain hauling routine, third gear.

Versatile 160:

Replication	Fuel Used	Time
1	395 mL	4' 47"
2	425 mL	---
3	425 mL	4' 38"
4	455 mL	4' 46"
5	420 mL	4' 39"
mean	424 mL	4' 43"
s.d.	21.33	

Electric Choremaster:

Replication	Energy Used	Time
1	1.32 kW-h	4' 39"
2	1.33 kW-h	4' 33"
3	1.30 kW-h	4' 37"
4	1.29 kW-h	4' 34"
5	1.32 kW-h	4' 37"
mean	1.312 kW-h	4' 36"
s.d.	.0164	

Table 16. Battery performance cycle data.

Warm battery charge-discharge cycle:

Date	Nov. 9	Nov. 10	Nov. 12	Nov. 13	Nov. 15
Temp	0 C	-5 C	+1 C	+3 C	-3 C
Wind	15 mph	15 mph	8 mph	12 mph	27 mph
Initial:					
S. G.	1260	1245	1225	1210	1160
Temp	23 C	22 C	20 C	20 C	24 C
Test:					
kW-hrs	3.90	3.99	3.87	3.85	4.01
Time	12' 10"	12' 16"	12' 11"	12' 21"	12' 53"
Final:					
S. G.	1245	1225	1210	1195	1140
Temp	24 C	23 C	22 C	22 C	25 C

Cold battery charge-discharge cycle:

Date	Nov. 20	Nov. 21	Nov. 22	Nov. 24	Nov. 25	Nov. 26
Temp	-1 C	-2 C	+3 C	+8 C	11 C	+2 C
Wind	14 mph	18 mph	8 mph	9 mph	15 mph	13 mph
Initial:						
S. G.	1270	1250	1230	1210	1190	1165
Temp	-2 C	-3 C	-2 C	+3 C	10 C	+7 C
Test:						
kW-hrs	5.30	5.37	4.70	4.35	4.24	4.72
Time	13' 43"	13' 50"	13' 15"	13' 00"	13' 02"	13' 58"
Final:						
S. G.	1250	1230	1210	1190	1165	1140
Temp	+3 C	+2 C	+6 C	+6 C	12 C	+9 C

Table 17. Effects of battery temperature and charge level on time taken to complete the battery performance evaluation cycle.

Maximum R-Square improvement for dependent variable "time".

Step 1: Independent variable "temperature" entered.
R-Square = 0.703

SOURCE	d.f.	SSE	MSE	F
Model	1	3.186	3.186	21.34
Error	9	1.344	0.149	
TOTAL	10	4.530		

	Beta-value	Std. error	F	PR>F
Intercept	13.579			
Temperature	-0.053	0.012	21.34	0.0011

Step 2: Independent variable "charge-level" added.
R-Square = 0.817

SOURCE	d.f.	SSE	MSE	F
Model	2	3.700	1.850	17.82
Error	8	0.831	0.104	
TOTAL	10	4.530		

	Beta-value	Std. error	F	PR>F
Intercept	13.579			
Temperature	-0.058	0.010	34.82	0.0004
Charge-level	-0.948	0.426	4.95	0.0568

Table 18. Effects of battery temperature and charge level on energy used to complete the battery performance evaluation cycle.

Maximum R-Square improvement for dependent variable "use".

Step 1: Independent variable "temperature" entered.
R-Square = 0.831

SOURCE	d.f.	SSE	MSE	F
Model	1	2.598	2.598	44.39
Error	9	0.527	0.059	
TOTAL	10	3.124		

	Beta-value	Std. error	F	PR>F
Intercept	4.942			
Temperature	-0.048	0.007	44.39	0.0001

Step 2: Independent variable "charge-level" added.
R-Square = 0.839

SOURCE	d.f.	SSE	MSE	F
Model	2	2.622	1.311	20.88
Error	8	0.502	0.063	
TOTAL	10	3.124		

	Beta-value	Std. error	F	PR>F
Intercept	4.807			
Temperature	-0.047	0.008	37.48	0.0003
Charge-level	0.206	0.331	0.39	0.5507

Notes:
d.f denotes degrees of freedom.
SSE denotes the sum of squared error.
MSE denotes the mean sum of squared error.
F denotes the test value.
PR>F denotes probability level at which variable is significant.

APPENDIX B:
Electric Vehicle Motors

The key item in an electric vehicle propulsion system is the motor, because it is the means by which electrical energy is converted to mechanical energy (Secunde, et al., 1983). Electric vehicle motors can be separated into two broad classifications: 1) direct-current (dc) types, and 2) alternating-current (ac) types. Direct current motors are designed to operate from a dc source, such as a battery, and require mechanical commutators and brushes. Alternating current motors are normally operated from an ac source, but in electric vehicles are powered from the battery by some type of dc-to-ac power inverter. The advantages of a dc propulsion system are relatively mature technology, controller technology, high efficiency, and, for the present, lower cost than an ac system. Disadvantages of the dc system are somewhat higher weight and brush maintenance requirements. The advantages of an ac system using the squirrel-cage induction motor are low weight, low motor cost, simplicity, high efficiency, low maintenance, and low system cost in the long term. The main disadvantage of the ac system is that the power conditioning technology is in the development stage and is not ready for production and wide use (Secunde, et al., 1983).

A) Direct Current Motors: Direct current motors have been used for many years in industrial applications, and therefore the technology for these systems has become relatively mature. Because of this, electric vehicle propulsion systems have in the past almost exclusively used some form of dc motor.

The variety of dc motors is extensive. A convenient method of grouping is by excitation means (electromagnet or permanent magnet). Electromagnetic excitation provides the main magnetic flux in the machine by means of a wound field and an external source of field power. Permanent magnet excitation provides flux by means of permanent magnets built into the machine.

1) Electromagnetically excited motors: These are the most common type of electric motors in power ratings appropriate for electric vehicle propulsion (5 to 40 kW). These motors can be grouped by field winding connections as series, shunt or compound motors.

a) Series motors: In series motors, magnetic flux is produced by field windings that are connected electrically in series with the motor armature as shown in Figure 17. These windings consist of few turns of large cross-section conductors for low resistance, since full motor current flows in them. The torque produced by a series motor is approximately proportional to the square of the armature (and motor) current. The series motor has excellent overload capability, which has made it popular in low speed electric vehicle applications. Four times rated torque can be delivered with only double the rated current, and, for short periods, the series motor can deliver nearly ten times rated torque. The series motor has a tendency to accelerate to high, usually destructive, speeds if the mechanical load is disconnected without suitable control safeguards. Therefore, this machine should not be used without overspeed protection in systems where driveline breakage is probable, such as belt-drive systems or systems with clutches. Characteristic torque-speed and torque-current curves for a series motor are shown in Figure 18.

Figure 17. Series motor electrical connections.

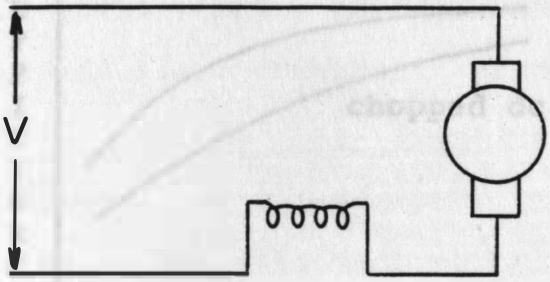
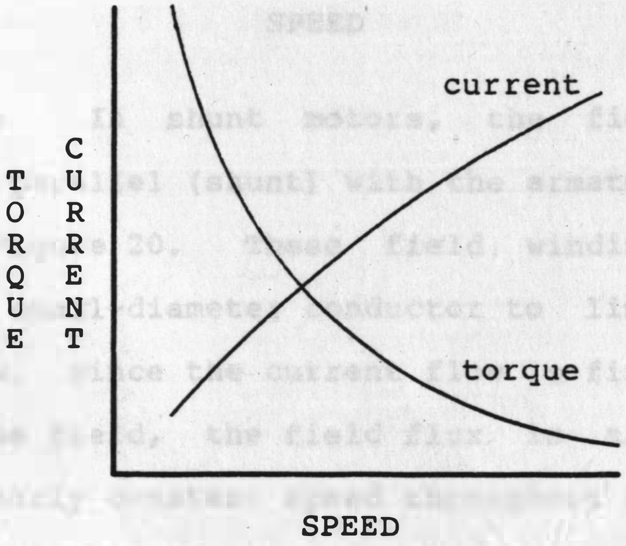


Figure 18. Typical series motor output characteristics.



Speed and torque control of series motors is obtained by varying the average applied dc voltage. This is normally accomplished with a silicon controlled rectifier (SCR) chopper. Although SCR controllers have high efficiency, series motors controlled by SCR choppers generally have a lower efficiency than when operated from a ripple-free dc supply (Edie, 1984). This reduced efficiency exists over much of the motor operating range, as shown in Figure 19.

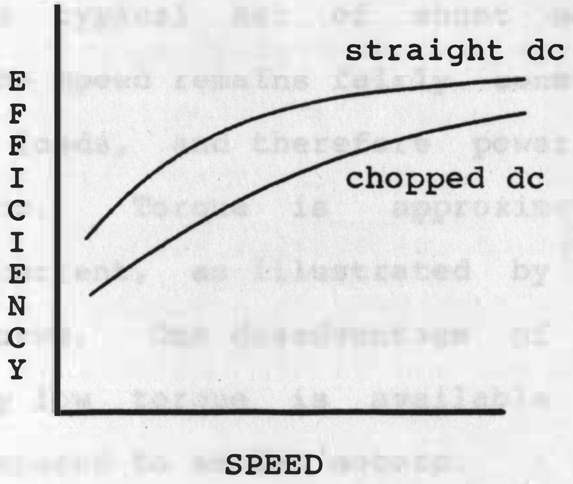


Figure 19. Efficiency losses in dc series motors due to SCR controllers (Edie, 1981).

b) Shunt motors: In shunt motors, the field windings are connected in parallel (shunt) with the armature windings, as shown in Figure 20. These field windings consist of many turns of small-diameter conductor to limit the amount of current flow. Since the current flow is fixed by the resistance of the field, the field flux is also fixed, which produces a nearly constant speed throughout the motor operating range. This constant speed characteristic is nearly ideal for powering hydraulic motors and power-take-off shafts (Buck and Hughes, 1981).

Figure 20. Shunt motor electrical connections.

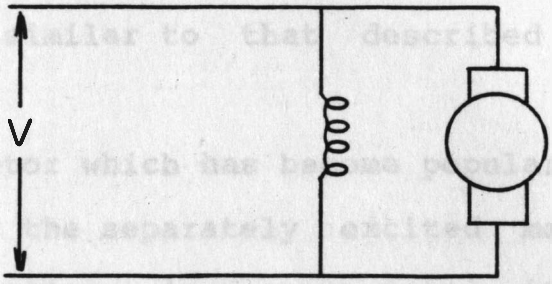
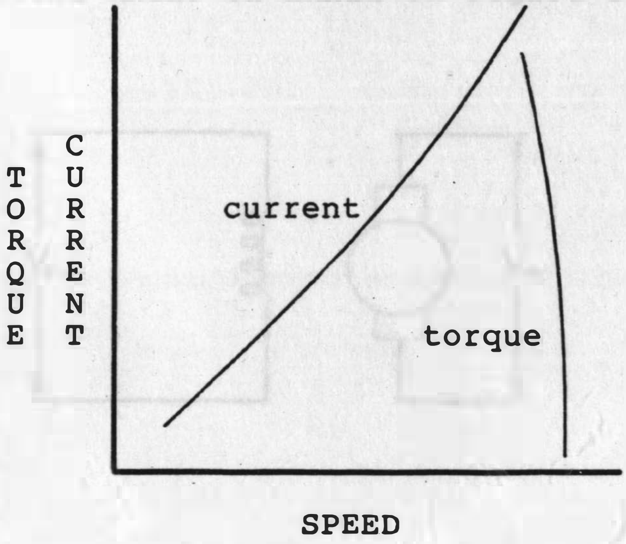


Figure 21 shows a typical set of shunt motor characteristic curves. The speed remains fairly constant through the full range of loads, and therefore power is nearly linear with torque. Torque is approximately proportional to armature current, as illustrated by the nearly straight current curve. One disadvantage of the shunt motor is that very low torque is available for starting heavy loads, as compared to series motors.

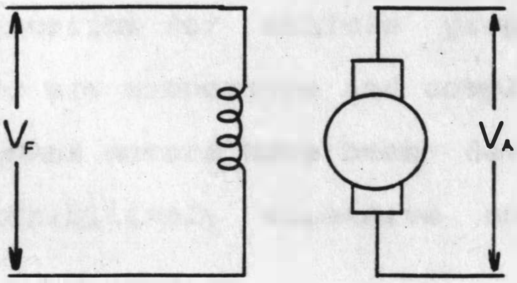
Figure 21. Typical shunt motor output characteristics.



Speed control of a shunt motor can be obtained for a limited range by adding a rheostat or SCR to vary the field current. Use of a chopper to control shunt motors results in an efficiency penalty similar to that described for series motors.

One type of shunt motor which has become popular in electric vehicle drives is the separately excited motor. This motor, as the name implies, is a shunt motor with a separate power supply for field and armature windings (Figure 22). The speed and torque of these motors can be controlled by varying either armature or field voltage or by a combination of armature ond field control. At low speeds, the motor is electrically configured similar to a series motor, to provide high starting torque. At high speeds, the motor is operated similar to a shunt motor, to maintain speed throughout a wide load range. A typical torque-speed curve for a separately excited motor is shown in figure 23.

Figure 22. Separately-excited motor connections.



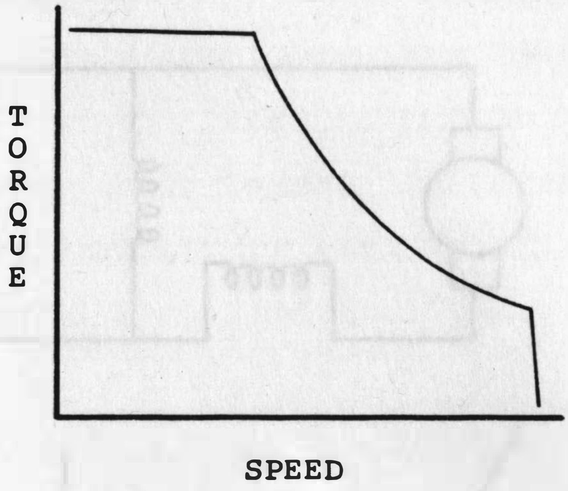


Figure 23. Typical separately-excited motor output characteristics.

c) Compound motors: Compound-wound motors use both series and shunt field windings in varying combinations for specific purposes (Figure 24). The shunt field limits overspeeding and the series field provides good starting torque. The characteristics of this motor depend on the balance between shunt and series fields. Figure 25 shows typical characteristics of a compound motor with an equal balance of shunt and series windings. These motors are often used for hydraulic system drives, because of their favorable torque-speed characteristics. Compound motors have not found wide application for vehicle propulsion, however, because controllers are cumbersome and complicated. Advanced controls for compound motors have been developed, but these controls are prohibitively expensive and need further development.

Figure 24. Compound motor electrical connections.

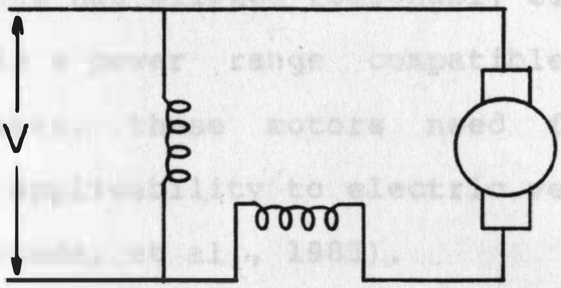
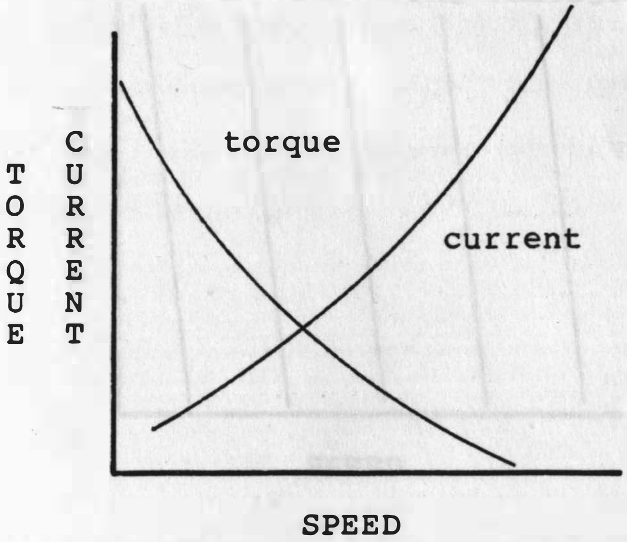


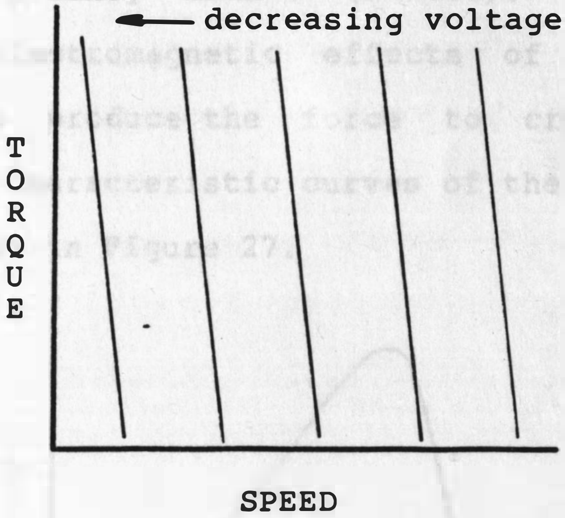
Figure 25. Typical compound motor output characteristics.



2) Permanent magnet excited motors: Permanent magnet (PM) motors can be considered to be similar to separately excited shunt motors in which the field excitation level is fixed and provided by permanent magnets. Speed and torque of these motors are controlled by means of armature voltage control. Typical torque-speed lines for a PM motor are shown in Figure 26. Since field power does not have to be supplied from an outside source, PM motors can be expected to be more efficient than equivalent

electromagnetically excited motors. The recent availability of rare earth-cobalt magnets has allowed reasonably sized PM motors to be designed in a power range compatible with electric vehicles. However, these motors need further development before their applicability to electric vehicles can be fully assessed (Secunde, et al., 1983).

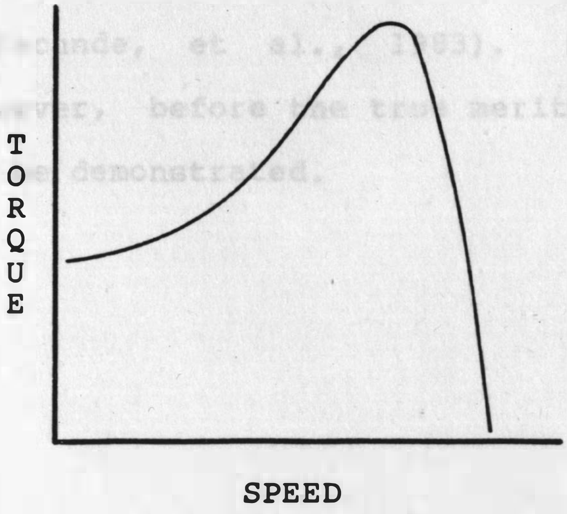
Figure 26. Permanent magnet dc motor output.



B) Alternating Current Motors: In general, ac motors are lower in cost than dc motors, and are more efficient and more reliable. Because they do not have commutators, ac motors can be designed for higher speeds than dc motors, and can therefore be considerably smaller for the same power rating. However, ac motors have been limited in mobile applications, due to control difficulties. Advances in semiconductor power electronics technology in recent years have made ac motors a more viable candidate for near-future propulsion service (Secunde, et al, 1983).

In ac electric vehicle propulsion, a three-phase "squirrel-cage" motor is generally used. Structurally, this motor is the simplest, most rugged and most reliable rotating machine available (Carlson, et al., 1981). The induction motor derives its name from the fact that currents flowing in the secondary member (rotor) are induced by ac currents flowing in the primary member (stator). The interaction between the electromagnetic effects of the stator and rotor currents produce the force to create rotation (Collie, 1979). Characteristic curves of the ac squirrel cage motor are shown in Figure 27.

Figure 27. Typical characteristics of ac three-phase "squirrel-cage" motors.



Single phase ac motors are generally not used for vehicle propulsion because of their low starting torque and need for special starting circuits. Also, single-phase ac motors are generally larger and heavier than equivalent polyphase motors. Three phase ac induction motors have become the standard in industry because efficiency is improved and the physical size and cost of three phase motors are less (Carlson, et al., 1981).

Two other ac motor systems which merit attention are the permanent magnet (PM) synchronous motor and the unexcited synchronous, or reluctance motor. The PM motor provides better speed control and better efficiency than the squirrel cage motor, with similar controls. The reluctance motor could be a simple, low-cost propulsion motor if it and its controls are adequately developed. Initial work has indicated that the reluctance motor system can be designed to provide performance similar to an induction motor system, but with simpler hardware (Secunde, et al., 1983). More development is needed, however, before the true merits of these two motor systems can be demonstrated.