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

James A. Ross and Gerald A. Wooldridge
Rohr Industries, Inc.
Advanced Transportation Systems

April 1978

Prepared for
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
Lewis Research Center
Under Contract NAS 3-20592

for

U.S. DEPARTMENT OF ENERGY
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ABBREVIATIONS

A	ampere (amp)
AC	alternating current
ACCEL	acceleration
A/D	analog-to-digital
aero	aerodynamic
Ah	ampere hour
ARM	armature
AVAIL	available
BATT	battery
CDA	Copper Development Association
cfm	cubic feet per minute
cy	cycle
D/A	digital-to-analog
DC	direct current
DECEL	deceleration
DOE	Department of Energy
DOT	Department of Transportation
eff	efficiency
EV	electric vehicle
FL	full load
F/R	forward/reverse
freq	frequency
ft	foot (feet)
GE	General Electric
GM	General Motors
hp	horsepower
hr or h	hour
Hz	Hertz (i.e. cycles per second)
ICE	internal combustion engine
in	inch

ABBREVIATIONS (continued)

kg	kilogram
km	kilometer
kPa	kilopascal
kVA	kilovolt ampere
kW	kilowatt
kWh	kilowatt hour
lb(s)	pound(s)
LU	look up
m	meter
MECH	mechanical
mfd	microfarad
mi	mile
MJ	megajoule
MOT	motor
mm	millimeter
mph	miles per hour
N	Newton
NEMA	National Electric Manufacturers Association
PCU	power conditioning unit (i.e. controller, inverter)
PF	power factor
PH	phase
PM	permanent magnet
PRELIM	preliminary
PWM	pulse width modulator
REGEN	regenerative
REL	Reliance
RMS	root mean square
rpm	revolutions per minute
R/V	rate-to-voltage
SAE	Society of Automotive Engineers
SCR	silicon controlled rectifier
sec or s	second
SEL	selector

ABBREVIATIONS (continued)

SI	System of International Units
SOTA	state-of-the-art
SPEC(s)	specification(s)
sync	synchronous
SW	switch
TACH	tachometer
temp	temperature
TRANS	transistor
US	United States
V	volt
VEH	vehicle
VEL	velocity
V/F	voltage-to-frequency
VV/VF	variable voltage/variable frequency
W/	with
Wh or Whr	watt hour
W/O	without
WT	weight

EXECUTIVE SUMMARY

The objective of this study was to prepare a preliminary design of a power train for a state-of-the-art 4-passenger electric vehicle capable of operating at highway speeds using conventional lead-acid batteries and to predict the expected performance with emphasis on maximizing range and overall system efficiency on the SAE J227a Schedule D driving cycle.

APPROACH

This power train design study was divided into three major activities:

(1) To assess the state-of-the-art (SOTA) of electric vehicles built since 1965 and obtain design/performance data for components applicable to the power train of a SOTA electric vehicle.

(2) To perform an engineering analysis, establish preliminary specifications, prepare a preliminary power train design and to predict by means of computation the performance of a vehicle using the power train design.

(3) To identify and evaluate technology improvements which have potential for improving the SOTA of power trains for electric vehicles.

SOTA was defined as employing techniques, devices and components which individually have been proven through reduction to practice and the design was to be based on commercially available parts which are available --

(1) as off-the-shelf items, or

(2) with short lead time due to manufacturing schedules, or

(3) as special orders involving limited design modifications.

RESULTS

The majority of the vehicles identified and evaluated during the literature and industry review were primarily conversions of production automobiles. Most of the other vehicles employed standard automatic components, consequently, the electric vehicles have not achieved the level of performance which can be obtained by utilizing components and technology within the SOTA. Most of the vehicle designs built to date are intended to maximize constant speed cruise range and do not emphasize acceleration or regenerative braking.

The components identified and selected as applicable to the design of a power train for a SOTA electric vehicle were:

- a separately excited (shunt) DC motor
- an induction motor and 3-phase controller
- a two-speed transmission
- a spiral gear differential
- steel belted radial tires.

A baseline of performance was established for previously built vehicles using the builders performance data adjusted by the ratio of their battery energy to the energy contained in the (16) 6 V batteries specified by the vehicle requirements as defined for this study. The maximum Schedule D range achieved on this basis was 59.7 km (37.1 mi). An analysis of a theoretical system with a 100% efficient motor and controller revealed that existing systems -

- are averaging less than 50% efficiency over the SAE cycle with respect to the theoretical system.
- have a combined motor/controller efficiency on the order of 78% in the constant speed cruise mode.

The predicted range on the D cycle for the theoretical system was 120 km (75 mi) with regenerative braking and 89 km (55 mi) without regenerative braking.

To aid in the evaluation and selection of the components for the SOTA power train, a computer simulation program was developed to predict travel range and performance of candidate component combinations.

Both DC and AC drive systems were evaluated using a computer power train model comprised of candidate motors and controller systems, a two-speed gear box and differential and steel belted radial tires. A predicted Schedule D range of 83.5 km (51.9 mi) was achieved using a separately excited (shunt) DC motor. An identical package powered by an induction motor and a 3-phase AC controller was calculated to have a range of 88.0 km (54.7 mi). With final adjustments to the specifications, the performance of the selected AC system was established at 90.4 km (56.2 mi).

Four near term improvements to the SOTA were identified, analyzed, and found to be capable of collectively increasing Schedule D range by 7% and constant speed cruise range by 18%. The improvements are:

- Higher battery voltage (12 V batteries)
- Overdrive gear for cruising
- Permanent magnet AC motor
- Automatic gear shifting

CONCLUSIONS

Based on the results of the industry review, the performance analyses and the design study, the following conclusions were drawn:

(1) Presently developed power train designs do not achieve the level of performance possible within the SOTA. The components judged to be most lacking in performance for an urban driving cycle were the motor and controller.

(2) An integrated system, specifically designed for maximum range on the Schedule D driving cycle, will increase travel range approximately 50%.

(3) Regenerative braking is a controlling factor for increased Schedule D range. Regenerative braking increases range by 16 to 23%.

(4) Greatest constant speed range is achieved by systems with separately excited DC motors, but this combination does not result in the greatest range for the Schedule D driving cycle.

(5) Greatest Schedule D range is achieved with 3-phase induction motors powered by variable voltage, variable frequency AC inverter/controllers.

(6) The range of the selected AC system represents a 52% improvement over previous designs adjusted for equivalent battery energy. The predicted Schedule D range is 90.4 km (56.2 mi).

(7) Near term improvements such as increased battery voltage, overdrive cruise gearing, permanent magnet AC motor, and automatic gear shifting will further increase performance by approximately 7% (collectively).

The selected power train design emphasizes coordination to achieve a totally integrated system of SOTA components as opposed to high efficiency for constant speed cruise. The induction motor and AC controller selected for the SOTA electric vehicle results in the greatest range based on the quantitative analysis and meets the established performance criteria established for this study.

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1.0 INTRODUCTION

Electric vehicles powered by batteries have been in use for many years. However, the travel range and performance of battery powered vehicles is substantially less than that of internal combustion engine vehicles. The most apparent shortcoming of electric vehicles is that only a limited amount of energy is available from the batteries on board the vehicle. One obvious way to improve their performance and range is to develop a better battery. So far, the battery industry has not developed a high energy and high power density, lightweight battery which can be produced at a reasonable cost and which has acceptable life.

In the past, emphasis has been placed on the battery as a means of solving the limited range and performance of electric vehicles. Recently, more attention is being directed toward the systems approach to develop and optimize the power train in order to achieve a suitable range and acceptable performance for a vehicle capable of being operated on public roads intermingled with existing internal combustion engine traffic.

This electric vehicle study is directed toward a systematic design of a power train for a battery powered vehicle based on SOTA technology and commercially available components. It consists of three major tasks:

(1) A search, review, and evaluation of the SOTA or previously developed power trains built since 1965.

(2) An engineering analysis and preliminary design of a SOTA power train.

(3) Identification and evaluation of selected near term SOTA improvements.

A SOTA electric vehicle is defined as an electric powered vehicle employing techniques, devices and components which individually have been proven through reduction to practice. Commercially available parts are defined as SOTA parts which are available:

- As off-the-shelf items, or
- With short lead time due to manufacturing schedules, or
- As special orders involving limited design modifications.

The power train elements evaluated in this study include all of the components that process, condition, or transmit power to the drive wheels, with the exception of the battery. Components such as motors, controllers, transmissions, differentials, and tires were considered in this SOTA review and preliminary power train design. Batteries were investigated only to establish their discharge characteristics.

The primary intent of this study is to establish a preliminary power train design based on the best combination of the currently available components and to assess its performance. A second objective is to identify improvements which can be achieved within the relatively near term. The output of this study could ultimately be incorporated in the design of a propulsion system for a prototype, urban, four-passenger electric vehicle with lead-acid batteries.

The Schedule D driving cycle of the Society of Automotive Engineers (SAE) Electric Vehicle Test Procedure J227a was specified as the principal basis of comparison of performance. Schedule D is characterized by an acceleration up to 72.4 km/hr (45 mph) and a 72.4 km/hr (45 mph) cruise followed by coast, deceleration, and idle periods, and is intended to represent a typical route in stop-and-go driving in urban areas.

During the industry and literature review, power trains were studied and evaluated as a basis for designing a power train for a SOTA electric vehicle. The result of the state-of-the-art review of existing vehicles built since 1965 is summarized in this report and the details are contained in Appendix A. Following the industry and literature review, selected key vehicles were studied and their travel range recomputed based on batteries equivalent to those specified for this preliminary design study. The adjusted performance of these existing vehicles provided the baseline for comparison to the predicted results of the SOTA design developed in this study.

Based on the SOTA assessment and the preliminary analysis, a set of preliminary specifications were derived for the power train to meet or exceed the specified vehicle requirements. The vehicle characteristics and requirements specified for the state-of-the-art electric vehicle are as follows:

- Passengers	4
- Curb Weight (without power train)	1021 kg (2250 lbs)
- Frontal Area	1.86 m^2 (20 ft^2)
- Aero Drag Coefficient	0.3
- Cruising Speed (no headwind)	88.5 km/hr (55 mph)
- Driving Cycle	SAE J227a, Schedule D
- Gradeability	10% at 48.3 km/hr for 0.8 km (30 mph for 0.5 mi)
- Batteries	(16) 6V Lead-Acid @ 29.5 kg (65 lbs) 132.5 Ahr and 0.093 MJ/kg (11.7 Whr/lb) @ 75 A 5.25 V at discharge

A preliminary power train design for a SOTA vehicle was prepared in accordance with the specified vehicle requirements and the derived preliminary specifications. A significant portion of the design effort was oriented toward predicting the travel range of various combinations of components considered in developing the SOTA power train design.

In order to predict the performance and allow comparisons of the power train components being considered, a computer program simulating the SAE Schedule D driving cycle was developed. Using this tool, each alternative was evaluated in terms of its maximum travel range on Schedule D as well as its characteristics during constant speed operation.

The results of the engineering analysis and the preliminary power train design are presented in this report. Near-term improvements to the SOTA through advanced technology consistent with reasonable costs were also identified and the most feasible areas were given a preliminary analysis to determine their potential improvement in range.

To facilitate comparison of the performance predictions with previously published data, the customary system of units was used in all calculations and the computer simulation program. For this report, however, the data has been converted to the International System of Units (as supplemented by DOE) and the customary units are given parenthetically.

2.0 REVIEW OF EXISTING ELECTRIC VEHICLES

2.1 STATE-OF-THE-ART ASSESSMENT

An industry and literature review was conducted to determine the SOTA of power train development and assess the components which might be applicable to the design of a SOTA power train for a four-passenger electric vehicle with lead-acid batteries.

The review was restricted to power trains and components of electrically powered vehicles that have been built since 1965. The emphasis of the review was to:

- Define and evaluate the present SOTA of power train systems and components that may be applicable to the design of a power train for a SOTA electric vehicle.
- Obtain design and performance data for applicable power train systems and components.
- Identify and evaluate technology improvements to power train systems and components which have the potential for improving overall electric vehicle performance.

A summary report of the SOTA review and evaluation is included as Appendix A and the vehicles reviewed and their performance characteristics are listed in table 2-1 of that report. A condensation of the report in terms of the major elements of the power train is presented and discussed in this section.

2.1.1 Motors

The majority of the electric vehicles built since 1965 are powered by relatively low power DC motors. Typically, the smaller motors were selected with emphasis on maximizing travel range based on more or less constant speed operation, thereby keeping motor size to a minimum. Acceleration was generally very poor because of the smaller motors. Series DC motors were used more frequently than other types because of their high torque at low speed characteristic and the simplicity of the required controls. As the performance and range desired for an urban electric vehicle increased, the characteristics of the series DC motor resulted in inefficient vehicle operation with excessively high battery currents.

More recently, the EV industry has begun to exploit the capabilities of advanced controllers and is selecting separately excited field (shunt) DC motors. Although vehicle performance and range are unsupported by comparable test data, a number of EV builders claim that the use of separately excited DC motor has resulted in lower energy consumption than those vehicles fitted with series DC motors. The increased range using the separately excited motor is attributed to higher average efficiency and the use of regenerative braking. Toyota claims that the driving range per battery charge is increased 20% in stop-and-go driving for these reasons.

Two firms (General Motors and Linear Alpha) have built several electric vehicles based on the use of a 3-phase AC induction motor. The AC motors were used because of their low cost, high reliability, high hp/lb and the elimination of the brush wear problem associated with DC motors. Although these prototype vehicles demonstrated the feasibility of an AC system operating from a battery source, the high cost of the AC controller offset the advantages of the AC motor. Both GM and Linear Alpha concluded that as the cost of AC controllers decreased, the practicality of an AC system would increase.

The EV industry is maturing as evidenced by the degree of increased sophistication of the more recent vehicle designs and by the increased performance and range being achieved. The previously developed designs are being reviewed with the intent of providing more acceptable performance. Improvements in performance are being achieved with separately excited DC motors and AC induction motor systems. The selection of a SOTA motor, however, cannot be made without due consideration for the controller technology. In reality, the motor and the controller must be considered as a pair.

2.1.2 Controllers

The most popular system used in existing vehicles is the DC chopper operating in conjunction with a series DC motor (without capability for regenerative braking). For low power, short range EV's (with speed adjustments suitable for operation in traffic), the use of a DC chopper with SCR's to control the armature current of the series DC motor is the most direct and practical approach. As the acceleration and power requirements increase to provide suitable performance in more realistically sized urban electric vehicles, the cost of controllers for series DC systems increases significantly.

As the controller cost for a series motor increased, as the range decreased because of greater battery drain and as power increased to provide adequate acceleration and cruising speeds, the search for more cost effective and more efficient motor/controller systems began. More recent vehicles such as the CDA Town Car, Toyota Compact Electric Passenger Car and other Japanese cars are using separately excited shunt DC motors which employ a smaller and lower cost controller in the field circuit to achieve increased travel range. There is also an additional benefit with shunt DC motor systems - the motor can be changed to a regenerative mode more easily than a series motor configuration. This also contributes to increased range.

The combination type controller for the separately excited DC motor of the CDA Town Car contributes to its range of over 66 km (41 mi) on the SAE Schedule D driving cycle. This controller uses a DC chopper for field control, and 2-step battery switching for control of the armature voltage. For vehicle speeds below 9.7 km/hr (6 mph), a resistor is connected in series with the armature to control low speed torque.

The field controller used in the CDA Town Car represents a significant improvement over series DC motor controllers. Speed control using the separately excited field means that much less power must be handled by the controller. This reduces the total controller loss. In contrast, the controller for a series DC motor must handle larger amounts of power and consequently has a greater loss. (This comparison assumes that each of the controllers has the continuous control necessary to operate in heavy traffic on public roads.)

Resistor control for smooth startup is generally considered a high loss technique. However, since this mode of operation represents such a small portion of the Schedule D driving cycle, the actual losses are not significant. This system would pose a problem if operation at low speed becomes significant. The use of a controller in the armature circuit would be an advantage in the latter case.

The losses in a field controller can be reduced further by using transistors rather than SCR's. The current handling capacity of SOTA transistors is adequate for the current requirements of a field controller. Transistor controllers are typically 95% efficient whereas thyristor (SCR) choppers are only 88 to 90% efficient because of the added losses in their auxiliary reactors and commutating thyristors. Combining the high efficiency of transistors with reduced power in a field controller results in lower controller loss.

Regardless of the motor configuration - shunt or series - new developments in transistor technology and paralleling techniques are expected to attract controller design toward the use of transistors. Transistors can switch off without using bulky and heavy auxiliary components which are required with SCR controllers. The higher switching frequency achievable with transistors results in lower battery and motor ripple currents and reduced associated losses.

Since 1965, two AC inverter controllers have been demonstrated in EV's by GM and Linear Alpha. Both units were 3-phase AC designs using SCR's, but were not competitive costwise with the DC chopper systems dominating at that time.

Recent developments in the AC controller field now make the 3-phase AC inverter a viable candidate as a controller for a battery powered electric vehicle. Variable speed AC drives have been developed for machine tool applications which have efficiciences on the order of 96 to 98%. Existing units are designed for operation at 480 V. Modifications of this design by changing to lower voltage transistors would permit this technology to be used in electric vehicle applications.

When the power required is low, DC systems are less expensive than an equivalent AC system. The 3-phase AC system requires a more complex controller which offsets the cost advantage of the lower cost AC motor. As the power requirement increases, the cost of DC controllers and motors increase at a greater rate than comparable AC systems. An economic analysis is needed to establish the cost relationship in more detail.

The characteristics of the controller and the motor must be matched to provide the overall performance necessary to meet the operational requirements of the specified driving cycle in an efficient manner. No specific controller is available which is directly adaptable to an electric vehicle without some degree of customizing. The individual parts and circuit technology exist; however, they do not exist in the form of an off-the-shelf commercial item. One key point which stands out is that each controller has been specifically designed to suit the individual requirements of the vehicle being developed.

Performance of prior systems and recent development in controller technology indicate that the separately excited DC system and the 3-phase AC inverter have the greatest potential for improving overall EV performance and for maximizing range.

2.1.3 Regenerative Braking

The application of regenerative braking to improve range has been given very little attention in the U.S., as evidenced by the relatively few cars which possess this capability.

Regenerative braking can increase travel range. However, there is controversy among EV designers whether or not it is cost effective. Vehicles primarily used in continuous highway type operations will derive very little benefit from regenerative braking bacause braking is such a small part of the total duty cycle. The braking mode for vehicles used in stop and go driving is a large percentage of the duty cycle, therefore much greater benefit can be derived from regenerative braking. The value or contribution to extending vehicle range is primarily a function of the duty cycle. A second but also important consideration is the cost effectiveness among various approaches (trade-offs) which could result in the same increase in range. These include additional components for regenerative braking, a larger battery pack, and/or operating cost to recharge a larger battery pack.

Regenerative braking does significantly extend the range of electric vehicles when the operation involves stop-and-go driving or driving on hilly terrain. Test results reported indicate the gain in cruising range is approximately 15% for stop-and-go driving. The Ripp-Electric vehicle equipped with regenerative controls achieved a 22% increase in travel range when tested according to the SAE J227a Schedule C driving cycle.

The use of regenerative braking in electric vehicles has not yet reached maturity. As the degree of sophistication in motor controllers increases, the implementation of regenerative braking becomes easier - almost to the point of being inherent. For instance, regenerative braking is achieved in separately excited DC systems by increasing the motor field current. The capability regenerative braking in AC systems is built in automatically because the components necessary for it to perform in the driving mode can also operate in the regenerative mode by reducing the motor input frequency.

2.1.4 Transmissions

For the most part, the reviewed electric vehicles which were conversions of production automobiles had inefficient power trains. Numerous attempts have been made with varying degrees of success to improve the mechanical system between the motor and the tires.

Many earlier vehicle builders tried to capitalize on the fact that the series DC motor inherently has high starting torque which starts from zero speed (i.e., without the idle speed of an internal combustion engine) and reversability without gearing to eliminate the need for a transmission in the power train. In most of these earlier designs, the motor is coupled directly to a differential. This type of power train is practical for a low cost, low speed utility vehicle, but it is not suitable for an urban vehicle because it does not meet public acceptance in terms of acceleration and performance and is not compatible with existing vehicle traffic.

The power train for the Sundancer Vehicle (McKee) uses a two-speed mechanical transmission directly coupled to a Dana differential axle. The transmission is manually shifted by a lever-operated cable assembly connected to the synchromesh unit. The overall system exhibits minimal complexity and the efficiency is reported to be 92%.

Although the transmission does add some mechanical losses, they are relatively minor compared to the tire losses. Nevertheless, the gain in acceleration, increase in gradeability, and reduction in motor currents justify the use of the transmission. The use of a multigear transmission helps to avoid high motor currents and justifies the added mechanical loss in the transmission.

2.1.5 Differentials

The majority of electric vehicles built to date employed the conventional automotive solid axle differential. A few designs deviated from this trend and employed dual belt drives (McKee) to achieve the differential action. There have been several designs wherein chain drives (Morse Hy-Vo) were used to drive the differential carrier in lieu of a pinion gear. The chain drive was used primarily because of its right angle input to the differential (CDA, McKee, McCulloch, Lucas).

Little effort has been expended to determine if reduction in losses through the differential are possible. The standard automotive hypoid gear differential has been assumed by many vehicle builders to be the most efficient design based on general statements that efficiency is always about 95%. Higher efficiency can be achieved with spiral bevel gears. This aspect is discussed in more detail in section 5.5 on driveline efficiency.

The contribution of improvements in the differential to the overall system efficiency are relatively small, but are worthy of consideration when maximum range and efficient overall performance are desired.

2.1.6 Tires

Steel belted radial tires are almost universally accepted as the tire with the lowest rolling resistance, and they are extensively used on EV's. Steel belted radials have 20% less rolling resistance than conventional bias tires. To further reduce the tire losses, high inflation pressures are frequently used. (Information on the tire losses is given in section 3.6 of Appendix A.)

According to the TRA (Tire and Rim Association) Manual, the maximum cold inflation pressure recommended for Load Range B tires is 220 kPa (32 psi). The TRA manual indicates that a 28 kPa (4 psi) increase is permissible if the maximum sustained speed is limited to 120 km/hr (75 mph). The high pressure technique for reducing tire loss can also be applied to Load Range D tires. The standard 276 kPa (40 psi) maximum for Load Range D tires can be raised to 303 kPa (44 psi) to achieve further reduction in tire loss.

Higher tire pressure and reduced tire load are well known techniques for reducing rolling resistance; however, one precaution - this combination may cause an unfavorable tread wear problem. High tire pressure also affects ride comfort and needs to be offset by vehicle suspension design.

There are no tires available which are specifically designed for EV's; however, the technology for reducing tire loss is known. If the demand was great enough, tire manufacturers would respond. Tires presently manufactured represent the optimum design for the service factors and speed range of present combustion engine vehicles. The reduced load and speed requirements for an EV make possible further reductions in tire loss through changes in construction while maintaining present performance levels with respect to wear, ride and handling. Additional study is required to investigate the possibility of changing tire construction to more closely match the service and load requirements of an EV with a maximum speed of 96 km/hr (60 mph).

2.1.7 Compatibility of Components

It is apparent that the current and past efforts to develop a battery powered urban vehicle power train have not reached the level of performance that can be achieved with SOTA components because the designs do not reflect a totally integrated system. All too frequently, the vehicles are developed by a firm with a specific product in mind, with very little attention given to integrating the components of the power train.

2.1.8 Typical Performance Shortcoming

Most of the EV's reviewed are not capable of meeting the Schedule D driving cycle of SAE J227a. The most apparent shortcoming is the inability to meet the minimum acceleration requirement of reaching 72.4 km/hr (45 mph) in 28 seconds. Some vehicles may contain components capable of performing the Schedule D driving cycle, but lack of performance data, variation in vehicle size/type and poor matching of power train components preclude valid comparison. The contribution of individual components cannot be singled out when the only data presented by the builders is the maximum range achieved by the vehicle.

2.1.9 Overall Assessment

The EV power trains developed to date have not yet reached the optimum performance which can be achieved with SOTA technology and components. Power trains of electric vehicles built to date basically fall into two categories:

(1) Conversions of existing production vehicles wherein the internal combustion engine was removed and replaced by a battery powered motor and controller.

(2) Custom built power trains generally comprised of off-the-shelf industrial or conventional automotive components.

Further effort is required to address the whole system, with emphasis on matching the components to improve system performance. Improvements in performance can be obtained by further investigation and optimization in the following areas:

- Lower loss tires
- Reduced overall gearing loss
- More efficient motors and controllers
- Reduced peak power drain
- Reduced drive train weight
- Regenerative braking

2.1.10 Conclusion

Results of the industry and literature review indicate that performance can be increased within the SOTA using commercially available components and technology by more thoroughly integrating the components in the power train such that their combined performance results in an improvement over other combinations. The components applicable to the design of a power train for a SOTA electric vehicle with potential for improved performance are:

- separately excited DC system
- AC induction motor and 3-phase controller
- two-speed transmission
- spiral gear differential
- steel belted radial tires

2.2 PERFORMANCE OF SELECTED KEY VEHICLES

Following the SOTA review, the performance of vehicles with high mileage claims by the manufacturer was examined in more detail. Since very few of the electric vehicles have been tested according to the SAE J227a Schedule D Test Procedures, the range at constant cruise speed was selected as the basis of comparison. In figure 1, the reported performance of the vehicles with highest mileage claims are plotted for comparison.

Using the CDA I car as an example, it is apparent that variations in batteries used in each of these vehicles preclude direct comparison of reported ranges. The curb weights and battery pack descriptions are listed in table I and the performance data for the CDA and Ripp-Electric vehicle are tabulated in more detail in table II. Range is a function of the number and type of batteries. Some adjustment was needed to equalize the battery energy available so that the range more precisely reflects the performance of each power train design rather than the size and number of batteries carried.

Using a ratio of the energy of 16 Exide EV106 batteries (equivalent baseline for this study) divided by the battery energy on board during the test and multiplied by the actual test mileage, adjusted performance claims have been computed and tabulated in table III. With a battery pack of 16 EV106's, the CDA II car would have an adjusted cruise range of 114.3 km (71 mi) at a constant speed of 64.4 km/hr (40 mph) compared to 107.9 km (67 mi) for the CDA I, and 98.2 km (61 mi) for the Ripp-Electric. This technique for adjusting the range in proportion to the battery size is an oversimplification because it does not take into account the weight difference, but it does provide sufficient accuracy for this comparison.

The actual differences are small, but can be explained when the features of each vehicle are analyzed as follows. The greater range of the CDA II over the CDA I is attributed to the more efficient transistorized controller used in the second generation CDA car. CDA I was mechanically identical but it had a less efficient SCR type controller. The slightly better performance of CDA I (107.9 km at 64.4 km/hr) compared to the Ripp-Electric (98.2 km at 64.4 km/hr) is believed to be due to the higher aerodynamic drag caused by the boxy shape of the Datsun 1200 body used on the Ripp-Electric vehicle.

A new DC system being developed by GE/Triad, which is very similar to the CDA car, is estimated to have an adjusted performance on Schedule D of 56.4 km (35 mi). The adjusted performance of the new GE/Triad system and the selected vehicles is summarized in table IV. The performance of the GE/Triad system is comparable to the performance of the selected key vehicles on the Schedule D cycle, but has 18% greater range at 64.4 km/hr (40 mph) constant speed cruise.

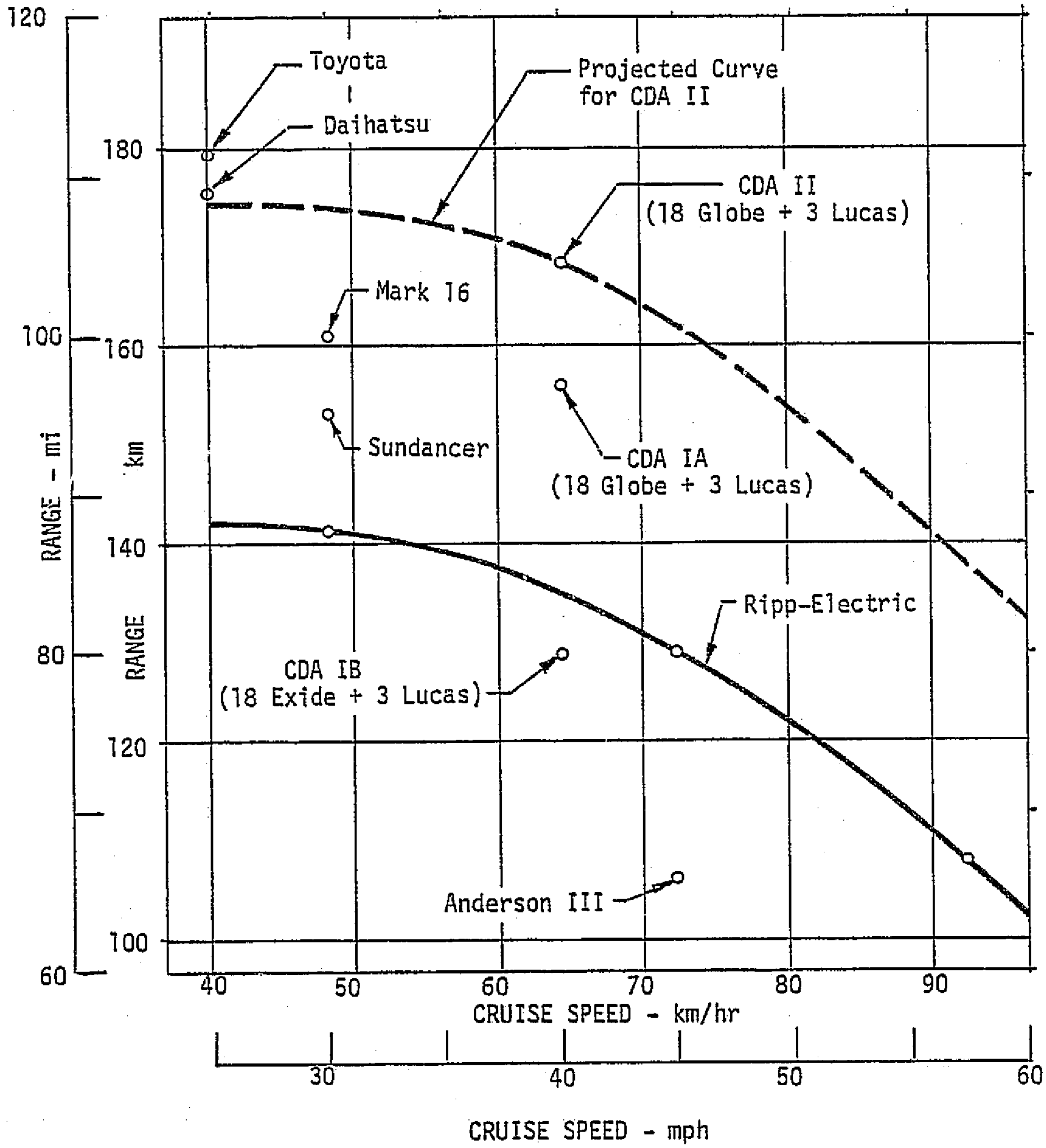


Figure 1. - Travel Range vs Cruise Speed for Selected Vehicles

TABLE I - VEHICLE WEIGHT AND BATTERY DATA FOR SELECTED VEHICLES

VEHICLE	CURB WEIGHT		BATTERIES TYPE & NO.
	kg	lbs.	
TOYOTA	1360	3000	Unknown
DAIHATSU	1134	2500	Unknown
MARK 16	726	1600	EV 106 (12)
SUNDANCER	726	1600	EV 106 (12)
ANDERSON III	1134	2500	EV 106 (12)
CDA IA	1406	3100	GC 2-21 (18) + Lucas (3)
CDA IB	1360	3000	EV 106 (18) + Lucas (3)
CDA II	1406	3100	GC 2-21 (18) + Lucas (3)
RIPP-ELECTRIC	1360	3000	LEV 115 (20)

TABLE II - PERFORMANCE DATA FOR SELECTED VEHICLES

VEHICLE			CDA IA	CDA IB	CDA II	RIPP-ELEC.
VEHICLE WEIGHT	Curb	kg	1406	1374	1406	1375
		lb	3100	3028	3100	3030
	Test	kg	1569	1537	1569	1452
		lb	3460	3388	3460	3200
BATTERIES			18 Globe 3 Lucas	18 EV 106 3 Lucas	18 Globe 3 Lucas	20 LEV 115
BATTERY WEIGHT		kg	563+34=597.	531+34=565.	563+34=597.	589.7
		lb	1242+75=1317	1170+75=1245	1242+75=1317	1300
RATING (At 75A)			162.5 Ah	132.5 Ah	162.5 Ah	144 Ah
SPECIFIC ENERGY		MJ/kg	0.1071	0.0929	0.1071	0.1011
		Wh/lb	13.5	11.7	13.5	12.74
TOTAL BATTERY ENERGY		MJ	64.0	52.4	64.0	59.6
		Wh	17,780	14,567	17,780	16,562
RANGE SCHEDULE D		km	66.5	54.9	86.9	--
		mi	41.3	34.1	54	--
			38 Cycles (1.75 km/cy)	33 Cycles (1.664 km/cy)	--	--
CRUISE RANGE 64.4 km/hr (40 mph)		km	156.1	128.7	165.8	133.6
		mi	97	80	103	83
RANGE SCHEDULE C		km	--	--	117.5	96.6
		mi	--	--	73	60
INCREASE IN RANGE W/REGEN. BRAKING		C*	--	--	6.7%	22.2%
		D*	--	--	12.7%	--
ACCELERATION			48.3 km/hr / 11.2 sec 30 mph / 11.2 sec	48.3 km/hr / 11.2 sec 30 mph / 11.2 sec	48.3 km/hr / 11.2 sec 30 mph / 11.2 sec	48.3 km/hr / 13.2 sec 30 mph / 13.2 sec

* C = Schedule C SAE J227a
D = Schedule D SAE J227a

TABLE III - ADJUSTED PERFORMANCE DATA FOR SELECTED VEHICLES

VEHICLE		CDA IA	CDA IB	CDA II	RIPP-ELEC.
TOTAL ENERGY	MJ	597x.1071=64.0	565x.0929=52.4	597x.1071=64.0	589.7x.1011=59.6
	Wh	1317x13.5=17,780	1245x11.7=14,567	1317x13.5=17,780	1300x12.74=16,562
ADJUSTED ENERGY	MJ	473x.0929=43.9	43.9	43.9	43.9
	Wh	1043x11.7=12,205	12,205	12,205	12,205
ADJUSTED RANGE SCHEDULE D		$\frac{12,205}{17,780}$x66.5=45.5 km (28.3 mi)	$\frac{12,205}{14,567}$x54.9=46.0 km (28.6 mi)	$\frac{12,205}{17,780}$x86.9=59.7 km (37.1 mi)	— —
ADJUSTED RANGE SCHEDULE C		— —	— —	.686x117.5=80.6 km (50 mi)	$\frac{12,205}{16,562}$x96.6=71.18 km (44.2 mi)
ADJUSTED RANGE 64.4 km/hr Cruise (40 mph)		.686x156.1=107 km (67 mi)	.838x128.7=108 km (67 mi)	.686x165.8=114 km (71 mi)	.737x133.6=98 km (61 mi)
ENERGY CONSUMPTION 64.4 km/hr Cruise (40 mph)		$\frac{43.9}{107}$ = .410 MJ/km (183 Wh/mi)	$\frac{43.9}{108}$ = .406 MJ/km (182 Wh/mi)	$\frac{43.9}{114}$ = .385 MJ/km (172 Wh/mi)	$\frac{43.9}{98}$ = .448 MJ/km (200 Wh/mi)

TABLE IV - ADJUSTED PERFORMANCE COMPARISON OF GE/TRIAD NEW SYSTEM VS. SELECTED VEHICLES

VEHICLE/SYSTEM		CDA I	CDA II	RIPP-ELEC	GE/TRIAD
MOTOR TYPE		SHUNT	SHUNT	SERIES	SHUNT
CONTROLLER TYPE		SCR	TRANS	TRANS	TRANS (FIELD) SCR (ARMATURE)
RANGE SCHEDULE D					
	km	45.5	59.7	--	56.3
	mi	29	37	--	35
CRUISE RANGE					
64.4 km/hr	km	107	114	98	135
(40 mph)	mi	67	71	61	84

Comparison Based on (16) EV 106 Batteries

3.0 VEHICLE REQUIREMENTS

3.1 POWER TRAIN DEFINITION

The power train as defined for this study includes all of the components, with the exception of the battery, that process, control, condition, or transmit power to the drive wheels and tires. It is comprised of the components encircled by the dotted lines in figure 2. The power train components being studied and evaluated include traction motors, controllers, transmissions, differentials/axles, brakes, and wheels/tires. The characteristics of the specified batteries are studied only to the extent that they influence the performance and efficiency of the power train.

3.2 SAE SCHEDULE D DRIVING CYCLE

The principal basis of analysis and evaluation employed during this preliminary design is the Schedule D driving cycle of the SAE Test Procedure for Electric Vehicles as shown in table V. The distance traveled during one cycle is approximately 1.6 km (1.0 mi). The actual mileage is influenced slightly by the rate of acceleration established during the acceleration, coast and brake periods. The effect on performance of varying the rate of acceleration in bringing the vehicle up to cruise speed is discussed in more detail in section 5.3.

3.3 PRELIMINARY SPECIFICATIONS

The first step of the power train design was to prepare preliminary specifications for the overall power train and the individual components. The emphasis was on maximizing vehicle range and overall efficiency on the SAE Schedule D driving cycle.

The vehicle characteristics specified for this study which affect the power train design are:

- Curb Weight (without power train)	1021 kg (2250 lbs)
- Frontal Area	1.86 m^2 (20 ft^2)
- Aero Drag Coefficient	0.3
- Cruising Speed (no head wind)	88.5 km/hr (55 mph)
- Driving Cycle	SAE J227a, Schedule D

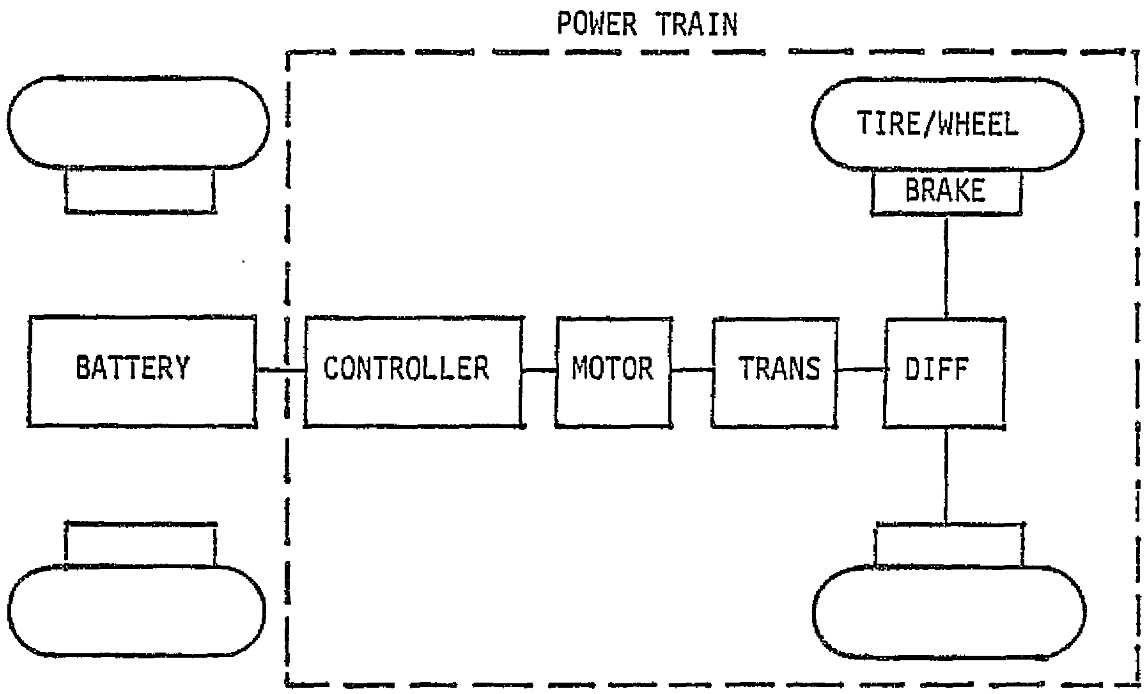


Figure 2. - Power Train Definition

TABLE V - DRIVING CYCLE DESCRIPTION FOR SAE J227a SCHEDULE D

	ACCEL.	CRUISE	COAST	BRAKE	IDLE	TOTAL
SPEED (km/hr) (mph)	0-72±1.5 0-45± 1	72 ± 1.5 45 ± 1	72 - 66 45 - 41 (see note 1)	66-0 41-0 (see note 1)	0 0 (see note 2)	-- --
TIME (sec)	28 ± 2	50 ± 2	10 ± 1	9 ± 1	25 ± 2	122 ±2
DISTANCE (km) TRAVELED (mi)	.282 .175	1.006 .625	.193 .120	.082 .051	0 0	1.563 .971
ACCELERATION (m/s^2) (mph/sec)	.72 1.61	0 0	-.18 -.40	-2.06 -4.60	0 0	-- --

NOTE: 1. The terminal speed given for the coast period is an approximate value based on the preliminary vehicle specifications established in section 3.3.

2. Idle time is the time after braking and before the cycle is restarted.

- Gradeability — 10% at 48.3 km/hr for 0.8 km (30 mph for 0.5 mi)
- Batteries — (16) 6V Lead Acid at 29.5 kg (65 lbs) 132.5 Ah and 0.093 MJ/kg (11.7 Wh/lb) at 75 A 5.25 V at discharge

The additional specifications which were derived as a result of the data gathered during the state-of-the-art search and component investigation are:

- Power Train Weight		340 kg (750 lbs)
- Acceleration		0-72.4 km/hr (0-45 mph) in 28 sec
- Tire Rolling Resistance		0.0883 N/kg (9 lbs/1000 lbs) (nominal at zero speed)
- Chassis Rolling Resistance		0.0098 N/kg (1 lb/1000 lbs)
- Transmission Efficiency	- Lo Gear	95%
	- Hi Gear	97%
- Differential Efficiency	- Lo Gear	97%
	- Hi Gear	96%
- Regenerative Braking		Yes

Steel belted radial tires inflated to 221 kPa (32 psi) were selected for the preliminary analysis. Tire rolling resistance versus vehicle speed for SOTA tires is illustrated in figure 3. A tire rolling resistance value slightly higher than the SOTA was selected for the preliminary specifications and analysis.

3.4 PRELIMINARY ANALYSIS

Based on the preliminary specifications, power versus vehicle speed requirements were developed. The gross vehicle weight used in the analysis is 1633 kg (3600 lbs), consisting of 340 kg (750 lbs) for the power train, 1021 kg (2250 lbs)for the body, and 272 kg (600 lbs) for four passengers Initially, the constant acceleration to the Schedule D cruise speed was used; however, upon further investigation, it was found that the energy consumed during Schedule D is a function of the acceleration profile. Three profiles were selected for evaluation:

(1) Constant acceleration at 0.72 m/s^2 (1.61 mph/sec) up to 72.4 km/hr (45 mph).

(2) Initial acceleration at 1.12 m/s^2 (2.50 mph/sec) up to 36.2 km/hr (22.5 mph), then 0.56 m/s^2 (1.25 mph/sec) up to 72.4 km/hr (45 mph).

(3) Initial acceleration at 2.24 m/s^2 (5.00 mph/sec) up to 12.1 km/hr (7.5 mph), then constant power for acceleration (declines from 2.24 to 0.38 m/s^2 at 72.4 km/hr (45 mph).

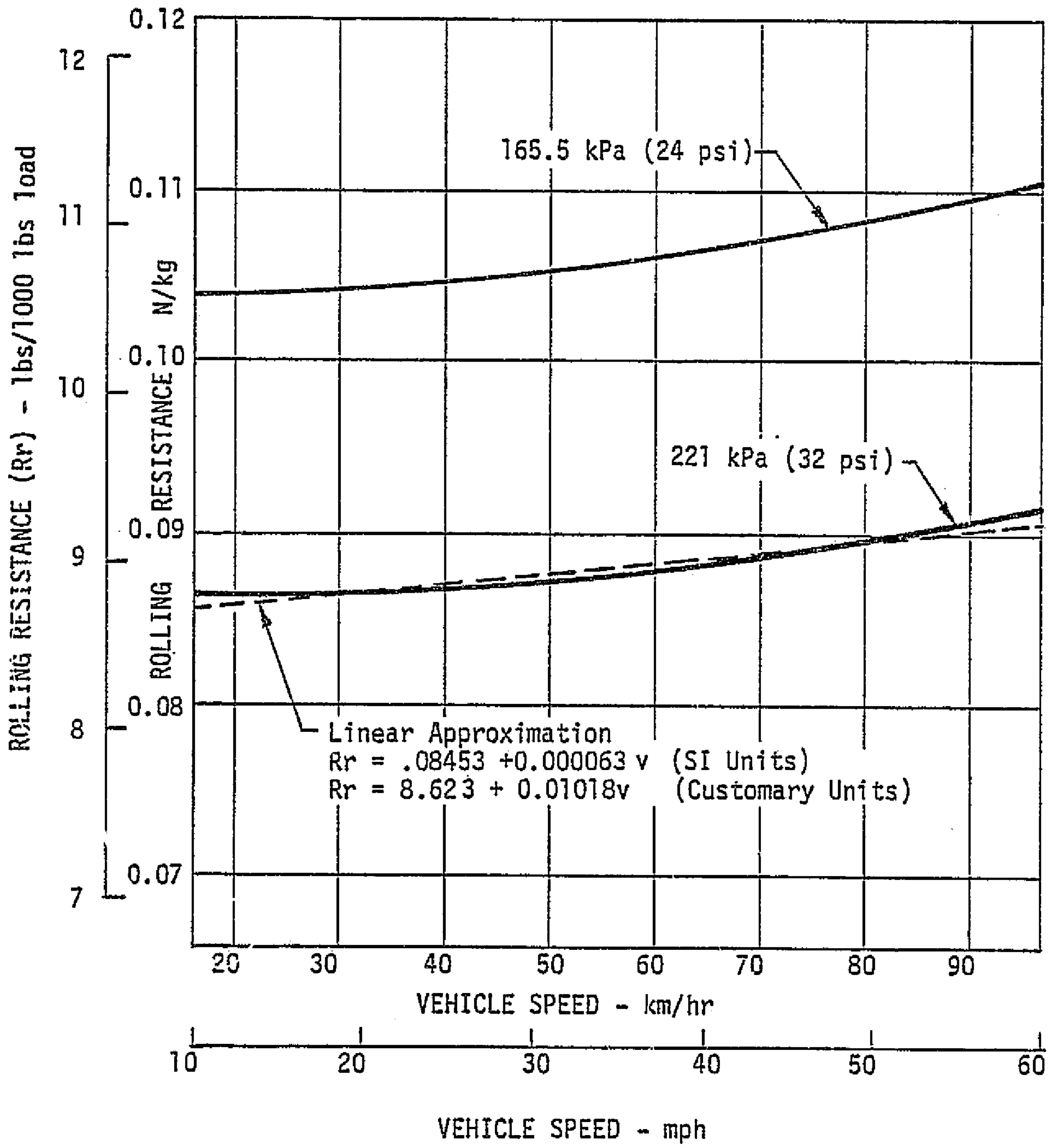


Figure 3. - Tire Rolling Resistance vs Vehicle Speed for 165 R 13 Steel Belted Radial Tires. (Load Range B).

The first profile represents the constant acceleration. The second profile represents acceleration using a two-speed transmission. The shift point for the transmission was arbitrarily set at half of the cruise speed with a 2 to 1 change in gear ratio. The accelerations were calculated to achieve 72.4 km/hr (45 mph) cruise speeds in 28 seconds. The principal objective in using the transmission was to avoid the high peak battery current associated with the first profile. The third profile was designed to maintain battery current more nearly constant during acceleration. The profile was obtained by combining a high initial acceleration within motor limits with constant power for acceleration during the remainder of the acceleration period. Gear ratio and shift speed do not influence the energy consumption in the "constant power" profile.

The power requirements versus vehicle speed for these acceleration profiles are given in figures 4, 5, and 6. These curves illustrate the motor power required to propel the vehicle during acceleration to 72.4 km/hr (45 mph) and also the power required during constant speed cruise up to 96.6 km/hr (60 mph). The three curves along the X-axis are the power required to overcome the losses associated with constant speed cruise conditions. The uppermost curve represents the total power required during the acceleration period. The added power for acceleration is comprised of two elements; the acceleration of a mass according to Newton's Second Law and the power required to overcome the additional mechanical losses attributed to increased torque during acceleration. The vehicle parameters used in these examples are listed in section 3.3.

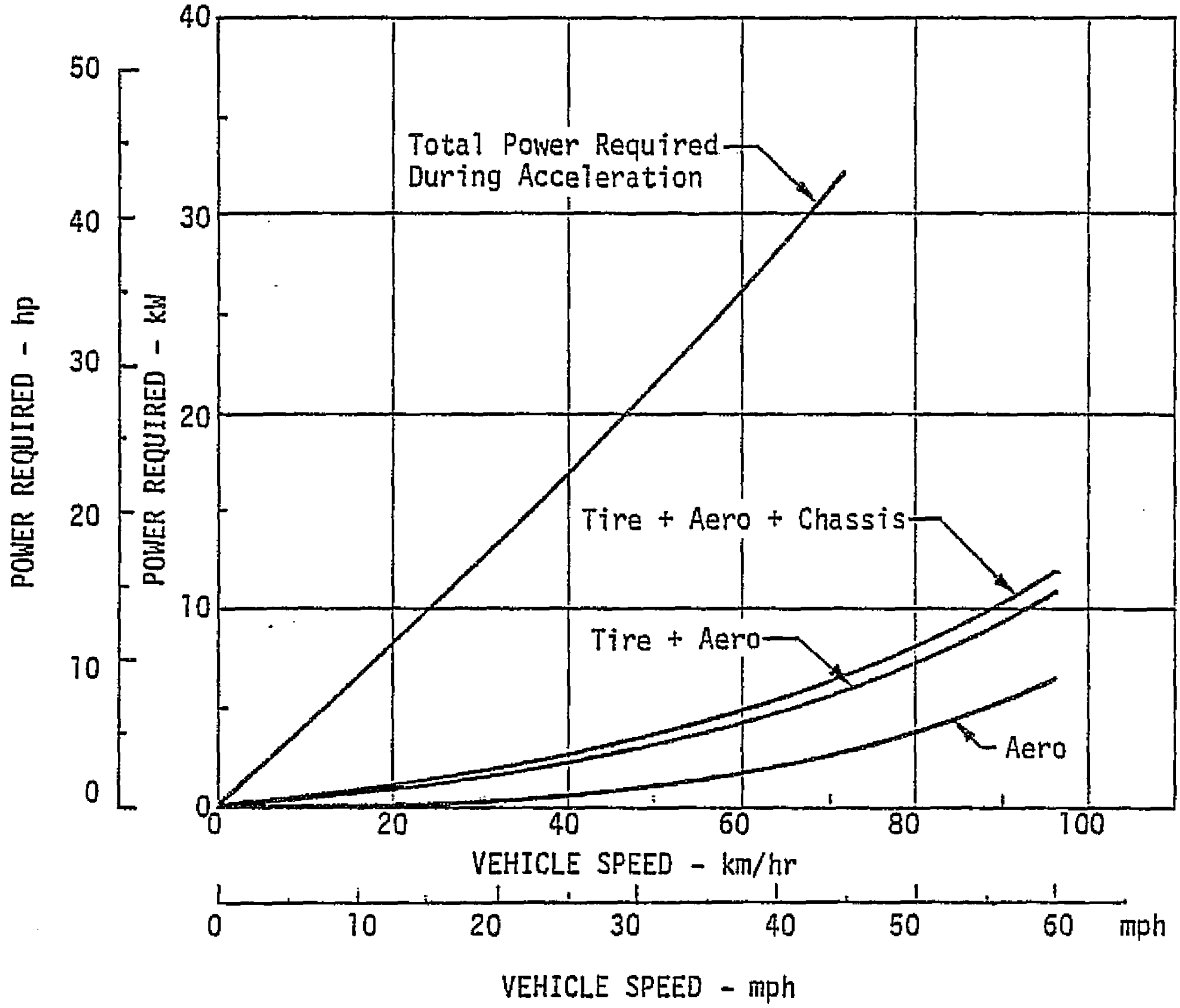
For these three acceleration profiles, the peak power and energy consumption during acceleration to 72.4 km/hr (45 mph) in 28 seconds are:

Acceleration Profile	Peak Power During Acceleration kW (hp)	Energy Consumption During Acceleration MJ (Whr)	Distance Traveled km (mi)	Average Energy Consumption Rate During Acceleration MJ/km (Whr/mi)
Constant, $0.72\ m/s^2$	31.7 (42.5)	0.544 (151)	0.282 (0.175)	3.11 (863)
$1.12\ m/s^2$, then $0.56\ m/s^2$	26.1 (35.0)	0.547 (152)	0.325 (0.202)	2.70 (749)
$2.24\ m/s^2$, then Constant Power	19.6 (26.3)	0.565 (157)	0.374 (0.232)	2.44 (677)

Note: The energy consumption and distance traveled data was extracted from computer simulation runs made during the preliminary analysis. Assumptions used in the simulation were:

- Gear efficiency: 93%
- Motor efficiency: 100%
- Controller efficiency: 100%
- Battery internal voltage: 96V
- Battery internal resistance: 0.048 ohms (total)

Seemingly, the energy required to accelerate the example vehicle to 72.4 km/hr (45 mph) in 28 seconds would be the same regardless of the acceleration

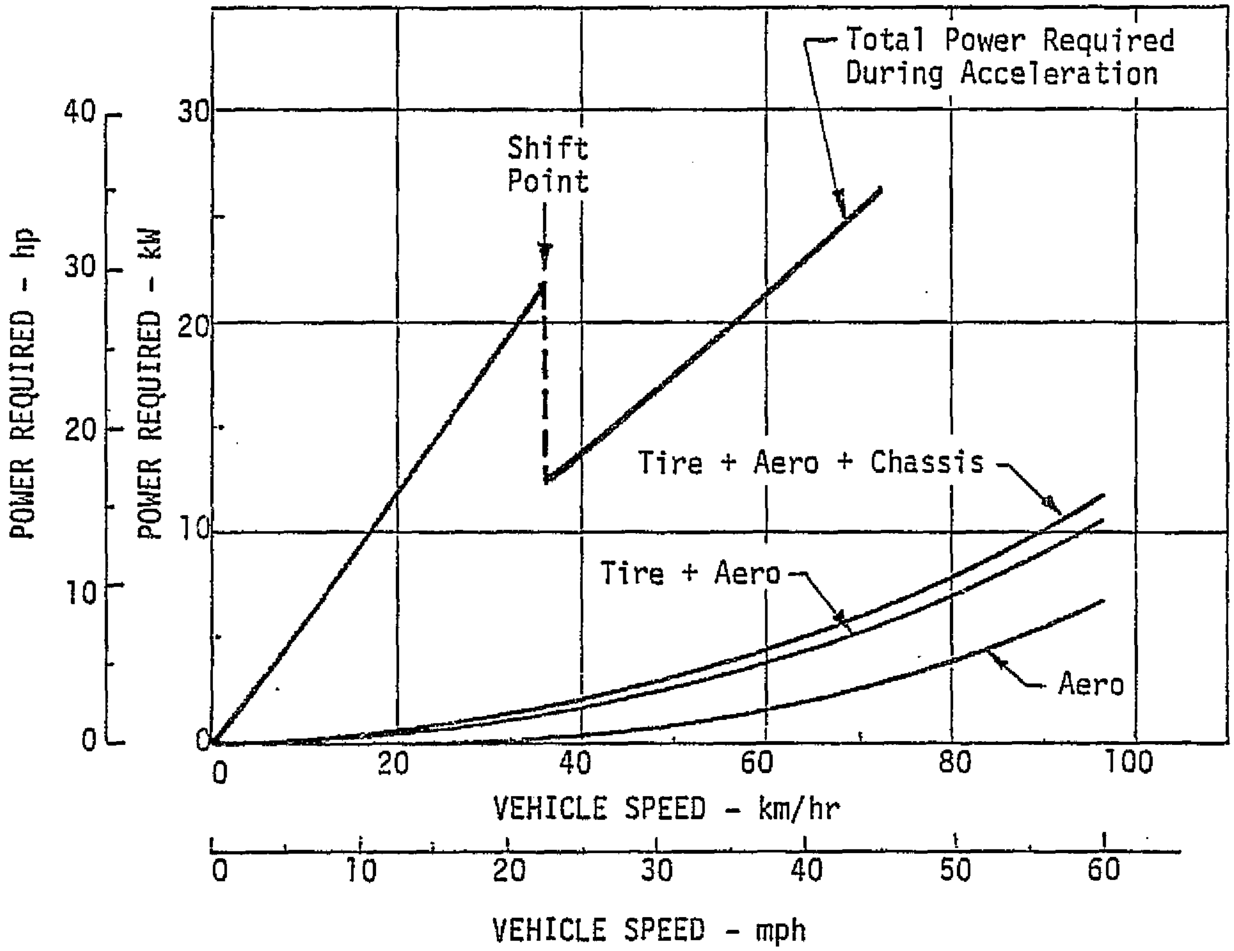


Gross Vehicle Wt. = 1633 kg (3600 lbs)

Acceleration = 0.72 m/s^2 (1.61 mph/s)

Theoretical Performance Based on 100% Efficiency for the Controller and Motor

Figure 4. - Power Required vs Vehicle Speed for the Constant Acceleration Profile

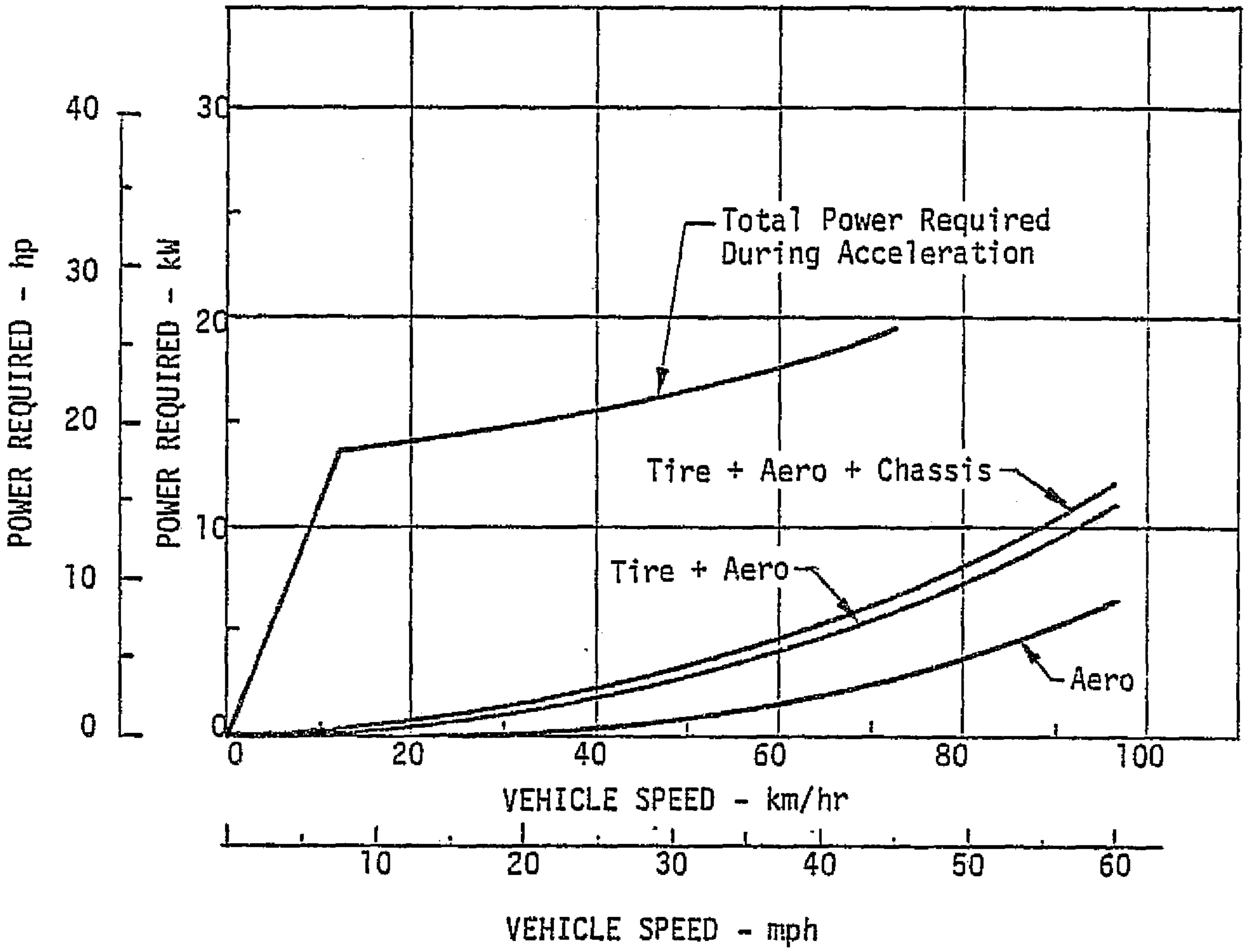


Gross Vehicle Weight - 1633 kg (3600 lbs)

Acceleration
Initial = 1.12 m/s^2 (2.5 mph/s) to 36.2 km/hr (22.5 mph)
Final =0.56 m/s^2 (1.25 mph/s) for 36.2 to 72.4 km/hr

Theoretical Performance Based on 100% Efficiency for the Controller and Motor

Figure 5. - Power Required vs Vehicle Speed for the Two-step Constant Acceleration Profile



Gross Vehicle Weight = 1633 kg (3600 lbs)

Acceleration
Initial = 2.24 m/s^2 (5.0 mph/s) to 12.1 km/hr (7.5 mph)
Final = Decreases from 2.24 m/s^2 to 0.38 m/s^2 at 72.4 km/hr (45 mph)

Theoretical Performance Based on 100% Efficiency for the Controller and Motor

Figure 6. - Power Required vs Vehicle Speed for the Constant Power Acceleration Profile

profile. However, there are three not so apparent differences which contribute to variations in Schedule D travel range:

(1) Slightly greater energy is required for the more rapid acceleration profiles because the vehicle is traveling at higher speeds earlier in the cycle. This creates greater total aerodynamic losses and, therefore, more energy is required.

(2) Higher acceleration also results in greater distance traveled even though the terminal speed and total time are identical. This compensates for the greater energy consumed.

(3) The reduction in peak power results in lower battery current which increases the battery efficiency.

Based on the preliminary analysis, the "constant power" approach requires less energy per unit distance to accelerate to the Schedule D cruise speed. The predicted Schedule D range based on the constant power acceleration profile should be greater than the others. For this reason, the constant power profile was selected as the baseline for evaluating performance of the candidate power train systems.

3.5 THEORETICAL PERFORMANCE

As a baseline for establishing the predicted performance of the power train design, the theoretical energy consumption during the SAE Schedule D driving cycle was computed. In this example, the controller and motor are considered to be operating at 100% efficiency. The other elements of the power train are the same as the preliminary specifications described. Using the constant acceleration profile, the motor power requirement versus cycle time is given in figure 7. The area under each segment of the curve represents the energy "consumed" or "recovered" during one repetition of the Schedule D driving cycle.

Based on this theoretical example, a total of 0.572 MJ (159 Whr) are consumed during each repetition of the driving cycle with regenerative braking. The energy consumed during the acceleration period is 0.444 MJ (123 Whr). An additional 0.328 MJ (91 Whr) is consumed during the cruise period. During the regenerative braking period, 0.20 MJ (56 Whr) are recovered. The efficiency of recharging the battery was assumed to be 80%. Using the energy available from 16 batteries with a total capacity of 43.94 MJ (12205 Whr), the theoretical Schedule D range is 120.0 km (75 mi). This is twice the range being achieved by existing vehicles with equivalent battery energy (ref. table IV). Energy recovery through regenerative braking theoretically increases the Schedule D travel range by 35%. These values are calculated and tabulated in table VI.

Comparison ranges for current vehicles against the theoretical 100% efficiency model indicate that existing drive systems are averaging less than 50% efficiency over the Schedule D cycle (ref. table VII). The combined motor and controller efficiency during constant speed cruise at 64.4 km/hr (40 mph) is relatively high - between 67 and 77% based on a comparison of ranges actually achieved versus the theoretically possible range of 154.7 km (96.1 mi). Cruise efficiencies of this

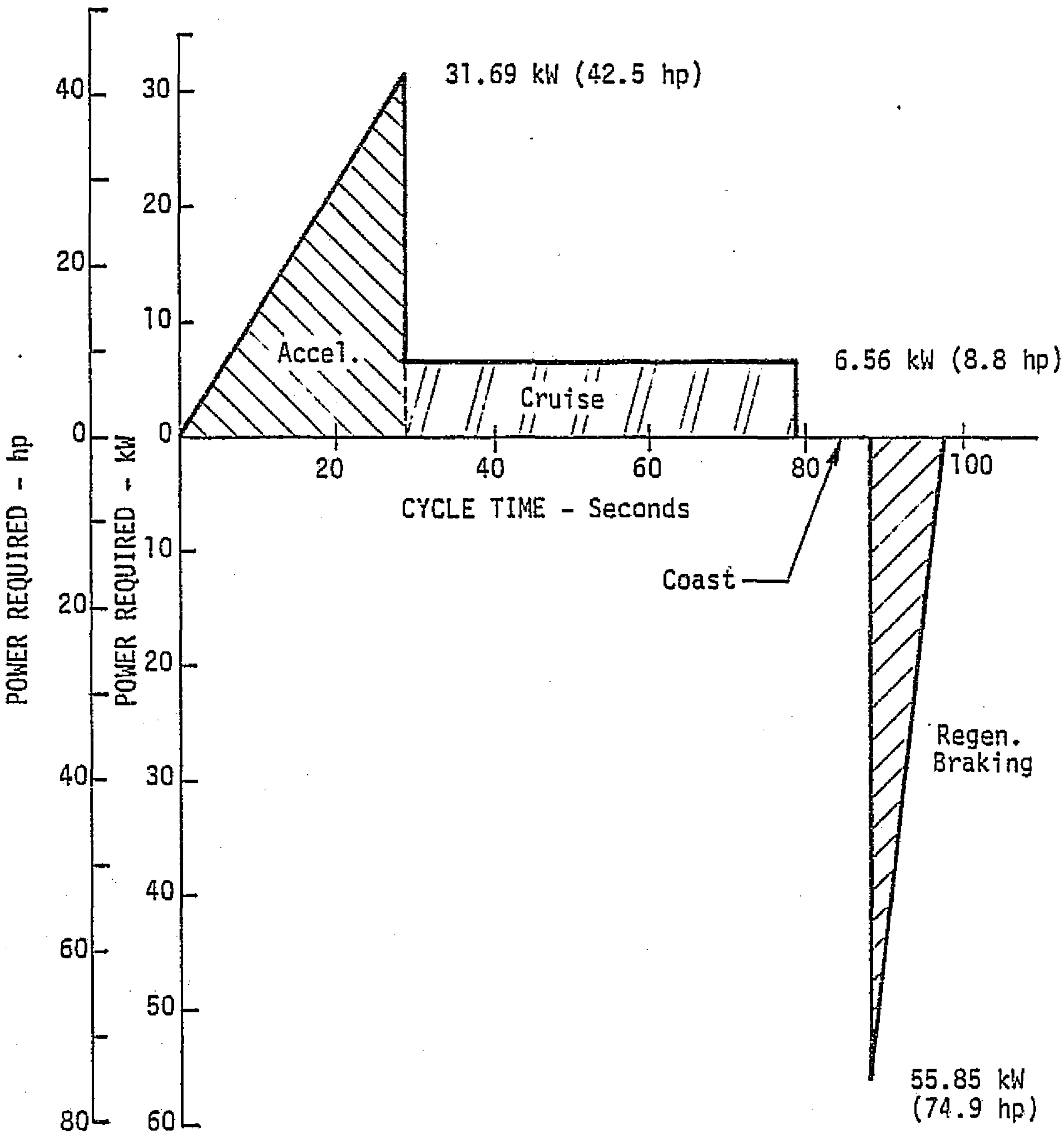


Figure 7. - Power Required vs Cycle Time for Theoretical Performance Based on SAE Schedule D Driving Cycle

TABLE VI - THEORETICAL PERFORMANCE BASED ON SCHEDULE D DRIVING CYCLE

	WITH REGENERATIVE BRAKING	W/O REGENERATIVE BRAKING
ENERGY CONSUMPTION		
ACCELERATION	$.5 \times \frac{31.69}{1000} \times 28 =$ .444	.444 (57%)
CRUISE	$\frac{6.56}{1000} \times 50 =$ .328	.328 (43%)
REGEN. BRAKING	$.8 \times .5 \times \frac{55.9}{1000} \times 9 =$ (.201)	0
TOTAL	.572 MJ/cy (159 Wh/cy)	.772 MJ/cy (214 Wh/cy)
SCHEDULE D CYCLES	$\frac{43.94\ MJ}{.571\ MJ/cy}$ = 77 cycles	$\frac{43.9}{.772}$ = 57 cycles
RANGE--SCHEDULE D	$\frac{1.563\ km}{cycle} \times 77 =$ 120 km (75 mi)	$\frac{1.563\ km}{cycle} \times 57 =$ 89 km (55 mi)
IMPROVEMENT WITH REGENERATIVE BRAKING	$\frac{120 - 89}{89}$ = 35%	--
ENERGY CONSUMPTION DURING CRUISE @ 72.4 km/hr (45 mph)	$\frac{.328\ MJ/cy}{1.006\ km/cy}$ = .326 MJ/km	.326 MJ/km
CRUISE RANGE @ 72.4 km/hr (45 mph)	$\frac{43.94\ MJ}{.326\ MJ/km}$ = 134.7 km (83.7 mi)	134.7 km (83.7 mi)
ENERGY CONSUMPTION* DURING CRUISE @ 64.4 km/hr (40 mph)	$\frac{.254\ MJ/cy}{.894\ km/cy}$ = .284 MJ/km	.284 MJ/km
CRUISE RANGE* @ 64.4 km/hr (40 mph)	$\frac{43.94}{.284}$ = 154.7 km (96.1 mi)	154.7 km (96.1 mi)

* Cruise Mode modified to 64.4 km/hr (40 mph)

ASSUME: Motor/Controller @ 100% Efficiency

(16) Batteries at .0929 MJ/kg (11.7 Wh/lb) at 75A

Total Energy Available = 16 x 29.6 kg x .0929 = 43.94 MJ (12,205 Wh) order of magnitude are considered to be very good, and it is unlikely that significant improvements can be made in this area. The conclusion is reached that there is considerable room for increasing range by improving motor and controller efficiency during the acceleration and regenerative braking periods of the driving cycle. In section 4, the final candidate power train configurations are discussed and evaluated using the computer simulation with the SAE Schedule D driving cycle.

TABLE VII - ADJUSTED PERFORMANCE COMPARISON
THEORETICAL SYSTEM VS.
SELECTED EXISTING VEHICLES

VEHICLE/SYSTEM		CDA I	CDA II	RIPP-ELEC	THEOR. SYS.
MOTOR TYPE		SHUNT	SHUNT	SERIES	--
CONTROLLER TYPE		SCR	TRANS	TRANS	--
RANGE SCHEDULE D	km	45.5	59.7	--	120
	mi	28.3	37.1	--	75
CRUISE RANGE 64.4 km/hr	km	107	114	98	154.7
(40 mph)	mi	67	71	61	96.1

4.0 FINAL ALTERNATES

4.1 POWER TRAIN CONFIGURATIONS

During the literature and industry review, the power train components and technology which represented the state-of-the-art were identified. The next step was to evaluate and select components for a state-of-the-art (SOTA) power train design. The components which were considered as applicable to a SOTA design were studied in more detail with respect to their capacity for meeting the vehicle requirements and preliminary performance specifications established in section 3. The selection criteria placed heavy emphasis on performance, efficiency, size, weight, and interaction with the other components.

Three power train configurations were developed which were felt to be suitable designs for a SOTA electric vehicle. These power train configurations are described below and illustrated in the pictorial drawings of figures 8, 9, and 10.

(1) Rear wheel drive: frame mounted motor driving a two-speed rigid transaxle.

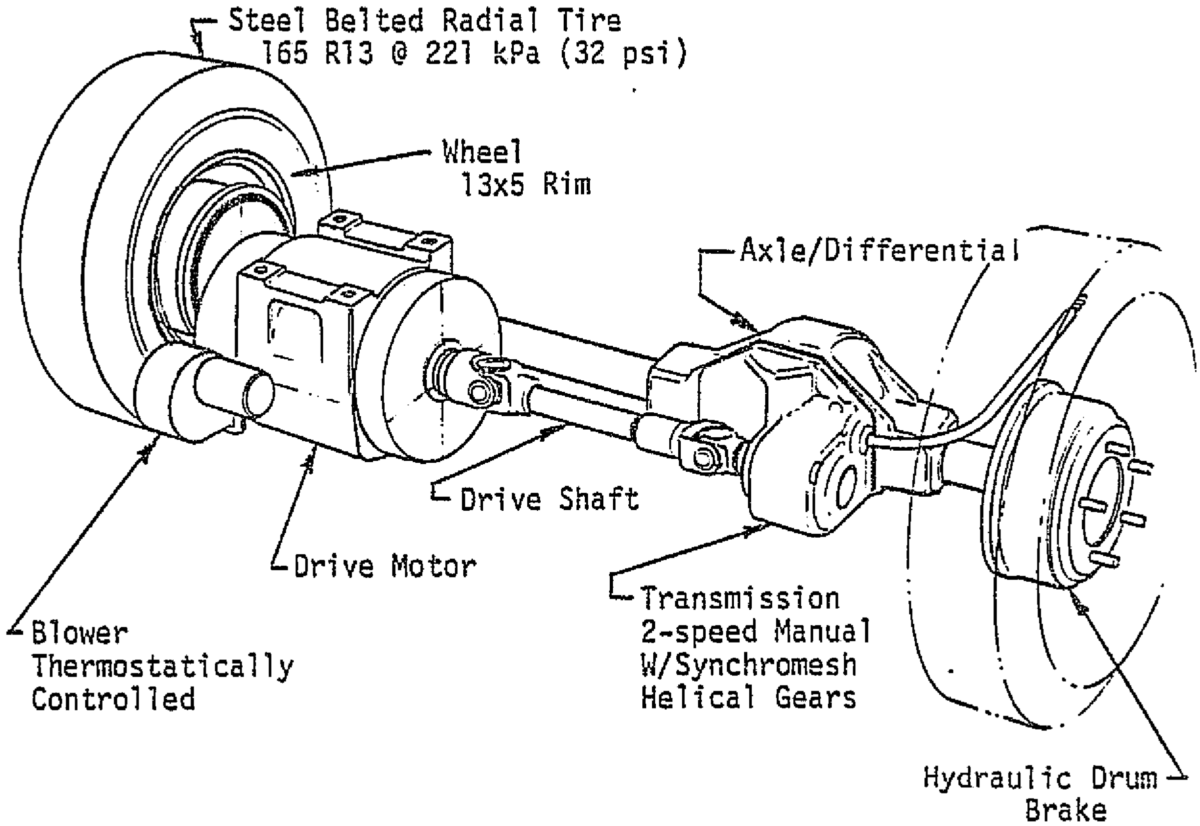
(2) Front or rear wheel drive, independent suspension: motor flange mounted to a two-speed transaxle unit.

(3) Front or rear wheel drive, fixed ratio drive: motor driving a Hy-Vo chain to a spiral bevel gear differential.

These combinations of components were selected because of their simplicity, compactness, low weight, and potential for high overall efficiency.

During the SOTA assessment, steel belted radial tires were identified as the tire with the lowest rolling resistance; therefore, this tire construction was selected for the SOTA design. A 165 R 13 tire was selected as the appropriate size for a four-passenger vehicle in the 1361 kg (3000 lb) class based on the load capacity recommendations in the Tire and Rim Association Manual supplemented by consideration for meeting the preliminary performance specification.

The selection of the other mechanical elements of these configurations was not as difficult as the motor and controller selection in that performance of these items in terms of efficiency has been established and recorded in sufficient detail to make engineering comparisons. The efficiencies of the motor and controller vary significantly with design and load, which makes their selection difficult. For this reason, a number of motor and controller combinations were evaluated using these configurations as models for the analysis.



Note: A line drawing of this configuration is given in Appendix B.

Figure 8. - Two-Speed Rigid Transaxle EV Power Train

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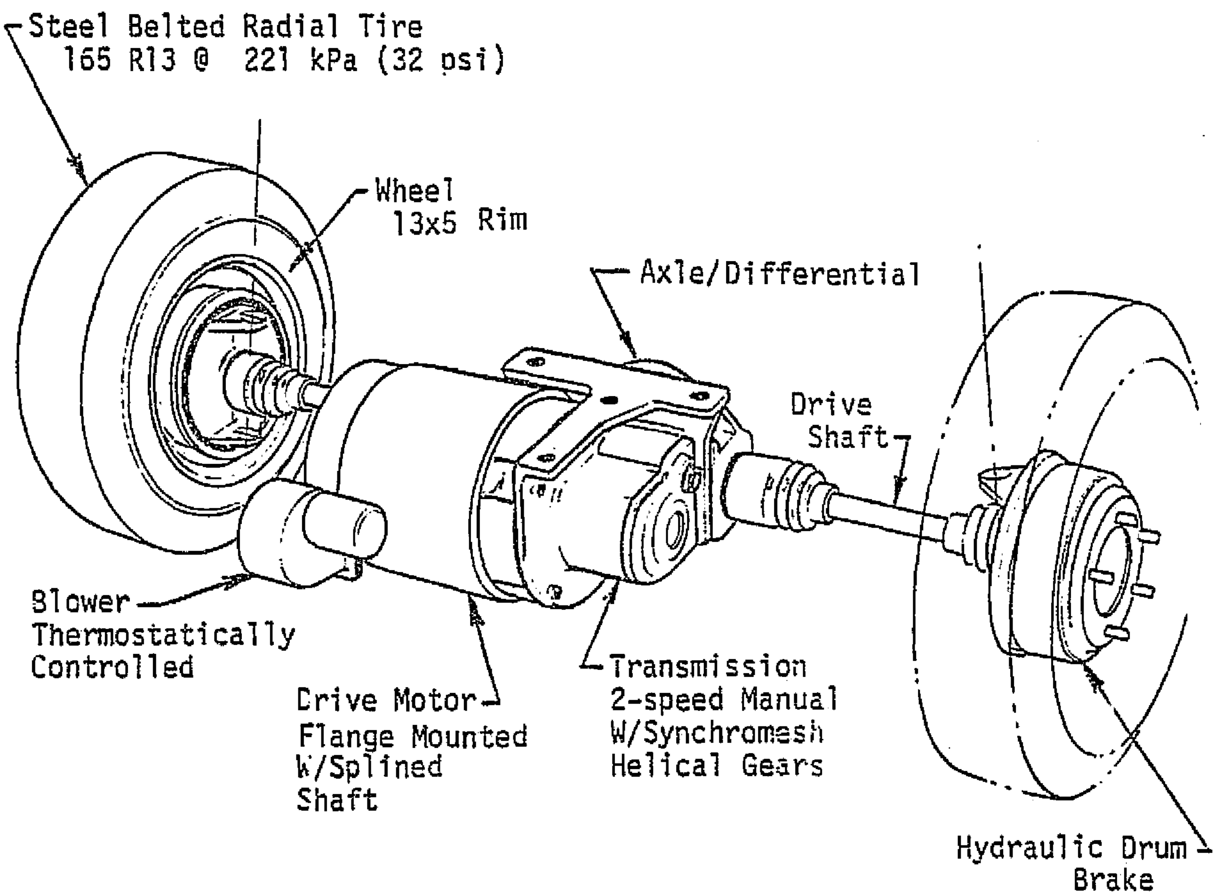


Figure 9. - Two-Speed Independent Suspension Transaxle EV Power Train

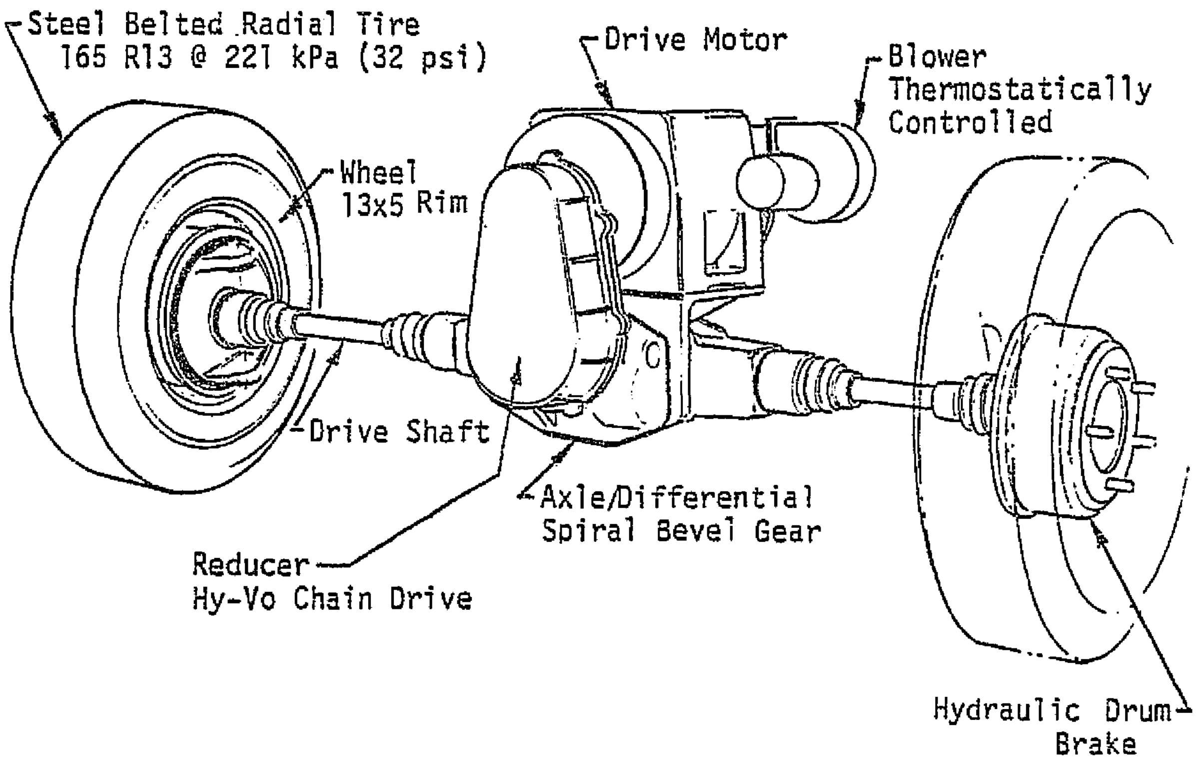


Figure 10. - Fixed-Ratio Independent Suspension EV Power Train

Two categories of motor drive systems were identified during the industry review as SOTA candidates:

(1) The separately excited DC motor with DC chopper controller (s).

(2) The AC induction motor with 3-phase inverter controller.

To optimize the design for range on the Schedule D driving cycle and ensure that valid alternatives were not arbitrarily eliminated, several DC and AC motor/controller combinations were selected for a more thorough evaluation in the computer analysis program. Exciting voltage for the AC motors and field current for the DC motors was optimized for each over their speed and torque ranges. A number of transmission ratios were simulated to determine optimum values for greatest range.

4.2 SELECTED MOTORS

Based on the results of the preliminary analysis and theoretical performance study, a screening was made to select the final candidate motors. Using the manufacturer's literature obtained during the component search, the performance of each of these motors was evaluated in terms of voltage, power available, efficiency of operation, and weight. Relatively few motors were identified as acceptable candidates (table VIII). The majority were eliminated because of insufficient capacity for acceleration and regenerative braking or because of poor power-to-weight ratio. For the final optimization and determination of the drive system with maximum range capability, the five motors identified by asterisks in table VIII were selected for detailed analysis. The selected motors are not unique and probably similar designs are available from other manufacturers, but these were considered to be representative of the SOTA and to be readily available.

The final selection of the motor sizes was predicated upon a desire to bracket the anticipated power requirement with motors slightly smaller and slightly larger than the anticipated requirements. Motor sizing for the Schedule D driving cycle requires a tradeoff between capacity for acceleration and regenerative braking. One motor of each type (DC and AC) was chosen with sufficient capability to provide adequate power with emphasis on the acceleration requirement (developed in section 3.4) and accepting the available capacity for regenerative braking. The higher capacity motors were chosen to provide maximum capacity for regenerative braking previously calculated in section 3.5 on theoretical performance.

Two variations of the 215T frame AC motor were selected to determine the relative value of efficiency versus weight in terms of vehicle range. The GE 215T is rated at 82% efficiency (at 60 Hz) with a weight of 38.6 kg (85 lbs) and the Reliance motor is rated at 89% (at 60 Hz) with a weight of 56.7 kg (125 lbs). The Northwest and Avon motors were not selected because of their lower published power-to-weight ratios compared to the GE motors. These heavier motors may have been designed with lower temperature rise or otherwise for greater life at rating. Insufficient information was available to select either of them over the others based on published ratings. The predicted performance on the SAE Schedule D driving cycle is presented in section 4.4.

The AC motors selected for the final analysis are standard frome sizes which have been wound to operate in conjunction with a variable voltage/variable frequency (VV/VF) AC controller. The voltage of the stator winding is determined by

TABLE VIII - CANDIDATE MOTORS FOR THE SOTA POWER TRAIN

TYPE	FRAME/MODEL	WEIGHT kg (lbs)	NO LOAD RPM	CONT. RATING POWER kW (hp)	CONT. RATING RPM	30 SECOND RATING POWER kW (hp)	30 SECOND RATING RPM	30 SECOND RATING kW/kg (hp/lb)
DC	*GE 2346	68.0 (150)	7800	22.6 (30.3)	5300	35.5 (47.6)	2500	.522 (.317)
	*GE 2364	104.3 (230)	6500	29.2 (39.2)	4900	49.2 (66.0)	3300	.472 (.287)
	NW 6473	104.3 (230)	4000	15.7 (20.1)	2450	31.3 (42.0)	1750	.300 (.183)
	AVON 14 (EVO)	124.7 (275)	5500	14.7 (19.7)	3450	35.5 (47.6)	2500	.285 (.173)
AC**	*GE 184T	31.3 (69)	9000	19.2 (25.7)	9000	44.7 (60.0)	9000	1.428 (.870)
	*GE 215T	38.6 (85)	9000	38.3 (51.4)	9000	88.1 (118.2)	9000	2.282 (1.391)
	*RELIANCE 215T	56.7 (125)	9000	38.3 (51.4)	9000	88.1 (118.2)	9000	1.554 (.946)

*Motors Selected For Final Evaluation

**Wound for 68 volts at 240 Hz

maximum available controller output voltage as established by the battery voltage (96 V). This principle of VV/VF operation for AC motors is discussed in section 4.2.1 These motors when operated at frequencies other than 60Hz will have losses different than their design values. Performance at variable speeds with the necessary variable frequency inverter was established by calculation.

4.2.1 Motor Performance Characteristics

Typically, the motor performance data developed and supplied by manufacturers is for constant speed/continuous duty operation and is inadequate for evaluation in variable speed situations such as those encountered in an electric vehicle. Their data is usually limited to the maximum continuous duty ratings at a specific speed. In order to evaluate motor performance over the range of torque and speeds experienced in electric vehicles, the manufacturers' data was transformed into a complete performance mapping in terms of efficiency, speed, and torque.

Manufacturers' performance curves such as those shown in figures 11 and 12 were converted into a format set up as input to the computer analysis program. The result of the conversion of the manufacturer's data for the BT 2364 motor (wound for 96 volt operation) into the necessary format is given in figure 13. This plot of motor efficiency versus motor speed over the entire torque range of the motor becomes the input to the computer simulation program for the Schedule D driving cycle. The computer analysis used this data to select the optimum operating point for maximum efficiency. This data format is explained in more detail in Appendix E on the computer simulation program.

The performance characteristics curves for the AC motors are given in figures 14, 15, and 16. These plots of motor efficiency were derived from manufacturers' data based on operation at 230 volts and 60 Hz. These AC motors are based on standard 230 V, 60 Hz, 3-phase frame sizes wound to operate at voltages commensurate with higher and lower frequencies using a variable voltage/variable frequency AC controller (approximately constant volts/Hz). Using the variable frequency control technique, standard 60 Hz motors can be operated at multiples of their normal rated speed, which results in increased power without changing the rated torque (i.e., current).

For example, a standard 215T frame size motor rated at 7.5 kW (10 hp) at 1740 rpm has a rated full load torque of 40.8 Nm (30.1 ft lbs). Using a variable frequency source instead of the normal fixed 60 Hz input, this motor design can be operated at 300 Hz to achieve 9000 rpm at the same rated torque. The result is 5 times the rated 7.5 kW (10 hp), or 37.5 kW (50 hp) at 9000 rpm, without changing the rated torque. The mechanical change required is replacement of the original bearings with optional stock high speed bearings. The increased frequency and speed results in increased windage, friction, copper and core loss. Windage loss increase is controlled by removing the internal fan. Bearing loss is kept to a minimum by using precision bearings suitable for the high speed operation. Coper loss is not appreciably higher in motors of this size because the coil wire size is considerably smaller than the "skin depth" associated with 300 Hz. Core loss increases by the 1.4 power of frequency and 1.6 power of motor voltage. Per unit slip decreases with speed for constant volts/Hz ratio. Leakage flux core loss is related to primary current and also increases with frequency. All the above factors were included in the total motor loss as a function of load and speed. Figures 14 through 16 show the net effect on efficiency for these motors. Continuous full torque operation at higher than 60 Hz would require additional cooling.

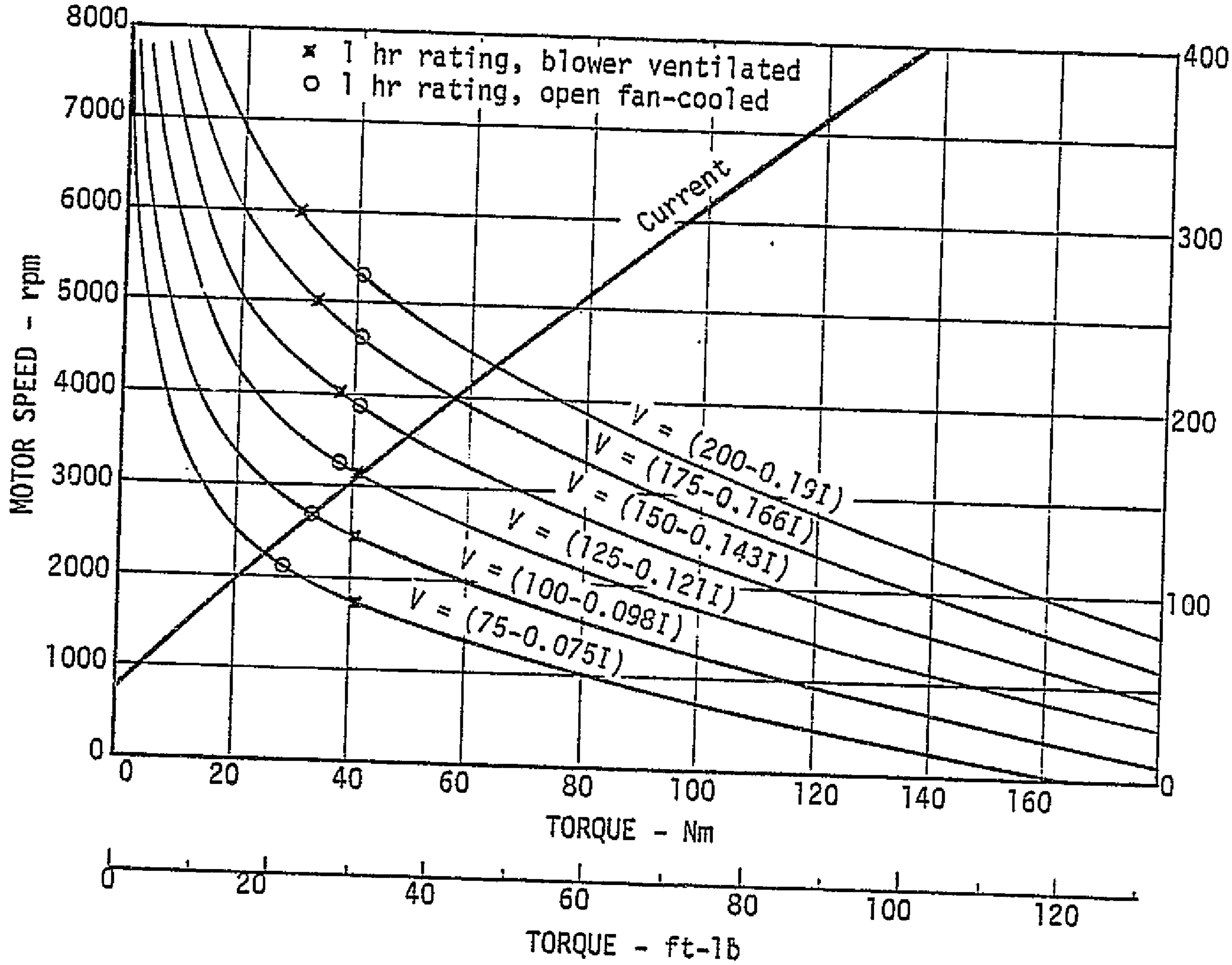


Figure 11. - Performance Characteristic Curves for the GE Model BT 2346 (DC Motor)

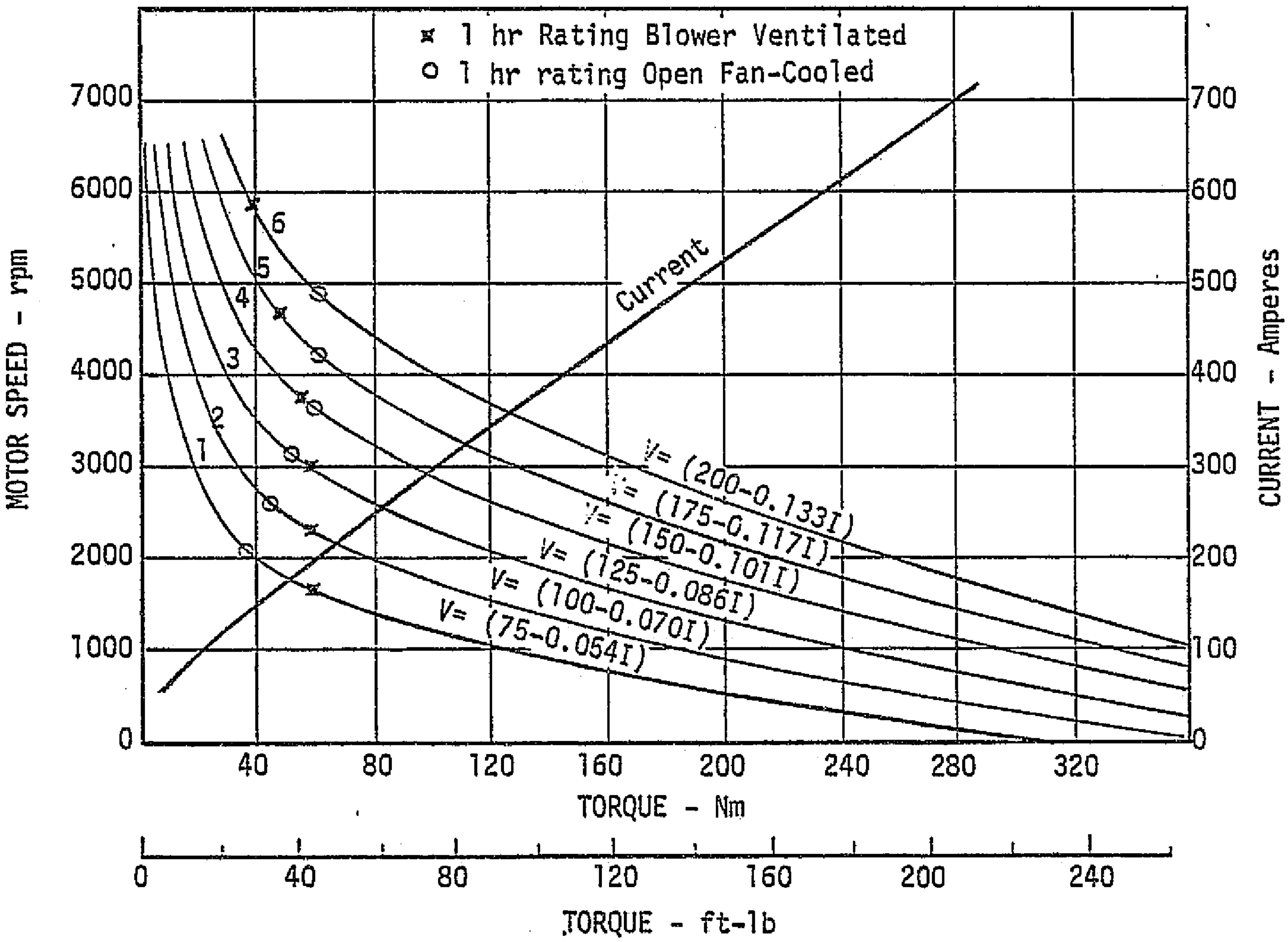


Figure 12. - Performance Characteristic Curves for the GE Model BT 2364 (DC Motor)

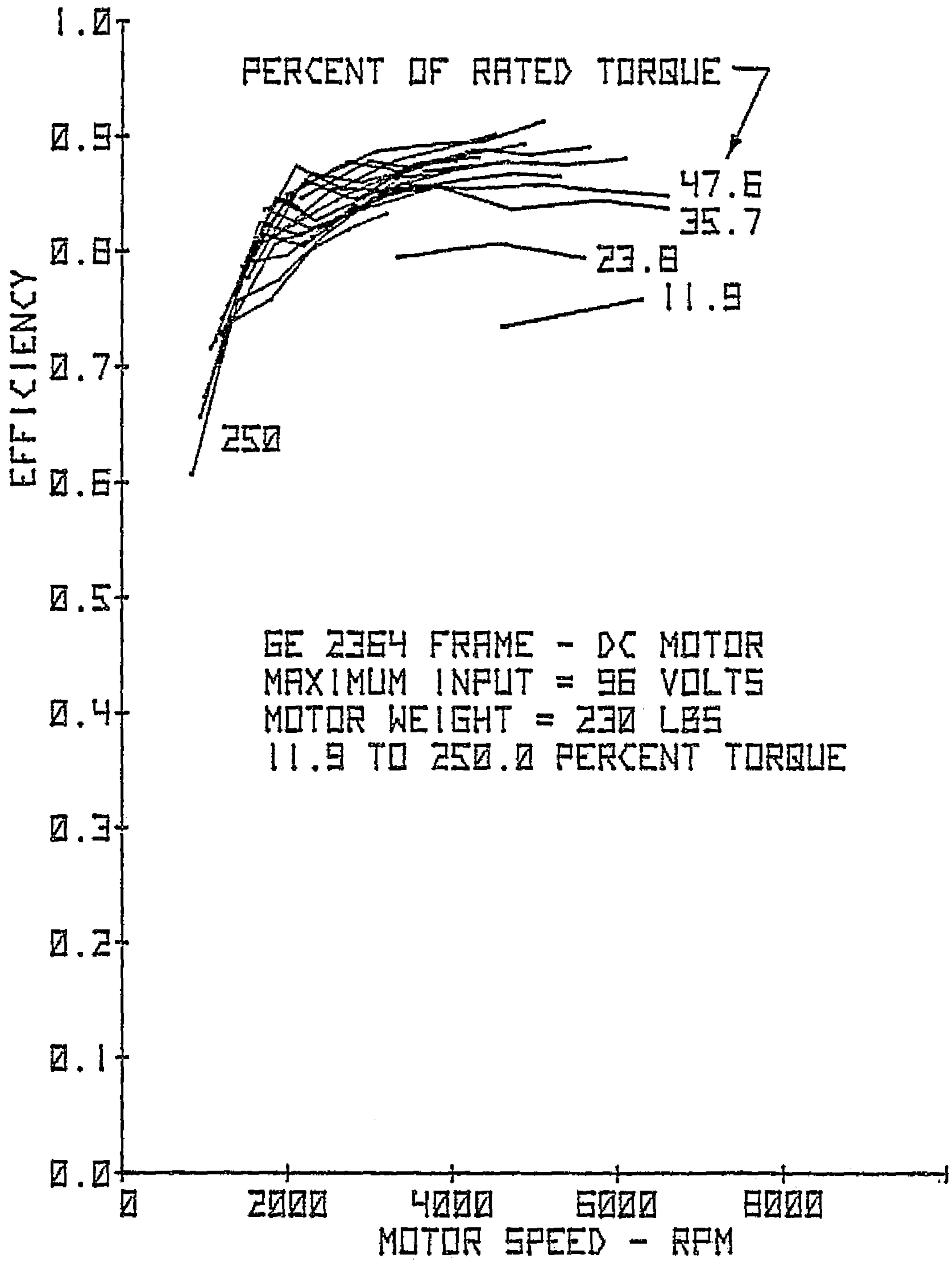


Figure 13. - Efficiency vs. Motor Speed for the GE BT 2364 (DC Motor)

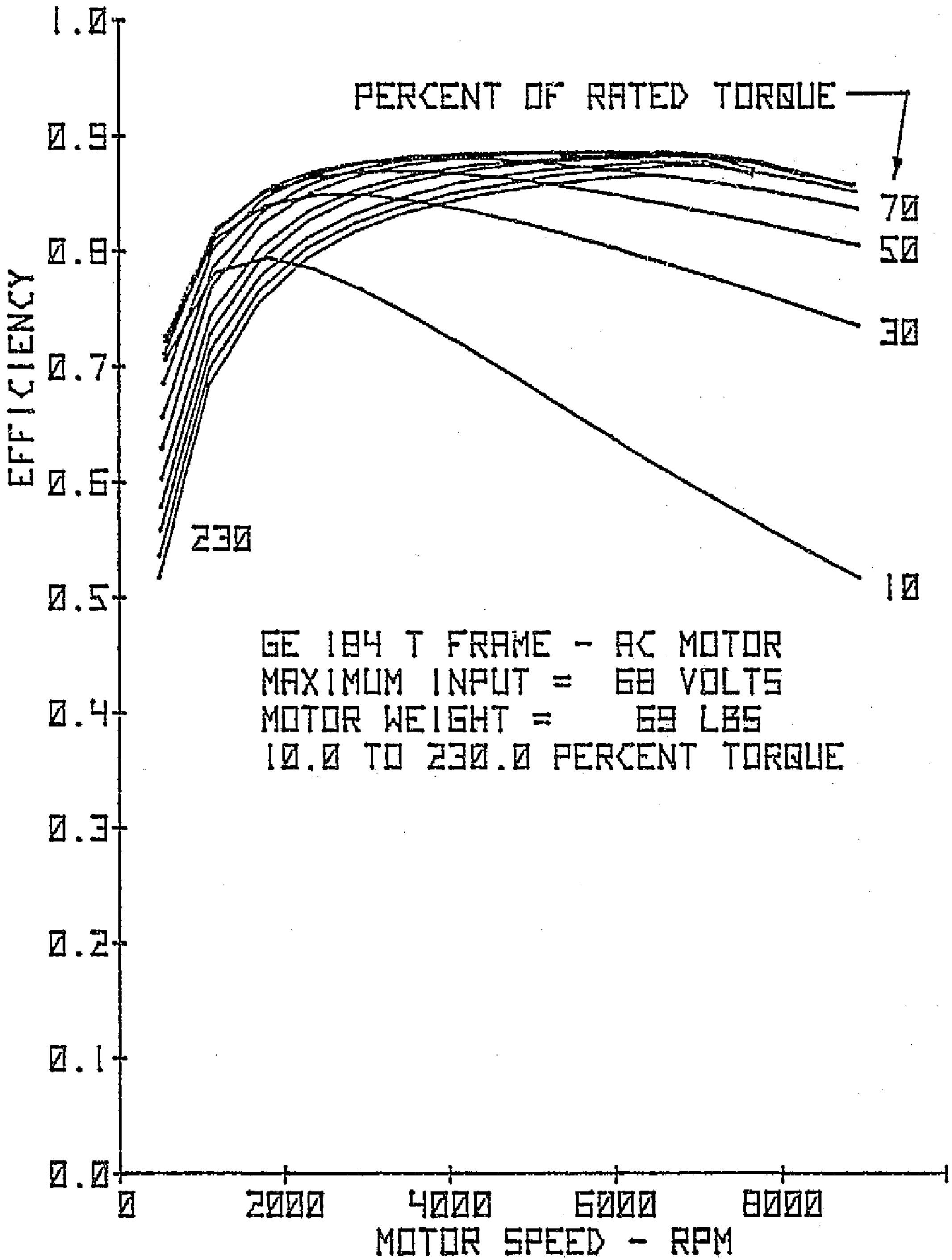


Figure 14. - Efficiency vs. Motor Speed for the GE 184T Frame (AC Motor)

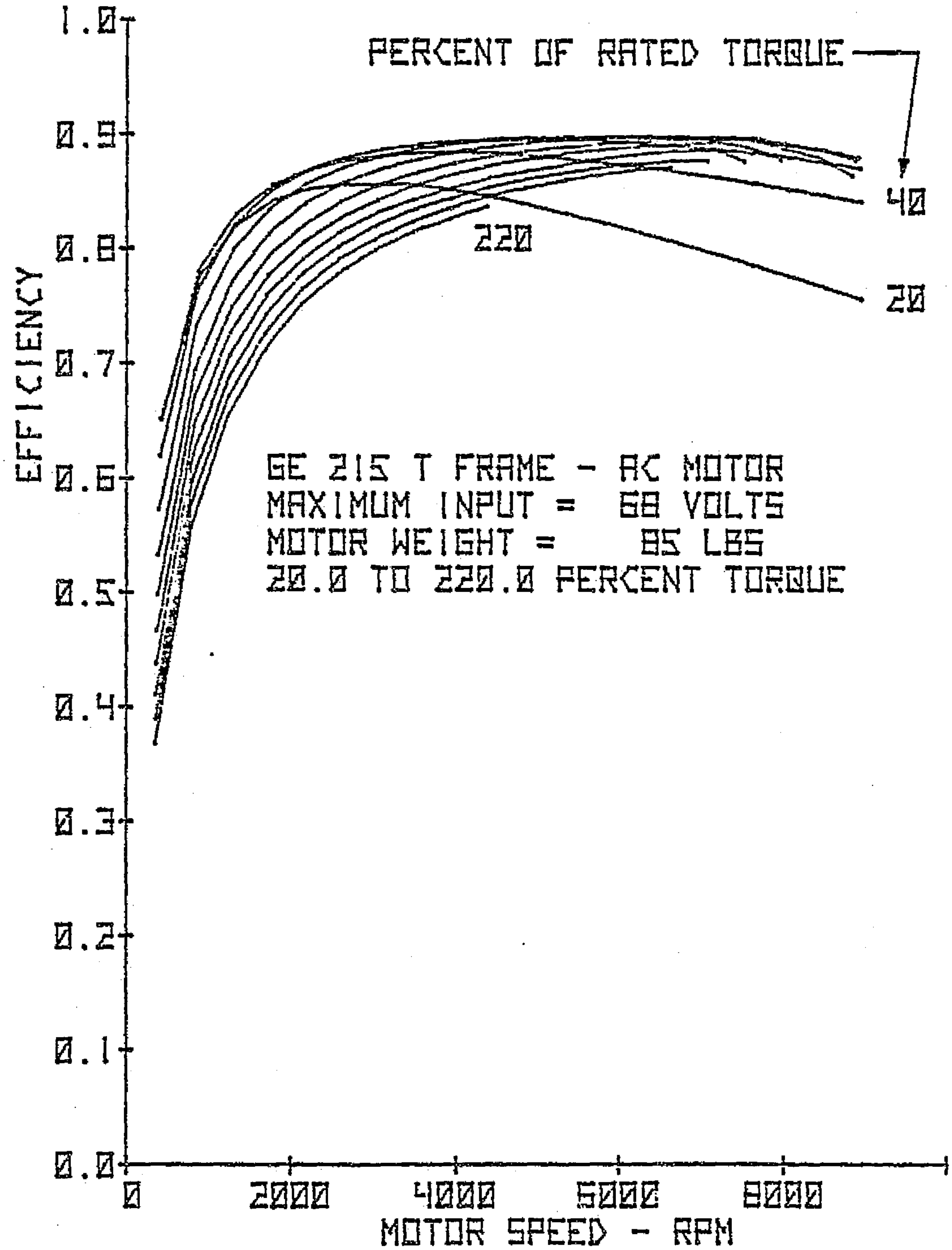


Figure 15. - Efficiency vs. Motor Speed for the GE 215T Frame (AC Motor)

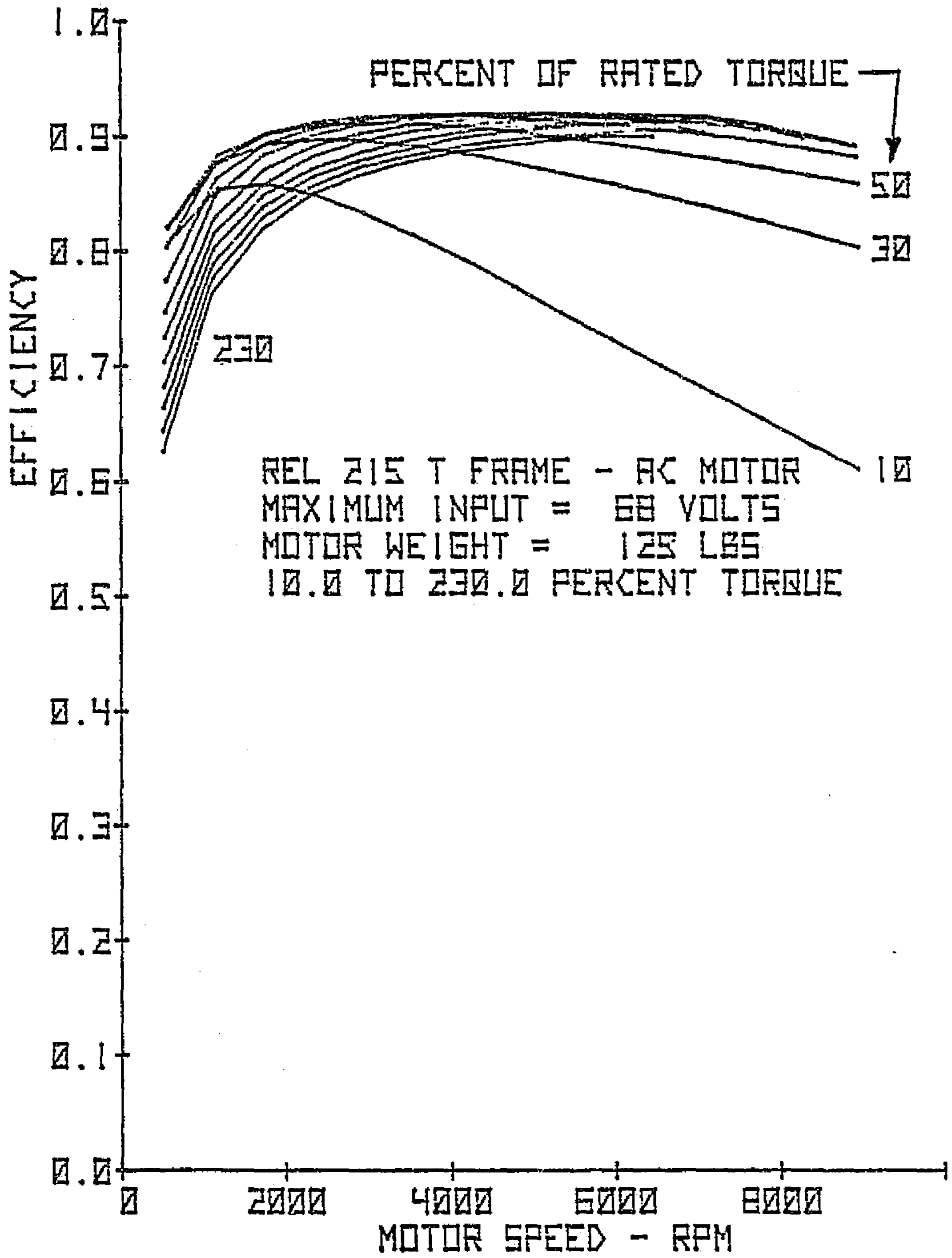


Figure 16. - Efficiency vs. Motor Speed for the RELIANCE 215T Frame (AC Motor)

The average motor loss for the aluminum frame 215T motor for the Schedule D cycle is 1.51 kW (ref. table D-1.2 to 1.5, Appendix D). Rated 60 H· oss for this motor is 1.65 kW (continuous). Air flow of 6,94 m^3/s (250 cfm) will result in an air temperature rise of 11°C (20°F) for 1.51 kW loss.

Operation at 88.6 km/hr (55 mph) constant speed results in calculated motor loss of 2.10 kW (ref. figure 42). Air temperature rise under this condition would be 15°C (27°F). Operation at 48.3 km/hr (30 mph) on a 10% grade results in a calculated motor loss of 3.15 kW with an air temperature rise of 23°C (41.4°F). With a fully charged battery, continuous operation on the 10% slope is limited by battery capacity to 12.6 minutes. Motor time constant will allow the 25% overload for this period of time without excessive temperature rise.

On an intermittent basis such as during acceleration and deceleration, these motors can be operated at 230% of their rated torque. This mode of operation is equivalent to high torque associated with normal startup.

4.2.2 Selection of Drive Ratio

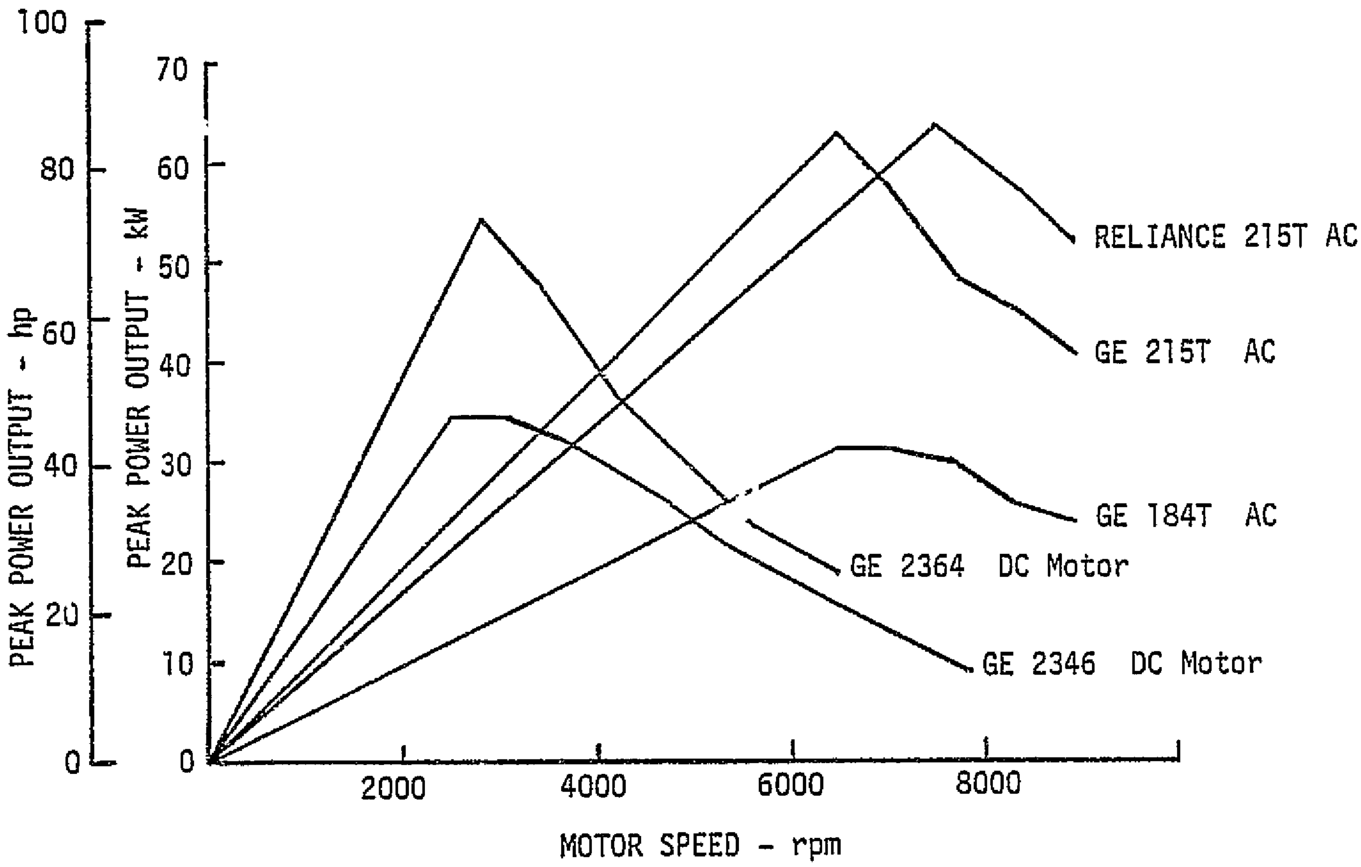
The first step in the selection of the drive ratio between the motor and tires is to establish the power available from the motor over its speed range. The peak power performance based on the 30-second rating (ref. table VIII) for each of the selected candidate motors is plotted in figure 17. The limits of the DC motors reflect their lower torque at high speeds because of the limitation of commutation associated with the high speed. The AC motors do not require commutators; therefore, they have no reduction in torque capability with higher speeds. Their limit is established by the mechanical aspect of rotation (i.e., balance and structural aspects) and by the output voltage of the controller which is established by the battery voltage. The constant voltage above the maximum determined by the battery results in reduced motor output at very high speeds.

Once the power versus motor speed curve is established for each of the motors, a study is required to ensure that sufficient power is available at the required motor speed assuming the appropriate mechanical drive ratio between the tires and the motor.

During this first stage of designing the motor drive, a selection of the drive ratio is established which relates motor speed to vehicle (road) speed. This relationship then establishes the power available at the desired vehicle speed. To meet the required performance, the power versus speed curve for the motor must envelop the power requirements established for the vehicle.

The two most important criteria for efficient performance and high travel range are that sufficient power must be available to meet the required acceleration profile and that the motor has capacity to handle the high power generated during regenerative braking. During the theoretical performance analysis, it was established that the estimated peak power generated during braking in the Schedule D cycle is 55.8 kW (74.9 hp).

The optimum solution was anticipated to be one which maximized the recovery of energy during the regenerative braking period of the Schedule D cycle. As a start, the motor speed at the peak of the horsepower curve was set to be equivalent



Percent of Rated Full Load Torque Used in Power Calculation:

GE 2346	333%
GE 2364	250%
GE 184T	230%
GE 215T	220%
REL 215T	230%

Figure 17. - Peak Power Output vs. Motor Speed for the Final Candidate Motors

to a vehicle speed of 72.4 km/hr (45 mph). In the Schedule D driving cycle, the regenerative braking begins at a speed slightly below 72.4 km/hr (45 mph) because the vehicle slows down slightly during the coast period. Each motor was analyzed to determine its optimum drive ratio for maximum range on the Schedule D cycle. The envelope of the power available versus the power required is illustrated for some of the candidates in figures 18 through 21. The constant power acceleration profile was used to demonstrate the performance of these combinations on a common basis.

Each of these graphs depicts the power available in low and high gear using the two-speed transmission selected for the baseline comparisons. As a first step, the drive ratio in high gear was established by matching the peak of the motor curve to provide maximum power near 72.4 km/hr (45 mph) - the point where regenerative braking begins in the Schedule D cycle. Using a 2:1 change in ratio between high and low gears, a second curve was added for low gear. The 2:1 change appeared to be a good compromise in gear ratio and provides adequate power for acceleration for all cases except the small AC motor (GE 184T) which required a 2.5:1 ratio in order to envelop the required acceleration power curve.

These variations and others were introduced into the computer analysis program to establish the optimum drive ratio for maximum range based on the Schedule D cycle. The results of the computer simulation runs are presented in sections 4.4, 5.1, and 5.3.

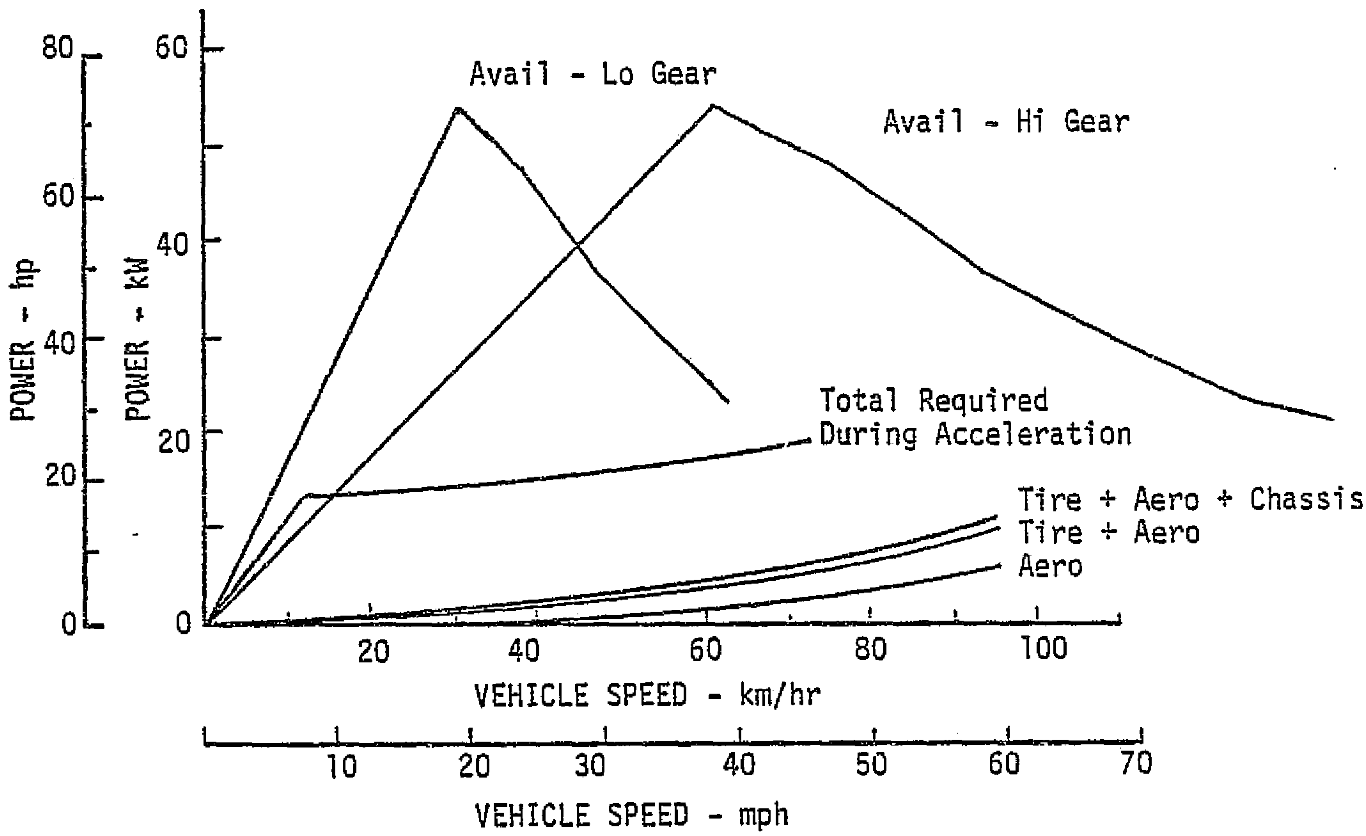
4.3 CONTROLLERS

During the industry and literature review, it was established that no two EV's use the same controller design and that each controller was specifically designed to suit the individual requirements of the system being developed. The technology of motor control has been reduced to practice, but controllers exist as "off-the-shelf" commercial items for series motor control only. These available controllers are SCR (low frequency transistor in the case of EVC) types and although modifiable for field or armature control, use with shunt motors are not potentially as efficient as SOTA transistor design would allow. SOTA transistor controllers have been used in electric cars (i.e. CDA II field controller and Ripp-Electric series motor controller). These SOTA transistor controllers are not presently available as standard commercial products but could be built with present technology. Two types of drive systems were identified as candidates for the SOTA electric vehicle:

(1) A separately excited DC motor and controller

(2) A 3-phase induction motor and AC inverter

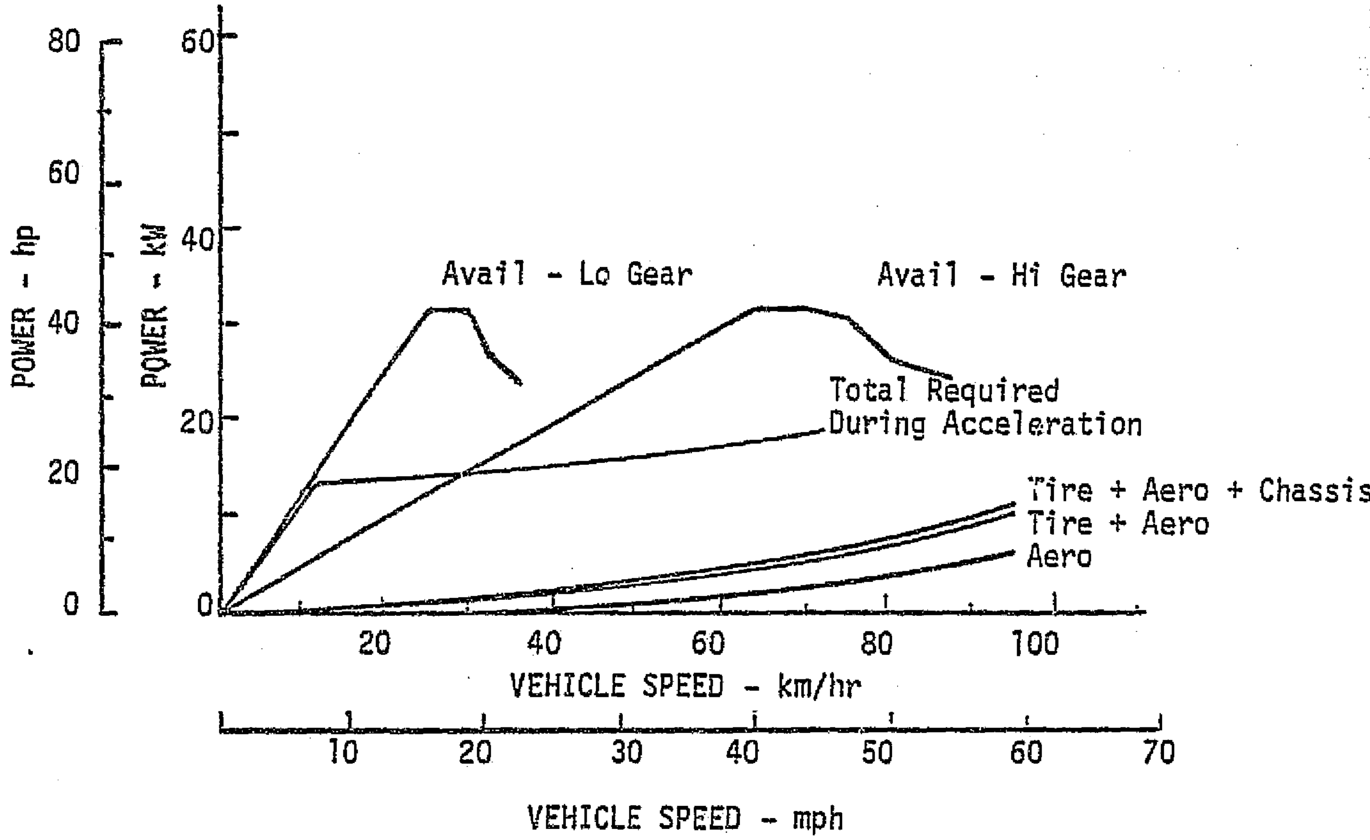
A comparison of the relative efficiencies, weight, cost, and regenerative braking characteristics of these types of controllers compared to a series DC motor system also substantiated these selections. In table IX these parameters are compared for systems which would have approximately the same performance in the SOTA baseline vehicle. The primary shortcoming of the series DC motor system is its requirement for full time armature control. Small series motor drive systems can operate in a bypass mode much of the time so that the road load balances the motor torque available; however, the variable speed performance requirements



Gross Vehicle Weight = 1633 kg (3600 lbs)

Acceleration
Initial = 2.24 m/s^2 (5.0 mph/s) to 12.1 km/hr (7.5 mph)
Final = Decreases from 2.24 m/s^2 to .38 m/s^2 at 72.4 km/hr (45 mph)

Figure 18. - Power Available vs. Power Required for the GE 2364 (DC Motor)



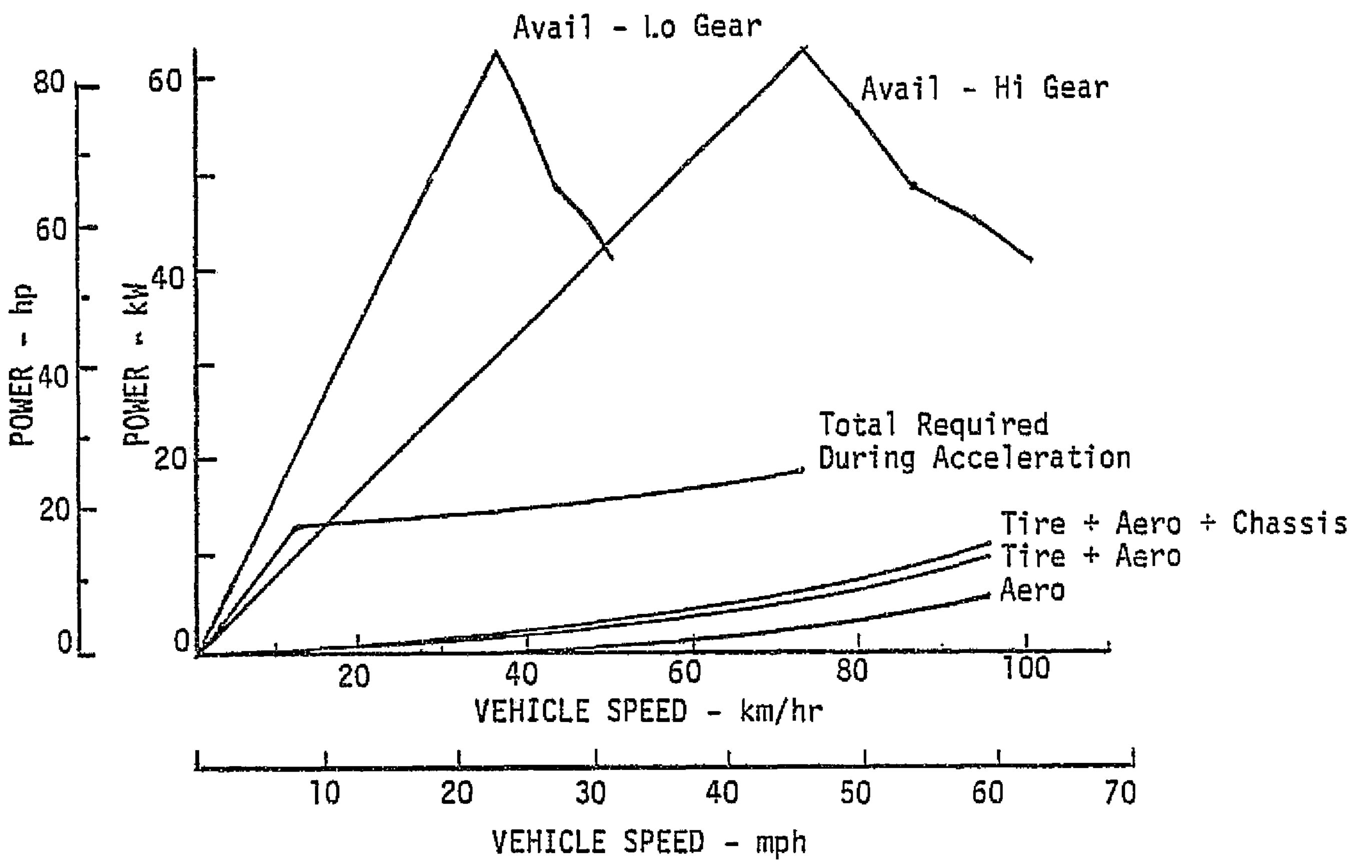
Gross Vehicle Weight = 1633 kg (3600 lbs)

Acceleration

Initial = 2.24 m/s^2 (5.0 mph/s) to 12.1 km/hr (7.5 mph)

Final = Decreases from 2.24 m/s^2 to .38 m/s^2 at 72.4 km/hr (45 mph)

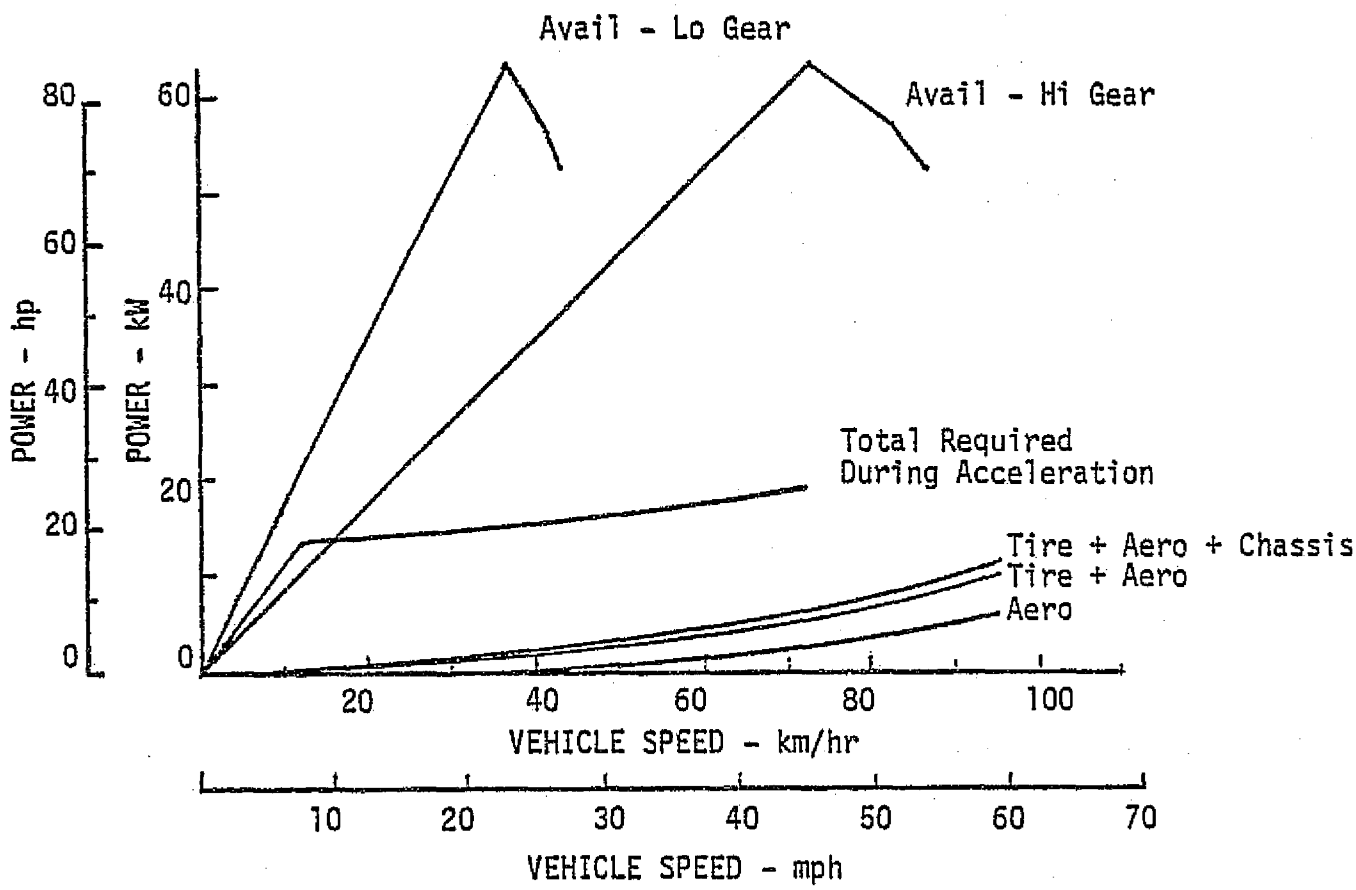
Figure 19. - Power Available vs. Power Required for the GE 184T (AC Motor)



Gross Vehicle Weight = 1633 kg (3600 lbs)

Acceleration
    Initial = 2.24 m/s^2 (5.0 mph/s) to 12.1 km/hr (7.5 mph)
    Final = Decreases from 2.24 m/s^2 to .38 m/s^2 at 72.4 km/hr (45 mph)

Figure 20. - Power Available vs. Power Required for the GE 215T frame (AC Motor)



Gross Vehicle Weight = 1633 kg (3600 lbs)

Acceleration

Initial = 2.24 m/s^2 (5.0 mph/s) to 12.1 km/hr (7.5 mph)

Final = Decreases from 2.24 m/s^2 to .38 m/s^2 at 72.4 km/hr (45 mph)

Figure 21. - Power Available vs. Power Required for the RELIANCE 215T frame (AC Motor)

TABLE IX COMPARISON OF DC AND AC SYSTEMS

Type	Series DC	Shunt DC	Induction AC
Number of Controllers Required	1	2	1
Auxiliary Components Required for Regenerative Braking	Yes	No	No
Controller Efficiency over Driving Cycle	0.85-0.90	0.95*	0.95
Average Motor Efficiency over 3:1 Speed	0.86*	0.86*	0.89
Motor-to-Vehicle Weight Ratio	0.069	0.069	0.026
Motor Cost	High	High	Approx.1/2 of DC
Controller Cost	Low	Medium	High
Potential for Cost Reduction	Very Little	Very Little	Considerable

* Ref: Electric Vehicle News-
November 1977, p. 14

of SOTA vehicle would result in continuous cycling of the bypass contactor in order to maintain constant speed for any condition other than maximum speed. They lack capability for regenerative braking without additional, and generally bulky, components (i.e., contactors) and have lower average efficiency over the full range of a driving cycle such as the Schedule D cycle. Both the separately excited DC (shunt) and the AC systems appear to have more potential as a SOTA controller.

The capacities and performance of previous cars such as the CDA Town Car, the Daihatsu Passenger Car, and the Toyota Compact Electric Car which employed separately excited DC motors and those based on AC induction motors - the Linear Alpha Van and the GM Electrovair - were studied and compared. The final conclusion was:

- As built, none of these controllers is suitable for use in a SOTA power train.

Each of these controller designs was sized and developed for a specific car with specifications different from those specified for the SOTA power train and, as such, would not have adequate capacity or performance.

In terms of operational advantages, the shunt DC motor system can be switched from power to regenerative braking smoothly without the use of contactors to reverse the windings as required with series DC motor systems. With a separately excited shunt system, the armature controller can be eliminated from the circuit during most of the driving cycle to reduce the total controller loss, which should increase travel range over comparable series motor systems. Field control by itself is adequate for cruise speed control of a shunt motor system.

An advantage of series motor control is that it requires only over-current limitation in order to protect the motor. Field current is automatically high when armature current is high so that armature reaction does not distort the flux null positions and cause commutator sparking. The shunt motor system has lower controller loss, as explained above, but the controller must prevent operation at low speed with low field current and provide overspeed protection against excessive high speed regenerative braking current. The shunt motor commutator can be destroyed at currents below rated value if the field current is insufficient to prevent flux position shift. Compensating poles can reduce this effect, but make reversing more difficult.

The AC induction motor weight is one-third to one-half that of a comparable DC motor which results in lower overall vehicle weight and lower energy requirement. Several AC systems were found. The motors were low cost, but the AC inverters tended to be expensive with power efficiency as low as the series DC motor controller (i.e., General Motors AC Electrovair II). AC motor controllers require three times as many power components as a comparable DC controller which creates some concern regarding reliability.

Based on these observations and conclusions, controllers for both DC (shunt) and AC systems were given further evaluation to determine their relative performance in a power train package.

4.3.1 Separately Excited DC System

The DC system selected for the final performance evaluation in the computer simulation program is depicted in figure 22. Two controllers are required for the separately excited shunt motor system. A fairly large capacity DC chopper is used in the armature circuit during low speed acceleration (up to 25% of maximum speed) and is bypassed when the armature voltage required is the same as battery voltage. At that point, speed is controlled by a smaller DC chopper in the field circuit, which provides continuous control for acceleration at higher speed, cruise, and regenerative braking modes.

A number of DC controllers were considered as suitable candidates for the armature circuit, which are listed in table X. These DC controllers were designed for series motor applications, but could be used for armature control of a shunt motor with the addition of an armature reactor. Most of these controller designs are based on thyristors (SCR's).

Controllers for the field circuit are not commercially available as off-the-shelf items, but certainly are within SOTA. A field controller in this type of system requires greater over voltage capability for field forcing than generally provided for in commercial units. It must also be capable of rapidly following the required motor speeds during the shifting of gears. Each of the vehicles with shunt controllers identified during the review were designed for the intended vehicle. It is primarily the logic system which is the unique or critical item within the system. A design of this type is achievable within the definition of the SOTA, but is beyond the scope of this study. For the candidate controller system, a design was assumed which could be based on the use of transistors or SCR's.

4.3.2 AC System

The AC system selected as a candidate for the SOTA EV power train is a 3-phase controller/inverter available from Rohr Industries. A single controller of this type is required between the batteries and the 3-phase induction motor, as shown in figure 23. A simplified schematic of the 3-phase AC controller is given in figure 24. Background on the testing of units similar to the EV design is discussed in Appendix C. The operation of this system is presented in more detail in section 6.2.2.

4.4 PREDICTED PERFORMANCE COMPARISON

Prediction of the performance of the final candidates was established using the specially developed computer simulation of the SAE Schedule D driving cycle described in Appendix E. Each alternative was evaluated in terms of its maximum travel range on Schedule D as well as its performance during constant speed operation.

During the preliminary runs, it was established that the acceleration profile based on the high initial acceleration followed by constant power for acceleration

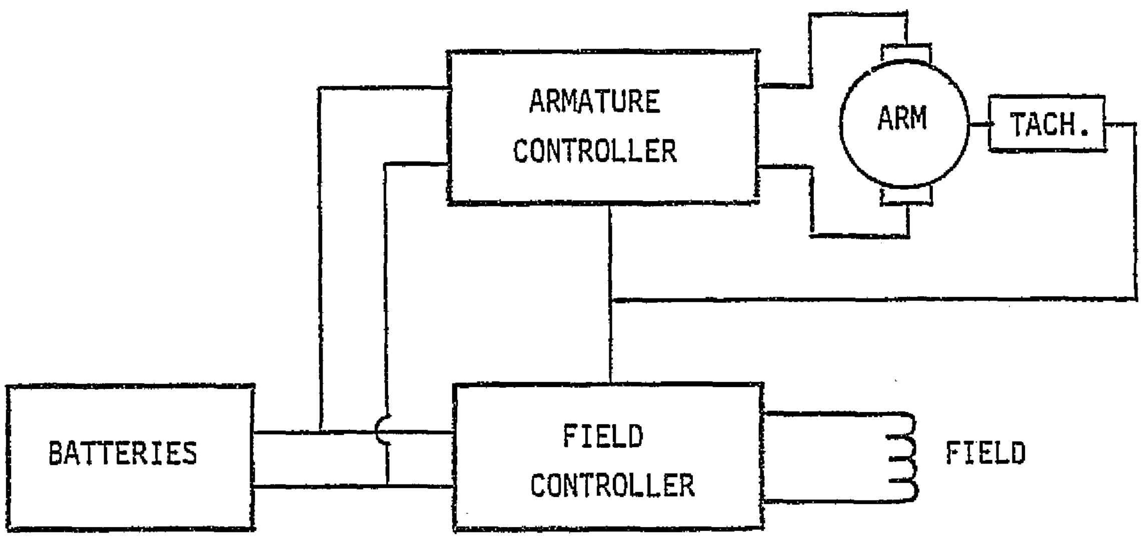


Figure 22. - Block Diagram of a DC System With
A Separately Excited Motor

TABLE X - CANDIDATE CONTROLLERS FOR THE SOTA POWER TRAIN

TYPE	MFGR/MODEL	CURRENT-A		VOLTAGE RATING	SPECIAL CYCLE	APPROXIMATE SIZE m (in)
		CONT	PEAK			
DC (SCR)	CABLEFORM MARK 10	300	800	96	FULL SPEED BYPASS	.3 x .3 x .15 (12 x 12 x 6)
DC (SCR)	SEVCON 7800	250	800	170	FULL SPEED BYPASS	.36 x .25 x .18 (14 x 10 x 7)
DC (SCR)	GE EV-1C	160	850	150	FULL SPEED BYPASS	.3 x .3 x .15 (12 x 12 x 6)
DC (TRANS)	EVC 600	600	600	96	NO BYPASS	.28 x .2 x .1 (11 x 8 x 4)
AC (TRANS)	ROHR 312	300	800	96	NOT APPLICABLE	.46 x .51 x .2 (18 x 20 x 8)

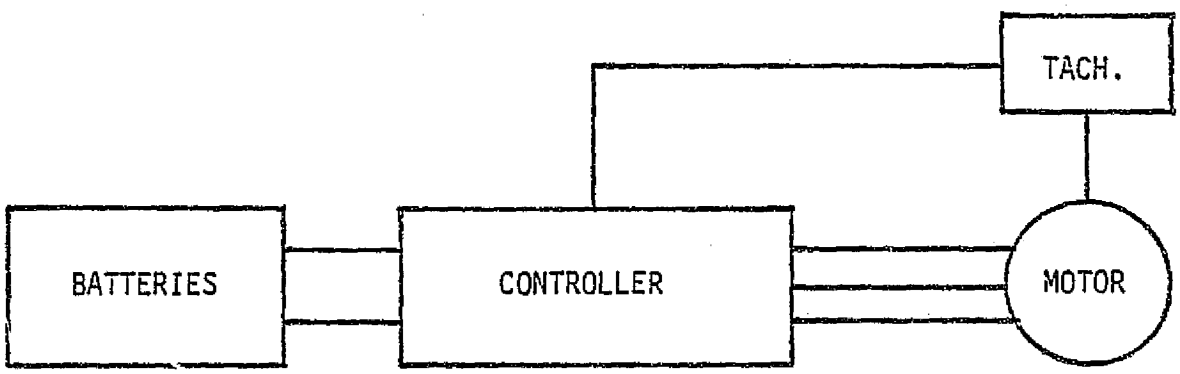


Figure 23. - Block Diagram of an AC System With a 3-Phase Induction Motor

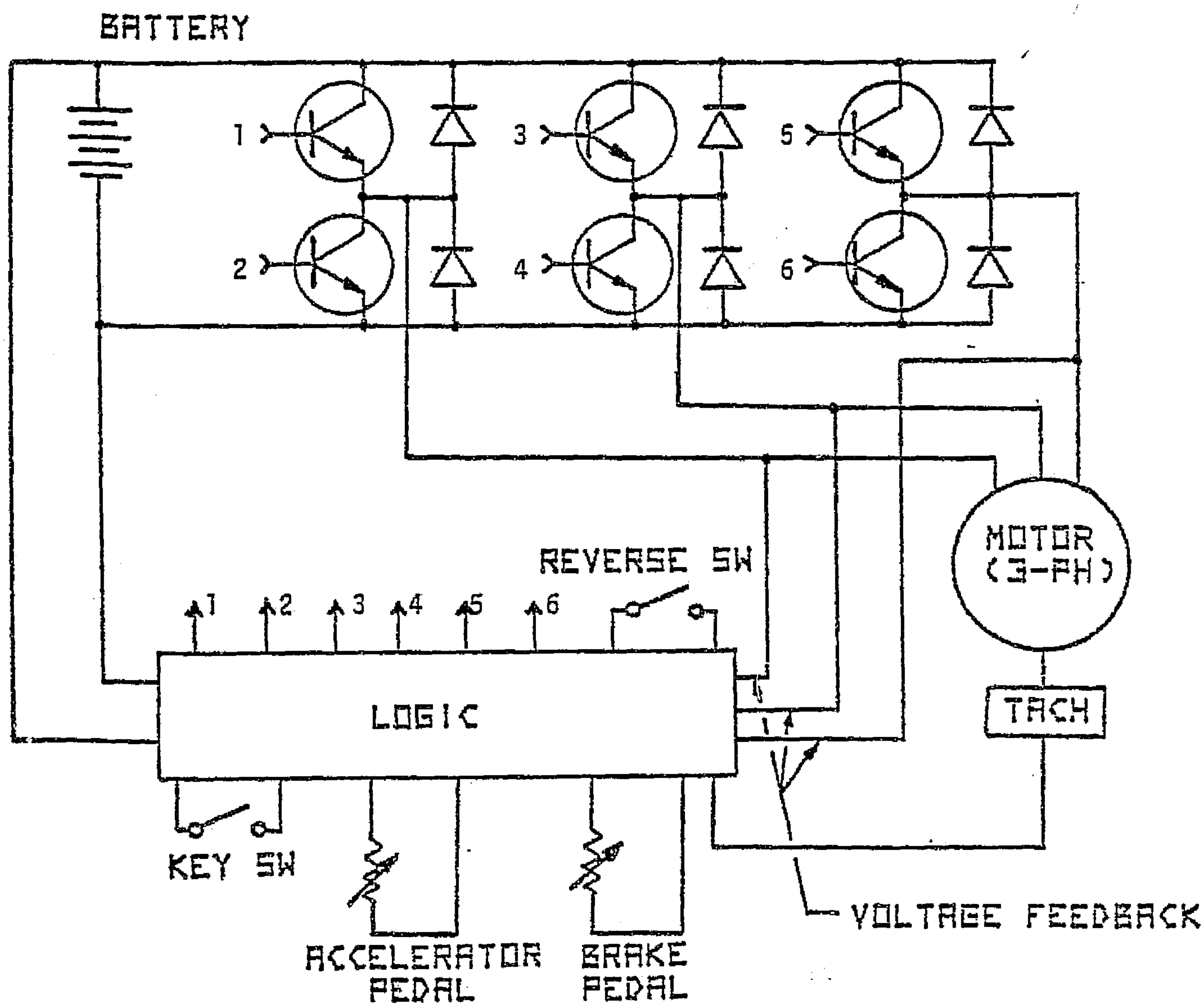


Figure 24. - Simplified Schematic of the 3-Phase AC Controller

resulted in higher mileage predictions for all cases. Therefore, the candidates were finalized using this approach. In the early stages of analysis, each motor was investigated to determine the optimum drive (gear) ratio for maximum travel range on Schedule D (ref. sections 4.2.2 and 5.5). Motor speed at 88.6 km/hr (55 mph) is used as means of expressing the overall drive ratio in high gear between the motor and wheels.

The comparison analyses were based on the power train configuration discussed in section 4.1 except that the weight variable attributed to motor differences was introduced and a specific tire was selected to meet the preliminary specifications established in section 3.3. The specifications established for the screening runs in addition to those initially given were:

- Power train weight (less motor)	125 kg (275 lbs)
- Vehicle gross weight (less motor)	1418 kg (3125 lbs)
- Tire rolling resistance 165R13 @ 221 kPa (32 psi)	0.085 N/kg (8.623 lbs/1000 lbs) (nominal at zero speed)
- Chassis rolling resistance	0.0098 N/kg (1.000 lbs/1000 lbs)
- Mechanical driveline efficiency	
Low gear (97% X 96%)	92%
High gear (95% X 97%)	93%

The remaining specifications were the same as those established for the preliminary specifications given in section 3.3.

The results of these simulation runs are tabulated in table XI. The variation in Schedule D range for the various motor systems is not large. The overall result is that for the Schedule D driving cycle, the higher powered motors can outperform the smaller units because their average overall cycle efficiency is higher. Simulations included the motor weights as shown in table XI.

The lower powered motors (both DC and AC) achieve the greatest range for constant speed operation, but are penalized in the Schedule D cycle by lower efficiency during acceleration and lack of capacity during regenerative braking. The higher powered motors are not as efficient during the constant speed cruise. The efficiency of the larger motors decrease drastically at low torque and high speed, but they perform better during the acceleration and regenerative braking modes.

Even though the Reliance 215T frame motor had a higher rated efficiency than the GE 215T (89 vs 82% @ 60 Hz), its 50% greater weight resulted in about 3% less range for a 72.4 km/hr (45 mph) cruise condition. The higher efficiency was beneficial during the acceleration and regeneration cycles, which resulted in greater range on the Schedule D driving cycle.

Power trains with greater power and more efficient motors are capable of recovering more energy during regenerative braking; however, there are additional

TABLE XI. - SIMULATION RESULTS FOR SAE SCHEDULE D CYCLE
CONSTANT POWER ACCELERATION PROFILE

MOTOR RPM @ 88.6 km/hr (55 mph)		GE 2346 (DC) 4000		GE 2364 (DC) 4000		GE 184T (AC) 9000		GE 215T (AC) 7850		REL 215T (AC) 7850		REL 215T (AC) 9000	
MOTOR WEIGHT	kg	56.7		104.3		31.3		38.6		56.7		56.7	
	lbs	125		230		69		85		125		125	
RANGE		km	mi	km	mi	km	mi	km	mi	km	mi	km	mi
SCHEDULE D		75.6	47.0	83.5	51.9	82.6	51.3	86.1	53.5	88.0	54.7	86.7	53.9
SCHEDULE D w/o REGEN. BRAKING		70.7	43.9	74.5	46.3	75.2	46.7	74.5	46.3	74.5	46.2	71.8	44.6
CRUISE @ 72.4 km/hr		115.9	72.0	114.7	71.3	109.6	68.1	110.6	68.7	107.7	66.9	101.4	63.0
BATT CURRENT (A)													
ACCELERATION		314		266		258		291		271		273	
CRUISE		84		85		89		88		90		96	
PEAK POWER		kW	hp	kW	hp	kW	hp	kW	hp	kW	hp	kW	hp
ACCELERATION		18.7	25.1	19.2	25.8	18.5	24.8	18.9	25.4	18.9	25.4	19.0	25.5
CRUISE		6.3	8.4	6.3	8.5	6.2	8.3	6.2	8.3	6.3	8.4	6.3	8.4
REGEN. BRAKING		31.9	42.7	42.4	56.9	27.8	37.3	47.1	63.1	50.4	67.5	55.4	74.3
ENERGY/CYCLE		MJ	Wh	MJ	Wh	MJ	Wh	MJ	Wh	MJ	Wh	MJ	Wh
ACCELERATION		.637	177	.583	162	.554	154	.569	158	.558	155	.965	157
CRUISE		.382	106	.385	107	.403	112	.400	111	.410	114	.436	121
REGEN. BRAKING		(.065)	(18)	(.104)	(29)	(.036)	(24)	(.130)	(36)	(.148)	(41)	(.173)	(48)
TOTAL		.954	265	.864	240	.871	242	.839	233	.821	228	.828	230
DISTANCE/CYCLE	km	1.6393		1.6393		1.7815		1.7815		1.6378		1.6367	
	mi	1.0186		1.0186		1.1070		1.0175		1.0177		1.0170	
RANKING		(6)		(4)		(5)		(3)		(1)		(2)	

bearing and windage losses in the larger motors which result in lower efficiency during cruise. The additional weight of the larger motors also results in additional rolling resistance.

The greatest range was obtained with the 215T frame AC motor combinations. The DC motor combinations resulted in greater predicted range at constant speed cruise because of their lower controller losses. The AC system with the heavier high efficiency motor resulted in greater predicted range on the Schedule D cycle, but had slightly lower range for constant speed operation.

Vehicle weights did not take into consideration that more space and additional structural weight would be required for the larger DC motors. Considering this and the fact that the 38.6 kg (85 lbs) AC motor resulted in greater range than the 104.3 kg (230 lb) DC motor on the simulated Schedule D cycle, the AC system using an aluminum frame 215T motor was selected for the SOTA power train design.

5.0 INFLUENCE OF PARAMETERS

5.1 REGENERATIVE BRAKING

The value of regenerative braking in terms of increased mileage was investigated and calculated as a part of the engineering analysis. In the theoretical analysis, it was estimated that a 35% improvement in Schedule D range could be achieved by recovering the kinetic energy during braking. This calculation allowed for 80% efficiency in recharging the battery, but was based on 100% efficiency in the motor and controller. The predicted improvement in range attributed to regenerative braking according to the Schedule D simulations runs is approximately 16%. The simulation analysis accounts for the motor, controller, and battery resistance losses established by the performance curves and data.

It has been reported by others that some form of "battery enhancement" is achieved when the batteries are given momentary reverse flows during the discharge cycle. The results of this report are based on battery curves charted for a continuous discharge cycle and do not include battery enhancement.

The energy recoverable during regenerative braking is a function of motor power versus speed curve. For a given motor, power trains which have high motor speed versus road speed have greater regenerative braking capacity. A power train which has a motor speed of 9000 rpm at 88.6 km/hr (55 mph) is capable of regenerating more power than one which is geared for 7850 rpm at that speed as long as the regenerated power is within the capacity of the controller. There is an overriding limit however. As the motor speed is increased, the cruise efficiency is reduced.

If the only criteria were to maximize the constant speed cruise range, a lower motor speed for a given road speed would result in increased range. The tradeoff of motor capacity to handle the high horsepower conditions during regenerative braking (and acceleration) must also consider the effect on sustained cruise operation. This factor is automatically taken into consideration when the Schedule D cycle is used as the basis of evaluation. The benefit actually derived is a function of the driving cycle. As the cruise speed is reduced, the amount of recoverable energy is reduced.

The data presented in table XII illustrates the variations in performance as the motor speed at 88.6 km/hr (55 mph) (i.e., overall drive ratio) is varied. As the motor speed was reduced, the Schedule D range decreased, but the steady state cruise range increased. For this example, 7850 rpm at 88.6 km/hr (55 mph) was chosen as the optimum motor speed, with priority to maximizing Schedule D range and next to maximizing constant speed cruise range.

5.2 TIRES

The sensitivity of range performance to tire rolling resistance was studied in detail during the industry search. It became apparent that steel belted radial tires had the lowest rolling resistance; however, the impact on range was undetermined. Rolling resistance for several variations in tire size and

TABLE XII - VEHICLE RANGE VS. DRIVE RATIO

MOTOR: GE 215T						
MOTOR SPEED @ 88.6 km/hr (55 mph)	6700		7850		9000	
DRIVE RATIO (HIGH GEAR)	8.221		9.632		11.043	
RANGE	km	mi	km	mi	km	mi
SCHEDULE D	84.8	52.7	86.1	53.5	86.1	53.5
SCHEDULE D W/O REGENERATIVE BRAKING	68.9	42.8	74.5	46.3	73.0	45.4
CRUISE @ 72.6 km/hr (45.1 mph)	114.4	71.1	110.5	68.7	107.0	66.5
INCREASE IN SCHEDULE D RANGE W/REGENERATIVE BRAKING	23.1%		15.6%		17.9%	
BASED ON BASELINE SPECIFICATIONS PER SECTION 4.4						

inflation pressures were injected into the simulation program to determine quantitatively the effect on vehicle range. The tire rolling resistance versus vehicle speeds are graphically given in figure 25. A change to one tire size larger increased the Schedule D range by 5% and increasing the inflation pressure by 27.6 kPa (4 psi) to the 248 kPa (36 psi) maximum for Load Range B tires increased the range by 2% as shown in figure 26.

5.3 ACCELERATION PROFILE

SAE EV Test Procedure J227a does not specify the profile to be used to accelerate to 72.4 km/hr (45 mph) in 28 seconds as prescribed for the Schedule D driving cycle. A constant acceleration from 0 to 72.4 km/hr (45 mph) is characterized by high power and high peak battery currents. Simulation runs were made to identify the degree of influence that the acceleration profile has on vehicle range. For these runs, the following profiles were established:

- Fixed gear ratio with 0.72 m/s^2 (1.61 mph/sec) constant acceleration to 72.4 km/hr (45 mph)
- Fixed gear ratio with 1.12 m/s^2 (2.5 mph/sec) initial acceleration to 36.2 km/hr (22.5 mph) then 0.56 m/s^2 (1.25 mph/sec) to 72.4 km/hr (45 mph)
- Two-speed transmission with 1.12 m/s^2 (2.5 mph/sec) initial acceleration to 36.2 km/hr (22.5 mph) then 0.56 m/s^2 (1.25 mph/sec) to 72.4 km/hr (45 mph)
- Two-speed transmission with 2.24 m/s^2 (5 mph/sec) initial acceleration to 12.1 km/hr (7.5 mph) then constant power for acceleration to 72.4 km/hr (45 mph)

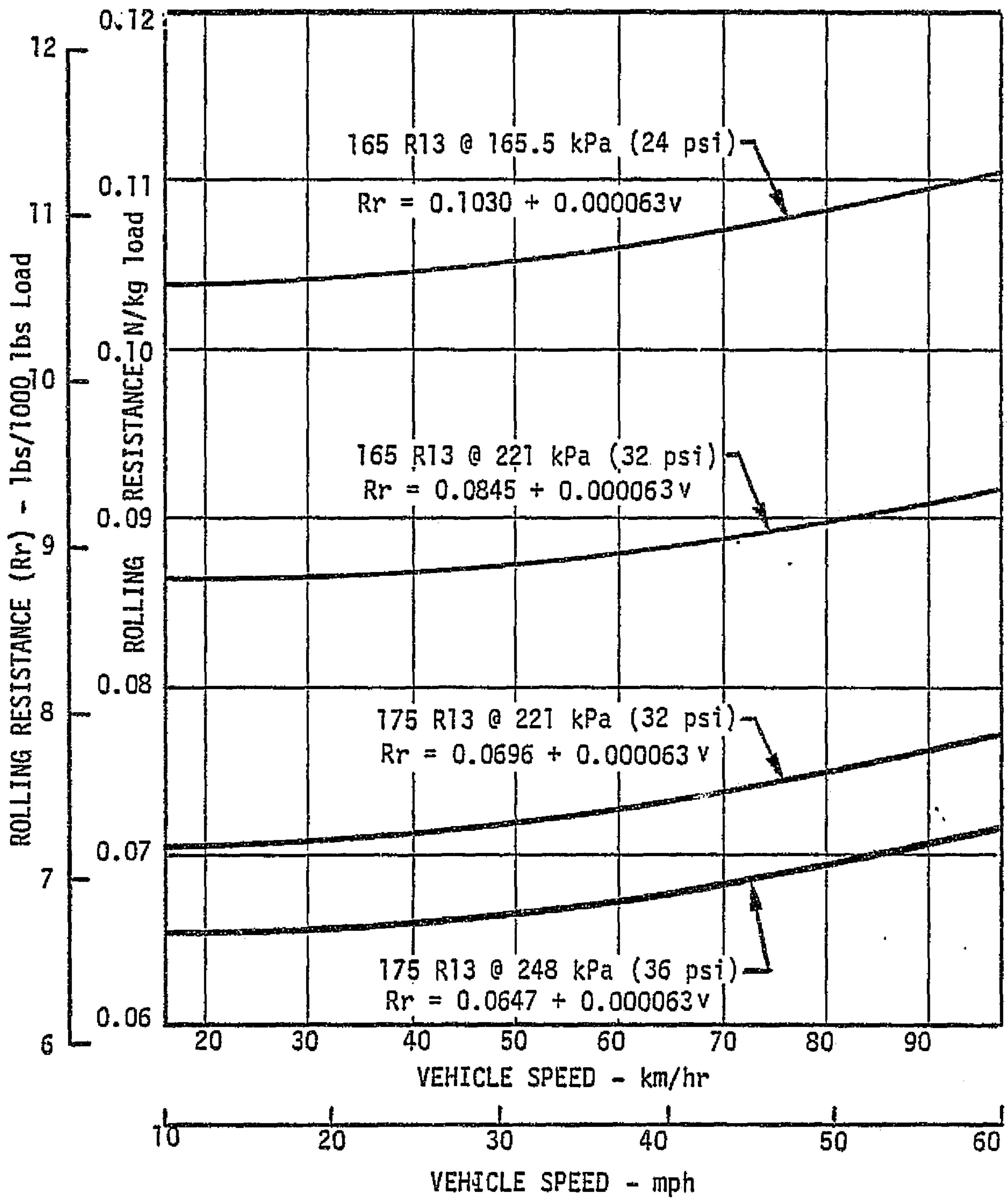
On the basis of Schedule D driving conditions, the high initial acceleration followed by constant power for acceleration resulted in the lowest energy consumption per unit distance during the acceleration mode and Schedule D range was the greatest. The peak power and battery current drawn using this approach was considerably lower. These computer simulation results are summarized in table XIII.

5.4 PAYLOAD OR WEIGHT

Vehicle range is fairly sensitive to gross vehicle weight. Reducing the load from four passengers to one driver increased the travel range on Schedule D by 13%. The curve of range versus number of passengers is given in figure 27.

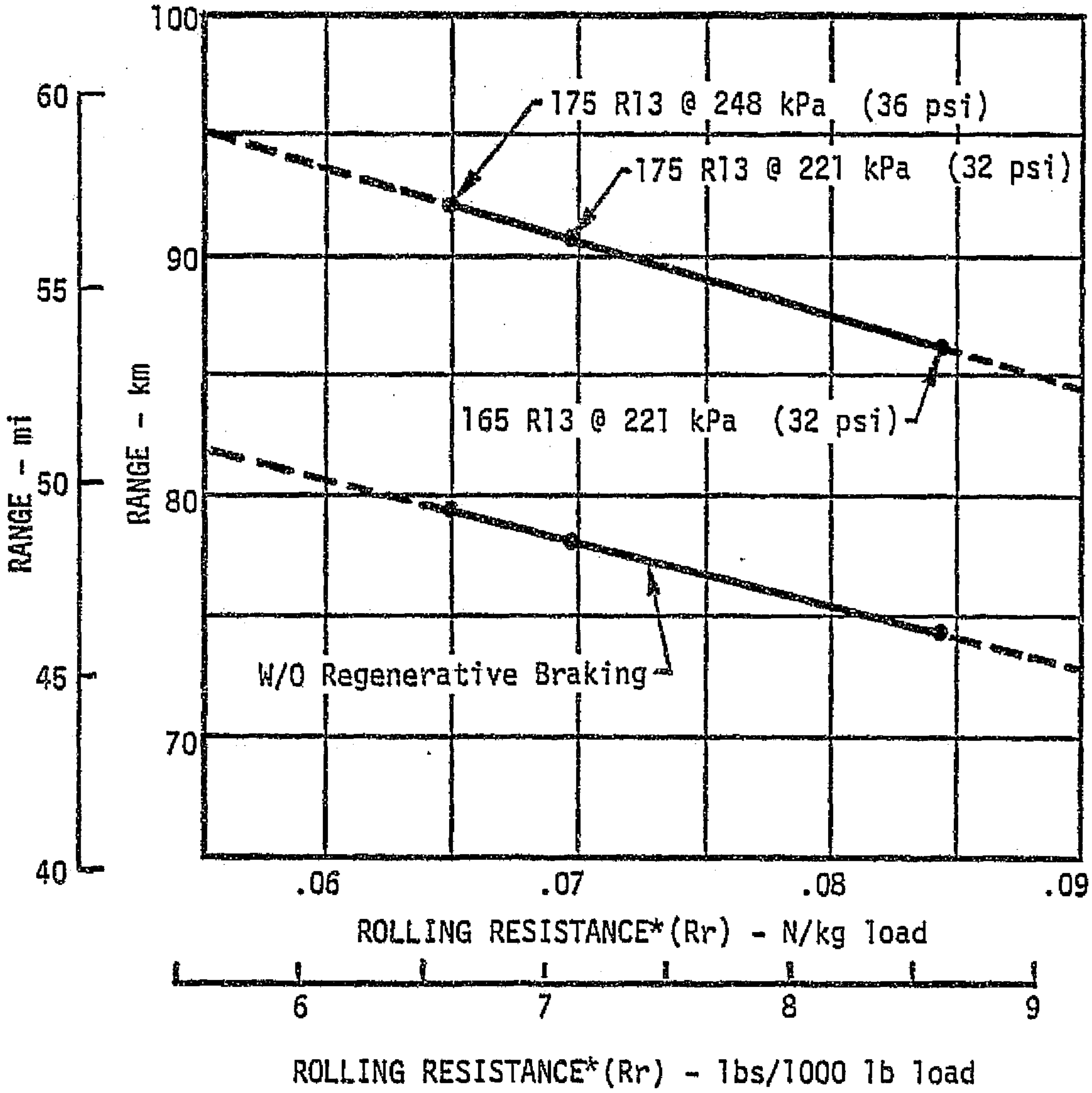
5.5 DRIVELINE EFFICIENCY

Frequently, designers and EV builders select a component or type of gears based on the handbook efficiency values which usually are only valid at peak rated load, without examining the specific operating conditions. Efficiency of the mechanical gearing items in the drive line such as the transmission and differential is also a function of the ratio of operating load to design load of the gears. Most components have fixed losses and variable losses. The variable losses are a function of load and speed. When oversized or overdesigned components are used in a system, the system will have lower operating efficiency because the fixed losses of the component are too great for that specific application. A plot



Vehicle Performance in Computer Simulation is Based Upon a Linear Approximation of Curves as Indicated.

Figure 25. - Tire Rolling Resistance vs. Vehicle Speed for Steel Belted Radial Tires (Load Range B)



* Nominal Rolling Resistance at zero speed for steel belted radial tires (ref: figure 25)

Based on Baseline Specifications Per Section 4.4

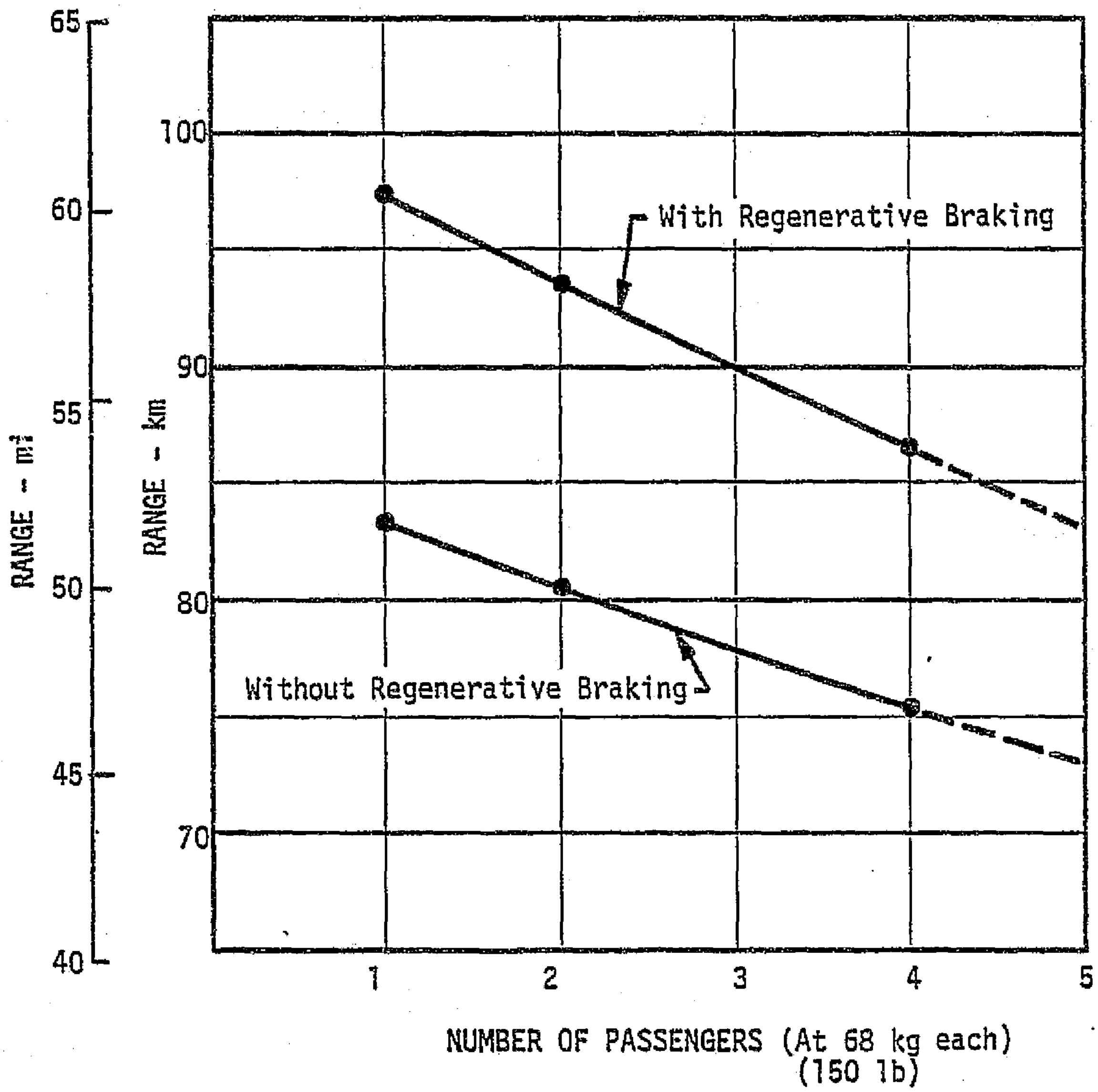
MOTOR: GE 215T with 7850 rpm = 88.5 km/hr (55 mph)
VEHICLE WEIGHT: 1456 kg (3210 lbs) (GROSS)

Figure 26. - Travel Range vs. Tire Rolling Resistance (SAE Schedule D Cycle)

TABLE XIII - TRAVEL RANGE VS. ACCELERATION PROFILE FOR THE SCHEDULE D DRIVING CYCLE

ACCELERATION PROFILE	0.72 m/s^2 (1.61 mph/sec)		1.12/.56 m/s^2 (2.5/1.25 mph/sec)		1.12/.56 m/s^2 (2.5/1.25 mph/sec)		2.24 m/s^2 (5 mph/sec), CONSTANT POWER	
TRANSMISSION TYPE	Fixed Ratio		Fixed Ratio		Two Speed		Two Speed	
RPM @ 88.6 km/hr (55 mph)	7850		7850		7850		7850	
RANGE	km	mi	km	mi	km	mi	km	mi
Schedule D	83.8	52.1	85.6	53.2	85.8	53.3	86.1	53.5
Schedule D w/o Regenerative Braking	72.4	45.0	74.2	46.1	74.0	46.0	74.5	46.3
BATT. CURRENT (A)								
Acceleration	471		344		371		291	
Cruise	87		87		87		88	
Regenerative Braking	-339		-339		-342		-343	
PEAK POWER	kW	hp	kW	hp	kW	hp	kW	hp
Acceleration	31.7	42.5	24.5	32.9	26.1	35.0	19.6	26.3
Cruise	6.1	8.2	6.1	8.2	6.2	8.3	6.2	8.3
Regenerative Braking	-46.4	-62.2	-46.4	-62.2	-46.9	-62.9	-47.1	-63.1

MOTOR: GE 215T GROSS VEHICLE WEIGHT: 1456 kg (3210 lbs)
Based on Baseline Specifications per section 4.4



Based on Baseline Specifications per section 4.4

Motor: GE 215T with 7850 rpm = 88.5 km/hr (55 mph)
Vehicle Curb Weight: 1456 - 272 = 1184 kg (2610 lbs)

Figure 27. - Travel Range vs. Number of Passengers (SAE Schedule D Cycle)

of efficiency versus torque ratio for a differential with spiral bevel gears is presented in figure 28.

Additional curves are shown for the overall efficiency of a differential and transmission combined. For these two additional curves, a fixed transmission efficiency was used. For analyses in this report, average efficiency values were used for the differential and transmission with consideration given to the range of torque ratio anticipated in the EV power train. A more precise analysis could be done by incorporating the efficiency versus torque formula into the load calculation in the computer simulation model.

5.6 BRAKES

Brake systems can adversely affect the performance of EV's if due consideration is not given to the differences in operation. The trend in automotive brakes has been toward the use of disc brakes for reasons of reduced fade, reduced weight and easier maintenance. Disc brakes, however, usually are designed to have the brake pad constantly wiping the disc to keep it clean. The wiping action reflects itself as a constant drag which represents a serious energy drain for an EV. Disc retractors or hold-offs are being investigated by brake manufacturers, but additional development is needed before satisfactory performance can be achieved. Drum brakes generally do not have the constant drag problem associated with disc brakes.

The use of regenerative braking to perform most of the braking action upsets the normal considerations in the selection of brakes. Regenerative braking will reduce the wear and maintenance of the mechanical brakes. With regenerative braking, the mechanical brakes will not be used as often. This may be a problem for disc brakes since the rotor is normally more exposed to the dirt, ice, snow, etc.

In view of the need for additional development to eliminate the drag associated with disc brakes, drum brakes were selected for the SOTA power train.

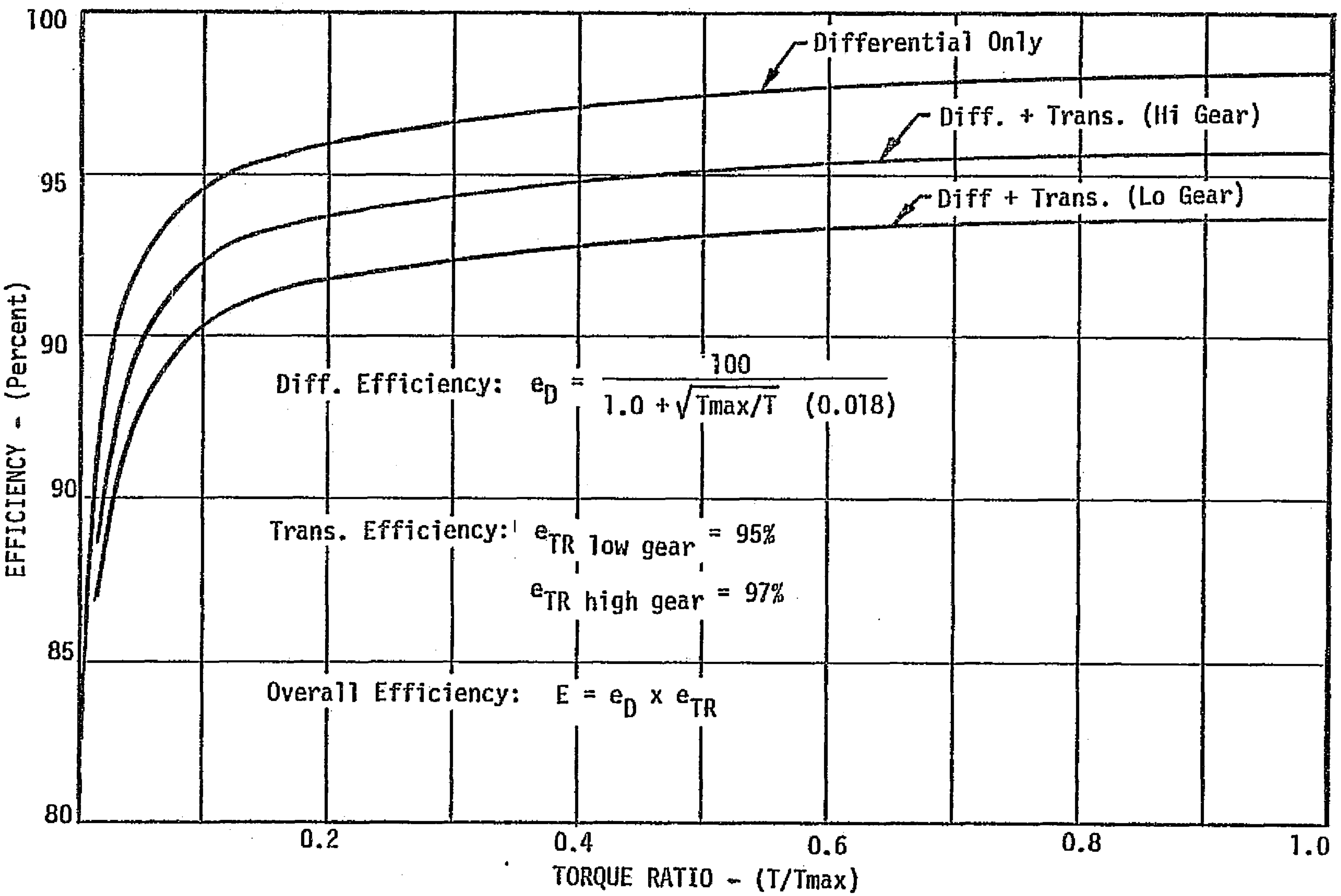


Figure 28. - Differential Efficiency vs. Torque Ratio for Spiral Bevel Gears

6.0 SELECTED SYSTEM

6.1 STATE-OF-THE-ART FINAL SELECTION

Based on the performance comparison established using the simulated SAE Schedule D driving cycle (ref. table XI), the power trains with the Reliance 215T motor and AC inverter have the greatest range and highest overall efficiency. Although the predicted 88.0 km (54.7 mi) range on Schedule D for the Reliance 215T is approximately 2% greater than the 86.1 km (53.5 mi) for the system with the General Electric 215T, the more efficient cruise performance of the GE 215T will result in greater range over the total spectrum of vehicle speeds and driving cycles anticipated in actual usage. Despite the higher rated efficiency of the Reliance motor (89 vs 82%), its actual cruise load efficiency (79 vs 82% for the aluminum frame GE motor) results in less range for constant speed cruise operation. The projected ranges at 72.4 km (45 mph) for the steel frame motor and aluminum frame motor are 107.6 km (66.9) mi and 110.5 km (68.7 mi) respectively. If the Schedule D range and the 72.4 km/hr cruise range are weighted equally (50% Schedule D and 50% constant speed @ 72.4 km/hr, the steel frame motor mean range is 97.8 km (60.8 mi) and the aluminum frame motor mean range is 98.5 km (61.2 mi). For these reasons, the power train powered by a motor and controller comparable to the GE 215T AC induction motor and the 3-phase variable voltage variable frequency AC inverter was selected as the combination of components to represent the SOTA power train for electric vehicles.

6.2 STATE-OF-THE-ART POWER TRAIN DESCRIPTION

The selected SOTA power train is illustrated in figure 29 and the summary description of the final selection of components is given in table XIV. A general arrangement drawing of the selected combination is given in figure 30.

The drive motor is flange mounted to the transmission housing which, in turn, is attached to the input side of the differential assembly. The motor output shaft is splined and connects directly to the transmission gearing. This type of connection keeps the overall size of the power train to a minimum. In the independent suspension configuration shown, this entire unit is frame mounted, thus reducing the unsprung weight. This configuration can be used as a rear or front wheel drive. A front wheel drive would give maximum traction during regenerative braking because of the load transfer to the front wheels during braking. Since only two tires are transmitting the forces, this effectively doubles the friction force at these tires. On dry road surfaces, this is not a problem. It only becomes a problem when the coefficient of friction is reduced due to water, ice, etc. Under reduced coefficient conditions, some of the energy normally recovered during regenerative braking may be lost. Range will probably be reduced because the friction brakes will be used to do more of the braking to avoid slippage at the front wheels.

The two-speed McKee transmission is manually shifted by the driver using

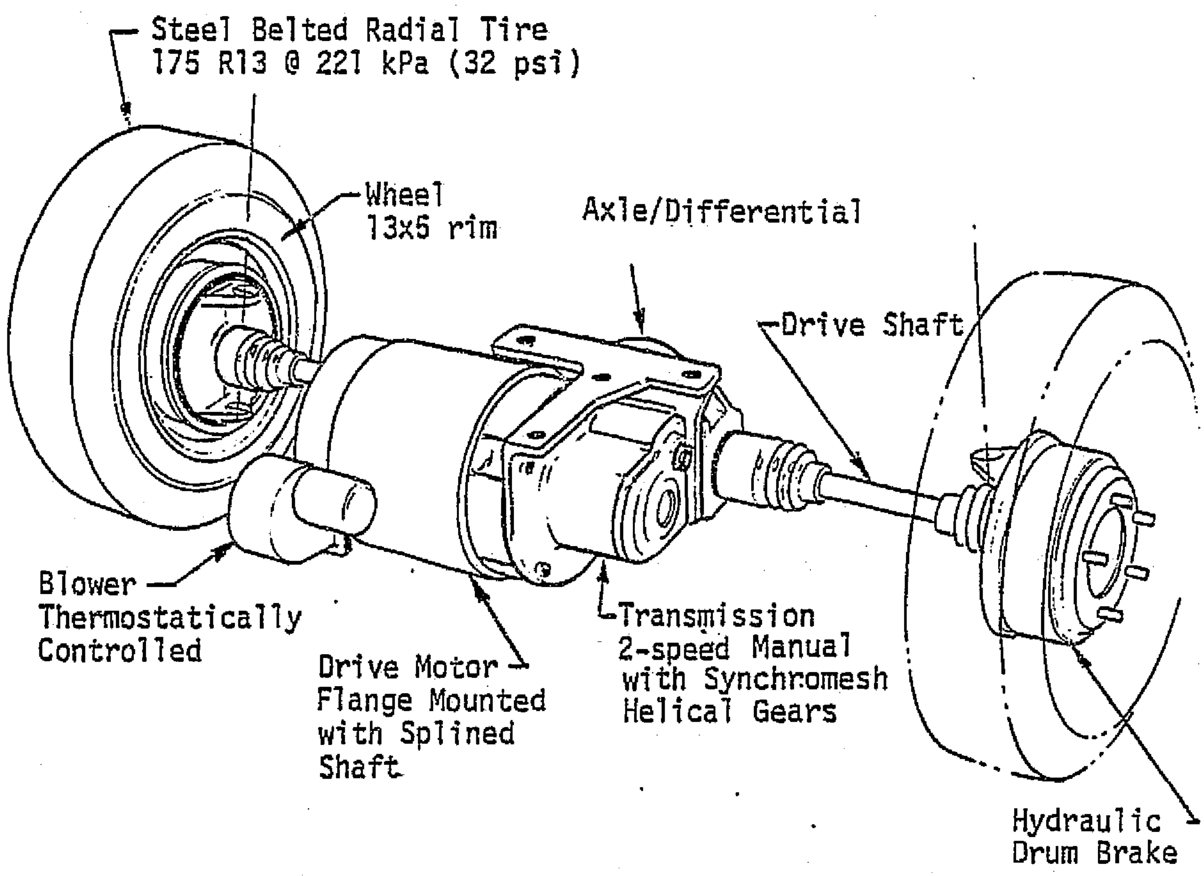


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Figure 29. - Final Selection for the SOTA EV Power Train

TABLE XIV - POWER TRAIN COMPONENT LIST FOR THE SOTA ELECTRIC VEHICLE

ITEM	WEIGHT kg	WEIGHT lbs
1. Drive Motor: AC, 3-phase, dripproof, blower cooled, 29.8 kW (40 hp) @ 7200 rpm, General Electric Frame #215T.	38.6	85
2. Controller: 88 kVA, 750 A, 3-phase, variable voltage, variable frequency, PWM inverter, all transistorized, regenerative braking, current limiting, blower cooled, Rohr Industries.	20.9	46
3. Blower (Motor): 12 V, 10 A, 6.94 m^3/s (250 cfm), thermostatically controlled.	2.3	5
4. Transmission: Modified McKee 2-speed manual with synchromesh and helical gears. Reduction ratio 1.91:1 in high gear, 3.82:1 in low gear.	20.4	45
5. Axle/Differential: Spicer Model #IS-18 aluminum housing, modified for McKee transmission. Helical gears, 5.17:1 ratio.	24.9	55
6. Driveshafts: Telescoping with Spicer/Dana RZEPPA (Ball spline) joints. (per set)	13.6	30
7. Wheels: Rim size 13 x 5. Kelsey & Hayes #98237. (per set of two).	13.6	30
8. Tires: Steel belted radial, 175 R13, load range B @ 221 kPa (32 psi). (per set of two).	20.0	44
9. Brakes: Hydraulic drum brakes.	9.1	20
TOTAL	163.3	360

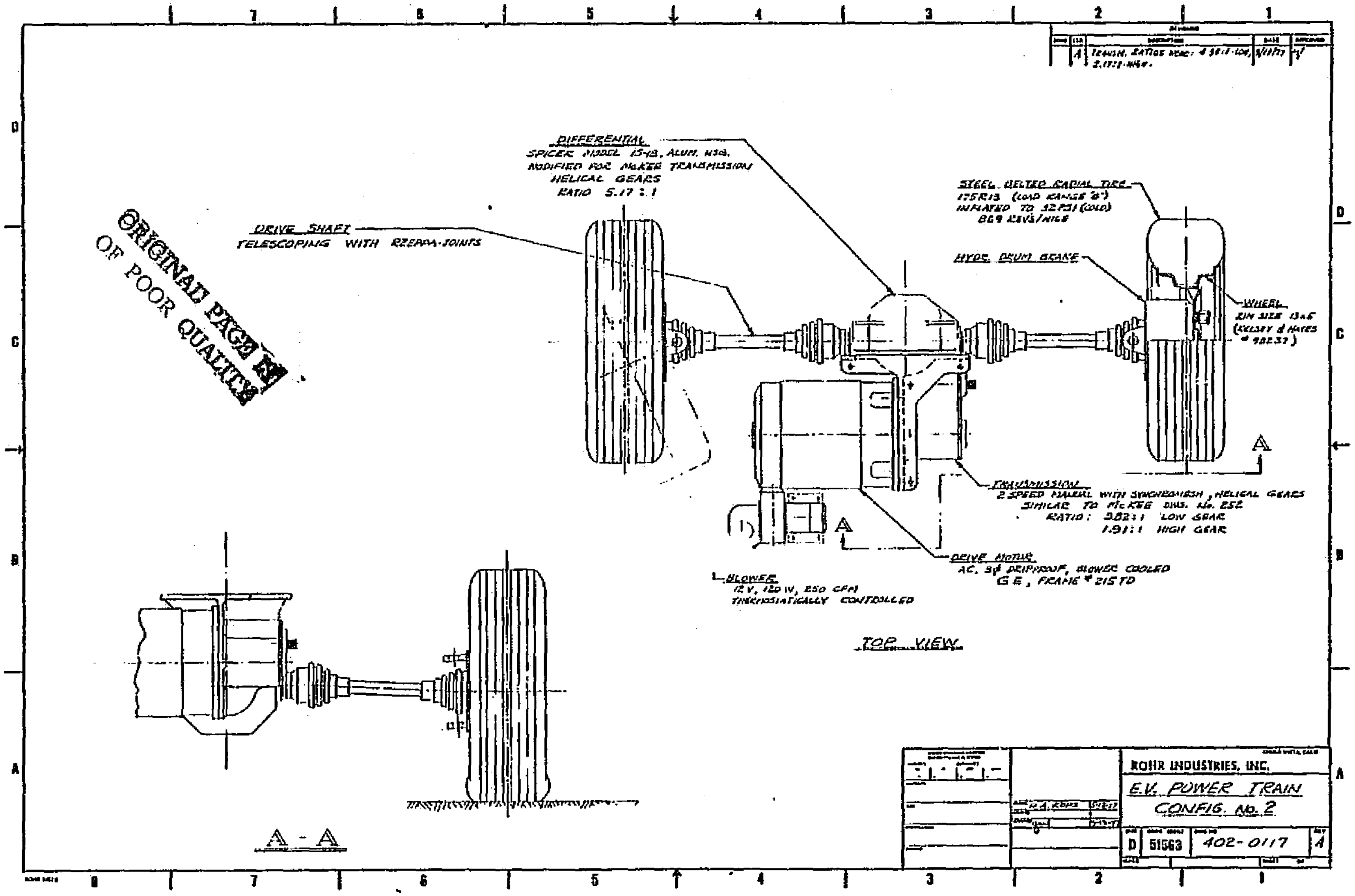

Figure 30. - General Arrangement For The SOTA EV Power Train

a lever-operated cable connected to the synchromesh unit. The transmission is shifted from one gear to the other by releasing the accelerator pedal to remove the load on the gear and then moving the shift lever to the desired gear position. The accelerator pedal can then be pressed to restore power to the wheels. A clutch is not required for this type of transmission. A method of automatically shifting the gears with an electronic control unit is discussed in section 7.4.

6.2.1 Motor

The motor description for the General Electric TRI-CLAD 700 line of aluminum frame motors is given in table XV. The specification for this EV application requires that standard winding voltage (230 volts at 60 Hz) be changed to match the voltage available from the inverter connected to the specified battery. The maximum output voltage of the controller is established by the battery voltage. The battery voltage using (16) 6 volt batteries would be 96 volts. On this basis, the maximum voltage possible from the controller would be 67.8 volts RMS (96 volts divided by the square root of 2). The 215T frame wound for 230 volts has 66 series turns per phase. This frame wound with 5 turns per phase would have a nominal rating of (5/66) X 230, which is equal to 17.4 volts at 60 Hz or 69.6 volts (4 x 17.4) at 240 Hz. This voltage and frequency provides the capacity to match the power requirement during regenerative braking from the 72.4 km/hr (45 mph) specified in the Schedule D driving cycle.

The 215T frame at the standard 60 Hz 230 power line voltage is rated for continuous operation at 40.8 Nm (30.1 ft-lbs) at 1740 rpm (equivalent to 7.5 kW or 10 hp). By operating this motor frame wound for a voltage commensurate with the 96 V battery source and increasing the frequency, the output power can be increased proportional to the speed (i.e., frequency) increase without changing the full load torque rating. During acceleration or regenerative braking, this motor can be operated for short periods at 200% of rated torque (ref. figures 15 and 17). Allowing for higher high frequency core loss and lower copper loss resulting from operation with the SAE "D" driving cycle, the total motor loss is lower than the continuous rated loss for this motor.

The structural design of this motor is adequate for speeds up to 13,000 rpm. A motor speed of 9000 rpm provides adequate margin for this application and it can be achieved within the limits of stock optional shaft bearings and optional rotor balancing. A motor speed of 9000 rpm is equivalent to a vehicle (road) speed of 101.5 km/hr (63.1 mph) which is in excess of the required 88.6 km/hr (55 mph). This provides adequate margin for overspeed operation (e.g., downhill driving). The remainder of the specifications are also factory available customizing options/accessories.

The motor cooling is achieved by a thermostatically controlled external blower driven by an accessory 12 V battery. This blower will limit motor temperature to 100° C. The external blower is coupled by a manifold or duct to the motor air inlets (2) at each each of the motor frame. The specific arrangement is a function of the vehicle configuration.

TABLE XV. - MOTOR DESCRIPTION/SPECIFICATION FOR THE SOTA POWER TRAIN

Manufacturer:	General Electric
Model Line:	TRI-CLAD 700 Aluminum Motor
Type:	K (NEMA Design B)
Frame:	215T
HP:	29.8 kW (40 hp) @ 7200 rpm
Torque:	40.8 Nm (30.1 ft lbs) at full load 89.5 Nm (66 ft lbs) at breakdown
Time Rating:	Continuous at rated full load torque
Synch. Speed:	7200
Volts:	69.2 (line to line)
Current:	364
Phases:	3
Frequency:	240 Hz
Enclosure:	Dripproof
Service Factor:	1.15
Ambient Temperature	40° C
Mounting Position:	Horizontal
Bearings:	Ball
Special Provisions: No internal fan (externally blower cooled) Dynamic balance to 9000 rpm Thermostat for auxiliary blower switch Type D Flange, unfooted Splined output shaft Extra varnish treatment	

6.2.2 Controller Description and Operation

The specifications and features of the selected AC controller are given in table XVI. The controller is a variable voltage variable frequency 3-phase sine wave current inverter (four quadrant) designed for controlling a 3-phase induction motor operating from a DC source. The AC controller selected for the SOTA EV power train is based on a design developed by Rohr Industries for industrial motor control applications. The major difference from previously produced controllers is the use of lower voltage transistors corresponding to the 96 V battery bank for the SOTA EV.

The input voltage is 96 VDC from a battery pack consisting of (16) 6 V batteries. The controller is rated at 88 kVA with a 750 A output. The output voltage varies from 0 to 68 V (rms) and the frequency varies from 1 to 300 Hz. The controller when coupled to a 3-phase induction motor is fully reversible and is designed for regenerative braking without the use of contactors. Torque control goes automatically from motoring to regenerative braking as the controller output frequency is changed to go from positive to negative slip in the motor.

The controller consists of two major elements - the power circuit (ref. figure 24) and the logic circuit (figure 31). The power portion of the controller is comprised of a number of standard power module cards of the plug-in printed circuit card type. The power modules contain the required number of parallel connected low current rated transistors to provide the current capability for both motoring and regenerative braking currents. The power modules are replaceable as a unit for servicing. The logic section consists of a DC to frequency converter, a 3-phase sine wave oscillator, a pulse width modulator (PWM), and a driver logic with feedback voltage attenuation. The block diagram of the logic circuit (figure 31) is drawn for clarity as if each block is a separate piece of hardware. In actual implementation, a microprocessor using only one digital-to-analog (D/A) converter, etc., is required and operates on a time shared basis in various positions on the circuit.

Motor control is achieved through the control of the frequency and the voltage applied. AC motors produce essentially constant torque for constant motor current. To realize constant torque at different speeds (rpm), the motor current is maintained constant while varying the frequency to correspond to the speed desired. This is achieved by varying the motor voltage and frequency over the range of operation.

The controller responds to the accelerator or brake pedal position by providing voltage and frequency to the motor which will operate the motor at its highest possible efficiency based on the torque and speed demanded. A motor look-up table (table XVI) is built into the logic motor control circuit to provide a basis for selecting the optimum conditions for highest efficiency. For example, at low torque levels, motor voltage is reduced in order to reduce the iron losses. For maximum acceleration or regenerative effort, motor voltage is increased to provide maximum magnetic flux. This technique of control results in performance similar to a series DC motor in that flux is maximum when motor torque demand is at maximum level.

The logic system uses a pulse train from the tachometer generator to develop the synchronous (no torque) frequency. The tachometer (figure 31) has two sensing

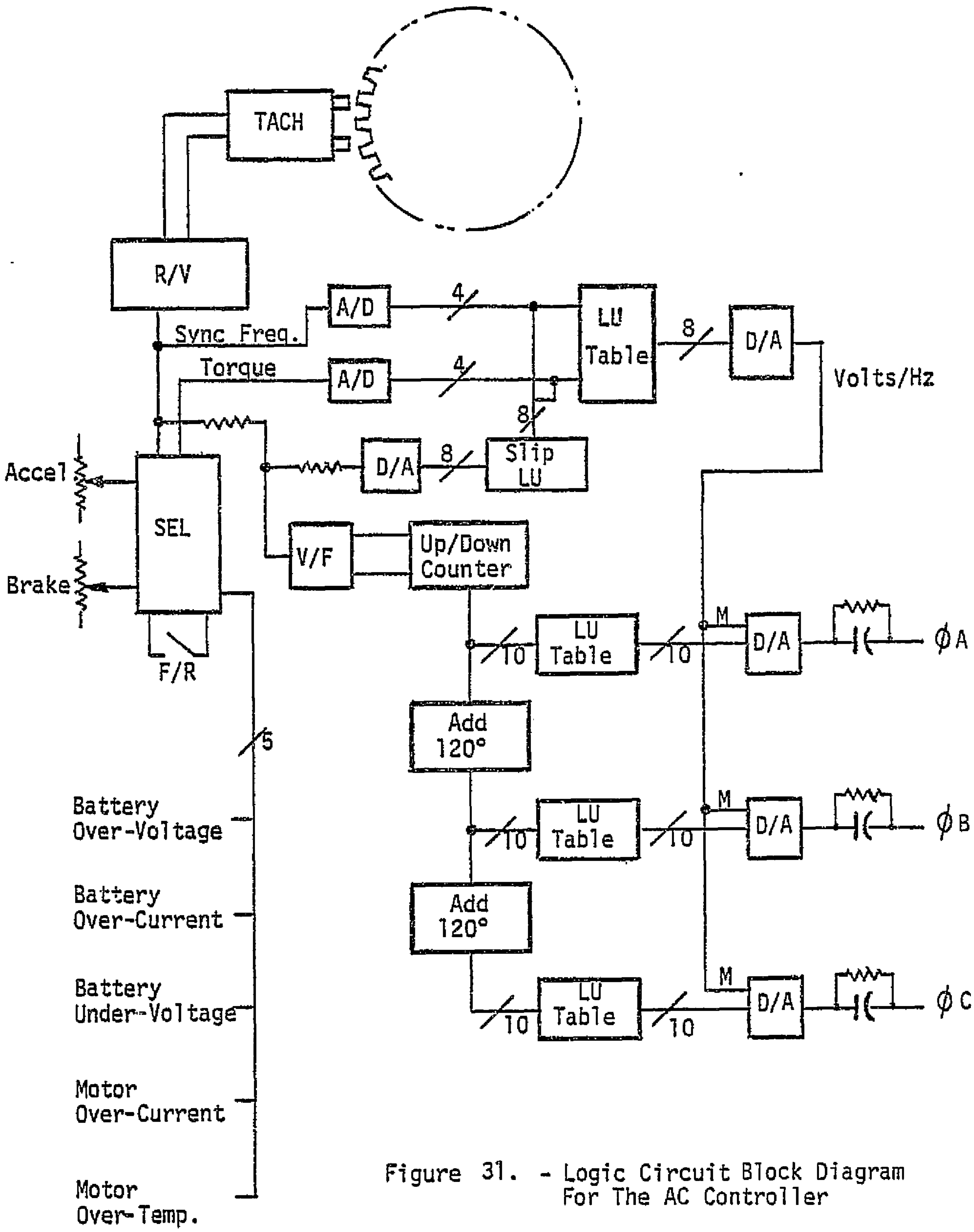

Figure 31. - Logic Circuit Block Diagram For The AC Controller

heads so that both direction and speed of the motor can be determined. The rate-to-voltage converter (R/V) provides a bipolar output to three receivers in proportion to motor speed, with polarity equal to rotation direction. The voltage-to-frequency (V/F) advances the counter at a rate which will result in synchronous frequency at the phase output if there is no input from the selection (SEL). The selector provides additional input to the torque analog-to-digital (A/D) converter in accordance with the setting of the accelerator or brake pedals. The selector overrides accelerator position if the brake pedal is actuated. The selector also disables the brake signal below 8 km/hr (5 mph), preventing motor plugging and battery waste when regeneration is not effective. The brake pedal always provides an output polarity opposite to that of the tachometer R/V output. The forward/reverse switch (F/R) changes the acceleration signal polarity to reverse the direction of rotation and vehicle travel. This switch can only function when the vehicle is stationary or moving at low speed.

The V/F converter has an output rate proportional to the absolute value of the sum of R/V and slip look-up table outputs. It has another output depending upon the polarity of this sum. This polarity controls the count up or down action and resulting phase rotation. The counter output passes through a read only memory where the count is converted to an equivalent fundamental and third harmonics sine angle. Similarly, the other two phases are generated by adding 120° and 240° to the phase A counter.

The look-up table harmonic wave outputs are converted by means of multiplying D/A converters. The multiplying inputs are provided by RPM and torque demand inputs derived from the look-up table. The output signals are differentiated by resistor-capacitor networks to provide the necessary increased voltage with frequency and are used as inputs to pulse width modulators to develop motor voltage. Additional inputs to the selector logic override the accelerator and brake controls in the event of battery over-voltage, under-voltage, over-current, motor over-current, or motor over-temperatore.

High speed transistors in the pulse width modulator circuit permit the use of a high carrier frequency (4 kHz). As a result of the high carrier frequency, the output current waveform is an almost perfect sine wave. This means there is no degradation in the motor efficiency even though it is powered by a VV/VF inverter (as opposed to 60 Hz power line). Motor primary and secondary leakage inductance serve as an adequate carrier frequency filter so that other electrical filter elements are not necessary. Additional data and further information on the background of the Rohr controller are presented in Appendix C.

6.3 PERFORMANCE PREDICTIONS

The predicted range of the selected system powered by the AC motor and controller when operated according to the SAE Schedule D driving cycle is 90.4 km (56.2 mi). This range represents a 52% increase in travel range over the best power train design built to date when each is based on a battery bank of (16)

TABLE XVI - CONTROLLER DESCRIPTION/SPECIFICATION FOR THE SOTA POWER TRAIN

MODEL:	312
MANUFACTURER:	Rohr Industries, Inc. P.O. Box 878 Chula Vista, CA 92012
TYPE:	Variable voltage, variable frequency, 3-phase sine wave current inverter (four quadrant)
APPLICATION:	Battery powered electric vehicle
INPUT VOLTAGE:	96 VDC Nominal (110 max, 80 min)
KVA RATING:	88 kVA
OUTPUT VOLTAGE:	0 to 68 V RMS (line to line)
OUTPUT CURRENT:	750 A/phase for 1 min, 400 A continuous
RIPPLE CURRENT:	Less than 20 A RMS in specified load
MOTOR LOAD PER PHASE:	Capacitance to ground, 0.01 mfd. Primary and secondary inductance (60 Hz), 10.2 microhenry. Primary resistance, 0.0028 ohms. Secondary resistance, 0.00092 ohms. Mutual inductance, 162 microhenry. Shunt resistance (60 Hz), 0.770 ohms.
OUTPUT FREQUENCY:	1 to 300 Hz
POWER LOSS:	
- No Load	0.080 kW
- Full Load	1.7 kW
COOLING:	Thermally cycled air flow from blower powered from a 12 V accessory battery.
OVERCURRENT PROTECTION:	Current limited output with inverse time limit rated at 350 A.
BATTERY PROTECTION:	Automatic limited power operation at low battery voltage.
SIZE (Approx.):	457.2 mm x 508 mm x 203.2 mm (18 in x 20 in x 8 in)
WEIGHT (Approx.):	20.86 kg (46 lbs)
CONTROL METHOD:	Accelerator or brake pedal position proportional to desired torque, V/Hz and slip Hz applied according to the motor lookup table as torque and rpm demand vary. Resulting motor current and efficiency shown in motor table for reference. Motor line-to-line voltage (RMS) shall be as shown except as limited by low battery terminal voltage. Slip frequency shall not exceed $\pm$ 5 Hz under any condition of acceleration or deceleration.

TABLE XVI - CONTROLLER DESCRIPTION/SPECIFICATION FOR THE SOTA POWER TRAIN (CONTINUED)

MOTOR LOOKUP TABLE

% TORQUE	RPM	SLIP HZ	V/HZ	AMP	EFF
20	427	0.76	0.218	137	0.651
20	875	0.84	0.194	137	0.773
20	1324	0.88	0.185	137	0.820
20	1772	0.92	0.179	138	0.842
20	2222	0.92	0.177	139	0.853
20	2671	0.97	0.173	140	0.857
20	3121	0.97	0.172	141	0.857
20	3570	1.02	0.168	142	0.855
20	4020	1.02	0.167	143	0.851
20	4470	1.02	0.167	144	0.846
20	4918	1.07	0.163	146	0.839
20	5368	1.07	0.163	147	0.832
20	5818	1.07	0.162	148	0.823
20	6266	1.12	0.159	151	0.815
20	6716	1.12	0.159	152	0.806
20	7166	1.12	0.158	154	0.796
20	7616	1.12	0.158	155	0.787
20	8066	1.12	0.158	156	0.777
20	8516	1.12	0.158	158	0.767
20	8965	1.18	0.155	161	0.757
40	424	0.88	0.292	193	0.652
40	874	0.88	0.269	193	0.780
40	1324	0.88	0.262	193	0.830
40	1774	0.88	0.258	193	0.855
40	2222	0.92	0.251	194	0.870
40	2672	0.92	0.249	195	0.878
40	3121	0.97	0.243	196	0.882
40	3571	0.97	0.242	197	0.885
40	4020	1.02	0.236	198	0.885
40	4470	1.02	0.236	199	0.884
40	4918	1.07	0.230	201	0.882
40	5368	1.07	0.230	201	0.879
40	5818	1.07	0.229	202	0.876
40	6266	1.12	0.224	205	0.872
40	6716	1.12	0.224	206	0.868
40	7166	1.12	0.224	206	0.863
40	7616	1.12	0.224	207	0.858
40	8065	1.18	0.218	210	0.853
40	8515	1.18	0.218	211	0.847
40	8965	1.18	0.218	213	0.842
60	411	1.30	0.315	247	0.620
60	861	1.30	0.283	247	0.762
60	1311	1.30	0.272	247	0.820
60	1761	1.30	0.267	248	0.851
60	2211	1.30	0.264	248	0.869
60	2661	1.30	0.262	249	0.880
60	3111	1.30	0.261	249	0.888
60	3561	1.30	0.260	250	0.892
60	4011	1.30	0.259	250	0.895
60	4461	1.30	0.258	251	0.896

TABLE XVI - CONTROLLER DESCRIPTION/SPECIFICATION FOR THE SOTA POWER TRAIN (CONTINUED)

MOTOR LOOKUP TABLE

% TORQUE	RPM	SLIP HZ	V/HZ	AMP	EFF
60	4911	1.30	0.258	252	0.896
60	5361	1.30	0.257	253	0.896
60	5811	1.30	0.257	253	0.895
60	6261	1.30	0.257	254	0.893
60	6711	1.30	0.256	255	0.891
60	7161	1.30	0.256	256	0.888
60	7611	1.30	0.256	257	0.885
60	8059	1.36	0.250	260	0.881
60	8503	1.58	0.234	272	0.876
60	8948	1.74	0.224	282	0.871
80	398	1.74	0.338	308	0.573
80	848	1.74	0.295	308	0.732
80	1298	1.74	0.281	308	0.799
80	1748	1.74	0.274	309	0.835
80	2198	1.74	0.270	309	0.857
80	2648	1.74	0.268	310	0.872
80	3098	1.74	0.266	310	0.882
80	3548	1.74	0.264	311	0.888
80	3998	1.74	0.263	311	0.893
80	4448	1.74	0.262	312	0.896
80	4898	1.74	0.262	313	0.898
80	5348	1.74	0.261	314	0.899
80	5798	1.74	0.261	314	0.900
80	6248	1.74	0.260	315	0.899
80	6698	1.74	0.260	316	0.898
80	7148	1.74	0.260	317	0.897
80	7598	1.74	0.259	318	0.896
80	8043	1.92	0.249	329	0.892
80	8487	2.11	0.239	342	0.887
80	8927	2.44	0.225	364	0.881
100	390	2.01	0.368	366	0.533
100	833	2.22	0.306	374	0.695
100	1283	2.22	0.289	375	0.771
100	1733	2.22	0.281	375	0.813
100	2185	2.22	0.276	375	0.840
100	2633	2.22	0.272	376	0.858
100	3083	2.22	0.270	377	0.870
100	3533	2.22	0.268	377	0.879
100	3983	2.22	0.267	378	0.886
100	4433	2.22	0.266	379	0.890
100	4883	2.22	0.265	379	0.894
100	5333	2.22	0.264	380	0.896
100	5783	2.22	0.264	381	0.898
100	6233	2.22	0.263	382	0.899
100	6683	2.22	0.263	383	0.899
100	7133	2.22	0.262	384	0.899
100	7583	2.22	0.262	385	0.898
100	8023	2.57	0.247	409	0.893
100	8465	2.83	0.239	427	0.888
100	8897	3.44	0.224	466	0.878

TABLE XVI - CONTROLLER DESCRIPTION/SPECIFICATION FOR THE SOTA POWER TRAIN (CONTINUED)

MOTOR LOOKUP TABLE					
% TORQUE	RPM	SLIP HZ	V/HZ	AMP	EFF
120	383	2.22	0.399	428	0.499
120	830	2.33	0.335	428	0.671
120	1277	2.44	0.308	431	0.748
120	1727	2.44	0.298	431	0.793
120	2169	2.70	0.283	444	0.821
120	2619	2.70	0.279	444	0.842
120	3069	2.70	0.276	445	0.856
120	3519	2.70	0.274	446	0.867
120	3969	2.70	0.272	446	0.876
120	4419	2.70	0.271	447	0.882
120	4869	2.70	0.270	448	0.887
120	5319	2.70	0.269	449	0.890
120	5769	2.70	0.268	449	0.893
120	6219	2.70	0.268	450	0.895
120	6669	2.70	0.267	451	0.896
120	7119	2.70	0.267	452	0.897
120	7569	2.70	0.266	453	0.897
120	8002	3.28	0.249	494	0.888
120	8436	3.79	0.238	529	0.880
120	8855	4.84	0.225	594	0.865
140	377	2.44	0.427	488	0.467
140	823	2.57	0.353	489	0.646
140	1269	2.70	0.325	491	0.728
140	1719	2.70	0.314	492	0.776
140	2165	2.83	0.302	496	0.806
140	2615	2.83	0.297	496	0.827
140	3065	2.83	0.294	497	0.843
140	3506	3.12	0.282	512	0.856
140	3956	3.12	0.280	512	0.866
140	4406	3.12	0.279	513	0.874
140	4856	3.12	0.278	514	0.879
140	5306	3.12	0.277	515	0.884
140	5756	3.12	0.276	515	0.888
140	6206	3.12	0.275	516	0.890
140	6656	3.12	0.275	517	0.892
140	7106	3.12	0.274	518	0.894
140	7547	3.44	0.265	542	0.890
140	7975	4.18	0.251	594	0.879
160	369	2.70	0.453	548	0.439
160	815	2.83	0.370	549	0.621
160	1261	2.97	0.340	552	0.708
160	1711	2.97	0.327	552	0.759
160	2156	3.12	0.314	557	0.791
160	2606	3.12	0.310	558	0.815
160	3056	3.12	0.306	558	0.832
160	3502	3.28	0.298	565	0.844
160	3952	3.28	0.296	566	0.854
160	4402	3.28	0.294	566	0.862
160	4852	3.28	0.293	567	0.869
160	5302	3.28	0.292	568	0.874

TABLE XVI - CONTROLLER DESCRIPTION/SPECIFICATION FOR THE SOTA POWER TRAIN (CONTINUED)

MOTOR LOOKUP TABLE					
% TORQUE	RPM	SLIP HZ	V/HZ	AMP	EFF
160	5742	3.61	0.282	587	0.880
160	6192	3.61	0.281	588	0.884
160	6642	3.61	0.281	589	0.886
160	7092	3.61	0.280	590	0.889
160	7518	4.39	0.266	646	0.877
180	361	2.97	0.477	608	0.412
180	806	3.12	0.386	610	0.598
180	1252	3.28	0.353	614	0.688
180	1702	3.28	0.339	614	0.743
180	2152	3.28	0.331	614	0.778
180	2597	3.44	0.320	620	0.802
180	3047	3.44	0.317	621	0.821
180	3497	3.44	0.314	622	0.835
180	3942	3.61	0.306	629	0.845
180	4392	3.61	0.304	630	0.854
180	4842	3.61	0.303	631	0.861
180	5292	3.61	0.302	631	0.867
180	5742	3.61	0.301	632	0.872
180	6186	3.79	0.295	642	0.875
180	6636	3.79	0.294	643	0.878
180	7068	4.39	0.283	683	0.877
200	356	3.12	0.505	668	0.390
200	802	3.28	0.406	668	0.578
200	1247	3.44	0.370	671	0.671
200	1692	3.61	0.350	677	0.726
200	2142	3.61	0.341	677	0.764
200	2592	3.61	0.335	678	0.791
200	3036	3.79	0.326	685	0.809
200	3486	3.79	0.323	686	0.825
200	3936	3.79	0.320	686	0.837
200	4386	3.79	0.319	687	0.847
200	4831	3.98	0.312	696	0.853
200	5281	3.98	0.311	697	0.860
200	5731	3.98	0.310	698	0.865
200	6181	3.98	0.309	698	0.870
200	6612	4.61	0.296	734	0.872
220	352	3.28	0.532	728	0.369
220	792	3.61	0.419	729	0.557
220	1242	3.61	0.386	730	0.655
220	1686	3.79	0.365	735	0.712
220	2136	3.79	0.355	735	0.751
220	2581	3.98	0.344	742	0.778
220	3031	3.98	0.339	743	0.799
220	3481	3.98	0.336	743	0.816
220	3925	4.18	0.329	753	0.827
220	4375	4.18	0.327	753	0.838
220	4825	4.18	0.325	754	0.846

TABLE XVI - CONTROLLER DESCRIPTION/SPECIFICATION FOR THE SOTA POWER TRAIN (CONTINUED)

REFERENCE DATA FOR MOTOR LOOKUP TABLE
RATED: HP= 10 FREQ= 60 VOLTAGE= 17.3 RPM= 1740 TORQUE= 30.20780943 AMPS= 358.859 EFF.= 0.82 P.F.= 0.83
PART LOAD: TORQUE= 15.10390471 RPM= 1774.033237 HP= 5.097796658 EFF.= 0.83 P.F.= 0.69
EQUIVALENT CIRCUIT: LO= 1.62379E-04 L1=L2= 1.01565E-05 RO= 0.770085 R1= 2.79364E-03 R2= 9.16574E-04

6 volt batteries. The adjusted performance comparison for previously built vehicles was dicussed in section 2.2.

As a result of the simulation runs and parametric studies (discussed in section 5), the final power train specifications were revised to reflect a slight reduction in the controller current requirement and slightly larger tire with a lower rolling resistance. A comparison of the final and preliminary baseline performance is summarized in table XVII. A 5% increase in the Schedule D range was achieved as a result of the changes in components (primarily attributed to the reduction in tire rolling resistance). The performance characteristics during a Schedule D cycle in terms of motor output power, motor current, motor efficiency, and battery current as a function of cycle time are given in figures 32 through 35. A complete tabulation of the data resulting from the computer simulation of the Schedule D cycle is included as Appendix D.

The influence of regenerative braking on the performance is graphically illustrated in figure 32. The peak power during braking is more than double the power required during acceleration. The peak power during braking (48.1 kw or 64.6 hp) turned out to be slightly less than the 55.85 kw (74.9 hp) (see figure 7) calculated during the theoretical analysis because of the lower kinetic energy of the final configuration. The gross vehicle weight was reduced by 177 kg (390 lbs)

The chop-off of the motor current (figure 33) during the regenerative braking period reflects the limitations of the motor look-up table represented by figure 15 because the 200 and 220% torque curves were not calculated at those motor speeds.

Although not printed out in the tabulated data, the motor efficiency during the Schedule D cycle is plotted in figure 34. The motor efficiency during acceleration quickly reaches the 89% level. The efficiency during cruise drops to 81%, but this is considered to be excellent performance in view of the light loads during constant speed cruise. The rapid decay in efficiency during regenerative braking reflects the decreasing speed and the increasing influence of the fixed losses at the lower speeds. .

The peak battery currents during acceleration and regenerative braking (figure 35) are almost equal (292 vs 347 A). The ability of the AC system to keep the battery current low even though the motor current is high can be seen by comparing the curves of figures 33 and 35. The battery current at the 72.4 km/hr (45 mph) cruise is 82 amperes - very close to the 75 ampere level used in the performance rating of the battery.

The final specifications and performance data for the selected power train are listed in table XVIII. The gross vehicle weight with four 68.0 kg (150 lb) passengers is 1456 kg (3210 lbs). Vehicle range at 88.6 km/hr (55 mph) is 75.3 km (46.8 mi). The highest vehicle speed (as defined by SAE J227a) sustainable for at least one hour starting with a fully charged battery is 82.9 km/hr (51.5 mph).

The vehicle is capable of a top speed of 101.5 km/hr (63.1 mph) on level road without a headwind and accelerates at full power to 72.4 km/hr (45 mph) in 13.5 seconds. The top speed is limited by the maximum allowable motor speed.

TABLE XVII- SIMULATION RESULTS (FINAL VS. PRELIMINARY) FOR THE SOTA POWER TRAIN

	PERFORMANCE BASED ON			
	FINAL SPECS		BASELINE SPECS	
MOTOR	GE 215T		GE 215T	
RPM @ 88.6 km/hr (55 mph)	7850		7850	
MOTOR WEIGHT	38.6 kg (85 lbs)		38.6 kg (85 lbs)	
RANGE	km	mi	km	mi
SCHEDULE D	90.4	56.2	86.1	53.5
SCHEDULE D W/O REGEN.	77.4	48.1	74.5	46.3
CRUISE @ 72.4 km/hr	119.2	74.1	110.5	68.7
CURRENT (A)	BATT	MOT	BATT	MOT
ACCELERATION	292	538	291	585
CRUISE	82	153	88	171
REGENERATIVE BRAKING	-347	-726	-343	-769
PEAK POWER	kW	hp	kW	hp
ACCELERATION	18.8	25.2	18.9	25.4
CRUISE	5.7	7.6	6.2	8.3
REGENERATIVE BRAKING	48.1	64.5	47.1	63.1
ENERGY/CYCLE	MJ	Wh	MJ	Wh
ACCELERATION	0.554	154	0.569	158
CRUISE	0.374	104	0.400	111
REGENERATIVE BRAKING	(0.133)	(37)	(0.130)	(36)
TOTAL	0.796	221	0.839	233
DISTANCE/CYCLE	1.63694 km (1.01736 mi)		1.63716 km (1.01750 mi)	
ACCELERATION PROFILE: 2.24 m/s^2 (5 mph/sec) THEN CONSTANT POWER				

TABLE XVIII- SPECIFICATIONS/PERFORMANCE FOR THE SOTA POWER TRAIN

GROSS VEHICLE WEIGHT (4 passengers)	1456 kg (3210 lbs)
VEHICLE CURB WEIGHT	1184 kg (2610 lbs)
POWER TRAIN WEIGHT	163 kg (360 lbs)
TIRE ROLLING RESISTANCE (Nominal @ 0 Vel.) 175 R13 @ 221 kPa (32 psi)	0.0696 N/kg load (7.1 lbs/1000 lb load)
CHASSIS ROLLING RESISTANCE	0.00981 N/kg load (1.0 lbs/1000 lb load)
MECHANICAL DRIVELINE EFFICIENCY	92% low gear 93% high gear
PEAK POWER	54.5 kW (73 hp) @ 6400 rpm
CONTROLLER CURRENT (Maximum)	750 A
ACCELERATION 0-32 km/hr (20 mph) (SCHEDULE D) 0-48 km/hr (30 mph) 0-72 km/hr (45 mph)	6 sec. 14 sec. 28 sec.
ACCELERATION 0-32 km/hr (20 mph) (Maximum) 0-48 km/hr (30 mph) 0-72 km/hr (45 mph)	4.2 sec. 7.1 sec. 13.5 sec.
MAXIMUM SPEED - 1 hr - SAE J227a	82.9 km/hr (51.5 mph)
MAXIMUM SPEED (9,000 rpm)	101.6 km/hr (63.1 mph)
RANGE - SCHEDULE D	90.4 km (56.2 mi)
RANGE - 10% slope @ 48 km/hr (30 mph)	10.1 km (6.3 mi)
CRUISE RANGE - 88.6 km/hr (55 mph)	75.3 km (46.8 mi)

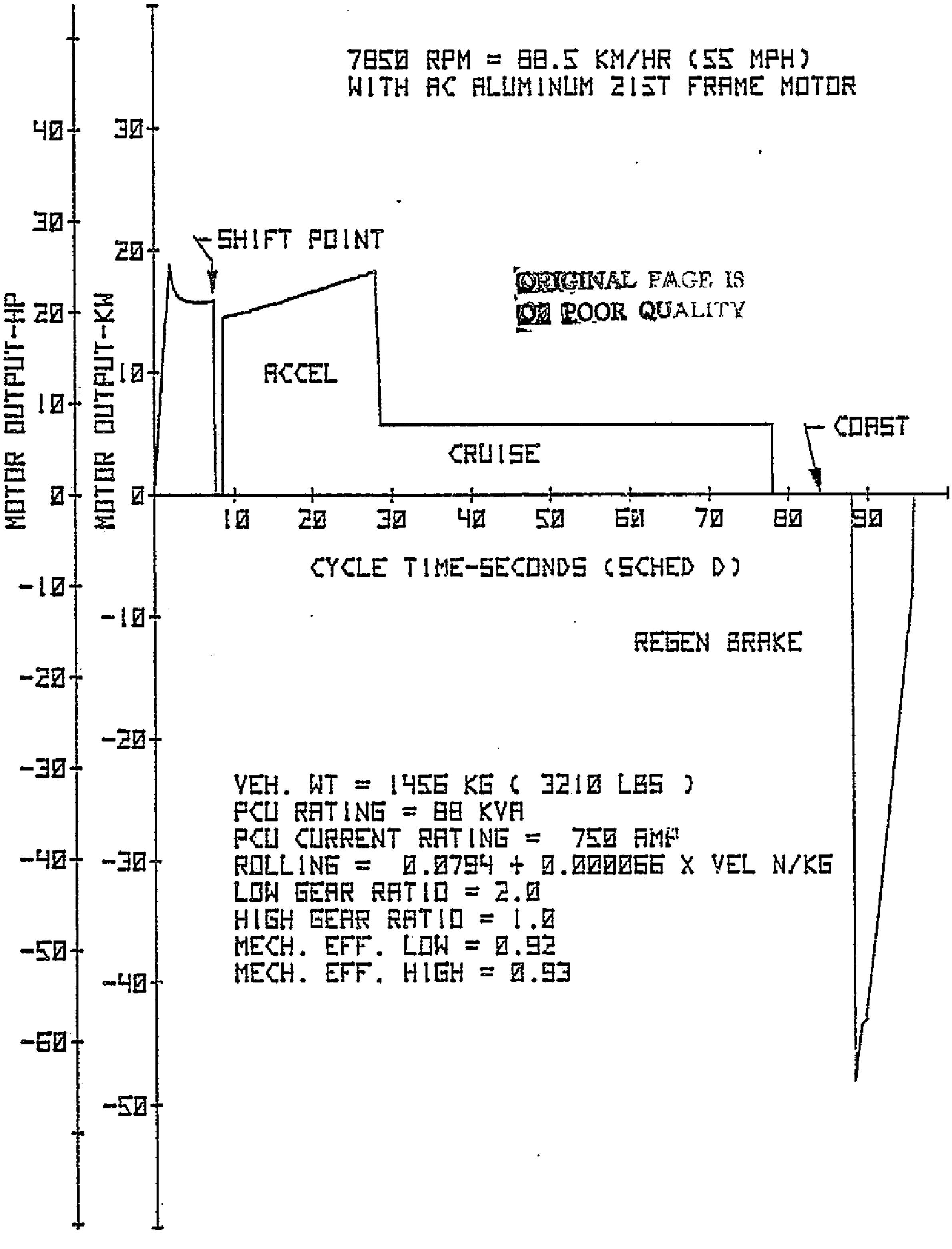

Figure 32. - Motor Output vs. Cycle Time
Based on Final Specifications

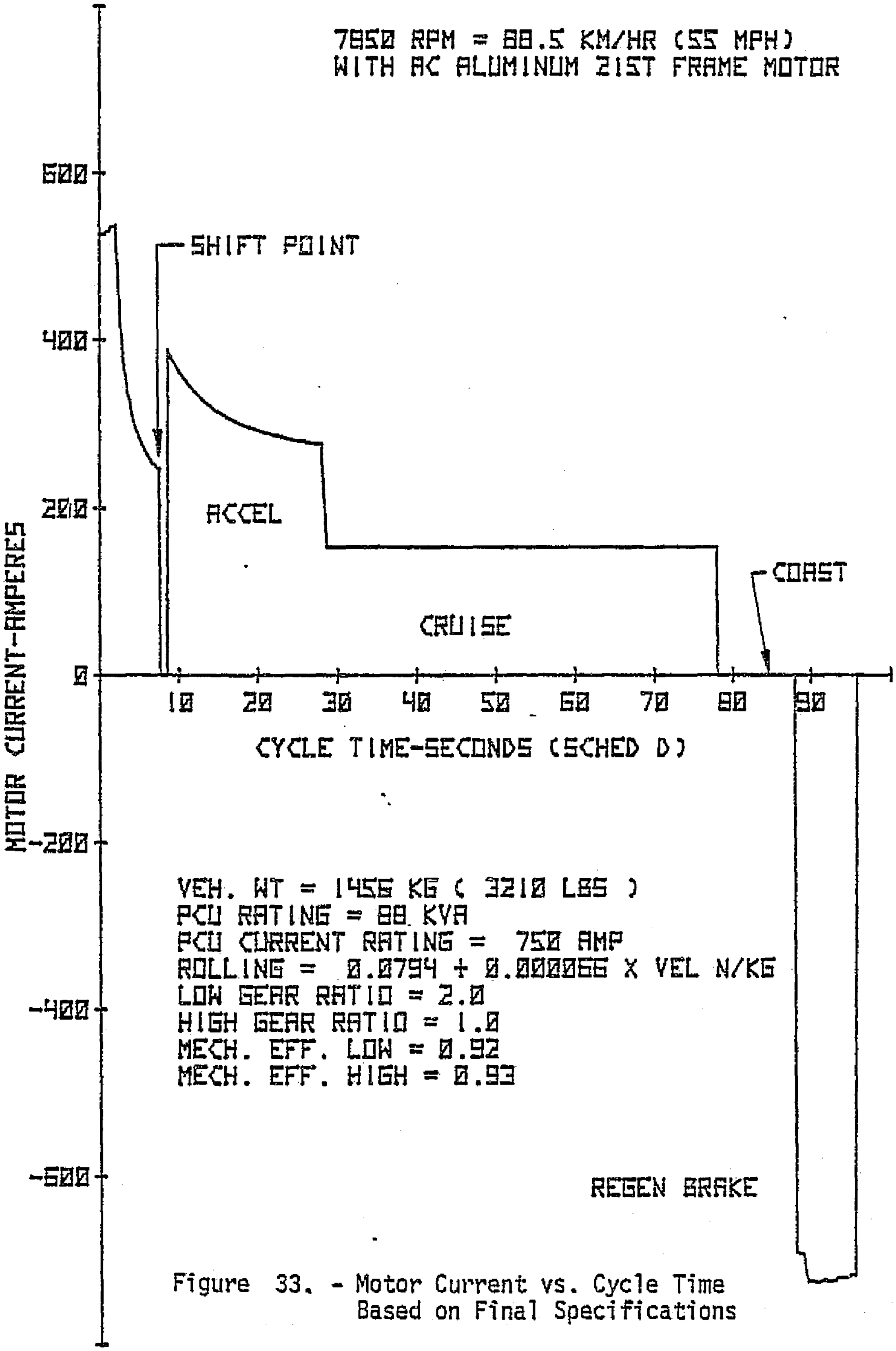

Figure 33. - Motor Current vs. Cycle Time
Based on Final Specifications

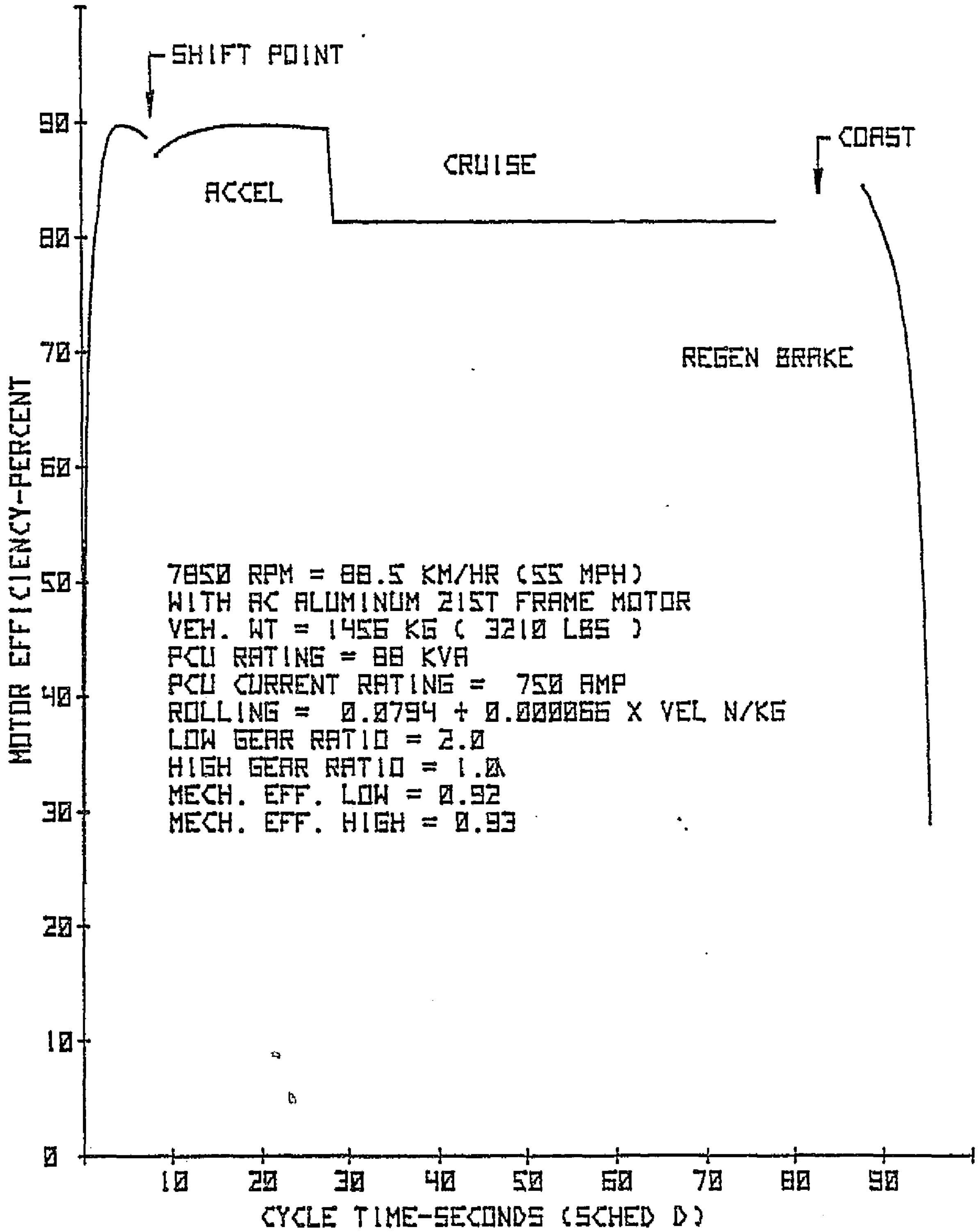

Figure 34.. - Motor Efficiency vs. Cycle Time
Based on Final Specifications

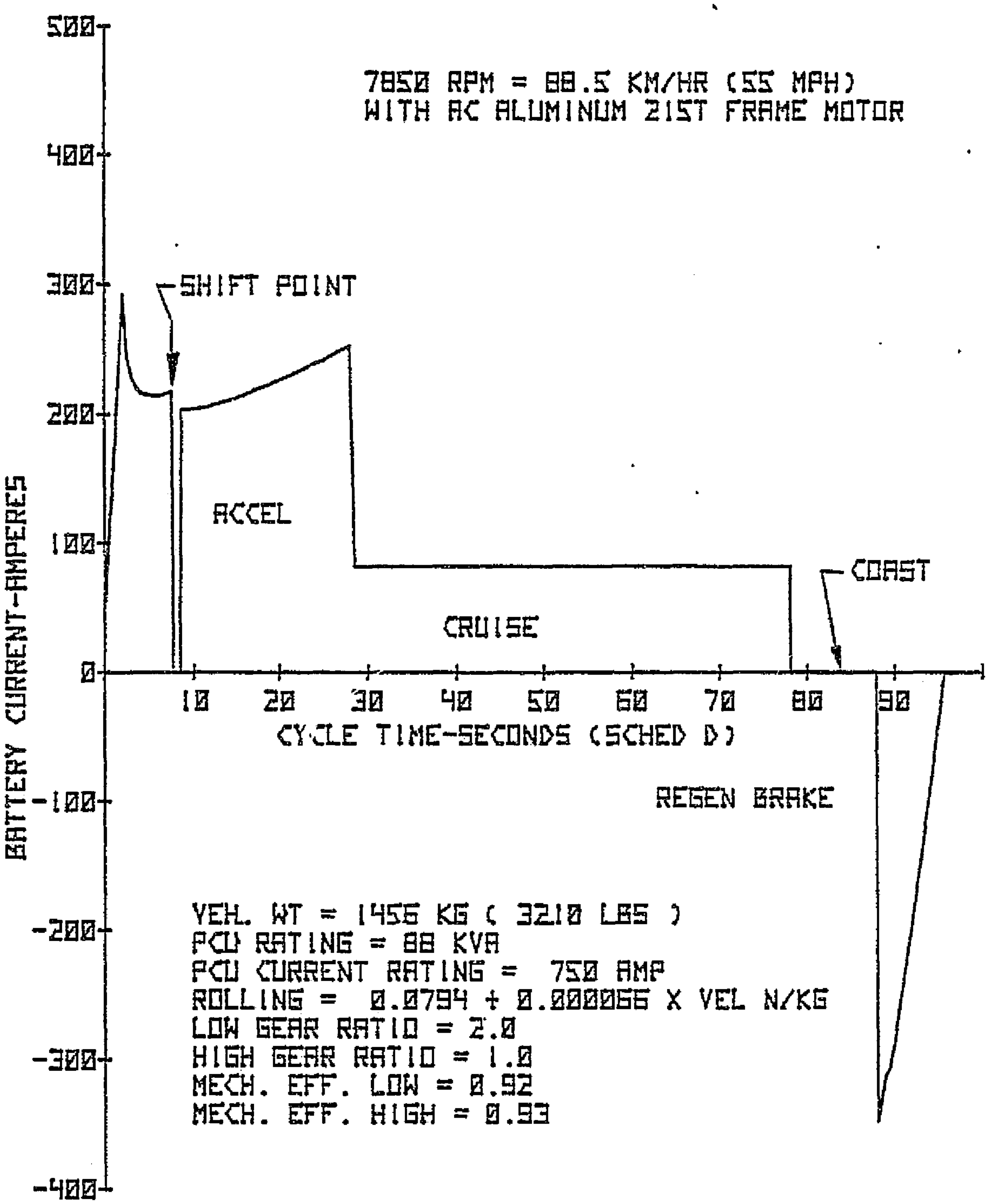

Figure 35. - Battery Current vs. Cycle Time Based on Final Specifications

The range performance of the vehicles used in all of the analyses in this report are based on batteries starting with a full charge. Acceleration and maximum speed performances are based on average of fully charged and 80% discharged condition. The battery voltages and currents represent average values during one complete discharge cycle (to 1.75 V/cell) at an ambient temperature of 27°C (80°F).

The power train supplied by the (16) batteries can travel continuously on a 10% grade at 48.3 km/hr (30 mph) for 10.1 km (6.3 mi). The limit in this situation is the amount of battery energy available. This vehicle requires 23.1 kW (30.9 hp) to travel at a steady 48.3 km/hr (30 mph) cruise on the 10% slope and draws 374 amperes from the battery. At this current level, a full battery charge is depleted in 12.5 minutes of continuous operation on the 10% slope. If the operation on the 10% grade was interspersed with short periods of rest, the total distance traveled on the slope could be as great at 17.1 km (10.6 mi).

The maximum speed on a 10% slope is 80.0 km/hr (50 mph) for 3.5 minutes (a range of 4.7 km or 2.9 mi) before the battery is discharged. Maximum allowable battery power limits the speed on the 10% slope to 80.0 km/hr (50 mph). The percent gradeability limit is 34.6% as defined by SAE J227a Section 8.

The maximum acceleration (vs time) the vehicle can achieve on a level road with the propulsion battery at the mean state of charge is shown in figure 36. Maximum acceleration versus vehicle speed is given in figure 37.

6.4 CONSTANT SPEED PERFORMANCE

The vehicle propulsion power required to overcome aerodynamic and rolling resistance based on constant cruise speeds is given in figure 38. Performance characteristics for steady speed cruise conditions in high gear are plotted in figures 39 through 45. These curves were obtained by modifying the cruise portion of the Schedule D computer simulation program to achieve the performance at speeds in addition to the 72.4 km/hr (45 mph) of Schedule D.

6.4.1 Range Versus Vehicle Cruise Speed

Cruise range for steady state operation is shown in figure 39. Below 32 km/hr (20 mph), range decreases because of constant controller losses and fairly constant motor magnetizing watt losses. The simulation assumed a constant controller loss of 0.003 times the rated volt-ampere capacity. This relatively small loss becomes significant at very low vehicle speeds where the road loads are low. To reduce this effect, portions of the controller could be put in an inactive mode unless required. This modification was not assumed since it has not been implemented in presently available controllers.

A significant point needs to be mentioned with respect to battery performance or capability in continuous duty situations such as constant speed cruise. The useful energy from a battery is a function of the discharge current and cycle. The least efficient use is for a continuous drain. The useful energy is greater when periods of rest are introduced.

The useful energy for the computer simulation was assumed to be 132.5 Ah

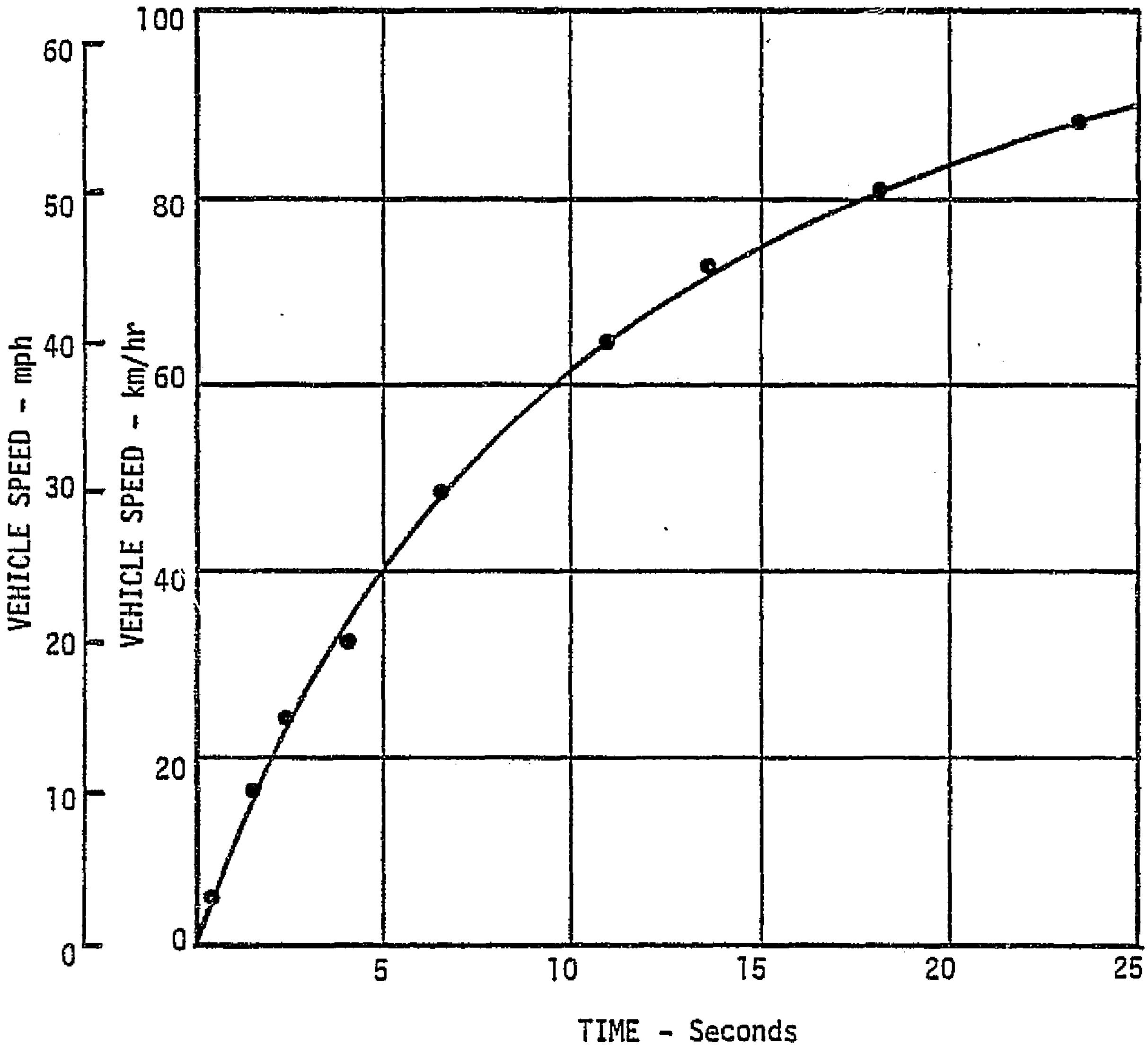

Figure 36. Vehicle Speed vs. Time During Maximum Acceleration for the SOTA EV Power Train

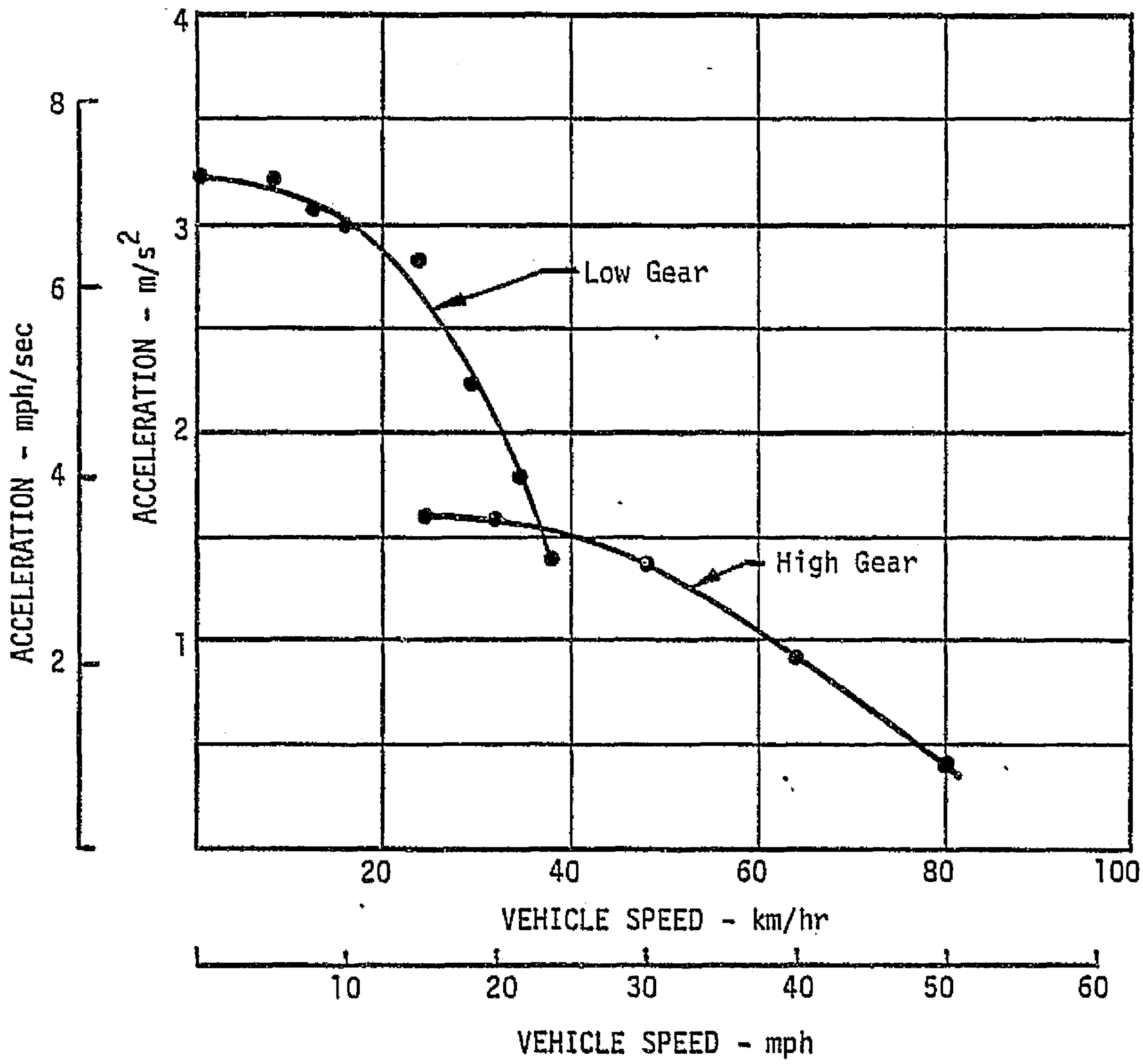

Figure 37. - Maximum Acceleration vs. Vehicle Speed for the SOTA EV Power Train

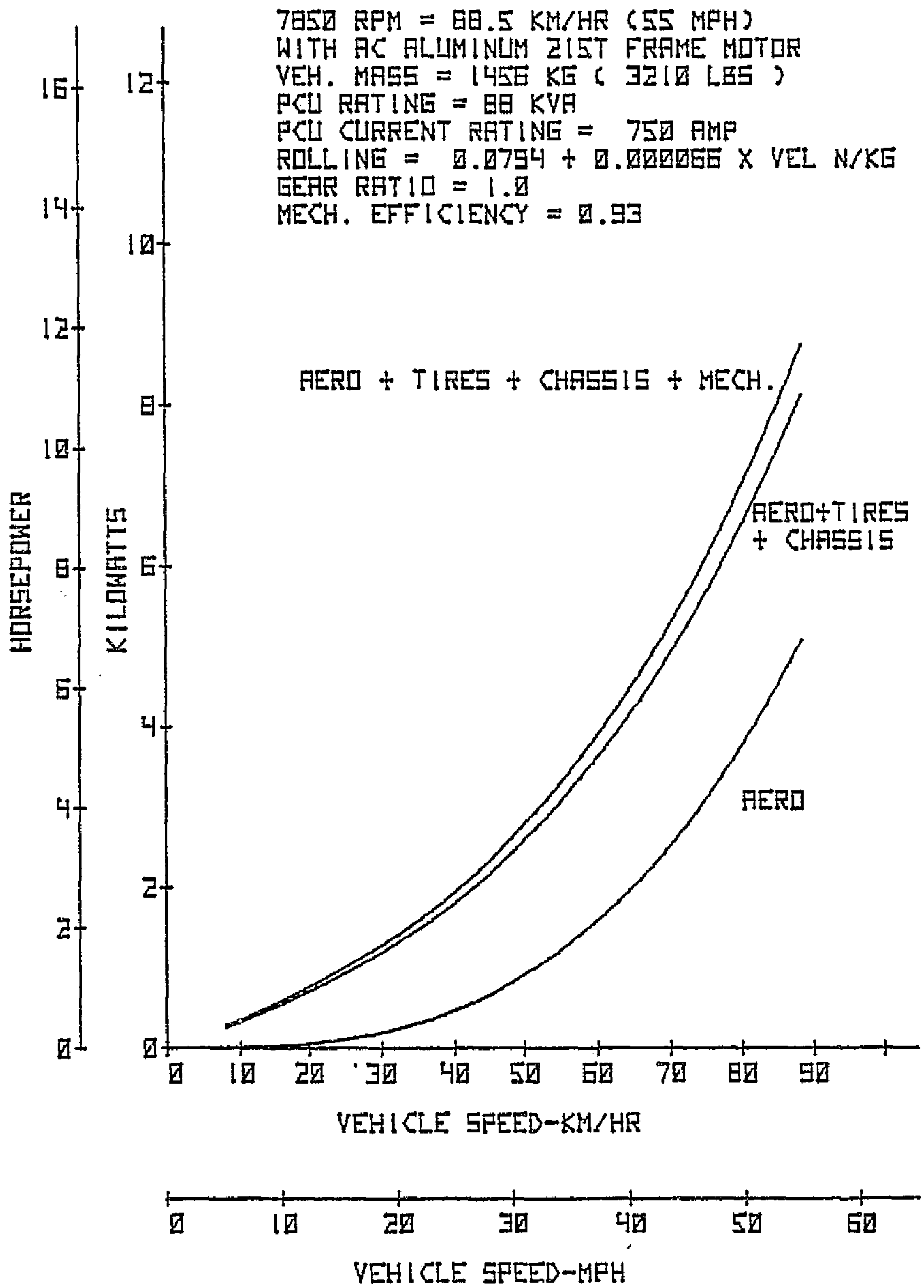

Figure 38. - Power Requirements for Constant Speed Cruise Based on Final Specifications

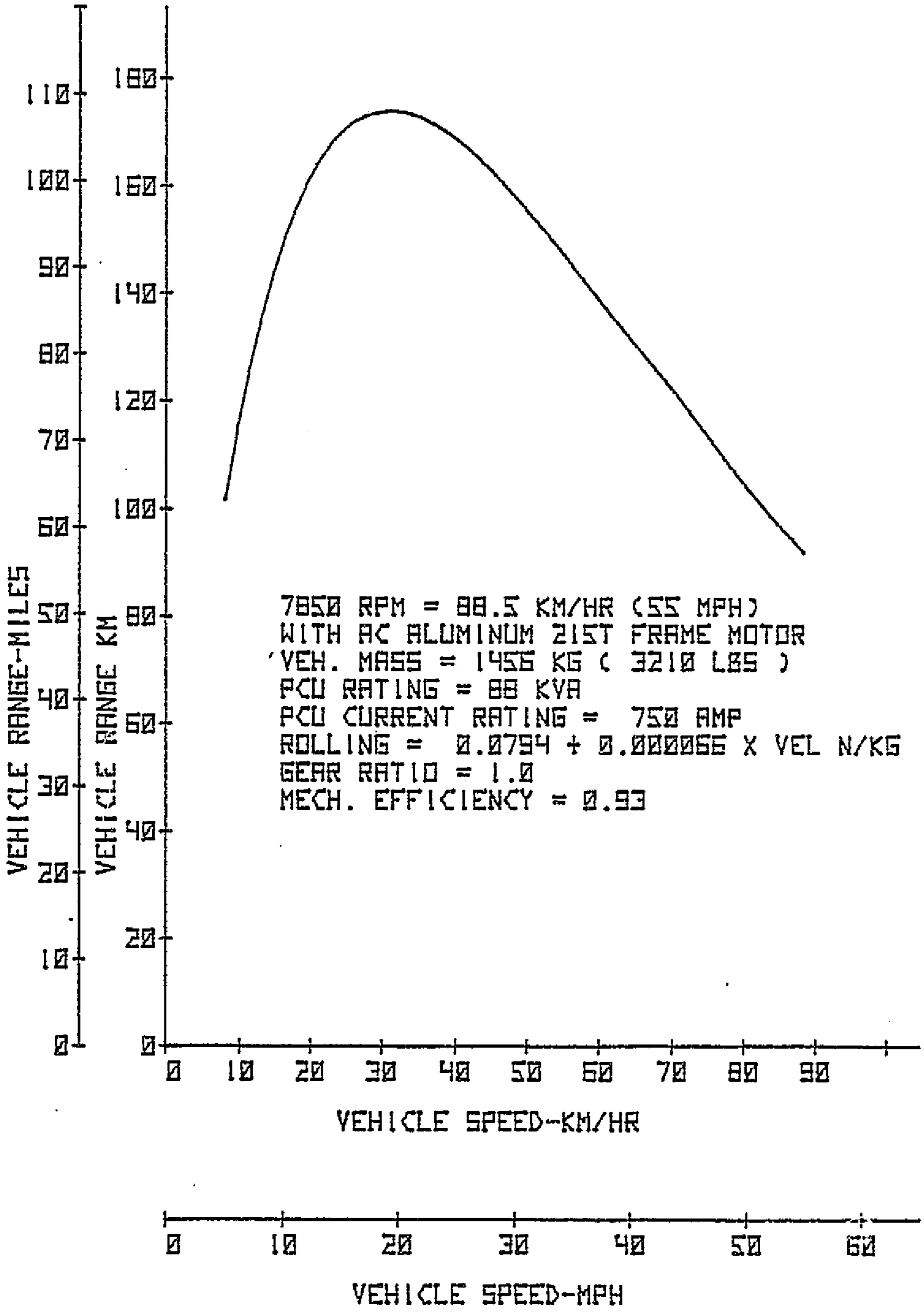

Figure 39. - Range vs. Cruise Speed (Constant) Based on Final Specifications

or 0.0093 MJ/kg (11.7 Wh/lb) for an average discharge current of 75 amperes at 27°C (80°F) ambient temperature until the terminal voltage drops to 5.25 V (1.75 V/cell). This is a reasonable average value since the current required during Schedule D cruise (the greatest portion of the cycle) is on the order of 70 to 85 A.

This constant speed curve is derived based on the energy consumption for each speed assuming that it is available from the battery on the basis of a constant 132.5 Ah independent of the current. For constant speed continuous duty from full charge to total discharge, the useful energy must be reduced when the current drain is greater than 75 A. Conversely, there would be greater useful energy when the current requirement is less than 75 A (e.g., 171 Ah is available at 25 A). The accuracy of the range calculations would be improved by introducing this variation.

This phenomenon imposes an overriding limit on range achievable for a single continuous discharge above 75 A. This fact was considered in section 6 for the range predictions at 88.6 km/hr (55 mph) cruise and on the 10% slope. As pointed out earlier, if the discharge cycle is broken into several shorter periods, the total useful energy would be increased and greater range would be achieved.

6.4.2 Energy Consumption vs Vehicle Cruise Speed

The energy or power consumption per unit distance according to road speed is plotted in figure 40. Energy consumption above and below 30 km/hr (20 mph) is influenced by the losses previously discussed in section 6.4.1.

6.4.3 Motor Current vs Vehicle Cruise Speed

Motor current (figure 41) does not vary significantly with speed because the influence of the controller logic in terms of establishing the optimum point for maximum efficiency. Over the entire speed range, motor torque and motor current are well below rated values. Most current is required for magnetizing and is reactive (wattless) current. At low speeds, torque is almost constant (rolling friction related). Since torque is a square function of exciting current, the slight reduction of torque required at constant low speed results in even smaller reduction in motor current. Motor kVA goes down as velocity goes down because of the reduction in motor voltage with motor frequency.

6.4.4 Motor Loss vs Vehicle Cruise Speed

Motor loss as a function of road speed is given in figure 42. Loss increases with speed because of increased load, bearing, and core losses as frequency increases. Motor loss at 8.05 km/hr (5 mph) is 0.2 kW.

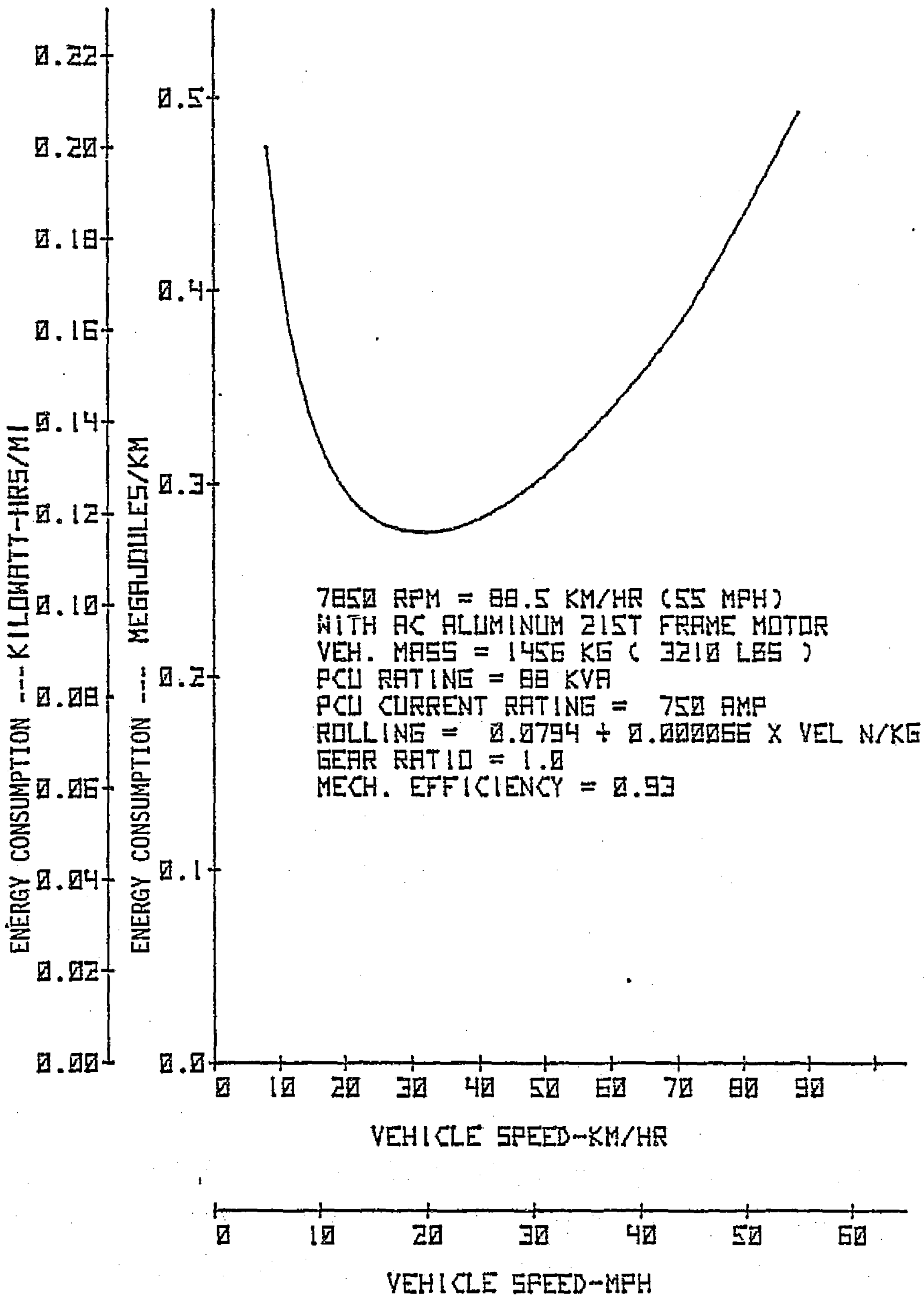

Figure 40. - Energy Consumption vs. Cruise Speed (Constant) Based on Final Specifications

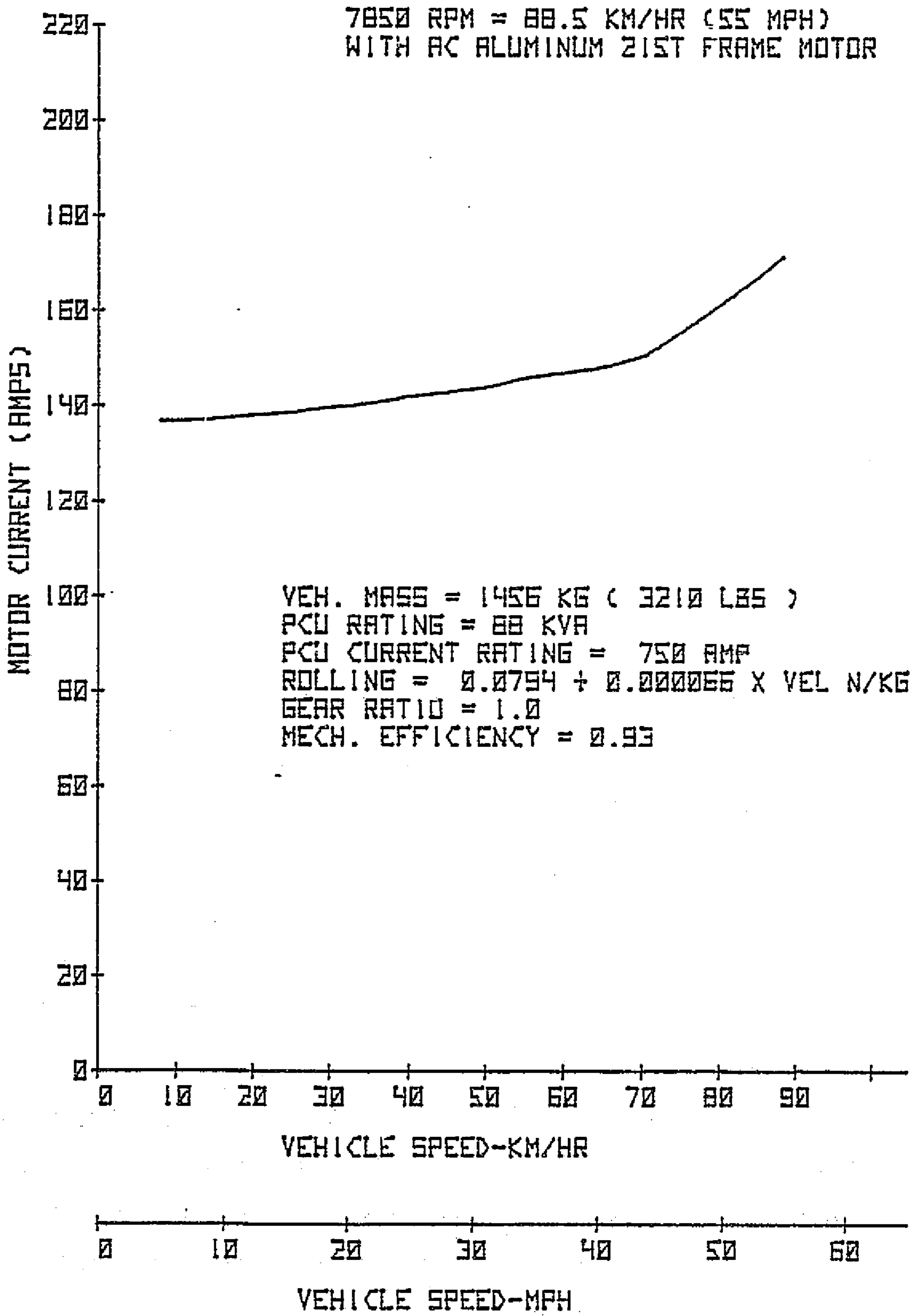

Figure 41. - Motor Current vs. Cruise Speed (Constant) Based on Final Specifications

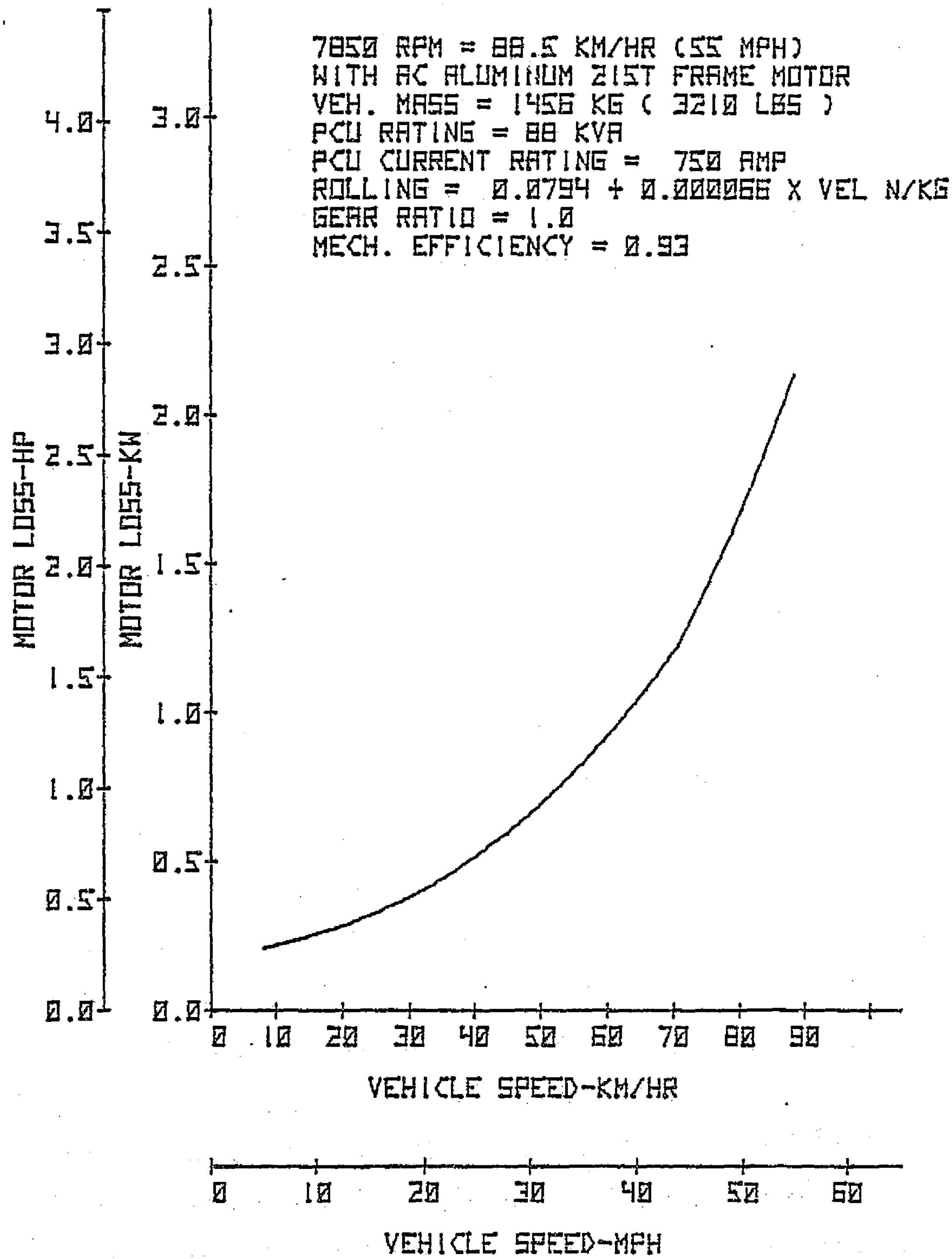

Figure 42. - Motor Losses vs. Cruise Speed (Constant) Based on Final Specifications

6.4.5 Motor Efficiency vs Vehicle Cruise Speed

Figure 43 shows the effect of the small 0.2 kW motor loss on low speed efficiency. As the road load decreases at the lower speeds, the fixed motor losses greatly influence the motor efficiency, causing it to drop significantly. A comparison of this curve with figure 34 shows the D cycle performance at much higher efficiency, especially during the important acceleration and regenerative braking periods, when large power is being handled. For constant speed below 24 km/hr (15 mph), only a fraction of a kilowatt road load exists, so that efficiency cannot be as good as at heavier loads. The low motor efficiency at low road speed would be compensated for by the fact that more useful battery energy can be achieved when the current drain is reduced, as discussed in section 6.4.1.

6.4.6 Battery Current vs Vehicle Speed

Figure 44 shows battery current versus constant vehicle speed. Battery current increases almost linearally with speed until aerodynamic drag becomes appreciable compared to rolling loads. Above this speed, battery current increases as the square of speed. Battery current is directly related to the true power required to propel the vehicle.

6.4.7 Controller Loss vs Vehicle Cruise Speed

Figure 45 illustrates controller loss for constant speed operation. At light loads corresponding to low vehicle speed, the constant controller loss term of 0.003 times rated kVA is significant. As vehicle speed increases, motor current increases, so that controller loss also increases.

6.5 JUSTIFICATION AND RATIONALE

At the conclusion of the preliminary analysis, mechanical components such as the transmission, differential, drive shaft, brakes, and tires, were selected for the model power train configurations. The principal design objectives were simplicity and compactness combined with high efficiency. On the basis of computer simulation runs supplemented by engineering judgment, it was possible to identify the efficient types and combinations which resulted in satisfactory performance. The most significant conclusion made with respect to the mechanical elements was that a fixed drive line ratio imposes such limitations on the system performance that a multigear transmission is required to meet the specifications.

During the early stages of analysis, the motor and controller were identified as the areas most lacking in proficiency and were given the greatest attention in the optimization task. Each of the candidate motor and controller combinations was "exercised" according to the SAE J227a Schedule D driving cycle to compute its optimum performance. The optimization concentrated on maximizing the vehicle range and overall efficiency by examining the performance during each mode of the cycle - acceleration, cruise, coast, and braking. It was during this evaluation that the most efficient acceleration profile was established. The fairly high initial acceleration, 2.24 m/s^2 (5 mph/sec), followed by constant power for acceleration resulted in the greatest range and was used as a basis for final selection of the motor and controller combination.

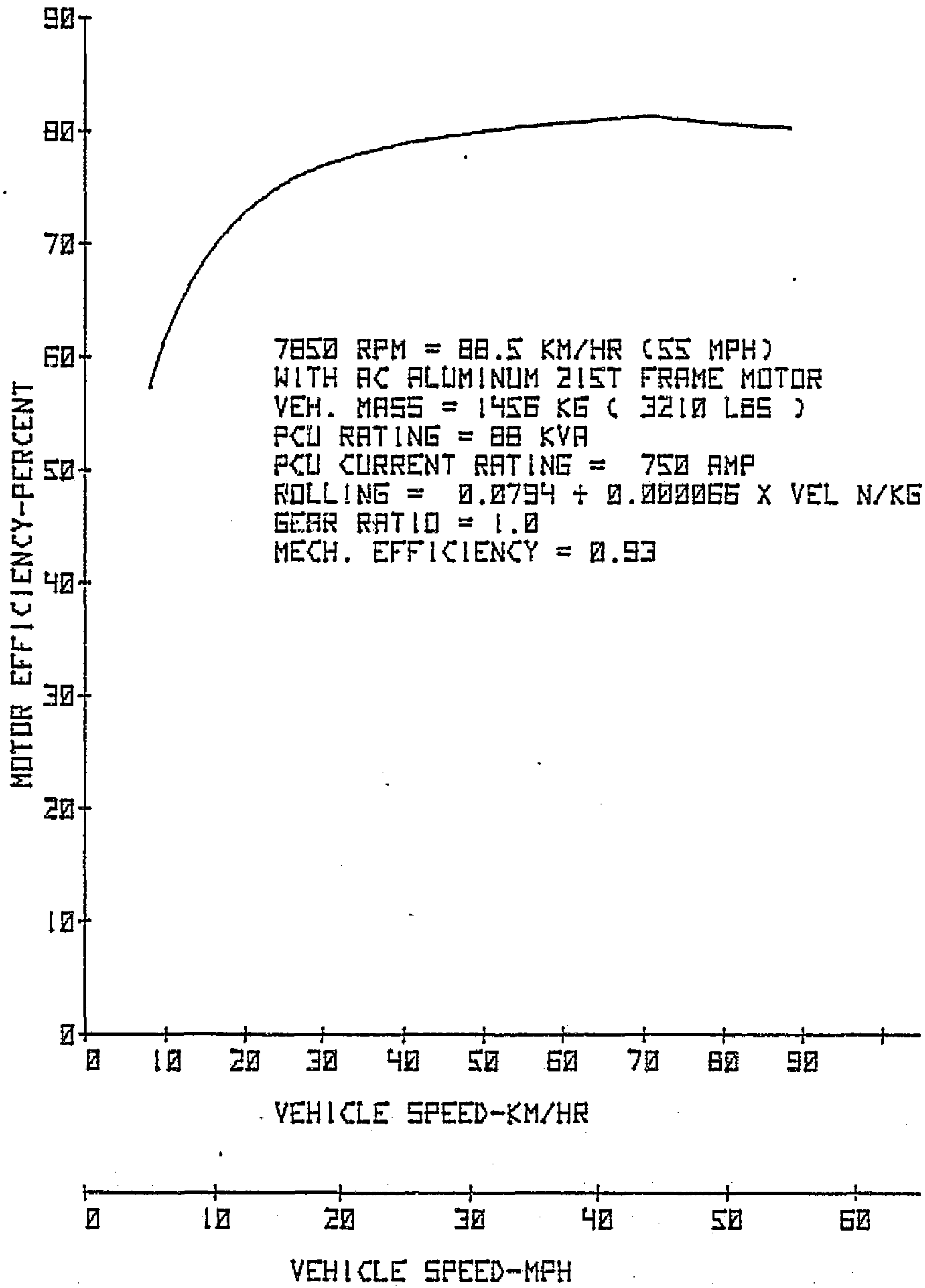

Figure 43. - Motor Efficiency vs. Cruise Speed (Constant) Based on Final Specifications

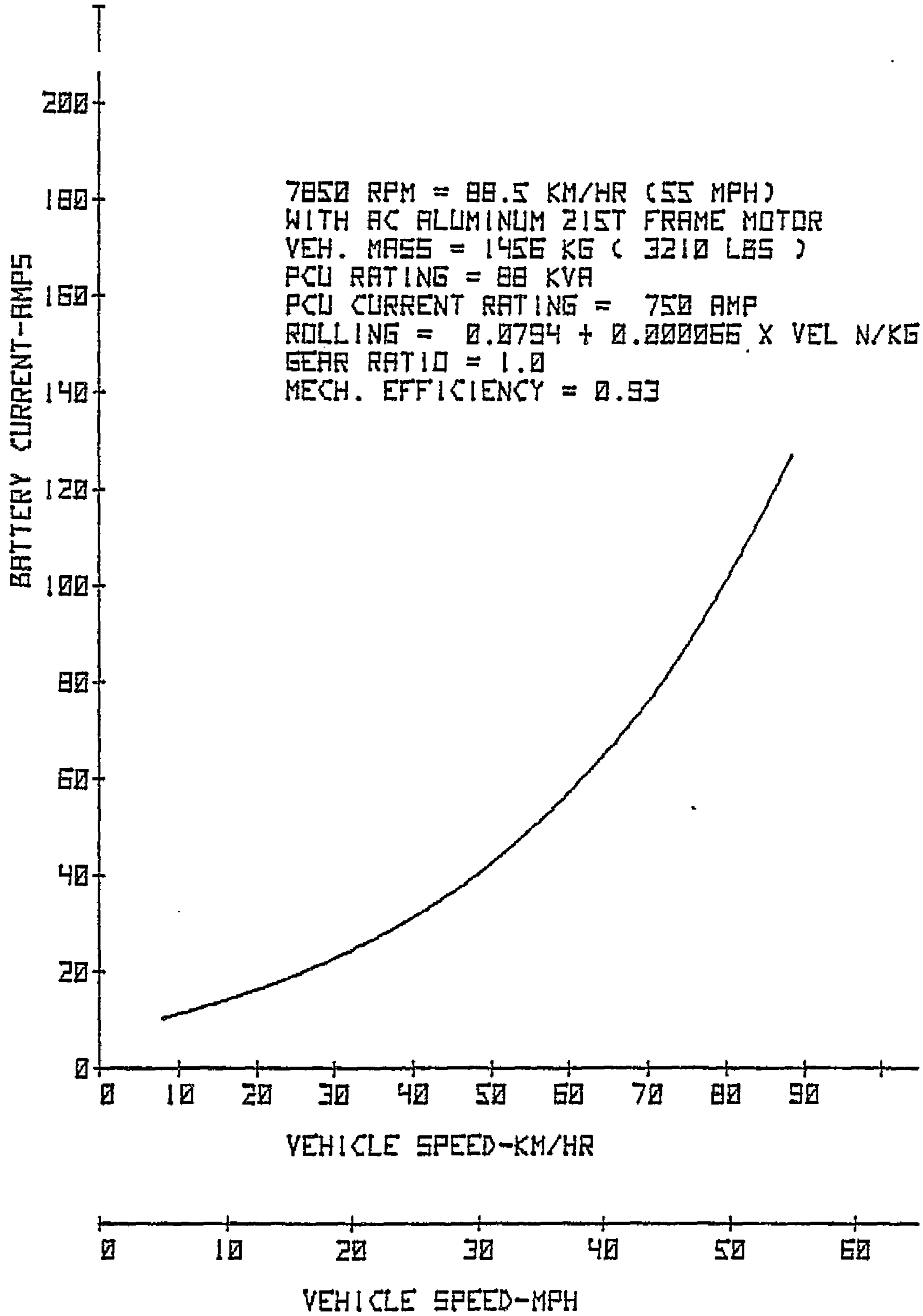

Figure 44. - Battery Current vs. Cruise Speed (Constant) Based on Final Specifications

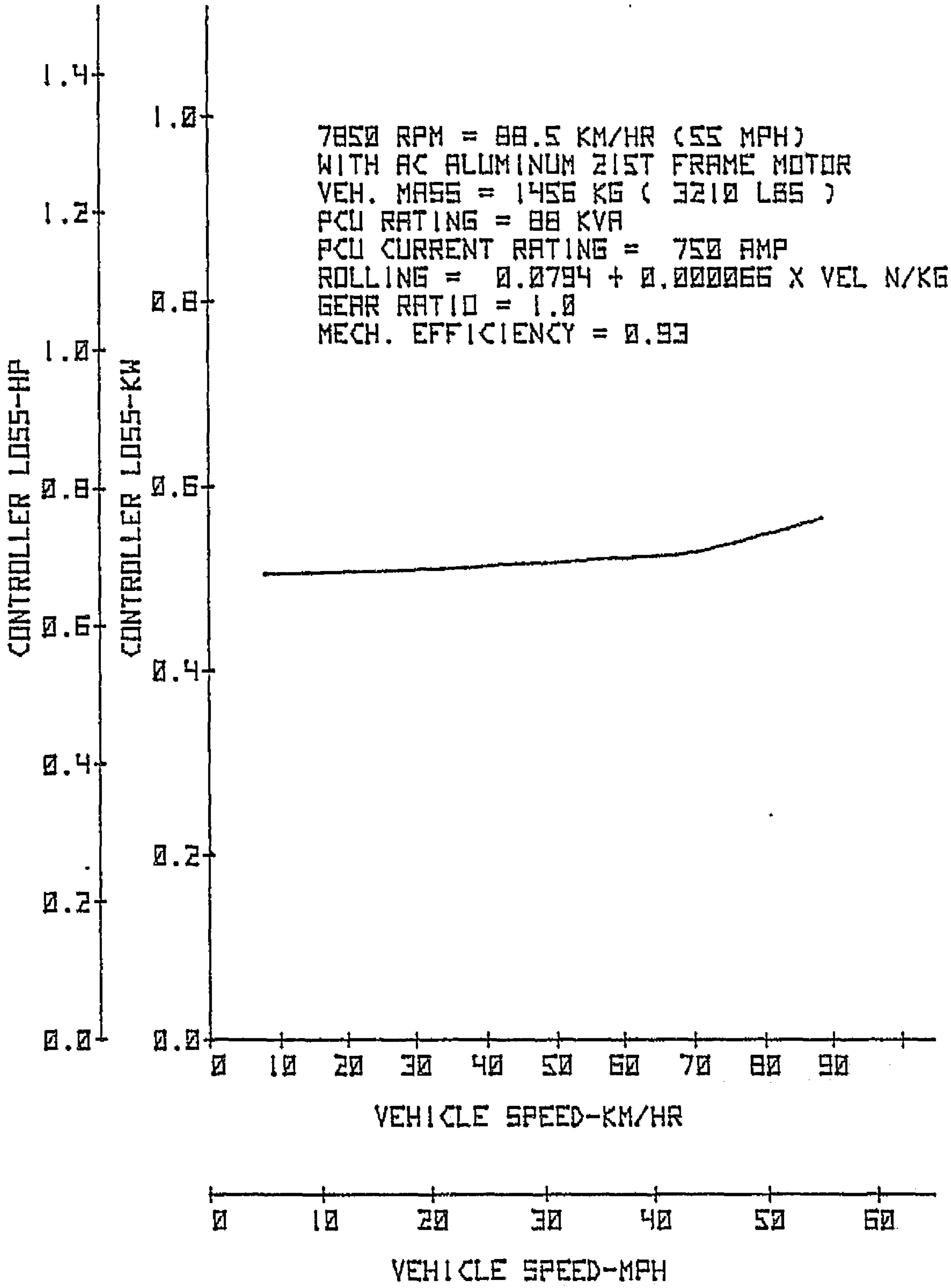

Figure 45. - Controller Losses vs. Cruise Speed (Constant) Based on Final Specifications

On the basis of maximum Schedule D range, the AC systems outranked the DC systems. The AC induction motor supplied by a 3-phase AC controller was finally selected as the design representative of the SOTA because it has the following advantages:

- Lightweight motor - 38.6 to 104.3 kg (85 vs 230 lbs) (section 4.2 & 4.3)
- Range of 90.4 km (56.2 mi) on Schedule D (section 6.3)
- High overall system efficiency (section 6.1)
- Regenerative braking without contactors (section 6.2.2)
- Reverse operation without contactors (section 6.2.2)
- Full time speed control (no bypass required)(section 6.2.2)
- Low cost motor (section 4.3)
- Reduced motor maintenance (no brushes) (section 2.1.1)
- High reliability (section 6.2.2)
- High energy recovery during regeneration (section 4.4 and table XI)
- Low energy consumption during cruise (section 4.4 and table XI)

The advantages of AC inverter controller powered by battery sources are not generally apparent to EV designers. The characteristics of the current drawn from a battery by an AC inverter do not include the high current spikes associated with SCR choppers. The elimination of the high current spikes results in increased range due to a more uniform battery current. The nearly constant battery drain for any given power level improves the efficiency of the battery and gives increased travel range per battery charge.

Consideration was given to future price trends in component costs. Refinements in circuitry and lower costs have created AC inverter drives which overcome the objection of earlier designs. The SOTA assessment considered the projected cost trend for candidate components and the fact that they are now manufactured in small quantities at relatively high cost. When manufactured in larger quantities, the costs will be low enough to be economically used in electric vehicles.

The analysis of improvement attributed to the use of regenerative braking showed a 17% increase in range. For this reason, prime consideration was given to systems with high capacity for regenerative braking.

In addition to the requirement for handling high power during regenerative braking, the acceleration requirement of Schedule D (0 to 72.4 km/hr or 45 mph in 28 sec) forces the selection of motors with greater capacity to meet the acceleration requirement with high efficiency. Approximately 52.2 kW (70 hp) (peak) is required in braking from 66.0 km/hr (41 mph). The high power motors require active voltage control during all three modes of use - acceleration, cruise, and regenerative braking.

The smaller and lighter AC motor will allow the chassis designer more flexibility in locating components in the vehicle. The unitized arrangement of the selected power train configuration can be easily incorporated into almost any conceivable vehicle body.

The selected AC system meets all of the requirements established for the preliminary power train design for a four-passenger SOTA electric vehicle with lead-acid batteries.

7.0 IMPROVEMENTS TO THE STATE-OF-THE-ART

7.1 INCREASED BATTERY VOLTAGE

The battery pack specified for this power train study is sixteen (16) six volt units which permits a maximum of 96 volts if they are connected in series. Changing to 12 volt batteries and increasing the series connected voltage to 192 volts would have several beneficial effects.

The higher voltage system permits the use of higher voltage power transistors at lower current levels. The higher voltage, lower current semiconductors will reduce the cost of the controller and other components which are current related such as conductors, connectors, fuses and disconnect switches. The size and weight of these items will also be reduced which in turn will increase range by a slight amount because the overall vehicle weight and rolling resistance is reduced. A 30% reduction in controller weight and cost is anticipated as a result of the increased voltage.

Controller efficiency will remain about the same since the major loss mechanism is switching loss. The major benefit at higher voltage to the Rohr controller is that 40% fewer transistors are required, thereby appreciably reducing the controller cost, size and weight.

Motor loss and size will not be affected by a higher voltage battery system. The motor rated voltage will be doubled and the current cut in half. Power wiring size will be reduced to one-fourth of the previous conductor volume at the same wiring loss.

At the higher voltage, the batteries can be charged using single phase 230 VAC and a transformerless battery charger. This is the most common power source (voltage) which results in a reasonable recharge time. The usual domestic 230 VAC source is a grounded center tap supply with 115 VAC of opposite phase at each terminal. For safety the vehicle motor, controller, and battery system should not ground to the vehicle frame. Insulation and isolation of the propulsion system components must meet building code requirements for 230 V system. The charging power cord must include a frame grounding conductor of sufficient capacity to protect the system from ground faults.

Previously, 12 V batteries of the deep discharge type have not been available commercially. Recently at least two manufacturers have made available 12 V deep discharge batteries with energy density as high as the currently available 6 V batteries. The size and weight of the new 12 V batteries are just about the same as the 6 V units. Twelve volt batteries are available from Trojan (type XH-30H) and Globe Union (type EV 27-18 and XDH-1).

7.2 OVERDRIVE CRUISE GEARING

Examination of the performance characteristics of the GE 215T AC system during the cruise mode of the driving cycle reveals that the motor torque is low (22% of rated torque) and that the motor efficiency is also low (approximately 82%). Review of the motor characteristic curves shows that the motor efficiency at low torque decays drastically at high rpm. It became apparent that reducing the motor speed during cruise, which increases the torque (power must remain the same), results in an increase in motor efficiency. Refer to figure 15.

A simulation run was made based on an assumed 2 to 1 reduction in drive ratio through the use of an overdrive gear in the cruise mode. Under this condition, the motor speed was reduced from 6432 to 3216 rpm and the torque increased from 22 to 45% of rated torque. The motor efficiency increase is attributed to reduction in bearing, windage and core losses in the motor. Winding copper loss will increase, but not as much as the other losses are decreased.

As a result of the increase in efficiency during the cruise mode, the range on Schedule D was increased 3.4%. This change does not appear significant at first, but checking the steady state 72.4 km/hr (45 mph) cruise mileage points out a 7.7% increase in range. These results are tabulated in table XIX.

The overdrive cycle assumes that the drive is shifted into the third gear immediately at the completion of the acceleration mode and that for regenerative braking, the transmission drops back to second gear for maximum recovery during braking.

Despite a thorough search within the transmission field, a suitable gearbox with an overdrive gear was not located. This technology is certainly achievable, but at the moment this type of transmission is not commercially available. Development is also needed to devise a way to achieve the rapid down-shift at the instant of brake application.

7.3 PERMANENT MAGNET AC MOTOR

A further near term improvement to the SOTA in power trains could be the development of a synchronous AC permanent magnet motor at the power level required. Efficiencies of presently available induction motors of this type vary from 85 to 91%. The permanent magnet (PM) motor operates with maximum flux density without the magnetization component of current required for the induction motor. Efficiency of the PM motor for the same power and weight can be in the order of 95%. Efficiency would remain high at low load during cruise; so that improvements in cruise range of 6 to 10% can be anticipated. Another advantage of the PM motor is improvement in power factor. The kVA rating of the controller can be reduced, which reduces the controller loss and cost as well.

7.4 AUTOMATIC GEAR SHIFTING

At least two approaches to automatic gear changing are worth considering. One uses a fluid coupling with torque converter during the automatic shift cycle. The fluid coupling should be locked out after shift to conserve power. Another

TABLE XIX - PERFORMANCE WITH OVERDRIVE GEAR
(IMPROVEMENT TO THE SOTA)

	WITH OVERDRIVE		W/O OVERDRIVE	
MOTOR	GE 215T		GE 215T	
RPM @ 88.6 km/hr (55 mph) HIGH GEAR	3925		7850	
MOTOR WEIGHT	38.6 kg (85 lbs)		38.6 kg (85 lbs)	
RANGE	km	mi	km	mi
SCHEDULE D	89.0	55.3	86.1	53.5
SCHEDULE D W/O REGEN.	76.7	47.7	74.5	46.3
CRUISE @ 72.6 km/hr (45 mph)	119.1	74.0	110.5	68.7
CURRENT (A)	BATT	MOT	BATT	MOT
ACCELERATION	291	585	291	585
CRUISE	82	226	88	171
REGENERATIVE BRAKING	-352	-779	-343	-769
PEAK POWER	kW	hp	kW	hp
ACCELERATION	18.9	25.4	18.9	25.4
CRUISE	6.2	8.3	6.2	8.3
REGENERATIVE BRAKING	48.4	64.9	47.1	63.1
MOTOR TORQUE @ CRUISE (% of FL)	45		22	
MOTOR RPM @ CRUISE	3216		6432	
ENERGY/CYCLE	MJ	Wh	MJ	Wh
ACCELERATION	0.569	158	0.569	158
CRUISE	0.371	103	0.400	111
REGENERATIVE BRAKING	(0.130)	(36)	(0.130)	(36)
TOTAL	0.81	225	0.839	233
DISTANCE/CYCLE	1.6399 km (1.0192 mi)		1.6372 km (1.0175 mi)	
BASED ON BASELINE SPECIFICATIONS PER SECTION 4.4				

viable possibility is to allow a programmed automatic shift to occur using the motor controller to synchronize the motor for the new gear ratio during the disengage period. The controller could initiate an upshift either when the vehicle is accelerated beyond a pre-established speed or when the driver releases the accelerator pedal momentarily below this speed to cause the shifting to occur on his demand. A downshift would occur when the driver pressed the accelerator hard or when the vehicle was traveling below a given pre-set speed. In either shift direction, a control sequence would be initiated to drive gear torque to zero, automatically disengage gears, change the motor speed to match the new ratio, engage the new gear ratio, and program the new torque at a rate to prevent excessive jerk. This automatic shift method does not require additional fluid clutches, or even the present mechanical synchromesh clutches. Motor rotational energy is conserved by regeneration into the battery instead of being lost during the gear change. Range will be improved slightly for these reasons.

8.0 SUMMARY OF RESULTS

8.1 STATE-OF-THE-ART EVALUATION

The current "state-of-the-art" of electric vehicle power trains does not reflect the capabilities of currently available components and technology. It is apparent that current and past efforts have not reached the level of performance that can be achieved with SOTA components because the designs do not achieve a totally integrated system.

The vast majority of the electric vehicles built since 1965 are based on drive-line components designed to match the characteristics of internal combustion engines. Most of the vehicles are conversions of production automobiles or employ combinations of standard industrial or automotive components and are not capable of meeting the SAE Schedule D driving cycle requirements.

An integrated system, specifically designed for maximum range on the SAE J227a Schedule D driving cycle, will increase the range achieved by existing power train designs.

The components/technologies selected as applicable to the design of a power train for a SOTA electric vehicle with potential for improved performance were:

- separately excited DC motor and controller system
- AC induction motor and 3-phase controller system
- two-speed transmission
- spiral gear differential
- steel belted radial tires

8.2 PRELIMINARY POWER TRAIN DESIGN

Throughout the SOTA review, it was apparent that valid comparison of reported ranges is not possible using the performance data published by the manufacturers. Variations in battery size and number precluded valid comparison of reported ranges. Using a ratio of the energy capacity of 16 EV 106 batteries to the energy capacity of batteries specified for the vehicle, the ranges reported for vehicles approximately equivalent to the SOTA requirements were adjusted to a common base and compared. (No allowance was given for the change in weight.) On this basis, the second generation car built for the Copper Development Association (CDA) has a range of 59.5 km (37.1 mi) for the

Schedule D driving cycle and 114 km (71 mi) based on a constant cruise speed of 64.4 km/hr (40 mph). This performance served as the starting point for the development of a SOTA design.

To evaluate the full potential of a SOTA design, an analysis was made to determine the theoretical energy consumption during each period of the SAE Schedule D driving cycle which was specified as the primary basis of evaluation. For this theoretical analysis, the load at the output shaft of the motor was used as a basis for calculating the energy required to propel the vehicle. This is another way of saying that the efficiencies of the motor and controller are assumed to be 100%. This calculation provided a basis for estimating the degree of improvement possible. This study and analysis established that:

- range is a function of the acceleration profile used to reach the 72.4 km (45 mph) cruise.
- maximum battery efficiency is achieved by systems that eliminate the high peak power and currents during acceleration.
- theoretical range on the Schedule D cycle is 120 km (75 mi) and 155 km (96 mi) at 64.4 km/hr (40 mph) cruise.
- regenerative braking theoretically increases range by 35% (for the Schedule D driving cycle).

A comparison of ranges of the selected vehicles against the theoretical 100% efficiency model indicates that existing drive designs are averaging less than 50% efficiency over the Schedule D cycle. Motor and controller efficiency during constant speed cruise is relatively high--on the order of 78%. The conclusion was reached that there is considerable room for increasing range by improving motor and controller efficiency during the acceleration and regenerative braking modes of the driving cycle.

A computer simulation model of the SAE Schedule D driving cycle was developed to aid in the evaluation and selection of components. The effects of changing component specifications were studied to establish their contribution to the overall system and their capacity for improving range. On the basis of these studies, it was established that:

- regenerative braking extends the Schedule D range by 16-23% (against the 35% improvement computed in the theoretical 100% efficiency model).
- reducing the tire rolling resistance by 17% (equivalent to one tire size larger) increases the Schedule D range by 5%.
- higher tire pressure increases travel range. (The gain in range must be traded off against tire wear and ride quality to establish acceptable limits).
- the "constant power" acceleration profile extends Schedule D range by 2.7% compared to constant acceleration.
- range is sensitive to vehicle weight. For instance, reducing weight by 204 kg (450 lbs) increases the Schedule D range by 13%.

Studies of the power available versus load established that multigear transmissions are required to meet the requirements of the Schedule D driving cycle and improve range. The optimum driveline ratio for maximum range was established by the simulation program for each candidate motor. Three power train configurations were developed as models to be used in the performance prediction analyses. These configurations were chosen because of their simplicity, low weight, and potential for high efficiency. At the conclusion of the component search, specific models were selected for the transmission, differential/axle, and tires. The final combination consists of a Spicer IS-18 differential modified to accept a McKee two-speed manually shifted synchromesh transmission as a transaxle arrangement. The 165 R13 steel belted radial tire was initially chosen as the baseline configuration for a nominal 1361 kg (3,000 lb) four-passenger vehicle. The selection of the type and model of the mechanical portions of the power train was not as difficult as the motor and controller selection because their efficiencies are established art and, generally speaking, do not vary significantly with load.

The performance of the motors and controllers had not been previously established for variable speeds associated with electric vehicles. Therefore, the motor/controller evaluation was given considerable attention in the computer simulation program. A detailed mapping of motor efficiency versus speed for each motor was made over the torque range and injected into the Schedule D simulation. Using the computer simulation program, the performance was predicted for the candidate motor/controller systems in combination with the model power train configuration. The results were:

Motor Model	GE 2346	GE 2364	GE 184T	GE 215T	REL 215T
Type	DC	DC	AC	AC	AC
Frame Construction	Steel	Steel	Aluminum	Aluminum	Steel
Weight - kg	68.0	104.3	31.3	38.6	56.7
lbs	150	230	69	85	125
Schedule D Range - km	75.6	83.5	82.6	86.1	88.0
mi	47.0	51.9	51.3	53.5	54.7
(Ranking)	(5)	(3)	(4)	(2)	(1)
Cruise Range @ 72.4 km/hr (45 mph) - km	115.9	114.7	109.6	110.6	107.7
- mi	72.0	71.3	68.1	68.7	66.9
(Ranking)	(1)	(2)	(4)	(3)	(5)

On the basis of Schedule D, the steel frame 215T (by Reliance) motor and AC controller resulted in the greatest predicted range of 88.0 km (54.7 mi) based on the preliminary specifications. The predicted cruise range at 72.4 km/hr (45 mph) is greater for the DC systems. Using the criteria of maximum range on Schedule D combined with maximum cruise range, the aluminum frame 215T (by GE) was selected as the optimum combination to represent the SOTA power train. The Schedule D range of the selected GE 215T AC motor system is 3% better than the best DC system (GE 2364) - attributed primarily to the lower weight and greater energy recovery (during regenerative braking) of the AC system. Lower motor cost, less motor maintenance, smaller overall size, reverse operation without contactors and higher overall system efficiency are additional advantages of the AC system.

As a result of the additional studies to determine the influence on range of changes in specification, the final configuration was revised to reflect a slight reduction in controller current capacity (850 to 750 A) and one size larger tires (165 R13 to 175 R13). A 5% increase in range was achieved. The predicted Schedule D range for a SOTA four-passenger urban electric vehicle using lead-acid batteries capable of cruising at highway speeds is 90.4 km (56.2 mi). This is an improvement of 52% over existing vehicles with an adjusted Schedule D range of 59.5 km (37 mi) using equivalent batteries. The principal components of the state-of-the-art power train are:

Motor:	3-phase AC induction rated at 29.8 kW (40 hp) @ 7200 rpm.
Controller:	3-phase variable voltage, variable frequency inverter rated at 88 kVA and 750 A.
Transaxle:	2-speed manual transmission mounted on a differential housing for an independent suspension.
Tires:	Steel belted radials, 175 R13 @ 221 kPa (32 psi), load range B.

The selected power train design has a weight of 163 kg (360 lbs) resulting in a gross vehicle weight of 1456 kg (3210 lbs) with four passengers. The vehicle is predicted to have a cruise range of 75.3 km (46.8 mi) at 88.6 km/hr (55 mph) and is capable of a top speed of 101.5 km/hr (63.1 mph) on level roads without a head wind. The vehicle can travel continuously on a 10% slope at 48.3 km/hr (30 mph) for 10.1 km (6.3 mi). The range of the vehicle in situations involving a continuous discharge cycle when the current is greater than 75 A is controlled by the useful energy obtainable from the battery.

8.3 IMPROVEMENTS TO THE STATE-OF-THE-ART

Near term power train improvements were studied and evaluated for potential of further increasing vehicle range or reducing cost. The use of 12 V batteries in lieu of 6 V batteries will permit the use of higher voltage switching semiconductors which, in turn, reduce the current requirement. Since cost of the power elements is a function of the current rating rather than voltage rating, the reduced current will also reduce the size and cost of the Rohr controller. The range will be increased slightly because the losses will also be lower, but it is the reduced cost which is of greatest benefit. Presently, two manufacturers are offering 12 V batteries at energy densities equivalent to the more prevalent 6 V units.

Consideration was given to the use of a third gear or overdrive gear as a means of increasing the efficiency and range for sustained constant speed operation. The addition of an overdrive gear which reduces the motor speed by a factor of two, increases the Schedule D predicted range by 3.4%, and steady state 72.4 km (45 mph) cruise by 7.7%. Such a third gear transmission was not located, but the design of a unit of this nature can be developed in the relatively near term.

A third improvement, predicted to increase steady state cruise range by 6 to 10%, is the development of a permanent magnet AC motor. The motor efficiency under light loads during a cruise mode can be increased 4 to 10% over currently available squirrel cage induction motors.

A fourth improvement which will improve the acceptance of electric vehicles by the public is addition of automatic rather than manual gear shifting. In the SOTA vehicle described, no shifting from standstill is required unless high acceleration is required. Starting in high gear is acceptable unless maximum performance is required. The improvement of adding automatic shifting makes high performance automatically available without operator attention. Range will also be increased slightly because the automatic shifting will reduce the time between gear changes and conserve the rotational energy of the motor.

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9.0 CONCLUSIONS

Based on the industry and literature review of presently developed electric vehicles and on the analyses and design effort conducted, the state-of-the-art (SOTA), of present vehicles has been assessed and a preliminary power train design for a four-passenger urban electric vehicle has been prepared which represents the SOTA achievable with commercially available components and technology which has been reduced to practice. As a result of these efforts, the following major conclusions were drawn:

(1) Presently developed power train designs do not achieve the level of performance possible within the SOTA. For the most part, the designs were not developed to meet the SAE Schedule D driving cycle and were comprised of components which lacked coordination in terms of overall system efficiency. The principal objective was maximum cruise efficiency (i.e., range). The components judged to be most lacking in performance for an urban driving cycle were the motor and controller.

(2) Increases in range and performance for electric vehicles can be gained within the SOTA using commercially available components and existing technology to reduce power train losses and to increase the compatibility of the drive line elements through system integration to properly select and size the components of the power train to match the lower power requirements associated with electric vehicles. An integrated system, specifically designed for maximum range on the SAE J227a Schedule D driving cycle, will increase travel range approximately 50% with the contractually specified batteries. The maximum range (Schedule D) achieved by existing designs with equivalent batteries is 59.7 km (37 mi).

(3) Regenerative braking is a controlling factor for increased range on the Schedule D driving cycle. Regenerative braking increases travel range by 16 to 23%. The power train designs which stress overall system efficiency perform better on the Schedule D cycle which includes modes of acceleration, cruise, coast, and regenerative braking.

(4) Greatest constant speed range utilizing SOTA components will be achieved using a shunt DC motor with separate armature and field controllers, but this combination does not result in greater range on the Schedule D driving cycle.

(5) Greatest range utilizing the specified urban driving cycle will be achieved with SOTA components using an AC induction motor and a 3-phase variable voltage, variable frequency inverter because of greater overall system efficiency and lower vehicle weight. Recent developments in the AC controller field make the AC induction motor

drive viable in a battery powered vehicle, and overcome the complexity and high cost previously associated with variable speed AC drives.

(6) A 52% improvement in range (over existing designs) can be achieved with an AC drive system with a total power train weight of 163 kg (360 lbs) using a 2-speed transaxle and steel belted radial tires. The Schedule D range will be 90.4 km (56.2 mi) and the vehicle will be capable of traveling 75.3 km (46.8 mi) at a cruise speed of 88.6 km/hr (55 mph).

(7) Near term improvements to the SOTA such as increased battery voltage (12 V in lieu of 6 V), overdrive cruise gearing, permanent magnet AC motor, and automatic shifting will increase Schedule D range approximately 7%, and cruise range up to 18%.

APPENDIX A

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

STATE-OF-THE-ART ASSESSMENT OF ELECTRIC VEHICLES

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ELECTRIC AND HYBRID VEHICLE PROGRAM

NOTICE

This report was prepared using customary units rather than SI units because the majority of the data was extracted from previously published documents based entirely on customary units. The continued use of the customary units was considered to be more appropriate for the earlier presentations made during this study.

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SUMMARY

A review and evaluation of presently built electric vehicles was made as a basis for establishing the state-of-the-art of power train components and technology. The objective of the review was to establish a base for the preliminary design of a power train for an electric vehicle which represents the state-of-the-art.

The review was restricted to power trains and components of electrically powered vehicles that have been built since 1965. The emphasis of the review was to:

- Define and evaluate the present state-of-the-art of power train systems and components that may be applicable to the design of a power train for a state of the art electric vehicle.

- Obtain design and performance data for applicable power train systems and components.

- Identify and evaluate technology improvements to power train systems and components which have the potential for improving overall electric vehicle performance.

The vehicles developed to date have generally been conversions of production combustion engine vehicles or "custom-built" designs of industrial or conventional automotive components and are not capable of meeting the SAE Schedule D driving cycle requirements. Many of the vehicles reviewed were built before the advent of the SAE Schedule D driving cycle, and as such, may not have been designed to meet the parameters later selected by the SAE Technical Committee. Even though some were developed after the Schedule D driving cycle was established, the builders may have had other objectives in mind.

Most of the power train studies utilize a series DC motor and silicon controlled rectifier (SCR) and do not employ regenerative braking. Recently a number of firms have built experimental cars using separately excited DC motors, but data on these configurations is limited. Two firms (GM and Linear Alpha) have successfully demonstrated the feasibility of an induction motor and 3-phase inverter as a drive system for a battery powered vehicle.

The majority of the electric vehicles built since 1965 are powered by relatively low power DC motors. Typically, the smaller motors were selected with emphasis on maximizing travel range based on more or less constant speed operation keeping motor size to a minimum. Acceleration was generally poor because of the smaller motors.

The EV industry is maturing, as evidenced by the degree of increased sophistication of the more recent vehicle designs and by the increased performance

and range being achieved. The previously considered designs are being reviewed with the intent of providing more acceptable performance. Improvements in performance are being achieved with separately exicted DC motors and AC induction motor systems. The selection of a state-of-the-art motor cannot be made without due consideration for the controller technology. In reality, the motor and the controller must be considered as a pair.

The characteristics of the controller and motor must be matched to provide the overall performance necessary to meet the operational requirements of the specified driving cycle in an efficient manner. No specific controller is available which is directly adaptable to an electric vehicle without some degree of customizing. The individual parts and circuit technology exist; however, they do not exist in the form of an off-the-shelf commercial item. One key point which stands out is that each controller has been specifically designed to suit the individual requirements of the system being developed.

The use of regenerative braking in electric vehicles has not yet reached maturity. As the degree of sophistication in motor controllers increases, the implementation of regenerative braking becomes easier - almost to the point of being inherent. For instance, regenerative braking is achieved in separately excited DC systems by merely increasing the field current. The capability for regenerative braking for some types of AC systems is built-in automatically because the components necessary for it to perform in the driving mode can also operate in the regenerative mode by merely reducing the motor input frequency. The extent of benefit derived from regenerative braking in terms of increased range is a function of the driving cycle and directly related to the efficiency of the power train - particularly the motor and controller package.

Although the transmission adds mechanical losses, they are relatively minor compared to the tire losses. Nevertheless, the gain in acceleration, increase in gradeability and reduction in motor currents justify the use of the transmission. The use of a multigear transmission helps to avoid high motor currents and justifies the added mechanical loss in the transmission.

Little effort has been expended to determine if reduction in losses through the differential are possible. The standard automotive hypoid gear differential has been assumed by many vehicle builders to be the most efficient. High EV efficiency can be achieved with spiral bevel gears. The contribution of improvements in the differential to the overall system efficiency are relatively small, but are worthy of consideration when maximum range and efficient overall performance are desired.

Steel belted radial tires are almost universally accepted as the tire with the lowest rolling resistance, and they are extensively used on EV's. Steel belted radials have 20% less rolling resistance than conventional bias tires. To further reduce the tire losses, high inflation pressures are frequently used. There are no tires available which are specifically designed for EV's; however, the technology for reducing tire loss is known. The reduced load and speed requirements for an EV make possible further reductions in tire loss through changes in construction while maintaining present performance levels with respect to wear, ride and handling. Additional study is required to investigate the possibility of changing tire construction to more closely match the service and load requirements of an EV with a maximum speed of 60 mph.

CONCLUSIONS

(1) Power trains in electric vehicles have not achieved the performance level which can be obtained by fully utilizing components and technology within the state-of-the-art.

(2) An integrated system, specifically designed for maximum range on the SAE J227a Schedule D driving cycle, will increase the range achieved by existing power train designs.

(3) The components/technologies considered applicable to the design of a power train for a state-of-the-art electric vehicle with potential for improved performance are:

- separately excited DC motor and controller system
- AC induction motor and 3-phase controller system
- two-speed transmission
- spiral gear differential
- steel belted radial tires

(4) Areas identified as having potential for improving overall electric vehicle performance were:

- permanent magnet motors
- infinitely variable transmissions
- low loss seals and bearings
- synthetic lubricants
- low loss tires for electric vehicles

1.0 INTRODUCTION

Electric vehicles powered by batteries have been in use for many years. However, the travel range and performance of battery powered vehicles is substantially below that of internal combustion engine vehicles. The most apparent shortcoming of electric vehicles is that only a limited amount of energy can be carried in the battery. One obvious way to improve their performance and range is to develop a better battery. So far, the battery industry has not developed a high energy, and high power density lightweight battery which can be produced at a reasonable cost and has acceptable life.

In the past, emphasis has been placed on the battery as the only means of solving the limited range and performance associated with electric vehicles. Recently, more attention has been directed toward the systems approach to develop and optimize the power train in order to achieve a suitable range and acceptable performance of a vehicle capable of being operated on public roads intermingled with existing vehicle traffic.

This report identifies the state-of-the-art of power train development in electric vehicles built since 1965 and addresses the feasible areas of technological improvements achievable within the state-of-the-art. The emphasis of effort during the investigation was to assess the state-of-the-art of present power train systems and components which might be applicable to the design of an improved power train using commercially available components and state-of-the-art technology. During the next design task, analyses will be made to establish the contribution to increased range due to power train improvements.

A state of the art (SOTA) electric vehicle is defined as an electric powered vehicle employing techniques, devices and components which individually have been proven through reduction to practice. Commercially available parts are defined as state-of-the-art parts which are available.

- As off-the-shelf items, or
- With short lead time due to manufacturing schedule, or
- As special orders involving limited design modifications.

The power train elements evaluated in this study include all of the components that process, condition, or transmit power to the drive wheels, with the exception of the battery. Components such as motors, controllers, transmissions, differentials, and tires were considered in this state of the art review and preliminary power train design study. Batteries were investigated only to establish the discharge characteristics.

Vehicles and power train components were evaluated, where applicable, with respect to:

- Performance characteristics, efficiency and losses.

- Reliability
- Size, weight, availability, and costs
- Interaction and compatibility with other components
- Regenerative braking.
- Potential for improvement by advanced technology.

The Schedule D driving cycle of the Automotive Engineers (SAE) Electric Vehicle Test Procedure J227a was used as the principal basis of evaluation of performance whenever possible.

The Schedule D cycle of the SAE Procedure is characterized by an acceleration up to 45 mph and a 45 mph cruise followed by coast, deceleration and idle periods, and is intended to represent stop-and-go driving typical of urban areas. The SAE Test Procedure provided a uniform basis for comparing vehicles in terms of:

- Range at steady speed
- Range when operated in a prescribed driving cycle
- Acceleration characteristics on a level road
- Gradeability limit and at speed
- Vehicle road energy consumption and economy
- Deceleration

The ultimate use of the data gathered is to prepare a preliminary design of a power train representing the best possible combination of components suitable for a four-passenger urban electric vehicle capable of cruising at speeds up to 55 mph. The estimated curb weight of this vehicle is approximately 3,000 lbs.

The overall assessment of the state-of-the-art of existing electric vehicles is presented in the following sections. Major components of the power train are discussed in terms of the approaches employed to date with special interest in identifying those areas which are pertinent as representative of the state-of-the-art. Component areas which have not yet reached their potential are identified and the possibilities for improvements are discussed.

2.0 EXISTING ELECTRIC VEHICLES - STATE-OF-THE-ART

2.1 STATE-OF-THE-ART ASSESSMENT

Power trains of electric vehicles built to date can be grouped into two categories:

- Conversions of existing production vehicles wherein the internal combustion engine was removed and replaced by a battery powered motor and controller.

- Custom built power trains generally comprised of off-the-shelf industrial or conventional automotive components.

There are a few notable exceptions which have deviated form this pattern such as the McKee Sundancer and Mark 16 designs, and the Mechanix Illustrated Urba-Car. The principal characteristics of representative vehicles built since 1965 are summarized in Table 2-1. The significant features are discussed in more detail in the component discussions which follow.

DC Motors

The majority of the electric vehicles built since 1965 are powered by relatively low power DC motors. The low power motors (5 to 10 hp) were selected with emphasis on maximizing the cruise range from a limited quantity of batteries. Typically, the vehicle weight to motor power ratio is on the order of 200 to 300 lbs/hp compared to 30 to 50 lbs/hp for internal combustion powered vehicles.

Controllers

The electric vehicle industry is shifting from the battery switching technique for controlling motor speed to the more sophisticated DC chopper because of its more efficient and infinitely adjustable speed control. The silicon controlled rectifier (SCR) is used by many; however, more recent developments in DC chopper design are based on transistors to achieve higher efficiencies.

Transmission/Differential

Numerous types of hardware have been used to couple the motor output to the wheels. The majority of the power trains built to date are based on conventional automotive transmissions and differentials. A few builders have employed less conventional components with emphasis on drive train simplicity and weight as a means of reducing mechanical losses.

TABLE 2-1.1

SUMMARY
ELECTRIC VEHICLE DESCRIPTIONS

VEHICLE MFR.	TYPE/ NO. OF PASS.	CURB WEIGHT LBS.	BATTERIES	MOTOR	CONTROLLER	TRANSMISSION	DIFFERENTIAL	TIRES	REGEN. BRAKING	PERFORMANCE RANGE (Miles @ mph)	DATA SOURCE
Metro Sedan EVA	Renault R-12 4	3750	Exide EV-106 96 V.	EVA 10 kW @ 3400 rpm Series DC	SCR Pulse Width Modulation (PWM)	Renault R-12 Original, Torque Converter & Auto. Transmission	Renault R-12 3.65:1 Ratio	Michelin Steel Radial 155R-13 32 psi		53 mph max. Range: 56.4 mi.@ 25 mph 34.0 mi.@ 35 mph 27.7 mi.@ 45 mph 28.0 mi.@ 53 mph	LRC Report Oct. 1976
Citi-Car Sebring-Vanguard	2	1300	Lead-Acid Exide EV-106 48 V.	G.E.6 HP @ 4100 rpm Series DC	Battery Switching Contactor 2 V. Level w/Auxiliary Resistor	None	Spur-Gear Trans-Axle by Terrell, 7.14:1 Ratio	Goodyear 4.80X12, 2-ply Nylon 50 psi		32 mph max.	LRC Report Oct. 1976
Electra-Van Jet Ind.	Subaru 2+2 or 2+500#	2500	Exide EV-106 84 V. Lead-Acid	Baldor 10 HP @ 3500 rpm, Series DC Forced Air Cooled	SCR PWM 84 V., Cableform	Subaru Orig. 4 speed Forward 1 speed Reverse	Transaxle w/half shafts 4.395:1 Ratio	Bridgestone K663 5X10 42 psi		44 mph max. 69.8 mi.@ 20 mph 46.4 mi.@ 30 mph 40.1 mi.@ 40 mph Sch. C = 23.3 mi.	LRC Report Oct. 1976
Otis P-500 Van Otis Elev. Company	2+750#	3620	Lead-Acid Exide EV-106 96 V.	Otis 10 HP @ 3500 rpm, Series DC Forced Air Cooled	SCR PWM by G.E. 96 V.	None	Motor Drives Rear Axle Diff. Ratio 5.17:1	Uniroyal 175 SR13 6-ply radial 32 psi		39 mph max. Sched. B. Range 21.1 Miles Acc. 4 mph/sec.	LRC Report Oct. 1976
CDA Town Car Triad Serv.	2	3100	Lead-Acid Globe GC 2-21 (18) 6 V 1242 lbs. Plus (3) 12 V Lucas for Field 75 lbs.	Sep. Excit. Field DC 4 Pole, 290 lbs.	Comb. Series Resist. + V. Switching + SCR	Chain Drive to Axle Diff. OA Ratio 4.95:1 Front wheel drive	Spiral Bevel	Michelin Steel Radial 145 SR 13 Front BR 70-13 Rear 48 psi		55 mph max. Sched. D=41.3 mi.	LRC Report Oct. 1976
Sundancer McKee Eng.	2	1600	Lead-Acid Exide 72 V.	8 HP @ 3520 rpm 4 Pole, Wave wound, Blower cooled	Voltage Swt., SCR 72 V.	McKee 2-speed 6.08:1 3.14:1 Trans-Axle w/Synchro mesh	Dana EG-20 with Spur Gear Input	Low Roll Res. 6.55 X 9 Experimental Goodyear		40-45 mi.@ 60 mph 95-100 mi.@ 30 mph 70-75 mi. Res. cycle 45-50 mi. Metro. cycle	SAE 720188
Anderson Third Gen. Anderson Power Co.	4	2520	Lead-Acid 72 V.	20 HP @ 4000 rpm, Series DC, 72 V Fan Cooled 170 lbs.	SCR PWM	2-speed, Planetary, Reverse				55 mph max. 60-70 mi.@ 45 mph cruise	SAE 720110

TABLE 2-1.2

SUMMARY

ELECTRIC VEHICLE DESCRIPTIONS

VEHICLE MFR.	TYPE/ NO. OF PASS.	CURB WEIGHT LBS.	BATTERIES	MOTOR	CONTROLLER	TRANSMISSION	DIFFERENTIAL	TIRES	REGEN. BRAKING	PERFORMANCE RANGE (Miles @ mph)	DATA SOURCE
Daihatsu S-37 Mini Cabover Daihatsu-Kogyo, Japan	2+	1654	Lead Acid (6) 12 V 125 AH/5H	5.3 kW Series DC 66 V 77 lbs.	SCR Chopper PWM	4 Forward 1 Reverse				40-50 mi. range	SAE 720189
Enfield 8000 Enfield Auto Ltd., England	2	2120	Lead-Acid (8) 12 V 110 AH @ 10 Hr. Rate	8 HP Series DC 4-Pole 48 V	Series-Parallel Voltage Switching		Live Axle, Resilient Coupling. Spiral Bevel 3.55:1	Radial 145 SR10 35 psi		44 mph max. 90 mi. Range	Auto Car Test Report 2/21/76
Transformer I Elec. Fuel Prop., Troy, Mich.	5	5850	Lead-Cobalt 180 V. Tri Polar	32 HP DC 1800 rpm @ 50 mph	Solid State Electronic	Automatic-Orig.	Orig. Hypoid	Steel Radial HR 78X15 Load Range "D"		50 mph cruise 60-70 mph max. 100 mi. range	EV News
Lt. Wt. Elec. Pass. Car Daihatsu (Japan)	4	2495		18 kW DC + Thyristor Comm	Trans. Chopper					55 mph max. 109 mi. Range @ 25 mph	EV News May 1976
Compact El. Pass. Car Toyota (Japan)	5	3032		20 kW DC Sep. Excited Field (40 kW Max.) 132 lbs.	SCR Chopper	3-speed Auto. w/o Torque Conv.	Low Loss Double Reduction Helical Gears to Diff.	Low Loss Tires		59 mph Max. 112 mi @ 25 mph	EV News May 1976
Linear Van Linear Alpha Skokie, Ill.	Van Dodge B-300	5950	(24) 6 V. 144 V. 220 AH	Special Low Slip AC, 144 V, 27 kW, 3-phase	Inverter 3-Phase Bridgect. Thyristors, Computer Control Var. Freq. Speed Control	Direct with 1.6:1 Overdrive	Orig. Hypoid		Regen. Braking Optional	56 mph Max. 35 mi. Range	An AC Drive EV By E. Wakefield
Mark 16 McKee Eng.	2	1614	Lead-Acid EV-106 (12) 6 V 851 lbs.	8 HP DC, 72 V (17 HP Max.) Tork-Link		Continuously variable belts (2) Centrif. clutch	At wheel Reducer 4.88:1 Hy-Vo	Goodyear 6.55X9 Low Roll.		60 mph Max. 100 mi. @ 30 mph 65-75 mi. City Driving	Mech. Ill. Road Test Feb. 1972 McKee Specs
McCulloch Elec. Car McKee Eng.	2	2800	Lead-Acid 108 V. (18) McCull.	15 HP PM DC 3600 rpm 108 V.	Solid State w/PWM; Auto. Current Lim., Transistor Protec.	2-speed Planetary 4:1 Ratio Torque Sensing	Morse Hy-Vo Chain Drive 3.8:1	Goodyear AR 70-13		75 mi. @ 55 mph 125 mi. @ 30 mph 60 mi. under 4 stops/mile	McCulloch EV Spec's Road Test July 1974

TABLE 2-1.3

SUMMARY
ELECTRIC VEHICLE DESCRIPTIONS

VEHICLE MFR.	TYPE/ NO. OF PASS.	CURB WEIGHT LBS.	BATTERIES	MOTOR	CONTROLLER	TRANSMISSION	DIFFERENTIAL	TIRES	REGEN. BRAKING	PERFORMANCE RANGE (Miles @ mph)	DATA SOURCE
"Ripp-Electric" W.E.Rippel	Datsun 1200 4	3200	Exide Mod. LEV-115 (20) 6 V.	Baker #1265 20 HP DC 4000 Max. RPM 205 lbs.	Spec.Design Transistor Chopper,Bi-directional transformerless charger	Datsun F4W56 4 Speed, 1 Rev. 1.404, 1,000:1 3.757, 2.169:1	Semi-floating Hypoid 3.90:1	SR165-13 30 psi front; 35 psi rear	Regen. Braking	61 mph Max. 85 mi.@ 30 mph 80 mi.@ 45 mph 66 mi.@ 57 mph	JPL Report 900-759
Pullman EV Lucas	4	5513	Lead-Acid 216 V. (36) 6 V. Rating: 110 Ah 2205 lbs.	50 HP Series DC 216 V by CAV Ltd. 4600 rpm @ 50 mph	SCR Chopper Lucas	Hy Vo Chain Reduction 2.38:1	Hy Vo Chain to Diff. 2.81:1	205-14 Steel Radial 8-Ply (D)	Regen.	50 mph Max. 140 mi.@ 30 mph 70 mi. City Driving	EV News May 1976
Electric Hornet Elec.Fuel Prop.	4	5500	EFP Tri Polar (24) 6 V 144 V Lead Cobalt	20 HP Series DC 7000 RPM	Modified English Forklift SCR Chopper	Orig.Hornet 3-Speed Manual 2.55:1 1.56:1 1.00:1	Orig. 4.44:1	Michelin Steel Radial 195 X 14 @ 36 psi		79 mph Max. 55 mi.@ 55 mph	Motor Trend Aug. 1971
Electro-vair II General Motors	4	3400	Silver-Zinc 530 V. (Open Circuit)	115 HP AC Induct.,Liquid-Cooled, 3 Phase, 13,000 rpm	Modulating Inverter 3 phase SCR	Fixed Gears	Orig.Corvair		Regen.	80 mph Max. 40-80 mi.range	The GM Ind. Motor Drive System by P.D. Agarwal
Electrovan General Motors	2+	7100	Hydrogen-Oxygen Fuel Cell. (Union Carbide)	125 HP, AC Induct., Liquid-cooled, 3 phase, 13,000 rpm	Modulating Inverter, 3 phase SCR				Regen.	70 mph Max. 100-150 mi.range	

Tire Losses

Almost universally, the electric vehicle designers have recognized that the tire losses represent a significant portion of the power requirement. At 55 mph cruise, approximately 50% of the total power is required to overcome the tire losses. Steel belted radial tires were used extensively and quite frequently were operated at higher than normal tire pressure to further reduce the losses.

AC Drive

Two firms (General Motors and Linear Alpha) have bulit several electric vehicles based on the use of a 3-phase AC induction motor. Although these prototype vehicles demonstrated the feasibility of an AC system operating from a battery source, the high cost of the AC controller offset the advantages of the AC motor. Both GM and Linear Alpha concluded that as the cost of AC controllers decreased, the practicality of an AC system would increase.

Regenerative Braking

The application of regenerative braking to improve range has been given very little attention in the U.S., as evidenced by the relatively few cars which possess this capability.

Regenerative braking can increase travel range; however, there is controversy among EV designers whether or not it is cost effective. Vehicles primarily used in highway type operations will derive very little benefit from regenerative braking because it is such a small part of the total duty cycle. A second consideration is that the cost of the additional components required to achieve regenerative braking might be more effective by trading off that cost against a larger battery pack and/or the operating costs to recharge the batteries in order to achieve an equal range without the additional circuitry/components necessary for regenerative braking. The value or contribution of regenerative braking in terms of extending vehicle range is a function of the driving cycle.

Compatibility of Components

It is apparent that the current and past efforts to develop an electric vehicle power train have not reached the level of performance that can be achieved with state-of-the-art components because the designs do not reflect an integrated system. Many of the vehicles were developed by firms with a specific product in mind with very little attention given to the other components in the power train.

Shortcoming

Most of the EV's developed to date are not capable of meeting the Schedule D driving cycle of SAE J227a. The most apparent shortcoming is the inability to meet the minimum acceleration requirement of reaching 45 mph in 28 seconds. The SAE Recommended Test Procedure (J227a) was developed quite recently, therefore, these vehicles were not designed to meet the SAE Schedule

D acceleration requirement. Some vehicles may contain components capable of performing the Schedule D cycle, but lack of performance data, variation in vehicle size/type, and poor matching of power train components preclude comparative evaluation.

Overall Assessment

The EV power trains developed to date have not yet reached the optimum performance which can be achieved with state-of-the-art technology and components. Power trains of electric vehicles built to date basically fall into two categories:

(1) Conversions of existing production vehicles wherein the internal combustion engine was removed and replaced by a battery powered motor and controller.

(2) Custom built power trains generally comprised of off-the-shelf industrial or conventional automotive components.

Further effort is required to address the whole system, with emphasis on matching the components to improve system performance. Improvements in performance can be obtained by further investigation and optimization in the following areas:

- Lower loss tires
- Reduced overall gearing loss
- More efficient motors and controllers
- Reduced peak power drain
- Reduced drive train weight
- Regenerative braking

2.2 MOTORS

The series DC motor was used more often than any other type of motor because of its wide range of torque at high efficiency. Since vehicle travel range is governed by the capacity of the battery and rate of battery drain, low power motors (5-10 hp) were used in relatively lightweight vehicles as a means of maximizing cruise range. Series DC motors were selected because they are simple, reliable, and require no complex controls. Their choice was also predicated by the series motor's "high torque at low speed" characteristic, with a possible elimination of the need for a transmission.

Numerous examples of the low power series DC motors are illustrated in Table 2-1., Vehicle Description Summary; however, only the Anderson 3rd Generation Electric Car, the EFP Hornet, and the Ripp-Electric have series DC motors of suitable capacity for an urban electric vehicle.

Operating from a limited fixed energy source such as a battery forces the design to become a compromise, resulting in poor acceleration in order to achieve acceptable cruising range. As the size, weight, performance and range desired in an electric vehicle increased, the acceptability of the series DC motor decreased. Motor types and techniques which favor increased range are being investigated. The simplicity of the series DC motor is outweighed by the need for greater acceleration and range.

More recently, the EV industry has begun to exploit the capabilities of advanced controllers and are selecting separately excited field (shunt) DC motors. Although their performance and range are unsupported by comparable test data, a number of EV builders claim that the separately excited DC motor showed lower energy consumption than those fitted with series DC motors. The increased range using the separately excited motor was attributed to higher average efficiency and the use of regenerative braking. Toyota claims that the driving range per battery charge is increased 20%.

Two Japanese vehicles of interest are those produced by Daihatsu and Toyota. The motor descriptions and performance data obtainable on these cars were extremely limited. The manufacturers claim a range of approximately 100 miles at 25 mph constant speed cruise. They appear to use separately excited DC motors based on the limited descriptions provided.

Performance data from motor manufacturers on variable speed DC motors powered by a chopper controller was almost non-existent, making selection of an efficient drive package extremely difficult.

DC motors have been the principal choice for powering EV's because they can be directly coupled to the battery with a minimum of controls. Two firms (General Motors and Linear Alpha) have built several electric vehicles based on the use of a 3-phase AC induction motor. The AC motors were used because of their low cost, high reliability, high hp/lb and the elimination of the brush wear problem associated with DC motors.

In 1966 General Motors designed an AC power train system and installed it in a conventional Corvair chassis. GM's objective was to essentially match the performance of the previous internal combustion engine. Special liquid cooled high speed (13,000 rpm) AC motors were built with 90 hp and 115 hp ratings. These motors at 1.4 lbs/hp were significantly lighter than typical DC motors which weigh approximately 10 lbs/hp. Despite the vast improvement in the state-of-the-art of EV drive motors, GM's AC drive was not considered practical because of the high cost of its AC controllers.

Since 1966, the EV industry has recognized that battery powered vehicles will not replace gasoline powered cars, and EV manufacturers have scaled down their goals. In 1972, Linear Alpha built an AC drive system with a more modest 36 hp AC motor. In this horsepower range, off-the-shelf AC motors are available at 4-5 lbs/hp -- less than half that of a comparable DC motor. Although Linear Alpha demonstrated the feasibility of an AC system, the high cost of the AC controllers offset the low cost of the AC motor. Both Linear Alpha and GM concluded that as the cost of AC controllers decreased, the practicality of the AC system would increase rapidly.

The selection of a specific motor capable of meeting the power requirements of an urban electric vehicle was not immediately apparent. The state-of-the-art motor for EV's appears to be split between the separately excited DC motor and the AC induction motor. The final selection will depend on the combined performance of the motor and the controller.

2.3 CONTROLLERS

Many types of motor speed control have been used in electric vehicles, ranging from simple battery switching to the sophisticated 3-phase AC inverter. Except for the golf cart/fork lift category, the EV industry has adopted the solid state electronic controller to achieve infinitely variable and more efficient speed control. The most frequently used system is the DC chopper in conjunction with a series DC motor (without capability for regenerative braking).

For low power short range EV's with adequate speed control for operation on public roads, the DC chopper based on SCR's to control the armature current of the series DC motor is the least complex and lowest cost combination. However, as the power requirement increases, the cost of the DC controller to handle the high armature current increases significantly. As the power requirement to provide adequate acceleration increased, the suitability and performance of the series DC motor has decreased. The search for more cost effective and more efficient motor/controller systems has prompted a number of firms to consider the shunt DC motor as a means of increasing range. More recent vehicles such as the CDA Town Car, Toyota Compact Electric Passenger Car, and other Japanese Cars have used the separately excited shunt DC motor to increase travel range.

The combination controller developed by Triad for the separately excited shunt DC motor of the CDA Town Car is capable of performing the SAE Schedule D driving cycle. This controller design is based on a SCR DC chopper for field control combined with 2-step battery switching; for vehicle speeds below 6 mph, a variable resistor was used to control the low speed torque buildup.

Since 1965, two AC inverter controllers have been demonstrated in EV's by GM and Linear Alpha. Both units were 3-phase AC designs using SCR's, but were not competitive costwise with the DC chopper systems dominating at that time.

When the power required is low, DC systems are less expensive than an equivalent AC system. The 3-phase AC system requires a more complex controller which offsets the cost advantage of the cheaper AC motor. As the power requirement increases, the cost of DC controllers and motors increase at a greater rate than comparable AC systems. An economic analysis is needed to establish the cost relationship in more detail.

The performance of controllers currently employed in electric vehicles have not reached the level of performance achievable within SOTA. DC motor control based on the principal of the separately excited field represents the most advanced design currently in use. Further improvements in overall performance of electric vehicles and travel range can be achieved by refinements to prior designs. The driveability of prior designs can be improved by employing controllers in both the armature and field circuits. Controllers based on the use of SCR's are commercially available in appropriate capacities for both applications. Although the basic controllers are readily available, the logic or control system for the separately excited systems have been one-of-a-kind designs. The individual parts and circuit technology are SOTA; however, they do not exist in the form of an "off-the-shelf" commercial item. The efficiency of DC controllers can also be improved by changing to a design based on the use of transistors.

Recent developments in the AC controller field now make the 3-phase AC inverter a viable candidate as a controller for a battery powered electric vehicle. Variable speed AC drives have been developed for machine tool applications which have efficiencies on the order of 96 to 98%. Current units are designed for operation at 480V. Modifications of this design by changing to lower voltage transistors would permit this technology to be used in electric vehicle applications.

These two types of controllers have the greatest potential for improving electric vehicle performance and range.

2.4 REGENERATIVE BRAKING

The use of regenerative braking in EV's as a means of extending vehicle range has been a controversial issue. Many builders of EV's claimed that the cost of providing regenerative hardware was greater than the cost of using a larger battery to accomplish the same range. They further claimed that the cost of electric power to charge the battery over the life of the vehicle was less than the amortized cost of the added equipment necessary to utilize regenerative braking. This may have been true when the application was on relatively small utility vehicles; however, these statements can no longer be justified with respect to the current objectives for urban electric vehicles.

Regenerative braking has not been used extensively in the U.S., but is almost always used in foreign vehicles as a means of increasing range per battery charge. Test results reported in the industry literature indicate that the gain in cruising range was approximately 15% for stop-and-go driving cycles. The Ripp-Electric vehicle equipped with regenerative braking controls achieved a 22% increase in travel range when tested on the SAE J227a Schedule C driving cycle.

The extent of benefit derived from regenerative braking in terms of increased range is a function of the driving cycle and directly related to the efficiency of the power train - particularly the motor and controller package. Consistent test results are not available for establishing a standard for regenerative braking. Further study and test are needed to determine the degree of energy recoverable through regenerative braking.

2.5 TRANSMISSIONS

The mechanical connections between the motor and tires employed in electric vehicles vary from direct coupling to a differential to infinitely variable transmissions. Typically, the transmissions utilized in the more recent vehicles are one of the following:

- Direct drive to the differential (i.e., no transmission)
- Fixed ratio input to the differential
- Manual transmission with clutch
- Automatic transmission without the torque converter
- Variable speed belt drive

For the most part, those electric vehicles which were conversions of production automobiles resulted in inefficient power trains. Numerous attempts have been made with varying degrees of success to improve the mechanical system between the motor and the tires.

Many electric vehicle builders tried to capitalize on the fact that the series DC motor has high starting torque (from a stop) and reversability without gearing to eliminate the need for a transmission in the power train. In most of these earlier designs, the motor was coupled directly to a differential. This type of power train was practical for a low cost, low speed utility vehicle, but is not suitable for an urban EV because it cannot meet the acceleration and performance required for an urban driving cycle.

In order to obtain higher speeds and improve performance, additional fixed ratio "gearing" was used as a means of torque multiplication. The result was either a vehicle which met the cruise requirement, but had insufficient acceleration or vice versa. Both requirements were not satisfied with a fixed ratio. The torque range was not broad enough to provide adequate acceleration or develop the power requirement for 45 to 55 mph cruise. During this period of industry development, emphasis was generally on obtaining maximum range with steady state conditions - totally overlooking the acceleration performance required for stop-and-go driving.

To meet the requirements of driving range, acceleration and grade climbing necessary for an urban commuter vehicle, "multi-gear" transmissions were considered as a means for improving performance. A variety of transmissions have been used, ranging from simple manual transmissions to infinitely variable automatic transmissions.

Almost universally, the developers of EV's using conventional automotive transmissions created inefficient power trains because the capacity of the components selected was sized to handle the higher power of internal combustion engines, and therefore, were overdesigned when used with smaller electric motors. Selection of components based on the efficiency at the peak load results in an inefficient match of components. The absolute value of power lost in the transmission should be the main consideration. A loss of 1 hp in friction when coupled with a 100 hp engine would be 99% efficiency. The same transmission coupled to a 10 hp motor would be only 90% efficient. The ratio of the operating load to the design load determines the actual operating efficiency.

Several novel low cost EV's have effectively employed a variable diameter sheave rubber-belt drive as a transmission with a speed range on the order of 4 to 1 (McKee's Mark 16, Mechanix Illustrated). The vehicle developed for the Mechanix Illustrated magazine utilized a control device which provided feedback to automatically adjust the speed ratio. Typical efficiencies for a V-belt transmission range from 87% at 4:1 ratio to 94% at 1:1.

A two-speed mechanical transmission directly coupled to a Dana differential axle was used in the McKee Sundancer vehicle. The transmission was shifted by a lever-operated cable assembly connected to the synchromesh unit. The overall gear efficiency of the McKee power train was reported to be 92%.

Although the transmission adds mechanical losses, the added mechanical loss is relatively minor compared to the tire losses. Nevertheless, the gain in acceleration, increase in gradeability and reduction in motor currents justify the use of the transmission. Further development is needed to more effectively match the sizing and type of the transmission with the motor.

Consideration for improving transmissions for electric vehicles should be given to:

- Two-speed manual with clutch
- Variable speed belt drive
- Two-speed automatic without torque converter
- Two-speed transaxle with synchromesh shifting mechanism

2.6 DIFFERENTIALS/AXLES

The majority of electric vehicles built to date have employed the conventional automotive solid axle differential. A few designs have deviated from this trend and have employed dual belt drives (McKee) to achieve the differential action. There have been several designs wherein chain drives (Morse Hy-Vo) were used to drive the differential carrier in lieu of a pinion gear. The chain drive was used primarily because of its right angle input to the differential (CDA, McCulloch, McKee, Lucas).

To achieve the performance required for urban EV's a gear reduction is required between the motor and the wheels. The use of a differential axle conveniently provides the necessary gear reduction. It is conceivable that a low speed motor could be coupled 1-to-1 to the wheels; however, motors operating at higher speeds have a definite advantage in power-to-weight ratio and are lower in cost. The application of a differential as a means of achieving the necessary speed reduction for direct (fixed ratio) drives is a convenient solution, but will result in high motor current at low speeds and excessive battery drain. Some attempts have been made to eliminate the differential axle by the use of separate drive motors for each wheel or by the use of double-ended motors driving separate variable diameter belt drives (McKee). The use of two drive motors and controls to properly match the wheel drive loads increases system cost. Dual belt drives will work satisfactorily at low speeds, but have stability problems at higher speeds because the power to the drive wheels cannot be properly matched.

Generally speaking, designers have overlooked the effect of operating load on the mechanical efficiency. This is particularty true in the case of motor substitutions in a production vehicle, creating the same inefficiency associated with operating load versus design load that was discussed previously with respect to transmissions.

Little effort has apparently been expended to determine if reductions in losses through the differential are possible. The standard automotive hypoid gear differential has been assumed to be the most efficient design based on its prevalent use in ICE automobiles. Higher efficiency can be obtained with spiral bevel gears. This is described more fully in section 3.5.

The contribution of improvements in the differential to the overall system efficiency is relatively small, but worthy of consideration to increase maximum range and overall performance. Additional investigation is needed to establish improvements which can be achieved by changes in the type of gears ordinarily used in differentials.

2.7 TIRES

Steel belted radial tires are almost universally accepted as the tire with the lowest rolling resistance, and they are extensively used on EV's. Steel belted radials have 20% less rolling resistance than conventional bias tires. To further reduce the tires losses, high inflation pressures are frequently used. Load Range "B" (per Tire and Rim Association) tires are the standard for the passenger car industry and have been accepted without question as the appropriate load rating/construction to be used on EV's. Tire sizes were usually selected according to the recommendations of the Tire and Rim Association (TRA) according to the total loaded vehicle weight.

An experimental, low profile (6.55X9) Goodyear tire was used by McKee Engineering on both the Sundancer and the Mark 16 vehicles. The rolling resistance was reported to be 48% less than a steel belted radial tire.

According to the TRA Manual, the maximum cold inflation pressure recommended for Load Range "B" tires is 32 psi. A 4 psi increase is permissible if the maximum sustained speed is limited to 75 mph. The high pressure technique for reducing tire loss can also be applied to Load Range D tires. The standard 40 psi maximum for Load Range "D" tires can be raised to 44 psi to achieve further reduction in tire loss.

Higher tire pressure and reduced tire load are well known techniques for reducing rolling resistance; however, this may cause an unfavorable tread wear problem. The high tire pressure will also affect ride comfort and needs to be offset by vehicle suspension design.

There are no tires available which are specifically designed for EV's; however, the technology for reducing tire loss is established. State-of-the-art tires are represented by steel belted radials operated at maximum inflation pressure. Rolling resistance of this combination is approximately 9 lbs per 1000 of vehicle weight. Tires presently manufactured represent the optimum design for the service factors and speed range of present combustion engine vehicles. The reduced load and speed requirements for an EV make possible further reductions in tire loss through changes in construction while maintaining present performance levels with respect to wear, ride, and handling. Additional study is required to investigate the possibility of changing tire construction to more closely match the service and load requirements of an EV with a maximum speed of 60 mph.

3.0 DESIGN CONSIDERATIONS FOR IMPROVEMENTS

The objective of this section of the report was to address the possibilities for improving what has been done by previous developers of electric vehicles. The major elements of the power train are discussed in terms of improvements which can be made within state-of-the-art to increase the driving range of an electric vehicle. To be successful, an electric vehicle must be designed "from the ground up" with its components complementing each other in the most efficient manner.

3.1 MOTORS

In heavy traffic, the electrical losses are far more important than the mechanical losses. The distance traveled per battery can be increased significantly by replacing the traditional series DC motor with a motor (and controller) which reduces the peak currents from the battery and which is more suitable for regenerative operation.

Shunt DC motors are generally thought of as constant speed motors with relatively low torque characteristics at low shaft speeds. By proper choice of control technique, the torque characteristics of a separately excited shunt motor can be made to match those of a series wound motor. The efficiency of the separately excited shunt configuration is better than the series motor because the motor windings can be optimized for the desired torque profile.

Another reason for selecting the separately excited motor is that it is more suitable in the regeneration mode than a series motor. The series motor can be switched to regeneration by reversing the field, but the performance is not efficient in regeneration. Detail performance data of shunt DC motors are not available from motor manufacturers. Despite the lack of specific data, the use of a separately excited DC motor appears to have merit.

Motor efficiency is influenced by the waveform of the supply source. The efficiency of DC motors operating from a chopper controller can be increased by the use of a laminated housing in addition to the usual laminated field structure.

The output of an induction motor can be significantly increased when coupled to a 3-phase variable voltage variable frequency power supply. An AC motor can be designed to operate at higher speeds than a DC motor which allows a smaller frame size and reduction in weight. By changing to improved bearings and balancing the rotor, a normal 1800 rpm induction motor can be operated at 4 or 5 times its nameplate rating. AC motors weigh approximately 4 lbs/hp compared to 10 lbs/hp for DC motors. This will reduce the overall power train weight and save energy. The full torque over the entire speed range characteristic of an AC motor may be an advantage during acceleration. Reversal of an AC motor is achieved within the logic system of the controller and does not require additional contactors. The AC motor eliminates classic brush wear problems of DC motors which reduces long term maintenance costs and increases reliability.

Regardless of the type of motor, higher shaft speed will result in reduced weight. The choice of high speed motor with gear box against a low-speed direct-coupled motor is largely a function of the benefits in terms of weight, efficiency, and system complexity.

Whether AC or DC, the use of aluminum end caps on the motor to reduce weight will result in increased driving range and acceleration. The use of thermally controlled separate blowers for motor cooling reduces the windage loss and improves the motor efficiency during high speed cruise. Efficiency also increases with increased voltage.

The process of motor selection and optimization requires investigation of the entire power train system to properly match component performance and thereby keep battery drain to the lowest possible level.

3.2 CONTROLLERS

Obviously, the controller must be selected to match the characteristics of the motor being used. Since controller cost increases at a faster rate than motor cost, systems which utilize a smaller controller have an advantage. Speed control using a separately excited field avoids the problems associated with handling the large armature currents inherent in a series DC motor and requires a much smaller controller.

Further improvement in the performance of the CDA/Triad shunt motor system can be achieved by redesigning the field controller using transistors rather than SCR's. The current handled by a field controller is much lower than the current handled in the armature circuit. This fact permits the use of transistors rather than the more conventional SCR's. Typically the efficiency of a SCR design is 85 to 90%, whereas a transistor design is usually about 95% efficient.

The advantages of an AC inverter powered by a battery source are not generally apparent to designers who associate only DC controllers with battery sources. The characteristics of the current drawn from a battery by an AC inverter do not include the high current spikes associated with SCR choppers, and offer increased range by more uniform battery current. With the AC controller, it is possible to obtain essentially full torque over the entire speed range. The efficiency of a transistorized AC inverter is 96 to 98%. The AC controller system is reversible and regenerative by switching the control circuits as opposed to the contactors required with DC systems.

AC inverter controllers based on the use of SCR's are costly because more individual parts are required for 3-phase and because they require additional commutating circuits to switch them. Recently, AC inverter controllers based on the use of low cost transistors connected in parallel have been used in specialty electric vehicles powered by 3-phase AC linear induction motors operating from a DC power distribution system.

Three-phase AC controllers based on the use of transistors are being built at 0.5 lbs/hp compared to the earlier SCR designs which were approximately 2.5 lbs/hp and were quite bulky.

Refinements in circuitry and lower costs are creating AC inverter drives which overcome the objection of earlier designs. The AC inverter offers a unique combination of 100% torque and speed control from zero to full speed which is expected to operate more efficiently during both the acceleration and regeneration cycles. The AC system draws the energy out of the battery much more efficiently than the DC chopper because it does not have high current spikes. The nearly constant battery drain for any given power level will improve the efficiency of the battery and will result in increased travel range per battery charge.

3.3 REGENERATIVE BRAKING

The benefits derived from regenerative braking can be increased and the cost of implementing it reduced by more careful consideration and selection of the total power train systems/components.

Regenerative braking has no value for constant speed cruise operation, but its value in extending vehicle range for stop-and-go driving can be considerable. Components of an effective EV power train must be compatible with efficient regenerative braking.

Regenerative braking is easier to implement with separately excited shunt motors than with series motors. The series motor can be switched to regenerative braking by changing the field momentarily to a shunt configuration or by reversing the field connection in conjunction with a second controller, but larger and higher cost contactors are required. The regenerative braking efficiency of a series motor is not as high as that of the separately excited field configuration because the larger controller of the series motor has greater losses when handling the high field currents.

A key issue of regenerative braking is the capacity of the battery to accept the high currents generated during the regenerative mode. Regenerative braking controls must include provision for sensing battery overcharge to avoid battery plate gassing.

The efficiency of the regenerative braking cycle can be increased by the use of an infinitely variable transmission to keep the motor speed high as the vehicle slows down. The efficiency of the motor as a generator is greater at higher rpm.

3.4 TRANSMISSIONS

As previously pointed out, designers/builders in the EV industry have frequently overlooked the mechanical portions of the power train. Recognizing that the actual mechanical losses are small when compared to the much higher tire and aerodynamic losses leads the designer to apply his efforts where the greatest gain can be achieved. As those areas become more refined, a point is reached where consideration for mechanical improvement becomes a worthwhile endeavor.

In theory, a variable-speed transmission offers the greatest potential increase in efficiency that can be achieved mechanically in an EV power train. With a variable speed transmission, the best combination of motor speed and torque could be selected to minimize current draw from the battery. The use of a speed variable transmission would also result in more efficient recovery of energy during regenerative braking. A mechanical variable speed transmission has not been developed which can stand up to the rigors of automotive service; however, variable diameter V-belt drives may be able to hold up when coupled to the smaller motors generally used in EV's.

The key to improving vehicle range is to remove the peak currents from the battery. The power requirement during acceleration is typically 3 to 4 times that at peak cruise. Even a 2-speed manual transmission significantly reduces the energy required to accelerate a vehicle. Long steep grades can be negotiated at high efficiency only when a multi-ratio transmission is included in the power train to keep the motor speed in the efficient range.

Transmission losses can be reduced by designing or selecting the transmission such that the operating load is as close as practical to the peak design capacity. The efficiency of gearing is maximum when operated at peak loads. The peak load capacity of gearing is on the order of 2 to 3 times the load at the endurance limit. When operated at less than the peak load, transmission efficiency is somewhat less. Consideration should be given to sizing the gearing to handle the load at maximum cruise when the gearing is stressed to the endurance limit and take advantage of the margin between the endurance limit and peak load stress to handle the acceleration loads. This technique would result in higher average efficiency over the operating cycle.

The use of a transmission to increase the torque output of the motor permits a smaller motor to be used. Even though the transmission gearing results in additional losses, the overall efficiency of the motor is increased. The added weight of the transmission is offset by reduced motor weight. At 10 lbs/hp, a 20 hp motor with a 2 to 1 transmission gearing change can outperform a 40 hp motor if the transmission weighs less than 200 lbs.

3.5 DIFFERENTIALS/AXLES

The use of converted production vehicles as a "test bed" to prove out the performance of electric motor drives in passenger vehicles has resulted in less than desirable performance. Many builders of custom electric vehicles have made the same error by attempting to use off-the-shelf automotive components without due regard for the fact that the efficiency of components must be given extremely high importance to offset the limited energy capacity of a battery.

Standard automotive hardware is designed for high power, peak loads, and excessive abuse associated with internal combustion engines. Electric motor drives, when more appropriately sized according to the loads experienced in EV power trains, do not require such heavy duty components.

At peak loads, the efficiency of accurately made, carefully assembled hypoid gears mounted on antifriction bearings is between 93 and 96%. At lighter loads, efficiency is less, and this aspect has been overlooked by electric vehicle designers and builders. Driving at full acceleration load would give approximately 95% efficiency for a typical hypoid differential; however, when the vehicle is cruising, the horsepower to the differential is reduced by a factor of four, and the efficiency decreases to 90%. As the cruising speed is lowered, efficiency drops even further to 85%.

The widespread use of hypoid gears in differentials by the automotive industry has caused many to overlook the fact that spiral bevel gears have higher efficiencies. The higher efficiency of spiral gears is even more noticeable at low operating loads. Improvement in efficiency of differentials on the order of 5 to 10% can be achieved by the use of spiral gears. It is interesting to note that only two electric vehicles built to date have been identified as utilizing the more efficient spiral bevel differential (CDA Town and Enfield 8000). Differential efficiencies can also be improved by operating the gears closer to their design load capacity.

The selection of the gear ratio is important as well. Gear efficiencies are higher at lower ratios, with a ratio of 1 to 1 being the best possible. However, since the relative difference in efficiency is small, the decision as to the ratio employed is far more dependent upon the choice of motor speed and transmission ratio and their associated efficiencies. Ratio for ratio, the majority of the speed reduction must take place within the transmission where the gearing efficiency is higher (compared to differentials).

Reduced mechanical losses and weight reduction can be achieved by:

- Implementing the use of more efficient spiral gears rather than hypoid gears.
- Sizing the overall load capacity in keeping with the operating load.
- Using aluminum housings.

3.6 TIRES

Interest in the rolling resistance or power loss of tires has grown considerably in the past few years. The rolling resistance of tires on an electric vehicle is one of the principal parameters which determines the overall performance. Rolling resistance is principally determined by three factors:

- Hysteresis of the tire materials
- Surface friction in the contact area
- Aerodynamic drag

Hysteresis of the materials and structure due to deflection as the tire rolls is the predominant contributor to power loss and represents 90 - 95% of the total. Surface friction in the tread-to-road contact area comprises 5-10%, and aerodynamic drag due to air friction contributes 1.5 - 3.0%.

It is evident that hysteresis due to internal friction of the tire materials is the key parameter affecting the power loss in tires and that emphasis for improvements should be concentrated here. Rolling tire deformation and its recovery is controlled by the tire material, construction, load, and inflation pressure.

Rubber composition has a significant influence on rolling resistance. Compounds with high rebound characteristics reduce the power loss in the tire. Figure 3-1 shows the relationship of rolling resistance to the rubber rebound characteristics. The 100% baseline is a conventional tire material with 60% rebound. Rolling

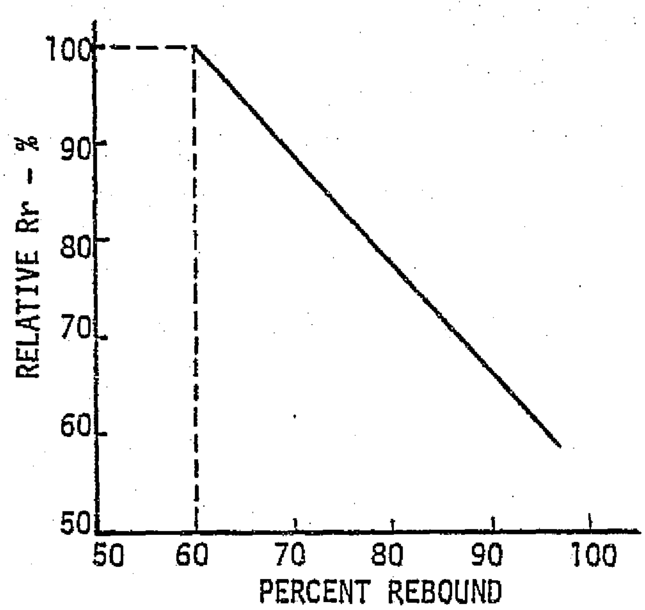

Figure 3-1. - Relative Rolling Resistance vs. Rebound

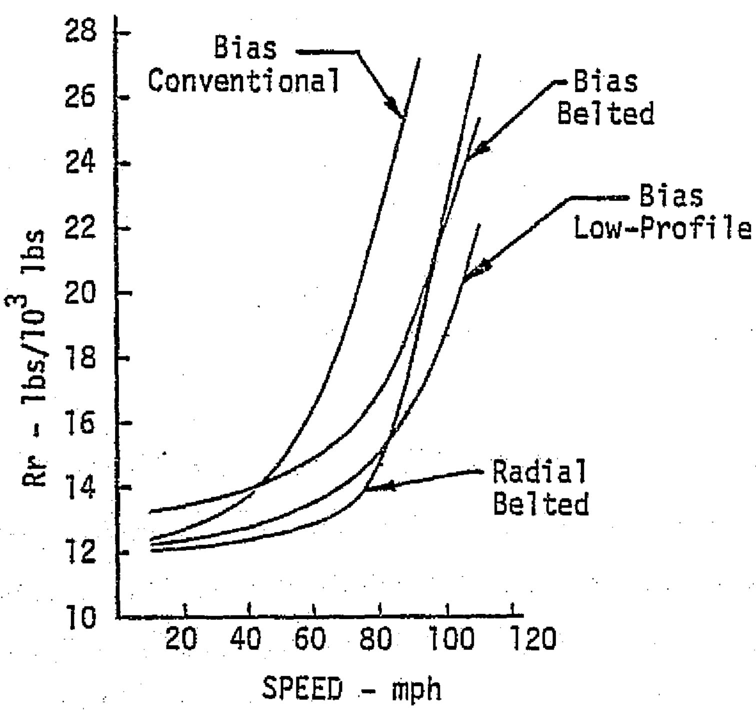

Figure 3-2. - Rolling Resistance vs. Speed by Generic Tire Type

resistance is directly related to the hysteresis properties, of which 60% is contributed by the rubber in the structure.

The angle of the cord within the carcass is the most important design parameter in tire engineering. Large cord angle configurations have lower rolling resistance because there is less flexing as the tire rolls. Conventional tire cords are built in a criss-cross pattern. This pattern, when flexed, produces hysteresis and internal friction losses. These losses are reduced significantly when the cord angle becomes 90° (i.e., radial). Radial cord flexing occurs in a simple geometrical plane, thereby producing lower friction losses. Figure 3-2 shows rolling resistance as a function of tire construction with emphasis on tire cord construction. The radial-belted tire has significantly lower rolling resistance than the conventional bias tire, which is due mainly to the cord angle differences. This is especially apparent in the speed range we are considering in EV design.

Further reduction in rolling resistance is achieved by belting the radial cords with steel, as can be seen in figure 3-3. Steel belting has greater resiliency to distortion, thereby reducing hysteresis loss. Tires constructed with steel belts rather than fabric have greater strength and more uniform heat distribution, which will result in greater passenger safety.

Load variation on the tire has a direct influence on the rolling resistance. Figure 3-4 shows the relationship of relative tire drag to percent of rated load. As the load on the tire decreases, the rolling resistance decreases. The use of oversized tires will lower tire losses.

Inflation pressure contributes greatly to change in rolling resistance. Figure 3-5 shows relative rolling resistance of a radial tire as a function of tire pressure. Rolling resistance was reduced more than 15% by increasing the pressure from 24 to 32 psi.

Low-aspect ratio tires (cross section height divided by cross section width) also reduce rolling resistance. However, at present, low-aspect tires are more difficult to produce and are not readily available. The rolling resistance reduction is 4% at 55 mph. Costs are relatively high for this type of tire construction.

The goal for a low loss tire must be tempered with the overall ability of a tire to perform its basic function. It should be emphasized that tires presently produced represent the optimum properties over the speed range capabilities of present combustion engine vehicles. When the maximum and average speed capacity of the vehicle is reduced, the potential for further reducing power loss is increased. For the urban EV, the best state-of-the-art commercially available tire is the steel belted radial. A separate EV tire rating with a lower top speed rating could permit higher tire pressures and, thereby, lower tire losses.

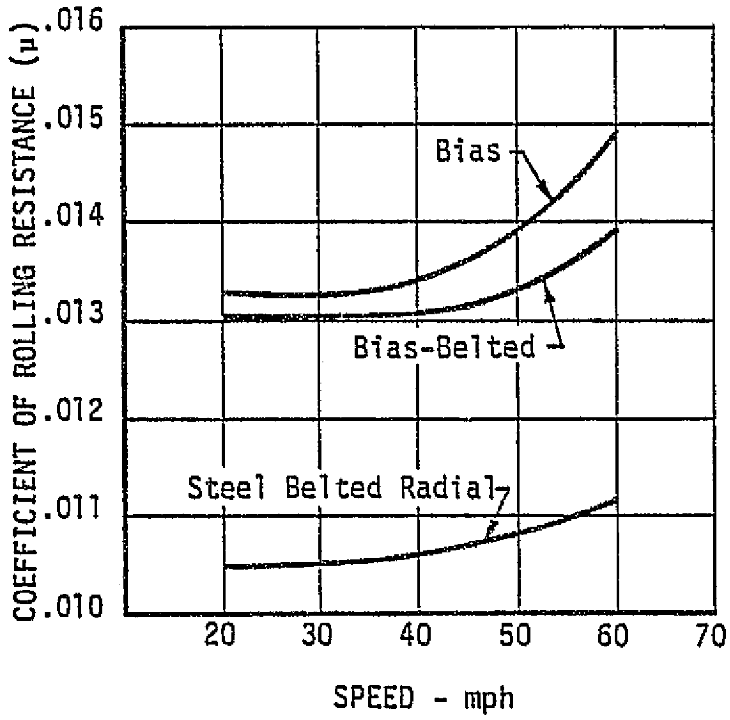

Figure 3-3. - Rolling Resistance vs. Speed - Bias & Steel Radial

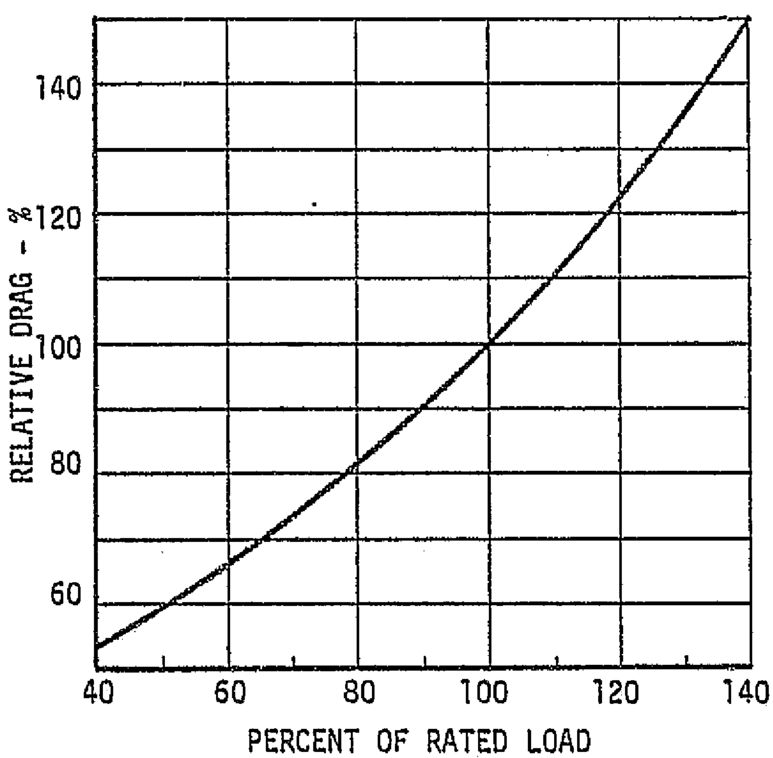

Figure 3-4. - Relative Drag vs. Rated Load

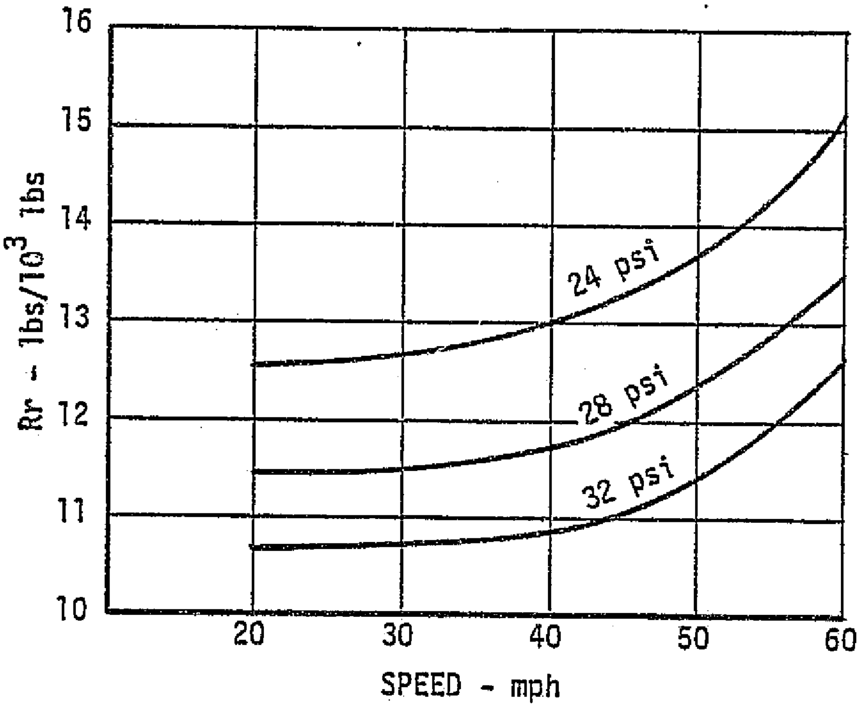

Figure 3-5. - Rolling Resistance vs. Tire Pressure and Speed

4.0 IMPROVEMENTS TO THE STATE-OF-THE-ART

4.1 MOTORS

The efficiency characteristics of both DC and AC motors when operated at reduced loads and speeds have not received very much attention by motor manufacturers because the present volume of usage is extremely low. Difficulty in obtaining this information is compounded by the variation in characteristics of the controllers. This fact is particularly true as it applies to AC motors operated under variable voltage, variable frequency conditions. As the market demand increases, additional data and performance will be a natural outgrowth.

Further improvements in efficiency are anticipated for both DC and AC motors as a result of higher shaft speeds, with AC benefiting the most. The efficiency of AC motors can be improved by the use of low resistance copper in lieu of aluminum in the rotor. The use of rare-earth magnetic materials may make possible permanent magnetic motors with increased efficiency and reduction in size.

4.2 TRANSMISSIONS

Infinitely variable transmissions (IVT) present great potential for increased travel range. The mechanical ratio can be varied to permit the motor to operate at the optimum speed for maximum efficiency based on the power required. The IVT can be programmed to adjust the motor speed for least current. The efficiency of energy recovery during regenerative braking can also be increased by programming the IVT to increase motor speed as the vehicle slows down. This approach is being developed in the combustion engine field with success; however, the durability of these transmissions is still lacking and the cost is higher than existing automatic transmissions.

4.3 BEARINGS AND SEALS

The mechanical drag cuased by bearings and seals on a conventional car amounts to about 2% of the total rolling resistance. Some improvement could be gained by incorporating the SKF double-row angular-contact ball bearing front spindle design used on some European cars. The unit is lighter than the conventional tapered bearing design. It is preloaded, lubricated and sealed for life. The mechanical loss in the spindle can be reduced by 20%, but since the actual loss in the bearings is so small, the overall contribution is probably less than 0.5% reduction in rolling resistance.

New, more efficient seal materials and designs could reduce the friction loss considerably. Flocked seals are being studied by several firms and offer hope of very low friction loss. The basic construction resembles a conventional labyrinth seal with short plastic fibers glued to the surfaces. The fibers close the gap, preventing entry of dust.

Conventional seals coated with Teflon should also be considered for reducing drag.

4.4 LUBRICATION

New synthetic lubricants are becoming available which improve low and high temperature performance by as much as 20%. Teflon particles suspended in the transmission or differential lube oil point toward reduced friction, particularly at startup. The use of spray-mist lubrication techniques can reduce the losses associated with churning of the normal sump design. One firearms manufacturer claims tremendous reduction in friction losses by totally coating the internal parts with Teflon. This technique may be of value in transmissions and differentials.

4.5 TIRES

Engineering development of tires specifically designed for use on urban electric vehicles is eminent. The energy conservation efforts to reduce fuel consumption on combustion vehicles through the use of low-loss tires will apply as well to tires for EV's. Reduced loading on the tires by virtue of lower top speed will allow readjustment of tire construction to reduce rolling resistance consistent with operational and safety requirements.

5.0 CONCLUDING REMARKS

The current "state-of-the-art" of electric vehicle power trains does not reflect the capabilities of currently available components and technology. It is apparent that current and past efforts have not reached the level of performance that can be achieved with state-of-the-art components because the designs do not achieve a totally integrated system.

An integrated system design which recognizes the requirements and the interactions of the components of the power train, will significantly extend the range of electric vehicles. Increased performance can be achieved by properly selecting and sizing components of the power train to match the lower power requirements associated with electric vehicles. The vast majority of the electric vehicles built since 1965 are based on drive-line components designed to match the characteristics of the internal combustion engine.

The attributes of regenerative braking as a means of energy recovery to extend range have been known for years. Unfortunately, vehicle developers have not been able to effectively employ this benefit because of the previous emphasis on maximum constant speed cruise range. Recent advancements in the state of the art of controllers as well as better definition of the driving cycle for an urban electric vehicle now makes regenerative braking a cost effective means of increasing the range obtainable from a specified lead-acid battery package.

Although much can be done to improve the range and performance of an electric vehicle using the DC motor by proper sizing and matching of the drive line components, recent developments in the AC controller field make the AC motor drive viable in a battery powered vehicle, and overcome the complexity and high cost generally associated with variable speed AC drives. At low power ratings, the DC drive system usually costs less than the AC system because lower cost of the AC motor is offset by the complex controller cost. As the power requirement increases, the cost of a DC motor increases substantially, thus reducing the cost difference between DC and AC systems.

Increases in range and performance for electric vehicles can be gained within the state-of-the-art using commercially available components and existing technology to reduce power train losses and to increase the compatibility of the drive line elements through system integration. The components considered applicable to the design of a power train for a state-of-the-art electric vehicle are:

- Induction motor and 3-phase AC controller
- Separately excited DC motor
- Two-speed transmission
- Spiral gear differential
- Steel-belted radial tires

The performance of these components needs to be established in more detail by incorporating them into a computer simulation of the SAE driving cycle. The output of the simulation runs will establish the potential for increasing the range of an electric vehicle using commercially available components and state-of-the-art technology.

APPENDIX A-1

VEHICLE DESCRIPTIONS

DESIGNATION	MANUFACTURER
Urba Electric	Electromatic Drive Corp. Lab. 628 Katella Road, Suite 28 Orange, California 92667
Sundancer	McKee Engineering Corporation 411 W. Colfax Street Palatine, ILL 60067
Mark 16	McKee Engineering Corporation 411 W. Colfax Street Palatine, ILL 60067
McCulloch	McKee Engineering Corporation 411 W. Colfax Street Palatine, ILL 60067
Ripp-Electric	W. E. Rippel Consultant to Jet Propulsion Laboratory California Institute of Technology Pasadena, CA

"URBA ELECTRIC" BY MECHANIX ILLUSTRATED

Manufacturer: Electromatic Drive Corp. Lab.
628 Katella Road, Suite 28
Orange, CA 92667
Mr. Darriel Hilman, Manager

Vehicle Description: This electric vehicle was designed and built "from ground up", lightweight tubular chassis with molded fiberglass body. GVW 1700 lb.

Motor: Rated 10 HP @ 4500 RPM aircraft type separately excited DC motor running at constant speed, blower cooled.

Controller: Voltage switching for starting and cruising. Speed control through variable sheave pitch dia. Current feed-back loop for overload protection. Regeneration is a result of the built-in speed control during coasting or downhill driving, regenerative brake can be added. 48 V. sys.

Transmission: Electronically controlled continuously adjustable belt drive plus fixed ratio roller chain drive with a differential.

Tires: Goodyear AR 70-13 steel belted radials.

Charger: On board, low rate overnight charging.

Batteries: Eight 6-Volt Trojan #J-244 plus one 12-Volt auxiliary battery. Total weight = 550 lb.

Performance: (All estimated) - Top speed 60-65 MPH
Acceleration 0-30 MPH in 9 sec.
Driving range at 35 MPH 100 mi.
Fully instrumented road test is planned.

SUNDANCER (Originally Mark 15)

Manufacturer: McKee Engineering Corp.
Palatine, Illinois

Vehicle Description: The Sundancer is a special design two passenger car with very low aerodynamic, chassis and inertia losses. The main portion of the chassis is fabricated of stainless steel as a tunnel to accommodate the battery rack. The bottom of this tube contains a series of rollers to facilitate removal or easy and fast exchange of the battery rack. The body is fiberglass. The front suspension is independent, with unequal length "A" - frames with coil springs and shocks. The steering rack and pinion are mounted on top of the backbone. The rear suspension is a Dana transaxle joined to the chassis by radius rods and shock absorbers with coil springs around them, forming a single "A" frame. Instead of doors, the top is hinged at the rear, can be raised and lowered for passenger entry or exit.

Controller Combination of contactor controller and SCR controller/charger

Transmission: Special McKee 2-speed manual transmission
Gear Ratios: 1st 6.08:1
2nd 3.14:1

Tires: 6.55 x 9 Goodyear low rolling resistance experimental. Tire pressure 30 PSI.

Motor: Type: Fork-link-DC-Series Field, 4 pole wave wound
Rating: 8 HP @ 3520 RPM for 1 hour, No blower
Weight: 83 lb.
Note: Separate blower draws cooling air from passenger compartment through the controls and the motor.

Battery Charger: Type: 72V. Sys - SCR controller/charger experimental
Bimodal device built by Tork-Link. End charge voltage 86.4V

Batteries: Main Traction - Mfr: ESB (Exide)
Lead Acid, golf cart type, EV-106
Normal Rating - 106 min. at 75 Amp (132.5 Amp-hr.)
Twelve 6-volt units used in 72 bolt series string, 9 in the backbone tunnel and 3 across the front
Weight: 750 lb.

Axle: Type: Rear Wheel Drive, Dana EG-20 unit, Al. HSG
Ratio: 4.88 to 1
Motor and transmission mounted on axle housing and directly coupled to the differential. Manual shifting through flexible cable, the shift lever operates a syncromesh unit between the gears.

Brakes: Disc Brakes, H&H NO. 500, 8 in. dia. x 1/4 in. Two discs on front hub. two discs on rear axle. No regenerative braking.

Specifications: Size & Weight:

Length	120 in.
Width	62 in.
Height	40 in.
Road Clearance	4-1/2 in.
Projected frontal area	12 sq. ft.
Gross vehicle weight	1600 lb.

MARK 16 MC KEE ELECTRIC COMMUTER

Manufacturer: McKee Engineering Corp.
Palatine, Illinois

Vehicle Description: The Mark 16 is a slightly modified version of the Sundancer. The changes incorporate new fully independent rear suspension with a dual belt adjustable speed drive. There is a gear reducer at each drive wheel instead of the two speed gear reducer and Dana axle combination. The rest of the car is the same as the Sundancer, the gross vehicle weight is also the same - approximately 1600 lb., including 750 lb. of batteries.

MC CULLOCH ELECTRIC CAR

Manufacturer: McKee Engineering Corp.
Palatine, Illinois

Vehicle Description: This EV is a larger version of the Sundancer. The tunnel frame chassis is longer, there are 18 6V lead-acid batteries for the propulsion motor. A 15 HP DC motor drives the rear axle through a torque-sensing two speed planetary and a Morse Hy-Vo chain transmission. The front suspension is an independent unequal "A" frame, coil springs, and shock absorbers. The rear suspension is also independent: a live axle with trailing arms, coil springs and shock absorbers. The body is made of fiberglass, two door coupe type.

Motor: Type (McCulloch) DC-Series Field
Rating: 15HP
Weight:

Controller: EVC monolithic switching transistors. Pulse width modulation at 400 Hz. Efficiency 98% or better.

Transmission: (1) "Torque-Sensing" two speed planetary reducer. Ratio: 4 to 1
(2) Morse Hy-Vo chain drive. Ratio: 3.80 to 1

Tires: Goodyear AR 70-13 steel belted radials.

Battery Charger: Charging capacity 25 amps at 120 V. output. Could use regenerative braking, but currently not used.

Batteries: Main Traction: Mfr: ESB (Exide)
Lead-Acid, Golf cart type, EV-106
Normal Rating - 106 min. at 75 amp
Eighteen 6 Volt units used in 108 volt series
Total Weight: 1260 lb.

Drive Axle: Type: Rear Wheel Drive
Ratio:

Specifications: Size & Weight: Length 166 in.
Width 68 in.
Height 46 in.
Frontal Area 15 sq. ft.
Gross Vehicle Weight 2760 lb.

"RIPP-ELECTRIC"

Designer: W. E. Rippel
Consultant to Jet Propulsion Laboratory
Californiia Institute of Technology
Pasadena, California

Vehicle Description: This advanced electric vehicle is a converted 1971 Datsun 1200, with the original power train retained. The drive system composed of:

Motor: A Baker-Otis Model #1265 totally enclosed 4-pole DC motor rated 20 HP at 4000 RPM, weight 205 lb., mounted under the hood.

Controls: Specially designed by W. Rippel transistor chopper control with bi-directional flow for regenerative braking and 300 amp current limit in both drive and brake modes.

Transmission: Original clutch, 4-speed manual gearbox and standard rear axle

Tires: Steel belted SR 165-13 radials.
Tire pressure: 30 psi front, 35 psi rear

Charger: On-board transformerless charger rated 2 kW. Total weight of controls and charger = 39 lb., mounted over back seat.

Batteries: Twenty 6-Volt lead-acid batteries, Exide Model LEV-115, rated 144 Amp-Hr @ 75 min. Total weight: 20 x 65 = 1300 lb., mounted in trunk.

Test Results:

1. Top speed: 53-61 mph
2. Const. Speed Range - 30 mph 85. mi.
   45 mph 80. mi.
   57 mph 66. mi.
3. SAE J227a Sched "C" range
   with regenerative braking - 60. mi.
   without regenerative braking - 49. mi.

APPENDIX A-2

COMPONENT	FIRMS CONTACTED
MOTORS	1. General Electric Erie, Pennsylvania
	2. Relinace Electric Co. Cleveland, Ohio
	3. Northwestern Electric Co. Div. of Emerson Electric Chicago, Illinois
	4. Prestolite Electrical An ELTRA Company Toledo, Ohio
	5. Santa Ana Electric Motors Santa Ana, California
CONTROLLERS	1. Square D Company Milwaukee, Wisconsin
	2. SEVCON, Div. of Technical Operations, Inc.
	3. General Electric Salem, Virginia
	4. EVC, Inc. Los Angeles, California
	5. HB Electrica Mfg. Co., Inc. Mansfield, Ohio

COMPONENT	FIRMS CONTACTED
TRANSMISSIONS	1. Traction Propulsion, Inc. Austin, Texas 512/837-7354
	2. Fluid Drive Engineering Co. Wilmette, ILL 312/251-5410
	3. New Process Gear, Div. of Chrysler Corporation East Syracuse, NY 315/432-4000
	4. Clark Equipment Co. Buchanan, Michigan 517/764-6000
	5. Cotta Transmission Co. Rockford, ILL 815/962-6671
	6. Borg Warner Corporation Chicago, Illinois 312/455-3120
	7. Sundstrand Corporation Denver, Colorado 303/428-3640
	8. Formsprag - Dana Division Chicago, ILL 312/888-5415
	9. Allison, Div. of GM Detroit, Mich. & Indianapolis, Inc. 313/592-5000
	10. Ford Motor Transmission Division of Ford Livonia, Michigan
	11. Orshansky Transmissions San Diego, CA 714/270-2841

COMPONENTS	FIRMS CONTACTED
TRANSMISSIONS - Cont	12. Dana Corporation Toledo, Ohio 419/531-7333
	13. Salisbury Los Angeles, CA
AXLES - GEARS	1. Dana Corporation Spicer Division Fort Wayne, IND 219/483-7174
	2. Eaton Corporation Richmond, IND 317/952-2571
TIRES & WHEELS	1. Firestone Tire & Rubber Corp Los Angeles, CA 213/583-7741
	2. Firestone Tire & Rubber Corp. Akron, Ohio 216/379-7000
	3. Tire & Rim Association Akron, Ohio 216/836-5553
	4. Cooper Tire Company Findlay, Ohio 419/423-1321
	5. Goodyear Tire & Rubber Los Angeles, CA 213/583-3083
	6. Michelin

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   SO: Machine Design, Oct. 17, 1974

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       AU: Clare E. Wise, Managing Editor, MD

   1.2 EV Design - Engineers In, Stylists Out
       AU: Richard T. Dann, Assoc. Editor,MD

   1.3 EV Motors - DC Now, AC Later?
       AU: Milton Leonard, Senior Ed., MD

   1.4 EV Controllers - Semiconductors Mean Extra Range
       AU: Frederick E. Bryson, Assoc. Ed., MD

   1.5 EV Connectors - Vital Link Between Car and Power
       AU: Earl E. Dalrymple & Diane E. Brody; Anderson Power Products, Boston, Mass.

   1.6 EV Transmissions - How Many Speeds?
       AU: Richard T. Dann, Assoc. Ed., MD

   1.7 EV Power Sources - Waiting for a Super Battery
       AU: Richard A. Jacobson, Sr. Ed., MD

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TI	Title
AU	Author
SO	Source
EV	Electric Vehicle
AE	Automotive Engineering
SAE	Society of Automotive Engineers
MD	Machine Design
PD	Product Design
BW	Business Week
PS	Popular Science
DOT	U.S. Department of Transportation
EPA	Environmental Protection Agency
ERDA	Energy Research and Development Administration
NASA	National Aeronautics and Space Administration
DAF	Deutsche Automobilgesellschaft Forschungslaboratorium (Germany)

APPENDIX B

TWO-SPEED RIGID TRANSAXLE
EV POWER TRAIN

Several power train configurations were developed during the design activity as candidates for a SOTA design.

One of these power train designs based on the use of a conventional rigid axle is shown in Figure B-1. A two-speed transmission designed by McKee Engineering is directly mounted to the differential axle housing. The drive motor is mounted on the vehicle chassis and is coupled to the transmission by a short conventional drive shaft with U-joints at each end.

This particular configuration was a viable candidate, but the configuration presented in Section 6 was selected because of its compactness and acceptability as a front wheel drive.

The power train configurations are discussed in more detail in Section 4 and a pictorial drawing of this configuration is shown in figure 8.

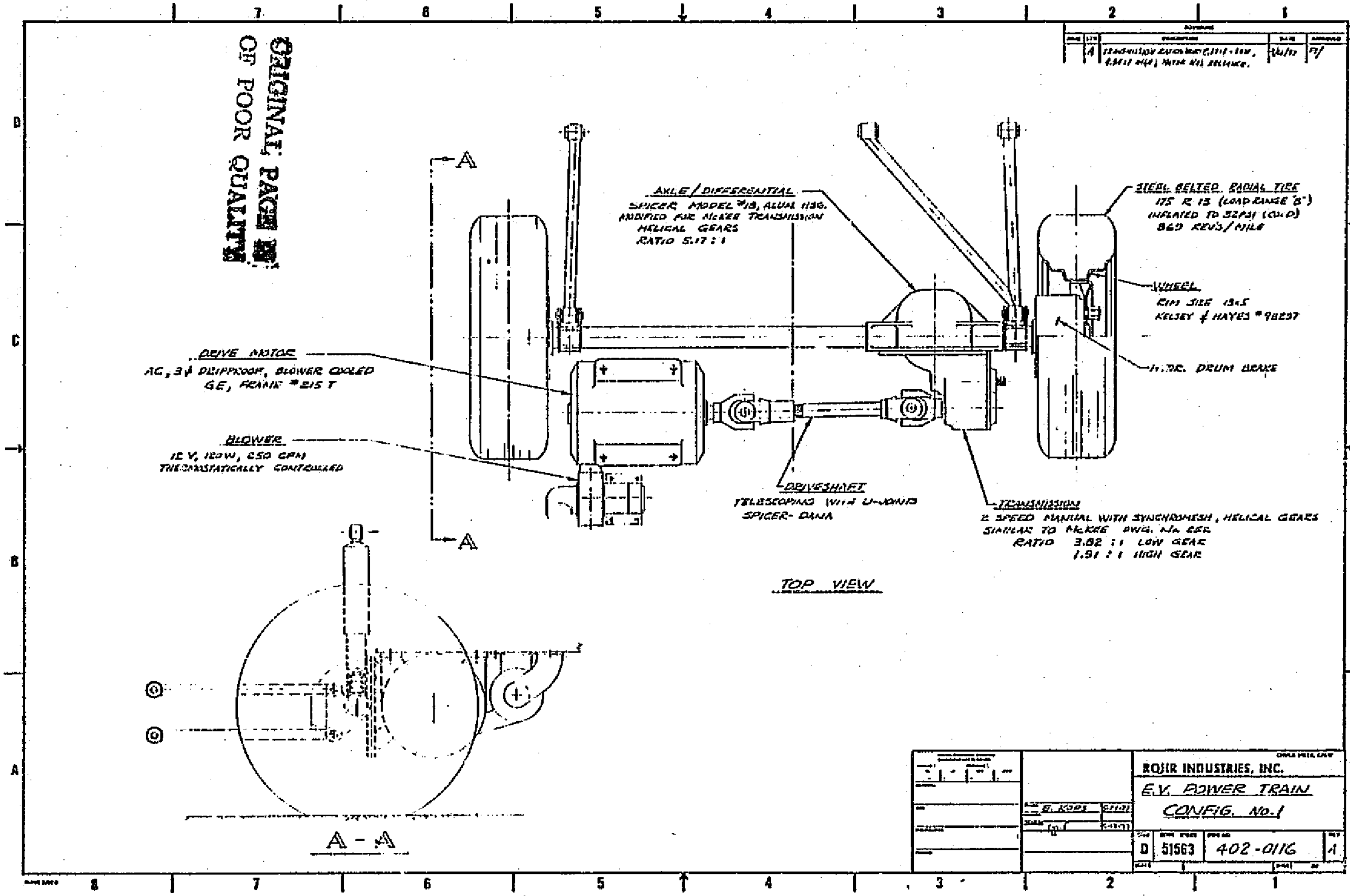

Figure B-1. - Two-Speed Rigid Transaxle - EV Power Train

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APPENDIX C

BACKGROUND OF ROHR CONTROLLER DEVELOPMENT

The AC motor controller discussed in this report is based upon equipment developed at Rohr Industries for the purpose of controlling the voltage and frequency to a set of 3-phase linear induction motors for transit vehicles.

DYNAMOMETER TEST SET-UP

A series of tests were performed with two of these motor control units connected to opposed 20 HP induction motors. Both controllers were driven from the same DC power source (battery or rectifier), so that one machine operated as a motor, driving the other machine as a generator. With this arrangement, it was possible to investigate the entire range of operating from 200% torque as a motor to 200% torque as a generator merely by changing the controller frequencies. Photographs of the dynamometer and battery bank setup are given in figures C-1 and C-2. One of the 3-phase 50 kVA motor controllers is shown in figure C-3.

Using the directly opposed motors, with a torque meter between them and power instrumentation on each of the motors, as well as differentially measuring the current and voltage from the power source, it was possible to precisely measure the power loss in the controllers or motors. This arrangement is schematically shown in the sample data sheet in figure C-4.

TEST RESULTS

The efficiencies of the controller and motor as measured in back-to-back dynamometer tests are given in table C-1. The controller efficiency ranged from 92 to 97%, depending on the specific operating condition of speed and torque.

Of major significance is the fact that there was no degradation in motor efficiency when it was powered by the variable voltage, variable frequency inverter rather than 60 Hz power line. A comparison of the manufacturer's efficiency data and the results of Rohr's tests is presented in table C-2. The Rohr tests show slightly higher efficiency, probably because the motor was not at maximum ambient or winding temperature when the tests were conducted.

A plot of power loss versus load current for the controllers in the motor control test is given in figure C-5. This plot represents data points for all output voltages and frequencies as measured during the test as the motor was operated over a wide range of speed and torque. Controller losses are a function of the load current, therefore, its power efficiency depends on the load characteristics. The reactive current in the motor contributes to controller loss, but not to work output. The average loss value represented by 0.3 of the kVA rating plus 1.6% of the kVA rating multiplied by the ratio of load current to full load current rating was used in establishing the performance data for the preliminary power train design.

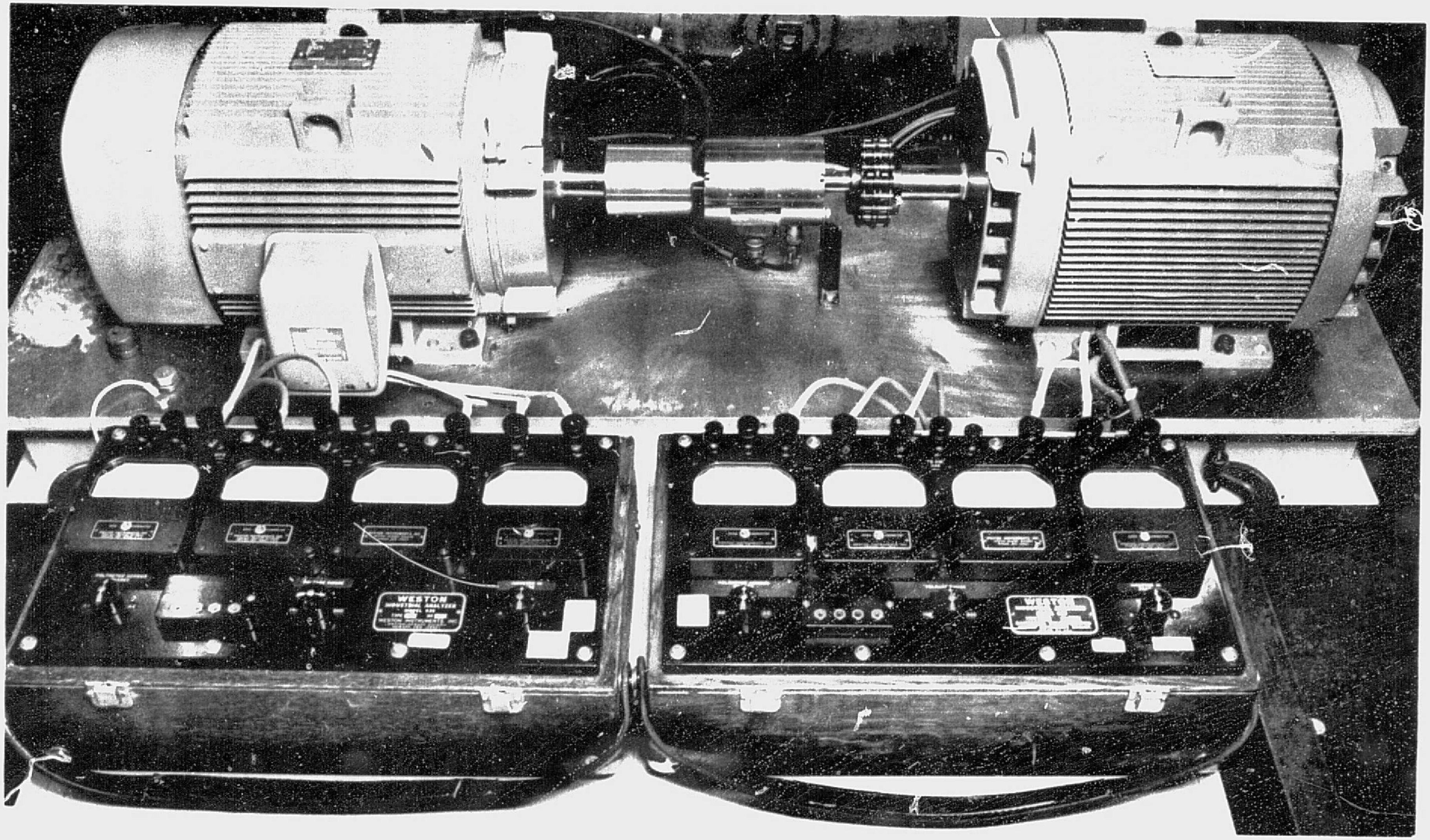


Figure C-1. Motor Control Dynamometer Test Set-Up

Figure C-2. Battery Bank

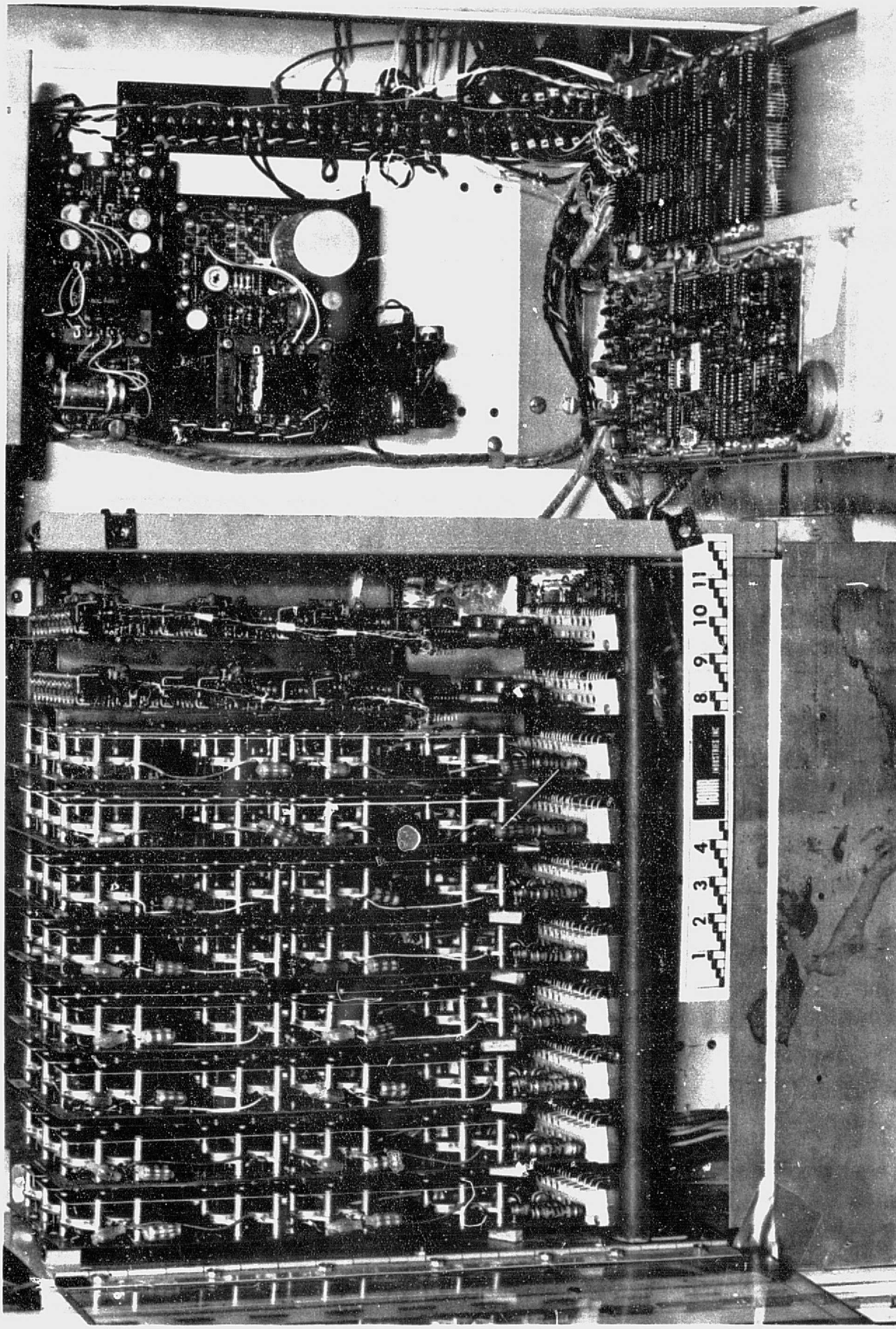


Figure C-3. Rohr 3-Phase AC Controller

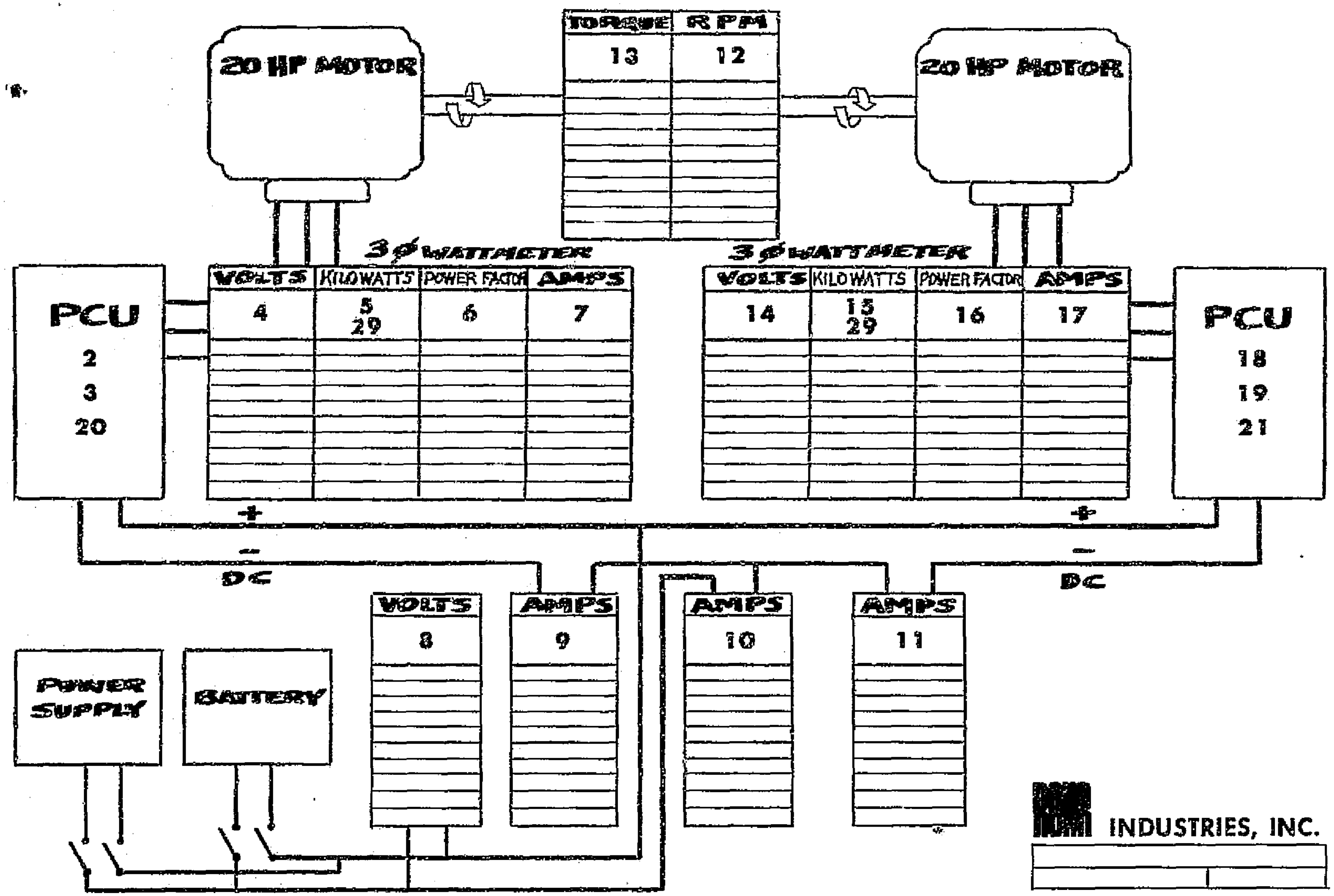


Figure C-4. - Sample Data Sheet for Motor Control Test

TABLE C-1.-CONTROLLER AND MOTOR EFFICIENCY VS. MOTOR SPEED AND TORQUE

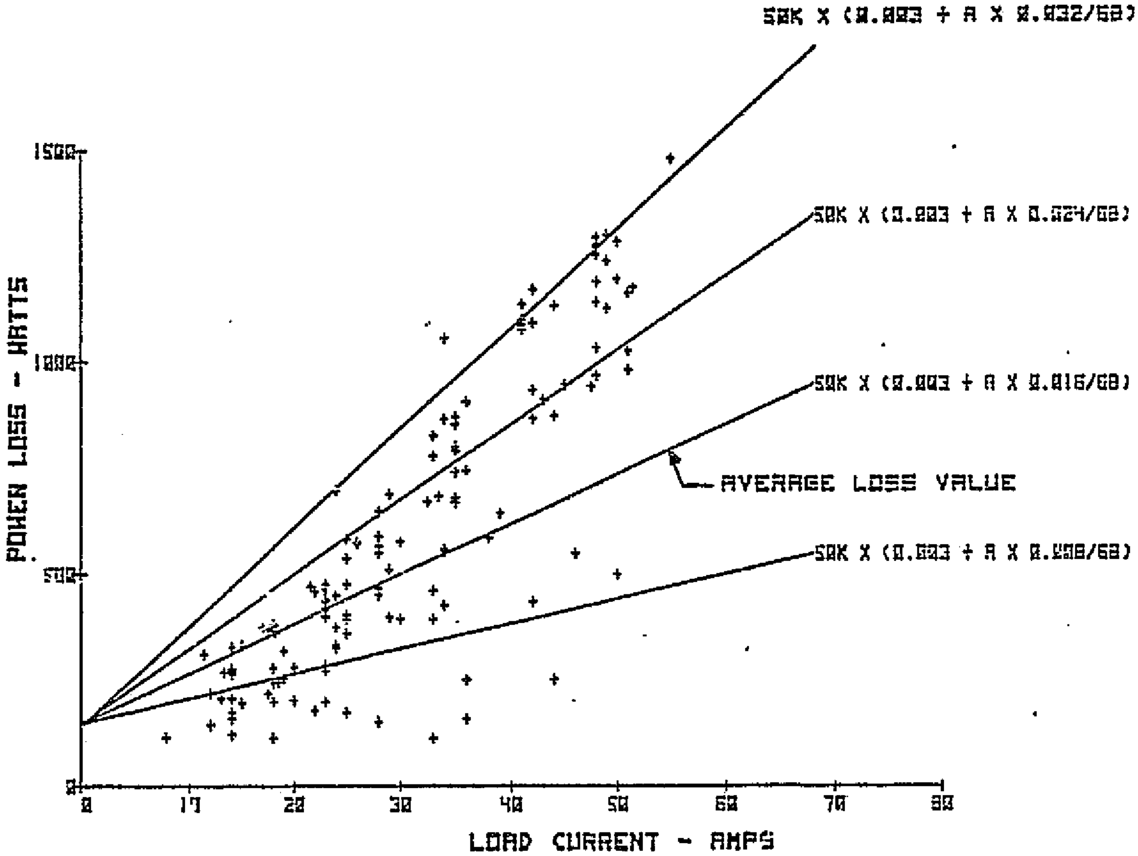
SPEED	EFFICIENCY					
	FULL LOAD		50% LOAD		25% LOAD	
	PCU	MOTOR	PCU	MOTOR	PCU	MOTOR
1755	92	87	97	85	-	-
2368	94	90	-	-	-	-
3585	96 Est	88 Est	-	-	95	78

CONTROLLER RATING: 50 kVA CONTINUOUS
80 kVA PEAK (1 MIN)

MOTOR: GE 256T AC MOTOR
14.9 kW (20 hp) at 1755 rpm
- WITH INTERNAL FAN
T = 81.1 Nm (59.8 ft-lbs)
3-PHASE 60 HZ

TABLE C-2 - MANUFACTURER'S DATA VS TEST RESULTS

AT RATED SPEED	MANUFACTURER'S DATA	TEST RESULTS	
	MOTOR EFFICIENCY (%)	MOTOR EFFICIENCY (%)	CONTROLLER EFFICIENCY (%)
FULL TORQUE	85	87	94
1/2 TORQUE	86	87	96



TEST RESULTS: POWER CONDITIONER LOSS VS. LOAD CURRENT
RESULTS OF SEVERAL TESTS AT VARIOUS LOAD IMPEDANCES
FREQUENCIES FROM 5 TO 120 HZ
50 KVA RATED UNIT WITH 20 HP MOTOR
DATE OF TEST 4/25/77 TO 4/27/77

Figure C-5. - Power Loss vs. Load Current

TABLE D-1.1. - TABULATED SCHEDULE D RESULTS FOR SELECTED POWER TRAIN

AC ALUMINUM 215T FRAME MOTOR WGT.(LBS)= 85

HP	FREQ.(HZ)	VOLT.	RPM	TORQ. FT-LBS	MASS. MOM.
10	60	17.30	1740	30.10	0.75

INPUT VEHICLE TITLE

7850 RPM = 88.5 KM/HR (55 MPH)

VEHICLE (LESS MOTOR) WGT.(LBS) :3125

PCU KVA RATING :88

PCU CURRENT RATING :750

MOTOR RPM AT 55 MPH :7850

LOW GEAR RATIO :2

HIGH GEAR RATIO :1

FIRST ACC. MPH/SEC :5

SHIFT POINT MILES PER HOUR :22.5

TRANS.& DIFF. EFF. IN LOW GEAR :.92

TRANS. & DIFF. EFF. IN HIGH GEAR :.95

TIRE COEFF. OF V^0 :8.1

TIRE COEFF. OF V :.0108

DRIVING SCHEDULE 1=C 2=D :2

TABLE D-1.2. - TABULATED SCHEDULE D RESULTS

FIRST ACCEL.= 2.24 M/S/S (5.0 MPH/S)

TIME SEC	ACC M/S2	VEL. KM/HR	DIST. KM	BAT AMP	MOT AMP	CHARGE REM.	MOT KW	MOT RPM	% TORQ	PCU LOSS	MOT LOSS
0.1	2.24	0.8	0.00001	55	527	0.99999	0.9	143	153	1.19	3.0
0.2	2.24	1.6	0.00004	65	527	0.99998	1.9	285	153	1.19	3.0
0.3	2.24	2.4	0.00010	77	527	0.99997	2.8	428	153	1.19	3.1
0.4	2.24	3.2	0.00018	90	528	0.99995	3.7	571	153	1.19	3.3
0.5	2.24	4.0	0.00028	100	528	0.99993	4.7	714	153	1.19	3.3
0.6	2.24	4.8	0.00040	110	528	0.99991	5.6	856	153	1.19	3.2
0.7	2.24	5.6	0.00055	123	529	0.99988	6.6	999	153	1.20	3.3
0.8	2.24	6.4	0.00072	134	530	0.99986	7.5	1142	153	1.20	3.3
0.9	2.24	7.2	0.00091	146	531	0.99983	8.4	1285	153	1.20	3.3
1.0	2.24	8.0	0.00112	158	531	0.99979	9.4	1427	153	1.20	3.4
1.1	2.24	8.8	0.00135	170	531	0.99976	10.3	1570	153	1.20	3.5
1.2	2.24	9.7	0.00161	182	531	0.99972	11.2	1713	153	1.20	3.5
1.3	2.24	10.5	0.00189	195	533	0.99968	12.2	1855	153	1.20	3.5
1.4	2.24	11.3	0.00219	208	535	0.99964	13.1	1998	153	1.20	3.6
1.5	2.24	12.1	0.00251	221	536	0.99960	14.1	2141	153	1.21	3.6
2.0	2.24	16.1	0.00447	292	538	0.99933	18.8	2856	154	1.21	3.9
2.5	1.68	19.1	0.00692	244	433	0.99905	16.9	3392	116	1.03	2.6
3.0	1.41	21.7	0.00975	228	374	0.99880	16.3	3844	99	0.92	2.1
3.5	1.25	23.9	0.01291	220	339	0.99856	16.0	4242	88	0.86	1.9
4.0	1.13	25.9	0.01638	216	314	0.99834	15.9	4603	80	0.82	1.8
4.5	1.04	27.8	0.02011	214	296	0.99811	15.8	4936	75	0.79	1.8
5.0	0.97	29.6	0.02410	214	283	0.99789	15.8	5246	70	0.76	1.8
5.5	0.91	31.2	0.02832	214	272	0.99766	15.8	5538	66	0.74	1.8
6.0	0.87	32.8	0.03276	214	263	0.99744	15.8	5815	63	0.73	1.8
6.5	0.82	34.3	0.03742	215	256	0.99721	15.8	6078	61	0.71	1.9
7.0	0.79	35.7	0.04227	216	250	0.99699	15.9	6330	58	0.70	1.9
7.5	0.76	37.0	0.04732	218	246	0.99676	15.9	6572	56	0.70	2.0

SHIFT POINT

TIME SEC	ACC M/S2	VEL. KM/HR	DIST. KM	BAT AMP	MOT AMP	CHARGE REM.	MOT KW	MOT RPM	% TORQ	PCU LOSS	MOT LOSS
7.6	-0.11	37.0	0.04835	0	0	0.99676	0.0	0	0	0.00	0.0
7.7	-0.11	37.0	0.04938	0	0	0.99676	0.0	0	0	0.00	0.0
7.8	-0.11	36.9	0.05041	0	0	0.99676	0.0	0	0	0.00	0.0
7.9	-0.11	36.9	0.05143	0	0	0.99676	0.0	0	0	0.00	0.0
8.0	-0.11	36.8	0.05246	0	0	0.99676	0.0	0	0	0.00	0.0
8.1	-0.11	36.8	0.05348	0	0	0.99676	0.0	0	0	0.00	0.0
8.2	-0.11	36.8	0.05450	0	0	0.99676	0.0	0	0	0.00	0.0
8.3	-0.11	36.7	0.05552	0	0	0.99676	0.0	0	0	0.00	0.0
8.4	-0.11	36.7	0.05654	0	0	0.99676	0.0	0	0	0.00	0.0
8.5	-0.11	36.7	0.05756	0	0	0.99676	0.0	0	0	0.00	0.0
8.5	-0.11	36.7	0.05756	0	0	0.99676	0.0	0	0	0.00	0.0

TABLE D-1.3. - TABULATED SCHEDULE D RESULTS

TIME SEC	ACC M/S2	VEL. KM/HR	DIST. KM	BAT AMP	MOT AMP	CHARGE REM.	MOT KW	MOT RPM	% TORQ	PCU LOSS	MOT LOSS
8.6	0.74	36.9	0.05858	204	388	0.99671	14.5	3275	103	0.95	2.1
9.0	0.72	38.0	0.06274	204	380	0.99654	14.6	3367	101	0.93	2.1
10.0	0.67	40.4	0.07364	205	363	0.99612	14.7	3588	96	0.90	2.0
11.0	0.64	42.8	0.08520	206	350	0.99569	14.9	3796	92	0.88	1.9
12.0	0.60	45.0	0.09740	207	339	0.99525	15.1	3993	88	0.86	1.9
13.0	0.58	47.1	0.11020	209	329	0.99482	15.3	4181	85	0.84	1.8
14.0	0.55	49.2	0.12358	211	321	0.99438	15.5	4361	83	0.83	1.8
15.0	0.53	51.1	0.13750	213	314	0.99393	15.7	4533	81	0.82	1.8
16.0	0.51	53.0	0.15196	216	308	0.99348	15.8	4699	79	0.81	1.8
17.0	0.50	54.8	0.16693	218	303	0.99303	16.0	4860	77	0.80	1.8
18.0	0.48	56.5	0.18239	221	299	0.99257	16.2	5015	75	0.79	1.8
19.0	0.47	58.2	0.19833	224	295	0.99210	16.4	5166	74	0.78	1.9
20.0	0.45	59.9	0.21474	227	292	0.99163	16.6	5312	73	0.78	1.9
21.0	0.44	61.5	0.23160	230	289	0.99115	16.8	5455	72	0.77	1.9
22.0	0.43	63.1	0.24890	233	286	0.99067	17.0	5593	71	0.77	1.9
23.0	0.42	64.6	0.26663	236	284	0.99018	17.2	5729	70	0.76	2.0
24.0	0.41	66.1	0.28478	239	282	0.98968	17.4	5861	69	0.76	2.0
25.0	0.40	67.5	0.30333	242	280	0.98917	17.7	5991	69	0.76	2.0
26.0	0.39	69.0	0.32229	246	279	0.98866	17.9	6117	68	0.75	2.1
27.0	0.39	70.4	0.34164	249	277	0.98814	18.1	6241	68	0.75	2.1
28.0	0.38	71.7	0.36138	253	276	0.98762	18.3	6363	67	0.75	2.2
28.5	0.37	72.4	0.37139	255	275	0.98735	18.4	6423	67	0.75	2.2

CONSTANT VEL. (45 MPH)

TIME SEC	ACC M/S2	VEL. KM/HR	DIST. KM	BAT AMP	MOT AMP	CHARGE REM.	MOT KW	MOT RPM	% TORQ	PCU LOSS	MOT LOSS
28.6	0.00	72.4	0.37340	82	153	0.98732	5.7	6423	21	0.53	1.3
28.7	0.00	72.4	0.37541	82	153	0.98730	5.7	6423	21	0.53	1.3
78.0	0.00	72.4	1.36697	82	153	0.97883	5.7	6423	21	0.53	1.3

COASTING

TIME SEC	ACC M/S2	VEL. KM/HR	DIST. KM	BAT AMP	MOT AMP	CHARGE REM.	MOT KW	MOT RPM	% TORQ	PCU LOSS	MOT LOSS
78.1	-0.23	72.3	1.36898	0	0	0.97883	0.0	6415	0	0.00	1.3
78.5	-0.23	72.0	1.37700	0	0	0.97883	0.0	6386	0	0.00	1.3

TABLE D-1.4. - TABULATED SCHEDULE D RESULTS

TIME SEC	ACC M/S2	VEL. KM/HR	DIST. KM	BAT AMP	MOT AMP	CHARGE REM.	MOT KW	MOT RPM	% TORQ	PCU LOSS	MOT LOSS
79.0	-0.23	71.6	1.38697	0	0	0.97883	0.0	6350	0	0.00	1.3
79.5	-0.23	71.2	1.39688	0	0	0.97883	0.0	6314	0	0.00	1.2
80.0	-0.22	70.8	1.40674	0	0	0.97883	0.0	6278	0	0.00	1.2
80.5	-0.22	70.4	1.41654	0	0	0.97883	0.0	6243	0	0.00	1.2
81.0	-0.22	70.0	1.42629	0	0	0.97883	0.0	6207	0	0.00	1.2
81.5	-0.22	69.6	1.43598	0	0	0.97883	0.0	6172	0	0.00	1.2
82.0	-0.22	69.2	1.44562	0	0	0.97883	0.0	6137	0	0.00	1.2
82.5	-0.22	68.8	1.45520	0	0	0.97883	0.0	6102	0	0.00	1.2
83.0	-0.22	68.4	1.46473	0	0	0.97883	0.0	6068	0	0.00	1.2
83.5	-0.22	68.0	1.47420	0	0	0.97883	0.0	6033	0	0.00	1.1
84.0	-0.21	67.6	1.48362	0	0	0.97883	0.0	5999	0	0.00	1.1
84.5	-0.21	67.2	1.49299	0	0	0.97883	0.0	5965	0	0.00	1.1
85.0	-0.21	66.9	1.50230	0	0	0.97883	0.0	5931	0	0.00	1.1
85.5	-0.21	66.5	1.51156	0	0	0.97883	0.0	5897	0	0.00	1.1
86.0	-0.21	66.1	1.52077	0	0	0.97883	0.0	5864	0	0.00	1.1
86.5	-0.21	65.7	1.52992	0	0	0.97883	0.0	5831	0	0.00	1.1
87.0	-0.21	65.4	1.53903	0	0	0.97883	0.0	5798	0	0.00	1.1
87.5	-0.21	65.0	1.54808	0	0	0.97883	0.0	5765	0	0.00	1.1
88.0	-0.20	64.6	1.55708	0	0	0.97883	0.0	5732	0	0.00	1.0

(IF NO REGEN.) APPROX. VEHICLE RANGE IS 77.36 KM (48.08 MI)

REG. BRAKING AND FRICTION BRAKING BLENDED

TIME SEC	ACC M/S2	VEL. KM/HR	DIST. KM	BAT AMP	MOT AMP	CHARGE REM.	MOT KW	MOT RPM	% TORQ	PCU LOSS	MOT LOSS
88.1	-2.02	63.9	1.55886	-347	690	0.97886	-48.1	5667	198	1.48	7.5
88.5	-2.02	61.0	1.56580	-332	692	0.97914	-46.0	5410	198	1.48	7.4
89.0	-2.02	57.4	1.57402	-313	694	0.97948	-43.5	5088	199	1.49	7.2
89.5	-2.02	53.7	1.58173	-305	726	0.97980	-43.0	4766	210	1.54	7.7
90.0	-2.02	50.1	1.58894	-285	725	0.98011	-40.2	4444	211	1.54	7.5
90.5	-2.02	46.5	1.59565	-263	726	0.98039	-37.4	4122	212	1.54	7.4
91.0	-2.02	42.8	1.60185	-240	726	0.98066	-34.6	3800	213	1.54	7.2
91.5	-2.02	39.2	1.60755	-218	724	0.98090	-31.8	3478	213	1.54	7.0
92.0	-2.02	35.6	1.61274	-194	725	0.98111	-28.9	3156	214	1.54	6.9
92.5	-2.02	31.9	1.61743	-170	725	0.98130	-26.0	2834	214	1.54	6.8
93.0	-2.02	28.3	1.62161	-145	724	0.98147	-23.1	2512	215	1.54	6.6
93.5	-2.02	24.7	1.62530	-120	721	0.98161	-20.2	2190	215	1.53	6.5
94.0	-2.02	21.1	1.62847	-93	721	0.98172	-17.2	1868	215	1.53	6.4
94.5	-2.02	17.4	1.63114	-66	720	0.98180	-14.3	1546	216	1.53	6.2
95.0	-2.02	13.8	1.63331	-39	718	0.98186	-11.3	1224	216	1.53	6.0
95.5	-2.02	10.2	1.63498	-9	718	0.98188	-8.4	902	216	1.53	5.9
95.8	-2.02	8.0	1.63573	0	0	0.98188	0.0	708	0	0.00	0.0
95.9	-2.02	7.3	1.63594	0	0	0.98188	0.0	644	0	0.00	0.0
96.0	-2.02	6.5	1.63614	0	0	0.98188	0.0	580	0	0.00	0.0

TABLE D-1.5. - TABULATED SCHEDULE D RESULTS

TIME SEC	ACC M/S2	VEL. KM/HR	DIST. KM	BAT AMP	MOT AMP	CHARGE REM.	MOT KW	MOT RPM	% TORQ	PCU LOSS	MOT LOSS
96.1	-2.02	5.8	1.63631	0	0	0.98188	0.0	515	0	0.00	0.0
96.2	-2.02	5.1	1.63646	0	0	0.98188	0.0	451	0	0.00	0.0
96.3	-2.02	4.4	1.63659	0	0	0.98188	0.0	386	0	0.00	0.0
96.4	-2.02	3.6	1.63670	0	0	0.98188	0.0	322	0	0.00	0.0
96.5	-2.02	2.9	1.63679	0	0	0.98188	0.0	258	0	0.00	0.0
96.6	-2.02	2.2	1.63686	0	0	0.98188	0.0	193	0	0.00	0.0
96.7	-2.02	1.5	1.63691	0	0	0.98188	0.0	129	0	0.00	0.0
96.8	-2.02	0.7	1.63694	0	0	0.98188	0.0	64	0	0.00	0.0

VEHICLE RANGE IS 90.36 KM (56.16 MI)

APPENDIX E

COMPUTER ANALYSIS PROGRAM

DESCRIPTION

The specially developed computer analysis program used to evaluate the power train components was designed to predict the overall performance of each of the candidate combinations in terms of their maximum range, based on the SAE Schedule D driving cycle. The program is written in BASIC language and is designed for use on a Hewlett Packard 9830 computer. It can also be used with minor modifications on most BASIC language computers.

The program determines the travel range for the selected combination of components over a simulated driving cycle by continuously calculating the performance of the system as the vehicle is "driven" through the prescribed load profile. Basically, the computer simulation calculates the battery charge consumed (the integral of the current time product) as a function of cycle time.

The cycle or load profile is fed into the computer in terms of rolling resistance, mechanical drag, aerodynamic drag, and acceleration forces as a function of cycle time. The program determines the operating condition in terms of motor torque and speed, then establishes the motor current and voltage for maximum efficiency. Next, the program calculates the losses in the controller and the resultant total battery current. Finally, the incremental battery charge consumed (or regenerated) is calculated, totaled, and transformed into percent of charge remaining for each point in time as the vehicle is "driven" through one repetition of the driving cycle.

Battery drain is continuously calculated during the acceleration and cruise portions of the cycle. During the regenerative braking mode, the program determines how much charge is returned to the battery. The computer is continuously monitoring the extent or percent of battery charge remaining. At the end of the cycle, the travel range in miles is established based on the total charge initially available in the batteries.

During regenerative braking, the maximum energy generated and returned to the battery is limited by the torque capacity of the motor at the operating speed at that instant. When the required deceleration rate cannot be met by the regenerative braking force, blended friction braking is introduced.

Rotational as well as translational inertia and change of rotational inertia during gear shifting are considered in the computer simulation.

A unique feature of the computer simulation is that a separately developed Rohr motor program is used to establish the optimum motor current and voltage for maximum efficiency based on the motor speed and torque required at that point in the cycle. The program is based on a look-up table for motor current, voltage, and efficiency versus speed and torque. (The plot of motor efficiency, torque, and speed for each motor is presented in section 4.2) An interpolation routine is used to derive values between points in the stored table. Data for the DC motors was derived from the manufacturer's characteristics curves (figures 11 and 12). Curves and corresponding look-up tables for the AC motors were derived by using equivalent circuit values from the motor test data supplied by the motor manufacturer and by adjusting operating torque and speed.

In addition to the performance and range established for the Schedule D driving cycle, the cruise portion of the computer program was separated out to provide constant speed performance data from 8 to 88.5 km/hr (5 to 55 mph). Using the reduced program, the travel range can be determined for constant speed cruise operation.

The computer simulation program is shown in the form of a flow chart in figure E-1. The first four steps of the flow chart represent the Rohr developed motor analysis program which is in turn an input to the program developed to simulate electric vehicle performance (the last three steps; according to the SAE Schedule D driving cycle. The output of the vehicle performance program is stored and can be plotted by means of a separate plot program.

ASSUMPTIONS IN SIMULATION

The battery characteristics of an EV 106 by ESB, Inc. were assumed for the computer analysis. The energy capacity of the batteries is based on (11.7 Whr/lb) equivalent to 132.5 Ahr (75 A for 106 minutes) at 27°C (80°F).

The average battery voltage during a complete discharge cycle is assumed to be 96 volts (1.99 volts/cell X 3 cells X 16 batteries) with a fixed internal resistance of 3.0 milliohms per battery. The use of 3.0 milliohms internal resistance allows for some degradation with battery age or change in operating temperature below 27°C (80°F).

The computer program bases its calculations on the following formula:

$$V_{batt} = 96 \text{ volts} - 16 \times .003 \times I_{batt}$$

Based on these battery assumptions, the battery and motor currents given in the simulation results represent the average values during the discharge cycle.

The controller loss for the AC system is based on a fixed loss of 0.3% of the kVA rating plus a variable loss of 1.6% of the kVA rating multiplied by the ratio of operating current to rated full load current. The controller loss in the DC systems is calculated on one-third of an equivalent 3-phase AC system based on the assumption that the complexity of a DC controller is equivalent to one phase of a 3-phase AC system with equivalent capacity. Using this assumption, the computer program is more easily adapted to the different systems. The basis for the AC system controller loss is discussed in more detail in Appendix C on the background of the Rohr controller development.

Step	Input/Output
Enter Motor Characteristics	Full Load Efficiency, Power Factor, Half Load Efficiency, Power Factor, Base Frequency, HP, Volts, No Load RPM, Full Load RPM, Maximum Volts, RPM, Motor Mass, Mass Moment of Inertia
Calculate Motor Equivalent Circuit	Primary and Secondary Resistance and Inductance, Shunt Resistance and Inductance
Generate Look-up Table for Best Efficiency	For 20% to 220% rated Torque; for 25% to 500% rated Frequency
Store Results	Motor Volts, Amps, Slip, Efficiency versus RPM and Torque
Enter Vehicle Characteristics	Vehicle Mass (less motor), Motor rpm at 88.6 km/hr (55 mph), Gear Ratios, Gear Efficiencies, Aero Coefficient, Frontal Area, Controller kVA and Current Rating, Fixed and Variable Chassis and Tire Coefficient
Enter Driving Cycle Characteristics	"C" or "D" Cycle, Acceleration Profile, Shift Velocity Point
Simulate Cycle, Output Data Each 0.1 Second, Store Results	Time, Acceleration, Velocity, Distance Traveled, Battery Amps, Motor Amps, Charge Remaining, Motor Power, Motor RPM, % Full Load Torque, Controller (PCU) Loss, Motor Loss, Battery Power

Figure E-1. - Computer Simulation Flow Chart

Several other assumptions made were:

- No gear shift during regeneration
- Motor remains engaged during coast
- Motor inertia energy during shifting is not conserved

INPUTS TO PROGRAM

The fixed vehicle requirements specified for use in the preliminary power train were entered into the program and were not considered to be variable for this analysis; however, they can be varied if desired. The input parameters which varied according to the components selected or according to changes in operation were:

- Vehicle weight/payload
- Motor weight
- Factor for rotational inertia of motor and wheels
- Gear ratio (low to high)
- Motor speed at 88.6 km/hr (55 mph)
- Tire and chassis rolling resistance coefficient
- Motor look-up table
- Controller !VA rating
- Controller current rating
- Transmission shift point
- Acceleration profile
- Transmission/differential efficiency (low and high gear)
- Driving cycle (SAE J227a Schedule C or D)

SIMULATION OUTPUTS

The most important output of the computer simulation program is the predicted travel range based on the SAE driving cycle with and without regenerative braking. To aid in the design optimization, a number of other outputs are tabulated with respect to cycle time as the vehicle progresses through one repetition of the driving cycle. They are:

- Acceleration - m/s^2 (mph/sec)
- Vehicle speed - km/hr (mph)
- Distance traveled - km (miles)
- Battery current - amperes
- Motor current - amperes
- Battery charge remaining - per unit
- Motor output - kW (hp)
- Motor speed - rpm
- Percent of rated torque
- Controller loss - kW (watts)
- Motor loss - kW (watts)

These outputs are computed every 0.1 second during the cycle and recorded on magnetic tape for processing. The output data is prepared in both table and graph form.

Using the condensed cruise program, additional constant speed performance data can also be obtained for vehicle speeds from 8 to 88.6 km/hr (5 to 55 mph).

- Range - km (miles)
- Energy consumption - MJ/km (Whr/mi)
- Controller losses - kW (hp)
- Motor losses - kW (hp)
- Motor efficiency - percent
- Battery current - amperes
- Motor current - amperes

PROGRAM LISTING

The major portion of the program listing for the constant power acceleration profile is included here to illustrate the nature of the computer simulation used to predict vehicle/power train performance based on the Schedule D driving cycle. A detailed presentation and discussion of the program is beyond the scope of this report. However, it is useful to illustrate the approach taken and the method of calculation to establish the Schedule D range and the operational characteristics of the motor and controller.

The detailed program listing is given in table E-1, but a simplified program sequence is as follows:

Data from previous program defining motor characteristics is loaded (see lines 4360 - 4410).

N vector array contains the rpm values for each torque value.

T vector array contains torque values.

D vector array contains general numerical data (rated power, base rpm, rated torque, mass, rated voltage, base full load and part load efficiencies, etc.)

R vector array contains rpm values over torque and frequency range.

E vector array contains efficiency values over torque and frequency range.

I vector array contains current (ampere) values over torque and frequency range.

In line 380, N = the number of different rpm values at the lowest torque value stored.

In line 400, K is assigned D(11), the controller kVA rating.

In line 410, I is assigned D(12), the controller current rating (ampere).

In line 430, W = D(10), the vehicle less motor weight (lbs).

In line 440, M = D(7), the motor mass moment of inertia (slug-ft^2)

In line 460, assigned from data in line 480; B is number of batteries; C0, initial charge (amp hours); W1, equivalent mass weight of wheels and other rotating components due to rotational inertia only in high gear ratio (lbs); W2, same for low gear ratio (lbs).

In line 520, assign R1 = total battery resistance = 0.003 times number of batteries (Ohms).

In line 540, assign A = the given drag coefficient (0.3) times the given frontal area (20 ft^2).

Line 550 sets the output print interval (C8) and data storage interval (C9) to 0.1 sec.

Lines 560 to 590 set storage array A and initialize to zero distance. D (miles); velocity, V0 (mph); time, T9 (sec); etc.

Line 600 defines H = D(1), rated power of motor at base frequency and voltage.

Line 610 defines R = D(4), full load rpm at rated torque at base frequency and voltage.

Line 620 defines R9 = D(13), motor rpm at 55 mph with unity gear ratio.

Line 630 defines H0 = motor power delivered at rated torque per mph with unity gear ratio.

Line 660 assigns A1 - D(16), initial acceleration (mph/sec).

Line 670 assigns E - D(18), low gear efficiency (per unit).

Line 680 assigns N0 = D(14), low gear ratio.

Line 690 assigns T2 = 1.5 seconds, end of constant acceleration interval.

Line 760 assigns T0 = 0.1 seconds, integration step size.

Subroutine 4020 performs integration. (Equations of motion).

Line 4030 calculates V1, new velocity (mph).

Line 4040 calculates R0, new motor rpm.

Line 4050 calculates D, distance traveled from zero (miles).

Line 4060 calculates H1, aerodynamic drag (hp).

Line 4070 calculates H2, tire and chassis loss (hp) using total vehicle weight; (W + D(8)). D(20) is tire plus chassis linear drag coefficient (lbs/lbs) and D(21) is the second order tire drag coefficient (lbs/lbs) per mph.

Line 4090 calculates H3, acceleration power (hp).

Line 4100 assigns V0, the new initial velocity = old first velocity V1.

Line 4110 returns program to line 820.

Line 820 calculates H4, motor shaft.

Line 830 calculates L, per unit motor torque.

Subroutine 2770 uses L and rpm to search stored motor data tables to find motor current . (I7) and efficiency (E7).

Line 3630 calculates LO, controller loss (watts).

Line 3650 calculates MO, motor loss (watts).

Line 3670, 3680 calculate P, battery supplied power (watts).

Line 3690 assigns E1, battery internal voltage = 6 times number of batteries.

Line 3710 solves for I1, battery current.

Line 3720 calculates E2, battery voltage at terminals.

Line 3800 through 4000 scale results for integer array A () storage and tape file storage each 10th pass.

This outlines the basic procedure and arithmetic. Other sections of the program change acceleration and gear ratios in accordance with time or velocity.

TABLE E-1.1. - SAMPLE PROGRAM LISTING

```
10 COM N,N8,F,VI[25]
20 REM PROGRAM WRITTEN IN ENGLISH UNITS OUTPUTS SI UNITS
30 D[1]=0
40 GOTO 290
50 DEF FNH(Z)
60 PRINT LIN(2)
70 WRITE (15,80)"";
80 FORMAT X,"TIME",2X,"ACC",3X,"VEL.",2X,"DIST.",2X,"BAT",2X,"MOT",X,"CHARGE"
90 WRITE (15,100)
100 FORMAT 3X,"MOT",2X,"MOT",2X,"%",3X,"PCU",2X,"MOT"
110 WRITE (15,120)"";
120 FORMAT X,"SEC",3X,"M/S2",X,"KM/HR",3X,"KM",4X,"AMP",2X,"AMP",2X,"REM."
130 WRITE (15,140)
140 FORMAT 4X,"KW",3X,"RPM",X,"TORQ",X,"LOSS",X,"LOSS"
150 RETURN 0
160 DEF FNW(Z)
170 WRITE (15,180)T9,A1*0.447,V1*1.609,D*1.609,I1,I7,1-C1/C0,L8/1000,R0,L;
180 FORMAT F5.1,F6.2,F5.1,F8.5,F5.0,F5.0,F8.5,F5.1,F5.0,F5.0
190 WRITE (15,200)L0/1000,M0/1000
200 FORMAT F5.2,F5.1
210 RETURN 0
220 DEF FNL(Z)
221 PRINT " ";
230 FOR Z9=1 TO 66
240 WRITE (15,250)"-";
250 FORMAT F3.0
260 NEXT Z9
270 PRINT
280 RETURN 0
290 REM   FILE: 4   2/8/78
300 REM*VEHICLE PERFORMANCE PROGRAM ***
310 DIM TS[200],RS[200],IS[200],ES[200],AI[10,15],NI[25],DS[25],V$[50]
320 W9=0
330 REM*LOAD MOTOR PERF. DATA
340 GOSUB 4360
350 FOR I=1 TO 25
360 IF T[I]=-1 THEN 380
370 NEXT I
380 N=I-1
390 BEEP
400 K=D[11]
410 I=D[12]
420 REM*W= VEH. WT. (LESS MOTOR) lb
430 W=D[10]
440 M=D[7]
450 REM****D(8)=WEIGHT OF MOTOR LBS
460 READ B,C0,W1,W2
470 REM #OF BAT. CELLS, INTIAL CHARGE AMP-HRS,EQ. WT. OF WHEELS (HIGH)&LOW
480 DATA 16,132.5,136.2,162.9
490 REM T=D(20)+D(21)*V1   H2= T*V1/375,000 (TIRE  DRAG)
500 REM***N8=NUMBER OF DATA POINTS STORED
510 REM**C8=PRINT CONTROL  C9=STORE CONTOL
520 R1=0.003*B
530 REM****AERO DRAG COEFF.*SQFT
540 A=0.3*20
550 C8=C9=0.1
560 MAT A=ZER
570 N8=V0=D=I0=N9=C1=T9=0
580 V0=D=0
590 I0=0
600 E=D[1]
```

TABLE E-1.2. - SAMPLE PROGRAM LISTING

```
610 R=D[4]
620 R9=D[13]
630 HO=H*R9/R/55
640 F=13
650 REM####### FIRST ACCEL=D(16)
660 A1=D[16]
670 E=D[18]
680 NO=D[14]
690 T2=1.5
700 WRITE (15,705)"FIRST ACCEL.="D[16]*0.44704," M/S/S (",D[16]"  MPH/S )"
705 FORMAT F5.2,2F4.1
710 Q=FNHO+FNLO
720 REM*T1=START TIME  T2=END TIME  TO=STEP SIZE, A1=ACCEL.,NO=1(HI) N=2(LO)GEAR
730 REM*C1=BATT. DISCH.
740 REM*INIT. CHAR.
750 RESTORE 770
760 READ TO,C8,C9
770 DATA 0.1,0.1,0.1
780 IF T9 >= T2 THEN 930
790 T9=T9+TO
800 REM NEW DIST,VEL,RPM,H1,H2,H3
810 GOSUB 4020
820 H4=H1+H2+H3
830 L=ABSH4/HO/V1/E*100/NO
840 REM CALCULATE CURRENT ,EFF. ECT.
850 GOSUB 2770
860 IF FO=1 THEN 880
870 GOTO 1340
880 REM*BAT. CHARGE
890 GOSUB 2730
900 REM OUTPUT INFO.
910 GOSUB 3750
920 GOTO 780
930 REM*CONSTANT POWER
940 TO=C8=C9=0.5
950 V=V1
960 IF V1 >= D[17] THEN 1020
970 A1=5*7.518167/V1
980 T9=T9+TO
990 REM*CONSTANT POWER EQUATIONS
1000 GOSUB 2540
1010 GOTO 960
1020 REM**** IF HIGH GEAR RATIO=LOW GEAR RATIO WE HAVE SINGLE SPEED
1030 T3=T9
1040 IF D[15]=D[14] THEN 1380
1050 PRINT LIN(2);TAB(5);"SHIFT POINT";LIN(1)
1060 Q=FNHO+FNLO
1070 C9=TO=C8=0.1
1080 A1=-(H1+H2)/W/V1/1.2156E-04
1090 H4=MO=L8=L=H3=LO=P=I1=I7=0
1100 IF T9 >= T3+1 THEN 1190
1110 A1=-(H1+H2)/W/V1/1.2156E-04
1120 T9=T9+TO
1130 REM*NEW DIST,VEL,RPM,H1,H2,H3
1140 GOSUB 4020
1150 RO=0
1160 REM*OUTPUT DATA
1170 GOSUB 3750
1180 GOTO 1100
1190 REM#####SECOND ACCEL.
1200 GOSUB 3770
```

TABLE E-1.3. - SAMPLE PROGRAM LISTING

```
1210 Q=FNHO+FNLO
1220 NO=D[15]
1230 TO=0.1
1240 C8=C9=0.1
1250 E=D[18]
1260 NO=D[15]
1270 IF V1 >= 45 THEN 1380
1280 T9=T9+TO
1290 A1=5*7.518167/V1
1300 REM*CONSTANT POWER EQUATIONS
1310 GOSUB 2540
1320 C8=C9=1
1330 GOTO 1270
1340 PRINT LIN(1);"********SORRY YOUR MOTOR JUST BLEW UP********";LIN(1)
1350 PRINT "VEH. ROAD HP  EXCEED MOTOR LIMITS (TORQUE &/OR RPM)";LIN(1)
1360 PRINT "END OF PROGRAM ** SELECT A LOWER MOTOR RPM OR A LARGER MOTOR";LIN(2)
1370 END
1380 REM######## CONST. VEL
1390 GOSUB 3770
1400 PRINT LIN(2);TAB(5);"CONSTANT VEL. (45 MPH)";LIN(1)
1410 Q=FNHO+FNLO
1420 T2=78*(D[22]=2)+38*(D[22]=1)
1430 TO=0.1
1440 C8=C9=0.1
1450 A1=0
1460 VO=V1
1470 T9=T9+TO
1480 REM*DIST,VEL,RPM,H1,H2,H3
1490 GOSUB 4020
1500 H4=H1+H2
1510 L=ABSH4/HO/V1/E*100/NO
1520 REM*** CALCULATE CURRENT,EFF. ECT.
1530 GOSUB 2770
1540 REM*BATT. CHARGE
1550 GOSUB 2730
1560 REM*OUTPUT DATA
1570 GOSUB 3750
1580 IF T9 >= T2 THEN 1720
1590 T9=T9+TO
1600 REM*BATT. CHAR.
1610 GOSUB 2730
1620 D=D+V1*TO/3600
1630 REM*OUTPUT
1640 GOSUB 3750
1650 C9=1
1660 C8=78
1670 IF INT(T9)=T9 THEN 1700
1680 TO=1-T9+INT(T9)
1690 GOTO 1580
1700 TO=1
1710 GOTO 1580
1720 REM####COASTING
1730 PRINT LIN(2);TAB(5);"COASTING";LIN(1)
1740 Q=FNHO+FNLO
1750 T2=88*(D[22]=2)+46*(D[22]=1)
1760 C8=C9=0.1
1770 TO=0.1
1780 L=H3=L8=I1=LO=P=I7=0
1790 IF T9 >= T2 THEN 2020
1800 T9=T9+TO
```

TABLE E-1.4. - SAMPLE PROGRAM LISTING

```
1810 A1=-(H1+H2+MO/746)/W/V1/1.2156E-04
1820 REM*DIST,VEL,RPM,H1,H2,H3
1830 GOSUB 4020
1840 H3=0
1850 H4=H1+H2
1860 L=T[1]
1870 REM*RPM BOUNDS
1880 Z3=N[1]-1
1890 Z4=N[2]
1900 GOSUB 4120
1910 IF Z5#0 THEN 1940
1920 MO=L*R[1]/R*H*(1/E[1]-1)*7.46*(RO/R[1])^2.5
1930 GOTO 1970
1940 M2=T[1]*R[Z5]/R*H*(1/E[Z5]-1)*7.46
1950 M3=T[1]*R[Z6]/R*H*(1/E[Z6]-1)*7.46
1960 MO=(RO-R[Z5])*(M3-M2)/(R[Z6]-R[Z5])+M2
1970 REM*OUTPUT
1980 H4=L=L8=0
1990 GOSUB 3750
2000 C8=C9=0.5
2010 GOTO 1790
2020 REM######REG. BRAKE
2030 PRINT LIN(1);"(IF NO REGEN.) THEN APPROX. VEHICLE RANGE IS*";LIN(1)
2040 PRINT CO/C1*(V1*9/7200+D)
2050 PRINT LIN(2);TAB(5);"REG. BRAKING AND FRICTION BRAKING BLENDED";LIN(1)
2060 Q=FNHO+FNLO
2070 C8=C9=0.1
2080 T2=97*(D[22]=2)+55*(D[22]=1)
2090 TO=0.1
2100 T9=T9+TO
2110 IF (97-T9)<0.05 THEN 2140
2120 A1=-V1/(T2-T9)
2130 GOTO 2150
2140 A1=-10
2150 REM*DIST,VEL,RPM,H1,H2,H3
2160 GOSUB 4020
2170 IF V1<4 OR I1>0 THEN 2310
2180 H4=H3+H2+H1
2190 L=ABSH4/HO/V1/E*100/NO
2200 REM*CAL. CURR,EFF.
2210 GOSUB 2770
2220 IF FO#0 THEN 2250
2230 L=L*0.95
2240 GOTO 2200
2250 REM*BATT. CHARGE
2260 GOSUB 2730
2270 REM****OUTPUT INFO.
2280 GOSUB 3750
2290 C8=C9=0.5
2300 GOTO 2100
2310 REM****NO MORE REGENER.
2320 C8=C9=0.1
2330 L=L8=MO=P=LO=I1=I7=0
2340 REM*BATT. CH.
2350 GOSUB 2730
2360 REM*OUTPUT
2370 GOSUB 3750
2380 T9=T9+TO
2390 REM*DIS,VEL,RPM,H1,H2,H3
2400 GOSUB 4020
```

TABLE E-1.5. - SAMPLE PROGRAM LISTING

```
2410 IF V1 <= 0 THEN 2440
2420 H4=H1+H2+H3
2430 GOTO 2360
2440 PRINT LIN(1);"    * VEHICLE RANGE IS * ";C0/C1*D;LIN(1)
2450 F=F+1
2460 STORE  DATA F,A
2470 STORE  DATA 39,D
2480 STORE  DATA 40
2490 BEEP
2500 PRINT LIN(1);"LOADING FILE 13 TO PROCESS DATA**HANG ON**";LIN(1)
2510 LOAD 13,10,10
2520 BEEP
2530 END
2540 REM#CONSTANT POWER
2550 V1=V1+T0*A1
2560 R0=R9*N0*V1/55
2570 D=D+T0*(V0+V1)/7200
2580 V0=V1
2590 H1=A*V1^3/146625
2600 H2=((W+D[8])/375000)*((D[20]*V1+D[21]*V1^2))
2610 REM1.685E-6=(2*PI/60/55/(5280/3600))^2
2620 H3=(W+D[8]+W1*(N0=1)+W2*(N0=2)+M*N0*N0*R9*R9*1.685E-06)*A1*V1*1.215E-04
2630 H4=H1+H2+H3
2640 L=ABSH4/H0/V1/E*100/N0
2650 REM**GET CURR,EFF.
2660 GOSUB 2770
2670 IF F0=0 THEN 1340
2680 REM*BAT. CHARGE
2690 GOSUB 2730
2700 REM*OUTPUT
2710 GOSUB 3750
2720 RETURN
2730 REM#UPDATE BATT. CH.
2740 C1=C1+T0*(I1+I0)/7200
2750 I0=I1
2760 RETURN
2770 REM***ARE WE BELOW MIN. TORQ. AND BELOW MIN. RPM
2780 REM***F0=0 WE REDUCED ACCEL.
2790 F0=1
2800 IF R0<R[1] AND L<T[1] THEN 3070
2810 REM**** ARE WE BELOW MIN. TORQ. AND ABOVE MIN. RPM
2820 IF (L<T[1]) AND (R0>R[1]) THEN 3150
2830 REM****ARE WE ABOVE THE MAX. TORQ. OF 220 %
2840 IF L>T[N] THEN 3020
2850 REM*FIND TORQUE>REQ.
2860 GOSUB 4240
2870 REM****WE ARE ON THE TORQ. CURVE WITH TORQ.>REQ.
2880 REM**** IS RPM. REQ. >=   THAN THE MIN. VALUE RPM POINT ON THIS CURVE
2890 IF R0 >= R[N[Z2]] THEN 3320
2900 IF R0<R[N[Z1]] THEN 2930
2910 PRINT "ABOVE MIN. RPM FOR LOWER TORQ. CURVE AND BELOW MIN. RPM FOR UPPER"
2920 BEEP
2930 L2=K*1000*(0.003+0.015*L/T[Z1]*I[N[Z1]]/I)
2940 L3=K*1000*(0.003+0.015*L/T[Z2]*I[N[Z2]]/I)
2950 M2=T[Z1]*R[N[Z1]]/R*H*(1/E[N[Z1]]-1)*7.46
2960 M3=T[Z2]*R[N[Z2]]/R*H*(1/E[N[Z2]]-1)*7.46
2970 M0=(L-T[Z1])*(M3-M2)/(T[Z2]-T[Z1])+M2
2980 L0=(L-T[Z1])*(L3-L2)/(T[Z2]-T[Z1])+L2
2990 I7=(L-T[Z1])/(T[Z2]-T[Z1])*(I[N[Z2]]-I[N[Z1]])+I[N[Z1]]
3000 GOTO 3660
```

TABLE E-1.6. - SAMPLE PROGRAM LISTING

```
3010 REM#TORQ. OR RPM. IS TOO HIGH
3020 DISP "ABOVE TORQ. OR RPM"
3030 WAIT W9
3040 BEEP
3050 F0=0
3060 RETURN
3070 IF W9=0 THEN 3100
3080 DISP "BELOW MIN. TORQ. & MIN. RPM"
3090 WAIT W9
3100 REM* BELOW MIN. TORQUE AND MIN. RPM
3110 L0=K*1000*(0.003+0.015*L/T[1]*I[1]/I)
3120 M0=L*R[1]/R*H*(1/E[1]-1)*7.46*(R0/R[1])^2.5
3130 I7=I[1]
3140 GOTO 3660
3150 REM#BELOW MIN. TORQ. & ABOVE MIN. RPM
3160 Z3=N[1]-1
3170 Z4=N[2]
3180 GOSUB 4120
3190 IF Z6=Z4 THEN 3010
3200 IF W9=0 THEN 3230
3210 DISP "BELOW MIN. TORQ. ABOVE MIN. RPM"
3220 WAIT W9
3230 L3=K*1000*(0.003+0.015*I[Z6]/I)
3240 L2=K*1000*(0.003+0.015*I[Z5]/I)
3250 M2=T[1]*R[Z5]/R*H*(1/E[Z5]-1)*7.46
3260 M3=T[1]*R[Z6]/R*H*(1/E[Z6]-1)*7.46
3270 M0=(R0-R[Z5])*(M3-M2)/(R[Z6]-R[Z5])+M2
3280 L0=(R0-R[Z5])*(L3-L2)/(R[Z6]-R[Z5])+L2
3290 I7=(R0-R[Z5])*(I[Z6]-I[Z5])/(R[Z6]-R[Z5])+I[Z5]
3300 GOTO 3660
3310 REM#UPPER TORQ
3320 IF W9=0 THEN 3350
3330 DISP "SEARCHING UPPER TORQ. CURVE"
3340 WAIT W9
3350 Z3=N[Z2]-1
3360 Z4=N[Z2+1]
3370 GOSUB 4120
3380 IF Z6=Z4 THEN 3010
3390 IF W9=0 THEN 3420
3400 DISP "UPPER TORQ,RPM BOUNDS FOUND"
3410 WAIT W9
3420 E9=((E[Z6]-E[Z5])/(R[Z6]-R[Z5]))*(R0-R[Z5])+E[Z5]
3430 I9=((I[Z6]-I[Z5])/(R[Z6]-R[Z5]))*(R0-R[Z5])+I[Z5]
3440 REM#LOWER TORQ
3450 IF W9=0 THEN 3480
3460 DISP "SEARCHING LOWER TORQ. CURVE"
3470 WAIT W9
3480 Z3=N[Z1]-1
3490 Z4=N[Z1+1]
3500 GOSUB 4120
3510 IF Z5#Z3 THEN 3580
3520 PRINT "WE ARE BELOW THE MIN. RPM VAL. GIVEN FOR THE LOWER TORQ. CURVE"
3530 BEEP
3540 Z5=Z3+1
3550 E8=E[Z5]
3560 I8=I[Z5]
3570 GOTO 3600
3580 E8=((E[Z6]-E[Z5])/(R[Z6]-R[Z5]))*(R0-R[Z5])+E[Z5]
3590 I8=((I[Z6]-I[Z5])/(R[Z6]-R[Z5]))*(R0-R[Z5])+I[Z5]
3600 REM***NOW INTERPOLATE FOR DIFF. IN TORQUE
```

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TABLE E-1.7. - SAMPLE PROGRAM LISTING

```
3610 E7=((E9-E8)/(T[Z2]-T[Z1]))*(L-T[Z1])+E8
3620 I7=((I9-I8)/(T[Z2]-T[Z1]))*(L-T[Z1])+I8
3630 LO=K*1000*(0.003+0.015*I7/I)
3640 REM***MOTOR LOSS WATTS
3650 MO=L*(HO/E7-HO)*7.46*NO*V1
3660 REM*L8=REAL MOTOR OUTPUT WATTS
3670 L8=L*SGNH4*V1*NO*HO*7.46
3680 P=LO+MO+L8
3690 E1=B*6
3700 REM***BATTERY AMPS
3710 I1=(E1/R1-SQR(E1*E1/R1/R1-4*P/R1))/2
3720 REM  E2= BATTERY VOLTAGE
3730 E2=E1-(I1*R1)
3740 RETURN
3750 REM##STORE & PRINT
3760 IF (T9/C8)#INT(T9/C8) THEN 3780
3770 Q=FNWO
3780 IF (T9/C9)#INT(T9/C9) THEN 4010
3790 N8=N8+1
3800 A[N8,1]=T9*10
3810 A[N8,2]=A1*100
3820 A[N8,3]=V1*100
3830 A[N8,4]=D*1000
3840 A[N8,5]=H1*100
3850 A[N8,6]=H2*100
3860 A[N8,7]=H3*100
3870 A[N8,8]=I7*10
3880 A[N8,9]=L*100
3890 A[N8,10]=LO
3900 A[N8,11]=MO
3910 A[N8,12]=L8/10
3920 A[N8,13]=I1*10
3930 A[N8,14]=E2*100
3940 A[N8,15]=C1*10000/C0
3950 IF N8#10 THEN 4110
3960 N8=0
3970 F=F+1
3980 STORE  DATA F,A
3990 MAT A=CON
4000 MAT A=(-1)*A
4010 RETURN
4020 REM*NEW DIST,VEL,RPM,H1,H2
4030 V1=VO+TO*A1
4040 RO=R9*NO*V1/55
4050 D=D+TO*(VO+V1)/7200
4060 H1=A*V1*V1*V1/146625
4070 H2=((W+D[8])/375000)*((D[20]*V1+D[21]*V1^2))
4080 REM 1.685E-6=(2*PI/60/55/(5280/3600))^2
4090 H3=(W+D[8]+W1*(NO=1)+W2*(NO=2)+M*NO*NO*R9*R9*1.685E-06)*A1*V1*1.2156E-04
4100 VO=V1
4110 RETURN
4120 REM*SEARCH FOR RPM BOUNDS IN TORQ. CURVE# N9
4130 Z5=Z3
4140 Z6=Z4
4150 IF Z5+1 >= Z6 THEN 4230
4160 Z=INT((Z5+Z6)/2)
4170 IF R[Z]=RO THEN 4230
4180 IF R[Z]>RO THEN 4210
4190 Z5=Z
4200 GOTO 4150
```

TABLE E-1.8. - SAMPLE PROGRAM LISTING

```
4210 Z6=Z
4220 GOTO 4150
4230 RETURN
4240 REM*SEARCH FOR TORQ. BOUNDS
4250 Z1=0
4260 Z2=N+1
4270 IF Z1+1 >= Z2 THEN 4350
4280 Z=INT((Z1+Z2)/2)
4290 IF T[Z]=L THEN 4350
4300 IF T[Z]<L THEN 4330
4310 Z2=Z
4320 GOTO 4270
4330 Z1=Z
4340 GOTO 4270
4350 RETURN
4360 LOAD  DATA 6,N
4370 LOAD  DATA 7,T
4380 LOAD  DATA 8,D
4390 LOAD  DATA 10,R
4400 LOAD  DATA 11,E
4410 LOAD  DATA 12,I
4420 RETURN
4430 END
```