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INTRODUCTION

The NASA Lewis Research Center has been charged by the U.S. Department of Energy (DOE) with the responsibility for all propulsion system research and development work in support of the DOE's Electric and Hybrid Vehicle (EHV) Program. A comprehensive propulsion component and system R&D project is being carried out which involves participation by a broad spectrum of industrial organizations and universities through contracts and grants, supported by in-house work at NASA Lewis. Since 1977, approximately $20 million has been spent to define the performance characteristics of commercially available propulsion components, to identify important interactions among components of a propulsion system and between the system and the traction battery, and to develop advanced components and systems. A unique test facility, the Road Load Simulator, was built at the NASA Lewis Research Center which permits accurate, reproducible, cost effective testing of propulsion systems under a wide variety of simulated vehicle and traffic environments.

This paper describes progress in the development of complete electric vehicle propulsion systems, and presents the results of tests on the Road Load Simulator of two such systems representative of advanced dc and ac drive technology. One is the system used in the DOE's ETV-1 integrated test vehicle which consists of a shunt-wound dc traction motor under microprocessor control using a transistorized controller. The motor drives the vehicle through a fixed ratio transmission. The second system, under development by the Eaton Corporation, uses an ac induction motor controlled by a transistorized pulse-width modulated inverter which drives through a two-speed automatically shifted transmission. The inverter and transmission both operate under the control of a microprocessor. The characteristics of these systems are also compared with the propulsion system technology available in vehicles being manufactured at the inception of the DOE program and with an advanced, highly integrated propulsion system upon which technology development was recently initiated.

PROPULSION SYSTEM DESIGN PHILOSOPHY

The approach to propulsion system development taken under the DOE's EHV Program is governed by the desire to create the technology necessary to make electric vehicles viable for urban/suburban applications. Studies have shown that this could open up a sizable market for electrics with a corresponding significant reduction in petroleum consumption.

The customary way to evaluate a given propulsion system concept is to compare its weight, efficiency, and cost to those of competing systems capable of achieving the same performance. Cost is generally considered to be composed of two elements, purchase price and life cycle cost. The latter is made up of the sum of the purchase price and the total operating and maintenance costs over the life of the system. For a commercial vehicle, life cycle cost dominates buyer decisions. However, the well-publicized "sticker shock" which has afflicted American automobile buyers for the past several years is graphic evidence that the purchase price becomes a dominant factor when a personal car is being acquired. Since recent studies (1, 2) have shown that propulsion system cost is expected to be the largest single contributor to purchase price for an electric vehicle, the DOE EV propulsion system R&D project has emphasized the potential for low cost as a major criteria for evaluating new technologies.

A second factor of importance is that most passenger cars in the United States are equipped with automatic transmissions, including 82 percent of all 1981 U.S. models produced. Thus it is considered important to develop transmissions which offer the convenience of automatic shifting but which do not impose a high energy burden on the system, in order to increase the marketability of the electric car.

STATE-OF-THE-ART, 1976

In 1977, the DOE supported a major assessment of the state-of-the-art of electric and hybrid vehicle technology (3). Table I summarizes the propulsion systems used in vehicles tested during the assessment, and those described in the literature at that time. It was found that the most commonly used propulsion system consisted of a dc series-wound traction motor controlled by a thyristor (SCR) chopper and coupled to the wheels either through a single-stage chain reduction (fixed ratio) or a four-speed manually shifted automotive transmission, with the fixed ratio chain reduction used somewhat more frequently. Performance of electric vehicles using these systems was found to be inferior to their conventional counterparts in terms of acceleration, maximum speed, and grade climbing ability, all of which reflect inadequate attention to propulsion system design. Tests on carefully designed vehicles, such as the Lucas "Limosine" showed that performance which was compatible with urban traffic could be achieved by providing a properly sized traction motor. The major limitation of propulsion technology at the inception of the DOE program was the lack of components which were designed for electric vehicle use. Most motors and controllers employed at that time were built for use in industrial forklift trucks, while available shifting transmissions were intended for conventional automobiles and trucks. While manual transmissions had high efficiencies, the automatic transmission of that day employed a torque converter for coupling the engine to the transmission gear sets, which introduced energy losses that were tolerable for the internal combustion engine powered vehicles, but significantly increased the energy consumption of the electric. In addition, power throughputs typical of an electric vehicle are lower than those for which such transmissions are designed, further reducing the efficiency since the transmission operates in an off-design condition.

Figure 1 illustrates the power required from the motor for a 1450 kg (3190 lb) urban electric car to traverse the SAE J227a driving schedule, and for constant speed operation on level ground, and for a grade. Examination of the figure shows that the motor is sized by the short-term power required for acceleration or to climb a 10 percent grade, rather than by the power required for steady cruising. Nominally, a motor with a continuous 1-hr rating of 15 kW (20 hp) and a 30-sec peak rating of 30 kW (40 hp) could provide the desired performance. A typical traction motor of this type was tested by NASA (4). The motor, which measured 0.36 m (14 in.) in diameter and 0.46 m (18 in.) in length weighed 85 kg (187 lb). The maximum efficiency of the motor over its entire operating range was found to be 86.5 percent.

Tests were also conducted on a small car three-speed automatic transmission (5) which showed why the transmission has such a significant impact on overall system performance. Maximum efficiencies, obtained only at maximum speed in each gear, were found to be 84 percent for first gear, 81 percent for second and 80 percent for third. This low efficiency resulted from torque converter losses which became significant at power levels typical of EV operating conditions, which were low compared to those at which the transmission was designed to operate. These results showed that new EV propulsion component and system technology was required to improve vehicle performance and maximize the range which could be obtained from any given level of battery technology.

PROPULSION SYSTEM TECHNOLOGY ADVANCES

In April 1977, General Electric began the development of Electric Test Vehicle No. 1 (ETV-1) for the DOE. This vehicle was to be developed using a total systems approach to optimize the integration of technologies tailored to the EV application. Therefore it was to incorporate technology improvements to achieve a level of performance substantially better than state-of-the-art vehicles. The ETV-1 propulsion system utilized a shunt-wound dc motor, transistorized armature and field choppers for motor control, and a transaxle containing a fixed-ratio speed reducer and differential. The system, shown on figure 2 was tested on the NASA Lewis Road Load Simulator (RLS) facility. The motor has a continuous rating of 15 kW (20 hp) at 96 V dc and a peak rating of 30 kW (40 hp). It measures 0.43 m (17 in.) in length, 0.30 m (12 in.) in diameter, and weighed 85 kg (187 lb). Maximum design speed is 523 rads/sec (5000 rpm). The motor is controlled by transistorized armature and field choppers regulated by a microprocessor. The motor is operated under armature control from 0 to 48 km/hr (0 to 30 mph) and under field control from 48 to 96 km/hr (30 to 60 mph), with battery current limited to 400 A in the armature. The controller weighs 50 kg (110 lb). Final speed reduction from the motor to the differential is accomplished with a two-stage fixed ratio chain reduction. This was connected to a modified differential from a front-wheel drive compact car. The transaxle, complete with speed reduction and differential weighs 40 kg (87 lb). Tests of the ETV-1 propulsion system (6) showed the maximum system efficiency to be approximately 80 percent. Test results presented in figure 3 show that this was achieved under high torque conditions experienced when the ETV-1 vehicle accelerates from 0 to 72 km/hr (0 to 45 mph) while performing the SAE J227a, Schedule D driving cycle. System efficiency as a function of ETV-1 vehicle speed is shown by the road load torque line. Under constant driving speed, the system efficiency varied from less than 50 percent at 40 km/hr (25 mph) to approximately 77 percent at 88 km/hr (55 mph). The integrated propulsion system energy efficiency over the SAE J227a, D driving cycle was measured to be 74.0 to 75.7 percent depending on the details of how the coast and braking portions of the schedule, which determine the effectiveness of regenerative braking, were performed. For comparison, computer simulations were made on the performance of a 1976 technology-level propulsion system installed in a Ford Escort subcompact automobile. The average efficiency of the dc series motor system was found to be 48.6 percent over the same SAE cycle. The efficiency does not include credit for regenerative braking since few U.S. vehicles used it at that time. The substantial impact of the transmission is illustrated by the fact that the system efficiency can be increased to 61.9 percent by replacing the full torque converter transmission in the simulation with a 1981 model semi-lockup three-speed automatic transmission, in which a splitter gear minimizes torque converter losses in second and third gear.

A.C. induction motor drives have long been recognized as possessing a number of advantages over dc drives, particularly in lower motor weight, lower manufacturing cost and reduced maintenance. The weakness of the ac drive has been the lack of compact, low-cost inverter designs suitable for vehicle use, and the high cost of power transistors needed for switching current in the inverter. In March, 1979, the Eaton Corporation began work on an experimental ac propulsion system for DOE/Lewis, consisting of an induction motor, pulse width modulated inverter with microprocessor control, and a specially designed two-speed hydraulically shifted automatic transmission. During Phase 1 of the contract, experimental propulsion components were built and tested individually and as a system breadboard by Eaton. In mid-1981, the breadboard underwent dynamic testing on the RLS at NASA Lewis. During Phase 2 of the contract, the system (designated the ACPS2) will be upgraded to final performance levels and configuration, tested in the laboratory and installed and operated in a testbed vehicle. A significant difference between the two designs is that the Phase 1 system operated at 144 V, while the Phase 2 design was raised to 192 V. The two-pole ac induction motor is rated at 18.6 kW (25 hp), and has a peak output of 34 kW (45 hp). The machine is 0.2 m (8 in.) in diameter, 0.5 m (20 in.) long and weighs 55 kg (122 lb). It operates at a maximum speed of 1309 rad/sec (12 500 rpm). The motor is oil cooled by transmission fluid circulated from the transaxle. The inverter is a three-phase transistorized bridge with a continuous power rating of 30 kW (40 hp), and weighs 45 kg (98 lb). A 110V/220V battery charger with microprocessor control is integrated into the inverter. The two-speed power-shifted transaxle is designed with ratio ranges of 2.67:1 and 4.55:1 and is connected to the motor with a 2.62:1 ratio chain reduction. It has no torque converter. The weight of the transaxle including transmission fluid is 34 kg (75 lb). Steady-state and dynamic performance tests were performed on the Phase 1 breadboard system which is shown in figure 4. Road load torques were based on a subcompact vehicle with physical charcteristics similar to a Ford Escort, and a test weight of 1475 kg (3244 lb). The overall system efficiency as a function of vehicle speed and transaxle output torque is shown on figure 5. The solid lines on the figure represent experimental data. The dotted portion between 40 and 56 km/hr (25 and 35 mph) indicate the region in which transmission shifting occurs. Data are lacking on the efficiency at the exact shift point. The maximum steady-state system efficiencies exceed those of the ETV-1 by approximately 5 to 7 percentage points up to 48 km/hr (30 mph). Between 48 km/hr and 80 km/hr (50 mph), the Eaton system efficiency lags the ETV-1 efficiency because of an inflection in the efficiency curve which occurs immediately after the shift to high gear. This is due to the lower inverter efficiency induced by the reduction in motor speed due to gear shifting. Maximum system efficiency is slightly above 80 percent at steady speeds of 88 to 97 km/hr (55 to 60 mph). The average efficiency over the motoring portion of the SAE J227a, Schedule D driving cycle was found to be 68 percent. This value will be higher when regenerative braking is included in the tests, and will increase further due to improvements in the inverter design being made during Phase 2.

As mentioned previously, the cost of ac drives will be influenced by the cost of power transistors. A growing market for industrial variable speed drives has caused dramatic reductions in power transistor costs in the past several years. This is illustrated in figure 6, where the cost of single transistors purchased for use in the Eaton inverter are plotted against the date of purchase. In a period of only 3 years, purchase price for a given switching capability has been reduced by a factor almost 3. Were these values corrected for inflation, the effect would have been even more vivid.

The Eaton ac system shows the attractiveness of advanced propulsion technology when configured in a more or less conventional manner. Opportunities still exist to introduce innovative packaging concepts into electric vehicle propulsion systems in order to further reduce size, weight, and cost. On April 15, 1982, Ford was awarded a $6.8 million research and development contract by NASA Lewis to develop and evaluate advanced integrated alternating current powertrain technology for electric vehicles.

The research effort culminates on the fabrication and test of an experimental proof-of-concept powertrain that will incorporate an ac induction motor and multispeed automatic transaxle contained in the same housing and operating on a common axis. Speed control is accomplished by transistorized power inverter and a microprocessor. The overall objective of the program is to assess the feasibility of the advanced electric vehicle powertrain to meet certain design specifications and goals in a Ford Escort or equivalent-sized vehicle. The performance goals for the vehicle are: 0 to 80 km/hr (0 to 50 mph) acceleration in less than 20 sec, a top speed of 97 km/hr (60 mph), the ability to climb a 30 percent grade, automotive industry acceptable drivability characteristics, and energy consumption of 155 Wh/km (250 Wh/mi) for the Federal Urban Driving Schedule. Excluding energy consumption, these goals represent what are believed by Ford to be the minimum requirements for high-volume commercially acceptable electric vehicles. The acceleration and top speed goals were established on the basis of providing a product competitive with ICE vehicles which is compatible with today's U.S. traffic conditions and capable of being used on freeways. The gradability goal was set based on design standards applicable to ICE vehicles to permit vehicles to negotiate curbs, chuckholes, and severely graded highways. The energy consumption goal was established based on the projected capabilities of the vehicle and propulsion system design and represents an aggressive target, based on state-of-the-art electric vehicle powertrains. A vehicle range target was not established as it is not the intent of this contract to undertake development or demonstration of advanced batteries.

A major effort of this program is to design, build, test and refine a multispeed motor/transaxle concept in which an ac motor, automatic transmission, final drive, and differential are all integrated into a single unit. This approach has a number of distinct advantages. The use of an ac motor permits several seals to be deleted which would otherwise be needed to isolate the brushes and commutator of a dc machine from the oily environment of the transaxle. As a result, the motor (rotor and stator) can be mounted and sealed in the transaxle and cooled by transaxle oil. The total weight and size will be less because the motor and transmission will each no longer require its own housing and mounting. There is also no need for separate final drive gears because the planetary transmission gears provide the final reduction, and the concentric design eliminates the need to transfer power from one axis to another. The shifting transmission will also permit achieving the required start-up torque, performance and efficiency goals with a smaller, lighter, and hence less costly motor.

It has been estimated that the integrated design can reduce powertrain weight by 25 percent compared to a carefully engineered system of conventional configuration. The reduced weight and size of the motor/transaxle will also permit taking advantage of beneficial secondary weight savings, as vehicle suspension members and body structural members can be reduced for additional weight savings. The resultant lighter vehicle would, therefore, have greater range with the same battery weight or can retain the same range with a smaller battery. The integrated motor/transaxle could be mounted on either the front or rear axle. The approach in this program is to demonstrate feasibility of the concept in a front-wheel-drive vehicle (fig. 7). A rear-wheel-drive version could offer a larger cost saving by eliminating four constant velocity joints required for front-wheel drive. The major disadvantage of this approach is that the powertrain is unsprung and is thus directly subjected to road vibration.

Ford is the prime contractor for the program. In addition to program management responsibilities, Ford has technical responsibility for overall system design, analysis, integration and testing, transaxle design and motor/transaxle integration, the vehicle control system, and the testbed vehicle. General Electric, as the major subcontractor, has technical responsibility for the design, integration, and testing of the electric subsystem, i.e., the ac motor, the transistorized power inverter, including a new high-power transistor, and the inverter/motor controller. General Electric is also responsible for bench integration and testing of the powertrain.

CONCLUSIONS

In comparing propulsion technology advancements, three factors are of importance: weight, efficiency, and cost. In evaluating progress over the past 6 years, weight and efficiency gains have clearly been made as shown in Table 2. Weight reductions of over 35 percent have already been achieved and the improvement will reach 50 percent with the development of the Ford system. Similarly, efficiency improvements of 25 percentage points, or stated another way, a reduction in energy consumption of 50 percent has been achieved. Taken together, and considering the additional weight savings in the vehicle structure, it would be expected that the range of an urban electric car using a given battery could be at least doubled by employing advanced propulsion technology.

Cost is a more difficult parameter to evaluate because one must estimate manufacturing costs using estimating relationships consistent with the scale and methods of production in the automobile industry. Few organizations outside of the automobile manufacturers themselves are competent to make such estimates. In addition, components such as traction motors and their electronic controls have not been produced in sizes needed for electric vehicle propulsion systems. There appears to be general agreement that ac induction motor drives are particularly attractive from a cost standpoint, and large-scale manufacturing processes already exist for at least fractional horsepower ac motors. However, work being done on low-cost dc motors and simplified dc systems under other NASA/DOE contracts indicates that it is still premature to eliminate dc systems from consideration. Whether ac or dc, the use of innovative design approaches, such as that being employed on the Ford contract will result in propulsion systems which are compatible with auto industry production methods and have significantly lower costs.

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TABLE 1

Electric Vehicle Propulsion Systems Circa 1976

Component/Variation	Frequency of Use: Vehicles Tested	Frequency of Use: Literature Citations
Traction Motor		
Type -		
D.C. Series	15	50
D.C. Shunt	5	24
D.C. Compound	1	5
A.C. Induction	0	5
Other	0	4
Size (kW) -		
0-10	10	37
10-20	6	37
20-30	2	12
> 30	2	21
Motor Controller		
Battery Switching	8	
Thyristor Chopper	10	
Transistor Chopper	3	
Transmission		
Fixed Ratio	11	68
Shifting, Manual	7	} 52
Shifting, Automatic	2	
CVT	1	4

TABLE 2

Weight and Efficiency of EV Propulsion Systems

System	Weight, KG (LBS)				Efficiency, % SAE J227a-D
	Motor	Controller/ Microprocessor	Transmission/ Transaxle	Total	
1976 SOA	85 (187)	25 (54)	101 (223)	211 (464)	49
ETV-1	99 (217)	50 (110)	40 (87)	188 (414)	74-76
Eaton ACPS2	55 (122)	45 (98)	34 (75)	134 (295)	68*
Ford IACP**	30 (65)	45 (100)	27 (60)	102 (225)	-

* Phase 1 Hardware, No Regeneration

** Estimated Values

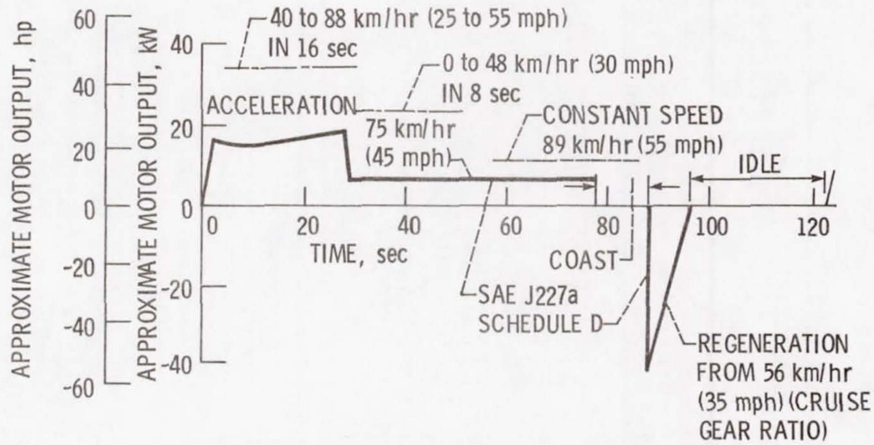

Figure 1. - Typical motor duty cycle-electric urban passenger vehicle.

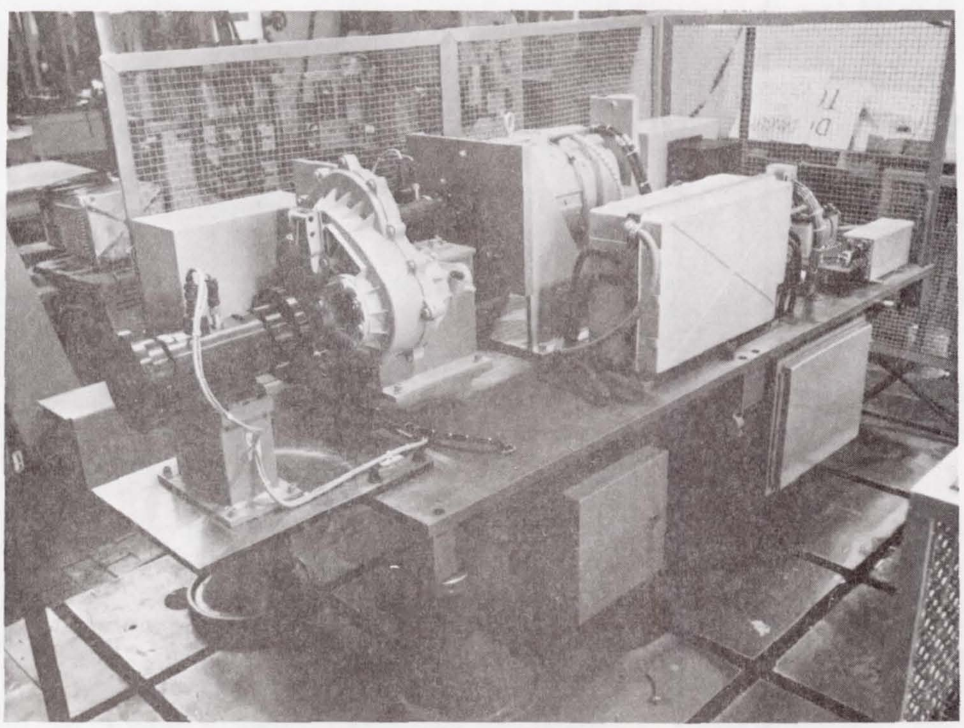

Figure 2. - ETV-1 propulsion system breadboard.

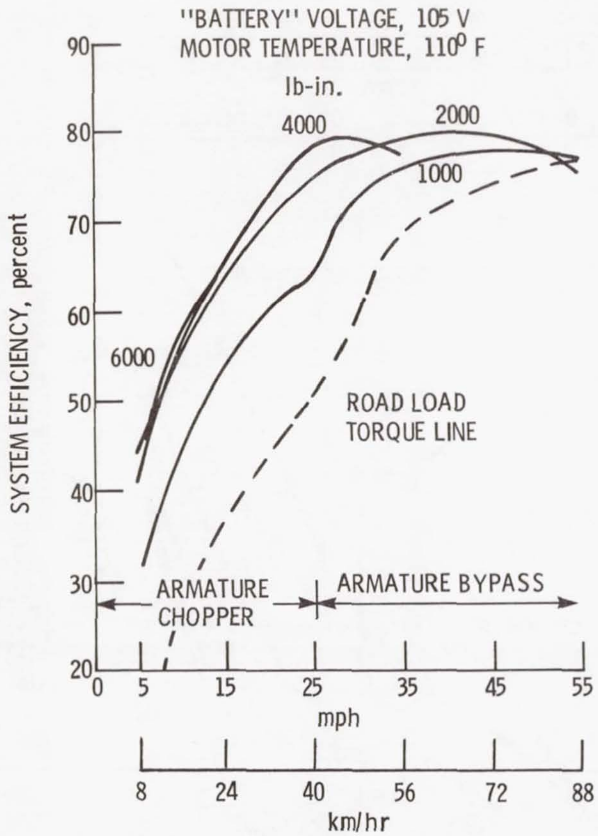

Figure 3. - ETV-1 propulsion system efficiency.

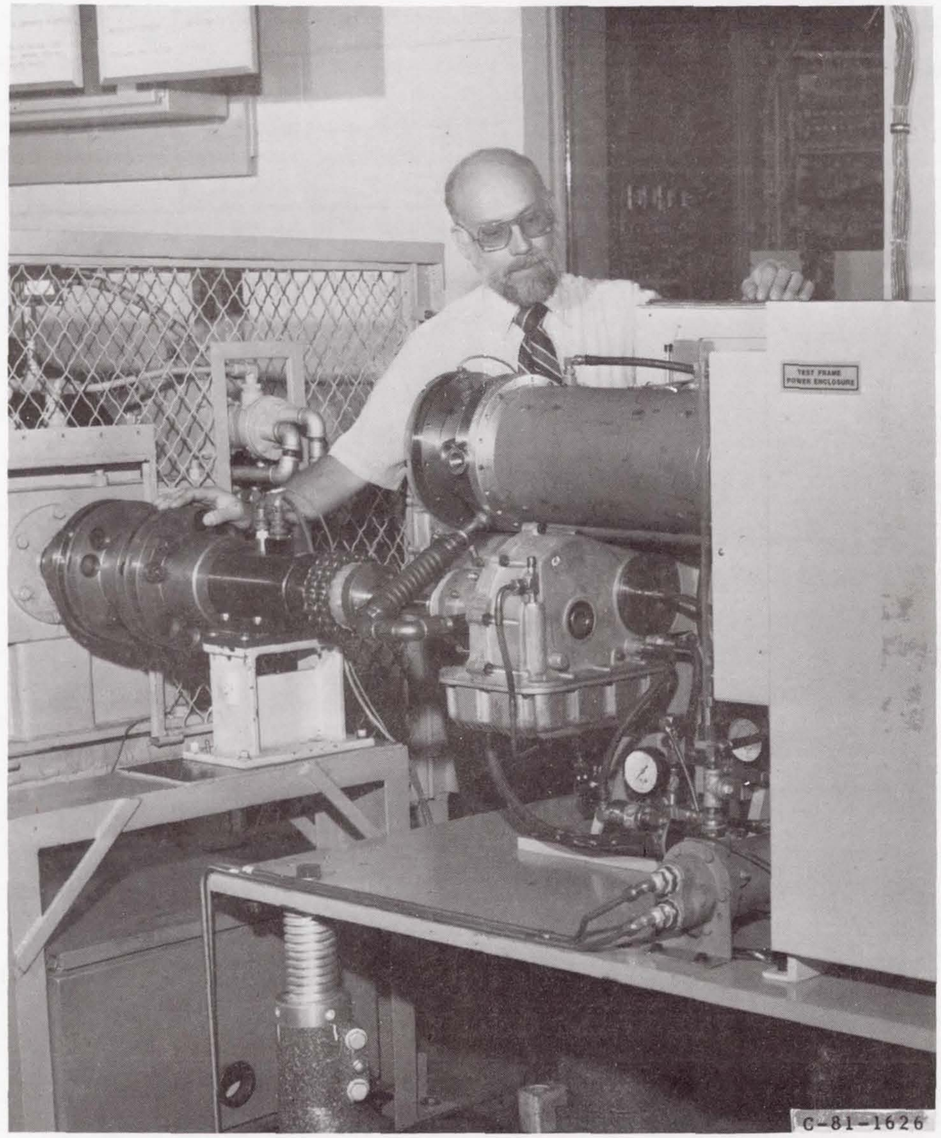

Figure 4. - Eaton AC propulsion system phase 1 breadboard.

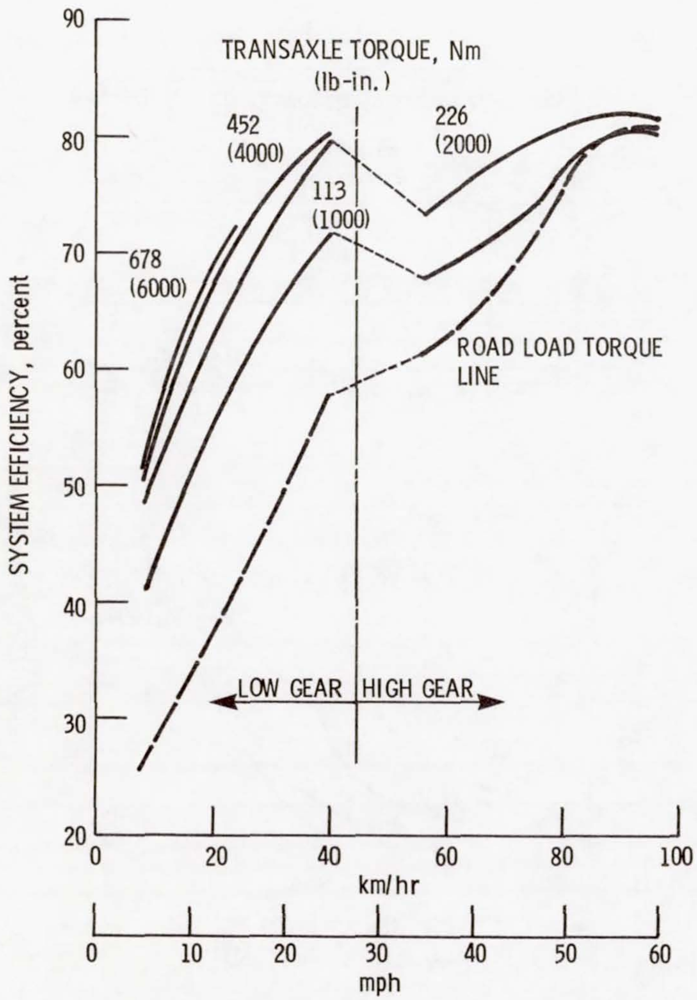

Figure 5. - Steady-state performance characteristics- Eaton AC system breadboard.

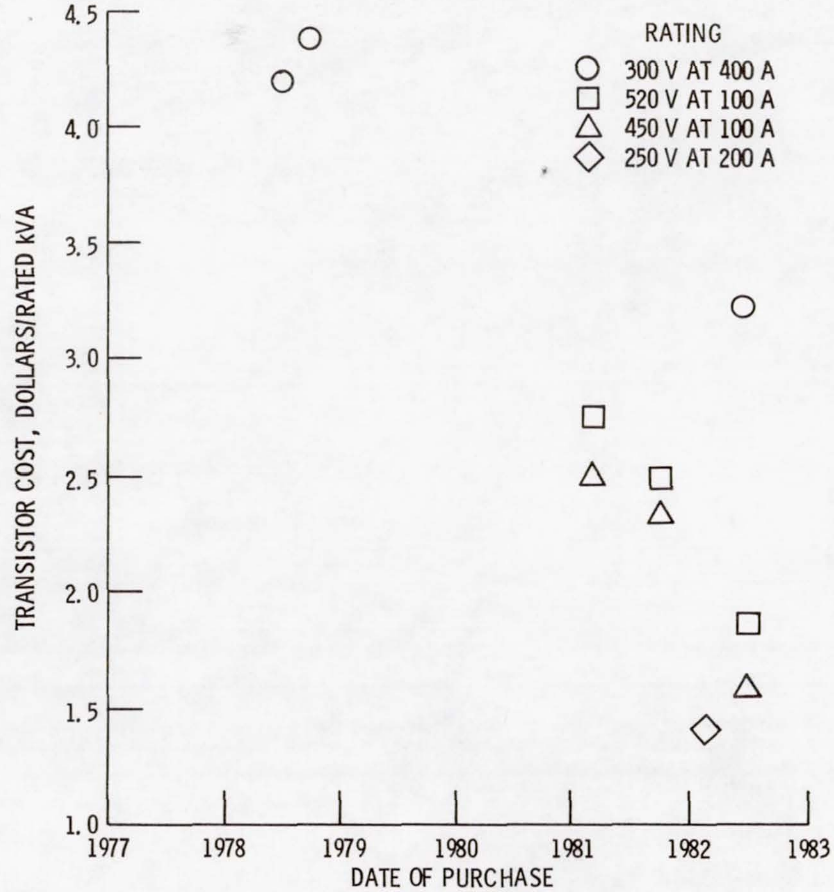

Figure 6. - Power transistor costs.

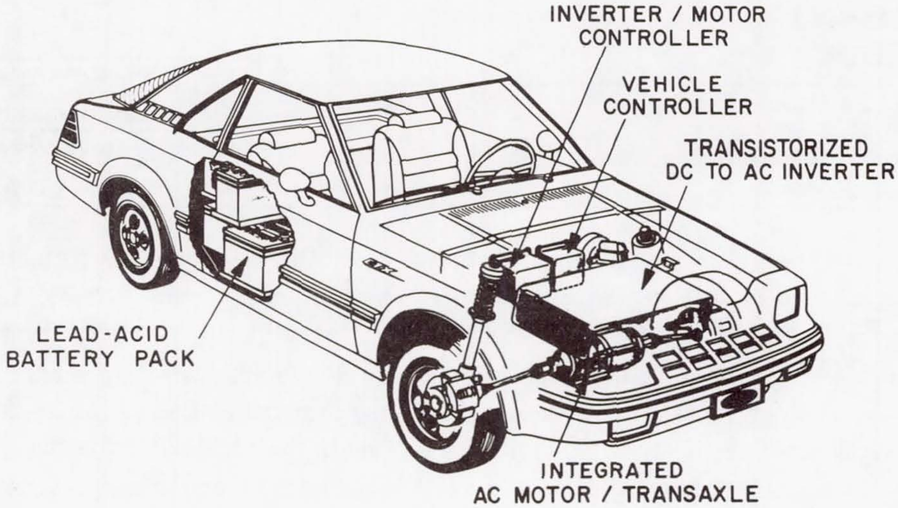

Figure 7. - Integrated alternating current powertrain.

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