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STEADY-STATE AND DYNAMIC EVALUATION OF THE ELECTRIC PROPULSION SYSTEM TEST BED VEHICLE ON A ROAD LOAD SIMULATOR

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E-1745

SUMMARY

In support of the DOE's Electric and Hybrid Vehicle Program, NASA's Lewis Research Center has the responsibility for propulsion system technology development. As part of this program the propulsion system from Lewis' electric propulsion system test bed vehicle was evaluated on the road load simulator (RLS). Track tests had previously been conducted on the vehicle.

The electric vehicle was built from components representative of 1976 technology, including a series-wound dc motor and a commercially available silicon-controlled rectifier (SCR) chopper type of controller. An 84-V battery pack was used with the system in the vehicle. A large motor-generator battery simulator was used in all of the RLS tests.

Steady-state tests were conducted over a wide range of differential outputs and vehicle speeds. Efficiencies of the system and of the individual components were mapped. The maximum system efficiency measured was 67 percent at 64-km/h (40-mph) vehicle speed and 113-N-m (1000-lb-in) differential torque. The effects of motor temperature on motor efficiency and of battery voltage on motor and controller efficiencies were evaluated.

Dynamic tests were also conducted on the system by running it over the SAE J227a B and C driving schedules. The energy efficiency over schedule B was 55 percent; that over schedule C was 58 percent. Over schedule B the total energy taken from the battery was 155 Wh/km (249 Wh/mile). Over schedule C, 178 Wh/km (287 Wh/mile) was removed from the battery.

INTRODUCTION

NASA's Lewis Research Center is responsible for the propulsion system technology development in support of DOE's Electric and Hybrid Vehicle Program. The electric propulsion system test bed vehicle (fig. 1) was built to evaluate electric vehicle propulsion systems and components on the road. The vehicle was used to determine the rolling resistance of a set of typical radial tires and to perform comparisons between road load simulator test and track test results.

The vehicle also serves as a baseline system representing 1976 electric vehicle technology with which to compare systems and components developed under the Electric and Hybrid Vehicle Program. The performance of the propulsion system was established by a combination of track and dynamometer tests.

Overall vehicle performance tests were conducted at the Transportation Research Center of Ohio. Those tests, reported in reference 1, included range at constant speed and over driving cycles, maximum acceleration, and maximum gradeability. Road power and energy consumption were determined from coastdown tests. Tire rolling resistance was determined on the track by towing tests. The propulsion system was removed from the vehicle and was installed on the road load simulator (RLS) test facility. Component and system efficiencies determined on the RLS for both steady-state and dynamic conditions are the subject of this report.

SYSTEM DESCRIPTION

The electric test vehicle was built by the Electric Vehicle Engineering Company of Boston, Massachusetts, using parts from existing vehicles where possible. The propulsion system, with a series dc motor and chopper controller, is typical of that used in electric vehicles made in 1976.

Motor

The motor (fig. 2) was manufactured by Northwestern Electric Company of Chicago, Illinois. It is a four-pole machine with a series field winding. Rating data and dimensions are given in table I. The motor is force ventilated from an external fan, with 0.118 m^3/sec (250 ft^3/min) of air required. The continuous-duty output power rating is 14.9 kW (20 hp). The motor had been thoroughly tested by the Lewis Research Center to study the effects of chopper control on dc motor performance. The results of this study are reported in reference 2.

Controller

The controller, a Pulsomatic Mark 10 furnished by Cableform Incorporated of Troy, Virginia, provides infinitely variable control of a dc series-wound motor. This is done by interrupting the battery voltage to the motor by a silicon-controlled rectifier (SCR) switch in a repetitive manner such that the motor receives a series of rapid voltage pulses. Since the pulse width is proportional to the throttle position, the average motor voltage is linear with throttle position. At low throttle positions the controller furnishes a 1-msec-wide "on" pulse. As the throttle demand increases, the time between pulses (or "off" period) becomes shorter and the on pulse becomes longer until both the on pulse and the off period equal 2 msec each, the frequency being 250 Hz. Further throttle increases result in longer on pulses, and the off periods become shorter until the off periods are reduced to 1 msec. Still further throttle increases cause the off period to become zero and the motor is directly connected to the battery. The controller consists of three separate units described as follows:

(1) Speed control unit. This box contains the control electronics of the controller and determines the output pulse frequency and duration. An input shaft protruding from this unit is attached to the throttle linkage.

(2) Power unit. This unit houses the SCR power switch that controls the power applied to the motor. Aluminum extrusions form heat sinks for the SCR's.

(3) Motor unit. The motor unit contains all of the components associated with power conditioning for the motor such as the forward and reverse contactors and free-wheeling diode. The heavy aluminum case provides diode heat sinking.

A simplified diagram of the controller is shown in figure 3.

Differential

The motor is coupled directly to the differential as there is no transmission in the vehicle. The differential ratio is 5.17. An alternative differential supplied with the vehicle has a ratio of 7.83.

TEST APPARATUS

Road Load Simulator

The road load simulator provides tire resistance, aerodynamic drag, inertial loads, and grade loads that duplicate the loads a propulsion system would see if installed in a vehicle on the road. The RLS uses a hydroviscous absorber to provide the road losses due to grade, rolling resistance, and aerodynamic drag. In addition a hydroviscous clutch and a 150-hp ac motor provide motoring capability. The absorber and clutch are composed of a set of disks that are free to move axially and are immersed in hydraulic oil (fig. 4). The oil provides viscous coupling that varies with the controlled thickness of the oil film between the disks. Viscous coupling is increased by forcing the disk pack closer together. The spacing between the disks is controlled by a hydraulic closed-loop control system. Inertial loads due to acceleration are supplied by flywheels that can be easily removed or added to the shaft. A total of nine flywheels can simulate vehicle weights of 450 to 3400 kg (1000 to 7500 lb) in 57-kg (125-lb) increments. A closed-loop speed control system positions the throttle of the test system to maintain a commanded speed. A programmable function generator provides the speed command signal. A complete description of the RLS facility is presented in reference 3.

Battery Simulator

A battery simulator (described in ref. 3) was developed to provide a stable power source for conducting steady-state performance tests on systems and components. The battery simulator, which consists of a large motor-generator set with a large capacitive filter, eliminates the normal variations in supply voltage from batteries caused by state of charge and age. The battery simulator simplifies the determination of supply voltage effects on the operation of the motor and controller.

Instrumentation and Data Acquisition System

Power into and out of each component of the propulsion system was measured. These measurement locations are identified in figure 5. The power measurements consisted of currents and voltages into wide-band wattmeters for electrical inputs and outputs and of torque and speed measurements for mechanical components. Current was measured with coaxial current shunts. In addition, temperature was measured in all components. Two thermocouples attached to the motor field windings were used to indicate motor temperature. Transmission temperature was measured by a thermocouple inserted through the oil drain.

The accuracy of the torque measurements is estimated to be ± 0.25 percent of full scale and that of the wattmeters, ± 0.4 percent of full scale. All measurements were recorded on the Lewis Research Center's central data system, where data are conditioned, converted to engineering units, and made available either for plotting on many of the Center's computer terminals or in batch processed listings.

TEST PROCEDURE

Steady-State Tests

Steady-state tests were conducted at the conditions of torque and speed shown in figure 6. These conditions represent the entire safe operational region of the motor. Component efficiencies were measured at each of the test conditions shown. In addition, effects of temperature on differential and motor efficiencies and effects of battery voltage on both motor and controller efficiencies were investigated at the conditions shown in the figure. The battery simulator was used for all steady-state tests. The battery voltage was set at 84 V. The battery voltage effects tests were repeated with battery voltages of 74, 64, and 54 V.

To present consistent results, all steady-state test points, with the exception of the temperature effects tests, were taken with a motor temperature of 49° C (120° F). Each condition of torque and speed was held long enough to take at least three readings of all measured variables. At each condition the motor temperature continued to increase so that each consecutive reading was at a higher value than the preceding reading.

Transient Tests

For transient tests the RLS was programmed to simulate conditions observed with the actual vehicle when it was tested at the Transportation Research Center of Ohio (ref. 1).

Aerodynamic drag was determined in coastdown tests on the vehicle by using the procedure developed by White and Korst (ref. 4). Ten coastdowns were conducted, five in each direction on the tracks. The average value of the aerodynamic coefficient times the vehicle cross-sectional area (C_dA) for 10 trials was 0.421 m^2 (4.53 ft^2). The average value for each of the five pairs of runs (one in each direction) varied from 0.388 to 0.454 m^2 (4.18 to 4.89 ft^2).

The tire rolling resistance was determined from towing tests. The procedure for conducting the towing tests is presented in detail in reference 5. The value used for tire resistance, which includes bearing friction and brake drag, was 0.0135 kilogram per kilogram of vehicle weight.

SAE J227a Driving Cycles

The performance characteristics of the propulsion system were determined over SAE J227a driving schedules B and C. The vehicle did not have the acceleration capability to meet the schedule D velocity profile. The desired driving schedule was programmed into the function generator of the speed control. A data point was taken every second during the cycle.

TEST RESULTS

Steady-State Tests

The steady-state test results consist of the measured efficiencies of the entire propulsion system and its components over a range of operating conditions. The efficiencies are presented as a function of differential output speed for a number of differential output torques. Superimposed on each plot are the efficiencies measured on the RLS at the vehicle road load torques as determined by the track test results.

Efficiency results. - System and motor efficiencies are shown in figure 7 as a function of vehicle speed for lines of constant differential torque. The controller efficiency, as shown in figure 8(a), increased from about 85 percent at 8 km/h (5 mph) to 94 percent at 64 km/h (40 mph) and was not greatly affected by torque. (Variations were within instrumentation error.) The differential efficiency was relatively independent of vehicle speed, as shown in figure 8(b).

Temperature effects. - Temperature effects on the motor and differential efficiencies for four selected conditions of speed and torque are shown in figure 9. For a temperature change from 24° to 60° C (75° to 140° F) the maximum decrease in efficiency was about 2-1/2 percent (fig. 9(a)). The final temperature the motor reached at 56-N-m (500-lb-in) torque was 39° C (102° F). The differential became more efficient when the lubricant heated and became less viscous. An 8 percent increase in efficiency is shown in figure 10 as the differential temperature increased from 24° to 88° C (75° to 190° F) for one of the four selected speed-torque combinations.

Battery state-of-charge effects. - Tests were conducted at two vehicle speeds, 16.1 and 48.3 km/h (10 and 30 mph) to determine the effect of a reduced battery voltage on the efficiency of both the motor and the controller. In both cases the efficiency either increased slightly or remained relatively constant as the battery voltage dropped, as shown in figures 11(a) and (b) for the controller and motor, respectively. As the controller chopper duty cycle increased to compensate for the reduced input voltage, the controller on time increased. The maximum efficiency for the controller and the motor probably occurred when the duty cycle was 100 percent (chopper always on).

Transient Tests

The propulsion system was tested over the B and C driving schedules of the SAE J227a test procedure. Selected propulsion system variables for these driving schedules are plotted in figure 12. The battery power and differential power, which represent the input and output of the system are presented in figure 13. Schedule B results are shown in figure 13(a) and schedule C results, in figure 13(b). The area between the battery power and differential power curves equals the energy losses of the system. If the power curves are integrated with respect to time over the cycle, the energy delivered from the battery and from the differential can be obtained.

The ratio of differential energy to battery energy is the energy efficiency of the system for that driving cycle. The energy efficiency for the schedule B driving cycle was determined to be 55 percent and that for the schedule C driving cycle, 58 percent. Total energy removed from the battery over schedule B was 155 Wh/km (249 Wh/mile). Over schedule C, 178 Wh/km (287 Wh/mile) was taken from the battery.

SUMMARY OF RESULTS

The electric test vehicle was tested on the road load simulator to examine its steady-state and dynamic performance.

Steady-state tests conducted over a range of output torques and speeds determined that the maximum system efficiency was 67 percent at a differential torque of 113 N-M (1000 lb-in) and a vehicle speed of 64 km/h (40 mph). System efficiency was dominated by the motor efficiency, which was a maximum of 80 percent at 113-N-M (1000-lb-in) differential torque and 64-km/h (40-mph) vehicle speed.

The differential efficiency was a maximum at the highest torque tested, 565 N-M (5000 lb-in). This is to be expected since gear torque losses do not increase linearly with applied torque but rather are dominated by fixed losses. The efficiency was a weak function of vehicle speed. The efficiency of the system could be increased by using a spiral bevel ring-and-pinion gear on the differential instead of the hypoid gear.

The motor efficiency was not greatly affected by motor temperature changes. The maximum change was a 2.5-percent drop in motor efficiency as the motor temperature changed by 40 deg C (72 deg F) at a vehicle speed of 40 km/h (25 mph) and a differential torque of 56 N-m (500 lb-in).

The effect of reducing the battery voltage, as would occur when the battery discharges, was to increase both motor efficiency and controller efficiency. The controller efficiency increased by about 4 percent as the battery voltage was dropped from 84 to 54 V at a vehicle speed of 48 km/h (30 mph). The effect was not dependent on torque at this speed. The maximum effect of battery voltage drop on the motor was at 16 km/h (10 mph) and 56-N-m (500-lb-in) differential torque. Under these conditions the motor efficiency increased 5.5 percent as the battery voltage was decreased from 84 to 54 V.

The efficiency of the system was determined as the propulsion system was operated over SAE J227a driving schedules B and C. The energy efficiency for the system was 55 percent over schedule B and 58 percent over schedule C.

For driving schedule B total energy removed from the battery was 155 Wh/km (249 Wh/mile). Over driving schedule C the system removed 178 Wh/km (287 Wh/mile) from the battery.

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5. Dustin, M. O.; and Slavik, R. J.: Rolling Resistance of Electric Vehicle Tires from Track Tests. DOE/NASA/51044-24, NASA TM-82836, 1982.

TABLE I. - MOTOR DATA

Manufacturer	Northwestern Electric Company
Model number	250-100-0033 A
Serial number	20631-DB
Rated continuous output power, kW (hp)	14.9(20)
Rated dc voltage, V	84
Rated dc current, A	210
Rated shaft speed, rad/sec (rpm)	419(4000)
Insulation class	F
Maximum ambient temperature, °C (°F)	40(72)
Average airgap length, mm (in.)	1.02(0.040)
Stator outside diameter, m (in.)	0.31(12.25)
Overall frame diameter, m (in.)	0.36(14.0)
Overall frame length, m (in.)	0.46(18.1)
Mass, kg (lbm)	84.8(187)
Armature winding resistance at 25° C (77° F), ohms	0.011
Series field winding resistance at 25° C (77°F), ohms	0.008
Preferred direction of rotation, viewed from antidrive end	Clockwise

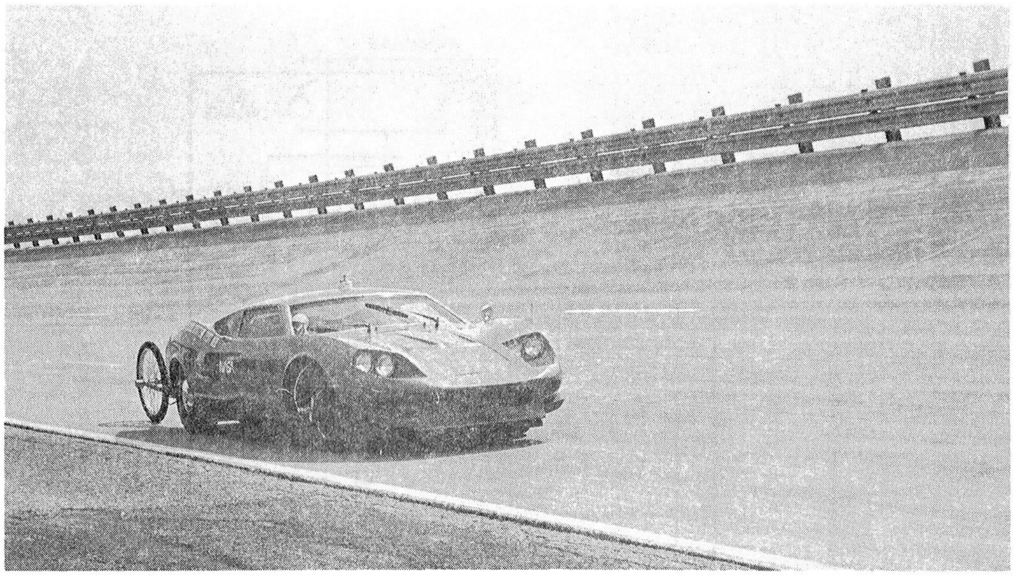

Figure 1. - Electric propulsion system test vehicle.

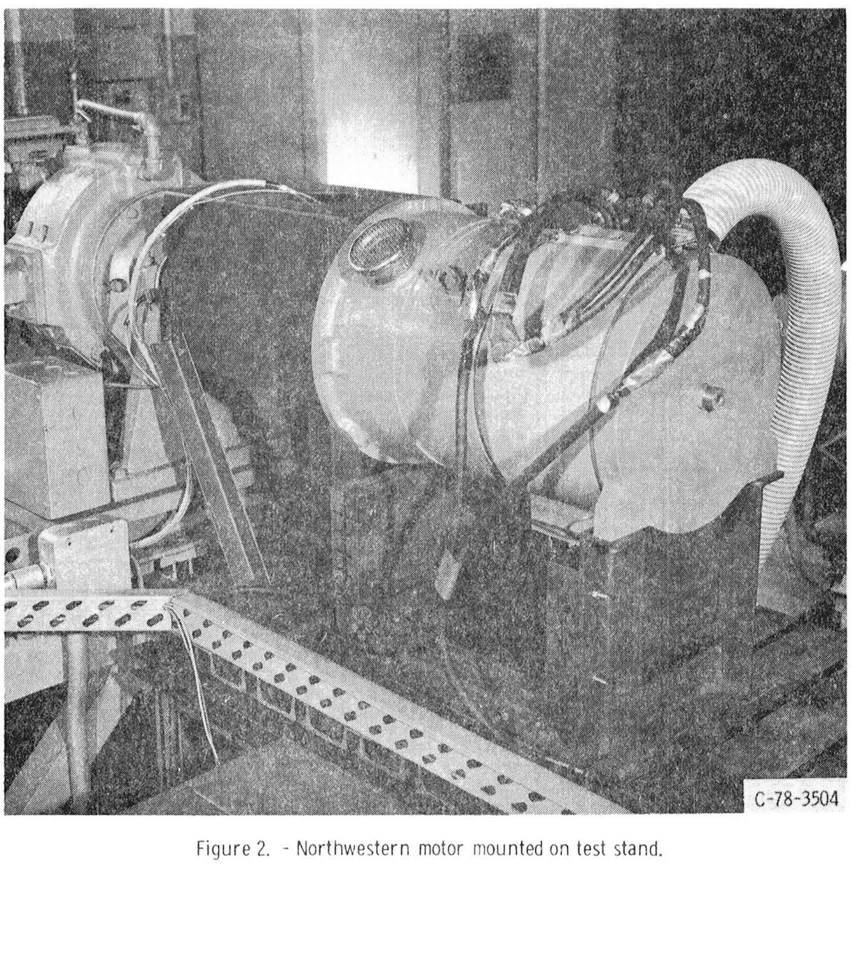

Figure 2. - Northwestern motor mounted on test stand.

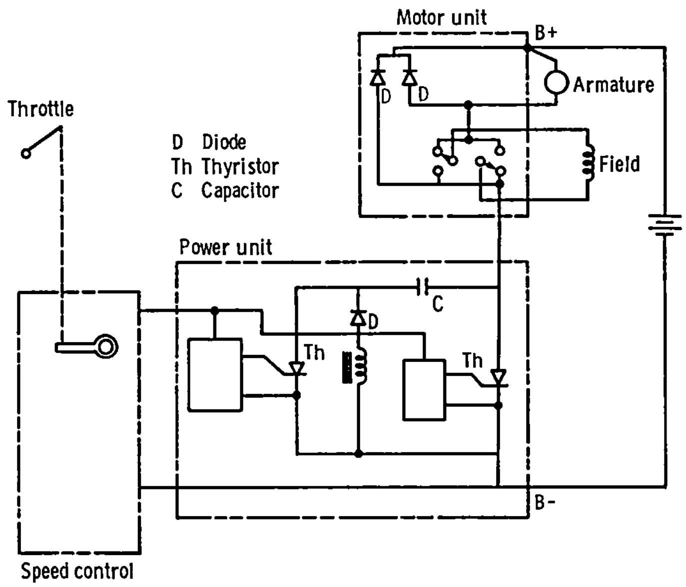

Figure 3. - Schematic diagram of controller.

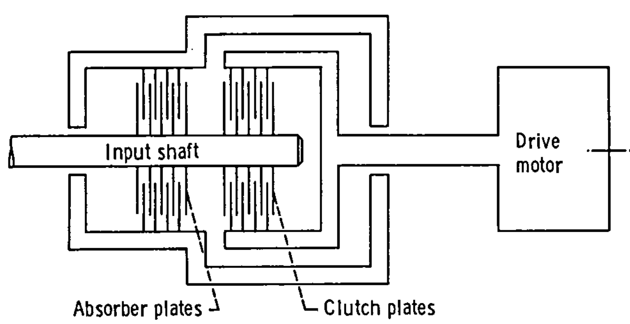

Figure 4. - Absorber and clutch.

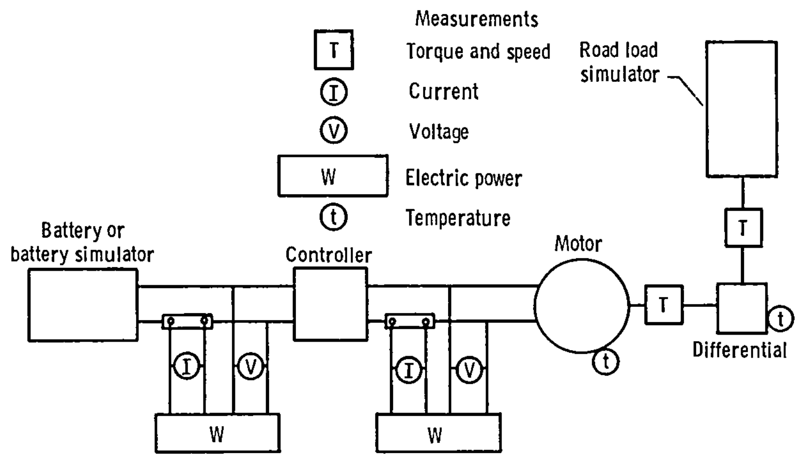

Figure 5. - Instrumentation for road load simulator tests.

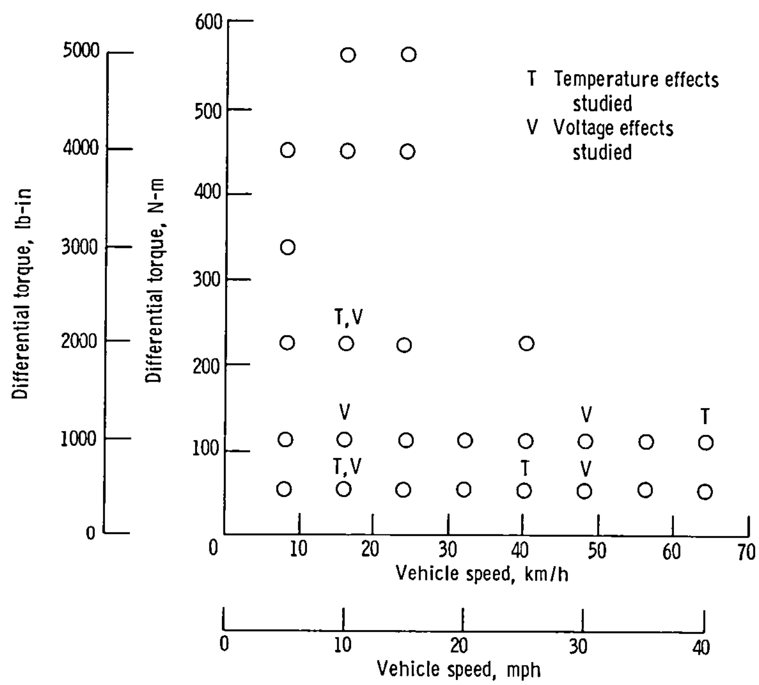

Figure 6. - Speed-torque map showing test conditions for steady-state performance.

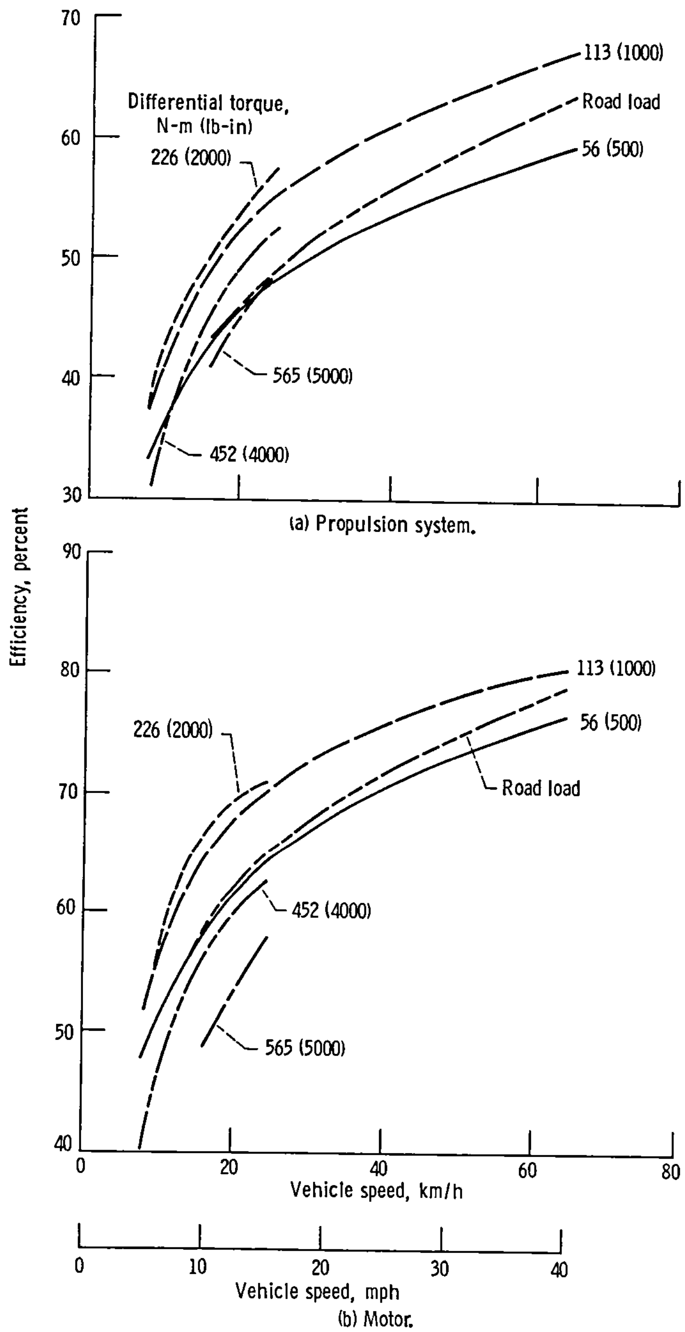

Figure 7. - Propulsion system and motor efficiencies as functions of vehicle speed on lines of constant differential torque.

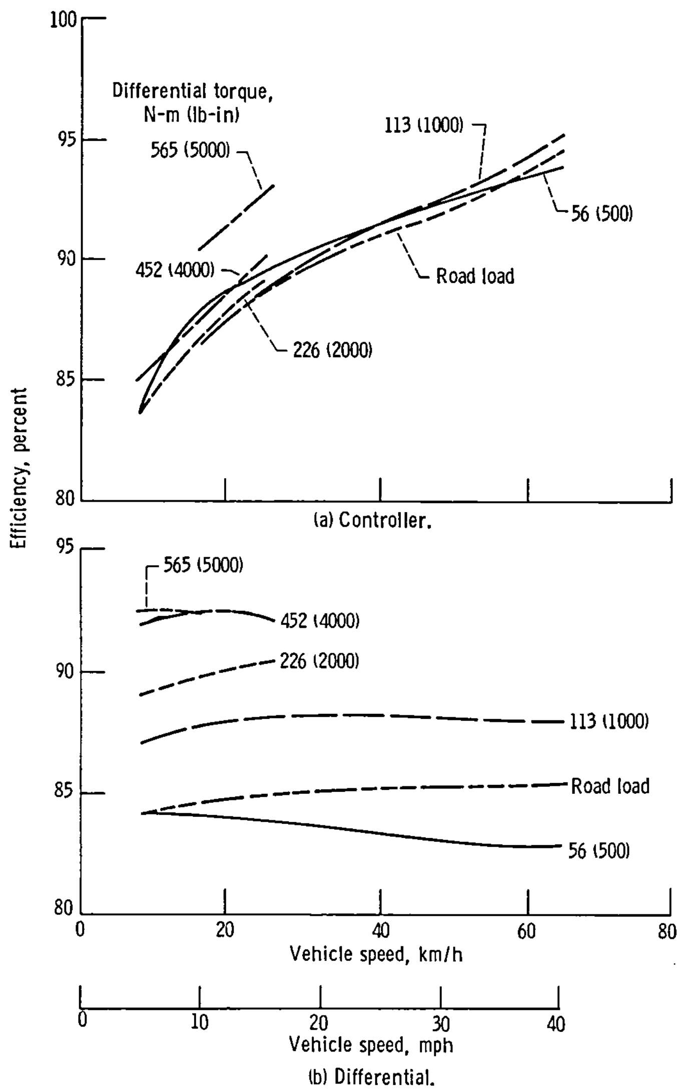

Figure 8. - Controller and differential efficiencies as functions of vehicle speed on lines of constant differential torque.

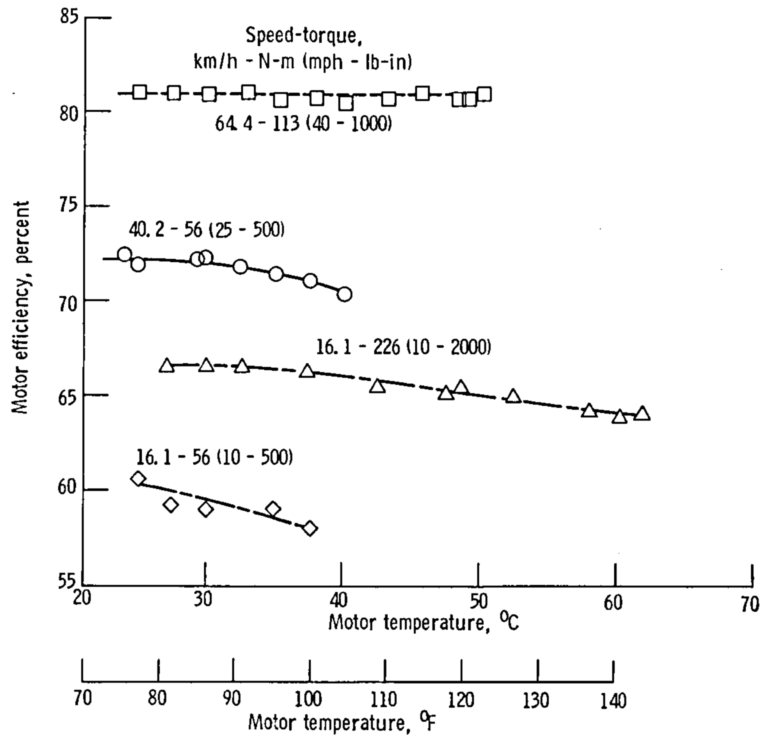

Figure 9. - Motor efficiency as a function of motor temperature on lines of constant differential torque and vehicle speed.

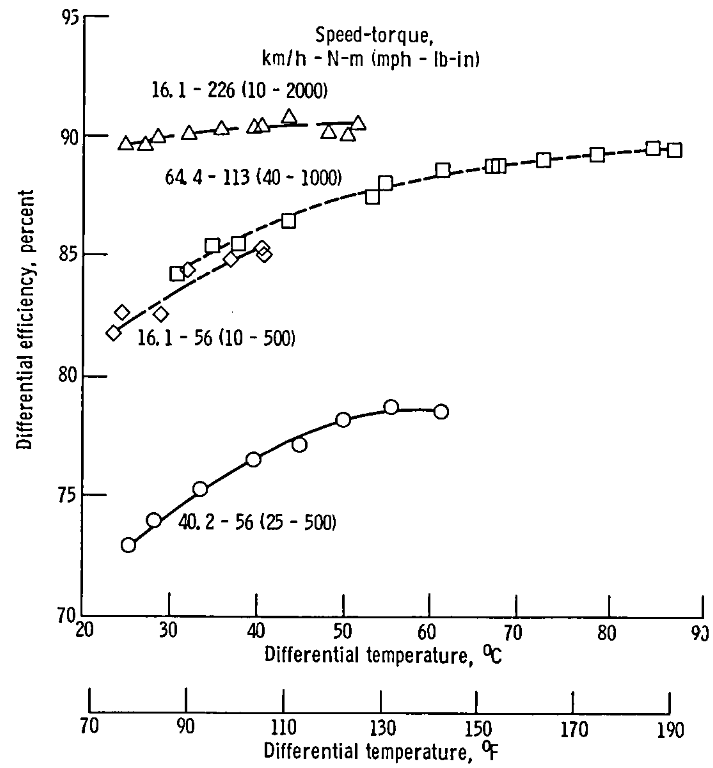

Figure 10. - Differential efficiency as a function of differential temperature on lines of constant differential torque and vehicle speed.

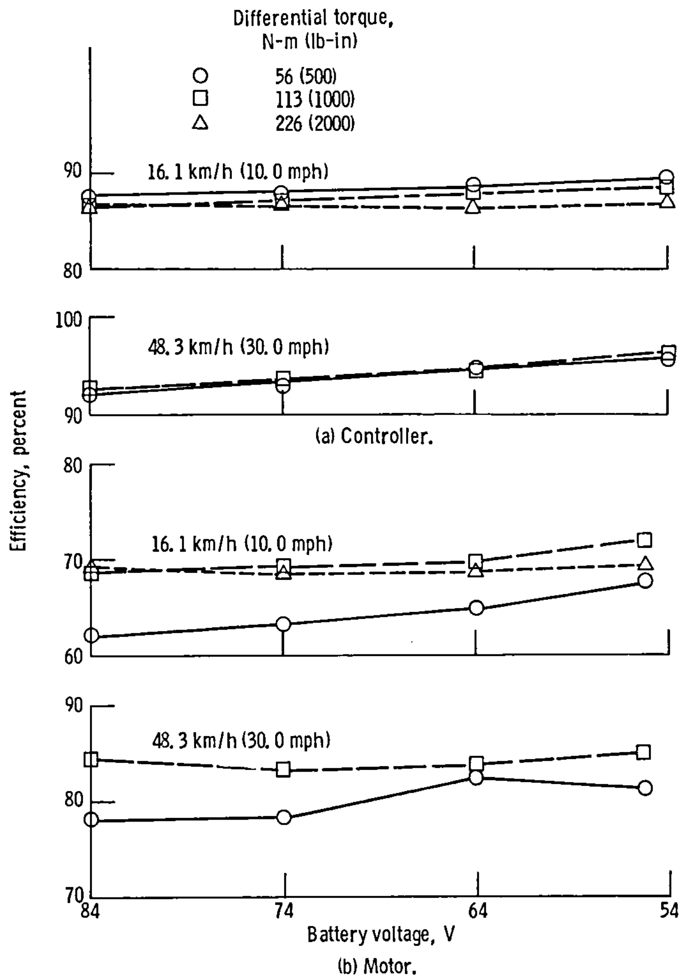

Figure 11. - Controller and motor efficiencies as functions of battery voltage. Battery power supplied by battery simulator.

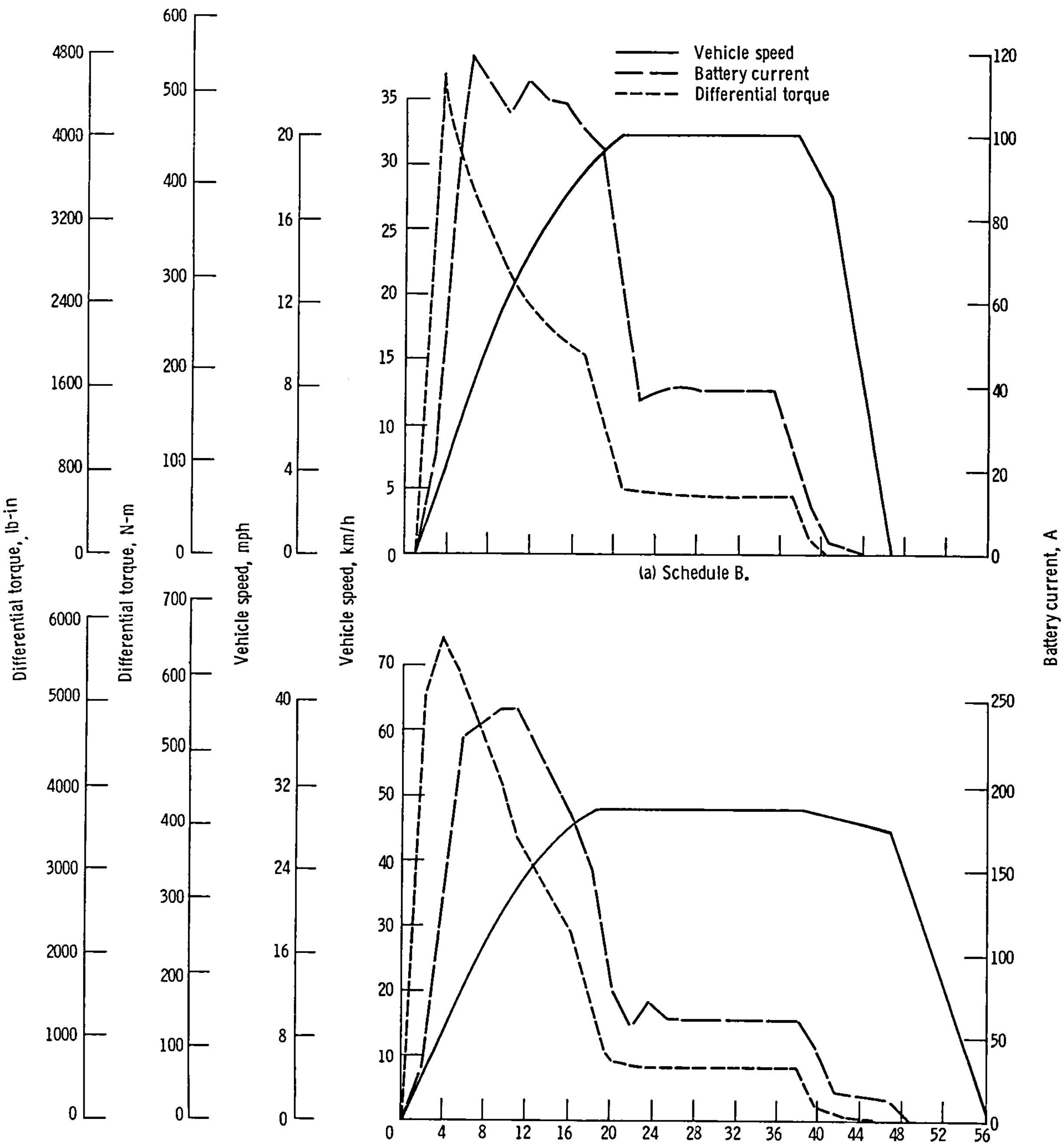

Figure 12. - Several system variables plotted as functions of time as system is driven over J227a schedules B and C.

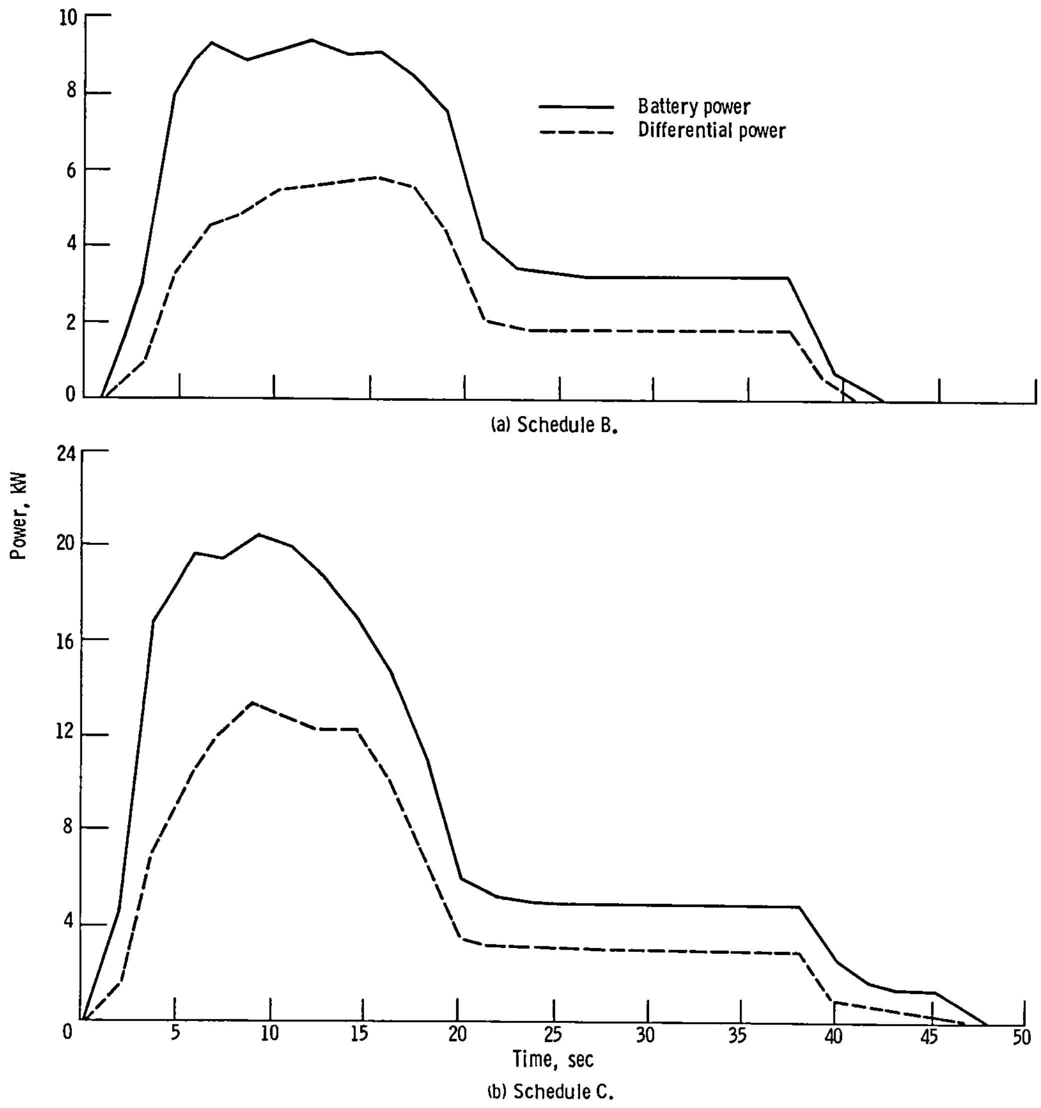

Figure 13. - Battery power and differential power as functions of time for SAE J227a driving schedules B and C.

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16. Abstract

The propulsion system of the Lewis Research Center's electric propulsion system test bed vehicle was tested on the road load simulator under the DOE Electric and Hybrid Vehicle Program. This propulsion system, consisting of a series-wound dc motor controlled by an infinitely variable SCR chopper and an 84-V battery pack, is typical of those used in electric vehicles made in 1976. Tests conducted on this vehicle will serve as a baseline with which to compare systems and components developed under the DOE program. Steady-state tests were conducted over a wide range of differential output torques and vehicle speeds. Efficiencies of all of the components were determined. Effects of temperature and voltage variations on the motor and the effect of voltage changes on the controller were examined. Energy consumption and energy efficiency for the system were determined over the B and C driving schedules of the SAE J227a test procedure.

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