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SIMULATION OF AN URBAN BATTERY BUS VEHICLE

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16. Abstract

This report describes the computer simulation of a battery-powered bus as it traverses an arbitrary mission profile of specified acceleration, roadway grade, and headwind. The battery-bus system components comprise a DC shunt motor, solid-state power conditioning unit with regeneration capability, and a battery source consisting of a multi-unit lead acid battery. The computer model determines vehicle tractive effort and power consumption and computes actual vehicle speed for a given mission profile. The program output data is tabulated in a form which allows easy recognition of the various operational modes and power-limited regimes.

The computer model uses a "modularization" format which facilitates the simulation of alternate propulsion systems involving the interchange of one system component for another. The model is applied to simulate the propulsion characteristics of a typical bus operating over a specified drive cycle. The results of this study demonstrate the applicability of the battery bus model for predicting bus propulsion characteristics under simulated drive conditions.

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PREFACE

This report describes a computer model of a battery-powered bus developed at the Transportation Systems Center to simulate the power/propulsion characteristics of an urban battery-bus. This model comprises the third in a series of models being developed at TSC to simulate different types of bus propulsion systems. These simulation models provide the capability for rapid evaluation of bus performance through the comparison of simulated bus performance with data obtained from engineering tests. The work conducted in this area is sponsored by the Urban Mass Transportation Administration and is part of a larger effort concerned with the demonstration and test evaluation of advanced bus propulsion concepts.

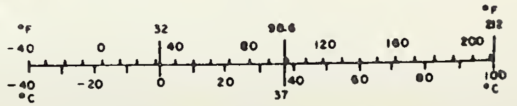
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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EXECUTIVE SUMMARY

This report describes a computer model of a battery-powered bus developed at the Transportation Systems Center to simulate power/propulsion characteristics of an urban battery-bus. This model comprises the third in a series of models being developed at TSC to simulate different types of bus propulsion systems. The work conducted in this area is sponsored by the Urban Mass Transportation Administration as part of a larger effort concerned with the demonstration and test evaluation of advanced bus propulsion concepts. The computer models developed by TSC provide the capability for rapid evaluation of bus performances and the comparison of simulated bus performance with that obtained from engineering tests. Such studies give important insights into the limitations inherent in the different propulsion systems and permit rapid assessments to be made of the future practicality of such systems.

Current efforts in other areas of bus propulsion simulation include the (1) cam-controlled trolley bus, (2) pure flywheel bus, (3) flywheel/battery hybrid bus, and (4) the flywheel/diesel hybrid bus with electric transmission. Studies have already been completed on the diesel engine model and the results documented in the reports, "Flywheel/Diesel Hybrid Power Drive: Urban Bus Vehicle Simulation," May 1978 by Larson and Zuckerberg;[1] "Diesel Bus Performance Simulation Program," April 1979 by Larson and Zuckerberg.[2] Upon the completion of these simulation studies, TSC will possess the capability of simulating a wide range of bus propulsion systems. Such capability should prove extremely useful in future evaluations and analyses of urban bus systems.

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[1] Larson, G.S. and H. Zuckerberg, Flywheel/Diesel Hybrid Power Drive: Urban Bus Vehicle Simulation, U.S. Department of Transportation, Urban Mass Transportation Administration, Washington DC, Final Report, UMTA-MA-06-0044-78-1, May 1978.

[2] Larson G. and H. Zuckerberg, Diesel Bus Performance Simulation Program, U.S. Department of Transportation, Urban Mass Transportation Administration, Washington DC, Final Report, UMTA-MA-06-0044-79-1, April 1979.

1. INTRODUCTION

1.1 BACKGROUND DISCUSSION

The development of battery-powered vehicles has progressed rapidly with the aid of advances in battery and lightweight vehicle technology. New improvements in vehicle design, battery construction, and motor controllers have resulted in reduced vehicle weight and drag as well as increased vehicle speed and range capabilities. While the present performance and economy of battery-powered vehicles cannot match that of internal combustion-powered vehicles, the trend towards minimizing environmental pollution increases the desirability of electric-powered vehicles. When compared with conventional vehicles, electric vehicles are extremely quiet and waste less energy at idle.

Research and development are now being conducted on numerous electric drive configurations. These include propulsion systems using flywheels for energy storage and hybrid systems using both batteries and flywheels for energy storage. A major program in bus propulsion technology is presently being sponsored jointly by the U.S. Department of Transportation and the U.S. Department of Energy. This program calls for the test evaluation and demonstration of two engineering prototype vehicles, one propelled by flywheel only, and the second propelled by a diesel/flywheel hybrid. The General Electric Company and the Garrett Airesearch Corporation are the prime contractors for these respective vehicle-propulsion technology programs.

The Transportation Systems Center at Cambridge, Massachusetts is conducting simulation studies of different bus propulsion systems anticipated in future urban bus transport systems. This report, which describes the simulation of a battery-powered bus, comprises one phase of this study. Two TSC reports have been published to date by Larson and Zuckerberg: "Flywheel/Diesel Hybrid Power Drive: Urban Bus Vehicle Simulation," Final Report, May 1978 and "Diesel Bus Performance Simulation Program," Final Report, April 1979. Additional efforts are in progress now to model other bus propulsion systems, including the cam-controlled trolley bus, battery/flywheel hybrid, and the flywheel/diesel hybrid. These models will be used eventually by both government and industry to aid in the preliminary assessment of the comparative performances of the different bus propulsion systems.

This report discusses the computer model developed to simulate a battery bus as it travels over a prescribed speed-time mission profile. The model is constructed of separate functional units referred to as a modularized format to simplify the logic in the program calculations as well as to make it easily adaptable to changes in the propulsion system components. The flexibility achieved through the use of this format increases the usefulness of the battery bus model both as a design tool and as an instrument for evaluating alternate types of bus propulsion systems.

1.2 SIMULATION DESCRIPTION

The computer program described in this report models a battery-powered vehicle as it traverses a defined mission profile of acceleration, cruising speed, roadway grade, and headwind. The vehicle acceleration (deceleration) and cruise velocity-versus-time requirements determine the propulsion power required by the vehicle. For a given mission profile, the vehicle power consumption is computed as output data. The power-limiting regions and system losses, which characterize the motor and battery, are easily identifiable from the output data.

The program describes a propulsion system comprising a battery source, dc traction motor, and a power conditioning unit (PCU) for the control of motor power. (See Figure 1-1.) A separately excited dc shunt motor was selected to be modeled because it gives relatively constant tractive effort while allowing easy speed control. Motor speed is voltage-controlled except at high speeds where field-weakening is required.

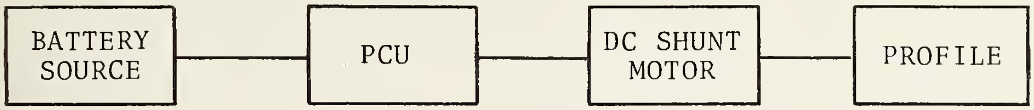

FIGURE 1-1. BLOCK DIAGRAM OF BATTERY BUS PROPULSION SYSTEM

The computer program utilizes a format which separates into individual subroutines those functions which relate to a particular system component. A description of this format is given in the next section.

1.3 MODULARIZED PROGRAM FORMAT

The modular program format simplifies the program logic and facilitates the substitution of alternate system components in the main program with a minimum of effort. This can be particularly advantageous in systems applications requiring calculations of vehicle performance with different types of motors and power conditioners.

The quantity which provides continuity throughout the program is power flow. Beginning with the power required to propel the vehicle, the power demand at each stage in the propulsion system is computed by summing power losses in successive system components. The total power supplied by the source, (battery bank), is determined in the final stage of calculations. Once this is known, the system power characteristics are defined for one instant in time in the mission profile. Successive calculations at later time intervals yield the complete power (demand) characteristics for one cycle in the mission profile.

The basic program consists of a main program plus four subroutines which perform specific calculations as required by the system components. The MAIN program provides the continuity for the ongoing successive calculations as well as program logic and CALL statements. A simplified flowchart illustrating the modularized concept is shown in Figure 1-2. The program execution begins with the MAIN program, followed by the subroutines PROF, MOTOR, PCU, and BATT, which describe the mission profile, motor, and battery respectively. The quantities at the left give the power required at each stage in the propulsion system; the quantities at the right indicate the input-output parameters associated with each subroutine. A more complete flowchart appears later in the report.

The subroutines contain the operating characteristics of each system component. Subroutine PROF computes the mission profile at successive time iterations. Included in the profile are vehicle acceleration and speed, position of the vehicle, roadway grade, and encountered headwind.

The subroutine MOTOR receives the request for the required tractive effort at a specified vehicle speed and computes the motor losses and total electrical input power required by the traction motor. The motor terminal voltage (VOLT) and armature current (AMP) are determined and appear as output quantities of subroutine MOTOR.

The subroutine PCU computes the power loss in the SCR chopper circuit and determines the total power required by the battery (minus the auxiliary power).

The subroutine BATT models the charge and discharge characteristics of a water-cooled lead-acid battery*. The modeling equations assume a <u>constant</u> discharge-charge rate, with the battery capacity being equal to that obtained at the <u>constant</u> discharge rate.[1] The battery current required to satisfy the output power demands is computed via the Newton-Raphson method. The battery is assumed to be discharged when it has delivered 60 percent of its rated (five hour) capacity.

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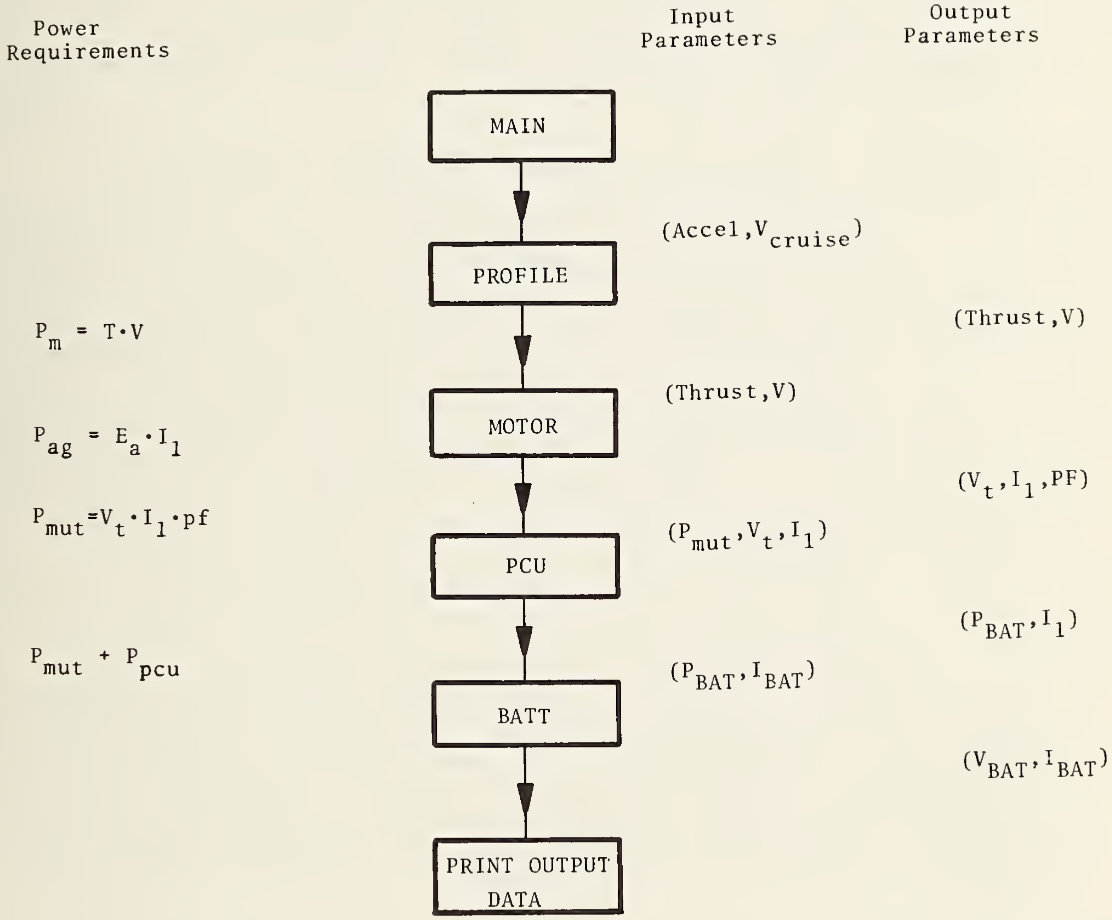
*This battery is manufactured in West Germany.



KEY

P_m = Mechanical Power
P_{ag} = Airgap Power
P_{mut} = Motor Input Power
P_{pcu} = PCU Input Power
P_{BAT} = Battery Output Power

FIGURE 1-2. SIMPLIFIED FLOWCHART ILLUSTRATING MODULARIZATION PROGRAM FORMAT

1.4 SIMULATION APPROACH

The computer program calculates the dynamic behavior of the vehicle as it travels over the prescribed profile route. Using as input the cruise velocity, the specified acceleration and deceleration plus their respective jerk-rate limits, and the distance between route stops, the program computes the speed-time profile at successive instants in time. This is followed by the calculation of the drive system powers, e.g., propulsion power, system power losses, and required battery power. The battery power and discharge current are summed (over time) to yield the total instantaneous energy and charge extracted from the battery.

The computer program includes regeneration in which the kinetic energy of the moving vehicle is converted into electrical power delivered to the battery. Constraints are introduced to limit the amount of regenerated power which the battery can accept. The increase in drive-cycle efficiency due to regeneration is easily determined from the computer output data.

The power control unit (PCU) is modeled as a chopper-flyback circuit with the capability of power transfer in either direction between source and load. Power transfer is assumed to take place irrespective of the voltage levels of the source and load components (i.e., power transfer can include a voltage step-up or step-down).

The battery source is modeled by an equivalent circuit comprising a fixed resistance (temperature dependent) and a load dependent resistance which is a function of the discharge current level and battery capacity. The battery capacity is expressed as a function of discharge current. Separate models are used to describe the battery discharge and charge characteristics. The models include the loss associated with the reduction in the charge delivered to the battery compared with that delivered by battery to load.

1.5 PERFORMANCE CRITERIA FOR ELECTRIC-BATTERY DRIVE

The computer program can be used to optimize the system components and to compute the battery, PCU, and motor losses for different drive conditions. This information is useful for establishing performance criteria and for sizing the various system components.

The computer program is designed to simulate different drive cycles and thereby study effects associated with the type of drive cycle as it relates to propulsion performance. The so-called A, B, and C drive cycles which describe idealized speed-time profiles are used to establish baseline criteria for typical mission profiles. The program has the additional capability of simulating arbitrary drive cycles which conform to prescribed cruise velocity and acceleration (deceleration) conditions.

Two factors are important in determining drive efficiency; (1) the proper rating of the major system components, and (2) the ability of the battery supply to meet the required energy and power demands. The ratings selected for the major components determine how heavily they are loaded in use. Too low a rating results in overloading and less efficient operation (higher power losses). Too large a rating introduces a penalty associated with increased size, weight, and cost of the system. The specifications of the battery size (capacity) is dictated by the ratings of commercially available batteries. The significant criteria, in this case, is battery energy density (energy/weight) and the ability of the battery to deliver large peak power. The total distance which the vehicle traverses between periods of battery recharging will be determined by the rating of the battery bank supply.

2. BASELINE SYSTEM: COMPONENTS AND MODES OF OPERATION

2.1 CONFIGURATION OF MAJOR COMPONENTS

The battery vehicle computer program simulates the power and propulsion characteristics of any generalized vehicle powered by a dc source. For purposes of analysis, a set of baseline system parameters were used in the simulation model. The values of these parameters which define the battery source, power controller, and dc traction motor, were chosen to be compatible with system components presently available. They do not represent the ultimate choice in terms of overall system efficiency. Advances in vehicle technology and battery development will likely yield better vehicle performance in the future than is predicted by the vehicle simulation program. The following sections describe the vehicle components used in the battery bus model.

2.1.1 Vehicle Bus

The vehicle chosen for simulation is a rubber-tired bus of approximately 18 tons weight, capable of accommodating 20 passengers plus the operator of the bus. On-board the vehicle is auxilliary equipment for supplying the necessary lighting as well as air-conditioning. Table 2-1 gives a summary of the bus parameters used in the battery bus simulation.

2.1.2 Battery Power Bank

The power source is modeled as a multiple battery cell comprising a total of 256 cells which has a charge capacity of 455 ampere-hours. Total energy capacity of the unit is 910 watt-hours. A summary of pertinent battery data is presented in Table 2-2.

Figure 2-1a shows the charge capacity as a function of discharge current. Intercepts on the curve give the expected ampere-hours output for different discharge times

TABLE 2-1. SUMMARY OF BATTERY BUS PARAMETERS

Bus Parameters	
Curb Weight	36,400 lb
No. of Passengers (150 lb each)	20
Gross Vehicle Weight	39,550 lb
Frontal Area	80 sq ft
Aerodynamic Drag Coeff.	.84
Rolling Drag Coeff.	.005
Airconditioning Compressor Power	6 kw
Aircompressor Load	1 kw
Airconditioning Condenser Blower Power	.6 kw
Environmental Control Blower	.6 kw

TABLE 2-2. BATTERY CELL CHARACTERISTICS

5 Hour Discharge Rate	
Cell Voltage	1.96 v
Discharge Current	91 amp
Capacity	455 AH
Energy Storage	910 Wh
Energy/Weight Ratio	31.4 Wh/kg
1 Hour Discharge Rate	
Cell Voltage	1.86 v.
Discharge Current	315 amp
Capacity	315 AH
Energy Storage	630 Wh (nominal)
Energy/Weight Ratio	21.7 Wh/kg
**	
Weight	29 kg
Maximum Discharge Current	600 amp

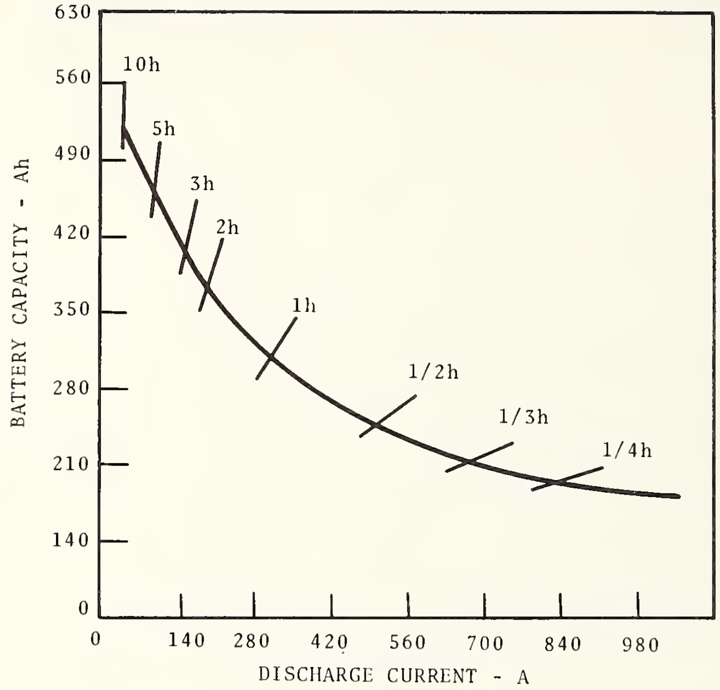


FIGURE 2-1a. BATTERY CAPACITY AS A FUNCTION OF DISCHARGE CURRENT

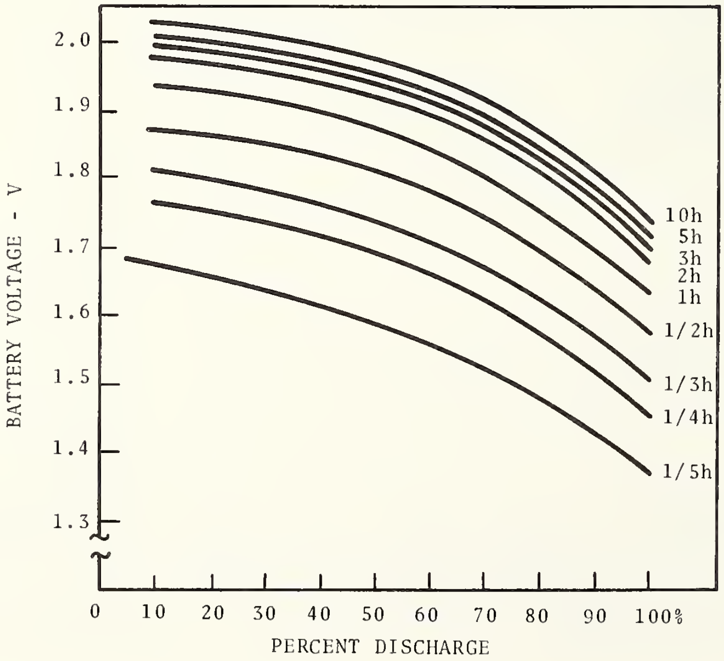


FIGURE 2-1b. BATTERY VOLTAGE AS A FUNCTION OF PERCENT DISCHARGE

with continuous discharge current. The corresponding cell output voltage as a function of percent of total ampere-hours output is shown in Figure 2-1b. The reduction in cell capacity and output voltage at high discharge current levels is evident in the figures.

The discharge current I, average discharge voltage U_m, and final discharge voltage U_s are given in Table 2-3.

TABLE 2-3. LEAD-ACID BATTERY CELL DISCHARGE DATA

Hr	C AH	I A	U_m V	U_s V
10	518	52.0	1.955	1.735
5	455	91	1.935	1.715
3	409.5	136.5	1.92	1.70
2	377.0	187.0	1.90	1.78
1	315	315	1.855	1.635
1/2	255.5	511	1.785	1.565
1/4	203	812	1.67	1.46

The charging current characteristics for the lead-acid cell follow the typical charging characteristics for lead acid storage batteries. Figure 2-2 presents charging voltage as a function of charging current for various states of battery charge relative to the ampere-hour capacity at the 10 hour-rate level, i.e., 518 A-h. Onset of gassing occurs at 2.4 volts per cell. The figure shows that charging current must be progressively reduced as the state-of-charge of the battery builds up to avoid battery gassing.

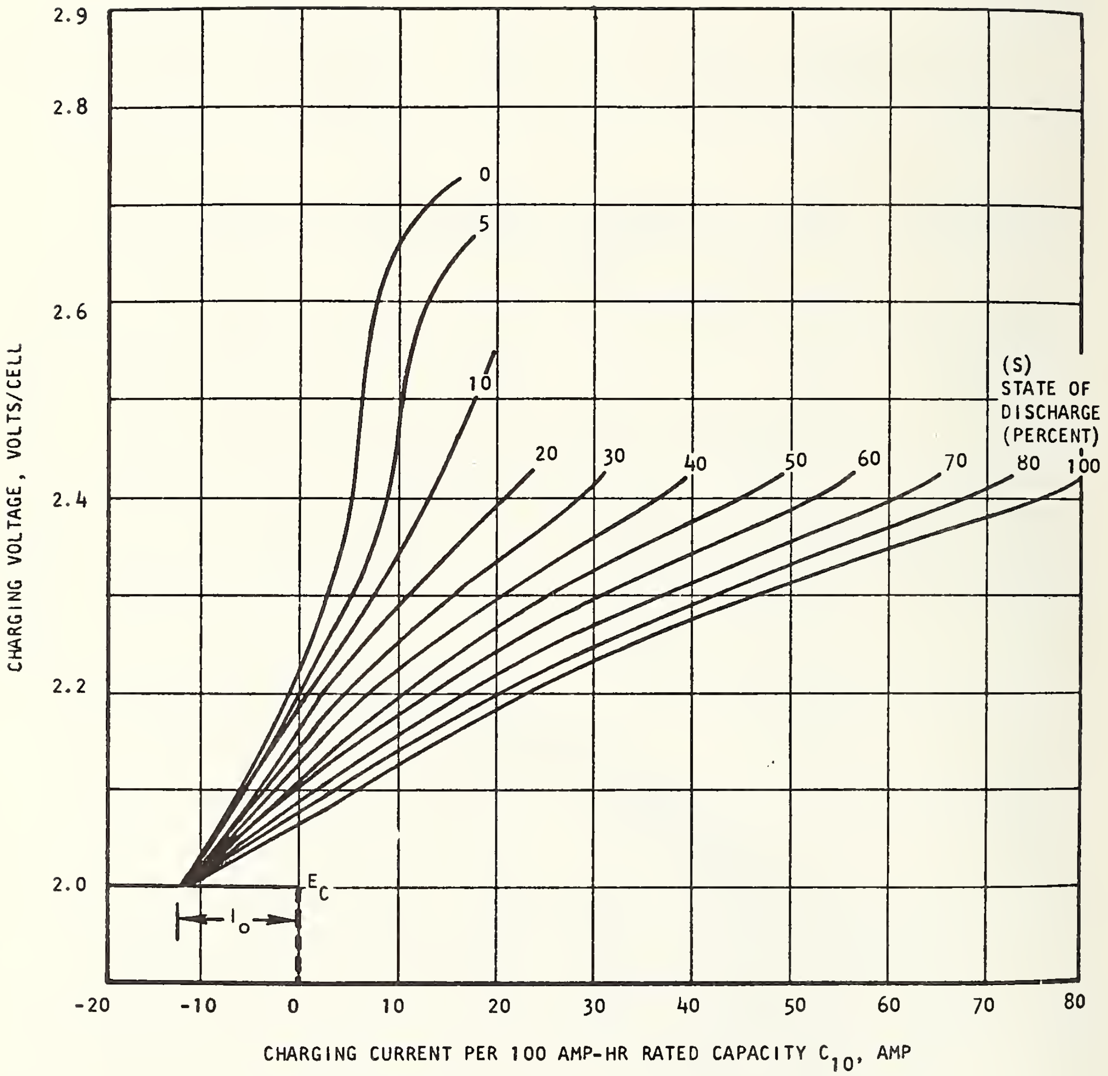


FIGURE 2-2. CHARGING CHARACTERISTICS FOR BATTERY CELL. (ABSCISSA SHOULD BE MULTIPLIED BY 5.18 FOR ACTUAL CHARGING CURRENT).

2.1.3 DC Traction Motor

The battery bus uses a separately excited dc shunt motor, which is coupled through a gear box with 11.42 gear ratio (step down) to the rear drive axle of the vehicle. The motor characteristics at rated output are listed in Table 2-4.

TABLE 2-4. DC TRACTION MOTOR RATINGS

Shunt (separately excited)	
Rated Speed	2,477 rpm
Power Output (continuous)	300 HP (323 kw)
Armature Current (rated load)	478 amp
Terminal Voltage (rated load)	530 volt
Rated Efficiency (field loss and blower power loss omitted)	92%

The motor losses depend on its speed and the relative motor excitation. The parameter, k, equal to (airgap) volts-per-rpm describes the motor excitation. The losses are assumed to be given by the following relations:

1) Iron Loss. The iron loss depends on both the motor speed and excitation. The loss is assumed to be given by the empirical relation,

$$P_{iron} = 2.629\text{x}10^{-4} * (k)^{1.29} (rpm)^{1.406} \text{ kw.}$$

2) Bearing Loss. The bearing loss is proportional to motor speed,

$$P_{bearing} = 0.001\text{x}(rpm) \text{ kw.}$$

3) Windage Loss. The windage power loss varies as the square of the motor speed,

$$P_{windage} = 1.475\text{x}(rpm/4540)^2 .$$

4) Primary I^2R Heating Loss. Primary resistance is taken to be .0405 ohm .

5) Shunt Field Loss. The shunt field loss as a function of field excitation (volt /rpm) is shown in Figure 2-3.

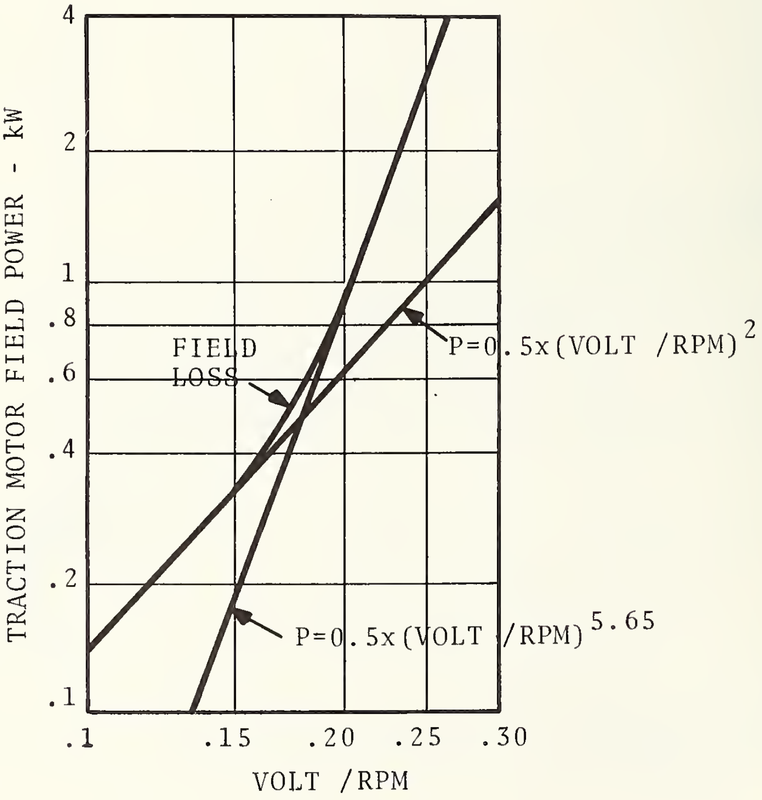


FIGURE 2-3. TRACTION MOTOR SHUNT FIELD LOSS

Below an excitation level of 0.18 volt /rpm, the field loss is described by a function involving the 5.65 power; above the excitation level of 0.18, field loss is given by the square of the excitation. Table 2-5 gives the motor losses for an assumed excitation of K_o equal to 0.215 (volt /rpm).

TABLE 2-5. DC MOTOR POWER LOSSES AT RATED SPEED

DC MOTOR POWER LOSSES*	
Iron Loss	2.14 kw
Bearing Loss	2.48 kw
Windage Loss	0.41 kw
Field Power Loss	see Figure 2-3

*Assumed excitation = 0.215 volt /rpm

The limiting conditions assumed for the dc traction motor are summarized in the table below.

TABLE 2-6. MAXIMUM TRACTION MOTOR RATINGS

MAXIMUM MOTOR RATINGS

Armature Current = 700 amperes
Terminal Voltage = 530 volt
Field Excitation = 0.215 volt /rpm (motoring)
Field Excitation = 0.230 volt /rpm (braking)

Motor Excitation. The motor excitation which determines the field (flux) in the dc motor is described by the input (airgap) volts per motor rpm. Since the machine flux results from both the field and armature windings both excitations must be considered in determining the effective motor excitation.

At low motor speeds, the motor back EMF is small and the terminal voltage must be reduced to limit armature current. The motor operates with maximum (field) excitation which is limited by the current through the field winding. The excitation k_o, in this case, is given by,

$$k_o = \frac{E_a}{rpm} \quad , \tag{1}$$

where

$$E_a = V_t - V_B - I_1 * R \tag{2}$$

V_t = motor terminal voltage

V_B = brush voltage drop = 2 volts

I_1 = armature current

R = armature resistance = 0.04 ohm .

The field (current) excitation k_o is set at 0.215 for the DC traction motor. The armature current I_1 is determined by the motor output power, or equivalently, the airgap power PTMA.

$$I_1 = \frac{PTMA}{E_a} \quad . \tag{3}$$

This assumes the armature current does not exceed the maximum allowed current AMPM. If I_1 given by Equation (3) exceeds AMPM, the motor output power must be reduced to satisfy Equation (3). The required motor terminal voltage V_t for this field-limited mode is (see Section 3.2),

$$V_t = k_o * rpm + V_B + PTMA * R/(K_o * rpm) \quad . \tag{4}$$

As the motor speeds up, the back EMF E_a increases and the motor terminal voltage rises. When the motor speed becomes such that the terminal voltage equals the maximum available voltage, VOLTM, the motor is voltage-limited. The excitation k_v, in this case, is

$$k_v = \frac{E_a}{rpm} .$$

and (see Section 3.2)

$$E_a = \frac{VOLTM - V_B}{2} + \frac{1}{2}\sqrt{(VOLTM - V_B)^2 - 4\ PTMA \cdot R} . \qquad (5)$$

The armature current given by Equation (3) must not exceed the maximum allowed current AMPM; otherwise the output power must be reduced to satisfy Equation (3).

Figure 2-4 shows the motor excitation volts/rpm for the dc traction motor computed for Drive Cycle C (see Section 5). The figure illustrates the field and voltage-limited operating regimes. In the voltage-limited regime, field-weakening is required to reach higher speeds.

Motor operation in the regenerative braking mode requires an increase in field excitation to develop the necessary EMF for reversing the armature current. (See Equation (2)). For this purpose the motor excitation is assigned a value k = .230 volt / rpm which is sufficient at high rpm's to cause the back EMF to exceed the motor terminal voltage. Regenerative braking is possible at all speeds for which the above condition exists.

2.1.4 Power Control Unit (PCU)

Power delivered by the battery source to the dc traction motor is controlled by a solid state unit consisting of a step-down chopper and a step-up (boost PCU) circuitry. By utilizing the bi-functional capability of the step down, step up dc to dc converters, it is possible with a single control unit to transfer power between the battery source and motor during both the motoring and regenerative braking modes. Without the voltage step-up capability, regenerative power transfer at the lower motor speed

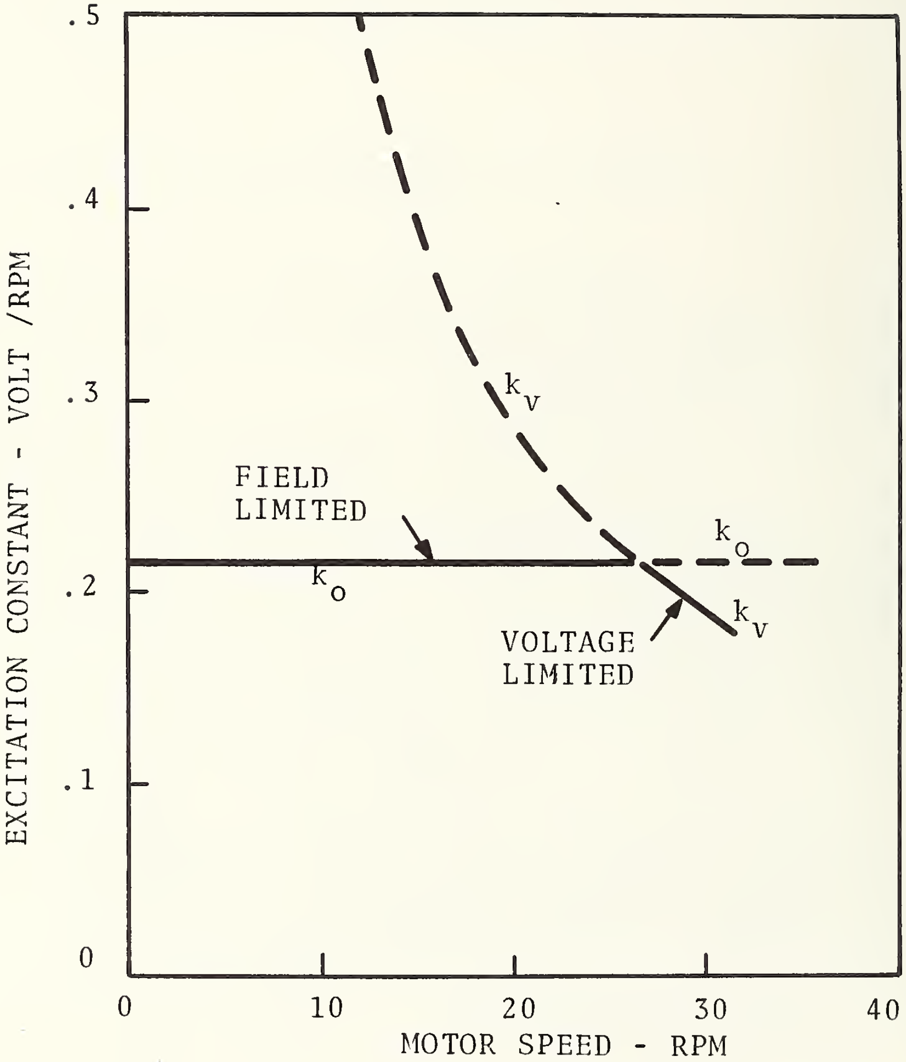


FIGURE 2-4. EXCITATION CONSTANT AS A FUNCTION OF MOTOR SPEED FOR DRIVE CYCLE C

range would be impossible and the propulsion system efficiency would be reduced. This type of control unit envisioned is described in the literature as a dc to dc converter[3] and incorporates a flyback booster and chopper regulator.

The control circuit is shown in its most simplified form in Figure 2-5a and 2-5b which describe respectively step-down and step-up (voltage) converters. The step-down converter utilizes SCR to periodically connect the power source to the load. A free-wheeling diode, FWD, provides the current continuity as required by the large inductance in the motor circuit. Output voltage is given by the time-average of the chopped voltage output signal.

Voltage step up is illustrated by the circuit shown in Figure 2-5b. Closing the SCR switch causes a large voltage to be developed across the inductance (LS). When the switch is opened, this voltage, plus additional induced voltages in the circuit (motor EMF), are placed in series with the battery. The series diode prevents battery discharge when the switch is closed. Reference 4 describes the operation of the step-up converter in more detail.

2.2 MODES OF OPERATION

The propulsion system of the battery bus operates in both the motoring and regenerative braking modes. In the former, power flow is from the battery source to the dc traction motor; in the latter, the motor acts as a generator and supplies power to the battery bank. In both operating modes, power losses exist in the different system components. These losses determine the ultimate efficiency of the bus propulsion system when operating with a given drive cycle.

The two operating modes are best illustrated by the diagrams shown in Figures 2-6a and 2-6b. The direction of power flow in the figures is indicated by arrows. The symbols used for the various loss terms are those used in the battery bus program.

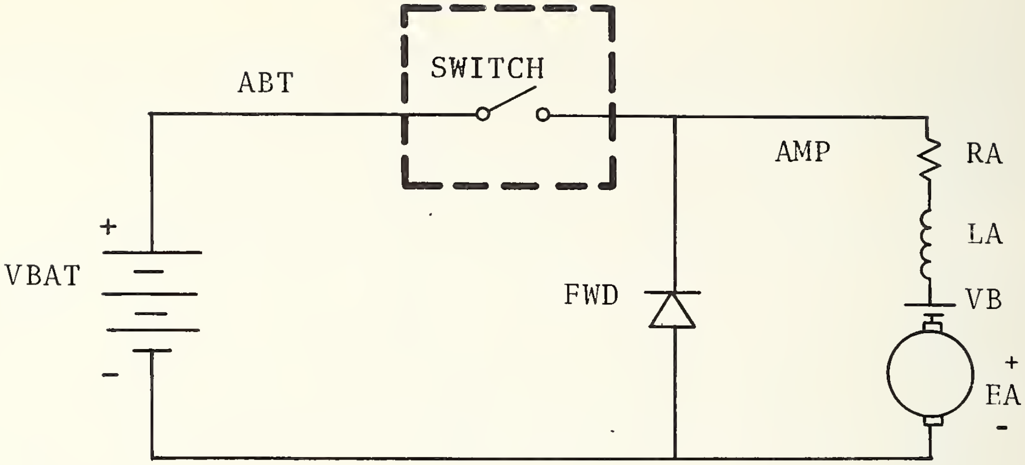


FIGURE 2-5a. PCU VOLTAGE STEP-DOWN CIRCUIT

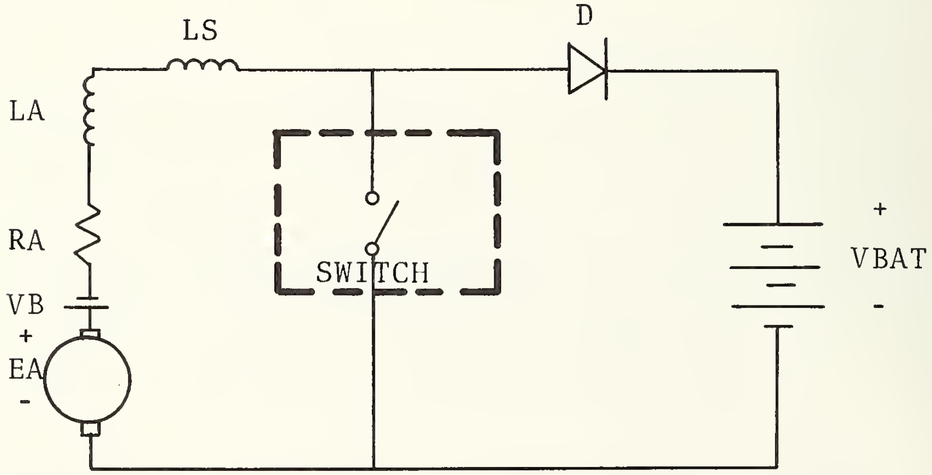


FIGURE 2-5b. PCU VOLTAGE STEP-UP CIRCUIT

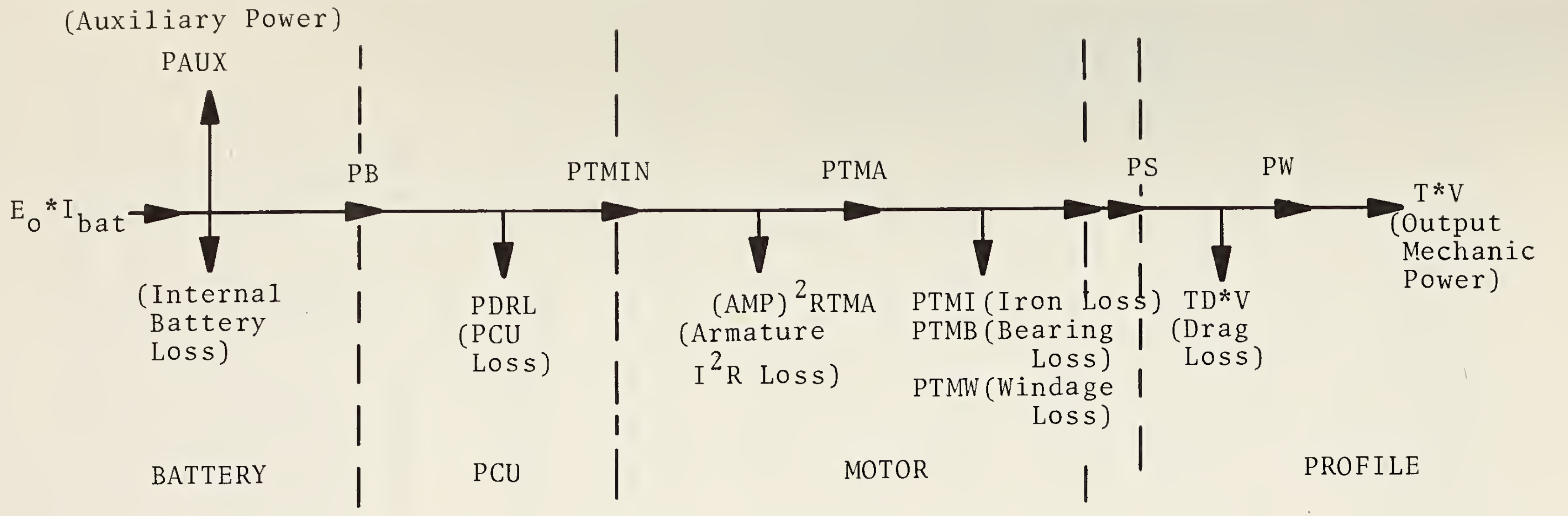


FIGURE 2-6a. POWER FLOW IN MOTORING MODE

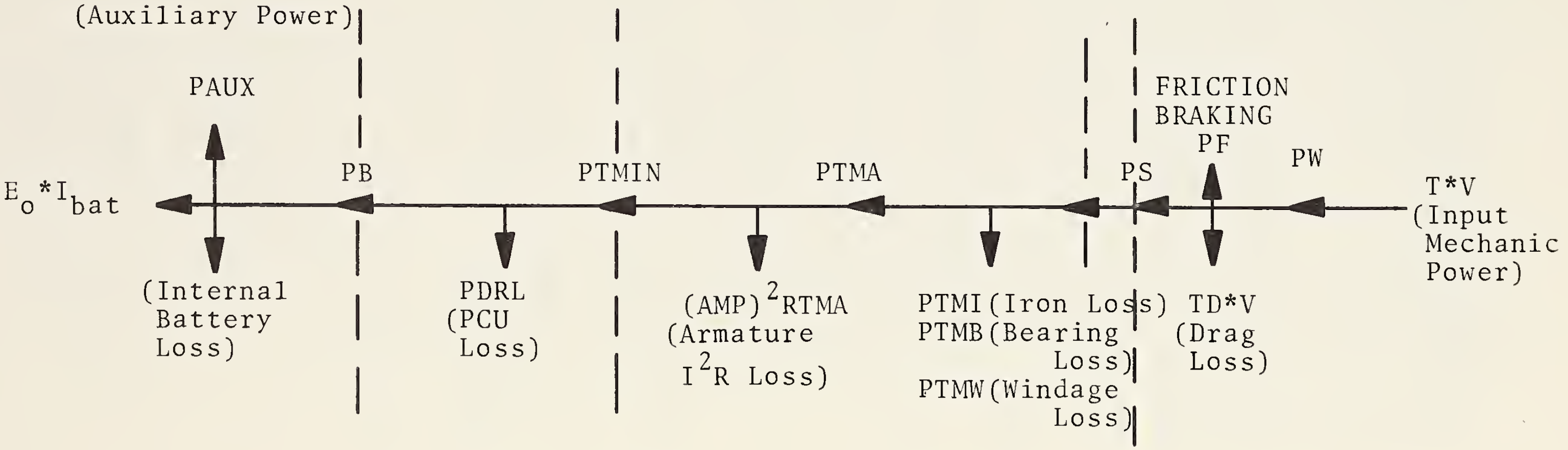


FIGURE 2-6b. POWER FLOW IN BRAKING MODE

Certain limitations in the flow of power to and from the battery exist which are not detailed in the figure. First, the battery is limited in the total current it can discharge. This affects the maximum power which the battery is capable of delivering. Second, the battery is limited in the amount of current it can accept during charging. Exceeding this limit results in battery gassing and subsequent deterioration in the chemical structure of the battery. The latter limit is referred to as gassing power limit. Both of these limits have an important effect on the maximum power output and efficiency of the battery.

The limiting conditions for bus operation in the motoring mode are:

1) Battery discharge current is limited to ABM = 422 amperes.
2) Motor armature current is limited to AMPMO = 700 amperes.
3) Motor terminal voltage is limited to VOLTMA = 530 volts.
4) Motor terminal voltage (VOLT) cannot exceed battery voltage (VBAT).
5) Field excitation is limited to rated excitation defined by CAYOA = 0.215 volt /rpm in the speed-voltage control mode.

Condition 1 above limits the maximum acceleration at the higher speed range while condition 4 defines the limiting condition for field weakening.

The limiting conditions for bus operation in the regenerative braking mode are:

a) Maximum charging power of the battery bank is limited to the gassing power PG. The gassing power is the battery power corresponding to a gassing voltage EG = 2.4 volt / cell.
b) Motor terminal voltage is limited to VOLTMD = 600 volts.
c) The field excitation is limited to the excitation constant value of CAYOD = 0.23 volt/rpm.

d) The battery has a charging efficiency of 90 percent as determined by the ratio of the actual charge stored to the total charge delivered to the battery.

2.3 MISSION PROFILE

The mission profile describes the position and speed of the vehicle at any given time. Usually the mission profile is a specified function of speed and time which the vehicle undergoes in operation. An alternate arrangement consists of requesting a desired vehicle acceleration and cruise velocity and allowing the vehicle to achieve a speed-time profile compatible with the requested acceleration and velocity input data. The latter arrangement corresponds to the one experienced in normal vehicle operation. Other considerations such as roadway grade and headwind are usually defined as part of the mission profile since they affect the required tractive effort needed to achieve a given vehicle acceleration or speed.

The battery bus program uses the alternate arrangement described above in determining the mission profile. Figure 2-7a shows the drive cycle used to describe the vehicle mission profile over an operating "interval." Figure 2-7b shows the vehicle acceleration, cruise velocity, and deceleration subject to limiting acceleration and deceleration jerk rates. The parameters required to define the vehicle drive cycle are:

VC = Cruise speed

ACCM = Requested acceleration

DECL = Requested deceleration

Dwell = Time spent at station stop

T1 = Time interval of initial deceleration

T2-T1 = Time interval for constant deceleration

T3-T2 = Time interval of final deceleration

AJERKR = Jerk rate.

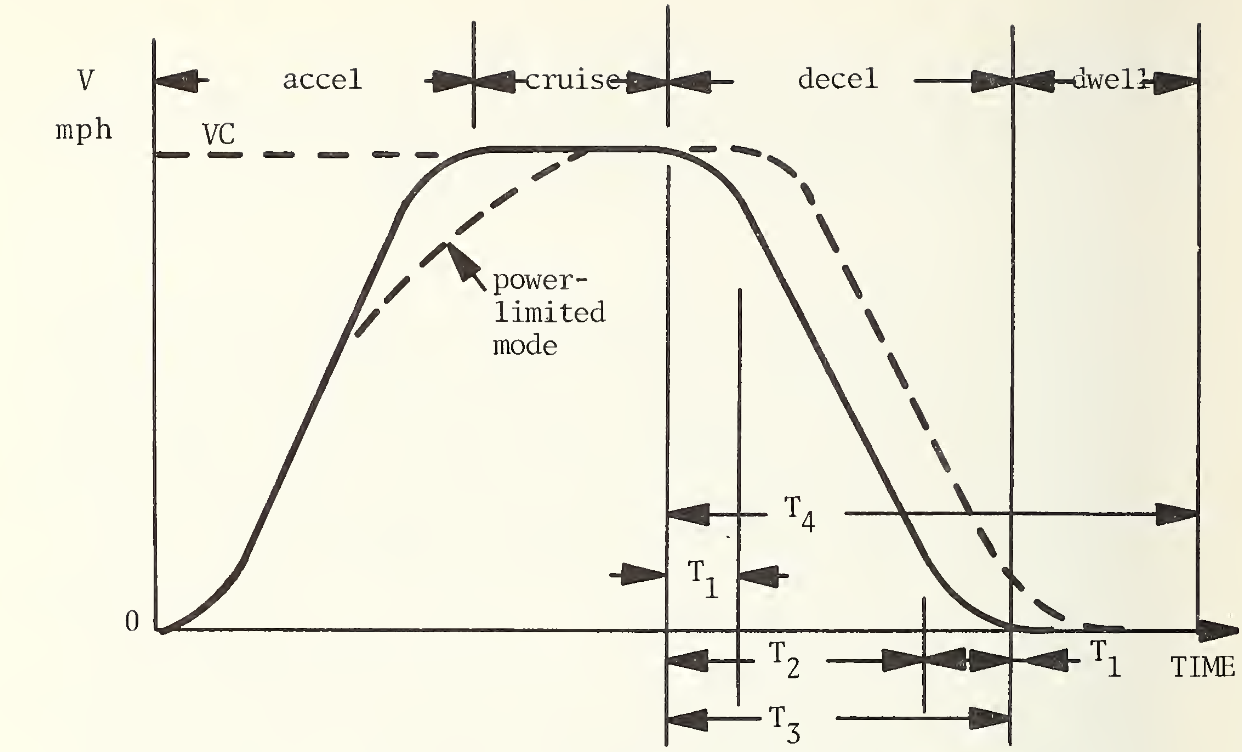


FIGURE 2-7a. SPEED-TIME PROFILE CHARACTERISTIC

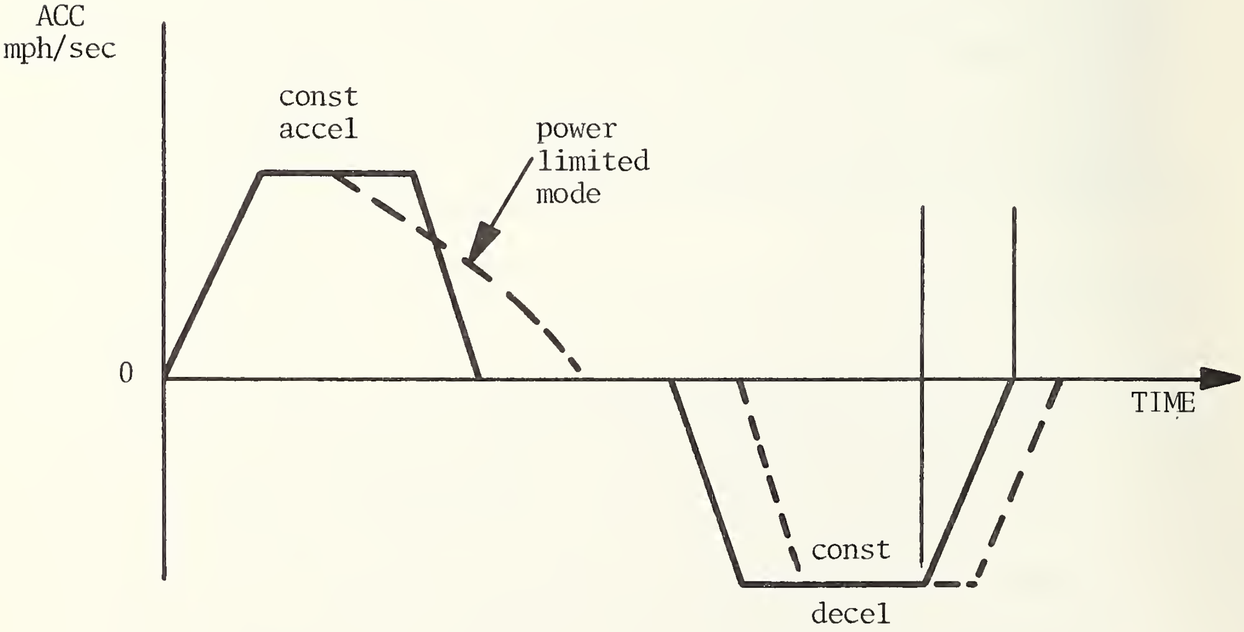


FIGURE 2-7b. ACCELERATION-(DECELERATION) TIME PROFILE

The total vehicle route comprises a multiple of driving cycles in which the vehicle stops at successive stations for a period of time (DWELL). The relevant parameters which describe the vehicle route are;

NS = Number of stops per mile

SR = Route length.

The possibility of different waiting periods between routes is included in the program.

TAUMU = Waiting time between routes.

Additional parameters needed to describe the roadway grade and headwind are;

GRADE = Roadway grade

HW = Headwind.

The mission profile is described by selecting one of three programmed driving cycles, A, B, and C. The cycles are defined by the constants given in Table 2-7.

The vehicle starts from rest in a jerk-limited mode. As the acceleration (ACC) increases to the required rate (ACCM), the jerk (AJERK), which is the rate of change of acceleration, is constrained by a specified limit (AJERKR). As the vehicle approaches cruise speed (VC), a jerk-limited decrease of acceleration is programmed. At the proper speed, the acceleration is reduced to zero at the jerk-limited rate (AJERKR) so that cruise speed is maintained at, or slightly above, the specified value. If either the motor power limit or battery current limit is encountered during acceleration, the vehicle will accelerate at a reduced rate up to cruise speed.

The vehicle's stopping distance (XB) is computed as a function of vehicle speed (V) and braking is initiated at the proper distance from the next stop. Ideal braking is assumed in that all of the required braking force is made available through a blend of regenerative and friction braking systems. The amount of power that the regenerative system can accept is determined by the

TABLE 2-7. DRIVING CYCLE DATA

Description	FORTRAN Symbol	Cycle A	Cycle B	Cycle C	Unit
Required acceleration rate	ACCM	1.44	3.5	2.5	mph/sec
Deceleration rate	DECL	2.2	3.5	2.5	mph/sec
Cruise speed	VC	31.0	31.0	25.0	mph
Maximum allowed jerk	AJERKR	3.5	3.5	3.5	mph/sec^2
Number of stops per mile	NS	4	8	5	--
Distance between stops	SS	0.25	0.125	0.20	mi
Dwell time at each stop	DWELL	30.0	16.0	20.4	sec
Additional dwell at end of route	TAUMU	0.0	0.0	330.0	sec
Number of passengers	NP	15	20	8	--
Route length	SR	6.0	6.0	6.0	mi
Number of transits of route	NT	4	4	4	--

battery gassing limit and the friction braking system absorbs the remainder. The programmed deceleration profile, which is also jerk-limited, brings the vehicle to rest with the specified constant deceleration rate (DECL).

At the end of the mission, a battery recharge model simulates charging the battery system to its original state. The results of the battery recharge are used to compute the total energy consumption and the battery efficiency for the particular mission profile.

3. MODELING THEORY AND EQUATIONS

This section contains the derivation of the equations used in the battery bus computer model as well as the definition of the more significant program parameters. In most cases, the same FORTRAN symbols have been used in the modeling derivations as appear in the program. An exception to this occurs in certain parts of the motor simulation model where it has been convenient to use standard electrical machine terminology. A complete listing of all model parameters is given in the Appendix to this report.

3.1 MISSION PROFILE MODEL

The mission profile of the battery bus is defined at the start of each run by selecting one of three drive cycles, called drive cycles A, B, and C. These drive cycles specify desired accelerations and cruise velocities as well as jerk rates for the moving vehicle. In response to the acceleration (deceleration) commands, the vehicle moves over a prescribed route with a speed-time 'profile' determined by the vehicle propulsion-drive characteristics. If the motor is unable to deliver the required tractive effort or if the power demand on the battery exceeds its output capability, the vehicle accelerates at a reduced level.

To maintain passenger comfort, the vehicle is limited to a specified jerk limit (AJERKR) during times of changing acceleration or deceleration. A dwell time (DWELL) is allowed at each stop to allow passengers to enter and exit the vehicle. Additional dwell time is added at the end of the route (TAUMO) to simulate a waiting period before beginning the next route. The number of stops per mile (NS) determines the distance between stops (SS). The vehicle gross weight (WT) includes the number of passengers (NP) and vehicle mass. The route length (SR) times the number of routes (NT) gives the total distance travelled by the vehicle.

Vehicle braking is always done at a jerk-limited rate (DECL). The regenerative power which the motor supplies to the battery is adjusted so that the battery gassing limit is never exceeded. Any additional braking power to meet the required deceleration is 'absorbed' by friction brakes. The braking is begun at a pre-determined distance from the next stop so that the vehicle comes to rest at the proper location. Figure 2-7a shows the velocity-time plot for one complete cycle of an arbitrary mission. The time segments for the deceleration are determined as follows:

T1 = DECL/AJERKR = Time from start of braking to start of constant deceleration [sec] (6)

T2 = V/DECL = Time from start of braking to completion of constant deceleration [sec] (7)

T3 = T1 + T2 = Total time of deceleration [sec] (8)

T4 = T3 + DWELL = Total time of cycle [sec] (9)

T4 = T4 + TAUMU = Additional time added between routes (10)

<u>where</u>:

DECL = Constant deceleration rate [mph/sec]

AJERKR = Jerk limit [mph/sec^2]

DWELL = Dwell time at each stop [sec]

TAUMU = Dwell time between routes [sec].

The stopping distance (XB) for the given deceleration rate and vehicle speed is computed as the product of the total time of deceleration (T3) and the average vehicle speed during deceleration (V/2.0). That is

XB (V/2.0) x T3/3600.0 = Stopping distance (11)

or:

XB = (V/2.0)*(DECL/AJERKR*V/DECL)/2. (12)

At each program iteration the vehicle's acceleration is computed as the net accelerating thrust divided by the equivalent vehicle mass (AMASS). In computing AMASS, a factor of 2300.0 lbs (10 percent of the vehicle bare weight) is added to the vehicle gross weight (WT) to account for the rotary inertia of the propulsion system components.

$$\mathrm{ACC} = \mathrm{TN/AMASS} = \text{Vehicle acceleration [mph/sec.]} \tag{13}$$

$$\mathrm{AMASS} = (\mathrm{WT} + 2300.0)/\mathrm{GEE} = \text{Vehicle accelerating mass [g-lb]} \tag{14}$$

$$\mathrm{WT} = \mathrm{WTCRB} + (\mathrm{NP} + 1)*\mathrm{WTP} = \text{Vehicle gross weight [lbf]} \tag{15}$$

<u>where</u>:

TN = Net accelerating thrust [lbf]

GEE = 21.927 = Acceleration due to gravity [mph/sec.]

WTCRB = 36400.0 = Vehicle curb weight [lbf]

NP = Number of passengers

WTP = 150.0 = Weight of a typical passenger [lbf].

The average vehicle acceleration (ABAR) over the computing time interval is then determined and numerically integrated to determine the vehicle's speed (V) during that time interval. The average speed (VBAR) is used to determine the distance travelled by the vehicle during each interval. The total time since the start of the run (THETA) is the sum of each computing time interval (TAU). During acceleration and deceleration, TAU equals 0.2 seconds, but during cruise and dwell, when the propulsion system parameters vary slowly, TAU is increased to 1.0 seconds in order to reduce the total computing time. The total distance travelled by the vehicle since the start of the run (S) is the sum of the distances travelled during each interval. The distance from the previous stop at which to begin braking (STAB) equals the distance between stops (SS) minus the stopping distance (XB). When the vehicle has gone the distance STAB, braking begins at the predefined deceleration rate (DECL), with allowances made for the specified jerk limit (AJERKR).

At each iteration, the drag forces acting on the vehicle are computed according to the following equations:

TG = WT*SIN (ATAN(GRADE)) = Grade drag [lbf] (16)

TR = CR*WT = Rolling drag [lbf] (17)

TA = 0.00258*CD*AF*(V + HW)**2.0 = Aerodynamic drag [lbf] (18)

TD = TG + TR + TA = Total drag force [lbf] (19)

where:

WT = Vehicle gross weight [lbf]

GRADE = Roadway grade [rad]

CR = 0.005 = Rolling drag coefficient

CD = 0.84 = Aerodynamic drag coefficient

AF = 80.0 = Vehicle frontal area [ft^2]

V = Vehicle speed [mph]

HW = Encountered headwind [mph].

The grade data is prestored in an array, G(25,2), which can contain up to 25 paired sets of grade values and the corresponding distances at which the grades are encountered. As the vehicle passes each distance at which the grade changes, a new value of GRADE is determined from the next indexed value in the array G(25,2). In this simulation, all grade values were zero.

The vehicle's traction force (TP) and propulsion power (PW) are computed as follows:

TP = TN + TD = Tractive Force [lbf] (20)

PW = 0.001989*TP*V = Propulsion power [kw] (21)

where:

TN = Net accelerating thrust [lbf]

TD = Total drag force [lbf]

V = Vehicle speed [mph].

The demanded motor shaft power (PS) is then related to the propulsion power (PW) by the rear axle efficiency (ETAG) according to:

$$PS = PW/ETAG \text{ (for motoring mode)} \qquad (22)$$

$$PS = PW*ETAG \text{ (for braking mode)} \qquad (23)$$

where:

PS = Motor shaft power [kw]

PW = Propulsion power [kw]

ETAG = 0.945 = Rear axle efficiency [pu].

If the demanded motor shaft power (PS) exceeds its limits (PSMA or PSMD), it is set equal to the proper limit. If either the battery current (ABT) or battery charging power (PB) exceed their limiting values (ABM or PG, respectively), the program reduces the motor shaft power demand until the limits are satisfied. This power limited mode is indicated by setting a control index number (IND) equal to unity from its normal value of zero. If one of these limits is encountered, the net accelerating thrust (TN) is recomputed to reflect a reduced acceleration capability.

3.2 MOTOR MODEL

The important characteristics of the dc shunt traction motor were given in Section 2.13. For convenience, the limiting values of motor parameters are summarized in Table 3-1. Modeling the traction motor requires determining the motor losses at any given instant in time.

The motor losses are found from empirical equations giving the windage-friction loss, iron loss, and shunt field loss as a function of motor speed and excitation. The traction motor losses are computed as follows:

$$PTMB = 0.001 * RPM = \text{Bearing loss [kw]} \qquad (24)$$

$$PTMW = 1.475 * (RPM/4540.0) ** 2.0 = \text{Windage loss [kw]} \qquad (25)$$

TABLE 3-1. SUMMARY OF TRACTION MOTOR DATA

Traction Motor Data

	FORTRAN Symbol	Value	Unit
Maximum shaft power - accel.	PSMA	223.7	kw
Maximum shaft power - decel.	PSMD	223.7	kw
Maximum armature current	AMPM0	700.0	amp
Maximum armature current on grades	AMPMG	770.0	amp
Maximum terminal voltage - accel.	VOLTMA	530	volt
Maximum terminal voltage - decel.	VOLTMD	600	volt
Excitation limit - accel.	CAY0A	0.215	volt /rpm
Excitation limit - decel.	CAY0D	0.230	volt /rpm
Excitation limit on grades	CAY0G	0.250	volt /rpm
Motor speed (at 50 mph)	RPM	(4570)	rpm
Bearing loss (at 4500 rpm)	PTMB	(4.50)	kw
Windage loss (at 4540 rpm)	PTMW	(1.475)	kw
Voltage drop across brushes	VB	2.0	volt
Armature resistance	RTMA	0.04048	ohm

$$\mathrm{RPM} = \mathrm{RATIO} * \mathrm{TF} * V \tag{26}$$

$$\mathrm{PTMI} = 2.629\mathrm{E}\text{-}04 * \mathrm{CAY}**1.29 * \mathrm{rpm}**1.406 = \text{Iron core loss [kw]} \tag{27}$$

$$\mathrm{PTMS} = 0.01 * \mathrm{PTMA} = \text{Stray load loss [kw]}$$

where motor speed (rpm) is related to vehicle speed by the following equation:

TF = 8.003 Tire Factor (rpm/mph) (28)

V = Vehicle Speed (mph)

RPM = Motor speed [rpm]

CAY = Exictation constant [volts/rpm]

PTMA = Air-gap power [kw]

RATIO = 11.2 Reduction Gear Ratio.

The air-gap power (PTMA) equals the motor shaft power (PS) plus the loss terms. That is:

$$\mathrm{PTMA} = \mathrm{PS} + \mathrm{PTMB} + \mathrm{PTMW} + \mathrm{PTMI} + \mathrm{PTMS}\ . \tag{29}$$

Motor speed is controlled in the <u>motoring mode</u> either by controlling motor terminal voltage (voltage-control) or shunt field excitation (field weakening). In the <u>voltage-control mode</u>, the shunt field is held constant as determined by the excitation constant (CAYO). Armature current (amp) and terminal voltage (VOLT) are given by,

$$\mathrm{AMP} = \mathrm{PTMA}/\mathrm{EB} * 1000 \quad \text{[Amperes]} \tag{30}$$

$$\mathrm{VOLT} = \mathrm{EB} + \mathrm{AMP} * \mathrm{RTMA} + \mathrm{VB} \quad \text{[Volt]} \tag{31}$$

where,

EB = Back EMF = CAYO*RMP [Volt] (32)

RTMA = Armature Resistance [Ohm]

VB = 2.0 Volts = Brush Voltage Drop [volt].

The armature current must not exceed the maximum overload current rating of the motor (AMPM).

$$\mathrm{AMP} \le \mathrm{AMPM}$$

If $\text{AMP} \geq \text{AMPM}$, then the armature current is set equal to AMPM and the terminal voltage is given by,

$$\text{VOLT} = \text{EB} + \text{AMPM*RTMA} + \text{VB} \ [\text{volt}]. \tag{33}$$

In the field control mode, motor terminal voltage (volt) is equal to the battery source voltage (VBAT). The back EMF (EB) is then found by substituting EB:

$$\text{EB} = \frac{\text{VBAT} - \text{VB} + \sqrt{(\text{VBAT} - \text{VB})\text{**}2 - 4000.\text{*PTMA*RMTA}}}{2.} \ [\text{volt}]. \tag{34}$$

Armature current (AMPA) is then given by Equation (26),

$$\text{AMP} = \text{PTMA/EB} \ [\text{amperes}]. \tag{35}$$

Condition $\text{AMP} \leq \text{AMPM}$ applies in this case also. If the motor armature current (AMP) exceeds the maximum rated overload current (AMPM), then AMP = AMPM and the back EMF is found from,

$$\text{EB} = \text{VBAT} - \text{VB} - \text{AMPM*RTMA} \ [\text{volt}]. \tag{36}$$

The excitation constant (CAY) required to determine iron motor losses is given by,

$$\text{CAY} = \text{EB/RPM} \qquad [\text{volt /rpm}]. \tag{37}$$

Motor speed is controlled in the braking mode by regenerative braking or by a combination of regenerative and friction braking. In the deceleration mode, regenerative braking is realized by increasing the field excitation constant (CAY) to CAYOD where

$$\text{CAYOD} = 0.23 \qquad [\text{volt /rpm}].$$

Since the motor now operates as a generator, the airgap power (PTMA) is negative and the armature current becomes negative and given by,

$$\text{AMP} = \text{PTMA/(CAYOD*RPM)} * 1000 \quad [\text{amperes}]. \tag{38}$$

The motor terminal voltage (volt) is found by substituting Equation 32 in Equation 27. Since the amount of generated power is limited to the gassing power limit of the battery bank, it is necessary to reduce the motor shaft power (PS) such that the resulting power delivered to the battery is less than or equal to the gassing power limit (PG). In this iterative process, air-gap power (PTMA) is reduced to satisfy this condition of power balance.

The traction motor field power (PTF) is computed as a function of the excitation level (CAY). At low excitation, the field power is proportional to excitation squared. At higher excitation levels, saturation effects require a higher exponent variation. The following equations are used to compute the field power:

$$\text{PTF} = 0.5 *(\text{CAY}/0.18) **2.0 \text{ (for CAY} \leq 0.18\text{) [kw]} \quad (39)$$

or:

$$\text{PTF} = 0.5 *(\text{CAY}/0.18) ** 5.646 \text{ (for CAY} > 0.18\text{) [kw].} \quad (40)$$

(See Figure 2-3.)

The traction motor input power (PTMIN) is computed as the product of armature current (amp) and terminal voltage (volt).

PTMIN = AMP*VOLT/1000.0 = Motor terminal power [kw].

The total traction motor power loss (PTML) does not include the field power (PTF), which is added to the auxiliary power load (PAUX). PTML is the difference between the input electric power (PTMIN) and output shaft power (PS). That is:

$$\text{PTML} = \text{PTMIN} - \text{PS} = \text{Total traction motor loss [kw].} \quad (41)$$

3.3 PCU MODEL

The PCU is modeled as a variable transformer which transfers power between the battery bank and motor load. Since the PCU is assumed to have voltage step-up, step-down capability, power transfer can take place in either direction between battery and load. The output of the PCU is determined by the motor power required to satisfy the bus propulsion needs. Since the motor impedance fixes the volts-per-current ratio, all PCU output quantities are known at all times during the drive cycle.

The power loss in the PCU is modeled as a three volt drop times armature current:

$$P_{PCU} = .003 \text{ x amp [kw]} . \qquad (42)$$

The controller input power is equal to the sum of the power delivered to the motor plus the PCU internal loss.

3.4 BATTERY MODEL

The power demanded from the battery (PB) at each time increment (TAU) is computed as the sum of the traction motor input power (PTMIN), the power conditioning unit loss (PCUL), and the total auxiliary power load (PAUX). The PCU loss is assumed to be directly proportional to the motor armature current (AMP). The auxiliary power term (PAUX) includes the motor field supply power (PTF). Additional terms (PAC and PCBLO) can be added to simulate air conditioning loads.

$$PB = PTMIN + PCUL + PAUX = \text{Battery Power [kw]} \qquad (43)$$

$$PCUL = 0.003 * ABS\ (amp) = \text{Power Conditioning unit loss [kw]} . \qquad (44)$$

$$PAUX = PTF + PTBLO + PBAUX + PECBLO + PLTG + PBC + PAIR + PAC + PCBLO = \text{Auxiliary power [kw]} \qquad (45)$$

<u>where</u>:

PTMIN = Traction motor input power [kw]

AMP = Traction motor armature current [kw]

PTF = Traction motor field power [kw]

PTBLO = 0.6 = Traction motor blower power [kw]

PBAUX = 0.2 = Battery auxiliary power [kw]

PECBLO = 0.6 = Environmental control blower [kw]

PLTG = 3.6 = Lighting power [kw]

PBC = 3.2 = Average battery charger load [kw]

PAIR = 1.0 = Average air compressor load [kw]

PAC = 6.0 = Air conditioning compressor power [kw]

PCBLO = 0.6 = Air conditioning condenser blower [kw].

The battery is modeled by empirical expressions relating battery voltage to discharge current (IBAT) and total amp-hours (AH) discharged by battery. The empirical constants were chosen to model the water-cooled battery having a 455 amp-hour rating, based on a shown discharge time. The expressions are strictly valid for continuous discharge only; for pulsed discharge, the expressions should be modified to describe the reduced battery capacity existing in pulsed operation.

The relative state of battery discharge (SB) is given by,

SB = AH/CAP = State of discharge [per-unit] (46)

where:

AH = total ampere-hours removed from battery [AH]

CAP = Instantaneous battery capacity [AH]

The battery capacity (CAP) is given by the empirical relation,

CAP = ABT *(CAYA*ABT**CN-CAYB) = Battery capacity at current ABT [AH] (47)

where:

ABT = Battery current during discharge [amp]

CAYA = 937.969 = Current term coefficient
CN = -1.204 = Current term exponent
CAYB = 0.10107 = Constant term [hr] .

The ampere hours discharged (AH) is determined by numerically integrating the battery current (ABT) over each time interval (TAU) from the start of the run. Where the value of AH equals 0.6 of the instantaneous capacity (CAP), the battery is effectively discharged (SB = 0.6).

In the discharge mode, the battery terminal voltage (VBAT) is described by the following function of battery current (ABT) and state of discharge (SB):

VBAT = ANC *(EO-RB*ABT-CAYD*SB**CM) = Battery terminal voltage [volt] (48)

where:

ANC = 256.0 = Number of cells per battery

EO = 2.045 = Open circuit voltage of each cell [volt]

RB = 0.000516 = Internal resistance of each cell [ohm]

ABT = Battery current [amp]

CAYD = 0.419 = Discharge term coefficient

SB = Stage of battery discharge [pu]

CM = 2.24 = Discharge term exponent.

Also:

PB = VBAT * ABT/1000.0 = Battery power [kw] (49)

or:

VBAT = 1000.0 * PB/ABT = Battery voltage [volt]. (50)

Equating Equation 48 and Equation 50 yields:

1000.0 * PB/ABT = ANC*(EO-RB*ABT-CAYD*SB**CM). (51)

Since the state of battery discharge (SB) is a complicated function of battery current (ABT), the solution of Equation (51) for battery current is not straightforward. The Newton-Raphson method is used to determine the battery current (ABT) which satisfies Equation (51).

In the charge mode, the battery terminal voltage (VBAT) is described by the following empirical function of battery current (ABT) and state of discharge (SB):

VCHG = EC + CAYC*(AIC+AIO) * SC ** Q = Charging voltage per cell [volt] (52) where:

EC = 2.0 = Charging constant [volt].

CAYC = 0.001178 = Charging resistance per cell [ohm].

AIC = Charging current [amp]

AIO = 42 - 1875 = Offset current [amp]

SC = State of charge [per-unit]

Q = -0.6552 = Charging exponent.

The state of charge (SC) is computed as the total ampere-hours removed from the battery since the start of the run (AH) divided by the ampere-hour capacity at the ten-hour discharge rate (C10), which is the lowest current discharge for which data was given. That is:

SC = AH/C10 = State of Charge [pu] (53)

where:

AH = Total amp-hrs removed from battery [AH]

C10 = 364.219 = Capacity at 10-hour rate [AH]

The battery charging power (PCHG) is given by:

PCHG = ANC * VCHG * AIC/1000.0 = Charging power [kw]. (54)

where:

ANC = 256.0 = Number of cells per battery

VCHG = Charging voltage per cell [volt]

AIC = Charging current (into the battery is positive AIC) [amps].

Solving Equation (52) for the charging current (AIC) yields:

AIC = (VCHG - EC)/(CAYC*SC**Q) - AI0 = Charging current [amp]. (55)

Substituting Equation (55) into Equation (54),

PCHG = ANC*VCHG* ((VCHG-EC)/(CAYC*SC**Q)-AI0)/1000.0 = Charging power [kw]. (56)

The power at which the battery commences gassing (PG) occurs at a charging voltage (VCHG) equal to the voltage gassing limit (EG). The gassing power limit (PG) can be found by setting VCHG equal to EG in Equation 51. That is:

$$PG = -ANC*EG*((EG-EC)/(CAYC*SC**Q) - AI0)/1000.0 \qquad (57)$$

= Battery gassing power limit [kw].

During charge, the battery power (PB) is kept below the gassing limit (PG) in magnitude. The negative sign of Equation 57 indicates power flow to the battery. Solving Equation 54 for VCHG and equating it to Equation 52,

$$1000.0 * PCHG/(ANC*AIC) = EC + CAY*(AIC + AI0) * SC**Q. \qquad (58)$$

Setting the charging power (PCHG) equal to the battery power (PG) in Equation 58 and solving for the charging current (AIC) yields,

$$AIC = (-BC+SQRT(BC**2.0+4.0*AC*CC)/(2.0*AC) \qquad (59)$$

= Charging current [amps]

<u>where</u>:

$$AC = ANC* CAYC * SC ** Q$$

$$BC = ANC*(CAYC*SC**Q*AI0+EC)$$

$$CC = 1000.0 * PB.$$

In the regenerative braking mode, the charging current is assigned the symbol AIC to distinguish it from the current during recharge at the end of the mission, which has the symbol ACHG. During charge, whenever the ampere-hours of the battery (AH) decrease, a charging inefficiency is introduced by dividing the charging ampere-hours by a factor (AHF) which equals 1.1. At the end of the run, the battery is charged back to its original state of charge. The charging current (ACHG) is set equal to a maximum value (AICM). The charging voltage (VCHG) and power (PCHG) are then computed from the following equations:

$$VCHG + EC + CAYC * (AICM + A10) * SC ** Q = \text{Charging voltage per cell [volt]} \qquad (60)$$

$$PCHG = ANC * VCHG * AICM/1000.0 = \text{Charging power [kw]} \qquad (61)$$

where:

EC = 2.0 = Charging constant [volt]

CAYC = 0.001178 = Charging resistance per cell [ohm]

AICM = 70.3125 = Maximum battery current during recharge [amp]

AI0 = 42.1875 = Offset current [amp]

SC = State of charge [pu]

Q = -0.6552 = Charging exponent

ANC = 256.0 = Number of cells of battery.

The charging ampere-hours (AH) are computed during each time increment (TAU), and the state of recharge (SC) is determined as:

$$SC = AH/C10 = \text{State of recharge [pu]} \qquad (62)$$

where:

AH = Ampere-hours replaced into battery [AH]

C10 = 364.219 = Battery capacity at 10-hour rate [AH].

4. PROGRAM OPERATION

A flowchart of the computer program is shown in Figure 4-1. Complete FORTRAN source listings are given in Section 5.1.

Each subroutine is first called to initialize parameters within that subroutine. On all subsequent calls, the initialization sections are skipped. Page and column headings are then written in the output data file FOR03.DAT and the program enters its main iteration loop.

At each time increment the subroutine PROF is called first to determine the mission profile conditions of acceleration, speed, and position of the vehicle, roadway grade, and encountered headwind. PROF also determines the total drag force on the vehicle and the required accelerating thrust, which is used to compute the vehicle's acceleration, speed and position at each instant of time. From the mission profile conditions, the tractive force, propulsion power, and motor shaft power are calculated. Then the subroutine MOTOR is called to compute the input electric power to the motor for the required output shaft power. The battery power is computed as the sum of the motor input power, the power lost in the PCU and the auxiliary power. The subroutine BATT is then called to determine battery current, voltage, and state of charge for the required battery power. The total energy and ampere-hours removed from the battery since the start of the run are also determined.

If either the battery current limit or gassing power limit is exceeded, the program reduces the demanded motor shaft power in small decrements and loops back through the MOTOR subroutine until the limit is satisfied. The program then writes one line of data in the output file FOR03.DAT. If plots are desired, one line of data is also written in the file, FOR22.DAT (this file is required as input to the plotting program, and contains the value of the six time-varying system parameters that are to be displayed). The time clock is then incremented if the end of the cycle has not been reached, and the program loops back to PROF for the next iteration.

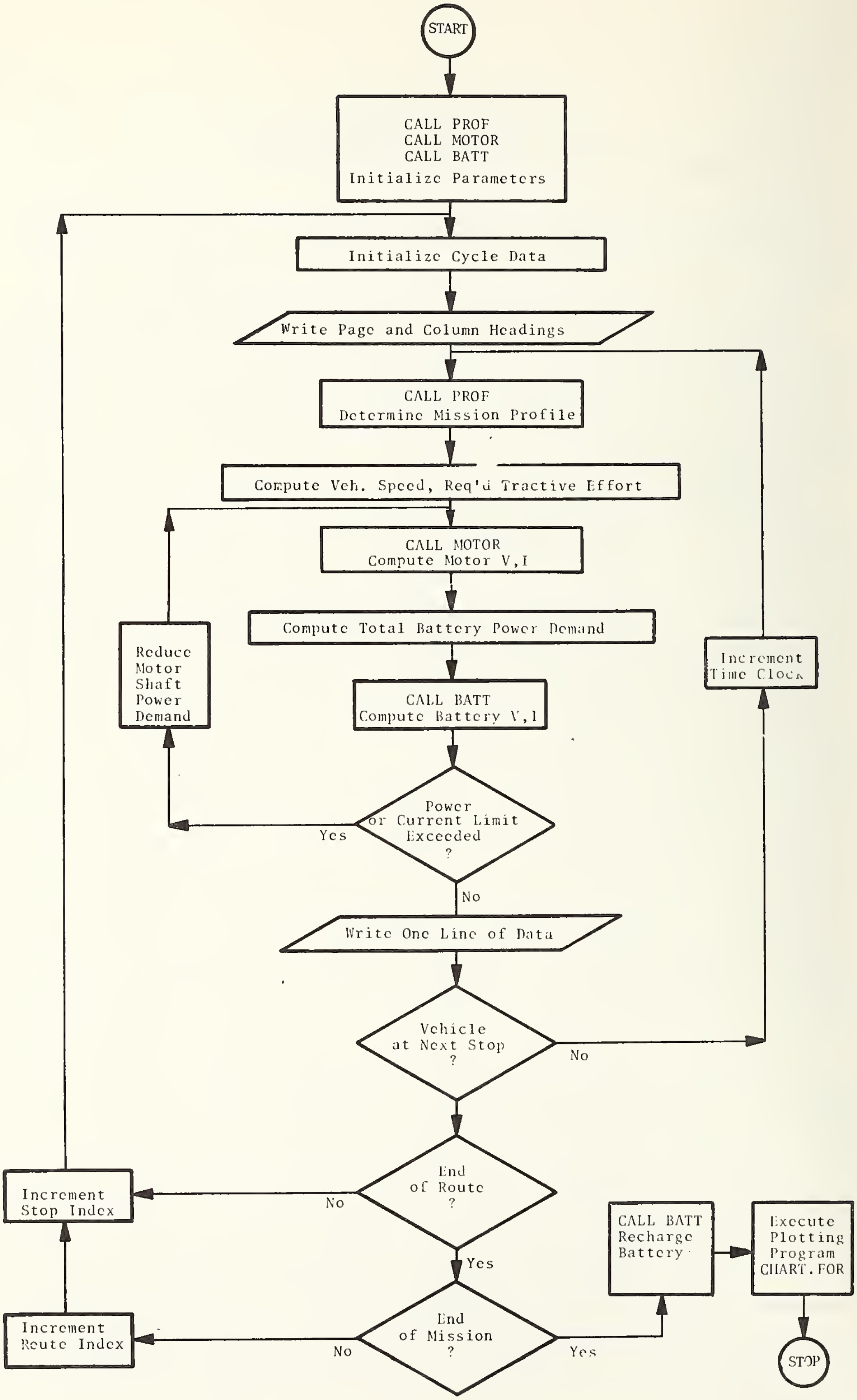


FIGURE 4-1. PROGRAM FLOWCHART

A specified number of driving cycles are made per mile, and at the end of each cycle, the stop index is incremented, page and column headings are written in FOR03.DAT, and the next cycle is begun. At the end of each route, which is a specified number of miles, the route index is incremented, page and column headings written, and the next route is begun. At the end of a specified number of routes, the mission is complete and subroutine BATT is called to write a run summary, execute the battery recharge model, and write the recharge results in FOR03.DAT.

The plotting program CHART.FOR can then be executed to display any six time-varying system parameters on an off-line CALCOMP pen plotter.

4.1 EXECUTING THE PROGRAM

The main program and all subroutines are contained in separate source files. By not combining all subroutines into one source file, compilation time is minimized if changes must be made to only a few files. The main program and all subroutines must be compiled and loaded into the computer's active core area before execution can begin. Loading is done using a command file, BUS.CMD, which contains the names of all files that must be loaded. Section 5.6 contains a listing of BUS.CMD, and the list of files to be loaded should correspond exactly to file names and extensions which exist on the disk area.

Once all files are compiled, the following command is typed on the user's terminal:

```
EXECUTE   @ BUS.CMD.
```

The subroutines are then loaded along with the main program and execution begins. The program first asks the user to specify one of three typical driving cycles which determine acceleration, cruising speed, number of stops per mile, route length, etc. A "1" is typed, followed by a carriage return, if Cycle A is desired, a "2" for Cycle B, or a "3" for Cycle C. The program then asks for a code number to indicate which type of output data is desired. A "1" will cause the output data file, FOR03.DAT, to be generated (see Section 3.5). A "2" will generate the plot file FOR22.DAT, which can later be used by the plotting program to produce CALCOMP plots of system parameters. A "3" will generate both files, a "4" neither. The code number is typed, followed by a carriage return, and the program proceeds unassisted. At the end of execution, the file FOR03.DAT is automatically queued for printing on the line printer. To print all FORTRAN source files contained in the command file BUSL.CMD (see Section 3.6) the following command is given:

```
LIST @  BUSL.CMD.
```

4.2 PLOTTING PROGRAM CHART.FOR

A plotting program has been developed to display any six time-varying system parameters on an off-line CALCOMP pen plotter. The program uses the standard CALCOMP subroutine calls, and writes instructions on a magnetic tape which are later interpreted by the plotting device to generate the plots. Figures 5-1a and 5-1b (Section 5) show sample plots for Driving Cycles A and B, respectively. The peak values of each parameter must be determined before execution and the approximate y-axis scales chosen. These scale values are entered during execution of the program, as are labels for each of the six strip-charts and the X-axis length in inches. See References 1 and 2 for further documentation of the plotting program. Section 5.7 contains a listing of the program which has the file name CHART.FOR.

5. APPLICATION OF COMPUTER PROGRAM TO BATTERY BUS OPERATION

This section describes the input data required by the Battery Bus Performance Program and presents typical input data required to simulate battery bus operation over a prescribed speed-time profile. The input data is listed in Table 5-1 according to the subroutine in which it is used; a complete glossary of computer quantities is given in Appendix A. The results of calculations based on the input data are displayed in graphical form in Figures 5-1a and 5-1b.

Much of the input data required in the program is of general character and not restricted to a particular type of system component. Thus, for example, in the subroutine PROF, data pertaining to vehicle weight, wind speed, and acceleration are required in any program in which a vehicle is being modeled. In other cases, however, the input data is related to the specific type of system component being used. In this program, the subroutine MOTOR models a shunt wound dc motor with power loss in the field winding in addition to the other loss contributions. The use of other dc motor types would require different program statements and corresponding set of input data to be used. The list of input data presented in Table 5-1 is meant to show the general requirements of this program and familiarize the reader with the type of data used in the program.

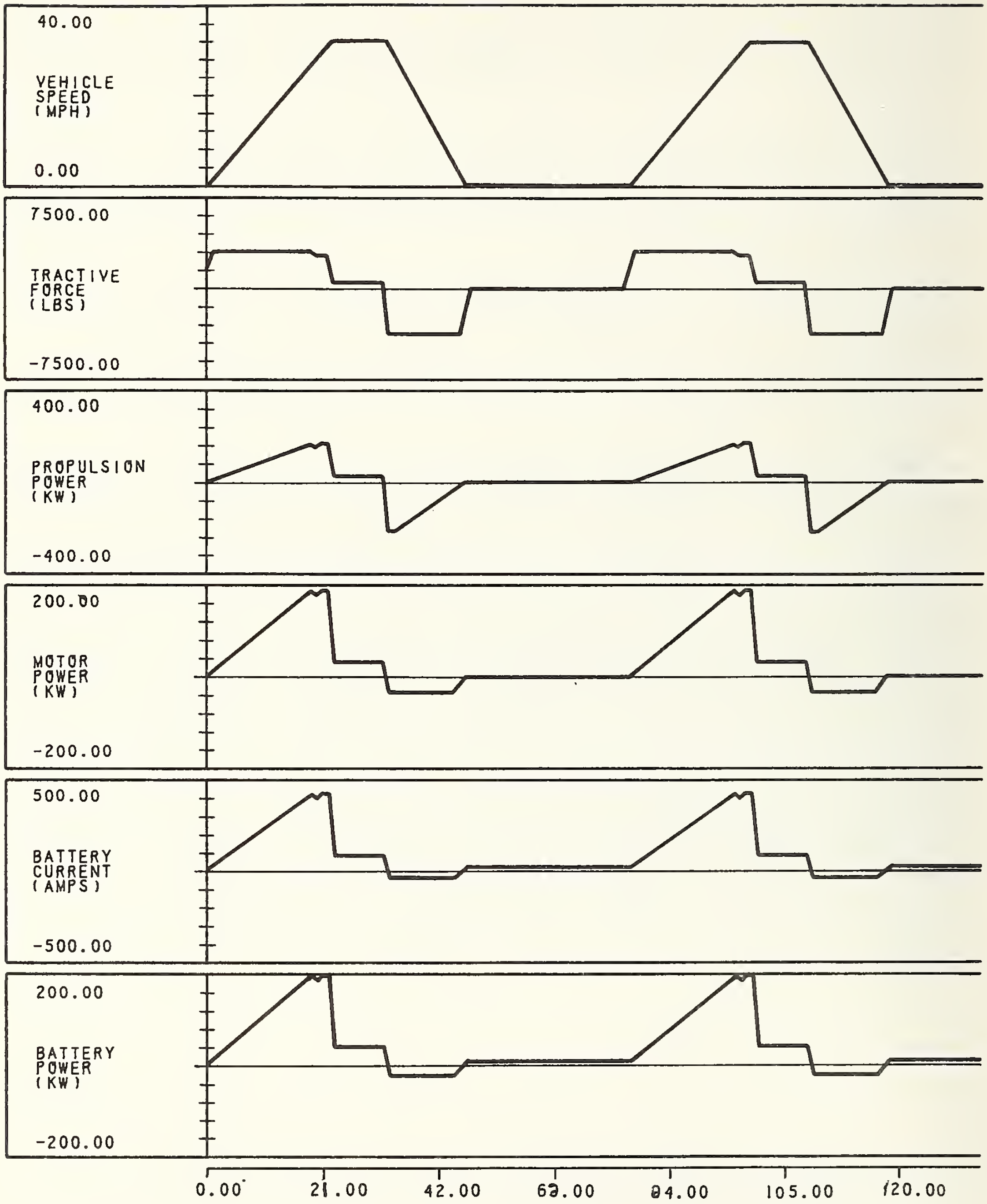


FIGURE 5-1a. CALCOMP PLOTS OF SYSTEM PARAMETERS - DRIVING CYCLE A

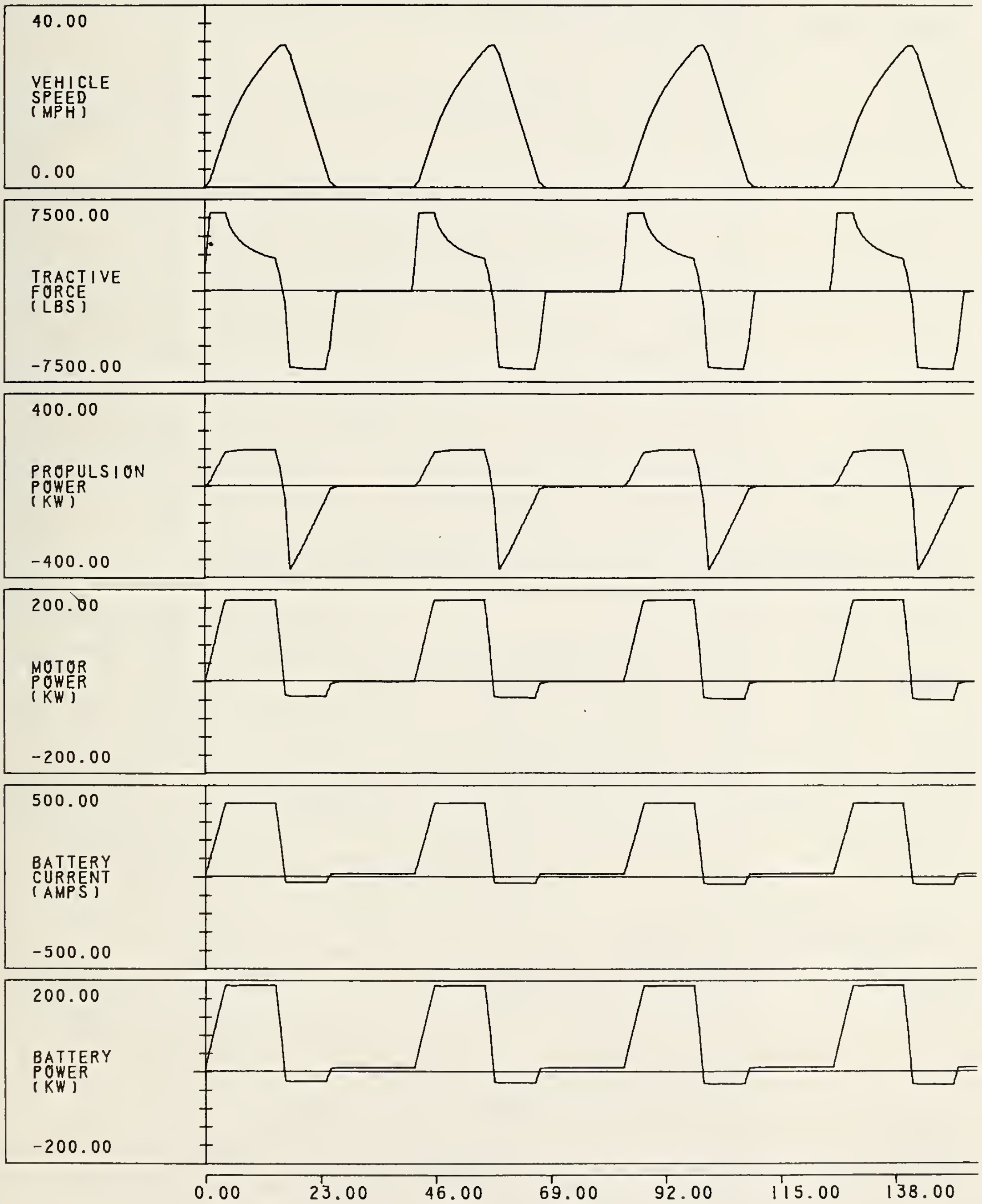


FIGURE 5-1b. CALCOMP PLOTS OF SYSTEM PARAMETERS - DRIVING CYCLE B

TABLE 5-1. COMPUTER INPUT DATA

Input Data Required by MAIN

TAU	Computing interval	1.0 sec
TIMX	Output interval	1.0 sec
ETAG	Rear end efficiency	.945
PAC	Air conditioning compressor power	6.0 kw
PCBLO	Air conditioning compressor blower	0.6 kw
PECBLO	Environmental control blower	0.6 kw
PAIR	Average air compressor load	1.0 kw
PLTG	Lighting power	3.6 kw
PBC	Average battery charger load	3.2 kw
PTBLO	Traction motor blower power	0.6 kw
PBAUX	Battery auxiliary power	0.2 kw
IAC	Air conditioning control mode	0

Input Data Required by Subroutine PROF

AJERK	Jerk rate	3.5 mph/sec^2
PHIW	Wind direction	0.0 deg
PHIR	Route direction	0.0 deg
WS	Wind speed	0.0 mph
AF	Vehicle frontal area	80. ft^2
CR	Coefficient of rolling friction	.005 lbf/lbm
WTCRB	Curb weight of vehicle	36,400 lb
WTP	Weight of typical passenger	150 lb

Data for drive Cycle B:

ACCM	Maximum acceleration	3.5 mph/sec
DECL	Deceleration	3.5 mph/sec
VC	Cruise speed	31 mph
NS	Number of stops per mile	8
DWELL	Dwell time at stop	16 sec
TAUMU	Makeup time	0 sec
NP	Number of passengers	20
SR	Route length	2 miles
NT	Number of routes per mission	1

TABLE 5-1. COMPUTER INPUT DATA (CONTINUED)

Input Data Required by Subroutine MOTOR		
AMPMO	Maximum traction motor current-normal	700. amp
AMPMG	Maximum traction motor current-on grade	770. amp
VOLTMA	Maximum traction motor input voltage-accel.	530. amp
VOLTMD	Maximum traction motor input voltage-decel.	600. amp
VB	Brush drop	2.0 volt
RTMA	Traction motor armature resistance	.0405 ohm
RATIO	Reduction gear ratio	11.42
TF	Tire factor	8.003
CAYOA	Excitation limit-acceleration	.215
CAYOD	Excitation limit-deceleration	.23
CAYOG	Excitation limit on grade	.25
PSMA	Maximum shaft power-acceleration	223.7 kw
PSMD	Maximum shaft power-deceleration	223.7 kw
Input Data Required by Subroutine BATT		
ANC	Number of cells in battery	256.
ABM	Max. allowable battery discharge current	421.88 amp
EO	Open circuit battery voltage	2.045 volts
EC	Battery charging equation constant	2.
EG	Battery gassing voltage	2.6 volts
AHR	Rated battery capacity	3.19.9 amp-h
SBO	Initial state of discharge	.05
C10	Battery capacity at 10 hour rate	364.2 amp-h
DD	Depth of discharge	0.6
CN	Exponent in battery capacity equation	-1.204

TABLE 5-1. COMPUTER INPUT DATA (CONTINUED)

Input Data Required by Subroutine BATT (Continued)

CM	Exponent in discharge equation	2.24
CAYA	Coefficient in battery capacity equation	939.07
CAYB	Constant in battery capacity equation	.10107
CAYC	Factor in charging equation	.001178
CAYD	Coefficient in discharge equation	.419
AIO	Offset current in charging voltage equation	42.188 amp
Q	Exponent in charging equation	-.6552
RB	Battery resistance in discharge equation	.00516 ohm
AICM	Maximum charging current	70.35 amp
ETACHG	Wayside charging station efficiency	.96
AHF	Ampere-hour factor	1.1

5.1 FORTRAN SOURCE LISTINGS AND DATA FILES

MAIN.FOR

```
C**** BATTERY BUS PERFORMANCE PROGRAM;
      COMMON /CPROF/WTCRB,TAU1,IAC,IDC,VC,NS,SS,DWELL,TAUMU,NP,WT,SR,NT,
     #  SN,TS,T4,TAU,JM,ISW,AJERKR,AF,CD,CR,ACCM,DECL
      COMMON /CMOTOR/IND,AMPMO,AMPMG,VOLTMA,VOLTMD,VB,RTMA,RATIO,
     #  TF,CAYOA,CAYOD,CAYOG,PSMA,PSMD
      COMMON /CPCU/PAC,PCBLO,PECBLO,PAIR,PLTG,PBC,PTBLO,PBAUX
      COMMON /CBATT/EBAT,S,THETA,I1,ANC,ABM,EO,EC,EG,AHR,SBO,C10,
     #  DD,CN,CM,CAYA,CAYB,CAYC,CAYD,AIO,Q,RB,AICM,ETACHG,AHF,TEMP
      DATA  TAU1/1.0/,TIMX/1.0/,ETAG/0.945/,IAC/0/
C**** SPECIFY DRIVING CYCLE;
      WRITE(5,214)
      READ(5,215) IDC
C**** SPECIFY OUTPUT FILES;
      WRITE(5,218)
      READ(5,215) IOF
      IF((IOF.EQ.1).OR.(IOF.EQ.3)) I1=1
      IF((IOF.EQ.2).OR.(IOF.EQ.3)) I2=1
      WRITE(5,216)
C**** INITIALIZATION;
      I=0
      II=1
      JM=1
      CALL PROF(V,ACC,GRADE,HW,S,TN,TD)
      CALL BATT(VBAT,ABT,PB,PG,AH,TAU,IND)
      IF(I1.NE.1) GO TO 35
C**** OUTPUT PAGE HEADING;
      WRITE(3,217) WTCRB,TF,RATIO,AF,CR,CD
      IF(IDC.EQ.1) WRITE(3,211)
      IF(IDC.EQ.2) WRITE(3,212)
      IF(IDC.EQ.3) WRITE(3,213)
      WRITE(3,221) SR,NT,NS,AMPMO,AMPMG,VOLTMA,VOLTMD,
     #  RTMA,PSMA,PSMD,EO,ANC,EG,AHR,RB,ABM
C**** INITIALIZE CYCLE DATA;
   35 ISW=1
      ACC=0.01
      V=0.01
      TAU=TAU1/5.0
      TIM=0.0
      IWC=1
      SN=S+SS
      IF(I1.NE.1) GO TO 40
C**** OUTPUT CYCLE DATA;
      WRITE(3,203) I,II,SS,NP,WT,VC,ACCM,DECL,DWELL,HW
C**** OUTPUT DRIVING CYCLE;
      IF(IDC.EQ.1) WRITE(3,211)
      IF(IDC.EQ.2) WRITE(3,212)
      IF(IDC.EQ.3) WRITE(3,213)
C**** OUTPUT AIR CONDITIONING STATUS;
      IF(IAC.EQ.1) WRITE(3,201)
      IF(IAC.EQ.0) WRITE(3,202)
C**** OUTPUT COLUMN HEADINGS;
      WRITE(3,204)
```

MAIN.FOR (CON'T.)

```
C**** DETERMINE PROFILE CONDITIONS;
   40 CALL PROF(V,ACC,GRADE,HW,S,TN,TD)
      IF(TS.GT.T4) GO TO 60     !END OF CYCLE!
C**** COMPUTE TRACTIVE FORCE, PROPULSION POWER, AND MOTOR SHAFT POWER;
      TP=TN+TD
      PW=0.001989*TP*V
      IF(TP.LT.0.0) PS=PW*ETAG
      IF(TP.GE.0.0) PS=PW/ETAG
      PS1=PS

C**** COMPUTE TRACTION MOTOR CURRENT, VOLTAGE, INPUT POWER, AND LOSSES;
   45 CALL MOTOR(PS,V,GRADE,AMP,VOLT,VBAT,CAY,PTF)
      PTMIN=VOLT*AMP/1000.0
      PTML=ABS(PTMIN-PS)
C**** COMPUTE PCU LOSSES AND AUXILIARY POWER;
      CALL PCU(AMP,VOLT,ABT,VBAT,PCUL,PAUX,PTF,IAC)
C**** COMPUTE BATTERY POWER, CURRENT, VOLTAGE, AND AMPERE-HOURS;
      PB=PTMIN+PCUL+PAUX
      CALL BATT(VBAT,ABT,PB,PG,AH,TAU,IND)
      IF(IND.EQ.1) GO TO 45    !POWER LIMITED MODE!
      IF(IND.EQ.2) GO TO 70    !BATTERY DISCHARGED!
      IF(PTMIN.GE.0.0) PG=0.0
C**** UPDATE TRACTIVE FORCE AND PROPULSION AND BRAKING POWER;
      IF(TP.GT.0.0) TN=TN-((PS1-PS)*ETAG)/(0.001989*(V+0.001))
      TP=TN+TD
      IF(TP.GE.0.0) PW=PS*ETAG
      IF(TP.LT.0.0) PF=PW-PS/ETAG
      IF(TP.GT.0.0) PF=0.0
C**** OUTPUT TIME HISTORY OVER CYCLE;
      IF((IWC.EQ.1).AND.(I1.EQ.1)) WRITE(3,206) THETA,ACC,V,S,GRADE,TP,
     #  TN,AMP,VOLT,ABT,VBAT,AH,PG,PB,PAUX,PCUL,PTML,PTMIN,PS,PW,PF
      IF((IWC.EQ.1).AND.(I2.EQ.1)) WRITE(22,219) THETA,V,TP,PW,PTMIN,
     #  ABT,PB
      IF(V.GT.VP) VP=V
      IF(ABS(TP).GT.ABS(TPP)) TPP=TP
      IF(ABS(PW).GT.ABS(PWP)) PWP=PW
      IF(ABS(PTMIN).GT.ABS(PTMINP)) PTMINP=PTMIN
      IF(ABS(ABT).GT.ABS(ABTP)) ABTP=ABT
      IF(ABS(PB).GT.ABS(PBP)) PBP=PB
      IWC=0
C**** INCREMENT PRINT CLOCK;
      TIM=TIM+TAU
      IF(TIM.GE.TIMX) IWC=1
      IF(TIM.GE.TIMX) TIM=0.0
C**** INCREMENT RUN TIME CLOCK;
      THETA=THETA+TAU
      IF(THETA.GT.10000.0) STOP
      GO TO 40
C**** END OF CYCLE;
   60 TS=0.0
      I=I+1
      II=I+1
      IF(S.GE.JM*SR-0.05) GO TO 65
```

```
      GO TO 35
C**** END OF ROUTE:
   65 JM=JM+1
      IF(S.GT.NT*SR-0.05) GO TO 70
      GO TO 35
C**** END OF MISSION:
   70 IF((IND.EQ.2).AND.(I1.EQ.1)) WRITE(3,209)
      IF(IND.EQ.2) WRITE(5,209)
      TMIN=THETA/60.0
      VAVE=S/(THETA/3600.0)
      SC=AH/C10
C**** WRITE RUN SUMMARY:
      IF(I1.EQ.1) WRITE(3,220) TMIN,S,I,VAVE,VP,TPP,PWP,PTMINP,
     #  ABTP,PBP,AH,SC,EBAT
C**** RECHARGE BATTERY:
      IND=2
      CALL BATT(VBAT,ABT,PB,PG,AH,TAU,IND)
  201 FORMAT(/,'  AIR CONDITIONING ON')

  202 FORMAT(/,'  AIR CONDITIONING OFF')
  203 FORMAT(1H1,//,'  DATA FOR TRAVEL BETWEEN STOPS',I4,' AND',I4,//,
     # '  DISTANCE BETWEEN STOPS       (SS)=',F7.3,' MI',//,
     # '  NUMBER OF PASSENGERS         (NP)=',I7,//,
     # '  VEHICLE GROSS WEIGHT         (WT)=',F7.0,' LBS',//,
     # '  CRUISING SPEED               (VC)=',F7.1,' MPH',//,
     # '  REQUIRED ACCEL. RATE       (ACCM)=',F7.1,' MPH/SEC',//,
     # '  DECELERATION RATE          (DECL)=',F7.1,' MPH/SEC',//,
     # '  DWELL TIME AT EACH STOP   (DWELL)=',F7.1,' SEC',//,
     # '  ENCOUNTERED HEADWIND         (HW)=',F7.1,' MPH',/)
  204 FORMAT(////,'  THETA  ACC    V     S   GRADE    TP      TN      AMP
     #  VOLT   ABT  VBAT    AH    PG     PB  PAUX  PCUL  PTML PTMIN
     #    PS    PW    PF ',/)
  206 FORMAT(1X,F6.1,2F5.1,F6.2,F6.3,2F7.0,4F6.0,10F6.1)
  209 FORMAT(/,'  BATTERY DISCHARGED...',//)
  211 FORMAT(/,'  MISSION :   DRIVING CYCLE A')
  212 FORMAT(/,'  MISSION :   DRIVING CYCLE B')
  213 FORMAT(/,'  MISSION :   DRIVING CYCLE C')
  214 FORMAT(/,' ENTER DRIVING CYCLE:',/,
     #  ' TYPE "1" FOR A, "2" FOR B, "3" FOR C:',/)
  215 FORMAT(I1)
  216 FORMAT(/,' WORKING...',//)
  217 FORMAT(1H1,13X,'BATTERY BUS PERFORMANCE PROGRAM',///,
     #'  VEHICLE :   BATTERY-POWERED MASS TRANSIT BUS',//,
     #'              CURB WEIGHT          (WTCRB)=',F7.0,' LBS',//,
     #'              TIRE FACTOR             (TF)=',F7.3,' RPM/MPH',//,
     #'              GEARBOX RATIO        (RATIO)=',F7.2,//,
     #'              FRONTAL AREA            (AF)=',F7.1,' SQ-FT',//,
     #'              ROLLING DRAG COEFF.  (CR)=',F7.3,//,
     #'              AERO. DRAG COEFF.    (CD)=',F7.3,/)
  218 FORMAT(/,' ENTER TYPE OF OUTPUT DESIRED:',/,
     #  ' TYPE "1" FOR DATA FILE FOR03.DAT,',/,
     #  ' TYPE "2" FOR PLOT FILE FOR22.DAT,',/,
     #  ' TYPE "3" FOR BOTH FILES,',/,
     #  ' TYPE "4" FOR NEITHER FILE:',/)
  219 FORMAT(1X,7F10.3)
      STOP
      END
```

PROF.FOR

```
      SUBROUTINE PROF(V,ACC,GRADE,HW,S,TN,TD)
      DIMENSION G(25,2)
      COMMON /CPROF/WTCRB,TAU1,IAC,IDC,VC,NS,SS,DWELL,TAUMU,NP,WT,SR,NT,
     # SN,TS,T4,TAU,JM,ISW,AJERKR,AF,CD,CR,ACCM,DECL
      DATA  GEE/21.927/,AJERKR/3.5/,PHIR/0.0/,PHIW/0.0/,WS/0.0/,
     # AF/80.0/,CD/0.84/,CR/0.005/,WTCRB/36400.0/,WTP/150.0/
      IF(INI.EQ.1) GO TO 1000
      INI=1
C**** INITIALIZATION;
      IF(IDC.EQ.1) GO TO 1
      IF(IDC.EQ.2) GO TO 2
      IF(IDC.EQ.3) GO TO 3
C**** DRIVING CYCLE A;
    1 ACCM=1.44
      DECL=2.2
      VC=31.0
      NS=4
      SS=1.0/NS
      DWELL=30.0
      TAUMU=0.0
      NP=15
      SR=6.0
      NT=4
      GO TO 4
C**** DRIVING CYCLE B;
    2 ACCM=3.5
      DECL=3.5
      VC=31.0
      NS=8
      SS=1.0/NS
      DWELL=16.0
      TAUMU=0.0
      NP=20
      SR=6.0
      NT=4
      GO TO 4
C**** DRIVING CYCLE C;
    3 ACCM=2.5
      DECL=2.5
      VC=25.0
      NS=5
      SS=1.0/NS
      DWELL=20.4
      TAUMU=330.0
      NP=8
      SR=6.0
      NT=4
```

```
C**** COMPUTE VEHICLE GROSS WEIGHT AND ACCELERATING MASS:
    4 WT=WTCRB+(NP+1)*WTP
      AMASS=(WT+2300.0)/GEE
C**** GRADE DATA:
      G(1,1)=0.0
      G(1,2)=0.0
      G(2,1)=100.0
      G(2,2)=0.0
      KG=1
      AJERK=AJERKR
      RETURN
C**** COMPUTE VEHICLE DYNAMICS:
 1000 ACC=TN/AMASS
      ABAR=(ACC+ACC1)/2.0
      ACC1=ACC
      V=V+ABAR*TAU
      VBAR=(V+V1)/2.0
      V1=V
      S=S+VBAR*TAU/3600.0
C**** DETERMINE HEADWIND AND GRADE:
      HW=-WS*COS(0.01745*(PHIR-PHIW))
   55 JG=KG+1
      IF(S.GE.G(JG,1)) GO TO 60
      GO TO 65
   60 KG=KG+1
      GO TO 55
   65 GRADE=G(KG,2)/100.0
C**** COMPUTE VEHICLE DRAG:
      TG=WT*SIN(ATAN(GRADE))
      TR=CR*WT
      TA=0.00258*CD*AF*(V+HW)**2.0*(V+HW)/ABS(V+HW+0.001)
      TD=TR+TA+TG
C**** STOPPING LOGIC & SPEED CONTROL:
      TNI=AJERKR*AMASS*TAU
      IF(ISW.EQ.0) GO TO 660
      XB=V*(DECL/AJERKR+V/DECL)/7200.0
      STAB=SN-XB
      IF(S.GE.STAB) GO TO 640
      IF(V.GT.(VC-ACC**2.0/AJERKR/2.0)) GO TO 100
      TN=TN+TNI
      IF(TN.GT.ACCM*AMASS) TN=ACCM*AMASS
      GO TO 120
C**** APPROACHING CRUISE SPEED:
  100 TN=TN-TNI
      IF(TN.LT.0) TN=0.0
      GO TO 120
C**** INITIATE STOP:
  640 IF(ISW.EQ.1) GO TO 650
      GO TO 660
```

PROF.FOR (CON'T.)

```
  650 ACC=0.0
      T1=DECL/AJERKR
      T2=V/DECL
      T3=T1+T2
      T4=T3+DWELL
      IF(S.GE.JM*SR-0.1) T4=T4+TAUMU
      ISW=0
      TS=0.0
  660 TS=TS+TAU
      IF(TS.GT.T1) GO TO 670
C**** ONSET;
      AJERK=-AJERKR
      GO TO 692
  670 IF(TS.GT.T2) GO TO 680
C**** DECELERATION;
      AJERK=0.0
      ACC=-DECL
      GO TO 694
  680 IF(TS.GT.T3) GO TO 690
C**** FLAIR;
      AJERK=AJERKR
      GO TO 692
  690 IF(TS.GT.T4) GO TO 120
C**** DWELL;
      AJERK=0.0
      ACC=0.0


      V=0.001
      TN=0.0
      TD=0.0
      S=SN
      TAU=TAU1
      GO TO 120
  692 ACC=ACC+AJERK*TAU
  694 TN=ACC*AMASS
  120 RETURN
      END
```

MOTOR.FOR

```
      SUBROUTINE MOTOR(PS,V,GRADE,AMP,VOLT,VBAT,CAY,PTF)
      COMMON /CMOTOR/IND,AMPM0,AMPMG,VOLTMA,VOLTMD,VB,RTMA,RATIO,
     #  TF,CAY0A,CAY0D,CAY0G,PSMA,PSMD
      DATA  AMPM0/700.0/,AMPMG/770.0/,VOLTMA/530.0/,VOLTMD/600.0/,
     #  VB/2.0/,RTMA/0.04048/,RATIO/11.42/,TF/0.003/,
     #  CAY0A/0.215/,CAY0D/0.23/,CAY0G/0.25/,PSMA/223.7/,PSMD/223.7/
C**** TURN OFF MOTOR IF VEHICLE IS AT REST:
      IF(V.LE.0.01) CAY=0.0001
      IF(V.LE.0.01) AMP=0.0
      IF(V.LE.0.01) VOLT=VBAT
      IF(V.LE.0.01) PTF=0.0
      IF(V.LE.0.01) RETURN
C**** REDUCE SHAFT POWER IF IN POWER LIMITED MODE:
      IF(IND.EQ.1) PS=PS*0.95
      IF(IND.EQ.1) GO TO 160
C**** COMPUTE MOTOR SPEED:
      RPM=RATIO*TF*V
      IF(PS.GE.0.0) GO TO 135
C**** BRAKING MODE POWER, VOLTAGE, AND EXCITATION LIMITS:
      IF(ABS(PS).GT.PSMD) PS=-PSMD
      VOLTM=VOLTMD
      CAY0=CAY0D
      GO TO 145
C**** MOTORING MODE POWER, VOLTAGE, AND EXCITATION LIMITS:
  135 IF(ABS(PS).GT.PSMA) PS=PSMA
      VOLTM=VOLTMA
      IF(VOLTM.GE.VBAT) VOLTM=VBAT
      CAY0=CAY0A
C**** ARMATURE CURRENT LIMIT AND INCREASED LIMITS ON GRADE:
  145 AMPM=AMPM0
      IF(GRADE.GT.0.15) AMPM=AMPMG
      IF(GRADE.GT.0.15) CAY0=CAY0G
```

```
C**** TRACTION MOTOR LOSSES;
      PTMB=0.001*RPM
      PTMW=1.475*(RPM/4540.0)**2.0
  160 PTMI=2.629E-04*CAY**1.29*RPM**1.406
C**** COMPUTE AIR GAP POWER;
      PTMA=(PS+PTMB+PTMW+PTMI)/0.99
C**** DETERMINE EXCITATION CONSTANT CAY;
      C1=(VOLTM-VB)/RPM
      C2=4000.0*PTMA*RTMA/(RPM**2.0)
      CAYV=(C1+SQRT(C1**2.0-C2))/2.0
      CAYI=1000.0*PTMA/(RPM*AMPM)
      IF(CAYV.GT.CAYI) GO TO 170
  165 PS=0.99*PS
      GO TO 160
  170 IF(CAY0.GT.CAYV) GO TO 175
      CAY=CAY0
      IF(CAY.GT.CAYI) GO TO 180
      GO TO 165
  175 CAY=CAYV
C**** UPDATE IRON LOSS AND AIR GAP POWER IF CAY RESET;
  180 PTMI1=2.629E-04*CAY**1.29*RPM**1.406
      PTMA=PTMA+PTMI1-PTMI
C**** COMPUTE ARMATURE CURRENT, TERMINAL VOLTAGE, AND FIELD POWER;
      AMP=1000.0*PTMA/(CAY*RPM)
      VOLT=CAY*RPM+VB+AMP*RTMA
      IF(CAY.LE.0.18) PTF=0.5*(CAY/0.18)**2.0
      IF(CAY.GT.0.18) PTF=0.5*(CAY/0.18)**5.646
      RETURN
      END
```

BATT.FOR (CON'T)

```
      SUBROUTINE BATT(VBAT,ABT,PB,PG,AH,TAU,IND)
      COMMON /CBATT/EBAT,S,THETA,I1,ANC,ABM,E0,EC,EG,AHR,SB0,C10,
     # DD,CN,CM,CAYA,CAYB,CAYC,CAYD,AI0,Q,RB,AICM,ETACHG,AHF,TEMP
      DATA  ANC/256.0/,ABM/421.875/,E0/2.045/,EC/2.0/,EG/2.6/,
     # AHR/319.922/,SB0/0.05/,C10/364.219/,DD/0.6/,CN/-1.204/,
     # CM/2.24/,CAYA/937.969/,CAYB/0.10107/,CAYC/0.001178/,
     # CAYD/0.4190/,AI0/42.1875/,Q/-0.6552/,RB/0.000516/,
     # AICM/70.3125/,ETACHG/0.96/,AHF/1.1/,TEMP/30.0/,TEMPM/30.0/,
     # TEMPF/100.0/
      IF(INI.EQ.1) GO TO 1000
      INI=1
C**** INITIALIZATION!
      AH=C10*SB0
      VBAT=E0*ANC
      RETURN
 1000 IF(IND.EQ.2) GO TO 720    !EXECUTE RECHARGE MODEL!
      IND=0      !NORMAL OPERATION!
C**** COMPUTE APPROXIMATE VALUE OF BATTERY CURRENT!
      ABT=1000.0*PB/(E0*ANC)
      IF(ABT.GE.0.0) GO TO 700
C**** BATTERY CHARGING!
C**** COMPUTE STATE OF CHARGE!
      SC=AH/C10
C**** COMPUTE GASSING POWER LIMIT!
      PG=-ANC*EG*((EG-EC)/(CAYC*SC**Q)-AI0)/1000.0
      IF(PB.LT.PG) IND=1     !GASSING POWER LIMIT EXCEEDED!
      IF(IND.EQ.1) RETURN
C**** COMPUTE CHARGING CURRENT!
      AC=ANC*CAYC*SC**Q
      BC=AC*AI0+ANC*EC
      CC=1000.0*PB
      AIC=(-BC+SQRT(BC**2.0-4.0*AC*CC))/(2.0*AC)
      ABT=-AIC
C**** COMPUTE BATTERY VOLTAGE!
      VBAT=1000.0*PB/(ABT+0.001)
      GO TO 711
C**** BATTERY DISCHARGING!
  700 IF(ABT.EQ.0.0) ABT=0.001
C**** COMPUTE BATTERY CAPACITY!
      CAP=(CAYA*ABT**CN-CAYB)*ABT
C**** CORRECT CAPACITY FOR TEMPERATURE VARIATION!
      FACT=1.0+(TEMP-TEMPM)/TEMPF
      CAP=CAP*FACT
C**** COMPUTE STATE OF DISCHARGE!
      SB=AH/CAP
C**** COMPUTE CURRENT CORRECTION FACTORS!
      ZETA=E0-RB*ABT-CAYD*SB**CM-1000.0*PB/(ABT*ANC)
      ZETAP=-RB+CAYD*CM*CAYA*SB**CM*ABT**(CN-1.0)
     # +1000.0*PB/(ANC*ABT**2.0)
      DELI=ZETA/ZETAP
      IF(ABS(DELI).LT.1.0) GO TO 710     !ITERATION COMPLETE!
```

```
C**** CORRECT BATTERY CURRENT!
      ABT=ABT-DELI
      IF(ABT.GT.ABM) IND=1    !BATTERY CURRENT LIMIT EXCEEDED!
      IF(IND.EQ.1) RETURN
C**** ITERATE TO REFINE BATTERY CURRENT APPROXIMATION!
      GO TO 700
C**** COMPUTE BATTERY VOLTAGE!
  710 VBAT=ANC*(E0-RB*ABT-CAYD*SB**CM)
C**** COMPUTE AVERAGE BATTERY POWER, ENERGY, AND AMPERE-HOURS!
  711 PBAVE=(PB+PB1)/2.0


      PB1=PB
      EBAT=EBAT+PBAVE*TAU/3600.0
      ABTAVE=(ABT+ABT1)/2.0
      ABT1=ABT
      DELAH=ABTAVE*TAU/3600.0
      IF(DELAH.LT.0.0) DELAH=DELAH/AHF
      AH=AH+DELAH
      IF(AH.GT.DD*AHR) IND=2     !BATTERY DISCHARGED!
      RETURN
C**** BATTERY RECHARGE MODEL!
  720 TAU=60.0
C**** OUTPUT CHARGING DATA COLUMN HEADINGS!
      IF(I1.EQ.1) WRITE(3,810)
C**** COMPUTE STATE OF RECHARGE!
  730 SC=AH/C10
      IF(SC.LE.SB0) GO TO 760     !RECHARGE COMPLETE!
C**** COMPUTE RECHARGE CURRENT AND VOLTAGE!
      ACHG=(EG-EC)/(CAYC*SC**Q)-AI0
      IF(ACHG.GT.AICM) GO TO 740
      VCHG=EG
      GO TO 750
  740 ACHG=AICM
      VCHG=EC+CAYC*(ACHG+AI0)*SC**Q
C**** COMPUTE RECHARGE POWER, ENERGY, AND AMPERE-HOURS!
  750 PCHG=ANC*VCHG*ACHG/1000.0
      ECHG=PCHG*TAU/3600.0+ECHG
      AH=AH-ACHG*TAU/(3600.0*AHF)
      CHGTIM=CHGTIM+TAU/60.0
C**** OUTPUT RECHARGING DATA!
      IF(I1.EQ.1) WRITE(3,820) CHGTIM,SC,ACHG,VCHG,PCHG,AH,ECHG
      GO TO 730     !CONTINUE ITERATION!
```

```
C**** RECHARGE COMPLETE:
  760 SC=SB0
C**** COMPUTE SPECIFIC CHARGING ENERGIES:
      EPM=ECHG/S
      EPM1=EPM/ETACHG
C**** COMPUTE OVER-ALL BATTERY EFFICIENCY:
      EFFBAT=EBAT/ECHG
C**** OUTPUT RESULTS OF BATTERY RECHARGE:
      IF(I1.EQ.1) WRITE(3,830) CHGTIM,SC,EPM,EPM1,EFFBAT
  810 FORMAT(1H1,///,' BATTERY CHAGRING DATA:',//,
     #  '  CHGTIM    SC  ACHG  VCHG  PCHG    AH  ECHG',/)
  820 FORMAT(1X,F6.1,F7.3,F6.1,F6.2,3F6.1)
  830 FORMAT(//,' RESULTS OF BATTERY RECHARGE:',//,
     #' CHARGING TIME                           (CHGTIM)=',F6.1,' MIN',//,
     #' STATE OF CHARGE                             (SC)=',F6.3,' PU',//,
     #' SPECIFIC ENERGY AT BATTERY INPUT       (EPM)=',F6.2,' KWHR/MI',//,
     #' SPECIFIC ENERGY AT CHG. STA. INPUT  (EPM1)=',F6.2,' KWHR/MI',//,
     #' BATTERY EFFICIENCY                      (EFFBAT)=',F6.3,' PU',/)
      STOP
      END
```

5.2 BATTERY BUS PERFORMANCE PROGRAM

BATTERY BUS PERFORMANCE PROGRAM

```
DRIVING CYCLE A

AIR CONDITIONING OFF


FROM STOP    1 TO    2

DISTANCE BETWEEN STOPS:     SS =    0.25 MI

NUMBER OF PASSENGERS:       NP =      15

CRUISING SPEED:             VC =    31.0 MPH

DWELL TIME:              DWELL =    30.0 SEC

ENCOUNTERED HEADWIND:       HW =     0.0 MPH



  THETA  ACC    V     S  GRADE    TP     TM    AMP  VOLT   CAY   ABT  VBAT    AH    PG    PB  PTF PAUX PDRL PTMIN    PS    PM    PF

    0.0  0.0  0.0  0.00 0.000     0.     0.    0.    0. 0.230    0.  524.  18.2   0.0   0.0  0.0  0.0  0.0   0.0   0.0   0.0   0.0
    1.0  1.4  1.2  0.00 0.000  2893.  2699.  319.   32. 0.215   41.  524.  18.2   0.0  21.7  1.4 10.6  1.0  10.1   5.2   5.0   0.0
    2.0  1.4  2.6  0.00 0.000  2894.  2699.  319.   60. 0.215   59.  524.  18.2   0.0  30.7  1.4 10.6  1.0  19.2  14.0  13.2   0.0
    3.0  1.4  4.0  0.00 0.000  2896.  2699.  320.   88. 0.215   78.  513.  18.3   0.0  39.8  1.4 10.6  1.0  28.3  22.8  21.5   0.0
    4.0  1.4  5.5  0.00 0.000  2898.  2699.  320.  117. 0.215   96.  511.  18.3   0.0  48.9  1.4 10.6  1.0  37.4  31.6  29.9   0.0
    5.0  1.4  6.9  0.00 0.000  2901.  2699.  321.  145. 0.215  114.  509.  18.3   0.0  58.1  1.4 10.6  1.0  46.6  40.4  38.2   0.0
    6.0  1.4  8.3  0.01 0.000  2904.  2699.  322.  173. 0.215  133.  506.  18.3   0.0  67.3  1.4 10.6  1.0  55.8  49.3  46.5   0.0
    7.0  1.4  9.8  0.01 0.000  2909.  2699.  322.  202. 0.215  152.  504.  18.4   0.0  76.5  1.4 10.6  1.0  65.0  58.1  54.9   0.0
    8.0  1.4 11.2  0.01 0.000  2914.  2699.  323.  230. 0.215  171.  502.  18.4   0.0  85.8  1.4 10.6  1.0  74.3  67.1  63.4   0.0
    9.0  1.4 12.7  0.02 0.000  2920.  2699.  324.  258. 0.215  191.  499.  18.5   0.0  95.2  1.4 10.6  1.0  83.7  76.1  71.9   0.0
   10.0  1.4 14.1  0.02 0.000  2926.  2699.  325.  287. 0.215  211.  497.  18.5   0.0 104.6  1.4 10.6  1.0  93.1  85.1  80.4   0.0
   11.0  1.4 15.5  0.02 0.000  2934.  2699.  326.  315. 0.215  231.  495.  18.6   0.0 114.1  1.4 10.6  1.0 102.6  94.2  89.0   0.0
   12.0  1.4 17.0  0.03 0.000  2941.  2699.  327.  343. 0.215  253.  490.  18.7   0.0 123.7  1.4 10.6  1.0 112.2 103.4  97.7   0.0
   13.0  1.4 18.4  0.03 0.000  2950.  2699.  328.  372. 0.215  274.  487.  18.7   0.0 133.4  1.4 10.6  1.0 121.8 112.6 106.4   0.0
   14.0  1.4 19.9  0.04 0.000  2960.  2699.  329.  400. 0.215  296.  484.  18.8   0.0 143.1  1.4 10.6  1.0 131.6 121.9 115.2   0.0
   15.0  1.4 21.3  0.04 0.000  2970.  2699.  330.  428. 0.215  318.  481.  18.9   0.0 153.0  1.4 10.6  1.0 141.5 131.3 124.1   0.0
   16.0  1.4 22.8  0.05 0.000  2981.  2699.  331.  457. 0.215  341.  478.  19.0   0.0 163.0  1.4 10.6  1.0 151.4 140.8 133.1   0.0
   17.0  1.4 24.2  0.06 0.000  2992.  2699.  333.  485. 0.215  364.  475.  19.1   0.0 173.1  1.4 10.6  1.0 161.5 150.5 142.2   0.0
   18.0  1.4 25.6  0.06 0.000  3004.  2699.  334.  513. 0.215  388.  472.  19.2   0.0 183.2  1.4 10.6  1.0 171.7 160.2 151.4   0.0
   19.0  1.4 27.1  0.07 0.000  3017.  2699.  344.  530. 0.210  413.  469.  19.3   0.0 193.6  1.2 10.4  1.0 182.2 170.0 160.7   0.0
   20.0  1.4 28.5  0.08 0.000  2879.  2548.  345.  530. 0.200  415.  468.  19.4   0.0 194.2  0.9 10.1  1.0 183.1 170.7 169.8   0.0
   21.0  1.3 29.8  0.09 0.000  2747.  2402.  345.  530. 0.191  414.  468.  19.5   0.0 194.0  0.7  9.9  1.0 183.1 170.5 178.5   0.0
   22.0  1.2 31.0  0.09 0.000  2621.  2263.  344.  530. 0.183  412.  469.  19.6   0.0 193.0  0.5  9.7  1.0 182.2 169.5 186.9   0.0
   23.1  0.0 31.5  0.10 0.000   366.     0.   57.  530. 0.183   78.  513.  19.7   0.0  40.3  0.5  9.7  0.2  30.3  24.2  22.9   0.0
   24.1  0.0 31.5  0.11 0.000   366.     0.   57.  530. 0.183   78.  513.  19.7   0.0  40.3  0.5  9.7  0.2  30.3  24.2  22.9   0.0
   25.1  0.0 31.5  0.12 0.000   366.     0.   57.  530. 0.183   78.  513.  19.7   0.0  40.3  0.5  9.7  0.2  30.3  24.2  22.9   0.0
   26.1  0.0 31.5  0.13 0.000   366.     0.   57.  530. 0.183   78.  513.  19.8   0.0  40.3  0.5  9.7  0.2  30.3  24.2  22.9   0.0
   27.1  0.0 31.5  0.14 0.000   366.     0.   57.  530. 0.183   78.  513.  19.8   0.0  40.3  0.5  9.7  0.2  30.3  24.2  22.9   0.0
   28.1  0.0 31.5  0.15 0.000   366.     0.   57.  530. 0.183   78.  513.  19.8   0.0  40.3  0.5  9.7  0.2  30.3  24.2  22.9   0.0
   29.1  0.0 31.5  0.16 0.000   366.     0.   57.  530. 0.183   78.  513.  19.8   0.0  40.3  0.5  9.7  0.2  30.3  24.2  22.9   0.0
```

```
30.1  0.0 31.5  0.17 0.000   366.     0.    57.  530. 0.183   78.  513.  19.9  0.0  40.3 0.5  9.7 0.2  30.3  24.2  22.9   0.0
31.1  0.0 31.5  0.17 0.000   366.     0.    57.  530. 0.183   78.  513.  19.9  0.0  40.3 0.5  9.7 0.2  30.3  24.2  22.9   0.0
32.1  0.0 31.5  0.18 0.000   366.     0.    57.  530. 0.183   78.  513.  19.9  0.0  40.3 0.5  9.7 0.2  30.3  24.2  22.9   0.0
32.7 -0.3 31.4  0.19 0.000  -291.  -656.   -19.  600. 0.208   -2.  600.  19.9 23.0  -0.9 1.1 10.3 0.1 -11.3 -17.2 -18.2   0.0
33.7 -2.2 29.7  0.20 0.000 -3774. -4124.   -56.  600. 0.219  -34.  665.  19.9 23.0 -22.7 1.5 10.7 0.2 -33.6 -39.1-224.7-183.3
34.7 -2.2 27.5  0.20 0.000 -3796. -4124.   -57.  583. 0.230  -33.  663.  19.9 23.0 -21.9 2.0 11.2 0.2 -33.2 -38.3-209.4-168.8
35.7 -2.2 25.3  0.21 0.000 -3817. -4124.   -61.  537. 0.230  -32.  661.  19.9 23.0 -21.4 2.0 11.2 0.2 -32.8 -37.4-193.8-154.3
36.7 -2.2 23.1  0.22 0.000 -3835. -4124.   -69.  490. 0.230  -34.  664.  19.9 23.0 -22.5 2.0 11.2 0.2 -33.9 -38.0-178.0-137.8
37.7 -2.2 20.9  0.23 0.000 -3852. -4124.   -74.  444. 0.230  -32.  661.  19.9 22.9 -21.4 2.0 11.2 0.2 -32.8 -36.4-161.9-123.4
38.7 -2.2 18.7  0.23 0.000 -3867. -4124.   -83.  397. 0.230  -33.  662.  19.9 22.9 -21.7 2.0 11.2 0.3 -33.1 -36.3-145.7-107.3
39.7 -2.2 16.5  0.24 0.000 -3881. -4124.   -94.  350. 0.230  -32.  662.  19.9 22.9 -21.5 2.0 11.2 0.3 -32.9 -35.7-128.2 -91.5
40.7 -2.2 14.3  0.24 0.000 -3893. -4124.  -112.  303. 0.230  -34.  664.  19.8 22.9 -22.3 2.0 11.2 0.3 -33.9 -36.2-112.6 -74.2
41.7 -2.2 12.1  0.24 0.000 -3903. -4124.  -132.  256. 0.230  -34.  664.  19.8 22.9 -22.3 2.0 11.2 0.4 -33.9 -36.0 -95.8 -57.8
42.7 -2.2  9.9  0.25 0.000 -3912. -4124.  -165.  209. 0.230  -34.  665.  19.8 22.9 -22.7 2.0 11.2 0.5 -34.4 -36.4 -78.9 -40.4
43.7 -2.2  7.7  0.25 0.000 -3919. -4124.  -216.  160. 0.230  -34.  665.  19.8 22.9 -22.8 2.0 11.2 0.6 -34.6 -36.9 -61.9 -22.9
44.7 -2.2  5.5  0.25 0.000 -3924. -4124.  -313.  110. 0.230  -34.  664.  19.8 22.8 -22.3 2.0 11.2 0.9 -34.5 -38.2 -44.8  -4.4
45.7 -2.2  3.3  0.25 0.000 -3928. -4124.  -348.   62. 0.230  -15.  627.  19.8 22.8  -9.5 2.0 11.2 1.0 -21.8 -26.2 -27.7   0.0
46.7 -2.2  1.1  0.25 0.000 -3929. -4124.  -349.   16. 0.230   13.  523.  19.8 22.8   6.6 2.0 11.2 1.0  -5.7  -9.9 -10.5   0.0
48.1  0.0  0.0  0.25 0.000     0.     0.     5.    2. 0.215   18.  523.  19.8  0.0   9.2 0.0  9.2 0.0   0.0   0.0   0.0   0.0
49.1  0.0  0.0  0.25 0.000     0.     0.     5.    2. 0.215   18.  523.  19.8  0.0   9.2 0.0  9.2 0.0   0.0   0.0   0.0   0.0
50.1  0.0  0.0  0.25 0.000     0.     0.     5.    2. 0.215   18.  523.  19.8  0.0   9.2 0.0  9.2 0.0   0.0   0.0   0.0   0.0
51.1  0.0  0.0  0.25 0.000     0.     0.     5.    2. 0.215   18.  523.  19.8  0.0   9.2 0.0  9.2 0.0   0.0   0.0   0.0   0.0
52.1  0.0  0.0  0.25 0.000     0.     0.     5.    2. 0.215   18.  523.  19.8  0.0   9.2 0.0  9.2 0.0   0.0   0.0   0.0   0.0
53.1  0.0  0.0  0.25 0.000     0.     0.     5.    2. 0.215   18.  523.  19.8  0.0   9.2 0.0  9.2 0.0   0.0   0.0   0.0   0.0
54.1  0.0  0.0  0.25 0.000     0.     0.     5.    2. 0.215   18.  523.  19.8  0.0   9.2 0.0  9.2 0.0   0.0   0.0   0.0   0.0
55.1  0.0  0.0  0.25 0.000     0.     0.     5.    2. 0.215   18.  523.  19.8  0.0   9.2 0.0  9.2 0.0   0.0   0.0   0.0   0.0
56.1  0.0  0.0  0.25 0.000     0.     0.     5.    2. 0.215   18.  523.  19.8  0.0   9.2 0.0  9.2 0.0   0.0   0.0   0.0   0.0
57.1  0.0  0.0  0.25 0.000     0.     0.     5.    2. 0.215   18.  523.  19.9  0.0   9.2 0.0  9.2 0.0   0.0   0.0   0.0   0.0
58.1  0.0  0.0  0.25 0.000     0.     0.     5.    2. 0.215   18.  523.  19.9  0.0   9.2 0.0  9.2 0.0   0.0   0.0   0.0   0.0
59.1  0.0  0.0  0.25 0.000     0.     0.     5.    2. 0.215   18.  523.  19.9  0.0   9.2 0.0  9.2 0.0   0.0   0.0   0.0   0.0
60.1  0.0  0.0  0.25 0.000     0.     0.     5.    2. 0.215   18.  523.  19.9  0.0   9.2 0.0  9.2 0.0   0.0   0.0   0.0   0.0
61.1  0.0  0.0  0.25 0.000     0.     0.     5.    2. 0.215   18.  523.  19.9  0.0   9.2 0.0  9.2 0.0   0.0   0.0   0.0   0.0
62.1  0.0  0.0  0.25 0.000     0.     0.     5.    2. 0.215   18.  523.  19.9  0.0   9.2 0.0  9.2 0.0   0.0   0.0   0.0   0.0
63.1  0.0  0.0  0.25 0.000     0.     0.     5.    2. 0.215   18.  523.  19.9  0.0   9.2 0.0  9.2 0.0   0.0   0.0   0.0   0.0
64.1  0.0  0.0  0.25 0.000     0.     0.     5.    2. 0.215   18.  523.  19.9  0.0   9.2 0.0  9.2 0.0   0.0   0.0   0.0   0.0
65.1  0.0  0.0  0.25 0.000     0.     0.     5.    2. 0.215   18.  523.  19.9  0.0   9.2 0.0  9.2 0.0   0.0   0.0   0.0   0.0
66.1  0.0  0.0  0.25 0.000     0.     0.     5.    2. 0.215   18.  523.  19.9  0.0   9.2 0.0  9.2 0.0   0.0   0.0   0.0   0.0
67.1  0.0  0.0  0.25 0.000     0.     0.     5.    2. 0.215   18.  523.  19.9  0.0   9.2 0.0  9.2 0.0   0.0   0.0   0.0   0.0
68.1  0.0  0.0  0.25 0.000     0.     0.     5.    2. 0.215   18.  523.  19.9  0.0   9.2 0.0  9.2 0.0   0.0   0.0   0.0   0.0
69.1  0.0  0.0  0.25 0.000     0.     0.     5.    2. 0.215   18.  523.  19.9  0.0   9.2 0.0  9.2 0.0   0.0   0.0   0.0   0.0
70.1  0.0  0.0  0.25 0.000     0.     0.     5.    2. 0.215   18.  523.  19.9  0.0   9.2 0.0  9.2 0.0   0.0   0.0   0.0   0.0
71.1  0.0  0.0  0.25 0.000     0.     0.     5.    2. 0.215   18.  523.  19.9  0.0   9.2 0.0  9.2 0.0   0.0   0.0   0.0   0.0
72.1  0.0  0.0  0.25 0.000     0.     0.     5.    2. 0.215   18.  523.  19.9  0.0   9.2 0.0  9.2 0.0   0.0   0.0   0.0   0.0
73.1  0.0  0.0  0.25 0.000     0.     0.     5.    2. 0.215   18.  523.  19.9  0.0   9.2 0.0  9.2 0.0   0.0   0.0   0.0   0.0
74.1  0.0  0.0  0.25 0.000     0.     0.     5.    2. 0.215   18.  523.  19.9  0.0   9.2 0.0  9.2 0.0   0.0   0.0   0.0   0.0
75.1  0.0  0.0  0.25 0.000     0.     0.     5.    2. 0.215   18.  523.  19.9  0.0   9.2 0.0  9.2 0.0   0.0   0.0   0.0   0.0
76.1  0.0  0.0  0.25 0.000     0.     0.     5.    2. 0.215   18.  523.  19.9  0.0   9.2 0.0  9.2 0.0   0.0   0.0   0.0   0.0
77.1  0.0  0.0  0.25 0.000     0.     0.     5.    2. 0.215   18.  523.  20.0  0.0   9.2 0.0  9.2 0.0   0.0   0.0   0.0   0.0
```

```
RUN SUMMARY:

TOTAL TIME OF MISSION:                       TMIN =  10.2  MIN

TOTAL DISTANCE TRAVELLED:                       S =   2.00 MI

STATE OF BATTERY CHARGE:                       SC =  0.087 PU

TOTAL ENERGY REMOVED FROM BATTERY:           EBAT =   6.33 KWHR


BATTERY CHARGING DATA:

       CHGTIM     SC    ACHG  VCHG  PCHG   AH   ECHG

         1.0    0.087   60.7  2.60  40.4  30.8   0.7
         2.0    0.085   58.7  2.60  39.1  29.9   1.3
         3.0    0.082   56.8  2.60  37.8  29.0   2.0
         4.0    0.080   54.9  2.60  36.6  28.2   2.6
         5.0    0.077   53.1  2.60  35.3  27.4   3.2
         6.0    0.075   51.3  2.60  34.2  26.6   3.7
         7.0    0.073   49.6  2.60  33.0  25.9   4.3
         8.0    0.071   47.9  2.60  31.9  25.1   4.8
         9.0    0.069   46.2  2.60  30.8  24.4   5.3
        10.0    0.067   44.6  2.60  29.7  23.8   5.8
        11.0    0.065   43.0  2.60  28.6  23.1   6.3
        12.0    0.063   41.5  2.60  27.6  22.5   6.7
        13.0    0.062   40.0  2.60  26.6  21.9   7.2
        14.0    0.060   38.5  2.60  25.6  21.3   7.6
        15.0    0.058   37.1  2.60  24.7  20.7   8.0
        16.0    0.057   35.7  2.60  23.8  20.2   8.4
        17.0    0.055   34.4  2.60  22.9  19.7   8.8
        18.0    0.054   33.1  2.60  22.0  19.2   9.2
        19.0    0.053   31.8  2.60  21.2  18.7   9.5
        20.0    0.051   30.6  2.60  20.4  18.2   9.9
        21.0    0.050   29.4  2.60  19.6  17.8  10.2

RESULTS OF BATTERY RECHARGE:

CHARGING TIME:                             CHGTIM =  21.0  MIN

STATE OF CHARGE:                               SC = 0.050  PU

SPECIFIC ENERGY AT BATTERY INPUT:             EPM =   5.10 KWHR/MI

SPECIFIC ENERGY AT CHG.STA. INPUT            EPM1 =   5.31 KWHR/MI

BATTERY EFFICIENCY:                        EFFBAT =  0.621 PU
```

COMMAND FILES - BUS.CMD AND BUSL. CMD

MAIN.REL	MAIN.FOR
PROF.REL MOTOR.REL	PROF.FOR MOTOR.FOR
EATT.REL	BATT.FOR CHART.FOR
	FORO3.DAT

PLOTTING PROGRAM - CHART.FOR

```
      REAL X(1000),ARRAY1(1000),ARRAY2(1000),ARRAY3(1000),
     * ARRAY4(1000),ARRAY5(1000),ARRAY6(1000)
      REAL MAX(6),C1(6),C2(6),C3(6),C4(6),C5(6),C6(6)
    8 WRITE(5,9)
    9 FORMAT(/,1X,'ENTER PEAK VALUES FOR PLOT SCALES,',/,
     # 1X,'(MINUS VALUE FOR PLUS-MINUS VARIABLE, NO ZEROS),',/,
     # 1X,'AND 3 TEN LETTER LABLES :',/)
      WRITE(5,10)
   10 FORMAT(1X,'CHANNEL 1 :')
      READ(5,11) MAX(1),C1(1),C2(1),C3(1),C4(1),C5(1),C6(1)
   11 FORMAT(F10.0,/,2A5,/,2A5,/,2A5)
      WRITE(5,30)
   30 FORMAT(/,1X,'CHANNEL 2 :')
      READ(5,11) MAX(2),C1(2),C2(2),C3(2),C4(2),C5(2),C6(2)
      WRITE(5,20)
   20 FORMAT(/,1X,'CHANNEL 3 :')
      READ(5,11) MAX(3),C1(3),C2(3),C3(3),C4(3),C5(3),C6(3)
      WRITE(5,40)
   40 FORMAT(/,1X,'CHANNEL 4 :')
      READ(5,11) MAX(4),C1(4),C2(4),C3(4),C4(4),C5(4),C6(4)
      WRITE(5,50)
   50 FORMAT(/,1X,'CHANNEL 5 :')
      READ(5,11) MAX(5),C1(5),C2(5),C3(5),C4(5),C5(5),C6(5)
      WRITE(5,60)
   60 FORMAT(/,1X,'CHANNEL 6 :')
      READ(5,11) MAX(6),C1(6),C2(6),C3(6),C4(6),C5(6),C6(6)
      WRITE(5,71)
   71 FORMAT(/,1X,'ENTER "X" AXIS LENGTH IN INCHES,',/,
     # 1X,'AND 1 FIVE LETTER LABEL :')
      READ(5,11) AXLEN,DX
      WRITE(5,70)
   70 FORMAT(/,1X,'ARE ALL ENTRIES CORRECT?',/,
     * 1X,'TYPE "1" FOR YES, "2" FOR NO:')
      READ(5,12) ITRY
   12 FORMAT(I1)
      IF(ITRY.NE.1) GO TO 13
      GO TO 100
   13 WRITE(5,80)
   80 FORMAT(/,1X,'RE-ENTER DATA :',/)
      GO TO 8
  100 CONTINUE
      WRITE(5,81)
   81 FORMAT(/,1X,'WORKING...',/)
  504 NT=1
  503 READ(22,502,END=501) X(NT),ARRAY1(NT),ARRAY2(NT),ARRAY3(NT),
     * ARRAY4(NT),ARRAY5(NT),ARRAY6(NT)
  502 FORMAT(1X,7F10.1)
      IF(ARRAY1(NT).GT.ABS(MAX(1))) ARRAY1(NT)=ABS(MAX(1))
      IF(ARRAY1(NT).LT.-ABS(MAX(1))) ARRAY1(NT)=-ABS(MAX(1))
      IF(ARRAY2(NT).GT.ABS(MAX(2))) ARRAY2(NT)=ABS(MAX(2))
      IF(ARRAY2(NT).LT.-ABS(MAX(2))) ARRAY2(NT)=-ABS(MAX(2))
      IF(ARRAY3(NT).GT.ABS(MAX(3))) ARRAY3(NT)=ABS(MAX(3))
      IF(ARRAY3(NT).LT.-ABS(MAX(3))) ARRAY3(NT)=-ABS(MAX(3))
```

PLOTTING PROGRAM - CHART.FOR (CON'T)

```
      IF(ARRAY4(NT).GT.ABS(MAX(4))) ARRAY4(NT)=ABS(MAX(4))
      IF(ARRAY4(NT).LT.-ABS(MAX(4))) ARRAY4(NT)=-ABS(MAX(4))
      IF(ARRAY5(NT).GT.ABS(MAX(5))) ARRAY5(NT)=ABS(MAX(5))
      IF(ARRAY5(NT).LT.-ABS(MAX(5))) ARRAY5(NT)=-ABS(MAX(5))
      IF(ARRAY6(NT).GT.ABS(MAX(6))) ARRAY6(NT)=ABS(MAX(6))
      IF(ARRAY6(NT).LT.-ABS(MAX(6))) ARRAY6(NT)=-ABS(MAX(6))
      NT=NT+1
      GO TO 503
  501 CONTINUE
      IF(MAX(1).GT.0.0)  ARRAY1(NT)=0.0
      IF(MAX(1).GT.0.0)  ARRAY1(NT+1)=MAX(1)/1.6
      IF(MAX(1).LE.0.0)  ARRAY1(NT)=MAX(1)/0.8
      IF(MAX(1).LE.0.0)  ARRAY1(NT+1)=-MAX(1)/0.8
      IF(MAX(2).GT.0.0)  ARRAY2(NT)=0.0
      IF(MAX(2).GT.0.0)  ARRAY2(NT+1)=MAX(2)/1.6
      IF(MAX(2).LE.0.0)  ARRAY2(NT)=MAX(2)/0.8
      IF(MAX(2).LE.0.0)  ARRAY2(NT+1)=-MAX(2)/0.8
      IF(MAX(3).GT.0.0)  ARRAY3(NT)=0.0
      IF(MAX(3).GT.0.0)  ARRAY3(NT+1)=MAX(3)/1.6
      IF(MAX(3).LE.0.0)  ARRAY3(NT)=MAX(3)/0.8
      IF(MAX(3).LE.0.0)  ARRAY3(NT+1)=-MAX(3)/0.8
      IF(MAX(4).GT.0.0)  ARRAY4(NT)=0.0
      IF(MAX(4).GT.0.0)  ARRAY4(NT+1)=MAX(4)/1.6
      IF(MAX(4).LE.0.0)  ARRAY4(NT)=MAX(4)/0.8
      IF(MAX(4).LE.0.0)  ARRAY4(NT+1)=-MAX(4)/0.8
      IF(MAX(5).GT.0.0)  ARRAY5(NT)=0.0
      IF(MAX(5).GT.0.0)  ARRAY5(NT+1)=MAX(5)/1.6
      IF(MAX(5).LE.0.0)  ARRAY5(NT)=MAX(5)/0.8
      IF(MAX(5).LE.0.0)  ARRAY5(NT+1)=-MAX(5)/0.8
      IF(MAX(6).GT.0.0)  ARRAY6(NT)=0.0
      IF(MAX(6).GT.0.0)  ARRAY6(NT+1)=MAX(6)/1.6
      IF(MAX(6).LE.0.0)  ARRAY6(NT)=MAX(6)/0.8
      IF(MAX(6).LE.0.0)  ARRAY6(NT+1)=-MAX(6)/0.8
      X(NT)=0.0
      TT=X(NT-1)/AXLEN
      IT=X(NT-1)/AXLEN
      IF(TT.GT.IT)  TT=IT+1.0
      X(NT+1)=TT
      CALL  PLOTS(0,0,16,0)
      CALL  PLOT(0.0,5.5,-3)
      CALL  PLOT(0.0,-11.0,-3)
      CALL  PLOT(0.0,0.5,-3)
      CALL  SYMBOL(0.0,1.0,0.5,1HX,0.0,1)
      CALL  SYMBOL(0.0,9.0,0.5,1HX,0.0,1)
      CALL  PLOT(2.0,0.0,-3)
      ZERO=0.0
      DO 602 N=1,6,1
      Y1=0.2+(N-1)*1.7
      Y2=Y1+0.52
      Y3=Y1+0.65
      Y4=Y1+0.78
      Y5=Y1+1.32
      M=7-N
      IF(MAX(M).GT.0.0)  CALL NUMBER(0.0,Y1,0.1,ZERO,0.0,2)
      IF(MAX(M).LE.0.0)  CALL NUMBER(0.0,Y1,0.1,MAX(M),0.0,2)
      CALL SYMBOL(0.0,Y2,0.1,C5(M),0.0,5)
      CALL SYMBOL(999.,999.,0.1,C6(M),0.0,5)
```

PLOTTING PROGRAM - CHART.FOR (CON'T)

```
      CALL SYMBOL(0.0,Y3,0.1,C3(M),0.0,5)
      CALL SYMBOL(999.,999.,0.1,C4(M),0.0,5)
      CALL SYMBOL(0.0,Y4,0.1,C1(M),0.0,5)
      CALL SYMBOL(999.,999.,0.1,C2(M),0.0,5)
      IF(MAX(M).GT.0.0) CALL NUMBER(0.0,Y5,0.1,MAX(M),0.0,2)
      IF(MAX(M).LE.0.0) CALL NUMBER(0.0,Y5,0.1,-MAX(M),0.0,2)
  602 CONTINUE
      CALL PLOT(1.5,0.0,-3)
      CALL AXIS(0.0,0.0,DX,-5,AXLEN,0.0,0.0,TT)
      DO 600 N=1,6,1
      IF(N.EQ.1) CALL PLOT(0.0,0.1,-3)
      IF(N.NE.1) CALL PLOT(0.0,1.7,-3)
      CALL PLOT(-1.75,0.0,2)
      CALL PLOT(-1.75,1.6,2)
      CALL PLOT(0.0,1.6,2)
      CALL PLOT(0.0,0.0,2)
      DO 601 NN=1,9,1
      PN=NN*0.160
      IF(NN.NE.5) CALL PLOT(-0.05,PN,3)
      IF(NN.EQ.5) CALL PLOT(-0.10,PN,3)
      CALL PLOT(0.05,PN,2)
  601 CONTINUE
      CALL PLOT(0.0,0.0,3)
      CALL PLOT(AXLEN,0.0,2)
      CALL PLOT(AXLEN,1.60,2)
      CALL PLOT(AXLEN,0.8,3)
      M=7-N
      IF(MAX(M).LE.0.0) CALL PLOT(0.0,0.8,2)
      CALL PLOT(0.0,1.6,3)
      CALL PLOT(AXLEN,1.6,2)
  600 CONTINUE
      NT=NT-1
      IF(MAX(6).GT.0.0) CALL PLOT(0.0,-8.5,-3)
      IF(MAX(6).LE.0.0) CALL PLOT(0.0,-8.7,-3)
      CALL LINE(X,ARRAY6,NT,1,0,0)
      IF(MAX(6).GT.0.0) CALL PLOT(0.0,-0.2,-3)
      IF(MAX(5).GT.0.0) CALL PLOT(0.0,1.9,-3)
      IF(MAX(5).LE.0.0) CALL PLOT(0.0,1.7,-3)
      CALL LINE(X,ARRAY5,NT,1,0,0)
      IF(MAX(5).GT.0.0) CALL PLOT(0.0,-0.2,-3)
      IF(MAX(4).GT.0.0) CALL PLOT(0.0,1.9,-3)
      IF(MAX(4).LE.0.0) CALL PLOT(0.0,1.7,-3)
      CALL LINE(X,ARRAY4,NT,1,0,0)
      IF(MAX(4).GT.0.0) CALL PLOT(0.0,-0.2,-3)
      IF(MAX(3).GT.0.0) CALL PLOT(0.0,1.9,-3)
      IF(MAX(3).LE.0.0) CALL PLOT(0.0,1.7,-3)
      CALL LINE(X,ARRAY3,NT,1,0,0)
      IF(MAX(3).GT.0.0) CALL PLOT(0.0,-0.2,-3)
      IF(MAX(2).GT.0.0) CALL PLOT(0.0,1.9,-3)
      IF(MAX(2).LE.0.0) CALL PLOT(0.0,1.7,-3)
      CALL LINE(X,ARRAY2,NT,1,0,0)
      IF(MAX(2).GT.0.0) CALL PLOT(0.0,-0.2,-3)
      IF(MAX(1).GT.0.0) CALL PLOT(0.0,1.9,-3)
      IF(MAX(1).LE.0.0) CALL PLOT(0.0,1.7,-3)
      CALL LINE(X,ARRAY1,NT,1,0,0)
      AXLEN=AXLEN+10.0
      CALL PLOT(AXLEN,0.0,999)
      STOP
      END
```

APPENDIX

GLOSSARY OF PROGRAM CONSTANTS AND VARIABLES

GLOSARY OF PROGRAM CONSTANTS AND VARIABLES

SYMBOL	DESCRIPTION	UNIT
ABAR	Average acceleration over TAU.	mph/sec
ABM	Maximum allowable battery discharge current.	amp
ABT	Battery current.	amp
ABTAVE	Average battery current over TAU.	amp
ABT1	Previous battery current.	amp
AC	Charging equation factor (regeneration).	---
ACC	Acceleration.	mph/sec
ACC1	Previous acceleration.	mph/sec
ACCM	Maximum acceleration.	mph/sec
ACHG	Charging current (recharge).	amp
AF	Vehicle Frontal area.	ft^2
AH	Ampere-hours removed from battery.	amp-hr
AHF	Ampere-hour factor.	---
AHR	Rated battery capacity (C5).	amp-hr
AIC	Charging current (regeneration).	amp
AICM	Maximum charging current (recharge).	amp
AI0	Offset current in charging voltage equation.	amp
AJERK	Jerk rate.	mph/sec^2
AJERKR	Maximum jerk rate.	mph/sec^2
AMASS	Equivalent vehicle accelerating mass.	g-lb
AMP	Traction motor armature current.	amp
AMPM	Maximum traction motor armature current.	amp
AMPMG	Maximum traction motor current on grade.	amp
AMPM0	Maximum traction motor current-normal.	amp
ANC	Number of cells in battery	---
BC	Charging equation factor (regeneration).	---
CAP	Battery capacity at current ABT	amp-hr
CAY	Excitation constant.	volts/rpm
CAYA	Coefficient in battery capacity equation.	hr
CAYB	Constant in battery capacity equation.	hr
CAYC	Factor in charging equations	--

GLOSSARY OF PROGRAM CONSTANTS AND VARIABLES (CONTINUED)

SYMBOL	DESCRIPTION	UNIT
CAYD	Coefficient in discharge equation.	volt /cell
CAYI	Excitation factor-current.	volt /rpm
CAYV	Excitation factor-voltage.	volt /rpm
CAY0	Excitation limit.	volt /rpm
CAY0A	Excitation limit-acceleration.	volt /rpm
CAY0D	Excitation limit-deceleration.	volt /rpm
CAY0G	Excitation limit on grade	volt /rpm
CC	Charging equation factor (regeneration).	---
CHGTIM	Recharge time.	min.
CM	Exponent in discharge equation.	---
CN	Exponent in battery capacity equation.	---
CR	Coefficient of rolling resistance.	lbf/lbm
C1, C2	Factors in excitation equation.	---
C10	Battery capacity at 10 hour rate.	amp-hr
DD	Depth of discharge (AHR base).	pu
DECEL	Deceleration limit.	mph/sec
DELAH	Ampere-hour increment.	amp-hr
DELI	Discharge current increment.	amp
DWELL	Dwell time at stop.	sec
EBAT	Energy removed from battery.	kw-hr
EC	Battery charging equation constant.	volts/cell
ECHG	Energy input to battery from charger.	kw-hr
EFFBAT	Battery efficiency.	pu
EG	Battery gassing voltage	volt /cell
EPM	Specific power to battery.	kw-hr/mi
EPM1	Specific power to wayside charging station.	kw-hr/mi
ETACHG	Wayside charging station efficiency.	pu
ETAG	Rear end efficiency.	pu
E0	Open circuit battery voltage.	volt /cell
G(25,2)	Array of grade data.	---
GEE	Acceleration due to gravity.	mph/sec

GLOSSARY OF PROGRAM CONSTANTS AND VARIABLES (CONTINUED)

SYMBOL	DESCRIPTION	UNIT
GRADE	Roadway grade.	rad
HW	Headwind (enroute component).	mph
I, II	Stop indices.	---
IAC	Air conditioning control code.	---
IDC	Driving cycle selection code.	---
IND	Power limited mode and recharge index.	---
INI	Initialization by-pass code.	---
IOF	Output file selection code.	---
I1,I2	Output control codes.	---
ISW	Stopping logic control code.	---
IWC	Output write command code.	---
JG	Grade index.	---
JM	Route length mile index.	---
KG	Grade index.	---
NP	Number of passengers.	---
NT	Number of stops per mile.	---
PAC	Air conditioning compressor power.	kw
PAIR	Average air compressor load.	kw
PAUX	Auxiliary power load.	kw
PBAUX	Battery auxiliary power.	kw
PBAVE	Average battery power over TAU.	kw
PBB	Battery power.	kw
PBC	Average battery charger load.	kw
PB1	Previous battery power.	kw
PCBLO	Air conditioning condenser blower.	kw
PCHG	Battery charging power.	kw
PCUL	Power conditioning unit loss.	kw
PECBLO	Environmental control blower.	kw
PF	Friction braking power.	kw
PG	Gassing power limit.	kw
PHIR	Route direction.	deg
PHIW	Wind direction.	deg

GLOSSARY OF PROGRAM CONSTANTS AND VARIABLES (CONTINUED)

SYMBOL	DESCRIPTION	UNIT
PLTG	Lighting power.	kw
PS	Traction motor shaft power.	kw
PS1	Demanded value of PS.	kw
PSMA	Maximum shaft power-acceleration.	kw
PSMD	Maximum shaft power deceleration.	kw
PTBLO	Traction motor blower power.	kw
PTF	Traction motor field power.	kw
PTMA	Traction motor air-gap power.	kw
PTMB	Traction motor bearing loss.	kw
PTMI	Traction motor iron loss.	kw
PTMI1	Updated value of PTMI.	kw
PTMIN	Traction motor armature circuit input.	kw
PTML	Total traction motor losses.	kw
PTMW	Traction motor windage loss.	kw
PW	Propulsion power.	kw
Q	Exponent in charging equation.	---
RATIO	Reduction gear ratio.	---
RB	Battery resistance in discharge equation.	ohm
RPM	Traction motor speed.	rpm
RTMA	Traction motor armature resistance.	ohm
S	Distance travelled.	mi
SB	State of discharge.	pu
SB0	Initial state of discharge.	pu
SC	State of discharge in charging equation.	pu
SN	Location of next stop.	mi
SR	Route length.	mi
SS	Stop spacing.	mi
STAB	Location of brake initiation point.	mi
TA	Aerodynamic drag.	lb
TAU	Computing interval.	sec

GLOSSARY OF PROGRAM CONSTANTS AND VARIABLES (CONTINUED)

SYMBOL	DESCRIPTION	UNIT
TAU1	Nominal value of TAU.	sec
TAUMU	Make-up time.	sec
TD	Total drag force.	lb
TF	Tire factor.	rpm/mph
TG	Grade drag.	lb
THETA	Time from start to run.	sec
TIM	Output clock time.	sec
TIMX	Output interval.	sec
TMIN	Total time of run.	min
TN	Net accelerating thrust.	lb
TNI	Jerk limited thrust increment.	lb
TP	Tractive effort desired.	lb
TR	Rolling resistance drag.	lb
TS	Stopping clock.	sec
T1	Time to completion of onset.	sec
T2	Time to completion of constant deceleration.	sec
T3	Time to completion of flair.	sec
T4	Time to completion of dwell.	sec
V	Vehicle speed.	mph
V1	Previous vehicle speed.	mph
VB	Brush drop.	volt
VBAR	Average vehicle speed over TAU.	mph
VBAT	Battery terminal voltage.	volt
VC	Cruise speed.	mph
VCHG	Charging voltage.	volt
VKE	Vehicle kinetic energy.	kw-hr
VOLT	Traction motor input voltage.	volt
VOLTM	Maximum traction motor input voltage.	volt
VOLTMA	Maximum traction motor input voltage-acceleration.	volt

GLOSSARY OF PROGRAM CONSTANTS AND VARIABLES (CONTINUED)

SYMBOL	DESCRIPTION	UNIT
VOLTMD	Maximum traction motor input voltage-deceleration.	volt
WS	Wind speed.	mph
WT	Gross weight of vehicle.	lb
WTCRB	Curb weight of vehicle.	lb
WTP	Weight of typical passenger.	lb
XB	Stopping distance.	mi
ZETA	Discharge current factor.	---
ZETAP	Discharge current factor.	---

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