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Optimization Methods Applied to Hybrid Vehicle Design

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ABS: The use of optimization methods as an effective design tool in the design of hybrid vehicle propulsion systems is demonstrated. Optimization techniques were used to select values for three design parameters (battery weight, heat engine power rating and power split between the two on-board energy sources) such that various measures of vehicle performance (acquisition cost, life cycle cost and petroleum consumption) were optimized. The apporach produced designs which were often significant improvements over hybrid designs already reported on in the literature. The principal conclusions are as follows. First, it was found that the strategy used to split the required power between the two on-board energy sources can have a significant effect on life cycle cost and petroleum consumption. Second, the optimization program should be constructed so

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1.0 SUMMARY

The overall objective of this work was to demonstrate the use of optimization methods as an effective design tool in the design of hybrid vehicle propulsion systems.

Specifically, optimization techniques were used to select values for three design parameters (battery weight, heat engine power rating and a parameter through which the required wheel power at each time instant was split between the two on-board energy sources) such that various measures of vehicle performance were optimized. The performance measures considered were acquisition cost, life cycle cost, petroleum consumption, or various weighted combinations of these. For specific values of the design parameters, vehicle performance was determined using a vehicle simulation. The optimization was carried out by coupling the simulation to a sophisticated, nonlinear programming code (GRG2) and running the two in combination.

The optimization approach was successful in coming up with designs which were often significant improvements over hybrid designs already reported on in the literature. Furthermore, it was found that the strategy used to split the required wheel power between the two on-board energy sources can have a significant effect on life cycle cost and petroleum consumption. More importantly, however, the work showed that it is quite feasible to couple a complex optimization program to a vehicle simulation program for the purpose of propulsion system design. It was also found that the optimization program should be constructed so that performance measures and/or design variables can be easily changed; in the conduct of the research it was often desirable to compare, say, the minimum life cycle cost design to the minimum petroleum

consumption design.

Another area in which important results were obtained was in understanding the effect the vehicle simulation program design has on both the computer run time of the overall optimization program and on the ability of the optimization program to even arrive at a meaningful solution. First, it was found that the computer run time could be significantly reduced by proper design of the types of trips the vehicle takes in a one year period. Specifically, if a trip consists of a combination of test cycles (accelerate-cruise-coast-brake cycles) and highway driving, then it is important that all the test cycles precede the highway driving, and that the same number of cycles are at the front end of each trip, no matter how long the trip.

Second, it was found that care must be taken in designing the cost and constraint expressions which are being used in the optimization so that they are relatively smooth functions of the design variables. Otherwise, the function surfaces may be severly distorted and create many local minima which will prevent the program from even approaching the global minimum. This is particularly true with regard to how the battery replacement cost is handled.

Finally, it was found that proper handling of constraints on battery weight and heat engine rating is particularly important for the success of an optimization study. These design variables cannot be allowed to be reduced to the point where the combined on-board power cannot meet the power demanded at the wheels. It was found that the way in which this "overload" constraint is handled strongly influences whether an optimization run gets "hung-up" at a non-optimal solution or finds the constrained, global optimum.

The principal conclusion reached from this research is that optimization methods provide a practical tool for carrying out the design of the propulsion system of a hybrid vehicle. Once the optimization program and the vehicle simulation are combined and operating, it is relatively easy to change objective functions and/or design variables so that designs based on different performance criteria (e.g. minimum life cycle cost design v.s. minimum petroleum consumption design) or different driving conditions, component characteristics or propulsion system configurations can be quickly carried out and compared. Use of optimization methods also force designers to make explicit their objective functions and constraints; thus designs carried out by different researchers are more readily and meaningfully compared.

This work has also lead to the conclusion that the way in which the demanded power at any instant of time is split between the two on-board power sources has a significant impact on vehicle cost and petroleum consumption. Although some preliminary results in this area are presented in this report, it would appear that future hybrid vehicle work should look at this question of power split on a more systematic basis.

2.0 INTRODUCTION

The energy crisis, dramatized by the oil embargo of 1973, has become one of the most serious long-term problems confronting the United States. In response to this crisis there has been a significant increase in the research and development of electric and hybrid vehicles in an attempt to reduce our dependence on foreign oil. The work discussed in this report is a part of that on-going effort.

2.1 RESEARCH OBJECTIVES

The primary objective of this work was to study the use of optimization methods for the design of propulsion systems for hybrid vehicles. The term hybrid vehicle as used in this report means a vehicle which contains a heat engine and gas tank as well as an electric motor and batteries. The configuration used here was a parallel hybrid with a continuously variable transmission. Of particular interest in this work was determining the ease or difficulty with which a sophisticated, nonlinear programming algorithm could be coupled to a vehicle simulation program for purposes of optimally designing the vehicle propulsion system. The design variables were heat engine power rating, the weight of the on-board batteries, and a parameter through which the power required at the wheels at each time instant was split between the two on-board power sources. The study considered optimizing various vehicle performance measures to determine how different performance measures influenced the final propulsion system design. The performance measures used were acquisition cost, life cycle cost, and petroleum consumption.

2.2 PREVIOUS WORK

There have been no studies reported in the literature which attempt a vehicle propulsion system design using optimization methods. Two recent studies [1,2] have looked at different aspects of the design of various types of hybrid vehicles. In each case, however, a final design is arrived at using a sound, but nevertheless ad hoc, selection process. Furthermore, the performance measure used to guide the selection is often not clearly stated, is modified or changed in the middle of a study, or is quite different from study to study. These factors combine to make it difficult to compare the results of one study to those of another. In contrast to this, use of optimization methods force standardization by requiring a designer to explicitly state the performance measure to be used, and to maintain the same measure in effect throughout the process of selecting final values for the design variables. Furthermore, with an optimization approach the selection process itself is standardized, and it also generally identifies the "best" values for the design variables so that the performance measure used is optimized (maximized or minimized, whichever is appropriate).

From the perspective of previous work on the problem of hybrid vehicle propulsion system design therefore, the work reported here represents the first time an attempt has been made to apply optimization methods to the design problem in order to come up with what may be considered the best or "optimal" design.

2.3 MAJOR TASKS

The conduct of the research fell naturally into a group of major tasks which are listed below:

1. Development of a vehicle simulation to be used to predict petroleum and electrical energy consumption as the vehicle is driven over the specified driving pattern. These consumptions provide a basis for computing overall performance measures such as life cycle cost.
2. Selection of a nonlinear programming algorithm (and associated program) which will be used to perform the optimization calculations.
3. Coupling the vehicle simulation program to the optimization program to allow optimal propulsion system designs to be carried out. In carrying out an optimal design calculation, the optimization program must run the simulation repeatedly. Consequently, a good deal of the work involved in coupling the two programs is in tailoring the vehicle simulation so that it runs efficiently, and so that vehicle performance is a smooth function of the design variables.
4. Translating various design goals into optimization problems. For each design goal this would include specifying (i) the system performance measure to be optimized, (ii) the design variables, and (iii) the proper constraints.

5. Generation and analysis of results using the combined optimization/vehicle simulation program.

In the sections which follow, each of the major task areas outlined above will be considered in depth.

2.4 REPORT ORGANIZATION

The report is organized as follows. Sections 3 through 6 present detailed information about the vehicle and its simulation. In particular, Sections 3 and 4 describe the vehicle and its propulsion system as well as the vehicle's basic method of operation along with the driving requirements it must meet over a ten year period. Section 5 details the way in which the various vehicle performance measures (life cycle cost, etc.) are calculated, while Section 6 describes the vehicle simulation.

The optimization design approach as it relates to hybrid vehicles is covered in Sections 7 through 9. Section 7 presents a general discussion of optimization methods which is useful background for subsequent sections. Section 8 deals with formulating hybrid vehicle design problems as optimization problems, while Section 9 describes some of the features of the actual optimization algorithm used in the study, as well as the reasons for its selection.

Section 10 discusses how the vehicle simulation program and optimization program were combined, and Section 11 presents and discusses particular vehicle design problems and the results obtained using the optimization approach; conclusions are presented in Section 12.

3.0 VEHICLE DESCRIPTION AND OPERATION

The vehicle selected to be studied in this research was essentially the same as the vehicle studied in [1]; it is a five-passenger sedan with a test mass of 2,049 kg. The details of the vehicle weight calculations are given in Appendix B.

3.1 PROPULSION SYSTEM

The propulsion system is a parallel hybrid configuration as shown in Figure 3-1. The traction motor is a brushless, DC, permanent-magnet motor operating from a battery voltage of 168 V. The motor is rated at 20 kw and has a top speed of 14,000 rpm. The ouput of the motor is connected to the transmission input through a gear which provides a 3.5:1 reduction of the motor speed.

The heat engine is assumed to be a four cylinder engine. Since in the optimization work the kilowatt rating of the engine is a design parameter which is varied, no specific rating for the engine is given. However, in the optimization studies that were conducted, the heat engine would normally start out at a rating of 65 kw. The output of the heat engine is directly connected to the input of the transmission (no speed reduction).

The transmission is a continuously variable transmission (CVT) which provides a range of ratios (input/output) from a 0.3:1 overdrive to a 3.33:1 speed reduction. The output of the CVT feeds the differential through a 12:1 speed reducer. The differential is assumed to have a ratio of 1:1. Thus, if the traction motor was running at its maximum speed of 14,000 rpm, and the CVT ratio was 0.3:1, the differential input would have a speed of 1,111 rpm.

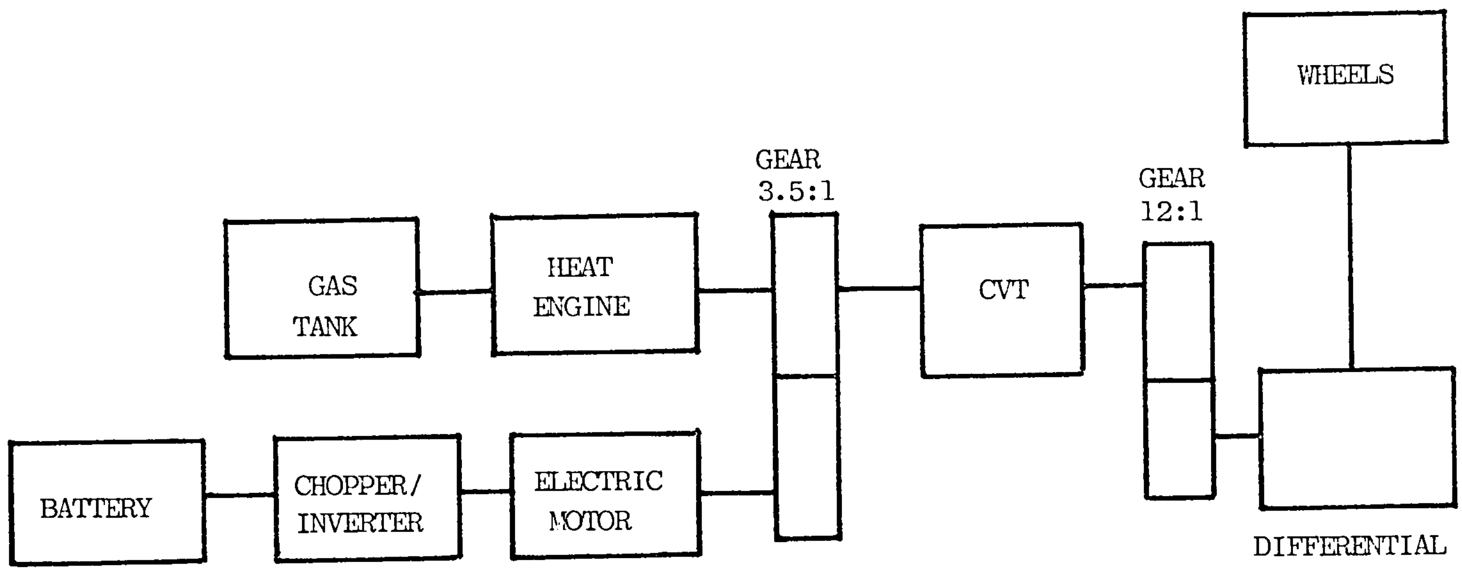

Figure 3-1. Propulsion System Configuration

The batteries are assumed to be lead-acid batteries with a system voltage of 168 V. In the optimization runs in which the battery weight was varied it was assumed that the system voltage remained the same and that a variation in battery weight meant the plate area of the battery cells was increased or decreased. A detailed description of the battery model used in the vehicle simulation is given in Appendix F.

Finally, it was assumed that a clutch existed between the heat engine and the CVT input to allow the heat engine to be decoupled from the system when it was not supplying power.

Section 6 and Appendix E (Vehicle Simulation) provide a detailed description of the simulation and the models used for all of the components in the propulsion system. Reference to that section and that appendix can give the reader a more thorough understanding of the components, their interrelationships, and how typical power consumption calculations were made.

3.2 VEHICLE OPERATION AND RATIO SELECTION

In order to avoid engine stalling, it was assumed that when the vehicle was starting from rest all power was supplied by the traction motor until the vehicle speed reached 4.82 km/hr (3.0 mph).

Whenever the vehicle was to brake to slow down, it was assumed that regenerative braking was used to the extent possible. If the maximum power rating of a component limited the fraction of the avialable power which could be regenerated, then it was assumed that normal braking was used to dissipate the excess energy.

In the early stages of the work, the CVT ratio was selected such that as the vehicle speed changed, the traction motor always ran at its most efficient operating speed. The disadvantage of this approach in the hybrid propulsion system studied is that the heat engine speed is also determined by the CVT ratio, and a ratio that operates the traction motor most efficiently often operates the heat engine very inefficiently. In fact, it was found that the traction motor efficiency is always in the 90% or above range independent of the ratio, whereas the heat engine efficiency can often be substantially improved by proper choice of the ratio. For this reason the CVT ratio was always selected to maximize the heat engine efficiency (except when the heat engine was not delivering any power). We note that a better approach might have been to base the ratio selection on the amount of power each source is delivering, as well as on the relative efficiency improvement possible from each source. A detailed description of the ratio selection procedure, along with the engine and traction motor data used, is given in Appendix G.

3.3 POWER SPLIT STRATEGY

In order to operate a hybrid propulsion system it is necessary to specify a strategy for splitting the required wheel power between the two power sources. The power split strategy must operate continuously, deciding at each instant of time how the total power is to be split. A realistic strategy generally is a function of vehicle velocity and acceleration, and battery state of charge.

An important part of this research was to use optimization methods to identify "optimal" strategies, or to select optimal values for parameters in a given strategy based on common sense. An example of a common-sense strategy which has been reported in the literature is the strategy proposed by AiResearch [1]. The AiResearch (AR) strategy is often used in the work discussed in the following sections; for this reason it is described in detail in Appendix H.

4.0 VEHICLE DRIVING REQUIREMENTS

In order to compute petroleum or electrical energy consumption (important factors in themselves, but also imporant factors in computing life cycle cost) it is necessary to specify how the vehicle is to be driven over its ten year life. Table 4-1 lists the lengths of eight different trip types for the vehicle, as well as the number of times the vehicle takes each trip type in one year.

Some portion of every trip is composed of Special Test Cycle (STC) driving. The STC is shown in Figure 4-1 and is a modified SAE J227A, D cycle; it contains a 14 second constant power acceleration period, followed by a 50 second, 72 km/hr (45 mph) cruise period, a 10 second coast period, and a 9 second braking period. Referring to Table 4-1, trips 1, 2 and 3 (trips less than 80 km in length) are made up of just a sequence of STC's, while trips 4 through 8 are made up of a combination of STC's and highway driving. Each of these latter trips consists of 28 STC's followed by enough highway driving to reach the total trip length. Highway driving is constant speed driving at 90 km/hr (56 mph).

The structuring of the longer trips to consist of a fixed number of STC's followed by varying lengths of highway driving had a big impact on reducing the computer run time of the overall vehicle simulation/optimization program. This is discussed in detail in Section 6 which deals with the vehicle simulation.

Table 4-1

Yearly Distribution of Trips

Trip Length Km	Trip Length Mi	Number of Trips Per Year
10	6.2	130
30	18.6	85
50	31.1	57
80	49.7	54
130	80.8	12
160	99.4	7
500	311.0	3
800	497.0	1

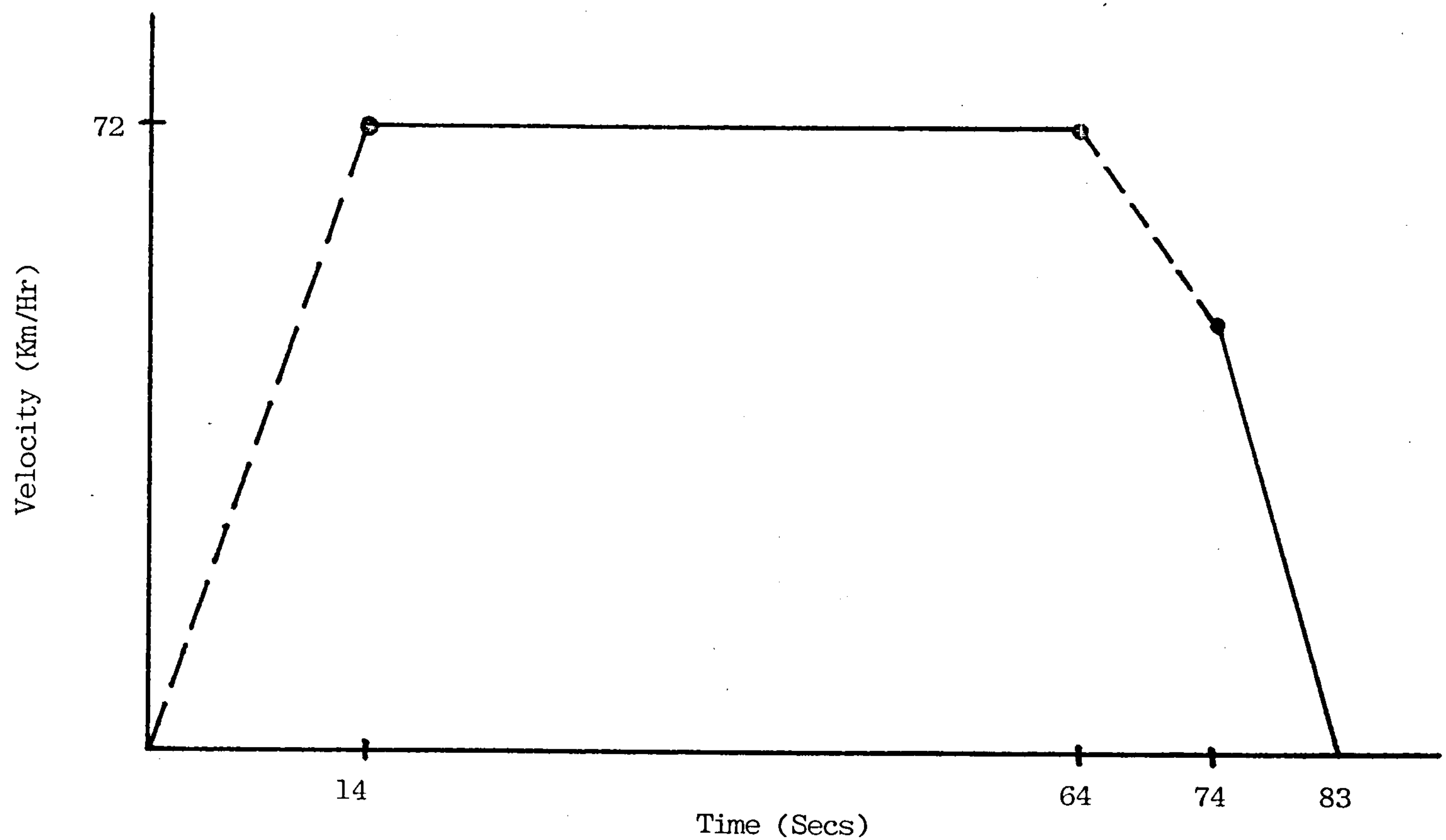

Figure 4-1. Special Test Cycle

5.0 ENERGY AND COST CALCULATIONS

This section details the methods used to calculate the yearly electrical energy consumption, yearly petroleum consumption and life cycle cost.

5.1 YEARLY ELECTRICAL ENERGY CONSUMPTION

The yearly electrical energy consumption calculation is based on first determining the total ampere-hours out of the battery for each of the trip types described in the previous section. The battery charging characteristic is then used to determine the energy required to replace those amp-hours (including a charging efficiency). Each of these results is multiplied by the number of such trips each year for each trip type, and the results then added to produce the total yearly electrical energy consumption. The details of the calculation are given below.

As explained in Section 6 on the vehicle simulation, it is necessary when calculating the electrical energy and petroleum consumptions for a particular trip to calculate the powers delivered by the battery and the heat engine at each time instant throughout the entire trip; it is not reliable, in general, to do it for just a few STC's and a segment of highway driving and then extrapolate the results for the entire trip. In the simulation, a small time step size is used and, for the electrical energy calculation, at each time increment in the trip the battery model is used to determine the battery voltage, current and state of charge for the power that must be delivered to the motor in that time increment (the calculation takes into account the chopper/inverter efficiency). In this way a total net amp-hours out of the battery for each trip type is determined: the total net amp-hours out includes the effect of regenerating capacity back into the battery during the braking phase of each STC. This total net capacity removed, together with an assumed charging current of 25 amps, is used to determine an average charging voltage from the battery charging characteristic (Appendix F). The average charging voltage is then multiplied by the total net capacity removed to determine the total energy that must be restored to the battery to bring it to a fully charged condition. Finally, to determine the total wall-plug energy, the above total energy is divided by a charger efficiency factor. This calculation is done for each trip type. The total, yearly electrical energy consumed is finally calculated by multiplying the energy consumed for each trip type by the number of such trips per year, and then adding these results.

If we let AH_i, i=1,..., 8, be the net amp-hours out of the battery for trip type i, V_i be average charging voltage to fully charge the battery after delivering AH_i amp-hours, EFF be the charger efficiency, N_i be the number of trips of type i made in one year, then the total, yearly electrical energy consumed, E_{TOT}, in megajoules, is given as

$$E_{TOT} = (3600/10^6) \sum_{i=1}^{8} (N_i AH_i V_i / EFF) \qquad (5\text{-}1)$$

5.2 YEARLY PETROLEUM CONSUMPTIONS

As noted above, when calculating electrical energy and petroleum consumptions it is necessary to calculate the powers delivered by the battery and heat engine at each time instant throughout the entire trip. In the simulation, the power delivered by the heat engine, the engine speed and the torque at each time instant are determined. The heat engine map (Appendix E) is then used to determine the fuel flow rate into the heat engine; multiplying this flow rate by the simulation time increment gives the fuel consumed over that time increment.

The procedure used to calculate the total, yearly petroleum consumption parallels the one used for electrical energy consumption: the total petroleum consumed for each trip type is determined by adding the fuel consumed over each time increment in the trip, these are multiplied by the number of trips of each trip type made per year, and the results then summed to produce the total petroleum consumption per year.

5.3 LIFE CYCLE COST CALCULATION

The life cycle cost is the sum of the vehicle acquisition cost, the petroleum, electrical energy, maintenance and repair, and battery replacement costs over a ten year period, minus the salvage value of the battery, the vehicle body and the power train.

It is assumed that the costs of petroleum and electricity increase in a linear fashion from year one to year ten. The arrays containing this information are GASCST(I) and KWCST(I); the particular values used are given in Appendix A.

Life cycle cost is computed in 1976 dollars, and it is assumed that there is no inflation. The cost for a future year is discounted to a present value using a discount factor (DISCNT in Appendix A).

The salvage value of the vehicle body and power train is taken to be 10% of the marked-up manufacturing cost, i.e. 10% of the difference between the acquisition cost and the list price of the battery (0.1*(ACQCST-BTLIST), see

Appendix A for definitions of variables).

The years in which a battery replacement is required depend upon the battery weight and the way in which the battery and heat engine are used. In calculating battery life it was assumed that there were 840 deep discharges in the lifetime of a battery [1], where a deep discharge is defined to be a discharge to 20% state of charge or below. The calculation procedure was to determine how far the battery was discharged when the vehicle made each of the trips defined in Section 4 (this was determined during the simulation of the vehicle to determine petroleum and electrical energy consumptions). If the battery state of charge dropped to only, say, 40% at the end of a particular short trip, then that trip represented 75% of a deep discharge. In this way the total number of deep discharges of the battery per year was determined and used to calculate the number of years in the battery life. If the battery state of charge fell below 20% during the part of a trip in which STC driving was being performed, regeneration back into the battery and subsequent use of the battery until its state of charge again fell below 20% was allowed, but only one deep discharge was attributed to that trip. The battery replacement cost had a mark-up factor which was twice that used in calculating the initial cost of the battery. The expression used to determine the replacement cost is

$$BTCOST = BATCST*(1.0 + 2.0*BTMKUP) \tag{5-2}$$

where

$$BATCST = BATCER*WGBATT \tag{5-3}$$

and where (see Appendix A) WGBATT, BATCER, BATCST, BTMKUP and BTCOST are battery weight, cost estimating ratio (CER), manufacturing cost, mark-up factor and replacement cost, respectively. The way in which the battery replacement cost was used in calculating life cycle cost was influenced by the method used to handle battery salvage value. In particular, battery salvage value was taken to be the cost of the last battery replacement multiplied by the ratio of the number of years left in the battery (at the end of the ten year vehicle lifetime) to the number of years in the battery life. Furthermore, instead of adding the total battery replacement cost to the year in which the replacement took place, each replacement cost was evenly distributed over the ten years in the lifetime of the vehicle. Although this is not quite representative of what would actually take place, it was necessary in order to produce a life cycle cost expression for the optimization studies which was a relatively smooth function of battery replacement cost. Furthermore, if it is assumed that the vehicle owner meets the battery replacement cost by borrowing money which is paid back over several years, then the above approach begins to more closely approximate reality. Based on the above discussion, the battery replacement cost assigned to each year in the ten year lifetime of the vehicle is given by

$$\mathrm{BATRYR} = \{[10.0/\mathrm{BATLFE})-1.0]*\mathrm{BTCOST}\}/10.0 \qquad (5\text{-}4)$$

where

$$\mathrm{BATLFE} = \mathrm{DISLFE}/\mathrm{DEEP} \qquad (5\text{-}5)$$

where BTCOST is as calculated above, and where BATRYR, BATLFE, DISLFE and DEEP are battery cost assigned to each year, battery lifetime, number of deep discharges in the battery lifetime, and the number of deep discharges per year, respectively.

Based on the discussion above, in Sections 5.1 and 5.2 and in Appendices C and D, the total yearly cost for operating the vehicle in year i is (see Appendix A for complete definitions of the variables)

$$VHCOST_i = E_{TOT}*KWCST_i + P_{TOT}*GASCST_i + BATRYR$$
$$+ MAINT + REPAIR \tag{5-6}$$

where E_{TOT} and P_{TOT} are the yearly electrical energy and petroleum consumed, respectively, $KWCST_i$ and $GASCST_i$ are the cost factors, and MAINT and REPAIR are the maintenance and repair costs, respectively. Letting the salvage value of the vehicle body and power train be (see above)

$$SALVGE = 0.1*(ACQCST - BTLIST) \tag{5-7}$$

and the discount factor for year i be

$$D_i = (1.0 + DISCNT)^{(i-1)} \tag{5-8}$$

where DISCNT is the discount rate, the life cycle cost is given as

$$LCCOST = ACQCST + \sum_{i=1}^{10} (VHCOST_i/D_i) - (SALVGE/D_{11}) \tag{5-9}$$

6.0 VEHICLE SIMULATION

In the optimization studies the vehicle simulation was used primarily to calculate the electrical energy and petroleum consumed by the vehicle in a one year period. Appendix E presents a detailed description of the modeling of the vehicle (the vehicle is described in general terms in Section 3) and of the way in which the petroleum and the electrical energy consumption was determined at each instant of time in the simulation interval. Section 5 describes the way in which these individual consumptions were used to calculate the yearly consumptions. The objective of this section is to discuss a number of features of the vehicle simulation effort (other than vehicle modeling) which were considered to have a significant impact on the simulation run time, on the outcome of optimization runs, or which represented particular features of vehicle operation which should be made explicit.

6.1 GENERAL COMPUTATIONAL PROCEDURE AND TRIP CHARACTERISTICS DESIGN

The purpose of this subsection is to describe the overall computational procedure used to calculate the fuel and energy consumptions for each trip in Table 4-1, and then to discuss how the structuring of these trips (STC and highway driving) can have a significant impact on simulation run time.

As discussed in Section 4, each trip to be simulated is either a sequence of just STC's or a combination of 28 STC's followed by varying lengths of highway driving. Since in this study the power split was allowed to vary with battery state of charge and/or vehicle acceleration, the power supplied by either on-board energy source could vary significantly from one part of a trip to another, particularly on those trips which depleted the battery. In the case of a depleted battery, the electrical energy supplied over the final STC would be zero, whereas that supplied over the first STC would be non-zero. Because of this, it was necessary to simulate the vehicle over the entire trip length for all trips: the fuel and energy consumption could not be calculated for one STC and a segment of highway driving, and then multiplied by appropriate factors to arrive at trip totals.

The calcuation procedure used is as follows. The longest all STC trip is 35 consecutive STC's. The simulation was therefore run for 35 consecutive STC's, and the "state" of the vehicle at the end of each STC was saved. By "state" is meant all the vehicle quantities necessary to resume the calculation from that point forward in time (petroleum consumed, battery amp-hours out and regenerated, state of charge, voltage, instantaneous and average currents, and whether the battery has discharged by the end of that STC). Knowing these quantities at the end of each STC, the fuel and energy consumption for trips consisting of just STC's (trips 1, 2, 3 in Table 4-1) can be calculated from simulating just the longest all-STC trip (trip 3).

To calculate the consumptions for trips involving highway driving, the simulation was initialized by the information saved at the end of the 28th STC, and highway driving was begun (in this way the 28 STC's preceeding highway driving need not be resimulated). At each time step in highway driving a test was made to determine if the shortest STC and highway trip had been completed; if so, the consumptions for that trip were computed and highway driving resumed until the next trip in Table 4-1 was completed. In this way, consumptions for all trips consisting of STC's and highway driving can be calculated by simulating just the longest trip (trip 8, Table 4-1).

The above calculation procedure where fuel and energy consumptions for all highway trips can be calculated from the longest trip depends on all highway trips having all of their STC's in the front of the trip, and all having the same number of STC's up front. If either of these conditions is changed, it would become necessary to simulate each trip separately. This could represent a significant increase in simulation run time. For example, the time step size in simulating STC driving is 1 second, and that used in simulating highway driving is 60 seconds (see Section 6.2). Since each STC is 83 seconds long, and there are 35 STC's in the longest all-STC trip, the total number of drive train power calculations required for trips 1, 2 and 3 in Table 4.1 is (1 x 83 x 35) = 2,905. The longest highway trip is 759 km of highway driving, driven at 90 km/hr, or a highway driving time duration of 8.44 hrs. A 60 second simulation time step would therefore require 506 additional power train calculations for all of the highway trips (trips 4 through 8), yielding a total of 3,411 calculations. If each highway trip had to be simulated separately (including the 28 STC's since they could be split differently between the beginning and end of each trip), the 28 STC's for the 5 highway trips would require a total of (5 x 28 x 83) = 2,324 computations, and the highway parts of trips 4 through 8 would require 26, 60, 80, 306, and 506 computations, respectively. The total number of computations would therefore be (26 + 60 + 80 + 306 + 506 + 2,324 + 2,905) = 6,207. Compared to the above total of 3,411, it is seen that the number of drive train power computations has almost doubled. Since these computations are by far the major computational burden of the simulation, and since the computation time is large to begin with, it is important to design the driving pattern so that computational efficiencies can be achieved.

6.2 SIMULATION TIME INCREMENT SELECTION

Another important factor in determining the length of time it takes the simulation to run is the time step size used in STC and highway driving. Since in a typical optimization run the yearly fuel and energy consumptions are computed 30 to 50 times, the choice of the time step size has a significant effect on overall computer run time.

Separate time step sizes were used for STC driving and highway driving: since highway driving is at a constant velocity, it was felt that a larger step size could be used without missing significant changes in the vehicle state (e.g. battery state of charge).

The time step sizes were selected by trying various values and observing the effects on petroleum consumption, electrical energy consumption and life cycle cost. In particular, the time step sizes were increased until a meaningful change in any of the above three quantities was observed; the values selected were set just below the values that produced a change. The STC time step size used was one second, and the time step size for highway driving was 60 seconds.

6.3 POWER OVERLOAD

One of the most frequent optimization problems studied was to choose battery weight and heat engine rating to minimize life cycle cost. Without constraints on this problem the answer would be to set both design variables to zero. Of course, the vehicle would then not be able to meet the yearly driving requirements. In this research, the condition in which both power sources were reduced in size to the point where they could not supply the power required at the wheels was called power overload. This condition could occur at any time in the yearly driving pattern, and it could occur for various combinations of heat engine rating and battery weight. The overload condition was handled in the optimization work by incorporating it as a constraint: combinations of battery weight and heat engine rating which produced overload were considered infeasible.

One method (which did not work) of handling this constraint was to set a flag if an overload condition occurred anywhere in the yearly driving patterns. This flag would indicate to the optimization scheme that the current choices for the design variables were infeasible, and new values would be tried. The problem with this method was that the constraint was a discontinuous (step) function of the design variables, and if it was violated the optimization method (GRG2) would attempt to find exactly where, in the current search direction (see Section 7), the constraint was just satisfied. This attempt (using Newton's Method for finding the roots of an equation) would fail and the optimization scheme could not determine a useful, new search direction to locate the optimimum.

In an attempt to visualize the shape of the constraint in the battery weight/heat engine rating plane, a series of simulation runs were made in the region of the constraint boundary (varying battery weight and heat engine rating for each run, and using the AiResearch power split (see Section 3.3 and Appendix H)). The result is shown in Figure 6-1 where it is seen that the constraint boundary is highly irregular. Even if the optimization method could find the boundary (for a particular search direction), once it began to move along the boundary it would get hung up at one of the many local minima.

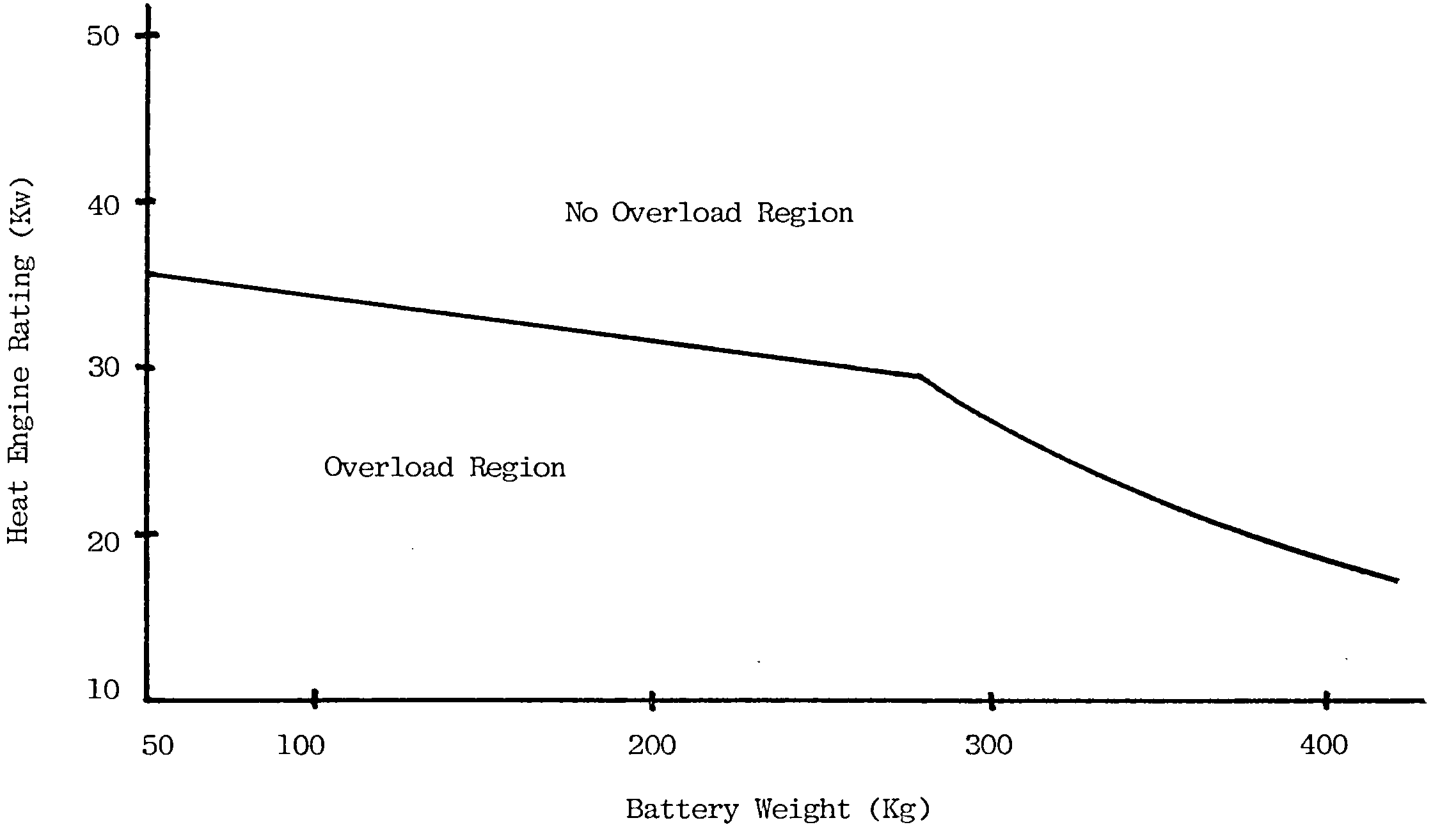

Figure 6-1. Overload Constraint Boundary

The method finally adopted for handling the constraint was to approximate it with two smooth curves as shown in Figure 6-1. For these smooth constraint functions the optimization scheme can easily find the location of the constraint boundary in a given search direction, and it can also move easily along the constraint boundary in search of the optimum. If we let x_1 = battery weight (kg), and x_2 = heat engine rating (kw), then the constraint equations are given as

$$P_{HE} > 37.0 - 0.02564\, W_B \qquad (W_B < 273) \qquad (6\text{-}1)$$

$$P_{HE} > 77.23 - 0.2268\, W_B + 1.982\text{x}10^{-4}\, W_B^2 \qquad (W_B > 273) \qquad (6\text{-}2)$$

The justification for using this approximate constraint boundary is that in any optimization study which chooses battery weight and heat engine rating to minimize life cycle cost, the objective is not necessarily to arrive at a design which just borders on overload. Having the small "cushion" above overload that use of the approximate constraint produces could be beneficial.

6.4 OTHER FEATURES OF THE SIMULATION

Several features of the simulation which should be mentioned are listed below.

First, since a clutch existed between the heat engine and the CVT, the heat engine could be decoupled from the drive train when it was not being used. Hence it was assumed that there was zero fuel consumption by the heat engine during idling.

A second feature was that no matter how the power split strategy split the CVT input power, the heat engine was not allowed to deliver any power if the vehicle velocity was below 3 mph. This came into play as the vehicle started from rest at the beginning of a STC.

A third feature (which is detailed in Appendix E) was that if either the battery or the heat engine could not deliver the power called for by the power split, the unmet power was assigned to the other power source and both the electrical and heat engine calculations were repeated.

7.0 OPTIMIZATION AS A DESIGN TECHNIQUE

It is now appropriate to consider optimization as a technique which can be used with the vehicle simulation previously described to obtain desired design results. It will become apparent in the discussion below that the role of optimization is that of systematically changing design parameters for use with the vehicle simulation until design objectives are met. Optimization techniques are based on a particular methodology and formalism which must be adapted to the design problem at hand. The purpose of this section is to define the terminology of optimization, briefly summarize the optimization problem mathematically, and discuss the general nature of solutions to such problems.

Each optimization problem has an objective function (or criterion function), $f(x)$, which is an algebraic function of the n components of the vector x, and which is to be minimized (or maximized). The objective function in a design problem provides a measure of the quality of the design such that its minimum value occurs for a value of x which represents the best design.

The components of x may be subject to upper and lower bounds,

$$x_{r_{min}} \leq x_r \leq x_{r_{max}} \tag{7-1}$$

where, for a given variable x_r, one, neither or both of these bounds may be present. Variables often are given bounds for reasons of physical realizability; e.g., both battery weight and heat engine power rating must be positive, and the percentage of power delivered from one source must be between 0 and 100.

In addition to bounds which apply to the variables themselves, we must consider constraints, functions of these variables which also must be maintained within limits. An optimization problem might contain m constraints

$$g_{j_{min}} \leq g_j(x) \leq g_{j_{max}} \qquad (j = 1,2,..,m) \tag{7-2}$$

where one or both of the limiting values on a particular constraint $g_j(x)$ may apply. The designer uses such constraint functions to calculate design characteristics which must be kept within upper or lower limits. A vehicle designer, for example, might want to place a lower limit on accelerating ability, or an upper limit on acquisition cost.

Since the objective functions and constraint functions applicable to hybrid vehicle design are generally nonlinear functions of x, we have a nonlinear optimization problem. Converting the scalar variables in equations 7-1 and 7-2 to vectors allows us to state the nonlinear optimization problem in a precise mathematical form:

$$\min_{x} f(x)$$

subject to

$$x_{min} \leq x \leq x_{max} \tag{7-3}$$

and

$$g_{min} \leq g(x) \leq g_{max} \tag{7-4}$$

The notation $\min_{x} f(x)$ means that f(x) is to be minimized with respect to x. Equations 7-3 and 7-4 are the vector versions of equations 7-1 and 7-2, respectively, and include all desired bounds and constraint relationships.

Nonlinear optimization problems such as the one stated above have been well known for some time, and many techniques have been developed for finding their solutions. Since f(x) and g(x) are assumed to be nonlinear, the techniques for solution of the problem are called nonlinear programming algorithms. Many of these have been developed over the past 25 years to provide a means of obtaining digital computer solutions to these problems [6,7,8,9] Some of these methods are discussed in Section 9.

Techniques for solution generally begin with an initial estimate, x_o, of the solution vector, which is feasible in that all bounds and constraints are satisfied, and proceed in an attempt to satisfy all of the necessary conditions for minimum f(x) while maintaining x feasible. The process terminates when these conditions are met, or when no further progress is possible.

Each nonlinear programming method has its own set of assumptions regarding the mathematical properties of f(x) and g(x). Although there are small differences from method to method, it is usually necessary for both f(x) and the elements of g(x) to be continuous, differentiable functions of x, with continuous first partial derivatives with respect to the components of x. These restrictions have important implications on the specifications of the objective and constraint functions for a design problem, as well as the development of simulation programs for optimization.

8.0 THE VEHICLE DESIGN PROBLEM AS AN OPTIMIZATION PROBLEM

Having considered a general description of an optimization problem in Section 7, it is now possible to consider application of optimization methods to the design of the hybrid vehicle described earlier in this report. This involves formulating the vehicle design problem in terms of vehicle design parameters which will become the variables of the optimization problem, defining any bounds or constraint functions associated with these variables, and selecting an objective function which represents the designer's primary goal in a mathematical fashion. The key to successful formulation of a vehicle design problem as an optimization problem is in specifying all of the needed ingredients for the optimization problem (variables, objective function, bounds and constraints) in a way which meaningfully includes all important aspects of the design problem.

The primary design variables for the hybrid vehicle design problem discussed here are the two power-sizing parameters, heat engine power rating (in kilowatts) and battery weight (in kilograms). Additional design parameters are introduced later (see Section 11) as part of a decision rule which is used on an instantaneous basis to decide how much power is to be used from each of the two on-board power sources.

Lower bounds of at least zero must be specified for both the heat engine power and the battery weight. This is because the optimization method will consider all possible values of the design parameters, even those which are physically meaningless, unless such bounds are imposed. From a designer's point of view, a hybrid vehicle which has a very low heat engine power rating or negligible battery weight is a single-power-source vehicle and not a hybrid vehicle; thus lower bounds were imposed to insure that the solution of the design problem by optimization produced a vehicle with both sources. The values of the lower bounds used in this study were 15 kw for the heat engine power rating and 60 kg for the battery weight.

Two primary objectives were considered in this study: life cycle cost ($) and life cycle petroleum consumption (liters). Both of these can be calculated using the calculation precedure discussed in Section 5, and the vehicle simulation discussed in Section 6.

The principal constraint function used in this study is the power overload constraint discussed in Section 6. It was necessary to impose this constraint in order to ensure that the designs resulting from the use of optimization represent vehicles which can produce sufficient power to successfully complete all the specified driving regimes. Other constraint functions can also be used for particular design problems, using as a constraint a function which could be an objective function for another design; for example, the design might call for the hybrid vehicle which has the minimum life cycle cost subject to the constraint that its total petroleum consumption be less than some prespecified amount.

There are many vehicle design problems which may be stated and solved as optimization problems. Listed below are several sample optimization problems for hybrid vehicle design. These same problems were solved as part of this study and are discussed later in this report where results are presented. In the statement of these problems, C_{LC} is the life cycle cost (in $), Vp is the total petroleum volume (in liters) used over a life cycle, P_{HE} is the heat engine power rating (in kilowatts), W_B is the battery weight (in kilograms) and P_o is the power overload function (≥ 0 when no overload occurs).

Sample Design Optimization Problem No. 1

Choose P_{HE} and W_B to minimize $C_{LC}(P_{HE}, W_B)$

subject to

$$P_{HE} > P_{HE_{min}}$$

$$W_B > W_{B_{min}}$$

$$P_o \geq 0$$

Sample Design Optimization Problem No. 2

Choose P_{HE} and W_B to minimize $V_P(P_{HE}, W_B)$

subject to

$$P_{HE} > P_{HE_{min}}$$

$$W_B > W_{B_{min}}$$

$$P_o \geq 0$$

Sample Design Optimization Problem No. 3

Choose P_{HE} and W_B to minimize $V_P(P_{HE}, W_B)$

subject to

$$P_{HE} > P_{HE_{min}}$$

$$W_B > W_{B_{min}}$$

$$P_o \geq 0$$

$$C_{LC} \leq C_{LC_{max}}$$

These three problems are typical of many which were considered in this study. All three are essentially vehicle power-sizing problems, where it is desired to find the proper values of the heat engine power rating and the battery weight. They vary according to their objective functions and, in problem No. 3, the imposition of an additional constraint besides the power overload constraint.

Other design problems considered later in this report involve constraining the total petroleum volume in the minimization of C_{LC}, examining the effect of petroleum pricing on design results, and parameterizing the power split decision rule. These problems are discussed with the results in Section 11.

9.0 SELECTION OF OPTIMIZATION METHOD

Several methods including variable metric and conjugate gradient methods [6, 7, 8, 9] are available for direct solution of nonlinear programming problems such as the type stated in Section 7 and applicable to the hybrid vehicle design problem. Indirect methods such as those based on the Newton-Raphson method are also available, but this class of methods was rejected because of the likelihood of divergence with a poor initial estimate of the solution. Most direct methods such as gradient and modified gradient method were originally developed for unconstrained optimization problems (no bounds or constraints) and must be modified to include constraints.

One proven method for successfully incorporating bounds and constraints into a direct search method was developed by Abadie and Carpentier [8]. The method, called the Generalized Reduced Gradient Method (GRG), uses linearized constraints, defines new variables which are normal to some of the constraints, and transforms the gradient to a new basis.

Lasdon and Waren, et. al. [10] have developed an extensively refined code (computer program) for general purpose implementation of the GRG optimization method. The code which is now called GRG2, has been successfully tried on test problems in competition with other nonlinear programming codes, and has consistently ranked high in the primary characteristics desired of such a code (accuracy, efficiency, reliability, and ease of use) [11, 12]. GRG2 easily incorporates bounds on the variables and a variety of constraints. It provides great flexibility which includes a choice of search method, a variety of stopping criteria, provisions for scaling of variables and constraint functions, and several options regarding the amount of detail provided in the printed output.

The designer who wishes to use GRG2 for optimization results must provide [13]:

1. a subroutine which computes the objective function and all of the constraint functions, given the optimization variables.
2. a data file which includes an initial point for the search, upper and lower bounds on variables and constraints (as applicable), and names for all variables and functions.

The designer may provide:

1. a subroutine for computing derivatives for gradients (otherwise the program uses finite difference approximations)
2. a subroutine for reporting needed output information which is not directly related to the optimization calculations
3. a file containing scale factors for the variables and constraints, and control parameters which specify how the detailed operation of the optimization search is to be carried out (e.g., search direction method, stopping criteria, constraint tolerances)

After a vehicle design problem has been properly formulated as an optimization problem, it is a fairly straight-forward procedure to write the subroutines and determine the data files indicated above. The most difficult part of this task is in writing the subroutine which computes the objective and constraint functions from the design parameters, since this normally involves the entire vehicle simulation as well as the computation of various vehicle costs.

10.0 IMPLEMENTATION OF THE GRG PROGRAM FOR VEHICLE DESIGN PROBLEMS

It was desired to combine the GRG2 optimization program with the hybrid vehicle simulation program in a way which would provide flexibility regarding specification of objective function, constraint functions, variables and bounds, so that a variety of hybrid vehicle design problems could be studied merely by changing a data file in the program.

This goal was accomplished by defining five functions of P_{HE} and W_B which would suffice for the calculation of all possible objective and constraint functions which were anticipated at the time the computer program was written. These functions are:

1. life cycle cost ($)
2. acquisition cost ($)
3. total petroleum volume in life cycle (liters)
4. linear combination of above three functions
5. power overload function

The fourth function was included to provide a weighted sum of three objective functions for the designer who wishes to compromise and not select a single objective from among the first three functions listed.

As described in Section 6.3, the power overload function was developed by simulating the hybrid vehicle for various pairs of values of the parameters (P_{HE},W_B) using a particular power split strategy developed by AiResearch Manufacturing Co. [1,5]. Regions where the hybrid vehicle was not able to meet the power demanded by the driving regime were identified and the power overload boundary was seen to be an irregular surface (Fig. 6-1) which was not amenable to treatment by nonlinear programming techniques; these techniques normally require a smooth, differentiable function for each constraint. In order to meet this requirement in at least an approximate way, the overload constraint boundary function, $P_O(P_{HE}, W_B)$, was approximated by two polynomial functions as follows:

$$P_{HE} > 37.0 - 0.02564\ W_B \qquad (W_B < 273) \qquad (6\text{-}1)$$

$$P_{HE} > 77.23 - 0.2268\ W_B + 1.982 \times 10^{-4}\ W_B^2 \qquad (W_B > 273) \qquad (6\text{-}2)$$

These functions were used with GRG2 for determining solutions to optimization problems which included the power overload constraint.

For examination of the power flow or power split strategy problem, where we are trying to find the parameters of a decision rule which specifies how much power comes from each on-board power source at each instant of time, the GRG/simulation program was provided with three different ways to determine the power split between the heat engine and the electric propulsion system:

1. the AiResearch algorithm [1]
2. a polynomial function
3. a parameterized version of the AiResearch algorithm

More detail on the particular functions involved will be provided in Section 11.

Further flexibility in the program was provided by defining a data file which could be used to specify which type of vehicle design problem was to be solved with a particular optimization run: (1) vehicle sizing, (2) power split optimization, or a combination of the two.

The overall organization of the vehicle design computer program involves an interaction between the GRG2 optimization program and the hybrid vehicle simulation program discussed in Section 6. The interconnection is illustrated in Figure 10-1. The reader should note that the GRG2 program selects values of the parameter vector, x, for simulation in the Hybrid Vehicle Simulation Program, and receives the calculated values of the five functions (which may be the objective function or constraint functions) from it. GRG2 then systematically adjusts x in such a way as to minimize the objective function while satisfying bounds and constraints. The REPORT subroutine in GRG2 is used to calculate and print output information about the hybrid vehicle which is not essential to the GRG2 program.

The next section discusses particular problems which were attempted using this program, and the results which were obtained.

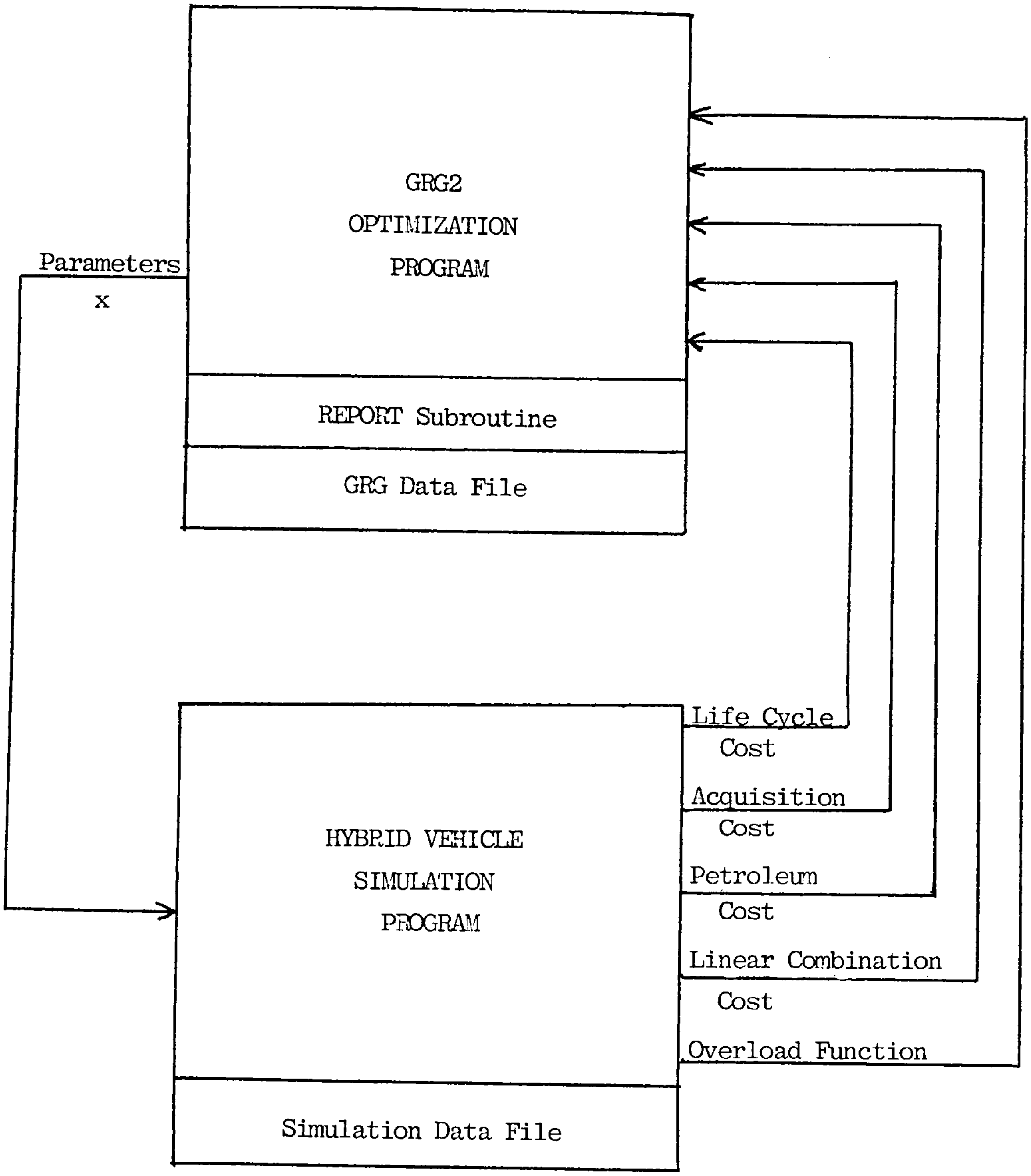

Figure 10-1 Interconnection of Optimization and Simulation Programs

11.0 RESULTS AND DISCUSSIONS OF RESULTS

Four different design problems were solved using the optimization approach discussed previously. Each of these problems is discussed in a separate subsection where the problem is defined and results are presented for that particular problem.

The two major problem areas considered were those of vehicle power source sizing and power split parameter optimization. The first three design problems deal with the sizing problem, including various design objectives and constraints, and the final design problem is concerned with optimizing the power split decision rule.

11.1 VEHICLE POWER SOURCE SIZING FOR MINIMUM LIFE CYCLE COST

The design objective here was to determine the proper power source sizing parameters, heat engine power (kw) and battery weight (kg), so that the life cycle cost of the hybrid vehicle is minimized and the final vehicle is able to meet all driving requirements as specified by the annual trip requirements and reflected in the vehicle simulation.

The optimization problem for this design problem is very similar to Sample Problem No. 1 in Section 8 of this report:

$$\min_{P_{HE}, W_B} C_{LC}(P_{HE}, W_B) \qquad (11\text{-}1)$$

subject to

$$P_{HE} \geq 15 \qquad (11\text{-}2)$$

$$W_B \geq 60 \qquad (11\text{-}3)$$

$$P_O(P_{HE}, W_B) \geq 0 \qquad (11\text{-}4)$$

and the AiResearch power split function which is specified in Appendix H.

Several initial estimates for the solution were tried, and all led to the same result:

$$\min_{P_{HE},W_B} C_{LC}(P_{HE},W_B) = C_{LC}\,(35.5,\ 60.0) = \$17,100 \tag{11-5}$$

This point is at the intersection of the overload constraint boundary and the lower bound for W_B. See Figure 11-1, which shows the optimization as it proceeded from the design parameters recommended by AiResearch [1], P_{HE} = 65 kw and W_B = 386 kg. Althought this point was reached in two iterations, it should be noted that each iteration included many evaluations of the objective function for the various pairs of (P_{HE}, W_B) values which were being considered. During the first iteration, the search proceeded in the negative gradient direction until the overload constraint boundary was reached, using longer and longer steps until the boundary was encountered. During the second iteration, the search moved along the overload constraint boundary until the lower bound on W_B was reached; several intermediate points were used along the constraint before the iteration was completed. The overall result is a reduction in life cycle cost from $20,796 to $17,100.

It is not surprising that the optimal design in this case occurred on the overload constraint boundary, since any point above this boundary would correspond to higher value of P_{HE}, W_B or both, leading to a higher life cycle cost, and any point below this boundary, although yielding a lower life cycle cost, would correspond to a vehicle not able to meet the specified driving requirements. It is also not surprising that the optimal solution occurs at the minimum value of W_B, since the nominal petroleum pricing used for this problem (See Section 5.3) makes it desirable to use as little electric power

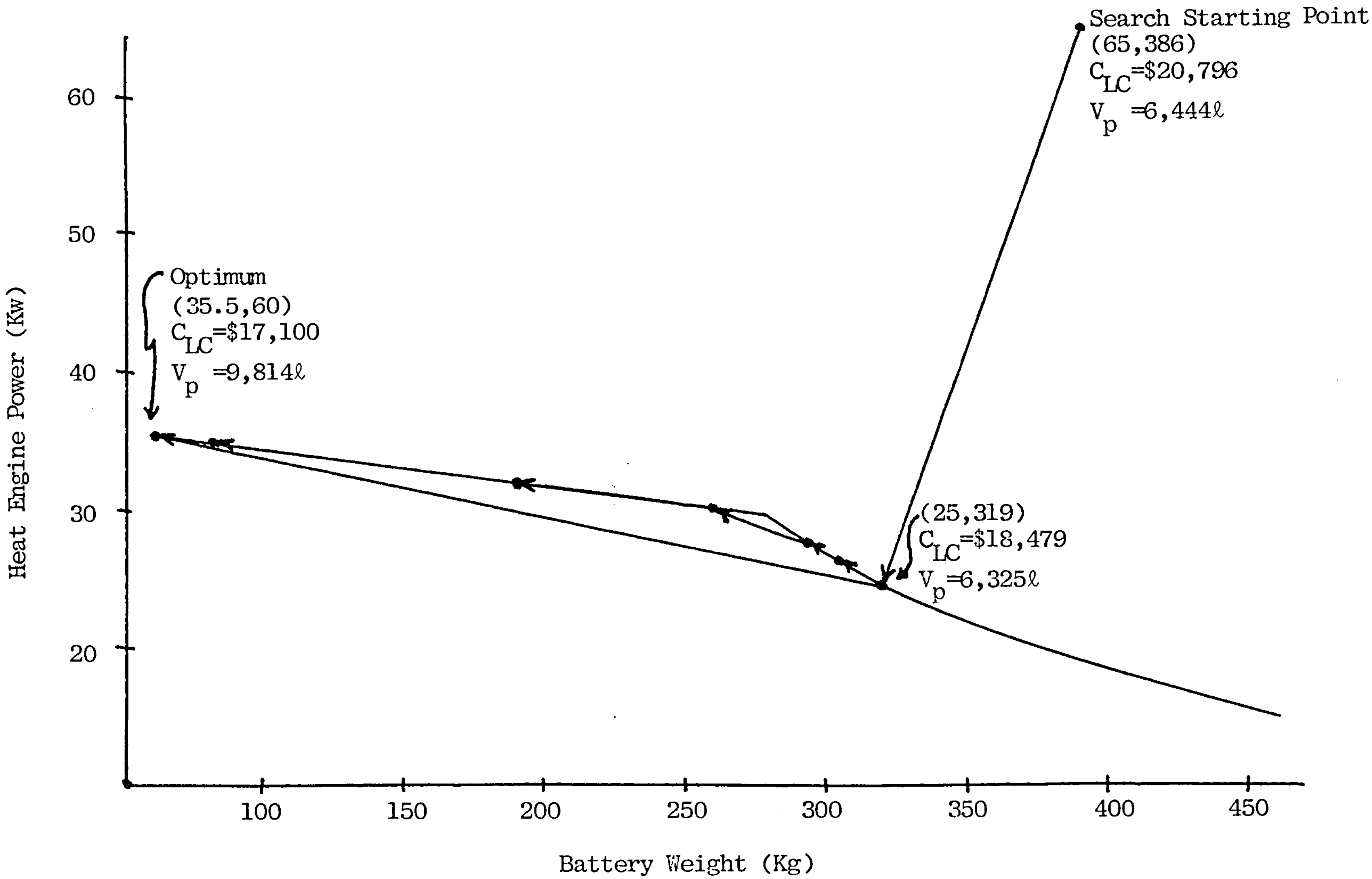

Figure 11-1 Power Source Sizing for Optimum Life Cycle Cost
(Petroleum Usage Unconstrained)

as possible if minimum life cycle cost is the objective.

A modified version of this problem was solved after including an additional constraint,

$$V_P \leq r\, V_p^* \tag{11-6}$$

to the optimization problem specified in equations 11-1 through 11-4. V_p^* is the petroleum volume, 9,814 liters, associated with the solution to the original optimization problem, and r ($0 < r \leq 1$) specifies a certain fraction of that amount. The purpose of this design problem was to investigate how the optimal power sizing parameters would change, and how the life cycle cost would increase in the case where less and less total petroleum volume is available for the life of the vehicle. This is a situation which could be quite realistic as world petroleum resources are depleted or when foreign supplies become unavailable.

The results for this modified problem are shown in Figure 11-2 for various values of r, from r = 1.0 to r = 0.60. The results show a steady increase of C_{LC} as r is decreased, rising from \$17,100 at r = 1.0 to \$18,679 at r = 0.60. These results demonstrate the utility of a hybrid vehicle when petroleum supplies are strictly limited, and more reliance must be placed on the electrical propulsion system.

11.2 VEHICLE POWER SOURCE SIZING FOR CHANGING PETROLEUM COSTS

The design problem considered here is similar to that of the last section, where life cycle cost is to be minimized, but where the price of petroleum is varied and its effect on the results is observed. The price of petroleum was varied by introducing a gas factor, γ, which scales all of the

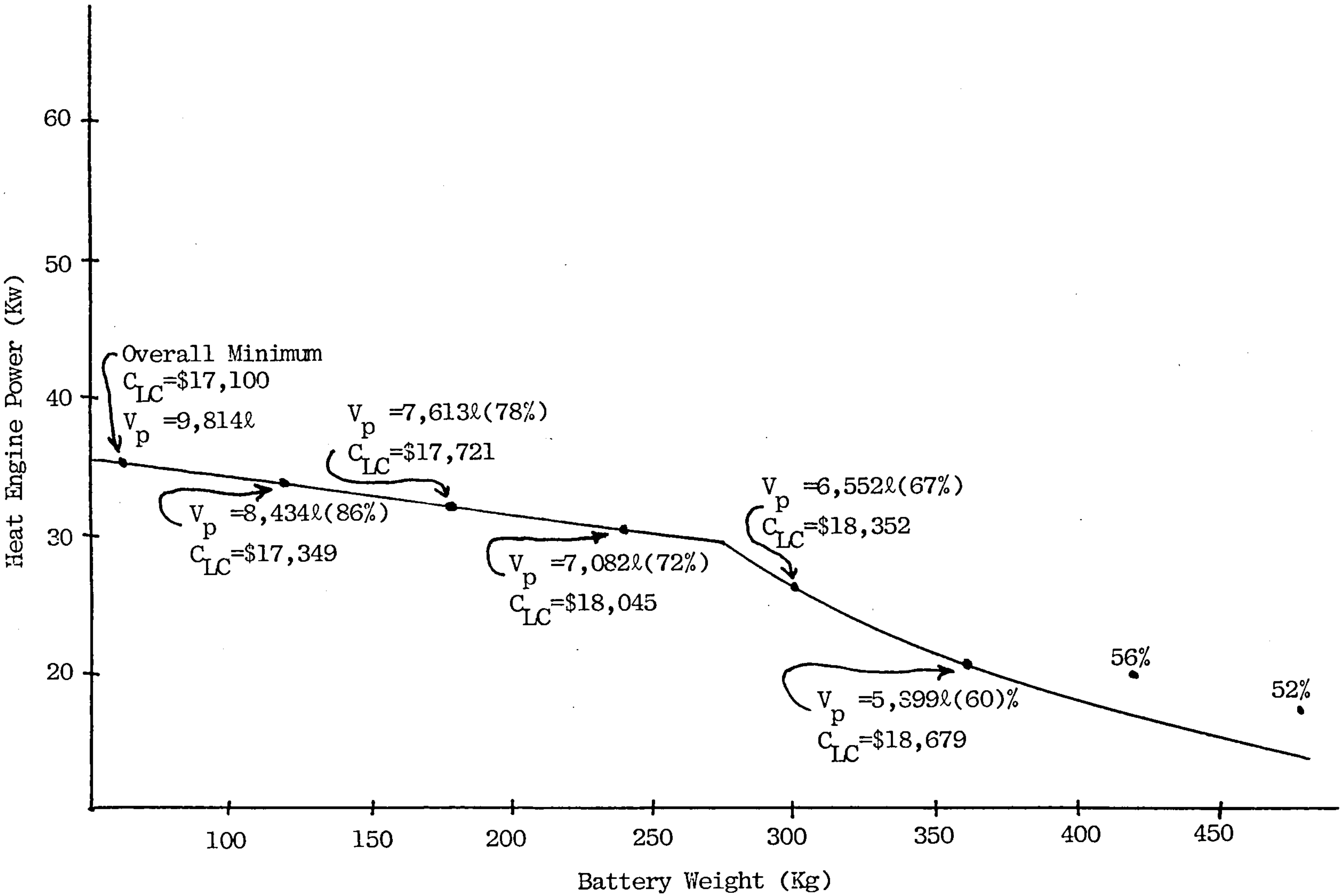

Figure 11-2 Power Source Sizing for Optimum Life Cycle Cost

(Petroleum Usage Constrained)

petroleum costs, $\gamma > 1.0$ (γ multiplies the array GASCST(I)).

The optimization problem for this design is:

$$\min_{P_{HE}, W_B} C_{LC}(P_{HE}, W_B, \gamma) \tag{11-7}$$

subject to equations 11-2, 11-3 and 11-4. The AiResearch power split function (see Appendix H) is again used and the value of γ is held constant during the optimization, so that this problem represents a family of optimization problems, each corresponding to a fixed value of γ.

The several optimization problems all used the same starting point, P_{HE} = 65 kw and W_B = 368 kg. The results are shown in Figure 11-3 for $\gamma = \{1.00, 1.25, 1.50, 1.75, 2.00, 2.50, 3.00, 5.00\}$. All results are on the boundary of the overload constraint function, with higher values of γ yielding designs which rely more and more on the electrical propulsion system. The life cycle costs associated with these results are listed in Table 11-1. It is clear from these results that the nominal petroleum pricing ($\gamma = 1.0$) which was used for much of this study is too low to justify a hybrid vehicle on the basis of life cycle cost; the optimization would yield $W_B = 0$ if this were permitted. Higher gas factors, however, show designs which have a much greater reliance on the electrical propulsion system.

11.3 VEHICLE POWER SOURCE SIZING TO MINIMIZE TOTAL PETROLEUM CONSUMPTION

The design problem considered here differs from the problems discussed in the last two sections in that the design objective was to minimize the total volume of petroleum used over the expected life of the vehicle. The rationale for this objective was that very low availability of petroleum could

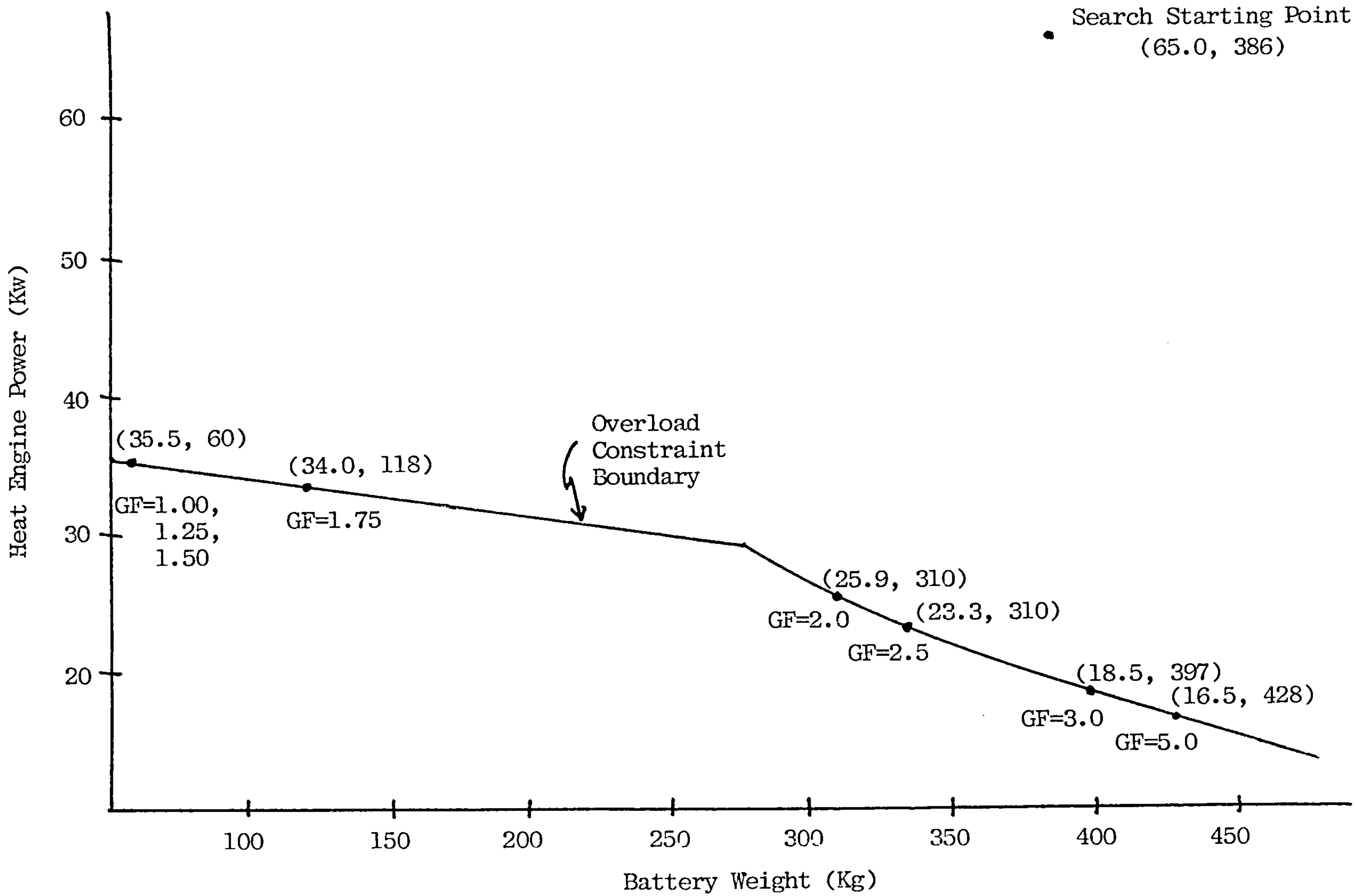

Figure 11-3 <u>Power Source Sizing for Optimum Life Cycle Cost</u>
(Various Petroleum Costs)

Table 11-1

Optimum Life Cycle Cost For Various Gas Factors

Gas Factor, γ	Optimum C_{LC} (\$)	P_{HE}(kw)	W_B(kg)
1.00	17,100	35.46	60.00
1.25	18,112	35.46	60.00
1.50	19,123	35.46	60.00
1.75	19,956	33.98	117.86
2.00	21,046	25.98	309.96
2.50	22,334	25.97	310.10
3.00	23,495	23.34	336.74
5.00	27,926	16.46	428.40

make a hybrid vehicle whose petroleum consumption was minimal very attractive, even at a somewhat higher price. Thus this problem, at least in its initial formulation, did not take costs into account explicitly.

The design optimization problem here is:

$$\min_{P_{HE}, W_B} V_p(P_{HE}, W_B) \tag{11-8}$$

subject to equations 11-2, 11-3 and 11-4, with the Airesearch power split function and $\gamma = 1.0$.

The result for this problem involving no costs was a hybrid vehicle with P_{HE} = 15.0 kw, and W_B = 457 kg. This design point is on the overload constraint boundary and sets the heat engine power at its lower limit, yielding total petroleum usage of 5,209 liters (compared to 9,814 when life cycle cost is minimized) and a life cycle cost of $19,337 (compared to $17,100 when life cycle cost is minimized). The results illustrate the trade off that occurs when the objective is low petroleum usage rather than minimum cost: the petroleum consumption decreases and the cost increases.

These results motivated another design optimization problem which was defined, starting with the problem above, by adding an additional constraint,

$$C_{LC}(P_{HE}, W_B) \leq 18,000 \tag{11-9}$$

This in effect asks for petroleum consumption which is superior to (lower than) that of the minimum-life-cycle-cost petroleum consumption, but which limits the cost increase. The result, as expected, was intermediate to the previous results for minimum life cycle cost and minimum petroleum consumption, with petroleum consumption of 7,2061 liters and a life cycle cost of

\$17,963. The design variables for this result were P_{HE} = 31.2 kw and W_B = 226 kg, a point on the overload constraint boundary.

The addition of this constraint illustrates the great flexibility of the optimization approach to hybrid vehicle design. It is easy for a designer to add such a constraint and repeat the optimization procedure in order to gain the desired result.

A summary of the results for the two problems discussed in this section as well as the minimum life cycle cost results are listed in Table 11-2.

Table 11-2

Summary of Optimization Results

Function Minimized	Constraint	P_{HE}(kw)	W_B(kg)	V_p(1)	C_{LC}(\$)
C_{LC}	none	35.5	60	9,814	17,100
V_p	$C_{LC} < 18,000$	31.2	226	7,206	17,963
V_p	none	15.0	457	5,209	19,337

11.4 POWER SPLIT OPTIMIZATION

This section discusses some particular problems which are in a class which may be described as power flow strategy problems. The general problem could include any number of on-board power sources, including storage devices, and is directed toward specifying the direction and amount of power flow for each power source at each instant of time. The result of solving the problem is called the power flow strategy because it is to be expressed as a set of strategy algorithms, or decision rules, dependent on some of the vehicle dynamic variables and internal variables, which permit calculation of each power flow as these variables change with time.

For the particular case of a hybrid vehicle considered here, with the two on-board power sources, the power flow strategy problem reduces to that of determining, at each instant of time, how much of the wheel power is supplied by the electric propulsion system, and how much by the heat engine. Battery charging during regeneration is handled as a separate consideration (see Appendix F). The power flow strategy then amounts to determining the power split between heat engine power and battery power, and so the problem was defined using a power split function, $s(t)$, $0 < s(t) < 1$, where the extremes correspond to all-petroleum ($s = 0$) and all-electric ($s = 1$) power.

It is important to recognize the infeasibility of finding $s(t)$ as the solution to an optimization problem. This would be possible only if we were to define a dynamic optimization problem with a prescribed vehicle driving regime (speed vs. time) for the entire life of the vehicle. This is unrealistic from two points of view: (1) the time interval involved would be so long that the computations could not be performed efficiently, and (2) it is not possible to predict the exact, second by second driving velocity of a vehicle realistically for the entire life of the vehicle, and for a substantial number of vehicles.

Thus the approach taken here was based on the parameterization of a strategy function or decision rule, with the power split strategy expressed in terms of variables likely to influence the ideal power split function, and using parameters whose values could be obtained using the same methodology and computer programs used to determine optimal vehicle sizing parameters.

This part of the project included two different approaches concerning the parameterization of the power split function, s(t). The first involved the parameterization of the AiResearch power split function, and the second involved the use of polynominal functions to represent s(t).

11.4.1 PARAMETERIZED AIRESEARCH POWER SPLIT FUNCTION

The power split function, previously discussed and used in the study by AiResearch Corporation [1] (also see Appendix H), contains several constants which could be treated as parameters. One of these, which was thought to be one of the most critical, is the value of the power split function during acceleration, s_a, which was given the value 0.3 in the AiResearch study. An optimization problem was formed with s_a as a parameter:

$$\text{Min} \quad C_{LC}(s_a) \tag{11-10}$$

$$\text{subject to} \quad P_{HE} = 65 \text{ kw} \tag{11-11}$$

$$W_B = 386 \text{ kg} \tag{11-12}$$

$$0 \leq s_a \leq 1.0 \tag{11-13}$$

and the remainder of the AiResearch power split algorithm. Equations 11-11 and 11-12 specify vehicle power sizing parameters which correspond to those of the AiResearch hybrid vehicle design; since this vehicle is easily able to meet the power demanded by the driving regime, it was not necessary to include the power overload function as a constraint for this problem.

This optimization problem was solved repeatedly for several values of the gas factor, γ, which was discussed in Section 11.2. Results, which are listed in Table 11-3, show that no electric power should be used during acceleration for the lowest values of the gas factor, and that the power split rises to 0.264 with $\gamma = 5.0$. The optimal life cycle costs rises correspondingly with the gas factor, as expected. These results show that the optimal distribution of power between the two sources is strongly dependent upon the petroleum price, and that a power split value of 0.3 could be justified only for a very large value of the gas factor.

Table 11-3

Optimal Power Split During Acceleration

Gas Factor, γ	Power Split, s_a	Life Cycle Cost, C_{LC}($)
1.0	0.000	20,000
1.5	0.000	21,886
2.0	0.114	23,303
2.5	0.194	24,669
3.0	0.231	26,021
4.0	0.248	28,702
5.0	0.264	31,364

11.4.2 POLYNOMIAL POWER SPLIT FUNCTION

Another approach to expressing the power split function in parameterized form is to use a simple polynomial function of vehicle variables with parameters to be determined through optimization. This leads to a problem of constraining s(t) to its specified range, $0 \leq s(t) \leq 1$, since any polynomial function of vehicle variables is likely to exceed this range during at least part of the driving regime. This problem cannot be treated directly through constraints on s(t) because that involves a dynamic optimization problem which is unrealistic in this application as discussed earlier.

The power split function was constrained through the use of limiting. Let $s_p(t)$ be the value of the power split polynomial function. Then

$$s(t) = \begin{cases} 0, & s_p(t) < 0 \\ s_p(t), & 0 \leq s_p(t) \leq 1 \\ 1, & s_p(t) > 1 \end{cases} \tag{11-14}$$

The polynomial function chosen for investigation involved two key vehicle variables, battery state of charge, c(t) and vehicle acceleration, a(t). Several polynomial functions were tried starting with the linear polynomial

$$s_p(t) = \alpha_0 + \alpha_1 \, c(t) + \alpha_2 \, a(t) \tag{11-15}$$

and later including higher-degree polynomial functions.

The search procedures of GRG2 did not produce worthwhile results with this approach. Typically, the search started with an initial estimate of the α parameters and failed to improve the objective function in several iterations, finally stopping because of lack of progress at a point very close to the initial estimate. Our conclusion about this is that it was not due to any deficiency in GRG2, but was due to a fundamental problem with the approach, in particular the limiting process defined by equation (11-14). The limiting apparently led to erroneous values of the gradient so that the search directions determined by GRG2 were not effective. It seems as if the changes used for the parameters had little or no effect because the value of

$s_p(t)$ calculated from the polynomial such as that in equation (11-15) was promptly and frequently overridden by the limiting action as the vehicle simulation was carried out. Approaches like the one described in Section 11.4.1, where a proven and acceptable power split function was parameterized, seem much more promising. The main reason for this is that such an approach allows incorporation of bounds on the parameters themselves in a direct manner, rather than the indirect approach used in the limiting of the polynomial function.

11.5 SUMMARY OF RESULTS

This section has treated the application of an optimization technique based on nonlinear programming to the design of hybrid vehicles. Four different design problems were solved using the digital computer program which combined the optimization algorithm with the hybrid vehicle simulation.

The method was successfully applied to vehicle power source sizing problems for a variety of design goals and specifications. It was found that all solutions were on the power overload constraint boundary such that, in each case, any reduction in the battery weight or heat engine power rating would yield a vehicle which would not be able to meet the power demands of the specified driving regime.

Two methods were considered for parameterizing the power split function which specifies, at each instant of time, what fraction of the total power demand is supplied by the electric propulsion system, and what fraction by the heat engine. The parameterization of the AiResearch power split function was found to be much more successful than using a polynomial power split function with limiting.

The use of optimization as a systematic approach to a variety of hybrid vehicle design problems was shown by these results to be very effective.

12.0 CONCLUSIONS

This study has led to several conclusions regarding the effective use of an optimization technique for hybrid vehicle design.

Efficient and effective use of an optimization technique for hybrid vehicle design depends heavily on a vehicle simulation program which is designed for this purpose. One of the main necessary features of such a simulation is that it must permit continuous variation of the power plant sizing parameters, battery weight and heat engine power rating.

Another area demanding attention in such a simulation is the way the specified driving pattern, including standard test cycles and highway driving, are incorporated into the simulation; this has impact both on computer run time, which must be minimized, and on the ability to accurately simulate long trips involving a declining state of charge for the batteries, since this state of charge affects the power split. One cannot get accurate results by merely simulating one standard test cycle and extrapolating the results.

Attention must be paid to the simulation time step sizes used in the simulation. They must be small enough to provide sufficient accuracy in the calculation of vehicle variables and costs, while remaining as large as possible for the purpose of minimizing computer run time; this is particularly important when the simulation is used in optimization, since the optimization program must run the simulation program dozens of times during the completion of one design problem.

Since the main purpose of the simulation program is to calculate functions which are used as the objective or constraint functions for the optimization program, the simulation program must be designed to produce these functions as smooth functions of the design parameters. Otherwise the optimization program is likely to calculate search directions which will not yield a successful result because of functional discontinuities, or the optimization is likely to stall at a false local minimum.

This research demonstrated that the handling of the power overload function is critical to obtaining successful results for power-sizing design problems. Design results for this problem are very likely to lie on the power overload constraint boundary, since the region above it represents increased life cycle cost and petroleum consumption, while the region below it represents a vehicle which will not be able to meet the power demand associated with the specified driving regime. The exact location of the power overload constraint boundary need not be determined; it is more important that this constraint be a smooth function so that the optimization program can work efficiently.

It is important to choose the optimization program and to carefully design the interface between the simulation program and the optimization program in order to provide considerable flexibility to the designer in the choice of the design objective, constraints and variables for a variety of design problems. This project demonstrated that this can be done successfully.

Standard procedures for improving the efficiency of the optimization program, including scaling of the design variables and functions, were used and were judged to be effective. Gradient calculations by finite differences required the use of double-precision arithmetic. These are points which the designer must keep in mind when developing optimization program applications.

The two methods of parameterizing the power split algorithm, which specifies how much electric power and heat engine power is used at any time, demonstrated the feasibility of this parameterization. The polynomial power split function which was limited in value did not produce useful results because the optimization program did not have a free hand in varying the power split function due to the limiting. The parameterization of the AiResearch algorithm was much more effective, and this general area of parameterizing an established algorithm is a promising area for future research. Optimization of the power split function, in particular, is a research area which should be pursued.

Optimization has been shown to be a useful tool for systematic design of hybrid vehicles. This research showed that it is possible to couple a sophisticated, general purpose optimization program to a complex hybrid vehicle simulation and produce a successful hybrid vehicle design using a reasonable amount of computer time.

APPENDIX A - DICTIONARY OF VARIABLES

```
FTN4,L
      PROGRAM HVPOP
C
C*************************************************************************
C***                                                                   ***
C***    PROGRAM HVPOP = HYBRID VEHICLE PERFORMANCE EVALUATION PROGRAM  ***
C***                                                                   ***
C*************************************************************************
C
C
C*************************************************************************
C**********                                                    **********
C**********              DICTIONARY OF VARIABLES               **********
C**********                                                    **********
C*************************************************************************
C
C
C VARIABLE          DESCRIPTION                  UNITS      SOURCE    VALUE
C
C*************************************************************************
C
C AACTL     ACTUAL CAPACITY WITHDRAWN         AMP-HOURS     CALC    *******
C           FROM BATTERY
C
C AACV(        MAP OF AVERAGE CHARGING VOLTAGE    VOLTS     CSU      HAVE
C  AACTL/MC)  VS ACTUAL CAPACITY REMOVED (FOR
C              A 25 AMP CHARGE RATE)
C
C ACCEL     AVERAGE ACCELERATION OVER ONE     METERS PER    CALC    *******
C           DRIVING CYCLE TIME INCREMENT    SECOND SQUARED
C
C ACQCST    ACQUISITION COST OF VEHICLE        DOLLARS      CALC    *******
C
C ACR       ARRAY OF CAPACITY REMOVED (USED   AMP-HOURS     NASA     HAVE
C           IN CALCULATING THE AVERAGE       PER KILOGRAM
C           CHARGING VOLTAGE)
C
C ALLETA(I)    ARRAY OF ELECTRIC ENERGY,      MEGAJOULS     CALC    *******
C              COMPUTED BY SUMMING THE CURRENT
C              OUT OF THE BATT, IN THE VARIOUS
C              TRIPS (FOR PRINTING)
C
C ALLETP(I)    ARRAY OF ELECTRIC ENERGY,      MEGAJOULS     CALC    *******
C              COMPUTED BY SUMMING THE POWER
C              OUT OF THE BATT, IN THE VARIOUS
C              TRIPS (FOR PRINTING)
C
C AESPED(1)    ARRAY OF ENGINE SPEEDS USED IN   RAD/SEC     NASA     HAVE
C              HC MAP INTERPOLATION
C
```

```
C AHCHG     AMP-HRS INTO BATTERY FROM HE          AMP-HOURS    CALC      *******
C           CHARGING
C
C AHEKW(I)   ARRAY CONTAINING HE POWER            KILOWATTS    NASA     I AHEKW(I)
C            RATINGS (USED IN FUEL RATE                                  1   37.
C            CALCULATIONS)                                               2   56.
C                                                                        3   75.
C                                                                        4  112.
C
C AHOUT     BATTERY AMP-HOURS OUT                 AMP-HOURS    CALC      *******
C
C ALLSTC    LENGTH OF LONGEST TRIP WHICH           METERS      NASA      50,001.0
C           USES JUST STC'S (NO HIGHWAY
C           DRIVING)
C
C ALPHA1    WEIGHTING PARAMETER FOR LIFE              -        CSU       VARIES
C           CYCLE COST IN OBJECTIVE FUNCTION
C
C ALPHA2    WEIGHTING PARAMETER FOR PETROLEUM         -        CSU       VARIES
C           COST IN OBJECTIVE FUNCTION
C
C ALPHA3    WEIGHTING PARAMETER FOR ACQUISITION       -        CSU       VARIES
C           COST IN OBJECTIVE FUNCTION
C
C APETT(I)   ARRAY OF PETROLEUM USED IN            LITERS      CALC      *******
C            THE VARIOUS TRIPS (FOR PRINTING)
C
C AREGEN    AMP-HOURS REGENERATED                 AMP-HOURS    CALC      *******
C
C ASMCER    CONSTANT USED TO CALC.               DOLLARS PER   NASA      0.1984
C           THE ASSEMBLY COST                     KILOGRAM
C
C ASMCST    VEHICLE ASSEMBLY COST                  DOLLARS     CALC      *******
C
C ATORQ(I)   ARRAY OF TORQUES CORRESPONDING TO       NM        NASA      HAVE
C            THE STANDARD 75 KW ENGINE USED TO
C            COMPUTE THE SCALED ARRAY OF TORQUES
C            USED FOR A DIFFERENT SIZED ENGINE
C
C BATCER    CONSTANT USED TO CALCULATE           DOLLARS PER   NASA      1.87
C           COST OF BATTERIES                     KILOGRAM
C
C BATCST    MANUFACTURING COST OF                  DOLLARS     CALC      *******
C           BATTERIES
C
C BATLFE    NO. OF YEARS IN BATTERY LIFE           YEARS       CALC      *******
C
C BATRPL    NO. OF BATTERY REPLACEMENTS IN           -         CALC      *******
C           VEHICLE LIFE
C
```

```
C BATSAL   SALVAGE VALUE OF BATTERY              DOLLARS      CALC      *******
C
C BENRGY   BATTERY ENERGY USED FOR THIS           JOULES      CALC      *******
C           INCREMENT IN THE DRIVING CYCLE
C
C BET(I)   GRADE ANGLE ARRAY FOR COMPLETE        DEGREES    CSU/NASA    ALL 0.
C           DRIVING CYCLE
C
C BETA     GRADE ANGLE AT THIS POINT             DEGREES      CALC      *******
C           IN THE DRIVING CYCLE
C
C BSFC     CONSTANT USED TO CALC MOST            RAD/SEC    CSU/NASA    4.2
C           EFFICIENT ENGINE SPEED FOR A         ----------
C          GIVEN PERCENT OUTPUT OF HE         % RATED POWER
C
C BTCOST   COST OF BATTERY REPLACEMENT           DOLLARS      CALC      *******
C           DURING VEHICLE LIFE
C
C BTLIST   LIST COST OF BATTERIES                DOLLARS      CALC      *******
C
C BTMAIN   BATTERY MAINTENANCE COST            DOLLARS PER    CALC      *******
C                                               KILOMETER
C
C BTMKUP   BATTERY MARKUP FACTOR                    -         NASA      0.3
C           (A CONSTANT BETWEEN 0 AND 1)
C
C CAPCTY   CELL CAPACITY                        AMP-HOURS     CALC      *******
C
C CAPKG    CAPACITY OF A BATTERY               AMP-HOURS/KG   CALC      *******
C           CELL PER KILOGRAM
C
C CDA      DRAG COEFFICIENT TIMES                 METERS      NASA      0.6
C          VEHICLE FRONTAL AREA                   SQUARED
C
C CHARGE(I)  ARRAY WHICH SAVES AT THE END       AMP-HOURS     CALC      *******
C             OF EACH STC THE TOTAL AMP-HRS
C             INTO THE BATTERY FROM HE CHARGING
C
C CHGCER   CONSTANT USED TO CALCULATE          DOLLARS PER    NASA      5.89
C           COST OF CHARGER                      KILOGRAM
C
C CHGCST   COST OF BATTERY CHARGER               DOLLARS      CALC      *******
C
C CHGEFF   BATTERY CHARGER EFFICIENCY               -         NASA      0.85
C
C CHGRC1   CONSTANT USED IN CALCULATING          KILOGRAMS    NASA      0.0
C          MASS OF CHARGER                        PER WATT
C
C CHGRKW   POWER RATING OF CHARGER              KILOWATTS     NASA      14.5
C
```

```
C CHIC1     CONSTANT USED IN CALCULATING        KILOGRAMS     NASA      0.91
C           MASS OF CHOPPER INVERTER             PER KW
C
C CHICER    CONSTANT USED TO CALCULATE          DOLLARS PER   NASA      14.00
C           CHOPPER INVERTER COST                KILOGRAM
C
C CHICST    COST OF CHOPPER INVERTER             DOLLARS      CALC      *******
C
C CHIKW     POWER RATING OF CHOPPER             KILOWATTS     NASA      40.0
C           INVERTER
C
C CHIMAN    CHOPPER INVERTER MAINTENANCE        DOLLARS PER   CALC      *******
C           COST                                 KILOMETER
C
C CHOOSE    IF EQUAL TO 1, ELECTRICITY COST         -         CSU       0.0
C           COMPUTED FROM ELECYR(I). IF EQUAL
C           TO 0, ELEC(I) REPLACES ELECYR(I)
C
C CLTCER    CONSTANT USED TO CALCULATE          DOLLARS PER   NASA      0.0
C           THE COST OF THE CLUTCH               KILOGRAM
C
C CLTCST    COST OF CLUTCH FOR VEHICLE           DOLLARS      CALC      *******
C
C COUNT     VARIALBLE USED IN DETERMINING           -         CALC      *******
C           WHICH YEARS BATT. REPLACEMENT
C           COSTS ARE ADDED
C
C CR        CONSTANT IN ROLLING                     -         CALC      *******
C           RESISTANCE FORCE CALCULATION
C
C CVTC1     CONSTANT USED TO CALCULATE          KILOGRAMS     NASA      1.07
C           CVT MASS                            PER KILOWATT
C
C CVTCER    CONSTANT USED TO                    DOLLARS PER   NASA      1.42
C           CALCULATE CVT COST                   KILOGRAM
C
C CVTCST    COST OF CVT                          DOLLARS      CALC      *******
C
C CVTKW     POWER RATING OF CVT                 KILOWATTS     NASA      90.0
C
C CVTMAN    CVT MAINTENANCE COST                DOLLARS PER   CALC      *******
C                                                KILOMETER
C
C CX(I)     ARRAY CONTAINING POWER SPLIT          MIXED       CALC      *******
C           PARAMETERS
C
C DEEP      NO. OF DEEP DISCHARGES OF               -         CALC      *******
C           BATTERY DURING VEHICLE LIFE
C
C DELR      INCREMENT FOR DECREASING CVT            -         CSU       0.1
```

```
C             RATIO TO PREVENT MOTOR FROM
C             STALLING
C
C DELSTC      FRACTION OF AN STC USED                  -             CALC      *******
C             IN CURRENT TRIP
C
C DELT        SIMULATION TIME STEP SIZE             SECONDS          CALC      *******
C
C DELTHW      SIMULATION TIME INCREMENT FOR         SECONDS          CSU       60.0
C             HIGHWAY DRIVING
C
C DELV        VEHICLE VELOCITY DECREASE PER         KILOMETERS       CALC      *******
C             TIME INCREMENT DURING BREAKING        PER SECOND
C             PHASE OF STC
C
C DIGRKW      POWER RATING OF GEAR BETWEEN          KILOWATTS        NASA      90.0
C             DIFFERENTIAL AND CVT (SEE ALSO
C             PGRATE)
C
C DHEKW       WHEN RUN21=2, THE AMOUNT HEKW         KILOWATTS        ARB
C             IS INCREMENTED FOR NEXT CCOMP CALL
C             WHEN RUN21=1 THE TOLERANCE ON HEKW
C
C DIFCER      CONSTANT USED TO CALCULATE            DOLLARS PER      NASA      2.42
C             COST OF A DIFFERENTIAL                KILOGRAM
C
C DIFCST      COST OF DIFFERENTIAL                  DOLLARS          CALC      *******
C
C DIFFC1      CONSTANT USED IN CALCULATING          KILOGRAMS        NASA      0.66
C             MASS OF DIFFERENTIAL                  PER KW
C
C DIFFKW      POWER RATING OF DIFFERENTIAL          KILOWATTS        NASA      90.0
C             (ALSO SEE PDRATE)
C
C DISCH(I)    ARRAY CONTAINING THE NUMBER              -             CALC      *******
C             OF BATTERY DISCHARGES PER YEAR
C             FOR THIS PARTICULAR TRIP TYPE
C
C DISCHG(     BATTERY DISCHARGE CURVE               VOLTS/CELL       NASA      HAVE
C SOC,IEFF)
C
C DISCNT      DOLLAR DISCOUNT RATE                     -             NASA      0.02
C
C DISEFF      FACTOR USED DURING DISCHARGE             -             CALC      ******
C             TO CONVERT BATTERY TERMINAL
C             ENERGY TO INTERNAL ENERGY
C
C DISFAC      THE AMOUNT OF BATTERY DISCHARGE          -             CALC      *******
C             DURING ONE TRIP OF THIS
C             PARTICULAR TRIP TYPE
```

```
C
C DISLFE   NO. OF DEEP DISHCHARGES IN             -         NASA      840.
C          BATTERY LIFE
C
C DLTSTC   SIMULATION TIME STEP SIZE           SECONDS   CSU/NASA   1.0
C          FOR STC DRIVING
C
C DWGBAT   WHEN RUN21=1, OR 2  THE AMOUNT      KILOGRAMS   ARB
C          WGBATT IS INCREMENTED FOR NEXT
C          GCOMP CALL
C
C EBTOT    TOTAL BATTERY ENERGY USED SINCE     MEGAJOULES  CALC      *******
C          START OF TRIP
C
C EBTOTL(I)   ARRAY WHICH SAVES AT THE END     MEGAJOULES  CALC      *******
C             OF EACH STC THE TOTAL BATTERY
C             ENERGY USED SINCE THE START
C             OF ALL STC'S
C
C EFF(KW,     CVT EFFICIENCY MAP                  -        NASA      HAVE
C  RATIO)      (A NUMBER BETWEEN 0 AND 1)
C
C EFFBC    COMBINED BATTERY CHARGER EFF.          -        NASA      0.75
C          AND BATTERY TURNAROUND EFF.
C
C EFFMTR(PERCENT    MOTOR EFFICIENCY MAP          -        NASA      HAVE
C RATED PWR,
C SPEED)
C
C ELCC(I)    ARRAY CONTAINING WALL PLUG        MEGAJOULES  CALC      ******
C            ELECTRICAL ENERGY (COMPUTED
C            ON AMP-HR BASIS) REQUIRED TO
C            MEET ELECTRICAL ENERGY
C            CONSUMPTION FOR THIS PARTICULAR
C            TRIP TYPE FOR ONE YEAR
C
C ELECST(I)   ARRAY CONTAINING ELECT. COST      DOLLARS    CALC      *******
C             FOR YEAR I
C
C ELECYR(I)   ARRAY CONTAINING WALL PLUG       MEGAJOULES  CALC      *******
C             ELECTRICAL ENERGY (COMPUTED
C             ON POWER BASIS) REQUIRED TO
C             MEET ELECTRICAL ENERGY
C             CONSUMPTION FOR THIS PARTICULAR
C             TRIP TYPE FOR ONE YEAR
C
C ENELEC   ELECTRICAL ENERGY CONSUMED          MEGAJOULES  CALC      *******
C          IN CURRENT TRIP (BASED ON POWER)
C
C ENRGY    ELECTRICAL ENERGY CONSUMED          MEGAJOULES  CALC      ******
```

```
C           IN CURRENT TRIP (BASED ON
C           AMP-HRS)
C
C FA        VEHICLE ACCELERATION FORCE           NEWTONS      CALC        *******
C
C FD        VEHICLE DRAG FORCE                   NEWTONS      CALC        *******
C
C FFHEKW(I)    ARRAY CONTAINING PENALTY/            -         NASA     I FFHEKW(I)
C              IMPROVEMENT FACTORS FOR                                 1 1.09718
C              VARIOUS HE POWER RATINGS                                2 1.05
C              (USED IN FUEL RATE                                      3 1.
C              CALCULATIONS)                                           4  .954545
C
C FGR       GRADE FORCE                          NEWTONS      CALC        *******
C
C FR        ROLLING RESISTANCE FORCE             NEWTONS      CALC        *******
C
C FRSCLE    FACTOR DEPENDENT ON HEKW ONLY          -          CALC        *******
C           USED IN MAKING DIFFERENT SIZED
C           HE MAPS FROM A 75 KW HE MAP
C
C FUELRT    HEAT ENGINE FUEL RATE              LITERS PER     CALC        *******
C                                                SECOND
C
C G(I)      ARRAY CONTAINING WEIGHTED OBJECTIVE    %          CALC        *******
C           AND CONSTRAINT FUNCTIONS
C
C GASCST(I)    ARRAY CONTAINING PRICE OF         DOLLARS      NASA    I GASCST(I)
C              PETROLEUM FOR EACH YEAR          PER LITER              1  0.32
C                                                                      2  0.35
C                                                                      3  0.38
C                                                                      4  0.41
C                                                                      5  0.44
C                                                                      6  0.47
C                                                                      7  0.50
C                                                                      8  0.53
C                                                                      9  0.56
C                                                                     10  0.59
C
C GRAV      ACCELERATION OF GRAVITY            METERS PER     CSU         9.807
C                                                SECOND
C                                                SQUARED
C
C GRC1      CONSTANT USED IN CALCULATING      KILOGRAMS PER   NASA        0.3
C           MASS OF GEAR                        KILOWATT
C
C GRCER     CONSTANT USED TO CALCULATE         DOLLARS PER    NASA        2.43
C           COST OF A GEAR                      KILOGRAM
C
C GRDCST    COST OF GEAR BETWEEN                 DOLLARS      CALC        *******
```

```
C          DIFFERENTIAL AND CVT
C
C GREFF(PERCENT    GEARS AND DIFFERENTIAL           -          NASA      HAVE
C  POWER,PERCENT   EFFICIENCY MAP,(A
C  SPEED)          CONSTANT BETWEEN ZERO
C                  AND 1.0)
C
C GRMCST   COST OF GEAR BETWEEN ELECTRIC        DOLLARS       CALC      *******
C           MOTOR AND CVT
C
C HEC1     CONSTANT USED IN CALCULATING      KILOGRAMS PER  NASA      0.0
C           MASS OF ENGINE                     KW SQUARED
C
C HEC2     CONSTANT USED IN CALCULATING       KILOGRAMS     NASA      2.84
C           MASS OF ENGINE                      PER KW
C
C HECER    CONSTANT USED TO CALCULATE        DOLLARS PER    NASA      1.43
C           HEAT ENGINE COST                   KILOGRAM
C
C HECOST   COST OF HEAT ENGINE                DOLLARS       CALC      *******
C
C HEKW     POWER RATING OF HEAT ENGINE        KILOWATTS     NASA      65.0
C           STARTING VALUE OF HEKW WHEN
C          RUN21=2
C
C HEMAIN   HEAT ENGINE MAINTENANCE COST      DOLLARS PER    CALC      *******
C                                             KILOMETER
C
C HEMAP(            HEAT ENGINE MAP           LITERS PER    NASA      HAVE
C TORQUE,SPEED)                                SECOND
C
C HOUT(I)  ARRAY WHICH SAVES AT THE END OF   AMP-HOURS      CALC      *******
C           EACH STC THE AMP HOURS OUT OF THE
C          BATTERY SINCE THE START OF THE STC'S
C
C HWYVEL   HIGHWAY VELOCITY FOR VEHICLE      METERS PER     NASA      25.0
C                                              SECOND
C
C I80DOD   BATTERY DISCHARGE FLAG                -          CALC      *******
C          (EQUALS 1 MEANS BATTERY IS AT OR
C           BELOW 80% DEPTH OF DISCHARGE)
C
C IAVE     AVERAGE BATTERY CURRENT SINCE        AMPS        CALC      *******
C          START OF STC DRIVING
C
C IBATT    BATTERY OUTPUT CURRENT               AMPS        CALC      *******
C
C IBMAX    BATTERY MAX. CHARGING CURRENT        AMPS        NASA      200.0
C
C IBTOLD   OLD VALUE OF BATTERY CURRENT         AMPS        CALC      *******
```

```
C
C IDOD(I)  ARRAY WHICH SAVES STATE OF           -        CALC     *******
C          DEPTH OF DISCHARGE FLAG AT
C          END OF EACH STC
C
C IEFF     BATTERY CELL CURRENT (ACCOUNTS      AMPS      CALC     *******
C          FOR CHANGE IN CELL RESISTANCE
C          DUE TO CHANGE IN CELL MASS)
C
C IEFFMX   MAX VALUE OF BATTERY EFFECTIVE      AMPS       CSU     700.
C          CURRENT
C
C IELEC    ELECTRICAL PATH CALC. FLAG (EQUALS    -        CALC     *******
C          1 IF ELECTRICAL PATH CALC WAS MADE
C          THIS ITERATION)
C
C IFILL    BATTERY CURRENT NEEDED TO CHARGE    AMPS      CALC     *******
C          BATTERY TO SOC OF 1.0
C
C IFLLBK   COUNTS NUMBER OF TIMES ACTUAL         -        CALC     *******
C          POWER SPLIT IS CHANGED FROM SPLIT
C          DETERMINED BY SPLIT FUNCTION
C
C IHECHG   BATTERY CHARGING FLAG (EQUAL TO 1     -        CALC     *******
C          MEANS BATTERY IS BEING CHARGED BY HE)
C
C IHWY     HIGHWAY DRIVING FLAG (EQUALS 1 IF     -        CALC     *******
C          DRIVING ON HIGHWAY RATHER THAN STC)
C
C IICHG    COUNTS ITERATIONS IN ATTEMPTING TO    -        CALC     *******
C          MATCH CALCULATED BATTERY VOLTAGE TO
C          BATTERY VOLTAGE ASSUMED IN MAKING
C          A HE CHARGING OF THE BATTERY
C          CALCULATION
C
C IITER    COUNTS ITERATIONS IN ATTEMPTING       -        CALC     *******
C          TO MATCH CALCULATED BATTERY
C          VOLTAGE TO BATTERY VOLTAGE ASSUMED
C          IN MAKING A BATTERY DISCHARGE
C          CALCULATION
C
C IIREGN   COUNTS ITERATIONS IN ATTEMPTING TO    -        CALC     *******
C          MATCH CALCULATED BATTERY VOLTAGE
C          TO BATTERY VOLTAGE ASSUMED IN MAKING
C          A POWER REGENERATION CALCULATION
C
C IMAX     NUMBER OF POWER SPLIT PARAMETERS      -        CSU      *******
C
C INOCHG   HE CHARGING INHIBIT FLAG              -        CSU      0
C          (=1 FOR NO HE CHARGING)
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C
C INOELE   FLAG WHICH INHIBITS FURTHER USE          --      CALC       *******
C          OF BATTERIES IF SOC FALLS BELOW
C          0.2 DURING HIGHWAY DRIVING
C          (=1 FOR INHIBIT)
C
C IOVRLD   POWER OVERLOAD FLAG (COUNTS NO.          -       CALC       *******
C          OF TIMES BATTERIES AND HEAT ENGINE
C          CANNOT MEET POWER REQUIRED BY VEHICLE)
C
C ISWITCH  POWER SWITCH FLAG (EQUALS 1 WHEN WE      -       CALC       *******
C          HAVE ALREADY ATTEMPTED TO SWITCH
C          EXCESS HEAT ENGINE POWER TO
C          ELECTRIC MOTOR)
C
C ITERMX   MAX NUMBER OF ITERATIONS ALLOWED         -     CSU/NASA     10
C          IN ATTEMPTING TO MATCH CALCULATED
C          BATTERY VOLTAGE TO BATTERY VOLTAGE
C          ASSUMED IN MAKING THE CALCULATION
C
C IVESTC(I)   ARRAY WHICH SAVES AT THE END OF     AMPS      CALC       *******
C             EACH STC THE AVERAGE CURRENT OUT
C             OF THE BATTERY SINCE THE START
C             OF THE STC'S
C
C IYEAR    INDEX INDICATING PRESENT YEAR IN         -       CALC       *******
C          LIFE CYCLE COST CALCULATIONS
C
C JTRIP    INDEX INDICATING PRESENT TRIP IN         -       CALC       *******
C          LIFE CYCLE COST CALCULATIONS
C
C KMPRYR   KILOMETERS TRAVELED PER YEAR        KILOMETERS   NASA       16,000.
C
C KWCST(I)    ARRAY CONTAINING PRICE OF        DOLLARS PER  NASA   I  KWCST(I)
C             ELECTRICITY FOR EACH YEAR         MEGAJOULE           1  .0111
C                                                                   2  .0125
C                                                                   3  .0139
C                                                                   4  .0153
C                                                                   5  .0167
C                                                                   6  .0181
C                                                                   7  .0194
C                                                                   8  .0208
C                                                                   9  .0222
C                                                                  10  .0236
C
C LCCOST   LIFE CYCLE COST                          DOLLARS    CALC       *******
C
C LENGTH   LENGTH OF THE CURRENT TRIP               METERS     CALC       *******
C
C LINCOM   LINEAR COMBINATION OF LIFE               DOLLARS    CALC       *******
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C           CYCLE COST, PETROLEUM COST
C           AND ACQUISITION COST
C
C MAINTC    VEHICLE MAINTENANCE COST          DOLLARS       CALC     *******
C           FOR ONE YEAR
C
C MARKUP    DEALER MARKUP FACTOR                 -          CALC     *******
C
C MC        MASS OF A BATTERY CELL            KILOGRAMS     CALC     *******
C
C MCSTND    MASS OF THE BATTERY CELL USED     KILOGRAMS     NASA     9.83
C           IN DEVELOPING THE BATTERY
C           DISCHARGE CURVE
C
C MNFCST    MANUFACTURING COST FOR VEHICLE    DOLLARS       CALC     *******
C
C MT        TOTAL MASS OF VEHICLE AND         KILOGRAMS     CALC     *******
C           PROPULSION SYSTEM
C
C MTGRKW    POWER RATING OF GEAR BETWEEN      KILOWATTS     NASA     40.0
C           ELECTRIC MOTOR AND CVT (ALSO
C           SEE PMGR1E)
C
C MTKWPK    ELECTRIC MOTOR PEAK KILOWATT      KILOWATTS     NASA     40.0
C           RATING (ALSO SEE PMTMAX)
C
C MTMAIN    ELECTRIC MOTOR MAINTENANCE COST   DOLLARS PER   CALC     *******
C                                             KILOMETER
C
C MTRC1     CONSTANT USED IN CALCULATING      KILOGRAMS     NASA     0.6
C           MASS OF ELECTRIC MOTOR             PER KW
C
C MTRCER    CONSTANT USED TO CALCULATE        DOLLARS PER   NASA     15.95
C           THE COST OF THE ELECTRIC MOTOR    KILOGRAM
C
C MTRCST    COST OF ELECTRIC MOTOR            DOLLARS       CALC     *******
C
C MTRKW     POWER RATING OF ELECTRIC MOTOR    KILOWATTS     NASA     20.0
C           (ALSO SEE PMTRTD)
C
C MTRSPD     AN ARRAY SPECIFYING MAXIMUM      RADIANS PER   NASA     HAVE
C  (PMTPCT)  EFFICIENCY MOTOR SPEED FOR A     SECOND
C            GIVEN OUTPUT POWER
C
C NC        NUMBER OF SERIES CONNECTED           -          NASA     84
C           BATTERY CELLS NECESSARY TO
C           REACH SYSTEM VOLTAGE
C
C NCORE     DIMENSION OF GRG ARRAY Z             -          CSU      6900
C
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C NCYCLE   NUMBER OF STC CYCLES ALREADY          -        CALC     *******
C          SIMULATED
C
C NCYLMX   MAX NUMBER OF STC'S IN ANY            -        NASA     35
C          PARTICULAR TRIP
C
C NHEKW    (WHEN RUN21 = 2) THE NO. OF           -        CSU      VARIES
C          DIFFERENT HEKW VALUES USED
C
C NOSTC    TRUNCATED VALUE OF STCNO              -        CALC     *******
C
C NN       NUMBER OF VARIABLE PARAMETERS         -        CSU      VARIES
C          FOR GRG
C
C NSTCFR   NUMBER OF STC'S IN THE FRONT          -        NASA     28
C          OF EACH TRIP REQUIRING
C          HIGHWAY DRIVING
C
C NTIME    INTEGER INDICATING NUMBER OF          -        CALC     *******
C          TIME INCREMENTS OF DRIVING
C          CYCLE ALREADY SIMULATED
C
C NTRIP    INDEX INDICATING WHICH TRIP IS        -        CALC     *******
C          BEING USED
C
C NTRIPX   MAXIMUM NUMBER OF TRIP TYPES          -        NASA     8
C
C
C PAXLE    POWER REQUIRED AT AXLE              WATTS      CALC     *******
C
C PBMAX    BATTERY MAX CHARGING POWER          WATTS      NASA     33,600.
C
C PBOUT    BATTERY OUTPUT POWER                WATTS      CALC     *******
C
C PCHG     HEAT ENGINE POWER USED TO           WATTS      CALC     *******
C          CHARGE BATTERIES
C
C PCVT     POWER REQUIRED AT CVT INPUT         WATTS      CALC     *******
C
C PCVTMX   MAXIMUM POWER RATING OF CVT         WATTS      NASA     90,000.
C
C PDPCT    DIFFERENTIAL OUTPUT POWER AS A      PERCENT    CALC     *******
C          PERCENT OF DIFFERENTIAL RATED
C          POWER
C
C PDRATE   DIFFERENTIAL RATED POWER (ALSO      WATTS      NASA     90,000.
C          SEE DIFFKW)
C
C PDRIVE   POWER REQUIRED AT DRIVE SHAFT       WATTS      CALC     *******
C
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C PELEC     ELECTRIC POWER REQUIRED AT            WATTS      CALC     *******
C            INPUT TO CVT
C
C PLTCST(I)   ARRAY CONTAINING PETROLEUM         DOLLARS    CALC     *******
C              COSTS FOR YEAR I
C
C PETROL    PETROLEUM VOLUME USED                 LITERS     CALC     *******
C            IN CURRENT TRIP
C
C PETSTC(I)   ARRAY WHICH SAVES AT THE END        LITERS     CALC     *******
C              OF EACH STC THE TOTAL PETROLEUM
C             VOLUME USED SINCE THE START OF
C              ALL STC'S
C
C PETYR(I)    ARRAY WHICH CONTAINS THE YEARLY     LITERS     CALC     *******
C              PETROLEUM CONSUMPTION FOR THIS
C             PARTICULAR TRIP
C
C PGEAR     POWER REQUIRED AT INPUT TO GEAR       WATTS      CALC     *******
C            BETWEEN CVT AND DIFFERENTIAL
C
C PGPCT     OUTPUT POWER OF GEAR BETWEEN          PERCENT    CALC     *******
C            CVT AND DIFFERENTIAL AS A
C           PERCENT OF GEAR RATED POWER
C
C PGRATE    RATED POWER FOR GEAR BETWEEN          WATTS      NASA     70,000.
C            CVT AND DIFFERENTIAL (SEE ALSO
C           DFGRKW)
C
C PHE       HEAT ENGINE POWER REQUIRED AT         WATTS      CALC     *******
C            INPUT TO CVT
C
C PHEMAX    MAX OUTPUT POWER OF HEAT ENGINE       WATTS      CALC     *******
C
C PHEST     ESTIMATED OUTPUT POWER OF HE          WATTS      CALC     *******
C           USED IN DETERMINING CVT RATIO
C
C PILOSS    INVERTER POWER LOSS                   WATTS      CALC     *******
C
C PINV      POWER REQUIRED AT OUTPUT OF           WATTS      CALC     *******
C            INVERTER
C
C PINVMX    MAX OUTPUT POWER OF INVERTER          WATTS      NASA     40,000.
C
C PMGPCT    POWER AT OUTPUT OF GEAR BETWEEN       PERCENT    CALC     *******
C           MOTOR AND CVT AS A PERCENT OF
C           GEAR RATED OUTPUT POWER
C
C PMGRTE    RATED OUTPUT POWER FOR GEAR           WATTS      NASA     40,000.
C           BETWEEN MOTOR AND CVT (ALSO
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C           SEE MTGRKW)
C
C PMOTOR   ELECTRIC MOTOR OUTPUT POWER            WATTS      CALC       *******
C
C PMT      ESTIMATED OUTPUT POWER OF MOTOR        WATTS      CALC       *******
C          USED IN DETERMINING THE CVT RATIO
C
C PMTMAX   ELECTRIC MOTOR MAX OUTPUT POWER        WATTS      NASA       40,000.
C          (ALSO SEE MTMAX AND MTKWPK)
C
C PMTPCT   MOTOR OUTPUT POWER AS A PERCENT       PERCENT     CALC       *******
C          OF RATED POWER (USED FOR RATIO
C          CALC)
C
C PMTRTD   RATED POWER OF MOTOR (SEE ALSO         WATTS      NASA       20,000.
C          MTRKW)
C
C POVRLD   ACCUMMULATION OF SQUARED VALUES        WATTS      CALC       *******
C          OF PSHORT                             SQUARED
C
C PREGEN   POWER AVAILABLE FOR REGENERATION       WATTS      CALC       *******
C          AFTER ROAD LOSSES
C
C PROAD    VEHICLE POWER LOSS DUE TO ROAD         WATTS      CALC       *******
C          LOSSES DURING BREAKING PHASE OF
C          STC
C
C PSHORT   DIFFERENCE BETWEEN DEMANDED POWER      WATTS      CALC       *******
C          AND POWER PROPULSION SYSTEM CAN
C          SUPPLY
C
C PUKRT(CURRENT/KG)    PEUKERT CURVE        AMP-HOURS/KG   NASA       HAVE
C
C PVBATT   VARIABLE USED TO PRINT VBATT           VOLTS      CALC       *******
C          AND VBCHG
C
C PWRSTP   TOTAL POWER AVAILABLE FOR              WATTS      CALC       *******
C          REGENERATION DURING THIS TIME
C          INCREMENT IN THE BREAKING
C          PHASE OF THE STC
C
C RCVT     CVT RATIO (OUTPUT SPEED                  -        CALC       *******
C          DIVIDED BY INPUT SPEED)
C
C RCVTMN   MINIMUM ALLOWABLE CVT RATIO              -        NASA       0.0
C
C RCVTMX   MAX ALLOWABLE CVT RATIO                  -        NASA       3.4
C
C RDIFF    GEAR RATIO OF DIFFERENTIAL (AXLE         -        NASA       1.0
C          SPEED DIVIDED BY SHAFT SPEED)
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C
C REGEFF   REGENERATIVE EFFICIENCY                 -          CALC        ******
C
C RIGEN(I)   ARRAY WHICH SAVES AT THE END      AMP-HOURS    CALC        *******
C            OF EACH STC THE AMP HOURS
C            REGENERATED INTO THE BATTERY
C            SINCE THE START OF ALL STC'S
C
C REGMIN   MINIMUM POWER WORTH REGENERATING       WATTS      NASA        1,000.
C
C REPAIR   VEHICLE REPAIR COST FOR ONE YEAR      DOLLARS     CALC        *******
C
C REPCHI   CHOPPER INVERTER REPAIR COST        DOLLARS PER   CALC        *******
C                                               KILOMETER
C
C REPCVT   CVT REPAIR COST                     DOLLARS PER   CALC        *******
C                                               KILOMETER
C
C REPMTR   ELECTRIC MOTOR REPAIR COST          DOLLARS PER   CALC        *******
C                                               KILOMETER
C
C REPRHE   HEAT ENGINE REPAIR COST             DOLLARS PER   CALC        *******
C                                               KILOMETER
C
C RGEAR    RATIO OF GEAR BETWEEN CVT               -         NASA        0.0833
C          AND DIFFERENTIAL (DRIVE SHAFT
C          SPEED DIVIDED BY CVT OUTPUT SPEED)
C
C RGRM     RATIO OF GEAR BETWEEN ELECTRIC          -         NASA        0.2857
C          MOTOR AND CVT (CVT INPUT SPEED
C          DIVIDED BY ELEC. MOTOR SPEED)
C
C RHO      AIR WEIGHT DENSITY                KILOGRAMS PER   CSU         1.225
C                                             CUBIC METER
C
C RUN21    A VARIABLE READ IN:                               ARB
C          0 FOR 1 GCOMP CALL (WITH ONLY A SUMMARY SHEET PRINTED)
C          1 FOR 1 GCOMP CALL (WITH B9 & A8 & SUMMARY SHEET PRINTED)
C          2 FOR MAKING A LCCOST GRID WITH HEKW
C            AND WGBATT AS THE AXIS
C          3 FOR MAKING POWER SPLIT VS CONSUMPTION
C            DATA
C
C RTIRE    TIRE RADIUS                            METERS     NASA        0.30
C
C SALVGE   SALVAGE VALUE OF VEHICLE               DOLLARS    CALC        *******
C
C SATORQ(I)   ARRAY OF SCALED TORQUES               NM       CALC        *******
C             USED IN FUEL RATE CALC
C
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C SFG(I)    ARRAY OF WEIGHTING FACTORS                -           CSU       VARIES
C           FOR ARRAY G
C
C SFX(I)    ARRAY OF WEIGHTING FACTORS                -           CSU       VARIES
C           FOR PARAMETERS OPTIMIZED BY GRG
C
C SOC       STATE OF CHARGE                           -           CALC      *******
C
C SOCL      THE MINIMUM STATE OF CHARGE               -           CALC      *******
C           ATTAINED BY THE BATTERY DURING
C           ACCELERATION
C
C SOCMAX    MAXIMUM STATE OF CHARGE TO                -           NASA      0.3
C           WHICH HE CHARGES BATTERY
C
C SOCSTC(I)    ARRAY WHICH SAVES THE STATE OF         -           CALC      *******
C              CHARGE OF THE BATTERY AT THE
C              END OF EACH STC
C
C STALL(WMT)    A FUNCTION WHICH GIVES        % RATED POWER       NASA      HAVE
C               THE MAX POWER FROM MOTOR
C               FOR A GIVEN SPEED
C
C STCDIS    DISTANCE OF ONE STC                     METERS        NASA      1,450.0
C
C STCNO     NUMBER OF STC'S IN CURRENT TRIP           -           CALC      *******
C
C TACCEL    TIME AT WHICH ACCELERATION             SECONDS        NASA      14.0
C           PHASE OF STC ENDS
C
C TAXLE     AXLE TORQUE                         NEWTON METERS     CALC      *******
C
C TBRAKE    TIME AT WHICH BRAKING PHASE            SECONDS        NASA      74.0
C           OF STC IS REACHED
C
C TCOAST    TIME AT WHICH COAST PHASE              SECONDS        NASA      64.0
C           OF STC IS REACHED
C
C TCVT      TORQUE AT INPUT TO CVT              NEWTON METERS     CALC      *******
C
C TCYCLE    TIME REQUIRED TO DRIVE ONE             SECONDS        NASA      108.0
C           DRIVING CYCLE (INCLUDING IDLING)
C
C TDRIVE    DRIVE SHAFT TORQUE                  NEWTON METERS     CALC      *******
C
C TGEAR     TORQUE AT INPUT TO GEAR             NEWTON METERS     CALC      *******
C           BETWEEN CVT AND DIFFERENTIAL
C
C THE       HEAT ENGINE OUTPUT TORQUE           NEWTON METERS     CALC      *******
C
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C TIME      SIMULATION TIME                      SECONDS       CALC       *******
C
C TMOTOR    OUTPUT TORQUE OF ELECTRIC          NEWTON METERS   CALC       *******
C            MOTOR
C
C TOTBAT    FIRST YEAR EQUIVALENT TOTAL          DOLLARS       CALC       *******
C            BATTERY REPLACEMENT COST
C           (SEE TOTELE)
C
C TOTBS     FIRST YEAR EQUIVALENT BATTERY        DOLLARS       CALC       *******
C            SALVAGE VALUE (THE AMOUNT OF
C           MONEY INVESTED IN THE FIRST
C            YEAR NECESSARY TO OBTAIN THE
C           AMOUNT THE BATTERIES WOULD BE
C            SOLD FOR IN THE TENTH YEAR)
C
C TOTELE    FIRST YEAR EQUIVALENT TOTAL          DOLLARS       CALC       *******
C            ELECTRICAL ENERGY COSTS, OBTAINED
C           BY COMPUTING THE SUM OF THE FIRST
C            YEAR EQUIVALENT YEARLY COSTS,
C           FOR ALL TEN YEARS, WHICH
C            ARE AMOUNTS, WHICH IF INVESTED IN
C           THE FIRST YEAR AT A FIXED INTEREST
C            RATE, YIELD THE COST OF ELECTRICAL
C           ENERGY FOR THE GIVEN YEAR
C
C TOTPET    FIRST YEAR EQUIVALENT TOTAL          DOLLARS       CALC       *******
C            PETROLEUM COST USED DURING
C           LIFE CYCLE (SEE TOTELE)
C
C TOTSAL    FIRST YEAR EQUIVALENT VEHICLE        DOLLARS       CALC       *******
C            SALVAGE VALUE (SEE TOTBS)
C
C TRIPLN(I)    ARRAY WHICH CONTAINS THE           METERS       NASA   I  TRIPLN(I)
C               LENGTH OF ALL THE REQUIRED                          1   10,000.0
C              TRIPS                                                2  30,000.
C                                                                   3   50,000.
C                                                                   4  80,000.
C                                                                   5   130,000.
C                                                                   6  160,000.
C                                                                   7   500,000.
C                                                                   8  800,000.
C
C TRIPNO(I)    ARRAY CONTAINING NUMBER OF EACH      -          NASA   I  TRIPNO(I)
C               OF THE INDIVIDUAL TRIPS PER YEAR                    1   130
C                                                                   2  85
C                                                                   3   57
C                                                                   4  54
C                                                                   5   12
C                                                                   6  7
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C                                                                  7 3
C                                                                  8 1
C
C TRIPTM   TIME IT TAKES TO MAKE A            SECONDS     CALC      *******
C          PARTICULAR TRIP
C
C TRIPYR   NUMBER OF TRIPS OF A PARTICULAR       -        CALC      *******
C          TYPE PER YEAR
C
C TSTOP    TIME AT WHICH VEHICLE MUST         SECONDS     NASA      83.0
C          STOP AT END OF STC
C
C V(I)     DRIVING CYCLE VELOCITY ARRAY     METERS PER    CALC      *******
C          (ENTRIES CALCULATED IN PROGRAM)    SECOND
C
C V1       VELOCITY AT END OF SIMULATION    METERS PER    CALC      *******
C          TIME STEP                          SECOND
C
C V2       VELOCITY AT BEGINNING OF         METERS PER    CALC      *******
C          SIMULATION TIME STEP               SECOND
C
C VAVE     AVERAGE VELOCITY OVER ONE        METERS PER    CALC      *******
C          DRIVING CYCLE TIME INCREMENT       SECOND
C
C VBATT    BATTERY VOLTAGE DURING DISCHARGE    VOLTS      CALC      *******
C
C VBCHG    BATTERY VOLTAGE DURING CHARGING     VOLTS      CALC      *******
C
C VBTOLD   VALUE OF BATTERY VOLTAGE            VOLTS      CALC      *******
C          FROM PREVIOUS ITERATION
C
C VCELL    BATTERY CELL VOLTAGE                VOLTS      NASA      2.05
C          (WHEN CELL IS FULLY CHARGED)
C
C VCHG(        BATTERY CELL CHARGE CURVE    CELL VOLTS    NASA      HAVE
C  AMP-HRS/KG,
C  CURRENT)
C
C VDELT    MAX ALLOWABLE DIFFERENCE BETWEEN    VOLTS      CSU       1.0
C          BATTERY VOLTAGE FROM LAST ITERATION
C          AND PRESENT CALCULATED BATTERY
C          VOLTAGE
C
C VELO     VELOCITY AT CURRENT TIME DURING  METERS PER    CALC      *******
C          COAST PHASE OF STC                 SECOND
C
C VHCOST(I)   ARRAY CONTAINING YEARLY         DOLLARS     CALC      *******
C             COST OF OPERATING VEHICLE
C
C VHWBTT   VALUE OF BATTERY VOLTAGE AT END     VOLTS      CALC      *******
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C           OF STC'S PRECEEDING ALL HIGHWAY
C           TRIPS
C
C VINT      BATTERY INTERNAL VOLTAGE           VOLTS         CALC      ******
C
C VMINHE    VEHICLE VELOCITY BELOW WHICH       METERS PER    NASA      1.34
C           NO HEAT ENGINE POWER CAN BE         SECOND
C           DEVELOPED
C
C VNEXT     VELOCITY VEHICLE HAS COASTED TO    METERS PER    CALC      *******
C           AT END OF CURRENT TIME INCREMENT    SECOND
C           DURING COAST PHASE OF STC
C
C VOLTOT    TOTAL HEAT ENGINE FUEL VOLUME       LITERS       CALC      *******
C           USED SINCE START OF TRIP
C
C WAXLE     ANGULAR SPEED OF AXLE              RADIANS PER   CALC      *******
C                                               SECOND
C
C WCONST    CONSTANT TERM IN MASS FORMULA       KILOGRAMS    CALC      *******
C           FOR VEHICLE
C
C WCURB     CURB MASS OF VEHICLE                KILOGRAMS    CALC      *******
C
C WCVT      SPEED AT INPUT TO CVT              RADIANS PER   CALC      *******
C                                               SECOND
C
C WDORTE    DIFFERENTIAL RATED OUTPUT          RADIANS PER   NASA      116.35
C           SPEED                               SECOND
C
C WDPCT     DIFFERENTIAL OUTPUT SPEED AS        PERCENT      CALC      *******
C           A PERCENT OF DIFFERENTIAL
C           RATED OUTPUT SPEED
C
C WDRIVE    ANGULAR SPEED OF DRIVE SHAFT       RADIANS PER   CALC      *******
C                                               SECOND
C
C WF        VEHICLE FIXED MASS                  KILOGRAMS    NASA      510.0
C
C WFCER     CONSTANT USED TO CALCULATE         DOLLARS PER   NASA      3.13
C           THE COST OF THE FIXED WEIGHT        KILOGRAM
C           OF THE VEHICLE
C
C WFCOST    COST OF FIXED WEIGHT OF             DOLLARS      CALC      *******
C           VEHICLE
C
C WGBATT    MASS OF BATTERIES                   KILOGRAMS    NASA      386.0
C           WHEN RUN21=1 OR 2 = STARTING
C           VALUE OF WGBATT
C
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C WGCHGR   MASS OF THE BATTERY CHARGER          KILOGRAMS    CALC      *******
C
C WGCHI    MASS OF THE CHOPPER INVERTER         KILOGRAMS    CALC      *******
C
C WGCLT    MASS OF CLUTCH                       KILOGRAMS    NASA      0.0
C
C WGCVT    MASS OF THE CVT                      KILOGRAMS    CALC      *******
C
C WGDIFF   MASS OF THE DIFFERENTIAL             KILOGRAMS    CALC      *******
C
C WGEAR    ANGULAR SPEED AT INPUT TO GEAR       RADIANS PER  CALC      *******
C          BETWEEN CVT AND DIFFERENTIAL          SECOND
C
C WGENG    MASS OF THE ENGINE                   KILOGRAMS    CALC      *******
C
C WGEXTR   MASS OF EXTRA COMPONENTS IN          KILOGRAMS    NASA      0.0
C          VEHICLE PROPULSION SYSTEM
C
C WGGRDF   MASS OF THE GEAR BETWEEN THE         KILOGRAMS    CALC      *******
C          DIFFERENTIAL AND THE CVT
C
C WGGRM    MASS OF THE GEAR BETWEEN             KILOGRAMS    CALC      *******
C          THE ELECTRIC MOTOR AND THE CVT
C
C WGMOTR   MASS OF THE ELECTRIC MOTOR           KILOGRAMS    CALC      *******
C
C WGORTE   RATED OUTPUT SPEED FOR GEAR          RADIANS PER  NASA      116.35
C          BETWEEN CVT AND DIFFERENTIAL          SECOND
C
C WGPCT    OUTPUT SPEED OF GEAR BETWEEN          PERCENT     CALC      *******
C          CVT AND DIFFERENTIAL AS A
C          PERCENT OF RATED OUTPUT SPEED
C
C WHE      HEAT ENGINE ANGULAR SPEED            RADIANS PER  CALC      *******
C                                                SECOND
C
C WHEFF    MOST EFFICIENT ENGINE SPEED          RADIANS PER  CALC      *******
C          FOR A SPECIFIED POWER OUTPUT          SECOND
C
C WHEMN    MIN ENGINE SPEED                     RAD/SEC     CSU/NASA   104.72
C
C WMORTE   RATED OUTPUT SPEED FOR GEAR          RADIANS PER  NASA      419.0
C          BETWEEN MOTOR AND CVT                 SECOND
C
C WMOTOR   ELECTRIC MOTOR ANGULAR SPEED         RADIANS PER  CALC      *******
C                                                SECOND
C
C WMT      MOTOR SPEED COMPUTED IN              RADIANS PER  CALC      ********
C          RATIO SUBROUTINE                      SECOND
C
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C WMTRMX   MAX SPEED OF MOTOR               RAD PER SEC   CSU        1,675.5
C
C WP       POWER TRAIN WEIGHT               KILOGRAMS     CALC       *******
C
C WPL      MAXIMUM DESIGN PAYLOAD           KILOGRAMS     NASA       415.0
C          FOR VEHICLE
C
C WPROP    MASS OF VEHICLE PROPULSION       KILOGRAMS     CALC       *******
C          SYSTEM
C
C WS       MASS OF STRUCTURE AND            KILOGRAMS     CALC       *******
C          CHASSIS FOR VEHICLE
C
C WSCER    CONSTANT USED TO CALCULATE       DOLLARS PER   NASA       3.00
C          THE COST OF THE STRUCTURE AND    KILOGRAM
C          CHASSIS FOR THE VEHICLE
C
C WSCOST   COST OF STRUCTURE AND            DOLLARS       CALC       *******
C          CHASSIS FOR VEHICLE
C
C WT       TOTAL MASS OF VEHICLE AND        KILOGRAMS     CALC       *******
C          PROPULSION SYSTEM
C
C WTL      TEST PAYLOAD FOR VEHICLE         KILOGRAMS     NASA       207.0
C
C XX       ARRAY OF PARAMETERS              MIXED         CALC       *******
C          OPTIMIZED BY GRG
C
C Z        OVERALL GRG LARGE MAIN ARRAY     -             CALC       *******
C
      STOP
      END
      END
```

APPENDIX B - CALCULATION OF VEHICLE MASS

This appendix details the method used to calculate the vehicle mass. The variable names used below correspond to the names used in the dictionary in Appendix A and also in the computer program. To obtain actual values used for any constants, refer to Appendix A. The overall vehicle mass formula is the same as that used in [1, 2]. The component mass formulas and the values for constants used in those formulas substantially agree with those found in [1, 5]. In the following, all masses are in kg.

Total Mass Calculation

If we let

WCONST = constant term in the total mass formula

WF = fixed mass of the vehicle (510 kg)

WPL = design payload (415 kg)

WPROP = mass of propulsion system

WT = total mass of vehicle

WTL = test payload (207 kg)

then

$$\text{WCONST} = \text{WTL} + \frac{0.23\ (\text{WPL}) + \text{WF}}{0.77} \tag{B-1}$$

and

$$\text{WT} = \text{WCONST} + \frac{\text{WPROP}}{0.77} \tag{B-2}$$

The mass of the propulsion system, WPROP, is calculated below.

Propulsion System Mass Calculation

We let (where the masses are in kg, and the component power ratings are in kw):

WGBATT	=	battery mass	WGENG	=	engine mass
WGCHGR	=	battery charger mass	WGGRM	=	mass of gear between motor and CVT
WGCLT	=	clutch mass	CVTKW	=	power rating of CVT
WGCVT	=	CVT Mass	HEKW	=	power rating of heat engine
WGMOTR	=	traction motor mass	DIFFKW	=	power rating of differential
WGGRDF	=	mass of gear between differential and CVT	MTGRKW	=	power rating of gear between motor and CVT
MTRKW	=	power rating of traction motor	DFGRKW	=	power rating of gear between CVT and differential
CHIKW	=	power rating of chopper/inverter	CHGRKW	=	power rating of battery charger
WGCHI	=	chopper/inverter mass			
WGDIFF	=	differential mass			

The quantities CVTC1, HEC2, MTRC1, CHIC1, DIFFC1, GRC1, CHGRC1 are all constants used below in the mass formulas; their values are given in Appendix A.

Using the quantities defined above, the component masses and the propulsion system mass are given by

WGCVT = CVTC1*CVTKW (B-3)

WGENG = HEC2*HEKW (B-4)

WGMOTR = MTRC1*MTRKW (B-5)

WGCHI = CHIC1*CHIKW (B-6)

WGDIFF = DIFFC1*DIFFKW (B-7)

WGGRM = GRC1*MTGRKW (B-8)

WGGRDF = GRC1*DFGRKW (B-9)

WGCHGR = CHGRC1*CHGRKW (B-10)

and

$$WPROP = WGCVT + WGENG + WGMOTR + WGCHI + WGDIFF + WGGRM + WGGRDF + WGCHGR + WGBATT + WGCLT \qquad (B-11)$$

In addition, the curb mass, WCURB, and the power train mass, WP, are given by

$$WCURB = WT - WTL \qquad (B-12)$$

and

$$WP = WPROP - WGBATT \qquad (B-13)$$

APPENDIX C - CALCULATION OF MANUFACTURING, MAINTENANCE, AND REPAIR COSTS

This appendix details the methods used to calculate the vehicle manufacturing, maintenance and repair costs. The variable names used below correspond to the names used in the dictionary in Appendix A and also in the computer program. To obtain actual values used for any of the constants, refer to Appendix A. The formulas and values for the constants used in these calculations are taken from [1, 4]. The component masses used below are calculated in Appendix B.

Manufacturing Costs

We let (where the masses are in kg)

WF = vehicle fixed mass	WGENG = engine mass
WGCVT = CVT mass	WGCHGR = battery charger mass
WGCHI = chopper/inverter mass	WGGRM = mass of gear between motor & CVT
WGDIFF = mass of differential	WGGRDF = mass of gear between differential and CVT
WS = structure and chassis mass	WGMOTR = mass of motor
WCURB = curb mass	WGCLT = mass of clutch

In addition, HECER, CVTCER, CHGCER, CHICER, GRCER, DIFCER, WFCER, WSCER, MTRCER, CLTCER and ASMCER are the various component cost estimating ratios (CER's) in \$/kg. The component costs are then calculated as

$$\text{HECOST} = \text{HECER*WGENG} \tag{C-1}$$

$$\text{CVTCST} = \text{CVTCER*WGCVT} \tag{C-2}$$

$$\text{CHGCST} = \text{CHGCER*WGCHGR} \tag{C-3}$$

$$\text{CHICST} = \text{CHICER*WGCHI} \tag{C-4}$$

$$GRMCST = GRCER*WGGRM \tag{C-5}$$

$$GRDCST = GRCER*WGGRDF \tag{C-6}$$

$$DIFCST = DIFCER*WGDIFF \tag{C-7}$$

$$WFCOST = WFCER*WF \tag{C-8}$$

$$WS = 0.3*(WPL + WPROP + WF) \tag{C-9}$$

$$WSCOST = WSCER*WS \tag{C-10}$$

$$MTRCST = MTRCER*WGMOTR \tag{C-11}$$

$$CLTCST = CLTCER*WGCLT \tag{C-12}$$

$$ASMCST = ASMCER*WCURB \tag{C-13}$$

The manufacturing cost is then the sum of these twelve component costs. Note that the battery cost is handled separately and is not included in the manufacturing cost (it is included in the calculation of acquisition cost in Section 5). Note also that the above manufacturing cost includes (in addition to the component costs) an assembly cost (ASMCST), a structure/chassis cost (WSCOST), and a fixed weight cost (WFCOST).

Maintenance Costs

It is assumed that maintenance is performed on the heat engine, motor, battery and chopper/inverter. HEMAIN, MTMAIN, BTMAIN, CVTMAN and CHIMAN are component maintenance costs ($/km), HEKW and MTKWPK are component power ratings (kw), BTLIST, BATCST and BTMKUP are battery list price, battery cost and battery markup factor, respectively, WGBATT and WGCHI are the weights of the battery and the chopper/inverter (kg), respectively, and BATCER and KMPRYR are the battery CER and the kilometers driven per year, respectively. With these definitions, the total yearly maintenance cost, MAINT, in dollars, is given as

$$MAINT = KMPRYR*(HEMAIN + MTMAIN + BTMAIN + CVTMAN + CHIMAN) \quad (C\text{-}14)$$

where

$$HEMAIN = [0.18 + 0.005*(HEKW/0.746)]/160.93 \quad (C\text{-}15)$$

$$MTMAIN = [0.06 + 0.002*(MTKWPK/0.746)]/160.93 \quad (C\text{-}16)$$

$$BATCST = BATCER*WGBATT \quad (C\text{-}17)$$

$$BTLIST = BATCST*(1.0 + BTMKUP) \quad (C\text{-}18)$$

$$BTMAIN = (0.004*BTLIST)/160.93 \quad (C\text{-}19)$$

$$CVTMAN = 0.063/160.93 \quad (C\text{-}20)$$

$$CHIMAN = [(36.83/2.0)*SQRT(WGCHI)]/(10.0*KMPRYR) \quad (C\text{-}21)$$

Most of the above expressions are taken from [4]. However, the chopper/inverter maintenance cost is taken from [1], but with the modification that half of the cost is assigned to maintenance and half to repair.

Repair Costs

It is assumed that repair is performed on the heat engine, motor, chopper/inverter and CVT. The yearly repair cost, REPAIR, in dollars, is given as

$$REPAIR = KMPRYR*(REPRHE + REPMTR + REPCVT + REPCHI) \quad (C\text{-}22)$$

where REPRHE, REPMTR, REPCVT and REPCHI are the component repair costs ($/km) calculated from (HEKW, MTKWPK, WGCHI and KMPRYR are all defined above)

$$REPRHE = [0.28 + 0.008*(HEKW/0.746)]/160.93 \quad (C\text{-}23)$$

$$REPMTR = [0.09 + 0.002*(MTKWPK/0.746)]/160.93 \quad (C\text{-}24)$$

$$REPCVT = [0.05 + 0.0013*(MTKWPK/0.746)]/160.93 \qquad (C\text{-}25)$$

$$REPCHI = [(36.83/2.0)*SQRT(WGCHI)]/(10.0*KMPRYR) \qquad (C\text{-}26)$$

APPENDIX D - CALCULATION OF ACQUISITION COST

The acquisition cost is a combination of the manufacturing cost of the vehicle drive train and body and the cost of the batteries. The vehicle acquisition cost, ACQCST, in dollars, is given as

$$\text{ACQCST} = \text{MARKUP*MNFCST} + \text{BATCST*}(1.0 + \text{BTMKUP}) \tag{D-1}$$

where MARKUP is the manufacturing cost markup factor, MNFCST is the manufacturing cost (calculated in Appendix C), BATCST is the battery cost, and BTMKUP is the battery markup factor. BATCST and MARKUP are calculated from (the ex-pression for MARKUP is taken from [4])

$$\text{BATCST} = \text{BATCER*WGBATT} \tag{D-2}$$

$$\text{MARKUP} = (29.176*10^{-5})\text{*MNFCST} + 1.40833 \tag{D-3}$$

and where WGBATT is the battery weight, and BATCER is the battery cost estimating ratio (CER).

APPENDIX E - VEHICLE SIMULATION

For each choice of the design variables (battery weight, heat engine rating and power split strategy) it is necessary to simulate the vehicle as it is driven over the specified yearly driving requirements (Section 4) in order to calculate yearly electrical energy and petroleum consumptions, the number of deep discharges of the battery per year, and whether at any point in any of the trips the on-board energy is insufficient to meet the power required at the wheels. This appendix gives the details of how that simulation was carried out. It includes a description of how each component in the power train was modeled as well as a description of the overall computational procedure used to determine the power required from each of the on-board energy sources at each instant of time in driving an STC or in highway driving. Reference should be made to Section 3.1 and Figure 3-1 for a description and diagram of the overall propulsion system and how the various components described below are interconnected.

E.1 COMPONENT MODELS

In this part of the appendix we describe the methods used to model each of the components in the drive train. It should be noted that this is a simulation of the steady state rather than the dynamic behavior of the vehicle: the component models are therefore steady state rather than dynamic models.

Battery Model: Of all the component models, the battery model is the most complex. Because of this complexity it is described in depth in its own appendix, Appendix F.

Heat Engine Model: The heat engine model used was a heat engine map [1] which plotted fuel flow rate (liters/sec) against engine speed (rad/sec) for a given engine torque (Nm). The map consisted of a set of such curves for different torques as shown in Figure E-1. The map was used to determine fuel flow rate corresponding to a known engine output torque and speed. The maps were stored as arrays, and double variable linear interpolation was used. The actual maps used in this study were the same as those used in [1], but with an added degree of complexity. In this study the heat engine rating was continually changed in a smooth fashion as the optimization algorithm searched for the optimum. Consequently, maps for any rating between a maximum and minimum rating had to be easily generated to carry out the optimization. From interpolation studies using the three maps given in [1] for ratings of 56 kw, 75 kw and 112 kw, it was found that the other maps could be generated from the 75 kw map by leaving the engine speed axis alone, and multiplying the fuel flow rate ordinate and the torque corresponding to each curve by a factor equal to the rating of the engine whose map is sought divided by 75. Thus, at the beginning of each simulation run, the map array for the given heat engine used for that simulation run would be generated and stored. Then at each simulation time increment, that array would be used with a double variable linear interpolation scheme to determine the fuel flow rate during that time increment.

<u>Chopper/Inverter</u>: The characteristic of the chopper/inverter that required modeling for the instantaneous power calculations was the power loss in the device. The model used was the same as that used in [1,2] and is given as

$$PILOSS = 3.0*(PINV/VBATT) + 0.035*PINV \qquad (E-1)$$

where PINV and VBATT are the chopper/inverter output power and battery voltage, respectively. The ratio (PINV/VBATT) is an estimate of the current

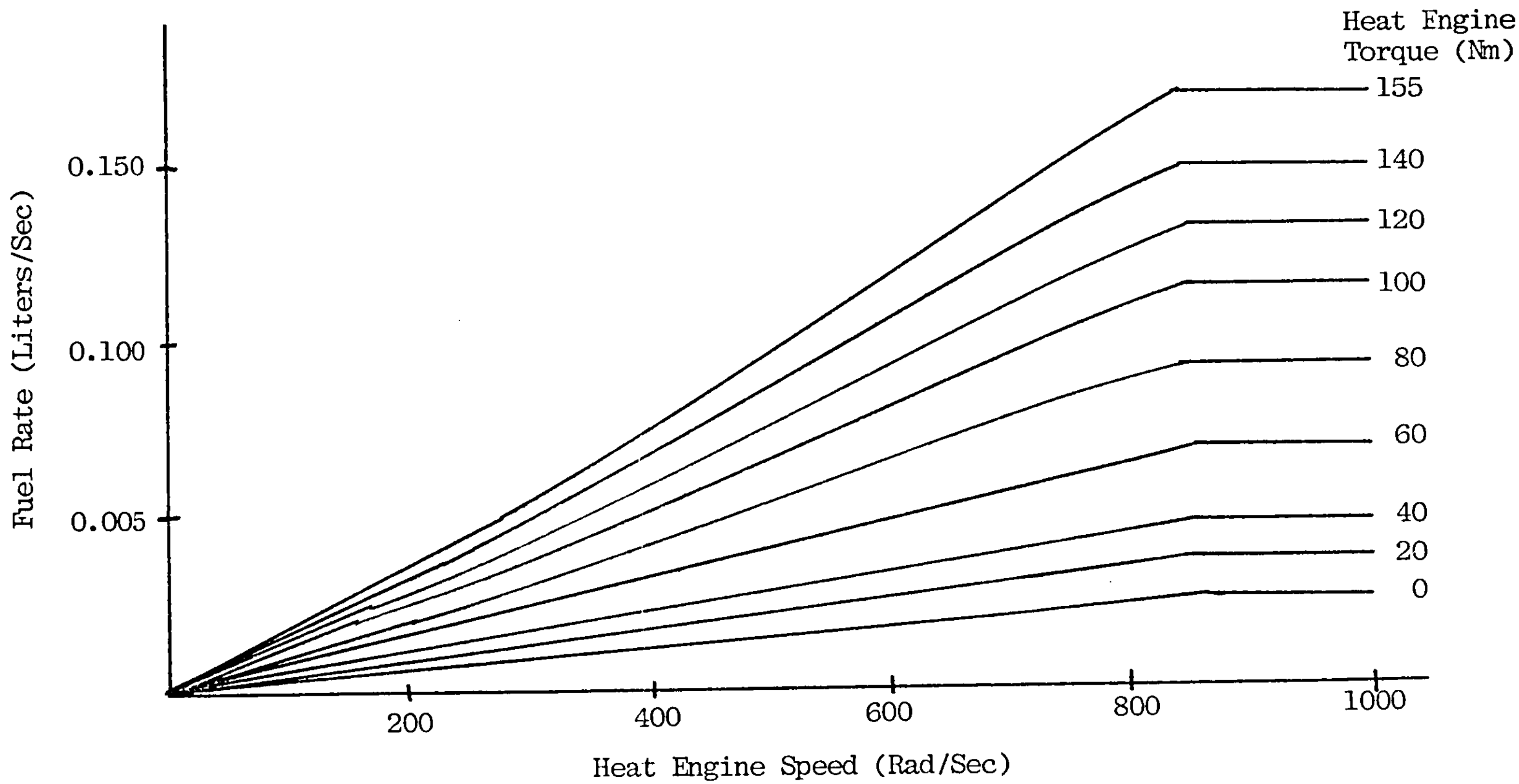

Figure E-1 Heat Engine Map

being drawn from the battery.

Electric Motor: The traction motor was a brushless, DC, permanent-magnet motor operating from a battery voltage of 168 V. It was rated at 20 kw and had a top speed of 14,000 rpm. The model for the motor was taken from [1] and is an efficiency map with motor efficiency plotted against percent rated output power (see PMTRTD and PMTPCT in dictionary) for a given motor speed. The map is shown in Figure E-2. However, in using the map it must be recognized that there is a stall-out speed for each percent rated output power: for the given output power the motor cannot be run below this speed without stalling. The stall-out map is used in selecting the CVT ratio; the stall-out map actually used for this motor is given in Appendix G where the ratio selection is discussed.

Continuously Variable Transmission (CVT): The CVT provides a range of ratios (input speed/output speed) which vary continuously from a 0.3:1 overdrive to a 3.33:1 speed reduction. The CVT model [1] is an efficiency map as shown in Figure E-3 where efficiency is plotted against output power for a given ratio.

Gears and Differential: The differential (with a speed ratio of 1:1) and the gears between the electric motor and the CVT input (providing a speed reduction from motor to CVT of 3.5:1) and between the CVT output and the differential input (providing a speed reduction of 12:1 from CVT to differential) were all modeled by the same efficiency map shown in Figure E-4 where gear efficiency is plotted against percent rated output power for a given percent rated input speed. The rated powers and speeds for the different gears are PDRATE, WDORTE, PMGRTE, WMORTE, PGRATE and WGORTE, and are found in the dictionary in Appendix A.

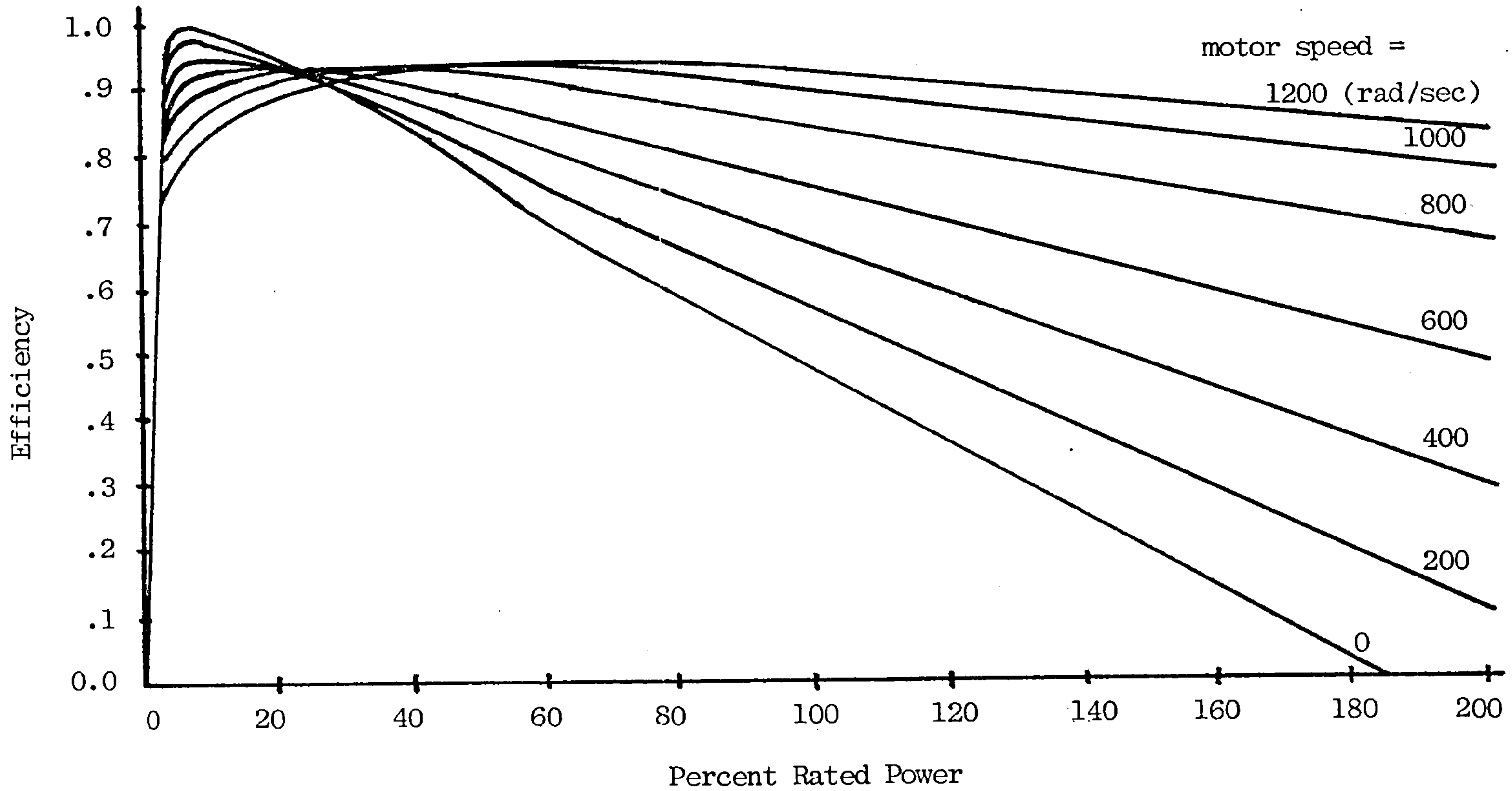

Figure E-2. Electric Motor Efficiency Map

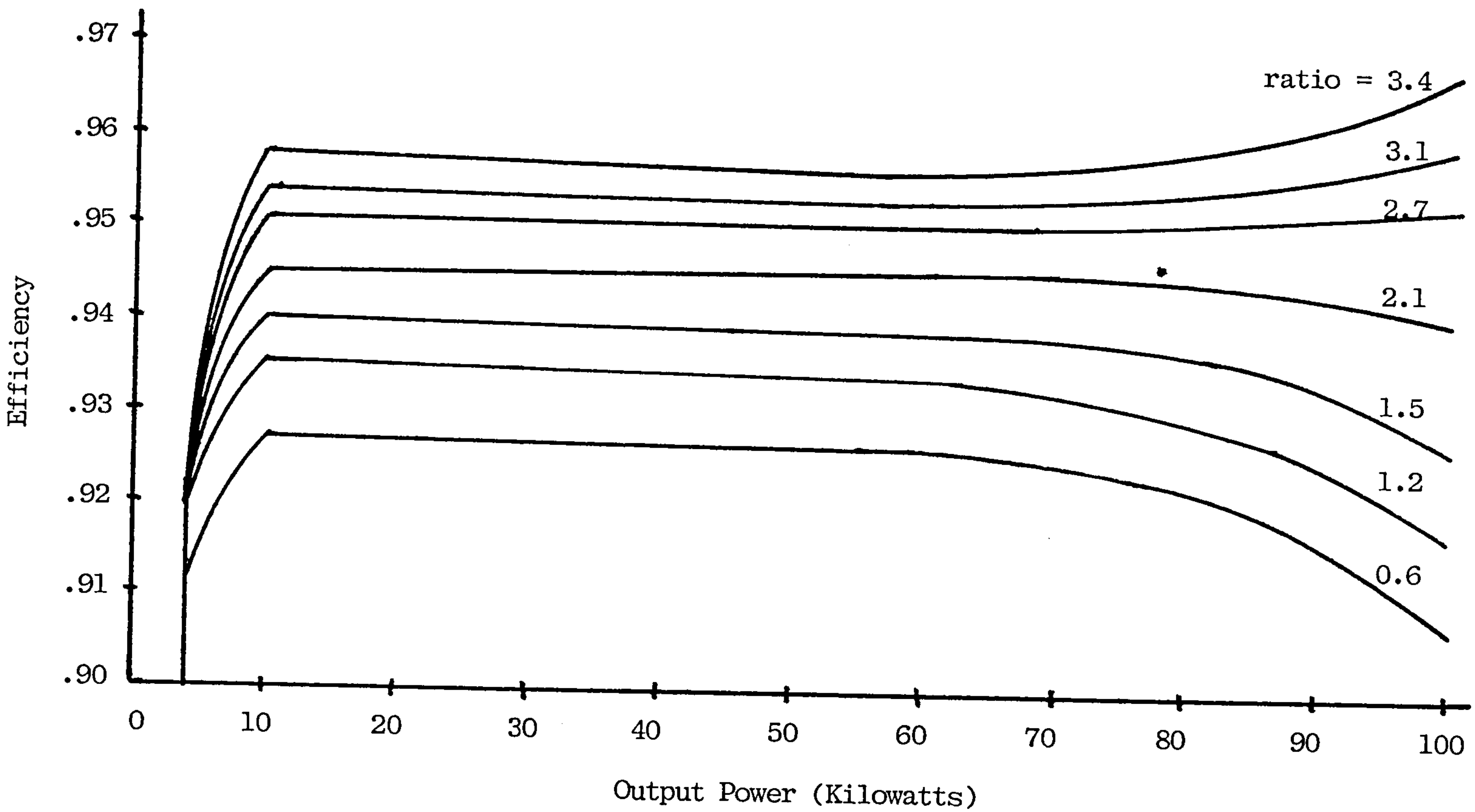

Figure E-3. CVT Efficiency Map

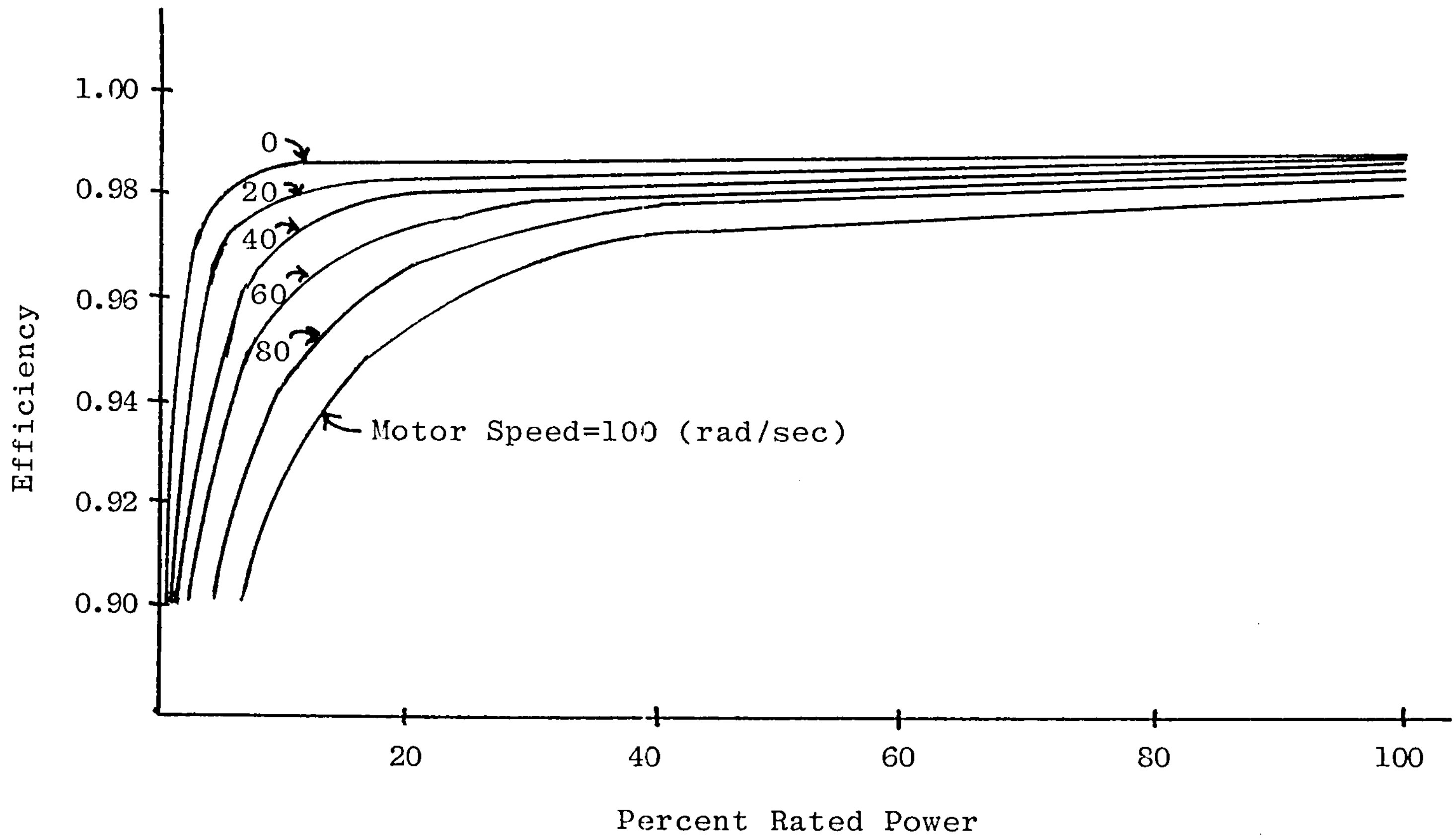

Figure E-4 Gear Efficiency Map

E.2 CALCULATION OF POWER REQUIRED AT THE AXLE DURING THE ACCELERATION AND CRUISE PHASES OF THE STC AND DURING HIGHWAY DRIVING

The power required at the axle is determined by summing the forces acting on the vehicle and multiplying this by the average velocity over the present simulation time increment. In particular, if the simulation time increment is Δ and current time is t, then the average velocity over the current simulation time interval is

$$V_a = (1/2)\ [v(t) + v(t+\Delta)] \tag{E-2}$$

where v(t) is the vehicle velocity at time t. The required acceleration over this time interval is

$$a(t) = [v(t+\Delta) - v(t)]/\Delta \tag{E-3}$$

If F_D, F_R, F_A and F_G are the drag force, rolling resistance force, acceleration force and grade angle force, respectively, then

$$F_D = C_d A \rho\ (V_a^2/2) \tag{E-4}$$

$$F_R = C_R M_T g \tag{E-5}$$

$$C_R = [10.0 + 0.01 V_a + (8 \times 10^{-5})\ V_a^2] \times 10^{-3} \tag{E-6}$$

$$F_A = (1.1)\ M_T\ V_a \tag{E-7}$$

$$F_G = M_T\ g \sin\ (\beta) \tag{E-8}$$

where all the forces are in newtons, g is the acceleration of gravity, M_T is the vehicle mass (kg), β is the grade angle at the current simulation time, $C_d A$ is the aerodynamic drag coefficient multiplied by the vehicle frontal area ($C_d A$= 0.6 m^2) and ρ is the air weight density (ρ = 1.225 kg/m^3). The factor of 1.1 in the expression for F_A takes into account accelerating the rotating inertias in the vehicle drive train. The power required at the axle at the current time is therefore given as

$$P_A = (F_D + F_R + F_A + F_G)\ V_a \tag{E-9}$$

The axle torque and speed, T_A and W_A, are obtained from

$$W_A = V_a/R_T \tag{E-10}$$

$$T_A = P_A/W_A \tag{E-11}$$

where R_T is the tire radius.

E.3 DRIVE TRAIN POWER CALCULATIONS FOR ACCELERATION AND CRUISE PHASES OF STC AND FOR HIGHWAY DRIVING

At each time step in the simulation a calculation is made to determine the petroleum and electrical energy consumed in that time step. This is done by moving the power required at the axle (see Section E.2) back through each component in the drive train. In the following discussion reference should be made to the component models given in Section E.1. It should be noted that the maps used in the calculations consist of data arrays, and a double variable or single variable linear interpolation routine (whichever is appropriate) is used to locate points not in the arrays.

Knowing the power, speed and torque at the axle, the differential efficiency map and ratio is used to determine the power, speed and torque at the input to the differential. The same exact calculation is then made to determine the power, speed and torque at the input to the gear between the CVT and the differential. At this point in the power train calculation the CVT ratio is determined so that the heat engine is run at its most efficient speed for the heat engine's current power level (this method of ratio selection is discussed in detail in Appendix G). Once the CVT ratio is known, along with the CVT output power, speed and torque, the CVT efficiency map and ratio can be used to determine the power, speed and torque at the input to the CVT. This CVT input power is then split between the heat engine and the electric motor and batteries using the power split strategy currently in force in the simulation; no matter what power split strategy is in use, the outcome is an allocation of a fraction of the total CVT input power to the heat engine and the remainder to the motor and batteries. There is a maximum allowable heat engine power, and the simulation off loads any excess to the electrical leg if the power split calls for more than the heat engine can deliver.

Once the heat engine output power and speed are known (the heat engine is directly connected to the CVT input so that its speed is the same as the CVT input speed), the heat engine output torque can be calculated (power/-speed) and used in conjunction with the speed to determine the fuel flow rate from the heat engine map. This fuel flow rate is then multiplied by the simulation time step size to determine the fuel consumption for the present simulation time increment. The computation of the total yearly fuel consumption using these fuel increments is discussed in Section 5.

The electrical leg computation proceeds by first calculating the power, torque and speed at the input to the gear between the motor and CVT by using the gear output power (from the power split) and speed in conjunction with the gear map and the known gear ratio. The motor input power can then be calculated using this output power and speed and the motor efficiency map. This establishes the power which must be supplied by the chopper/inverter.

The loss in the chopper/inverter is modeled by an equation requiring the chopper/inverter output power, which is known, and the battery current, which is not known at this point in the calculation. However, it is reasonable to assume that (i) if the simulation time step is small, the battery voltage does not change significantly from one simulation time step to the next, and (ii) the losses in the chopper/inverter are small. Under these assumptions, the battery current for the present time increment (for use in the chopper/-inverter loss equation) can be estimated by dividing the battery voltage at the last simulation increment into the present chopper/inverter output power and using this result in the chopper/inverter loss equation. This procedure allows calculation of the required battery output power.

To calculate the battery voltage, current and state of charge requires use of the battery model and an iterative procedure. An iteration procedure is required because the present battery current is not known, yet this current is required in order to use the battery model to calculate battery voltage and state of charge. At this point in the calculation, the only battery quantities which are known are the battery present output power, and the battery current, voltage and state of charge which existed at the last simulation time increment. The iterative procedure used to arrive at present values for these last three quantities is to guess at the present battery voltage (using the value from the last simulation time step; at start-up the battery is fully charged and the first value is the system voltage) and divide this into the known output power to obtain an estimate of the battery current. Knowing the ouput current, the battery model (Appendix F) is used to calculate a battery state of charge and voltage. This new battery voltage is then compared to the assumed value: if it differs by less than a specified limit (VDELT in Appendix A) the calculation is completed; if the difference is greater, the new voltage is assumed to be the battery voltage, a new current is computed and the process is repeated. An upper limit on the number of such iterations was used, but the process always converged in three or less iterations.

At this point the drive train power calculation is complete and the simulation moves to the next time interval. However, there are a number of special features in the drive train power calculation related to limiting which should be mentioned.

First, there are limits on the heat engine power and the electrical energy available at any instant of time in the simulation. If the power required at the CVT input is split in such a way that either the electrical leg or the heat engine leg cannot meet the demand, a calculation is made to determine the maximum power available from the limiting leg, this is moved through any components between the source and the CVT input, and the other leg's demand is increased by the appropriate amount (with the other leg's power calculation redone if necessary). If a situation arises in which both power sources together cannot meet the total demand, the vehicle is considered to be overloaded. The topic of overload is discussed in detail in Section 6.

In the battery calculation it is important to make sure the battery current does not exceed a maximum value (this limit must be scaled each time the battery mass is changed). As described above, the battery current is computed by dividing the battery voltage into the battery output power. If this current turns out to be excessive (at low battery voltages) when the battery calculation is finished, the available power from the battery must be estimated (by multiplying the maximum allowable current by the battery voltage just calculated), the battery calculation redone, this new battery output power moved through the electrical leg components to the CVT input, and the difference between the total power and the available electrical power made up by increasing the heat engine required power and redoing the heat engine leg computation.

E.4 CALCULATIONS FOR COASTING PHASE OF THE STC

In the coasting phase of the STC the vehicle simply coasts for ten seconds (see Section 4). The coasting phase always begins at the same cruise velocity of 72 km/hr, but the velocity the vehicle has at the end of the coast period (and hence the amount of energy available for regeneration) depends upon the battery weight and heat engine rating (the rating determines the engine weight); consequently the coast phase final velocity changes during a simulation run and the coast period must be simulated for each STC.

The velocity at the end of the coast phase was computed as follows. For each time step in the coast phase the current values for the drag, rolling resistance and grade forces (using the vehicle velocity at the beginning of the time step) were computed (see Section E.2). Adding these, dividing by the vehicle mass and multiplying by the time step size (DELT) yielded the decrease in vehicle velocity over the current simulation step. This was repeated for each time step in the coast phase to determine the vehicle velocity at the end of the coast phase.

E.5 CALCULATION OF DRIVE TRAIN POWER REGENERATION DURING THE BRAKING PHASE OF THE STC

In regenerating power back into the battery it was assumed that if the power available at any time fell below some minimum (REGMIN), regeneration would stop and the vehicle would come to rest through normal braking. Also, if in the drive train calculation the regenerated power at the input to any component exceeded that component's maximum rating, the power passed on was assumed to be equal to that maximum, and the difference was assumed to be dissipated by normal braking.

The first step in the calculation in each simulation time increment is to determine the regenerative power available at the axle for that time increment. Knowing the velocity at the start of the braking phase, and the length of time allowed for braking, the velocity decrease and the average velocity for each simulation time step can be determined. The velocity decrease over the time step is used to calculate the decrease in kinetic energy the vehicle must undergo in that time step; dividing this by the time step yields the vehicle total power reduction over that time interval. The average velocity is used to compute the drag, rolling resistance and grade forces, and these are then added and multiplied by the average velocity to obtain the power lost to the road in the time interval. The difference between these two powers is the power available for regeneration. The calculation then proceeds in a manner similar to that used in the drive train power calculation during acceleration and cruise (Section E.3): the power is moved through each component (differential, gear, CVT, gear, motor, and chopper/-inverter), but with the difference that the component efficiencies multiply the output power to obtain the input power, rather than divide it as was the case earlier. When the battery is finally reached, the battery input power is known, but the current and voltage are not known. An iterative scheme is therefore again needed which guesses a battery voltage, uses that to calculate a battery current, and then uses this current with the battery <u>charging</u> model to calculate a battery voltage and state of charge. If the assumed and calculated voltages do not agree, the calculated value is used as a new starting point and the process repeated. This scheme was also found to converge rapidly (less than three iterations). Care must be taken to check that battery input power and current do not exceed maximums (which change with changing battery mass).

APPENDIX F - BATTERY MODEL

The model used for the battery is based on the model described in [3]. The batteries are assumed to be lead-acid batteries with a system voltage of 168 volts, a cell voltage of 2.0 volts and 84 cells connected in series.

F.1 SCALING THE BATTERY MODEL

In the optimization studies the battery mass is continually changed. This change is interpreted as a change in the mass of each cell; the number of cells in the battery is assumed to be constant at 84. To handle this situation, all of the battery maps (discussed in the next subsection) were scaled (where necessary) so that they represented a battery comprised of one-kilogram cells. Calculations were therefore carried out on a per kilogram basis, and the results then scaled back up to the actual mass of each cell. The actual mass of each cell is equal to the total battery mass divided by 84. The way in which the maps were scaled should be clear from the discussions in the following subsections.

F.2 CALCULATION OF BATTERY VOLTAGE AND STATE OF CHARGE DURING DISCHARGE IN HIGHWAY DRIVING AND IN THE ACCELERATION AND CRUISE PHASES OF AN STC

Using the battery model given in [3], the battery voltage and state of charge at any time instant in the simulation are calculated as follows. First, the average current since the start of the trip (assuming a fully charged battery at the start of the trip) is calculated as

$$I_A = (1/T) \int_0^T i(t)dt \qquad \text{(F-1)}$$

where T is the length of time into the trip, and $i(t)$ is the current at any time $t \in [0, T]$. In the simulation, I_A was actually computed by dividing the ampere-hours (amp-hrs) out of the battery by T (ignoring regeneration). The current out of each cell (and out of the battery since the cells are in series) on a per kilogram basis is (I_A/M_C), where M_C is the mass of a cell, i.e. $M_C = M_B/N_C$ where M_B is the battery mass and N_C the number of cells. This average battery output current per cell kilogram is then used in conjunction with the scaled Peukert curve, Figure F-1, to determine the capacity per kilogram (amp-hrs/kilogram), AH_1, available from each cell in the battery (and hence the capacity per kilogram available from the battery) if the battery is discharged at a current equal to the average current per kilogram computed above. The total capacity from a battery with cells of mass M_C is then $AH_2 = M_C AH_1$. Next, the net amp-hours out of the battery since the start of the trip is computed as

$$AH_3 = TI_A - AH_R \qquad \text{(F-2)}$$

where T and I_A are as defined above, and AH_R is the total amp-hrs regenerated into the battery (since the start of the trip) during the braking phases of the STC's. The battery state of charge, SOC, at the current time is, then,

$$SOC = 1 - (AH_3/AH_2) \qquad \text{(F-3)}$$

The battery voltage is obtained from the battery discharge characteristic shown in Figure F-2. This discharge characteristic gives cell voltage as a function of both state of charge and cell current for a cell of a given

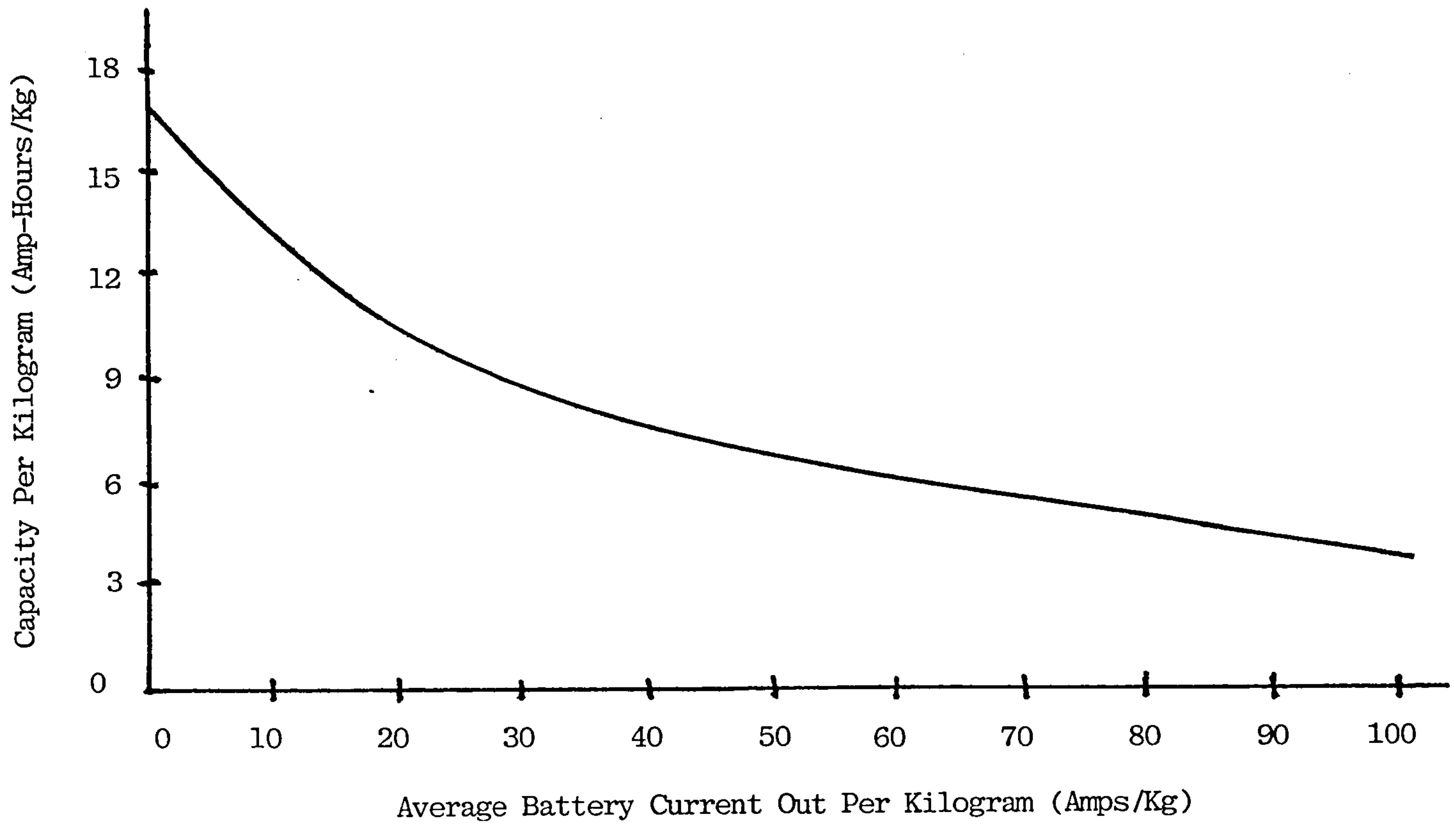

Figure F-1. Scaled Peukert Curve

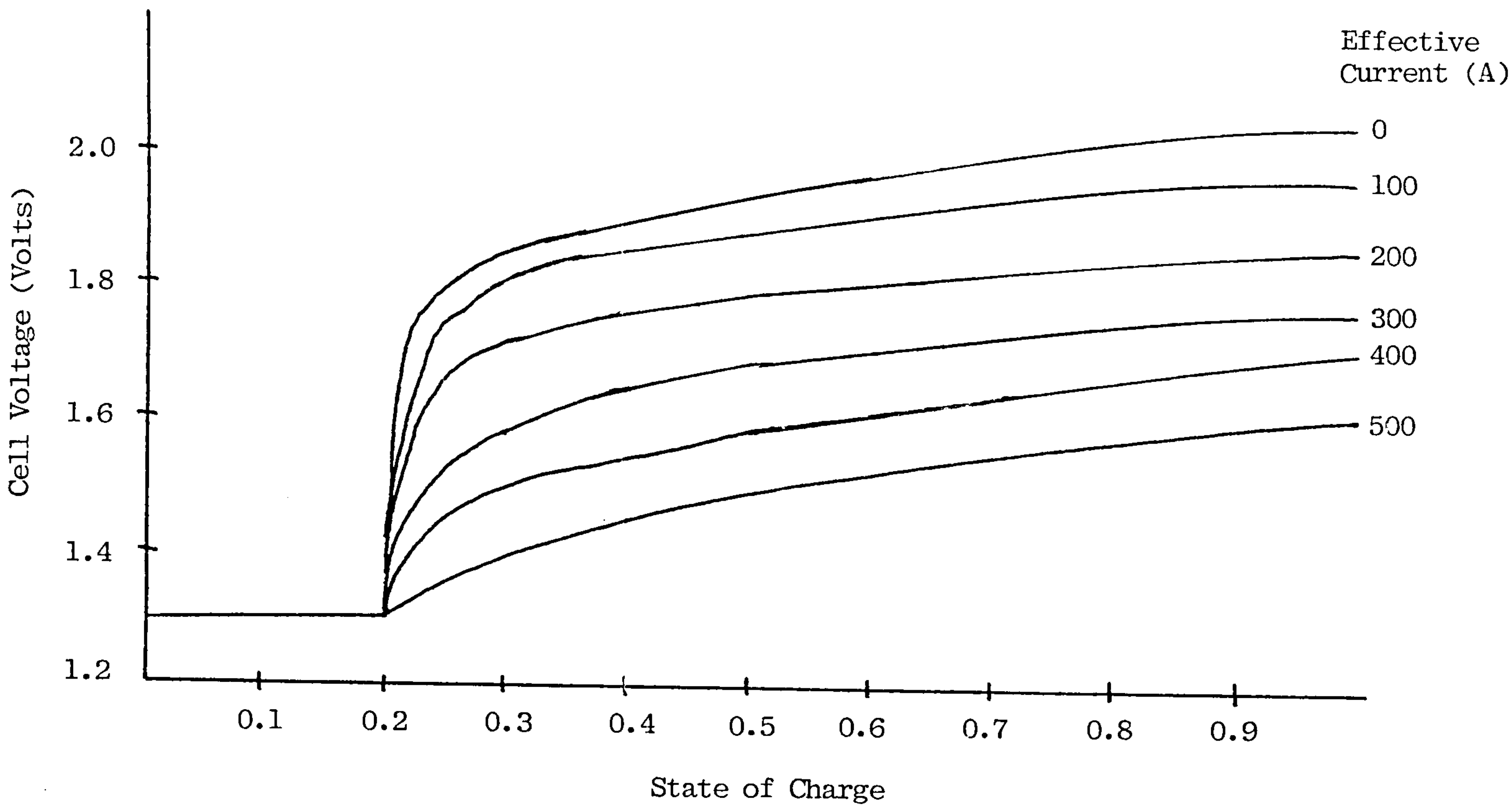

Figure F-2 Battery Discharge Characteristic mass. Since the batteries are not used if the SOC drops below 0.2, the cell voltage is assumed constant below this SOC. If the mass of the cell changes, the internal resistance will change (increasing cell mass is interpreted to mean more plate area, hence a smaller interval resistance). This is handled by multiplying the battery current by (M_{STND}/M_C) where M_C is the cell mass and M_{STND} is the mass of the standard cell (taken to be 9.83 kg) used in generating the discharge curve in Figure F-2. This scaled current is then used with the state of charge to enter the discharge characteristic and determine the cell voltage. Finally, the battery voltage is obtained by multiplying the cell voltage by the number of cells in the battery.

F.3 BATTERY CHARGING AT END OF TRIP

This section presents the details of the calculations involved in determining the wall plug electrical energy required to charge the battery to a fully charged condition after a trip is completed. Calculations for regeneration back into the battery during the breaking phase of an STC is covered in Section F.4. At the end of a trip the net amp-hours out of the battery is known; net amp-hours is the difference between total amp-hours out and amp-hours put back from regeneration during the braking phases of STC's driven in the trip. If AH_N is this net amp-hours out, then the amp-hours delivered per kilogram for a cell is AH_N/M_C, where M_C is the mass of a cell. Assuming a charging current of 25 amps, the charging characteristic for a cell (on a per kilogram basis) shown in Figure F-3 can be entered at AH_N/M_C and an average charging voltage for a cell can be determined; multiplying this by the number of cells gives an average charging voltage for the battery. In the actual simulation, an additional map (AACV in Appendix A) was generated from the

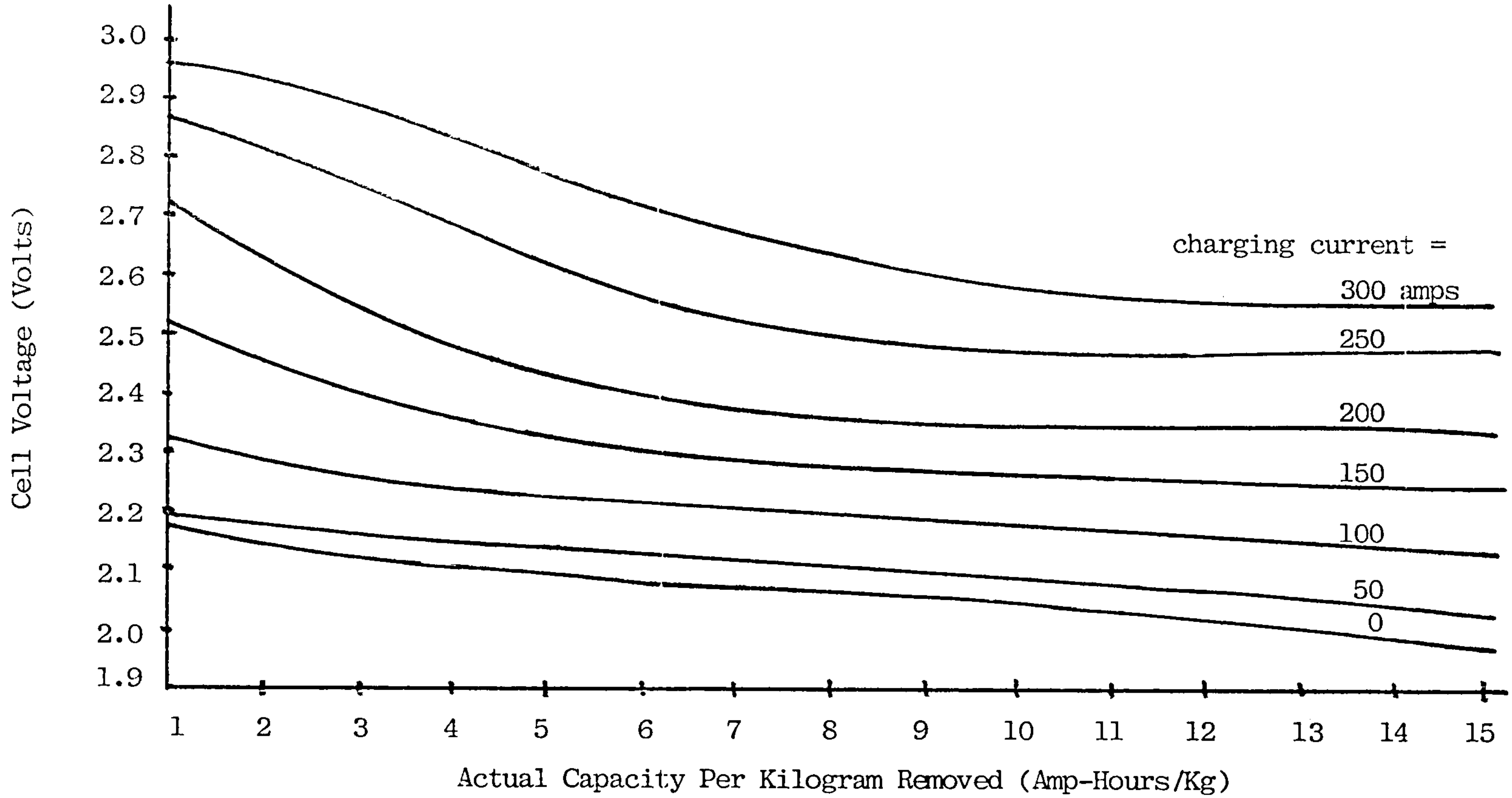

Figure F-3. Battery Cell Charging Characteristic charge characteristic which gave the average charging voltage (for a charging current of 25 amps) as a function of AH_N/M_C. Multiplying this average battery charging voltage by the net amp-hours out determines the electrical energy needed from the charger to recharge the battery. Finally, dividing this energy figure by the charger efficiency yields the total wall plug energy required to recharge the batteries.

F.4 CALCULATION OF BATTERY VOLTAGE AND STATE OF CHARGE DURING REGENERATION IN THE BRAKING PHASE OF AN STC

Appendix E covers the details of the calculation procedure used to determine how much of the vehicle power at the wheels available for regeneration during the braking phase of an STC actually arrives at the battery terminals at each time increment in the simulation (taking into account efficiencies and maximum power levels of the drive train components). This section explains how that power alters the battery voltage and state of charge. As explained in Appendix E, at each time step in the simulation the regenerated power calculation determines a regenerated power at the battery terminals (PBOUT) and a battery current (IEFF). The current and power to be regenerated must be limited by the maximum current and power that the battery can handle, and these limits must be scaled each time the battery mass is changed by the ratio of the present battery mass to a standard battery mass. At this point in the regeneration calculation, the calculation of the battery SOC is carried out; this calculation is exactly the same as described in Section F.2, with the exception that the most recent current increment in the calculation of I_A is negative (current is now into the battery) or, if amp-hours are used to calculate I_A, the regenerated amp-hrs are increased for the most recent simulation increment, the net amp-hours out of the battery is computed (total out minus regenerated) and I_A calculated from these net amp-hrs out.

The battery voltage is calculated from the charge characteristic given in Figure F-3. Specifically, the net amp-hours used in calculating I_A above is divided by the cell mass to determine the net amp-hrs per kilogram for a battery cell. Then, using both the effective battery current (IEFF) mentioned above and this cell net amp-hrs per kilogram in conjunction with the battery charge characteristic in Figure F-3, a cell charging voltage is determined. Multiplying this by the number of cells in the battery yields a battery voltage for the present simulation time increment. In the actual battery calculation an iteration scheme is required because the current (IEFF) is not really known a priori to allow determination of the battery voltage from the charging characteristic (see Appendix E for a description of this iterative precedure).

APPENDIX G - CVT RATIO SELECTION PROCEDURE

In this study the CVT ratio was selected (at each time step in the simulation) such that the heat engine was operated at its most efficient speed. The reason for employing this approach rather than the approach used in [1] in which the ratio was selected to operate the traction motor at its most efficient speed was that the traction motor efficiency was always in the range of 90% or above (Appendix E) whereas the heat engine efficiency could be substantially improved by proper choice of the ratio.

The most efficient heat engine speed for a given engine output power was determined from the Brake Specific Fuel Consumption (BSFC) map for a 75 kw engine shown in Figure G-1. Each characteristic on the map is engine BSFC (in grams/sec of petroleum flow rate per megawatt of output power) as a function of engine output power (in percent of rated power) with engine speed held constant. For example, if the engine speed is held constant at 104.7 rad/sec, the BSFC decreases as the engine output power increases from zero to 25% of rated output power (more power output from the engine requires a higher engine speed; the characteristic essentially stops at 25% of rated power). Also, for a given output power, the speed corresponding to the characteristic with the lowest BSFC represents the most efficient operating speed since for that output power that particular speed produces the lowest fuel flow rate. For example, for output powers below 30%, the most fuel efficient engine speed is 104.7 rad/sec; at 50% it is 209.4 rad/sec; at 75% it is 314.12 rad/-sec; at 100% it is 418.9 rad/sec. For intermediate output powers linear interpolation was used to determine the most fuel efficient speed for each heat engine output power. The result is shown in Figure G-2.

At each time increment in the simulation the CVT output power is calculated (Appendix E). To continue the drive train power calculation and

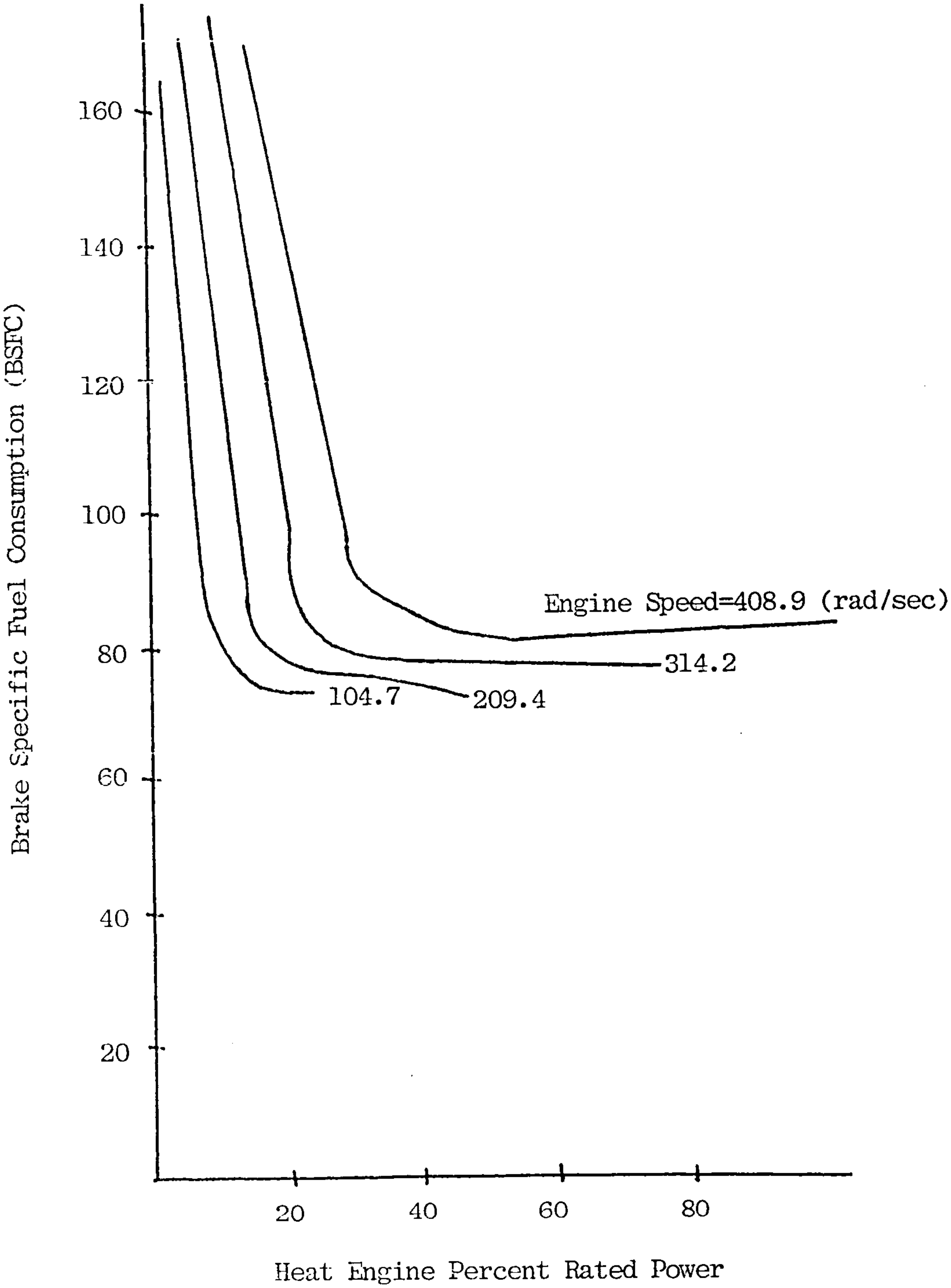

Figure G-1 Brake Specific Fuel Consumption (BSFC) Map for a 75 Kilowatt Engine

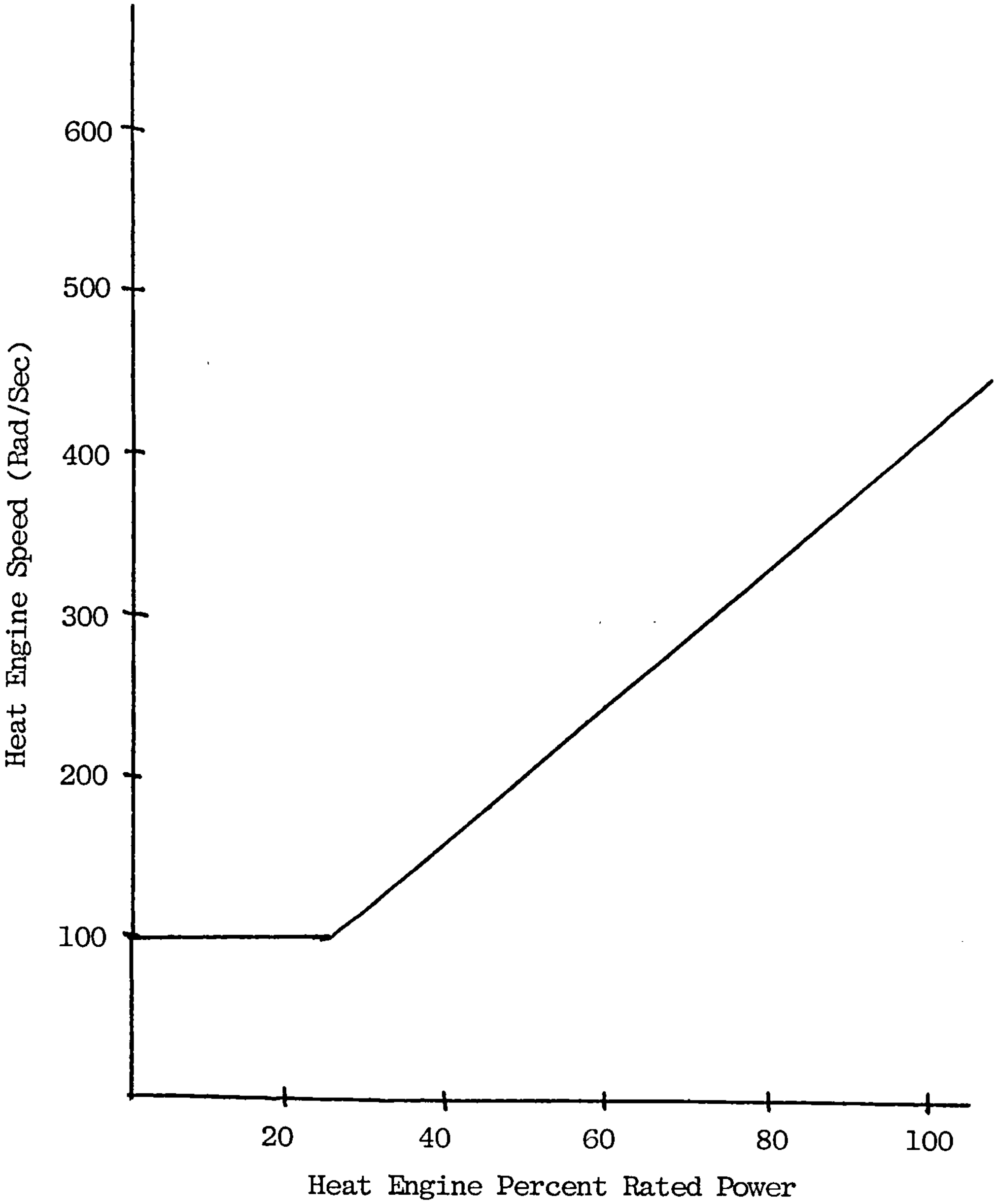

Figure G-2 <u>Most Fuel-Efficient Engine Speed vs. Engine Output Power</u>

determine the CVT input power, the CVT ratio must be known in order to determine the CVT efficiency. However, selecting the ratio to run the engine at its most fuel efficient speed requires knowledge of the engine output power. Since this is not known, the calculation procedure estimates it with the value which existed at the previous simulation time increment. Since the drive train power and power split are not changing rapidly from one time increment to the next, the heat engine output power should not change much either. Consequently, the calculation procedure is as follows: after the CVT output power is calculated, the previous heat engine output power and Figure G-2 are used to determine the best engine speed; this speed and the CVT output speed determine a CVT ratio (which is checked and limited to upper and lower bounds as appropriate). Knowing the CVT ratio, the CVT input power can be calculated and split between the heat engine and traction motor, and the calculation proceeds as described in Appendix E.

Modifications to the above approach occur under several conditions. First, if in the previous iteration the heat engine power was zero, the ratio is selected to run the traction motor at its most efficient speed. The map used for this purpose is shown in Figure G-3. This handles the case where the power split calls for all of the CVT input power to be met by the traction motor. Second, each time the ratio is selected to run the engine most efficiently, a check must be made to make sure this ratio doesn't call for a traction motor speed which, at the present traction motor output power level, would cause the motor to stall. The stall out curve is shown in Figure G-4: for a given percent rated output power the curve yields the minimum motor speed to avoid stalling the motor. If the selected ratio would result in motor stall, the ratio is decremented by small steps until the stall-out con-

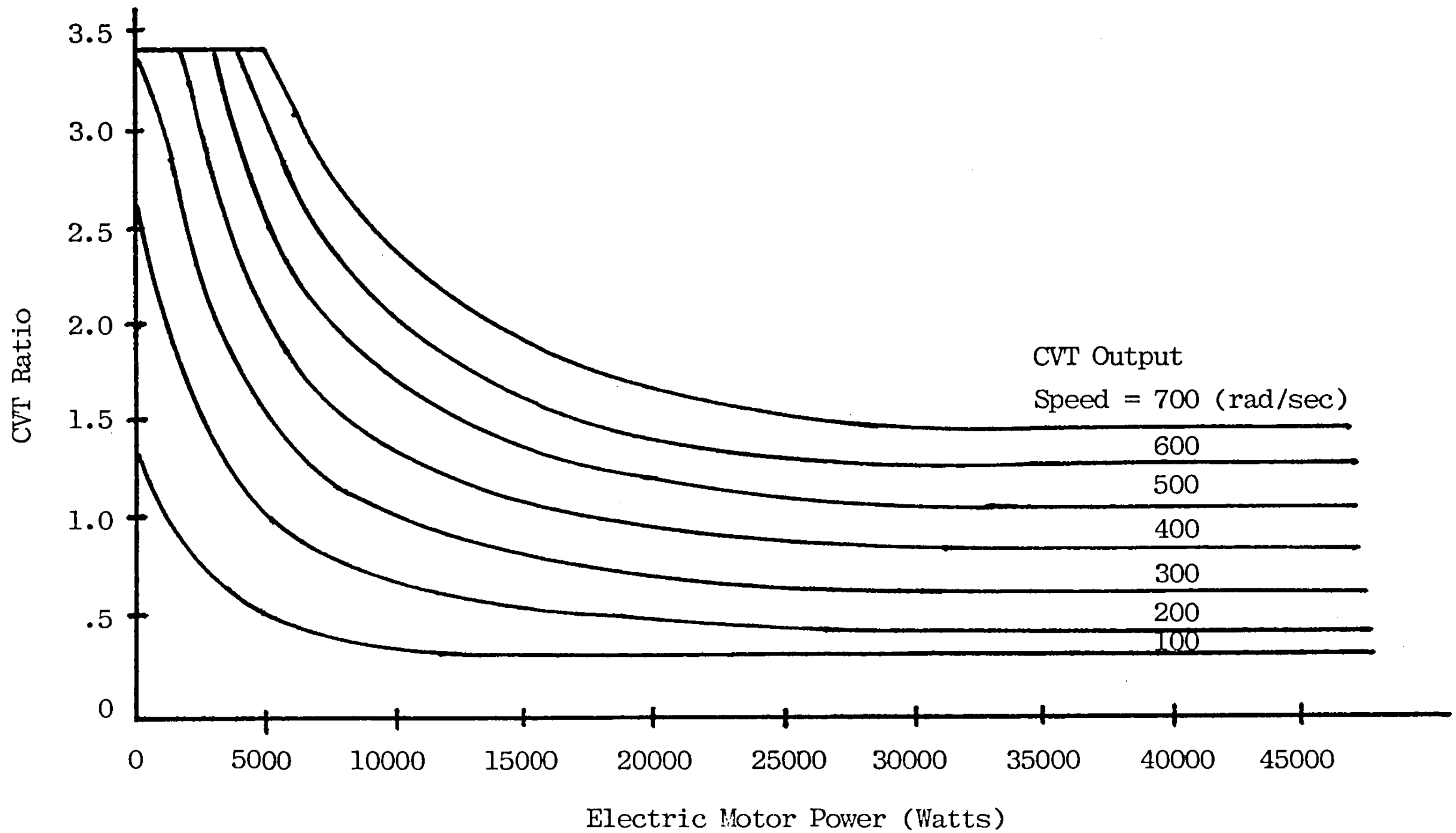

Figure G-3. CVT Ratio for Most Efficient Electric Motor Speed

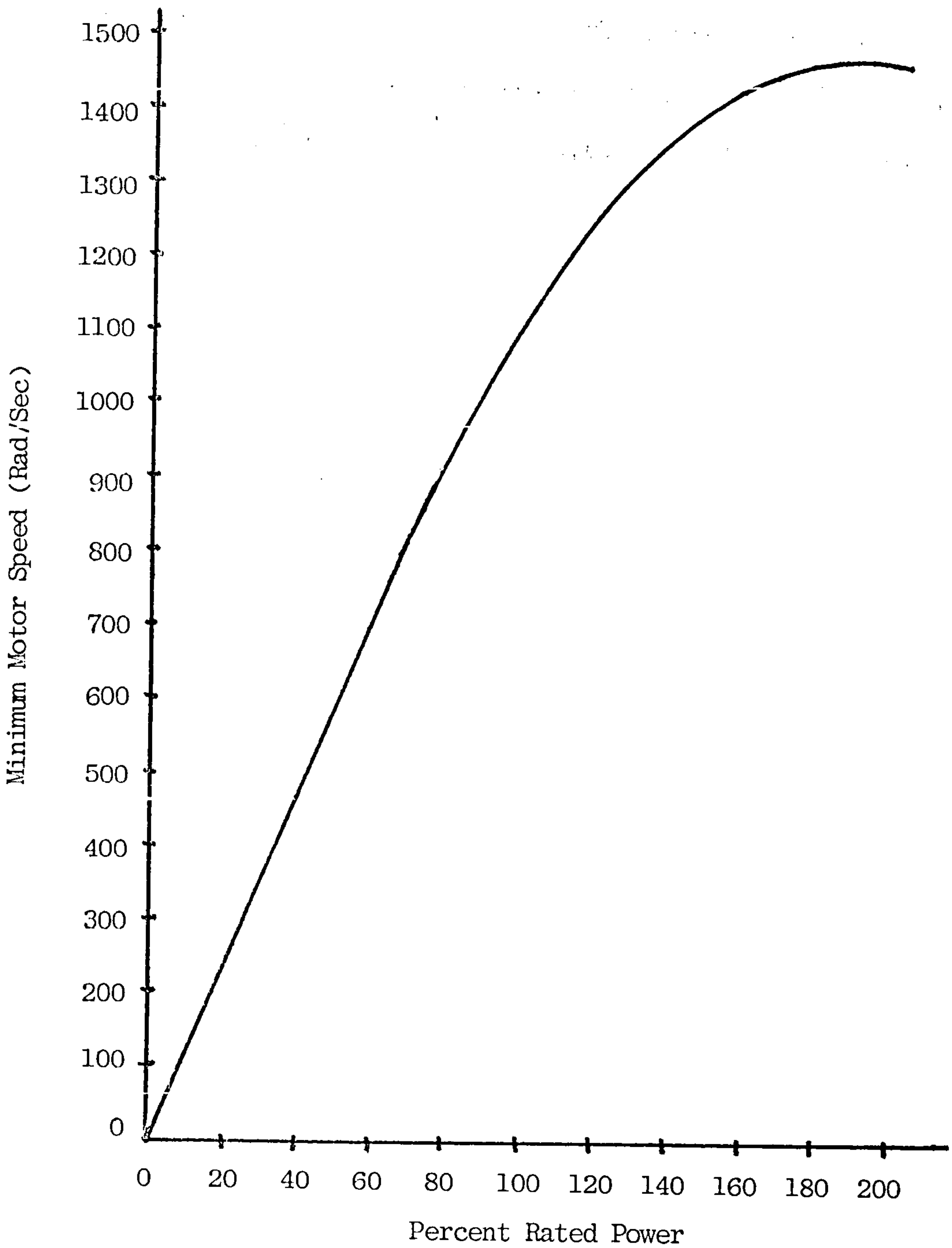

Figure G-4. Traction Motor Stall-Out Curve dition no longer exists. Finally, if the ratio selected to run the engine most efficiently calls for a motor speed which is excessive, then the ratio is changed to run the motor at its mazimum speed.

A copy of the ratio selection program is given in Appendix I.

APPENDIX H - AIRESEARCH POWER SPLIT STRATEGY

Since the AiResearch power split strategy [1] was used in parts of this study it is worthwhile including it here for reference. A listing of the program is given in Appendix I. The decision of how much of the CVT input power to assign to the heat engine and how much to the traction motor depends on the battery state of charge and whether or not the vehicle is accelerating. If the acceleration is zero, the state of charge above 20%, and the vehicle is not in a hill climb (CVT input power is < 20 kw), the power split is 100% electric. If the vehicle is in a hill climb, the split is 30% electric, 70% heat engine. If the acceleration is zero but the battery state of charge is below 20% (independent of hill climb), the split is 100% heat engine.

If the vehicle is accelerating (independent of whether the battery is above or below 20% state of charge), the split is 30% electric and 70% heat engine. However, this split is modified if the CVT input power exceeds 80% of the maximum rating of the heat engine: in this latter case the heat engine power is set to the CVT input power or its maximum rating, whichever is smaller, and the remaining required power is delivered by the traction motor.

```
FTN4,L
C ADDING THE D OPTION WILL PRINTOUT DATA (LCCOST,POVRLD,SOCL) TO
C FILE A8 FOR RUN21=3 (VALUES OVER A SPECIFIED RANGE OF HEKW AND
C WGBATT). THE TWO WRITE STATEMENTS FOLLOWING STATEMENT #109 MUST
C ALSO BE COMMENTED ( C ).
      PROGRAM HVPOP(3,100)
C  HYBRID VEHICLE PERFORMANCE OPTIMIZATION PROGRAM
C*****************************************************************************
C
C  THIS MAIN PROGRAM READS IN INITIAL VALUES, SETS UP THE DRIVING CYCLE
C  ARRAYS (VELOCITY AND GRADE ANGLE), SCALES THE GRG2 VARIABLES, AND
C  CALLS THE OPTIMIZATION PROGRAM.
C
C*****************************************************************************
      LOGICAL SOVRLD,SNOTC,SMOOTH
      REAL KMPRYR
      INTEGER RUN21
      COMMON RUN21
      COMMON/ALPHA/ALPHA1,ALPHA2,ALPHA3
      COMMON/CC/CDA,RDIFF,RGEAR,RGRM,RTIRE
      COMMON/MAP/DISCHG(101,6),EFFMTR(81,7),HEMAP(6,6),
     &GREFF(101,11),VCHG(13,12),ATORQ(6),AESPED(6),ARATIO(10)
      COMMON/OMISC/CHOOSE,SMOOTH
      COMMON/SCALE/SFX(17),SFG(20),NN
      COMMON/STC/V(831),BET(831),TRIPLN(8),TRIPNO(8)
      COMMON/TIMEC/DLTSTC,DELTHW,TACCEL,TCOAST,TBRAKE,TSTOP,TCYCLE
      COMMON/VARY/ WTL,INOCHG
      COMMON/YEARC/PETYR(15),ELECYR(15),ELEC(15),DISCH(15)
      COMMON GF
      DIMENSION G(20),XX(17),AVELA(15)
      DIMENSION IBUF(98)
      DIMENSION HE(3),LINEO(161),LINES(161)
      DATA HEKW/65./, WGBATT/386./, XX(3)/.7/, XX(4)/0./, XX(5)/0./
      DATA AVELA/0.,3.2777,5.8611,7.9166,9.9722,11.333,12.583,13.722,
     &14.805,15.777,16.75,17.639,18.5,19.333,20.111/
      CALL LGBUF(IBUF,98)
C
C READING INITIAL VALUES OF OPTIMIZATION PARAMETERS
    1 READ(5,*) NN,(XX(I),I=3,NN),HEKW,WGBATT,DHEKW,DWGBAT,NHEKW,NWGBAT
    2 READ(5,*) DLTSTC,DELTHW,WTL,CHOOSE,INOCHG,RUN21,GF
    3 READ(5,7) SMOOTH
    7 FORMAT(L1)
      WRITE(6,2000) XX(3),XX(4),XX(5)
 2000 FORMAT(
     &' CONSTANT TERM IN POWER SPLIT FUNCTION=',F8.3,/
     &'       TERM USED TO WEIGHT ACCELERATION=',F8.3,/
     &'   TERM USED TO WEIGHT STATE OF CHARGE=',F8.4)
      WRITE(6,2005)HEKW,WGBATT
 2005 FORMAT(/,
     &'     HEKW=',F8.4,/
```

```
     &'   WGBATT=',F8.4,/)
      IF(SMOOTH) WRITE(6,2006)
 2006 FORMAT('           SMOOTH=TRUE')
      IF(.NOT.SMOOTH) WRITE(6,2007)
 2007 FORMAT('           SMOOTH=FALSE')
      WRITE(6,2008) GF
 2008 FORMAT(//'    GAS FACTOR (GF)=',F7.3,//)
      WRITE(6,2010) DLTSTC,DELTHW,CHOOSE
 2010 FORMAT(
     &'                            STC TIME INCREMENT (DLTSTC)=',F8.2,/
     &'                        HIGHWAY TIME INCREMENT (DELTHW)=',F8.1,/
     &'(CHOOSE=0 FOR ELECST COMPUTATIONS BASED ON ',
     &'ELEC(I) & ENRGY) CHOOSE=',F2.0)
      XX(1)=HEKW
      XX(2)=WGBATT
C  SCALING OF OPTIMIZATION PARAMETERS
      DO 10 I=1,NN
 10   XX(I)=XX(I)/SFX(I)
C  SET UP SAE DRIVING CYCLE.
      IMAX=IFIX(TACCEL/DLTSTC)+1
      IDEL=1
      IF(DLTSTC.GT.1.) IDEL=DLTSTC
      DO 20 I=1,IMAX
C  FIND DRIVING CYCLE VEL. AND STORE IN V(I)
      T=FLOAT(I-1)*DLTSTC
      TMIN=INT(T)
      TMAX=TMIN+FLOAT(IDEL)
      IBOT=INT(TMAX)+1-IDEL
      ITOP=IBOT+IDEL
      IF(ITOP.LE.15) GOTO 20
      ITOP=15
      IBOT=15-IDEL
      TMAX=14.
      TMIN=TMAX-FLOAT(IDEL)
 20   V(I)=((T-TMIN)*AVELA(ITOP)+(TMAX-T)*AVELA(IBOT))/(TMAX-TMIN)
      K=I-1
      IMAX=K+IFIX((TCOAST-TACCEL)/DLTSTC)+1
      DO 30 I=K,IMAX
30    V(I)=20.
C     DO 40 I=1,IMAX
C     T=DLTSTC*FLOAT(I-1)
C40   WRITE(1,2030) T,V(I)
 2030 FORMAT('T=',F5.2,3X,'V(I)=',F9.5)
      IMAX=IFIX(TSTOP/DLTSTC)+1
      DO 50 I=1,IMAX
 50   BET(I)=0.
C     CALL GRG(Z,NCORE)
      IRUN21=RUN21+1
      GOTO (101,151,202,303,404,505),IRUN21
 101  CALL GCOMP(G,XX)
```

```
      WRITE(8,2040)
 2040 FORMAT('   HEKW     WGBATT    LCCOST    POVRLD     SOCL ')
      WRITE(8,2050) XX(1),XX(2),G(1),G(5),G(13)
 2050 FORMAT(F9.4,1X,F9.3,1(1X,F9.2),1X,G11.4,1X,F9.7,1X,F9.1)
      IF(SMOOTH) WRITE(8,106)
      IF (.NOT.SMOOTH) WRITE(8,107)
 106  FORMAT('  SMOOTH=TRUE')
 107  FORMAT('  SMOOTH=FALSE')
      WRITE(8,883) G(2)
 883  FORMAT(/,' TOTPET=',F9.3)
      STOP 101
C----------
C---
 151  CALL GCOMP(G,XX)
      STOP 151
C---
C========
C UDH = 1  WHEN OVERLOAD REGION LIES BELOW CURRENT HEKW OVERLOAD THRESHOLD
C          CURVE (SEARCH FOR FIRST ADMISSIBLE RUN, THEN GET CURVE
C     =-1  WHEN OVERLOAD REGION LIES ABOVE CURRENT HEKW OVERLOAD THRESHOLD
C          CURVE (SEARCH FOR FIRST OVERLOAD, THEN GET CURVE)
C UDW = 1  WHEN WGBATT INCREASES IN THE SEARCH
C     =-1  WHEN WGBATT DECREASES IN THE SEARCH
C SOVRLD = TRUE TO SEARCH FOR AN OVERLOAD AFTER WGBATT HAS BEEN CHANGED
C SNOTC   = TRUE TO SEARCH FOR A NEW OVERLOAD THRESHOLD CURVE
 202  TWGBAT=WGBATT+DWGBAT*FLOAT(NWGBAT-1)
      BWGBAT=WGBATT
      WRITE(8,2060)
 2060 FORMAT('   HEKW     WGBATT    LCCOST    POVRLD    SOCL')
      UDW=1
      UDH=-1
      SNOTC=.FALSE.
      SOVRLD=.FALSE.
      DO 190 K=1,5
      I=1
 60   CONTINUE
      WRITE(1,2060)
      WRITE(9,2060)
C
C SEARCH FOR NEXT OVERLOAD AT WGBATT=300
      IF(K.EQ.1) GOTO 90
      J=K-2
      IF(J/2*2.EQ.J) UDH=-UDH
      IF(K.GE.3) UDW=-UDW
      WGBATT=300.
      XR=HE(3)
      SNOTC=.TRUE.
      SOVRLD=.FALSE.
      IF(K/2*2.EQ.K) GOTO 70
      SNOTC=.FALSE.
```

```
      GOTO 90
C
C SEARCH FOR FIRST NEW OVERLOAD CURVE WITH CONSTANT STEP SIZE
 70   XR=XR-DELX*UDH
      GOTO 150
 80   IF(G(5).LE.0.) GOTO 70
      SNOTC=.FALSE.
C
C INCREMENT BATTERY WEIGHT & TEST IF ITS OUT OF RANGE
 90   XX(2)=WGBATT+DWGBAT*FLOAT(I-1)*UDW
      IF(XX(2).LE.TWGBAT) GOTO 100
      I=NWGBAT
      GOTO 180
 100  IF(XX(2).GE.BWGBAT) GOTO 110
      I=NWGBAT
      GOTO 180
 110  IF(SNOTC.OR.K.NE.1) GOTO 150
      IF(I.NE.1) GOTO 130
      SOVRLD=.FALSE.
      DELX=2.
      UDH=1
      XR=15.
      GOTO 140
C
C SEARCH FOR OVERLOADS & DOUBLE STEP SIZE WITH FAILURE
 120  IF(G(5).LE.0.) GOTO 130
      SOVRLD=.FALSE.
      GOTO 160
C
C DOUBLE STEP SIZE
 130  DELX=DELX*2.
      XR=XR-DELX*UDH
      SOVRLD=.TRUE.
      GOTO 150
 140  CONTINUE
 150  XX(1)=XR
      CALL GCOMP(G,XX)
      WRITE(1,2070) XX(1),XX(2),G(1),G(5)
      WRITE(9,2070) XX(1),XX(2),G(1),G(5)
 2070 FORMAT(F9.3,1X,F9.3,1(1X,F9.2),1X,G11.4,1X,F9.7,1X,F9.1)
      IF(SOVRLD) GOTO 120
      IF(SNOTC) GOTO 80
      IF(G(5).LE.0..AND.DELX.LE.DHEKW) GOTO 170
      IF(G(5).GT.0.) GOTO 160
      DELX=AINT(DELX*5.)/10.
      IF(DELX.LE.0.) DELX=DHEKW/2.
      XR=XL+DELX*UDH
      GOTO 140
 160  XL=XR
      XR=XR+DELX*UDH
```

```
      GOTO 150
 170  CONTINUE
      WRITE(8,2070) XX(1),XX(2),G(1),G(5),G(13)
      IF(XX(2).EQ.100.) HE(1)=XX(1)
      IF(XX(2).EQ.200.) HE(2)=XX(1)
      IF(XX(2).EQ.300.) HE(3)=XX(1)
 180  I=I+1
      IF(I.LE.NWGBAT) GO TO 60
 190  CONTINUE
      STOP 202
C========
C++++++++
 303  CONTINUE
D     WRITE(8,2090)
D2090 FORMAT('   HEKW     WGBATT    LCCOST    POVRLD     SOCL ')
      DO 108 I=1,NHEKW
      XX(1)=HEKW-DHEKW*FLOAT(I-1)
      DO 109 J=1,NWGBAT
      XX(2)=WGBATT+DWGBAT*FLOAT(J-1)
      CALL GCOMP(G,XX)
D     WRITE(8,3000) XX(1),XX(2),G(1),G(5),G(13)
D3000 FORMAT(F9.3,1X,F9.3,1(1X,F9.2),1X,G11.4,1X,F9.7,1X,F9.1)
      WRITE(8,3003) XX(1),XX(2),G(2),G(1)
 3003 FORMAT(F9.3,3(5X,F9.3))
C     LINEO(J)=1H.
C     IF(G(5).GT.0.) LINEO(J)=1H@
C     IF(G(2).GT.1072.) LINEO(J)=1H@
C     LINES(J)=1H^
C     IF(G(13).LT..2) LINES(J)=1H+
 109  CONTINUE
C WRITES POVRLD GRID. COMMENT IF USING D OPTION (DATA PRINTOUT).
C     WRITE(8,3005) (LINEO(J),J=1,NWGBAT)
C WRITES SOCL GRID.  COMMENT IF USING D OPTION (DATA PRINTOUT).
C     WRITE(9,3005) (LINES(J),J=1,NWGBAT)
C     WRITE(9,3005) (LINEO(J),J=1,NWGBAT)
 3005 FORMAT(17X,161A1)
 108  CONTINUE
C     WRITE(6,320)
 320  FORMAT(' FILE A8 CONTAINS THE POVRLD GRID:',/
     &,'       FOR NO OVERLOAD (POVRLD.LE.0)',/
     &,'    @ WHEN AN OVERLOAD OCCURS (POVRLD.GT.0)',/
     &,'FILE B7 CONTAINS THE SOCL GRID:',/
     &,'    ^ WHEN ELECTRIC POWER IS AVAILABLE DURING ACCELERATION',/
     &,'    + WHEN ELEC. POWER IS NOT AVAILABLE DURING ACCELERATION')
      STOP 303
C+++++++
C*******
 404  DO 409 I=1,21
      XX(3)=.05*FLOAT(I-1)
 409  CALL GCOMP(G,XX)
```

```
      STOP 404
C******
C@@@@@@@
 505  CONTINUE
      DO 510 I=1,481
      XX(2)=WGBATT+1.0*FLOAT(I-1)
      IF(XX(2).LE.273.) XX(1)=37.0-0.02564*XX(2)
      IF(XX(2).GT.273.) XX(1)=77.2334-0.2267756*XX(2)
     &+1.9819E-04*XX(2)*XX(2)
      CALL GCOMP(G,XX)
      WRITE(8,520) XX(1),XX(2),G(1),G(7),G(8),G(9)
 520  FORMAT(F9.4,5(3X,F9.4))
 510  CONTINUE
      STOP 505
C@@@@@@@
      END
      END
```

```
FTN4,L
      SUBROUTINE GCOMP(G,XX)
C*****************************************************************************
C
C  THIS EVALUATES THE CONSTRAINT AND OBJECTIVE FUNCTIONS FOR GRG2 GIVEN THE
C  THE GRG2 PARAMETERS, WHICH ARE POWER RATING OF THE HEAT ENGINE, BATTERY
C  WEIGHT, AND THE POWER SPLIT PARAMETERS.
C
C*****************************************************************************
      REAL MT,MNFCST,KMPRYR,MTKWPK,LCCOST,MAINTC,LINCOM
      DIMENSION G(20),XX(17)
      INTEGER RUN21
      COMMON RUN21
      COMMON GF
      COMMON/ALPHA/ALPHA1,ALPHA2,ALPHA3
      COMMON/MOTOR/MTKWPK
      COMMON/RSPLT/ACCEL,SOC,PCVT,CX(15),VAVE,PHEMAX, PHE,PELEC
      COMMON/SCALE/SFX(17),SFG(20),NN
      COMMON/YEARC/PETYR(15),ELECYR(15),ELEC(15),DISCH(15)
      COMMON BTCOST,BATRYR,BATLFE
      DIMENSION ELECST(10),PETCST(10)
      DATA KMPRYR/16000./, WP/20./
C
C  THIS PROGRAM TAKES VALUES FOR THE IC ENGINE SIZE, BATTERY WEIGHT
C  AND POWER SPLIT FUNCTION PARAMETERS, AND COMPUTES THE VALUES OF
C  THE OBJECTIVE AND CONSTRAINT FUNCTIONS
C
      HEKW=XX(1)*SFX(1)
      WGBATT=XX(2)*SFX(2)
      IMAX=NN-2
      DO 115 I=1,IMAX
115   CX(I)=XX(I+2)*SFX(I+2)
C  CX IS VECTOR OF UNSCALED POWER FLOW PARAMETERS
      CALL WGHT(HEKW,WGBATT, WT,MT,WGCHI,WP)
      CALL MFCST(WGBATT,WGCHI, MNFCST)
      CALL AQCST(MNFCST,WGBATT, BATCST,ACQCST)
      CALL MAINT(HEKW,MTKWPK,BATCST,KMPRYR,WP,WGCHI, BTLIST,MAINTC)
      CALL REPAR(HEKW,MTKWPK,WP,WGCHI,KMPRYR, REPAIR)
C  TRAVL USES POWER FLOW PARAMETERS
      CALL TRAVL(HEKW,WGBATT,MT, PETYR,ELECYR,ELEC,DISCH,POVRLD,PETV10,
     &SOCL,BGPCVT)
      IF(RUN21.LE.1) WRITE(6,425) MT,WGBATT,WP,MNFCST,ACQCST,MAINTC,
     &REPAIR,HEKW,POVRLD
425   FORMAT(//'*************** SUMMARY DATA ***************',/
     &'                      TOTAL MASS (MT) =',F9.3,/
     &'               BATTERY MASS (WGBATT) =',F9.3,/
     &'              POWER TRAIN WEIGHT (WP) =',F9.3,/
     &'          MANUFACTURING COST (MNFCST) =',F9.3,/
     &'            ACQUISITION COST (ACQCST) =',F9.3,/
     &'      YEARLY MAINTENANCE COST (MAINTC) =',F9.3,/
```

```
     &'             YEARLY REPAIR COST (REPAIR) =',F9.3,/
     &'                  HE POWER RATING (HEKW)=',F8.3,/
     &'SUM OF POWER OVERLOAD SQUARED (POVRLD)=',F8.3)
      CALL LIFE(PETYR,ELECYR,ELEC,DISCH,BTLIST,ACQCST,MAINTC,REPAIR,
     &BATCST, LCCOST,PETCST,ELECST,TOTPET)
C
C MY CONVENTION IS TO SEPARATE GIVEN AND RETURNED VALUES BY A BLANK
C AND TO COMMUNICATE CALC VALUES BY ARGUMENT LIST AND MAPS BY COMMON
C STATEMENTS
C
      LINCOM=ALPHA1*LCCOST+ALPHA2*TOTPET+ALPHA3*ACQCST
      G(1)=LCCOST*SFG(1)
      G(2)=TOTPET*SFG(2)
      G(3)=ACQCST*SFG(3)
      G(4)=LINCOM*SFG(4)
      G(5)=POVRLD*SFG(5)
      G(7)=BTCOST
      G(8)=BATRYR
      G(9)=BATLFE
      G(13)=SOCL
      G(14)=BGPCVT
      RETURN
      RETURN
```

```
      SUBROUTINE TRAVL(HEKW,WGBATT,MT, PETYR,ELECYR,ELEC,DISCH,POVRLD,
     &PETV10,SOCL,BGPCVT)
C***********************************************************************
C
C  THIS SIMULATES BOTH STC AND HIGHWAY DRIVING FOR THE VEHICLE.
C  IT CALCULATES THE YEARLY FUEL CONSUMPTION, ELECTRICITY USAGE, AND
C  THE NUMBER OF DEEP DISCHARGES OF THE BATTERY.
C
C***********************************************************************
      LOGICAL SMOOTH
      INTEGER RUN21
      REAL INTEQ,INTNQ
      REAL MT,IAVE,IBATT,IVESTC,KMPRYR,IBMAX,IEFFMX,IBTOLD
      REAL KWCST,LENGTH,MT,MTGRKW,MTKWPK,MC,NC,IEFF,MCSTND
      DIMENSION PETYR(15),ELECYR(15),ELEC(15),DISCH(15)
      DIMENSION EAKWHR(15),AEKHA(15),AEKHP(15)
      DIMENSION AHEKW(4),FFHEKW(4),SATORQ(6)
      COMMON RUN21
      COMMON/CC/CDA,RDIFF,RGEAR,RGRN,RTIRE
      COMMON/CHARG/AACV(8),ACR(8)
      COMMON/EFCVT/APCVT(8),ARCVT(7),EFF(8,7)
      COMMON/LIMIT/ NTRIPX, ITERMX
      COMMON/MAP/DISCHG(101,6),EFFMTR(81,7),HEMAP(6,6),
     &GREFF(101,11),VCHG(13,12),ATORQ(6),AESPED(6),ARATIO(10)
      COMMON/OMISC/CHOOSE,SMOOTH
      COMMON/PHY/GRAV,RHO
      COMMON/PRINT/APETT(15),AELETA(15),AELETP(15)
      COMMON/RRATO/NTIME,WGEAR,RCVT,PMOTOR,PMTRTD,PGEAR
      COMMON/RSPLT/ACCEL,SOC,PCVT,CX(15),VAVE,PHEMAX, PHE,PELEC
      COMMON/STC/V(831),BET(831),TRIPLN(8),TRIPNO(8)
      COMMON/TIMEC/DLTSTC,DELTHW,TACCEL,TCOAST,TBRAKE,TSTOP,TCYCLE
      COMMON/TRIP/CHARGE(36),EBTOTL(36),HOUT(36),IDOD(36),
     &IVESTC(36),PETSTC(36),SOCSTC(36),REGEN(36)
      COMMON/VARY/ WTL,INOCHG
      DATA AHEKW/37.,56.,75.,112./
      DATA FFHEKW/1.09718,1.05,1.,0.954545/
      DATA ALLSTC/50001./, HWYVEL/25.0/, STCDIS/1450.0/, CHGEFF/0.85/
      DATA NC/84./,WDORTE/116.35/,WGORTE/116.35/,WMORTE/419./
      DATA NSTCFR/28/, PCVTMX/90000./, NCYLMX/35/
      DATA PDRATE/90000./, PINVMX/40000./
      DATA PGRATE/90000./, PMGRTE/40000./, REGMIN/1000./
      DATA PMTMAX/40000./, SOCMAX/.3/, VCELL/2.05/
      DATA VDELT/1./, MCSTND/9.83/, PBMAX/33600./, IBMAX/200./
      DATA EFFBC/.75/, IEFFMX/700./
C CALCULATE THE MASS OF A BATTERY CELL
      MC=WGBATT/NC
C  INITIALIZE VARIABLES
      I80DOD=0
      AHOUT=0.
      AREGEN=0.
```

```
      SOC=1.0
      SOCL=1.0
      BGPCVT=0.
      POVRLD=0.
      INOELE=0
      IHWY=0
      ISWTCH=0
      NTIME=1
      VBCHG=200.
      VOLTOT=0.
      AHCHG=0.
      IOVRLD=0
      IFLLBK=0
      EOTOT=0.
      VBATT=NC*VCELL
C  SET TIME, TIME STEP AND CYCLE COUNTER FOR DRIVING A SEQUENCE OF STC'S
      TIME=0.
      NCYCLE=1
      DELT=DLTSTC
      PHEMAX=1000.*HEKW
      FRSCLE=HEKW/75.*SVINT(FFHEKW,HEKW,AHEKW,4)
      DO 5 I=1,6
 5    SATORQ(I)=ATORQ(I)*(HEKW/75.)
C------------------------------------------------------------------------
C---------------------------- ACCELERATION AND CRUISE PHASE ---------------
C-------------------------------- AND HIGHWAY DRIVING ---------------------
C------------------------------------------------------------------------
C  CALC. AVERAGE VELOCITY AND ACCELERATION OVER CURRENT TIME STEP
 10   V1=V(NTIME+1)
      V2=V(NTIME)
      VAVE=(V1+V2)/2.
      ACCEL=(V1-V2)/DELT
      BETA=BET(NTIME)
C     CALC DRAG FORCE OF VEHICLE
 20   FD=CDA*RHO*VAVE*VAVE/2.
C     CALC ROLLING RESISTANCE FORCE
      CR=(10.+0.01*VAVE+0.00008*VAVE*VAVE)/1000.
      FR=CR*MT*GRAV
C  INITIALIZE POWER SWITCH FLAG
      ISWTCH=0
C  CALC. GRADE FORCE
      FGR=MT*GRAV*SIN(BETA)
C  CALCULATE VEHICLE ACCELERATION FORCE
      FA=1.1*MT*ACCEL
C  CALC. POWER REQ'D AT AXLE
      PAXLE=(FD+FR+FGR+FA)*VAVE
C  CALC. AXLE SPEED AND TORQUE
      WAXLE=VAVE/RTIRE
      TAXLE=PAXLE/WAXLE
C  CALC. DIFFERENTIAL INPUT SPEED, TORQUE, POWER
```

```
      WDRIVE=WAXLE/RDIFF
      PDPCT=(PAXLE/PDRATE)*100.
      WDPCT=(WAXLE/WDORTE)*100.
      PDRIVE=PAXLE/INTEQ(GREFF,PDPCT,WDPCT,100.,100.,
     &1.,-1.,10.,-10.,101,11)
      TDRIVE=PDRIVE/WDRIVE
C  CALC. TORQUE, SPEED, POWER AT INPUT TO GEAR BETWEEN CVT AND DIFFERENTIAL
      WGEAR=WDRIVE/RGEAR
      PGPCT=(PDRIVE/PGRATE)*100.
      WGPCT=(WDRIVE/WGORTE)*100.
      PGEAR=PDRIVE/INTEQ(GREFF,PGPCT,WGPCT,100.,100.,
     &1.,-1.,10.,-10.,101,11)
      TGEAR=PGEAR/WGEAR
C  DETERMINE CVT RATIO (RCVT)
      CALL RATIO
C  CALC. TORQUE, SPEED, POWER AT CVT INPUT
      PCVT=(PGEAR)/(INTNQ(EFF,(PGEAR/1000.),RCVT,100.,3.4,
     &APCVT,ARCVT,8,7))
      IF(PCVT.GT.BGPCVT) BGPCVT=PCVT
      WCVT=WGEAR/RCVT
      TCVT=PCVT/WCVT
C  DETERMINE POWER SPLIT (RESULT IS PHE AND PELEC)
      CALL SPLIT
C  IS USE OF BATTERIES PROHIBITED
      IF(INOELE.NE.1) GOTO 33
      PELEC=0.
      PHE=PCVT
C  IS ELECTRIC POWER NEGLIGIBLE
 33   IF(PELEC.LT.50.) GOTO 31
C  IS BATTERY 80% DISCHARGED
      IF(SOC.GE.0.2) GO TO 32
31    PHE=PHE+PELEC
      IF(PELEC.GT.0.) IFLLBK=IFLLBK+1
      PELEC=0.
      PMOTOR=0.
      PINV=0.
      PBOUT=0.
      IBATT=0.
      IELEC=0
      GO TO 80
 32   IF(SOC.GE.SOCMAX) GOTO 30
      IF(IHECHG.NE.1) GOTO 30
      GOTO 31
C     CALC. INPUT QUANTITIES TO GEAR BETWEEN MOTOR AND CVT
30    IELEC=1
      WMOTOR=WCVT/RGRM
      PMGPCT=(PELEC/PMGRTE)*100.
      WMGPCT=(WCVT/WMORTE)*100.
      PMOTOR=PELEC/INTEQ(GREFF,PMGPCT,WMGPCT,100.,100.,
     &1.,-1.,10.,-10.,101,11)
```

```
      IFG1=PELEC/PMOTOR
      TMOTOR=PMOTOR/WMOTOR
C  DOES MOTOR OUTPUT POWER EXCEED PEAK
      IF(PMOTOR.LE.PMTMAX) GOTO 50
C  SET MOTOR POWER AT MAX
      PMOTOR=PMTMAX
C  CALC. NEW MOTOR TORQUE
      TMOTOR=PMOTOR/WMOTOR
C  CALC. NEW ELECTRIC POWER AT CVT INPUT
40    PMGPCT=(PMOTOR/PMGRTE)*100.
      PELEC=PMOTOR*INTEQ(GREFF,PMGPCT,WMGPCT,100.,100.,
     &1.,-1.,10.,-10.,101,11)
      EFG2=PELEC/PMOTOR
      IFLLBK=IFLLBK+1
C  SET ENGINE POWER TO MEET TOTAL REQ'D POWER
      PHE=PCVT-PELEC
C  CALC MOTOR INPUT (INVERTER OUTPUT) POWER
50    PMTPCT=(PMOTOR/PMTRTD)*100.
      PINV=PMOTOR/INTEQ(EFFMTR,PMTPCT,WMOTOR,200.,1466.,
     &2.5,-2.5,146.61,439.82,81,7)
      EFM1=PMOTOR/PINV
C  DOES INVERTER OUTPUT POWER EXCEED MAX
      IF(PINV.LE.PINVMX) GOTO 55
C  SET INVERTER POWER AT MAX AND COMPUTE NEW MOTOR OUTPUT POWER
      PINV=PINVMX
      PMTPCT=(PINV/PMTRTD)*100.
      PMOTOR=PINV*INTEQ(EFFMTR,PMTPCT,WMOTOR,200.,1466.,
     &2.5,-2.5,146.61,439.82,81,7)
      EFM1=PMOTOR/PINV
C  COMPUTE NEW ELECTRIC POWER AT CVT INPUT
      PMGPCT=(PMOTOR/PMGRTE)*100.
      PELEC=PMOTOR*INTEQ(GREFF,PMGPCT,WMGPCT,100.,100.,
     &1.,-1.,10.,-10.,101,11)
C  COMPUTE NEW HEAT ENGINE POWER
      PHE=PCVT-PELEC
      IFLLBK=IFLLBK+1
C  CALC INVERTER LOSSES AND INPUT POWER USING OLD VALUE OF BATTERY VOLTAGE,
C  AND RESET ITERATION COUNTER
55    PILOSS=3.0*(PINV/VBATT)+0.035*PINV
      PBOUT=PINV+PILOSS
      IITER=0
C-----------------------------------------------------------------------
C---------------------------- DISCHARGING BATTERY VOLTAGE LOOP ----------
C-----------------------------------------------------------------------
C  CALCULATE BATTERY CURRENT USING BATTERY VOLTAGE FROM LAST ITERATION
41    IBATT=PBOUT/VBATT
C  SAVE OLD VALUE OF BATTERY VOLTAGE
      VBTOLD=VBATT
      PVBATT=VBATT
      IBTOLD=IBATT
```

```
C  CALC BATTERY AMP-HRS OUT
      AHOUT=AHOUT+(IBATT*DELT/3600.)
C  IS THIS HIGHWAY DRIVING
      IF(IHWY.NE.1.) GOTO 57
C  CALC AVERAGE BATT CURRENT FOR STC AND HIGHWAY DRIVING
      IAVE=(3600.*AHOUT)/(TIME+DELT)
      GOTO 58
C  CALC AVERAGE BATT CURRENT SINCE START OF STC DRIVING
57    IAVE=(3600.*AHOUT)/((TIME+DELT)+FLOAT(NCYCLE-1)*TSTOP)
C  FIND CELL CAPACITY PER KILOGRAM
58    CAPKG=PUKRT(IAVE/MC)
C  CALC AMP-HRS PER CELL
      CAPCTY=CAPKG*MC
C  CALC ACTUAL CAPACITY WITHDRAWN AND STATE OF CHARGE
      AACTL=AHOUT-AREGEN-AHCHG
      SOC=1.-(AACTL/CAPCTY)
      IF(SOC.LT.SOCL.AND.ACCEL.NE.0.) SOCL=SOC
C  CHANGE CELL CURRENT TO ACCOUNT FOR CHANGE IN CELL RESISTANCE
      IEFF=IBATT*(MCSTND/MC)
C  CALC BATTERY VOLTAGE FROM DISCHARGE CURVE
      VBATT=NC*INTEQ(DISCHG,SOC,IEFF,1.,IEFFMX,.01,-.01,100.,-100.,
     &101,6)
C  DOES CALCULATED BATTERY VOLTAGE EQUAL BATT VOLTAGE ASSUMED AT START OF CALC
      IF(ABS(VBATT-VBTOLD).GT.VDELT) GOTO 59
      GOTO 71
C  HAVE WE ITERATED THE MAX NO. OF TIMES
59    IF(IITER.GE.ITERMX) GOTO 60
C  RESET AMP-HRS OUT OF BATT. AND INCREMENT ITERATION COUNTER
      AHOUT=AHOUT-(IBATT*DELT/3600.)
      IITER=IITER+1
      GOTO 41
C  SET BATTERY VOLTAGES AND CURRENTS TO OLD VALUES
60    VBATT=VBTOLD
      IBATT=IBTOLD
      IEFF=IBATT*(MCSTND/MC)
C  WAS THE EFFECTIVE BATTERY CURRENT ABOVE ITS MAX
71    IF(IEFF.LE.IEFFMX) GOTO 70
C  COMPUTE BATTERY CURRENT CORRESPONDING TO MAX EFFECTIVE CURRENT
      IBATT=IEFFMX*(MC/MCSTND)
C  COMPUTE NEW BATTERY OUTPUT POWER
      PBOUT=IBATT*VBATT
C  ESTIMATE NEW INVERTER OUTPUT POWER
      PINV=PBOUT-3.0*IBATT-0.035*(PBOUT-PILOSS)
C  ESTIMATE MOTOR OUTPUT POWER AND ELECTRIC POWER AT CVT INPUT
      PMTPCT=((PINV*0.9)/PMTRTO)*100.
      PMOTOR=PINV*INTEQ(EFFMTR,PMTPCT,WMOTOR,200.,1466.,
     &2.5,-2.5,146.61,439.82,81,7)
      PMGPCT=(PMOTOR/PMGRTE)*100.
      PELEC=PMOTOR*INTEQ(GREFF,PMGPCT,WMGPCT,100.,100.,
     &1.,-1.,10.,-10.,101,11)
```

```
      IFLLBK=IFLLBK+1
C  CALC NEW HE POWER
      PHE=PCVT-PELEC
C  IF BATT IS DISCHARGED SET 80% DOD FLAG
 70   IF(SOC.LT.0.2) I80DOD=1
C  CALC. BATT. ENERGY USAGE FOR THIS INCREMENT
      BENRGY=(PBOUT*DELT)/1.E+06
C  CALC BATT INTERNAL VOLTAGE AND ENERGY WEIGHTING FACTOR
      VINT=NC*INTEQ(DISCHG,SOC,0.,1.,IEFFMX,.01,-.01,100.,-100.,101,6)
      DISEFF=VINT/VBATT
C  CALC. TOTAL BATT ENERGY USAGE SINCE START OF TRIP
      EBTOT=EBTOT+BENRGY*DISEFF
C-----------------------------------------------------------------------
C---------------------------- HE CHARGING COMPUTATIONS -----------------
C-----------------------------------------------------------------------
C  IS HE CHARGING INHIBITED
 80   IF(INOCHG.EQ.1) GOTO 101
C  IS BATT DISCHARGED
      IF(SOC.LT.0.2) GO TO 90
C  IS BATT PRESENTLY BEING CHARGED
      IF(IHECHG.NE.1) GOTO 101
C  IS BATT BELOW MAX CHARGING LEVEL
      IF(SOC.LT.SOCMAX) GOTO 90
C STOP CHARGING
      IHECHG=0
      GOTO 101
C  IS THIS HIGHWAY DRIVING
 90   IF(IHWY-1) 102,103,103
C  INHIBIT ALL FURTHER USE OF BATTERIES
 103  INOELE=1
      GOTO 105
C  IS THIS THE CRUISE PHASE OF THE STC
 102  IF(TIME.LT.TCOAST.AND.TIME.GE.TACCEL) GOTO 105
 101  PCHG=0.
      GOTO 140
C  SET BATT CHARGING FLAG
105   IHECHG=1
C  IS POWER SPLIT BEING CHANGED
      IF(PELEC .GT. 0.) IFLLBK=IFLLBK+1
C  SET HE POWER TO TOTAL
      PHE=PHE+PELEC
      PBOUT=0.
      PELEC=0.
      PMOTOR=0.
      PINV=0.
C  HAS ELECTRIC POWER BEEN CHARGED TO BATT THIS ITERATION
      IF(IELEC.NE.1) GOTO 106
C  RESET BATTERY QUANTITIES
      AHOUT=AHOUT-(IBATT*DELT/3600.)
      EBTOT=EBTOT-BENRGY*DISEFF
```

```
      IBATT=0.
C  CALC CHARGING POWER
106    PCHG=PHEMAX-PHE
       IF(PCHG .GE. 0.) GO TO 100
       PCHG=0.
       GOTO 140
C  CALC  POWER SUPPLIED TO ELECTRIC MOTOR
100    WMGPCT=(WCVT/WMORTE)*100.
       PMGPCT=(PCHG/PMGRTE)*100.
       PMOTOR=PCHG*INTEQ(GREFF,PMGPCT,WMGPCT,100.,100.,
      &1.,-1.,10.,-10.,101,11)
C  IS THE CHARGING POWER GREATER THAN THE MAX MOTOR POWER
       IF(PMOTOR.LE.PMTMAX) GOTO 110
C  SET POWER AT MAX AND CORRECT POWER CHARGED TO HE
       PMOTOR=PMTMAX
       PMGPCT=(PMOTOR/PMGRTE)*100.
       PCHG=PMTMAX/INTEQ(GREFF,PMGPCT,WMGPCT,100.,100.,
      &1.,-1.,10.,-10.,101,11)
C  CALC POWER FROM GENERATOR TO INVERTER
110    WMOTOR=WCVT/RGRM
       PMTPCT=(PMOTOR/PMTRTD)*100.
       PINV=PMOTOR*INTEQ(EFFMTR,PMTPCT,WMOTOR,200.,1466.,
      &2.5,-2.5,146.61,439.82,81,7)
C  IS INVERTER POWER TOO GREAT
       IF(PINV.LE.PINVMX) GOTO 120
C  SET POWER AT MAX AND CORRECT POWER CHARGED TO HE
       PINV=PINVMX
       PMTPCT=(PINV/PMTRTD)*100.
       PCHG=PINV/(INTEQ(EFFMTR,PMTPCT,WMOTOR,200.,1466.,
      &2.5,-2.5,146.61,439.82,81,7)
      & *INTEQ(GREFF,PMGPCT,WMGPCT,100.,100.,1.,-1.,10.,-10.,101,11))
C  INITIALIZE ITERATION FLAG
120    IICHG=0
       EFM1=PINV/PMOTOR
C-----------------------------------------------------------------------
C------------------------------ HE CHARGING BATTERY LOOP ----------------
C-----------------------------------------------------------------------
C  CALCULATE BATT INPUT POWER AND CURRENT
123    PBOUT=-PINV+3.0*(PINV/VBCHG)+0.035*PINV
       IBATT=PBOUT/VBCHG
       PVBATT=VBCHG
C  IS CHARGING POWER TOO GREAT
       IF(PBMAX*(MC/MCSTND)+PBOUT.GE.0.) GOTO 121
C  SET CHARGING POWER AT MAX AND CALC NEW BATT CURRENT
       PBOUT=-PBMAX*(MC/MCSTND)
       IBATT=PBOUT/VBCHG
C  IS CHARGING CURRENT TOO LARGE
121    IF(IBMAX+IBATT.GE.0.) GOTO 122
C  SET BATT CURRENT AT MAX AND RECALCULATE CHARGING POWER
       IBATT= -IBMAX
```

```
      PBOUT=IBATT*VBCHG
C  SAVE OLD VALUE OF BATTERY VOLTAGE
 122   VBTOLD=VBCHG
C  CALC. CHARGING AMP-HRS AND ACTUAL AMP-HRS
      AHCHG=AHCHG-(IBATT*DELT/3600.)
      AACTL=AHOUT-AHCHG-AREGEN
C  CALC AVER BATT CURRENT FOR STC AND HIGHWAY DRIVING
      IF(IHWY.NE.1) GOTO 125
      IAVE=3600.*AHOUT/(TIME+DELT)
      GOTO 130
C  CALC AVER BATT CURRENT SINCE START OF STC DRIVING
 125   IAVE=(3600.*AHOUT)/((TIME+DELT)+FLOAT(NCYCLE-1)*TSTOP)
C CALCULATE STATE OF CHARGE AND BATTERY VOLTAGE DURING CHARGING
 130   CAPKG=PUKRT(IAVE/MC)
      CAPCTY=CAPKG*MC
      SOC=1.0-(AACTL/CAPCTY)
      IEFF=-IBATT*(MCSTND/MC)
      VBCHG=NC*INTEQ(VCHG,(AACTL/MC),IEFF,15.,300.,1.,0.,25.,0.,13,12)
      REGEFF=NC*INTEQ(DISCHG,SOC,0.,1.,IEFFMX,.01,-.01,100.,-100.,
     &101,6)
     &/VBCHG
C  DOES CALC VOLTAGE EQUAL VOLTAGE ASSUMED
      IF(ABS(VBCHG-VBTOLD).LE.VDELT) GO TO 133
C  HAVE WE ITERATED MAXIMUM NUMBER OF TIMES
      IF(IICHG.GE.ITERMX) GO TO 134
C  INCREMENT ITERATION COUNTER AND RESET CHARGING AMP-HRS INTO BATT
      IICHG=IICHG+1
      AHCHG=AHCHG+(IBATT*DELT/3600.)
      GO TO 123
C  SET BATTERY VOLTAGE TO OLD VALUE
 134   VBCHG=VBTOLD
C  LIMIT SOC TO MAX
 133   IF(SOC.GT.1.0) SOC=1.
C  STOP CHARGING IF BATTERY HAS REACHED MAX CHARGING LEVEL
 131   IF(SOC.GE.SOCMAX) IHECHG=0
C  CALC TOTAL BATT ENERGY USED SO FAR ON THIS TRIP OR FROM START OF STC'S
      EBTOT=EBTOT+((PBOUT*DELT)/1.E+06)*REGEFF
C  INCREASE REQ'D HE POWER TO INCLUDE CHARGING POWER
      PHE=PHE+PCHG
C  IS HE POWER TOO LARGE
  140 IF(PHE.LE.PHEMAX) GOTO 160
C  IS BATT DISCHARGED
      IF(SOC.GE.0.2) GOTO 141
      IOVRLD=IOVRLD+1
      PSHORT=PCVT-PHEMAX-PELEC
      IF(PSHORT) 136,136,137
  136 WRITE(7,1072) PSHORT
  1072 FORMAT(" AN ERROR HAS OCCURED IN COMPUTING THE",
     &" SUM OF THE SQUARED POWER OVERLOAD (POVRLD=",F9.2,")")
      GOTO 160
```

```
 137  POVRLD=POVRLD+PSHORT*PSHORT
      GOTO 160
C  HAVE WE ATTEMPTED TO SWITCH MORE POWER TO ELECTRIC MOTOR
141   IF(ISWTCH.NE.1) GOTO 142
      IOVRLD=IOVRLD+1
      PSHORT=PCVT-PHEMAX-PELEC
      IF(PSHORT) 136,136,137
C  SET SWITCH FLAG
142   ISWTCH=1
C  DID WE USE ELECTRIC POWER IN THIS INCREMENT
      IF(PELEC.LE.0.) GOTO 150
C  RESET AMP HOURS OUT OF BATT
      AHOUT=AHOUT-(IBATT*DELT/3600.)
      EBTOT=EBTOT-BENRGY*DISEFF
C  SWITCH EXCESS POWER TO ELECTRIC MOTOR
  150 PHE=PHEMAX
      PELEC=PCVT-PHE
      IFLLBK=IFLLBK+1
      GOTO 30
C  CALC HE TORQUE,SPEED, FUEL FLOW RATE
 160  WHE=WCVT
      THE=PHE/WHE
      FUELRT=INTNQ(HEMAP,THE,WHE,PHEMAX/200.,840.0,SATORQ,AESPED,6,6)
     & *FRSCLE
      BSFC1=FUELRT/PHE*4178722.1
C  CALC HE FUEL VOLUME USED SINCE START OF TRIP
      VOLTOT=VOLTOT+(FUELRT*DELT)
C  INCREMENT TIME
      TIME=TIME+DELT
      NTIME=NTIME+1
C$
C  HIGHWAY PRINTOUT
      IF(IA.EQ.IA/57*57.AND.RUN21.EQ.1) WRITE(8,401)
      IA=IA+1
  401 FORMAT('1','NCYCLE    TIME      VAVE     WDRIVE    WGEAR     WCVT     ',
     &,'WHE        THE     WMOTOR     IAVE        I80DOD    IFLLBK   IOVRLD ',
     &'  ISWTCH     IITER     IHECHG    IICHG    IIREGN')
      IF(RUN21.EQ.1) WRITE(8,5000) NCYCLE,TIME,VAVE,WDRIVE,WGEAR,WCVT,
     &WHE,THE,WMOTOR,
     &IAVE,I80DOD,IFLLBK,IOVRLD,ISWTCH,IITER,IHECHG,IICHG,IIREGN
 5000 FORMAT(I4,2X,F8.0,1X,F8.2,1X,F8.3,1X,F8.2,1X,F8.3,1X,F8.3,1X,
     &F8.2,1X,F8.2,1X,F8.3,1X,8(I8,1X))
      IF(IB.EQ.IB/57*57.AND.RUN21.EQ.1) WRITE(9,402)
  402 FORMAT('1','NCYCLE    TIME     PAXLE     PDRIVE    PGEAR     PCVT    ',
     &'  RCVT       PHE      PCHG      PELEC     PMOTOR     PINV   ',
     &'   PBOUT      IBATT     VBATT      SOC       PROAD    PREGEN   ',
     &'   BSFC',4X,'FUELRT',5X,'EFM1')
      IB=IB+1
      IF(RUN21.EQ.1) WRITE(9,5010) NCYCLE,TIME,PAXLE,PDRIVE,PGEAR,
     &PCVT,RCVT,PHE,PCHG,
```

```
     &PELEC,PMOTOR,PINV,PBOUT,IBATT,PVBATT,SOC,PROAD,PREGEN,
     &BSFC1,FUELRT,EFM1
 5010 FORMAT(I4,2X,F8.0,1X,F8.1,1X,F8.1,1X,F8.1,1X,F8.1,1X,F8.3,1X,
     &F8.1,1X,F8.2,1X,F8.1,1X,F8.1,1X,F8.2,1X,F8.2,1X,F8.2,1X,
     &F8.2,1X,F8.4,1X,F8.2,1X,F8.2,1X,F9.4,1X,F10.8,1X,F7.6)
C$
C  IS THIS HIGHWAY DRIVING
      IF(IHWY.EQ.1) GOTO 170
C  HAS THE 'COAST' PHASE OF THE STC BEEN REACHED
      IF(TIME-TCOAST)  10,180,180
C  HAS HIGHWAY DRIVING BEEN COMPLETED FOR THIS TRIP
 170  CONTINUE
C
      IF(TIME-TRIPTM)  20,300,300
C-----------------------------------------------------------------------
C------------------------------ COAST PHASE ----------------------------
C-----------------------------------------------------------------------
C  SET HEAT ENGINE CHARGING POWER TO ZERO
 180  PCHG=0.
      ITER=0
      ICHG=0
      PVBATT=NC*INTEQ(DISCHG,SOC,0.,1.,IEFFMX,.01,-.01,100.,-100.,
     &101,6)
C  CALC CURRENT VELOCITY
      VELO=V(NTIME)
C  CALC VEHICLE DRAG FORCE
  190 FD=CDA*RHO*VELO*VELO/2.
C  CALC ROLLING RESISTANCE FORCE
      FR=MT*GRAV*(10.+0.01*VELO+0.00008*VELO*VELO)/1000.
C  CALC GRADE FORCE
      BETA=BET(NTIME)
      FGR=MT*GRAV*SIN(BETA)
C  CALC VEHICLE VELOCITY AT END OF TIME INCREMENT
      VNEXT=VELO-(DELT*(FGR+FD+FR)/MT)
C  CALC AVERAGE CURRENT AND VELOCITY
      IAVE=(3600.*AHOUT)/(TIME+FLOAT(NCYCLE-1)*TSTOP)
      VAVE=.5*(VELO+VNEXT)
C  ZERO ALL DRIVE TRAIN POWERS, ETC
      PAXLE=0.
      PDRIVE=0.
      PGEAR=0.
      PCVT=0.
      PELEC=0.
      PHE=0.
      PMOTOR=0.
      PINV=0.
      PILOSS=0.
      IBATT=0.
      PBOUT=0.
      THE=0.
```

```
C  CALC DRIVE SHAFT SPEEDS
      WHE=0.
      WDRIVE=VAVE/(RTIRE*RDIFF)
      WGEAR=WDRIVE/RGEAR
      WCVT=WGEAR/RCVT
      WMOTOR=WCVT/RGRM
C  INCREMENT TIME
      TIME=TIME+DELT
      NTIME=NTIME+1
      FUELRT=0.
C$
      IF(IA.EQ.IA/57*57.AND.RUN21.EQ.1) WRITE(8,401)
      IA=IA+1
      IF(RUN21.EQ.1) WRITE(8,5000) NCYCLE,TIME,VAVE,WDRIVE,WGEAR,
     &WCVT,WHE,THE,WMOTOR,
     &IAVE,I80DOD,IFLLBK,IOVRLD,ISWTCH,IITER,IHECHG,IICHG,IIREGN
      IF(IB.EQ.IB/57*57.AND.RUN21.EQ.1) WRITE(9,402)
      IB=IB+1
      IF(RUN21.EQ.1) WRITE(9,5010) NCYCLE,TIME,PAXLE,PDRIVE,PGEAR,
     &PCVT,RCVT,PHE,PCHG,
     &PELEC,PMOTOR,PINV,PBOUT,IBATT,PVBATT,SOC,PROAD,PREGEN,
     &BSFC1,FUELRT,EFM1
C$
C  SAVE VELOCITY
      V(NTIME)=VNEXT
C  HAS THE BRAKING PART OF THE STC BEEN REACHED
      IF(TIME.GE.TBRAKE) GOTO 195
C INITIALIZE VELOCTITY FOR NEXT TIME INCREMENT
      VELO=VNEXT
      GOTO 190
C-----------------------------------------------------------------------
C---------------------------------- BRAKING PHASE ----------------------
C-----------------------------------------------------------------------
C  CALC VEL DECREASE PER TIME INCREMENT DURING BREAKING
195   DELV=(VNEXT*DELT)/(TSTOP-TBRAKE)
C  CALC THE AVERAGE VELOCITY OVER THE NEXT TIME INCREMENT
  200 V1=V(NTIME)
      V2=V1-DELV
      VAVE=(V1+V2)/2.
C  CALC POWER LOST DUE TO ROAD LOSSES FOR THIS INCREMENT
      FD=CDA*RHO*VAVE*VAVE/2.
      FR=MT*GRAV*(10.+0.01*VAVE+0.00008*VAVE*VAVE)/1000.
      BETA=BET(NTIME)
      FGR=MT*GRAV*SIN(BETA)
      PROAD=(FGR+FR+FD)*VAVE
C  CALC THE POWER DUE TO VEHICLE ENERGY CHANGE
      PWRSTP=(MT*1.1/2.)*((V1*V1)-(V2*V2))/DELT
C  CALC POWER AVAILABLE FOR REGENERATION
      PREGEN=PWRSTP-PROAD
C  IS REGEN POWER ABOVE MIN
```

```
      IF(PREGEN-REGMIN) 230,230,231
C  SET REGENERATED POWERS TO ZERO
230   PAXLE=0.
      PDRIVE=0.
      PGEAR=0.
      PCVT=0.
      PMOTOR=0
      PINV=0.
      PILOSS=0.
      PBOUT=0.
      PHE=0.
      IBATT=0.
      PELEC=0.
      GOTO 235
C  IS BATTERY FULLY CHARGED
231   IF(SOC.GE.1.0) GOTO 230
C  CALC AXLE SPEED AND TORQUE
      WAXLE=VAVE/RTIRE
      TAXLE=PREGEN/WAXLE
      PAXLE=PREGEN
C  CALC DRIVE SHAFT TORQUE, SPEED, POWER
      WDRIVE=WAXLE/RDIFF
      PDPCT=(PREGEN/PDRATE)*100.
      WDPCT=(WAXLE/WDORTE)*100.
      PDRIVE=PREGEN*INTEQ(GREFF,PDPCT,WDPCT,100.,100.,
     &1.,-1.,10.,-10.,101,11)
      TDRIVE=PDRIVE/WDRIVE
C  CALC QUANTITIES AT DIFFT'L SIDE OF CVT
      WGEAR=WDRIVE/RGEAR
      PGPCT=(PDRIVE/PGRATE)*100.
      WGPCT=(WDRIVE/WGORTE)*100.
      PGEAR=PDRIVE*INTEQ(GREFF,PGPCT,WGPCT,100.,100.,
     &1.,-1.,10.,-10.,101,11)
      TGEAR=PGEAR/WGEAR
C  CALC CVT RATIO
      PHE=0.
      CALL RATIO
C  CALC QUANTITIES ON ENGINE SIDE OF CVT
      WCVT=WGEAR/RCVT
      PCVT=(PGEAR)*(INTNQ(EFF,(PGEAR/1000.),RCVT,100.,3.4,
     &APCVT,ARCVT,8,7))
      TCVT=PCVT/WCVT
C  LIMIT CVT POWER TO MAX
      IF(PCVT.GT.PCVTMX) PCVT=PCVTMX
      PELEC=PCVT
C  CALC POWER AT MOTOR SIDE OF MOTOR GEAR REDUCER
      WMOTOR=WCVT/RGRM
      PMGPCT=(PCVT/PMGRTE)*100.
      WMGPCT=(WCVT/WMGRTE)*100.
      PMOTOR=PCVT*INTEQ(GREFF,PMGPCT,WMGPCT,100.,100.,
```

```
     &1.,-1.,10.,-10.,101,11)
      TMOTOR=PMOTOR/WMOTOR
C  IF REGENERATION POWER IS GREATER THAN MAX MOTOR POWER SET POWER AT MAX
      IF(PMOTOR.GT.PMTMAX) PMOTOR=PMTMAX
C  CALC POWER FROM GENERATOR TO INVERTER
      PMTPCT=(PMOTOR/PMTRTD)*100.
      PINV=PMOTOR*
     &INTEQ(EFFMTR,PMTPCT,WMOTOR,200.,1466.,2.5,-2.5,146.61,439.82,81,7)
C  INITIALIZE ITERATION COUNTER
      IIREGN=0
C  IF INVERTER POWER IS TOO GREAT SET POWER AT MAX
      IF(PINV.GT.PINVMX) PINV=PINVMX
      EFM1=PINV/PMOTOR
C  CALC BATTERY INPUT POWER AND CURRENT
C--------------------------------------------------------------------------------
C-------------------------------- REGENERATIVE BATTERY VOLTAGE LOOP ---------------
C--------------------------------------------------------------------------------
 245  PBOUT=-PINV+3.0*(PINV/VBCHG)+0.035*PINV
      IBATT=PBOUT/VBCHG
      PVBATT=VBCHG
C  IS CHARGING POWER TOO LARGE
      IF(PBMAX*(MC/MCSTND)+PBOUT.GE.0.) GOTO 239
C  SET POWER AT MAX AND RECALCULATE BATT CURRENT
      PBOUT=-PBMAX*(MC/MCSTND)
      IBATT=PBOUT/VBCHG
C  IS CHARGING CURRENT TOO LARGE
 239  IF(IBMAX+IBATT.GE.0.) GOTO 241
C  SET CURRENT AT MAX AND RECALCULATE CHARGING POWER
      IBATT=-IBMAX
      PBOUT=IBATT*VBCHG
C  SAVE OLD VALUE OF BATT VOLTAGE
 241  VBTOLD=VBCHG
C  CALC BATT AMP-HRS OUT AND AVER BATT CURRENT SINCE START OF STC'S
      AREGEN=AREGEN-(IBATT*DELT/3600 )
      AACTL=AHOUT-AREGEN-AHCHG
      IAVE=(3600.*AHOUT)/(TIME+FLOAT(NCYCLE-1)*TSTOP)
C CALC STATE OF CHARGE AND BATTERY VOLTAGE DURING REGENERATION
      CAPCTY=MC*PUKRT(IAVE/MC)
      SOC=1.0-(AACTL/CAPCTY)
      IEFF=-IBATT*(MCSTND/MC)
      VBCHG=NC*INTEQ(VCHG,(AACTL/MC),IEFF,15.,300.,1.,0.,25.,0.,13,12)
      REGEFF=NC*INTEQ(DISCHG,SOC,0.,1.,IEFFMX,.01,-.01,100.,-100.,
     &101,6)
     &/VBCHG
C  DOES CALC BATTERY VOLTAGE EQUAL ASSUMED VOLTAGE
      IF(ABS(VBCHG-VBTOLD) .LE. VDELT) GOTO 243
C  HAVE WE ITERATED THE MAX NO OF TIMES
      IF(IIREGN.GE.ITERMX) GOTO 244
C  INCREMENT ITERATION COUNTER AND RESET A-H INTO BATT
      IIREGN=IIREGN+1
```

```
      AREGEN=AREGEN+(IBATT*DELT/3600.)
      GOTO 245
C  SET BATT VOLTAGE TO OLD VALUE
 244  VBCHG=VBTOLD
C  LIMIT SOC TO MAX
 243  IF(SOC.LE.1.0) GOTO 242
      SOC=1.0
C  CALC BATTERY CURRENT REQUIRED TO FULLY CHARGE BATTERY
      AREGEN=AREGEN+(IBATT*DELT/3600.)
      IFILL=3600./DELT*(AHOUT-AREGEN-AHCHG)
      IBATT=-IFILL
      AREGEN=AREGEN-(IBATT*DELT/3600.)
      AACTL=AHOUT-AREGEN-AHCHG
      IEFF=-IBATT*(MCSTND/MC)
      VBCHG=NC*INTEQ(VCHG,(AACTL/MC),IEFF,15.,300.,1.,0.,25.,0.,13,12)
      REGEFF=NC*INTEQ(DISCHG,SOC,0.,1.,IEFFMX,.01,-.01,100.,-100.,
     &101,6)
     &/VBCHG
      PBOUT=VBCHG*IBATT
      PVBATT=VBCHG
C  SET TOTAL ENERGY OUT OF BATTERY TO ZERO
      EBTOT=0.
      GO TO 235
 242  CONTINUE
C  CALC TOTAL BATT ENERGY USED ON THIS TRIP OR FROM START OF STC'S
      EBTOT=EBTOT+((PBOUT*DELT)/1.E+06)*REGEFF
C  INCREMENT TIME
  235 TIME=TIME+DELT
      NTIME=NTIME+1
C$
      IF(IA.EQ.IA/57*57.AND.RUN21.EQ.1) WRITE(8,401)
      IA=IA+1
      IF(RUN21.EQ.1) WRITE(8,5000) NCYCLE,TIME,VAVE,WDRIVE,WGEAR,
     &WCVT,WHE,THE,WMOTOR,
     &IAVE,IGODOD,IFLLBK,IOVRLD,ISWTCH,IITER,IHECHG,IICHG,IIREGN
      IF(IB.EQ.IB/57*57.AND.RUN21.EQ.1) WRITE(9,402)
      IB=IB+1
      IF(RUN21.EQ.1) WRITE(9,5010) NCYCLE,TIME,PAXLE,PDRIVE,PGEAR,
     &PCVT,RCVT,PHE,PCHG,
     &PELEC,PMOTOR,PINV,PBOUT,IBATT,PVBATT,SOC,PROAD,PREGEN,
     &BSFC1,FUELRT,EFM1
C$
C  HAVE WE REACHED THE STOP PHASE OF THE STC
      IF(TIME.GE.TSTOP) GOTO 236
      V(NTIME)=V2
      GO TO 200
C  CALC AVER CURRENT FOR ALL STC'S
  236 IAVE=(AHOUT*3600.)/(FLOAT(NCYCLE)*TSTOP)
C  AT END OF THIS STC, SAVE: BATT SOC, AVERAGE CURRENT,PETROLEUM VOLUME,
C  ELECTRICAL ENERGY, AMP-HRS OUT, AMP-HRS REGEN AND BATT. STATE-
```

```
C  ALL SINCE START OF STC'S
      IDOD(NCYCLE)=I80DOD
      IVESTC(NCYCLE)=IAVE
      HOUT(NCYCLE)=AHOUT
      REGEN(NCYCLE)=AREGEN
      EBTOTL(NCYCLE)=EBTOT
      PETSTC(NCYCLE)=VOLTOT
      SOCSTC(NCYCLE)=SOC
      CHARGE(NCYCLE)=AHCHG
C*
      I6=I6+1
      IF(I6/NCYLMX*NCYLMX.EQ.I6.AND.RUN21.LE.1) WRITE(6,404)
     &(I,EBTOTL(I),HOUT(I),IDOD(I),IVESTC(I),PETSTC(I),REGEN(I),
     &SOCSTC(I),CHARGE(I),I=1,NCYCLE)
404   FORMAT(' ',/1X,' I',5X,'EBTOTL(I)',4X,'HOUT(I)',4X,'IDOD(I)',
     &4X,'IVEST(I)',3X,'PETSTC(I)',3X,'REGEN(I)',2X,'SOCSTC(I)',3X,
     &'CHARGE(I)',/36(I2,3X,2X,F9.5,2X,F9.5,3X,I8,3X,F9.5,
     &4(2X,F9.5)/))
C*
C  IS THIS THE END OF THE STC WHICH PRECEEDS ALL HIGHWAY DRIVING?
      IF (NCYCLE-NSTCFR) 238,237,238
C  SAVE PRESENT VALUE OF BATTERY VOLTAGE
237   VHWBTT=VBATT
C  INITIALIZE POWER REGENERATION VARIABLES
238   PREGEN=0.
      PROAD=0.
      IIREGN=0
C  HAVE WE GONE THE MAX NO OF STC'S
      IF(NCYCLE-NCYLMX) 240,250,250
C  INCREMENT CYCLE COUNTER AND INITIALIZE TIME
240   NCYCLE=NCYCLE+1
      TIME=0.
      NTIME=1
      GOTO 10
C  INITIALIZE TRIP CONSUMPTION VARIABLES
250   PETROL=0.
      IHWY=0
      ENELEC=0.
      NTRIP=1
C  DETERMINE LENGTH OF CURRENT TRIP
260   LENGTH=TRIPLN(NTRIP)
C  IS TRIP ALL STC'S
      IF(LENGTH.GT.ALLSTC) GOTO 290
C  CALC NUMBER OF STC'S IN TRIP
      STCNO=LENGTH/STCDIS
      NOSTC=STCNO
      DELSTC=STCNO-FLOAT(NOSTC)
C  CALC AMP-HRS FOR THIS TRIP
      AACTL1=HOUT(NOSTC)-REGEN(NOSTC)-CHARGE(NOSTC)
      AACTL2=HOUT(NOSTC+1)-REGEN(NOSTC+1)-CHARGE(NOSTC+1)
```

```
      AACTL=AACTL1+(AACTL2-AACTL1)*DELSTC
C   CALC PETROL CONSUMPTION FOR THIS TRIP
      PETROL=PETSTC(NOSTC)+DELSTC*(PETSTC(NOSTC+1)-PETSTC(NOSTC))
      APETT(NTRIP)=PETROL
C   CALC ELEC ENERGY CONSUMPTION FOR THIS TRIP USING POWER AND USING AMP-HRS
      ENELEC=EBTOTL(NOSTC)+DELSTC*(EBTOTL(NOSTC+1)-EBTOTL(NOSTC))
      AELETP(NTRIP)=ENELEC
      ENRGY=NC*AACTL*3.6E-03*SVINT(AACV,AACTL/MC,ACR,8)
      AELETA(NTRIP)=ENRGY
C*
C*
C   DETERMINE NO OF SUCH TRIPS/YEAR
      TRIPYR=TRIPNO(NTRIP)
C   DETERMINE YEARLY PETROL AND ELECT CONSUMPTION FOR THIS TRIP
      PETYR(NTRIP)=TRIPYR*PETROL
      ELECYR(NTRIP)=TRIPYR*ENELEC
      ELEC(NTRIP)=TRIPYR*ENRGY
C   WAS THE BATT DISCHARGED SOMETIME DURING THIS TRIP
      IF(IOUD(NOSTC).NE.1) GOTO 265
      DISFAC=1
      GOTO 267
265   DISFAC=(1.-SOCSTC(NOSTC))/0.8
C   CALC NO OF DISCHARGES PER YEAR FOR THIS TRIP TYPE
267   DISCH(NTRIP)=DISFAC*TRIPYR
C   IS THIS THE LAST TRIP TYPE
 270  IF(NTRIP.GE.NTRIPX) GOTO 271
      NTRIP=NTRIP+1
      GO TO 260
C   DETERMINE WALL PLUG ENERGY REQ'D TO MEET ELECT. ENERGY CONSUMPTION
 271  DO 280 I=1,NTRIPX
      ELEC(I)=ELEC(I)/CHGEFF
      AELETA(I)=AELETA(I)/CHGEFF
      AELETP(I)=AELETP(I)/EFFBC
 280  ELECYR(I)=ELECYR(I)/EFFBC
      IF(RUN21.LE.1) WRITE(6,126)
126   FORMAT(1X,' I',7X,'DISCH(I)',3X,'PETYR(I)',3X,'ELECYR(I)',
     &5X,'ELEC(I)',5X,'TRIPNO(I)',3X,'TRIPLN(I)',10X,
     &3X,'PETROL',6X,'ENELEC',6X,'ENRGY')
      DO 6579 I=1,8
 6579 IF(RUN21.LE.1) WRITE(6,408) I,DISCH(I),PETYR(I),ELECYR(I),
     &ELEC(I),TRIPNO(I),TRIPLN(I),APETT(I),AELETP(I),AELETA(I)
  408 FORMAT(1X,I2,5X,F9.4,2X,F9.4,3X,F9.4,6X,F9.4,3X,F6.0,4X,F9.0,10X,
     &,1X,F10.4,2X,F10.4,2X,F10.4)
C++++++++++++++++++++++++++++++++++++++++++++++++
      SUMA=0.
      EAKWY=0.
      SUMP=0.
      PLTVY=0.
      PETV=0.
      DO 83341 I=1,8
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      EAKWHR(I)=ELEC(I)/3.6
      AEKHA(I)=AELETA(I)/3.6
      AEKHP(I)=AELETP(I)/3.6
      PETV=PETV+APETT(I)
      PETVY=PETVY+PETYR(I)
      SUMA=SUMA+AEKHA(I)
      SUMP=SUMP+AEKHP(I)
83341 EAKHY=EAKHY+EAKWHR(I)
      IF(RUN21.NE.4) GOTO 323
      IF(CX(1).NE.0.) GOTO 33244
      WRITE(7,3346)
      IF(RUN21.EQ.4) WRITE(8,3346)
      IF(RUN21.EQ.4) WRITE(9,3346)
      WRITE(10,3346)
 3346 FORMAT(2X,'PS',10X,'1',11X,'2',11X,'3',11X,'4',11X,'5',11X,
     &'6',11X,'7',11X,'8',10X,'SUM',/'****')
33244 CONTINUE
      WRITE(7,3432) CX(1),(AEKHA(I),I=1,8),SUMA
      WRITE(8,3432) CX(1),(APETT(I),I=1,8),PETV
      WRITE(9,3432) CX(1),(AEKHP(I),I=1,8),SUMP
      WRITE(10,3432) CX(1),(EAKWHR(I),I=1,8),EAKHY
 3432 FORMAT(1X,F4.2,1X,8(F11.5,1X,),F11.5)
 323  CONTINUE
C++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
      IF(RUN21.LE.1) WRITE(6,3431) IOVRLD,POVRLD,PETVY,EAKHY,INOCHG
 3431 FORMAT('IOVRLD=',I5,2X,'POVRLD=',G13.7,2X,'TOTAL PETROLEUM ',
     &'VOLUME PER YEAR (PETVY)=',F9.2,' LITERS/YEAR',5X,
     &'TOTAL ELECTRIC ENERGY CONSUMPTION PER YEAR (EAKHY)=',F9.2,
     &' KILOWATT HOURS/YEAR',5X,'INOCHG=',I1)
      PETV10=PETVY*10.
      RETURN
C  CALC TIME IT TAKES TO MAKE THIS TRIP
270   TRIPTM=FLOAT(NSTCFR)*TSTOP+((LENGTH-FLOAT(NSTCFR)*STCDIS)/HWYVEL)
C  IS THIS THE FIRST TRIP REQUIRING HIGHWAY DRIVING
      IF(IHWY.NE.0) GOTO 20
C  INITIALIZE BATT MODEL AND FUEL CONSUMPTIONS
C     VBATT=VHWBTT
      AHOUT=HOUT(NSTCFR)
      I00DUD=IDUD(NSTCFR)
      IAVE=IVESTC(NSTCFR)
      VOLTOT=PETSTC(NSTCFR)
      EBTOT=EBTOTL(NSTCFR)
      AREGEN=REGEN(NSTCFR)
      AHCHG=CHARGE(NSTCFR)
C  SET VELOCITY, ACCELERATION AND GRADE FOR HIGHWAY DRIVING
      VAVE=HWYVEL
      ACCEL=0.
      BETA=0.
C  INITIALIZE TIME TO START OF HIGHWAY DRIVING
      TIME=FLOAT(NSTCFR)*TSTOP
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C   INITIALIZE BATTERY MODEL QUANTITIES FOR START OF HIGHWAY DRIVING
      CAPCTY=MC*PUKRT(IAVE/MC)
      AACTL=AHOUT-AREGEN-AHCHG
      SOC=1.0-(AACTL/CAPCTY)
C   SET HIGHWAY FLAG TO HIGHWAY DRIVING CONDITION
      IHWY=1
C   SET HWY DRIVING TIME INCREMENT
      DELT=DELTHW
      GOTO 20
C   CALC YEARLY PETROL CONSUMPTION FOR THIS TRIP TYPE
300   TRIPYR=TRIPNO(NTRIP)
      PETYR(NTRIP)=TRIPYR*VOLTOT
      PETROL=VOLTOT
      APETT(NTRIP)=PETROL
C   CALC YEARLY ELEC ENERGY CONSUMPTION FOR THIS TRIP TYPE
      ELECYR(NTRIP)=TRIPYR*EBTOT
      ENELEC=EBTOT
      AELETP(NTRIP)=ENELEC
      ELEC(NTRIP)=TRIPYR*NC*AACTL*3.6E-03*SVINT(AACV,AACTL/MC,ACR,8)
      ENRGY=ELEC(NTRIP)/TRIPYR
      AELETA(NTRIP)=ENRGY
C   SET DISCHG FACTOR TO FULL DISCHG IF BATT WAS DISCHARGED DURING THIS TRIP
      IF(I80DOD.NE.1) GOTO 310
      DISFAC=1.
      GOTO 320
C   CALC DISCHG FACTOR
310   DISFAC=(1.-SOC)/0.8
C   CALC NO OF YEARLY DISCHARGES FOR THIS TRIP TYPE
320   DISCH(NTRIP)=DISFAC*TRIPYR
      GOTO 270
      END
      END
```

```
      SUBROUTINE RATIO
C***********************************************************************
C
C  THIS DETERMINES RATIO OF THE CONTINUOUSLY VARIABLE TRANSMISSION BASED ON
C  THE LAST VALUE OF THE GEAR POWER.  AT VEHICLE START UP TIME THE VALUE
C  IS SET TO A MINIMUM OF .3.  THE RATIO VALUE IS LIMITED TO PREVENT
C  EXCESSIVE MOTOR SPEED.  THE MAXIMUM VALUE IS 3.4.
C
C***********************************************************************
      REAL MTRSPD(5),APRP(5),AWMT(6),STALL(6)
      COMMON/CC/CDA,RDIFF,RGEAR,RGRM,RTIRE
      COMMON/RRATO/NTIME,WGEAR,RCVT,PMOTOR,PMTRTD,PGEAR
      COMMON/RSPLT/ACCEL,SOC,PCVT,CX(15),VAVE,PHEMAX, PHE,PELEC
      DATA  RCVTMX/3.4/,RCVTMN/0.3/,WMTRMX/1675.5/, DELR/0.1/
      DATA BSFC/4.2/, WHEMN/104.72/
      DATA MTRSPD/586.431,879.646,1172.86,1319.47,1466.08/
      DATA AWMT/0.,586.431,879.646,1172.86,1319.47,1466.08/
      DATA STALL/0.,50.,75.84,109.57,129.79,200./
      DATA APRP/19.4,36.7,64.3,75.5,101./
C  IS VEHICLE JUST STARTING UP
      IF(NTIME.NE.1) GO TO 10
C  SET RATIO AT MINIMUM
      RCVT=RCVTMN
      RETURN
C  WAS HE POWER USED IN THE LAST ITERATION
 10   IF(PHE.GT.0.) GO TO 20
C  PICK RATIO TO MAXIMIZE MOTOR EFF
      PMT=PGEAR/(0.93*0.98)
C  COMPUTE MOTOR POWER IN PERCENT OF RATED POWER
      PMTPCT=(PMT/PMTRTD)*100.
      RCVT=WGEAR/(SVINT(MTRSPD,PMTPCT,APRP,5)*RGRM)
C     LIMIT RATIO SO MOTOR SPEED IS NOT EXCESSIVE
      WMT=WGEAR/(RCVT*RGRM)
      IF(WMT.LE.WMTRMX) GO TO 40
      WMT=WMTRMX
      RCVT=WGEAR/(WMT*RGRM)
      GO TO 40
C  ESTIMATE A HE OUTPUT POWER FOR THIS ITERATION
 20   PHEST=(PHE/(PHE+PELEC))*(PGEAR/0.93)
C  CALC MOST EFFICIENT HE SPEED
      WHEFF=BSFC*(PHEST/PHEMAX)*100.
      IF(WHEFF.LT.WHEMN) WHEFF=WHEMN
C  CAL RATIO
      RCVT=WGEAR/WHEFF
C  CAL MOTOR SPEED
      WMT=WGEAR/(RCVT*RGRM)
C  CALC REQUIRED MOTOR POWER AT THIS SPEED
      PMT=(PGEAR/0.93)-PHEST
      PMTPCT=(PMT/PMTRTD)*100.
C  CAN MOTOR DELIVER THIS POWER AT THIS SPEED
```

```
 30    IF(PMTPCT.LT.SVINT(STALL,WMT,AWMT,6)) GO TO 40
C  DECREASE RATIO TO INCREASE MOTOR SPEED
       RCVT=RCVT-DELR
       WMT=WGEAR/(RCVT*RGRM)
       IF(RCVT.GT.RCVTMN) GO TO 30
C  IS RATIO ABOVE UPPER LIMIT
 40    IF(RCVT.GT.RCVTMX) RCVT=RCVTMX
       IF(RCVT.LT.RCVTMN) RCVT=RCVTMN
       RETURN
       END
       END
```

```
FTN4,L
      SUBROUTINE SPLIT
C*****************************************************************************
C
C  THIS DETERMINES THE POWER SPLIT BETWEEN THE HEAT ENGINE AND THE
C  ELECTRIC MOTOR.  IT IS A FUNCTION OF THE ACCELERATION AND THE STATE
C  OF CHARGE OF THE BATTERY.
C
C*****************************************************************************
      COMMON/RSPLT/ACCEL,SOC,PCVT,CX(15),VAVE,PHEMAX, PHE,PELEC
C  PS =0 WHEN ONLY HEAT ENGINE USED
C  PS =1 WHEN ONLY BATTERIES USED
      DATA VMINHE/1.34/
C  IS VEHICLE VELOCITY BELOW MIN
      IF(VAVE-VMINHE) 10,10,20
 10   PS=1.0
      GOTO 30
 20   PS=CX(1)+CX(2)*ACCEL+CX(3)*SOC
      IF(PS.GT.1.) PS=1.
      IF(PS.LT.0.) PS=0.
 30   PELEC=PCVT*PS
      PHE=PCVT*(1.0-PS)
      RETURN
      END
      END
```

```
FTN4,L
      SUBROUTINE SPLIT
C*****************************************************************************
C
C  THIS DETERMINES THE POWER SPLIT BETWEEN THE HEAT ENGINE AND THE
C  ELECTRIC MOTOR.  IT IS A FUNCTION OF THE ACCELERATION AND THE STATE
C  OF CHARGE OF THE BATTERY. (AIRESEARCH POWER SPLIT)
C
C*****************************************************************************
      COMMON/RSPLT/ACCEL,SOC,PCVT,CX(15),VAVE,PHEMAX, PHE,PELEC
C  PS =0 WHEN ONLY HEAT ENGINE USED
C  PS =1 WHEN ONLY BATTERIES USED
      DATA VMINHE/1.34/
C  IS VEHICLE VELOCITY BELOW MIN
      IF(VAVE-VMINHE) 10,10,20
 10   PS=1.0
      GOTO 80
 20   IF(ACCEL.NE.0.) GOTO 40
      IF(SOC.LE..2) GOTO 70
C  IS THIS A HILL CLIMB
      IF(PCVT.GE.20000.) GOTO 30
      PS=1.
      GOTO 80
 30   PS=.3
      GOTO 80
C  IS REQUIRED POWER TOO LARGE
 40   IF(PCVT.GE. .8*PHEMAX) GOTO 50
      PS=.3
      GOTO 80
 50   PHE=PCVT
      IF(PHE.LE.PHEMAX) GOTO 60
      PHE=PHEMAX
      PELEC=PCVT-PHEMAX
      PS=PELEC/PCVT
      RETURN
 60   PHE=PCVT
      PELEC=0.
      PS=0.
      RETURN
 70   PS=0.
 80   PELEC=PCVT*PS
      PHE=PCVT*(1.0-PS)
      RETURN
      END
      END
```

```
      REAL FUNCTION PUKRT(IAVE)
C***************************************************************************
C
C  CALCULATES CAPACITY PER KILOGRAM OF BATTERY BASED ON THE AVERAGE
C  CURRENT PER KILOGRAM OUT OF THE BATTERY.  IT IS LIMITED TO A
C  MINIMUM OF 0.5.
C
C***************************************************************************
      REAL IAVE
      IF(IAVE.LT.10.173) GOTO 10
      PUKRT=22.30811 - 3.796940*ALOG(IAVE)
      IF(PUKRT.LT. .5) PUKRT=.5
      RETURN
10    PUKRT=16.98881-.3806714*IAVE
      RETURN
      END
```

```
      FUNCTION SVINT(ARRAY,X,XARRAY,IDIM)
C***************************************************************************
C
C  SINGLE VARIABLE INTERPOLATION SUBROUTINE.  SPACING BETWEEN DATA
C  POINTS OF THE INDEPENDENT VARIABLE NEED NOT BE EQUAL.
C
C***************************************************************************
      DIMENSION ARRAY(IDIM),XARRAY(IDIM)
      IDM1=IDIM-1
      DO 5 IMAX=2,IDM1
      IF(X.LE.XARRAY(IMAX)) GO TO 7
 5    CONTINUE
7     IMIN=IMAX-1
      SVINT=((X-XARRAY(IMIN))*ARRAY(IMAX)+
     &(XARRAY(IMAX)-X)*ARRAY(IMIN))/(XARRAY(IMAX)-XARRAY(IMIN))
      RETURN
      IND
      END
```

```
      REAL FUNCTION INTNQ(ARRAY,XX,YY,XTOP,YTOP,XARRAY,YARRAY,IDIM,JDIM)
C*************************************************************************
C
C  DOUBLE VARIABLE INTERPOLATION SUBROUTINE.  BOTH VARIABLES NEED NOT
C  HAVE EQUAL SPACING BETWEEN DATA POINTS.
C
C*************************************************************************
C  THIS LINEAR INTERPOLATION MUST TAKE INTO ACCOUT VALUES OF X AND Y LYING
C  ABOVE AND BELOW THE MAXIMUM AND MINIMUM VALUES IN THE ARRAY
      DIMENSION XARRAY(IDIM),YARRAY(JDIM),ARRAY(IDIM,JDIM)
      X=XX
      Y=YY
      IF(X.GT.XTOP) X=XTOP
      IF(Y.GT.YTOP) Y=YTOP
C  FIND INDICES ON X ARRAY
      IDM1=IDIM-1
      DO 5 IMAX=2,IDM1
      IF(X.LE.XARRAY(IMAX)) GO TO 7
 5    CONTINUE
 7    IMIN=IMAX-1
C     FIND THE INDICES OF THE VALUES IN THE YARRAY WHICH BRACKET THE
C     ACTUAL Y VALUE
      JDM1=JDIM-1
      DO 15 JMAX=2,JDM1
      IF(Y.LE.YARRAY(JMAX)) GO TO 17
 15   CONTINUE
 17   JMIN=JMAX-1
C     INTERPOLATE TO FIND THE ARRAY VALUES CORRESPONDING TO THE
C     BRACKETING X VALUES AND THE ACTUAL Y VALUES
      ALOWY=((X-XARRAY(IMIN))*ARRAY(IMAX,JMIN)+
     &(XARRAY(IMAX)-X)*ARRAY(IMIN,JMIN))/(XARRAY(IMAX)-XARRAY(IMIN))
      AHIGHY=((X-XARRAY(IMIN))*ARRAY(IMAX,JMAX)+
     &(XARRAY(IMAX)-X)*ARRAY(IMIN,JMAX))/(XARRAY(IMAX)-XARRAY(IMIN))
C     INTERPOLATE BETWEEN THE ABOVE ARRAY VALUES TO FIND THE ARRAY VALUE
C     CORRESPONDING TO THE ACTUAL Y VALUE
      INTNQ=((Y-YARRAY(JMIN))*AHIGHY+(YARRAY(JMAX)-Y)*ALOWY)/
     &(YARRAY(JMAX)-YARRAY(JMIN))
      RETURN
      END
      END
```

```
      REAL FUNCTION INTEQ(ARRAY,XX,YY,XTOP,YTOP,
     &XCON1,XCON2,YCON1,YCON2,IDIM,JDIM)
C*************************************************************************
C
C  DOUBLE VARIABLE INTERPOLATION SUBROUTINE.  BOTH VARIABLES MUST HAVE
C  EQUAL SPACING BETWEEN THE DATA POINTS.
C
C*************************************************************************
      DIMENSION ARRAY(IDIM,JDIM)
C
      X=XX
      Y=YY
      IF(X.GT.XTOP) X=XTOP
      IF(Y.GT.YTOP) Y=YTOP
C X=FLOAT(I)*XCON1+XCON2
C Y=FLOAT(I)*YCON1+YCON2
C
C     FIND THE INDICE OF THE X VALUE WHICH BRACKETS THE ACTUAL X VALUE
      IMIN=(X-XCON2)/XCON1
      IF(IMIN.LT.1) IMIN=1
      IF(IMIN.GE.IDIM) IMIN=IDIM-1
      IMAX=IMIN+1
      XMIN=FLOAT(IMIN)*XCON1+XCON2
      XMAX=XMIN+XCON1
C     FIND THE INDICE OF THE Y VALUE WHICH BRACKETS THE ACTUAL Y VALUE
      JMIN=(Y-YCON2)/YCON1
      IF(JMIN.LT.1) JMIN=1
      IF(JMIN.GE.JDIM) JMIN=JDIM-1
      JMAX=JMIN+1
      YMIN=FLOAT(JMIN)*YCON1+YCON2
      YMAX=YMIN+YCON1
C     INTERPOLATE TO FIND THE ARRAY VALUE CORRESPONDING TO THE BRACKETING
C     X VALUES AND THE ACTUAL X VALUES
      ALOWY=((X-XMIN)*ARRAY(IMAX,JMIN)+
     &(XMAX-X)*ARRAY(IMIN,JMIN))/(XMAX-XMIN)
      AHIGHY=((X-XMIN)*ARRAY(IMAX,JMAX)+
     1(XMAX-X)*ARRAY(IMIN,JMAX))/(XMAX-XMIN)
C     INTERPOLATE TO FIND THE ARRAY VALUE CORRESPONDING TO THE ACTUAL
C     Y VALUE
      INTEQ=((Y-YMIN)*AHIGHY+(YMAX-Y)*ALOWY)/(YMAX-YMIN)
      RETURN
      END
      END
```

```
      SUBROUTINE WGHT(HEKW,WGBATT, WT,MT,WGCHI,WP)
C***************************************************************************
C
C  THIS CALCULATES THE TOTAL MASS AND CURB MASS OF THE VEHICLE.
C
C***************************************************************************
      REAL MT,MTRC1,MTRKW,MTGRKW
      INTEGER RUN21
      COMMON RUN21
      COMMON/KILOG/WGENG,WGCVT,WGCHGR,WGGRM,WGGRDF
     &,WGDIFF,WF,WPL,WPROP,WS,WGMOTR,WGCLT,WCURB
      COMMON/VARY/ WTL,INOCHG
      DATA CVTC1/1.07/, CVTKW/90.0/, HEC1/0.0/, HEC2/2.84/
      DATA MTRC1/0.6/, MTRKW/20.0/, CHIC1/0.71/, CHIKW/40.0/
      DATA WGEXTR/0.0/
      DATA DIFFC1/0.66/, DIFFKW/90.0/, GRC1/0.3/, MTGRKW/40.0/
      DATA DFGRKW/90.0/, CHGRC1/0.0/, CHGRKW/14.5/
C  COMPUTE CONSTANT TERM IN VEHICLE WEIGHT FORMULA
C  (FROM MTI,APPENDIXB)
      WCONST=((0.23*WPL+WF)/0.77)+WTL
C  CALC. PROPULSION SYST. COMPONENT WEIGHTS
C  CVT
      WGCVT=CVTC1*CVTKW
C  HE
      WGENG=(HEC1*HEKW+HEC2)*HEKW
C  MOTOR
      WGMOTR=MTRC1*MTRKW
C  CHOPPER/INV.
      WGCHI=CHIC1*CHIKW
C  DIFF'L
      WGDIFF=DIFFC1*DIFFKW
C  GEAR BETWEEN MOTOR AND CVT
      WGGRM=GRC1*MTGRKW
C  GEAR BETWEEN DIFF & CVT
      WGGRDF=GRC1*DFGRKW
C  CHARGER
      WGCHGR=CHGRC1*CHGRKW
C  CALCULATE PROPULSION SYSTEM WEIGHT
      WPROP=WGENG+WGCVT+WGMOTR+WGCHI+WGDIFF+WGGRM+WGGRDF+WGCHGR
     &+WGEXTR+WGBATT+WGCLT
C  CALCULATE VEHICLE TOTAL WEIGHT
      WT=WCONST + WPROP/0.77
C  CALCULATE VEHICLE TOTAL MASS
      MT=WT
C  CALCULATE CURB MASS OF VEHICLE
      WCURB=WT-WTL
C  CALC. POWER TRAIN WEIGHT
      WP=(WPROP-WGBATT)
      A=WGCVT+WGGGRM+WGGRDF+WGDIFF
      IF(RUN21.LE.1) WRITE(6,2001) WCURB,WF,WGBATT,WGCHGR,WGCHI,WGCLT,
```

```
     & WGCVT,WGDIFF,WGENG,WGEXTR,WGGRDF,WGGRM,WGMOTR,WP,WPL,WPROP,
     &WT,WTL,A
2001 FORMAT(//'************ VEHICLE MASSES ***********',/
     &'                    CURB MASS OF VEHICLE (WCURB)=',F9.3,/
     &'                         FIXED VEHICLE MASS (WF)=',F9.3,/
     &'                      BATTERY WEIGHT (WGBATT)=',F9.3,/
     &'                          CHARGER MASS (WGCHGR)=',F9.3,/
     &'                   CHOPPER INVERTER MASS (WGCHI)=',F9.3,/
     &'                             CLUTCH MASS (WGCLT)=',F9.3,/
     &'                                 CVT MASS (WGCVT)=',F9.3,/
     &'                     DIFFERENTIAL MASS (WGDIFF)=',F9.3,/
     &'                             ENGINE MASS (WGENG)=',F9.3,/
     &'EXTRA VEHICLE PROPULSION COMPONENT MASS (WGEXTR)=',F9.3,/
     &'MASS OF GEAR BETWEEN CVT & DIFFERENTIAL (WGGRDF)=',F9.3,/
     &'         MASS OF GEAR BETWEEN MOTOR & CVT (WGGRM)=',F9.3,/
     &'                   ELECTRIC MOTOR MASS (WGMOTR)=',F9.3,/
     &'                             POWER TRAIN MASS (WP)=',F9.3,/
     &'                       MAXIMUM PAYLOAD MASS (WPL)=',F9.3,/
     &'                   PROPULSION SYSTEM MASS (WPROP)=',F9.3,/
     &'                                  TOTAL MASS (WT)=',F9.3,/
     &'                           TEST PAYLOAD MASS (WTL)=',F9.3,/
     &'WGCVT+WGGGRM+WGGRDF+WGDIFF=',/
     &'                TRANSMISSION & DRIVE TRAIN WEIGHT=',F9.3)
      RETURN
      END
      END
```

```
      SUBROUTINE MFCST(WGBATT,WGCHI, MNFCST)
C*****************************************************************************
C
C  THIS DETERMINES THE MANUFACTURING COST OF THE VEHICLE AS A FUNCTION
C  OF THE VARIOUS MASSES.
C
C*****************************************************************************
      REAL MNFCST,MTRCER,MTRCST
      INTEGER RUN21
      COMMON RUN21
      COMMON/KILOG/WGENG,WGCVT,WGCHGR,WGGRM,WGGRDF
     &,WGDIFF,WF,WPL,WPROP,WS,WGMOTR,WGCLT,WCURB
      DATA HECER/1.43/, CVTCER/1.42/, CHGCER/5.89/
      DATA CHICER/14.0/, GRCER/2.43/, DIFCER/2.42/, WFCER/3.13/
      DATA WSCER/3./, MTRCER/15.95/, CLTCER/0.0/
      DATA ASMCER/0.1784/
C  CALCULATES MANUFACTURING COSTS FOR PROPULSION SYSTEM COMPONENTS
C
      HECOST=HECER*WGENG
      CVTCST=CVTCER*WGCVT
      CHGCST=CHGCER*WGCHGR
      CHICST=CHICER*WGCHI
      GRMCST=GRCER*WGGRM
      GRDCST=GRCER*WGGRDF
      DIFCST=DIFCER*WGDIFF
      WFCOST=WFCER*WF
      WS=0.3*(WPL+WPROP+WF)
      WSCOST=WSCER*WS
      MTRCST=MTRCER*WGMOTR
      CLTCST=CLTCER*WGCLT
      ASMCST=ASMCER*WCURB
C  CALCULATE TOTAL MANUFACTURING COST
      A=CVTCST+GRMCST+GRDCST+DIFCST+CLTCST
      MNFCST=HECOST+CVTCST+CHGCST+CHICST+GRMCST+GRDCST
     &+DIFCST+WFCOST+WSCOST+MTRCST+CLTCST+ASMCST
      IF(RUN21.LE.1) WRITE(6,1900) WS
1900  FORMAT(
     &'                    STRUCTURE & CHASSIS MASS (WS)=',F9.3)
      IF(RUN21.LE.1) WRITE(6,2000) ASMCST,CHGCST,CHICST,CLTCST,CVTCST,
     &DIFCST,GRDCST,GRMCST,HECOST,MNFCST,MTRCST,WFCOST,WSCOST,A
 2000 FORMAT(/"************ MANUFACTURING COSTS FOLLOW *************",/
     &'                    ASEMBLY COST (ASMCST)=',F9.3,/
     &'                    CHARGER COST (CHGCST)=',F9.3,/
     &'           CHOPPER INVERTER COST (CHICST)=',F9.3,/
     &'                     CLUTCH COST (CLTCST)=',F9.3,/
     &'                        CVT COST (CVTCST)=',F9.3,/
     &'               DIFFERENTIAL COST (DIFCST)=',F9.3,/
     &'   GEAR BETWEEN DIFF & CVT COST (GRDCST)=',F9.3,/
     &'  GEAR BETWEEN MOTOR & CVT COST (GRMCST)=',F9.3,/
     &'                HEAT ENGINE COST (HECOST)=',F9.3,/
```

```
&'        TOTAL MANUFACTURING COST (MNFCST)=',F9.3,/
&'             ELECTRIC MOTOR COST (MTRCST)=',F9.3,/
&'   COST OF VEHICLE FIXED WEIGHT (WFCOST)=',F9.3,/
&'    COST OF STRUCTURE & CHASSIS (WSCOST)=',F9.3,/
&'       CVTCST+GRMCST+GRDCST+DIFCST+CLTCST=',F9.3)
 RETURN
  END
 END
```

```
      SUBROUTINE MAINT(HEKW,MTKWPK,BATCST,KMPRYR,WP,WGCHI,BTLIST,MAINTC)
C*****************************************************************************
C
C  THIS CALCULATES THE YEARLY MAINTENANCE COST OF THE VEHICLE AS A FUNCTION
C  OF HEAT ENGINE, BATTERY, AND VEHICLE MAINTENANCE, AND ANNUAL DRIVING
C  DISTANCE.
C
C*****************************************************************************
      REAL KWCST,MTKWPK,KMPRYR,MAINTC,MTMAIN
      INTEGER RUN21
      COMMON RUN21
      COMMON/BATT/BTMKUP
      COMMON/COST/GASCST(10),KWCST(10)
C  CALCULATE COMPONENT MAINTENANCE COSTS ($/KM)
      HEMAIN=(0.10+0.005*(HEKW/0.746))/160.93
      MTMAIN=(0.06+0.002*(MTKWPK/0.746))/160.93
      BTLIST=BATCST*(1.+BTMKUP)
      BTMAIN=(0.0004*BTLIST)/160.93
      CVTMAN=0.063/160.93
C  (AR-H P. 78)     1/2 MAINTANENCE   1/2 REPAIR
      CHIMAN=((36.83/2)*SQRT(WGCHI))/(10.*KMPRYR)
C  CALCULATE MAINTENANCE COST FOR ONE YEAR
      MAINTC=(HEMAIN+MTMAIN+BTMAIN+CVTMAN+CHIMAN)*KMPRYR
      IF(RUN21.LE.1) WRITE(6,2020) BTLIST
 2020 FORMAT('          LIST COST OF BATTERIES (BTLIST)=',F9.3)
      IF(RUN21.LE.1) WRITE(6,2030) BTMAIN,CVTMAN,CHIMAN,HEMAIN,
     &MAINTC,MTMAIN
 2030 FORMAT(//'************* MAINTENANCE COSTS FOLLOW **************',/
     &'         BATTERY MAINTENANCE COST PER KILOMETER (BTMAIN)=',F9.8,/
     &'             CVT MAINTENANCE COST PER KILOMETER (CVTMAN)=',F9.8,/
     &'CHOPPER INVERTER MAINTENANCE COST PER KILOMETER (CHIMAN)=',F9.8,/
     &'     HEAT ENGINE MAINTENANCE COST PER KILOMETER (HEMAIN)=',F9.8,/
     &'                          TOTAL MAINTENANCE COST (MAINTC)=',F9.8,/
     &'  ELECTRIC MOTOR MAINTENANCE COST PER KILOMETER (MTMAIN)=',F9.8)
      RETURN
      END
      END
```

```
      SUBROUTINE REPAR(HEKW,MTKWPK,WP,WGCHI,KMPRYR, REPAIR)
C*****************************************************************************
C
C  THIS CALCULATES THE YEARLY VEHICLE REPAIR COST AS A FUNCTION OF THE
C  ANTICIPATED REPAIR COSTS FOR THE HEAT ENGINE, MOTOR, CVT, POWER TRAIN,
C  AND CHOPPER INVERTER.
C
C*****************************************************************************
      REAL KMPRYR,MTKWPK
      INTEGER RUN21
      COMMON RUN21
      REPRHE=(0.28+0.008*(HEKW/0.746))/160.93
      REPMTR=(0.09+0.002*(MTKWPK/0.746))/160.93
      REPCVT=(0.05+0.0013*(MTKWPK/0.746))/160.93
      REPCHI=((36.83/2.)*SQRT(WGCHI))/(10.*KMPRYR)
C  CALCULATE YEARLY REPAIR COST
      REPAIR=(REPRHE+REPMTR+REPCVT+REPCHI)*KMPRYR
      IF(RUN21.LE.1) WRITE(6,2020) REPAIR,REPCHI,REPCVT,REPMTR,REPRHE
 2020 FORMAT(//'***************** REPAIR COSTS FOLLOW **************',/
     &'                         TOTAL REPAIR COST (REPAIR)=',F9.3,/
     &'CHOPPER INVERTER REPAIR COST PER KILOMETER (REPCHI)=',F9.8,/
     &'               CVT REPAIR COST PER KILOMETER (REPCVT)=',F9.8,/
     &'  ELECTRIC MOTOR REPAIR COST PER KILOMETER (REPMTR)=',F9.8,/
     &'                HE REPAIR COST PER KILOMETER (REPRHE)=',F9.8)
      RETURN
      END
      END
```

```
      SUBROUTINE AQCST(MNFCST,WGBATT, BATCST,ACQCST)
C***************************************************************************
C
C  THIS DETERMINES THE ACQUISITION COST OF THE VEHICLE AS A FUNCTION OF THE
C  MANUFACTURING COST, BATTERY MANUFACTURING COST, AND THE MARKUP FACTOR.
C
C***************************************************************************
      REAL MARKUP,MNFCST
      INTEGER RUN21
      COMMON RUN21
      COMMON/BATT/BTMKUP
      DATA BATCER/1.87/
C  CALCULATE THE MARKUP FACTOR
      MARKUP=(29.176E-5)*MNFCST+1.40833
C  CALCULATE BATTERY COST
      BATCST=BATCER*WGBATT
C  CALCULATE ACQUISITION COST (COST TO CONSUMER)
      ACQCST=MARKUP*MNFCST+BATCST*(1.+BTMKUP)
      IF(RUN21.LE.1) WRITE(6,101) BATCST,MARKUP
101   FORMAT(
     &'MANUFACTURING COST OF BATTERIES (BATCST)=',F9.3,/
     &40X,'@@ @@ @@ DEALER MARKUP FACTOR (MARKUP)=',G11.5)
      RETURN
      END
      END
```

```
FTN4,L
      SUBROUTINE LIFE(PETYR,ELECYR,ELEC,DISCH,BTLIST,ACQCST,MAINTC,
     &REPAIR,BATCST,LCCOST,PETCST,ELECST,TOTPET)
C*****************************************************************************
C
C  THIS CALCULATES THE LIFE CYCLE COST OF THE VEHICLE BASED ON TEN YEARS
C  USAGE.  IT IS A FUNCTION OF THE ACQUISITION, MAINTENANCE, REPAIR,
C  BATTERY, FUEL, AND ELECTRICITY COSTS OVER THAT PERIOD.
C
C*****************************************************************************
      LOGICAL SMOOTH
      REAL KWCST,MAINTC,LCCOST
      INTEGER RUN21
      COMMON RUN21
      COMMON GF
      COMMON/BATT/BTMKUP
      COMMON/COST/GASCST(10),KWCST(10)
      COMMON/LIMIT/NTRIPX,ITERMX
      COMMON/OMISC/CHOOSE,SMOOTH
      COMMON BTCOST,BATRYR,BATLFE
      DIMENSION PETYR(15),ELECYR(15),ELEC(15),DISCH(15),
     &PETCST(10),ELECST(10)
      DIMENSION VHCOST(10)
      DATA DISCNT/0.02/,DISLFE/840./
C  CALC PETROL AND ELEC COSTS: INITIALIZE YEAR INDEX AND TOTAL COSTS
      DO 5 IYEAR=1,10
      PETCST(IYEAR)=0.
5     ELECST(IYEAR)=0.
      DO 10 IYEAR=1,10
      DO 10 JTRIP=1,NTRIPX
C  ADD COSTS FOR THIS TRIP TO TOTAL COSTS
      PETCST(IYEAR)=PETCST(IYEAR)+PETYR(JTRIP)*GASCST(IYEAR)*GF
10    ELECST(IYEAR)=ELECST(IYEAR)+(CHOOSE*ELECYR(JTRIP)+
     &(1.-CHOOSE)*ELEC(JTRIP) )*KWCST(IYEAR)
C  CALC NO. OF DEEP DISCHARGES OF BATT. DURING ONE YEAR
      DEEP=0.
      DO 20 JTRIP=1,NTRIPX
20    DEEP=DEEP+DISCH(JTRIP)
C  CALC NO. OF YEARS IN BATT LIFE
      BATLFE=DISLFE/DEEP
C  CALC BATT REPLACEMENT COST
      BTCOST=BATCST*(1.+2.*BTMKUP)
C  CALC TOTAL VEHICLE COST FOR ONE YEAR
      COUNT=1.
      TOTBAT=0.
      BATRYR=(((10./BATLFE)-1.)*BTCOST)/10.
      DO 40 IYEAR=1,10
      VHCOST(IYEAR)=PETCST(IYEAR)+MAINTC+ELECST(IYEAR)+REPAIR
      IF(.NOT.SMOOTH) GOTO 35
      VHCOST(IYEAR)=VHCOST(IYEAR)+BATRYR
```

```
      TOTBAT=TOTBAT+BATRYR/(DISCNT+1.)**(IYEAR-1)
      GO TO 40
C  IS THIS A YEAR FOR BATT REPLACEMENT
 35   IF(FLOAT(IYEAR).LE.COUNT*BATLFE) GOTO 40
C  ADD IN BATT REPLACEMENT COST
      VHCOST(IYEAR)=VHCOST(IYEAR)+0.9*BTCOST
      TOTBAT=TOTBAT+BTCOST/((DISCNT+1.)**(IYEAR-1))
      COUNT=COUNT+1.
40    CONTINUE
C  CALC VEHICLE AND POWER TRAIN AND BATT SALVAGE VALUE
      SALVGE=0.1*(ACQCST-BTLIST)
      BATSAL=0.5*BTLIST*(COUNT-(10./BATLFE))
      IF(SMOOTH) BATSAL=0.
C  CALC LIFE CYCLE COST
      LCCOST=0.
      TOTPET=0.
      DO 50 IYEAR=1,10
      TOTPET=TOTPET+PETCST(IYEAR)/((DISCNT+1.)**(IYEAR-1))
50    LCCOST=LCCOST+VHCOST(IYEAR)/((DISCNT+1.)**(IYEAR-1))
C  SUBTRACT SALVAGE VALUES
      LCCOST=LCCOST-(SALVGE+BATSAL)/((DISCNT+1.)**10)
C  ADD IN AQUISITION COST
      LCCOST=LCCOST+ACQCST
      IF(RUN21.LE.1) WRITE(6,131) BATLFE,BATSAL,LCCOST,BTCOST,SALVGE
 131  FORMAT(
     &'                BATTERY LIFE (BATLFE) =',F9.3,/
     &'        BATTERY SALVAGE VALUE (BATSAL) =',F9.3,/
     &'             LIFE CYCLE COST (LCCOST) =',F9.3,/
     &'    BATTERY REPLACEMENT COST (BTCOST) =',F9.3,/
     &'               SALVAGE VALUE (SALVGE) =',F9.3)
      IF(RUN21.LE.1)
     &WRITE(6,404) (I,PETCST(I),ELECST(I),VHCOST(I),I=1,10)
404   FORMAT(' ',/1X,'YEAR',5X,'PETROLEUM COST',3X,
     &'ELECTRICITY COST',3X,'VEHICLE COST',/
     &'  I',10X,'PETCST(I)',8X,'ELECST(I)',8X,'VHCOST(I)',
     &/10(1X,I2,2X,3(8X,F9.5)/))
      RETURN
      END
      END
```

```
      BLOCK DATA
C**************************************************************
C
C     BLOCK DATA
C
C**************************************************************
      LOGICAL SMOOTH
      REAL KWCST,MTKWPK,IVESTC
      COMMON/ALPHA/ALPHA1,ALPHA2,ALPHA3
      COMMON/BATT/BTMKUP
      COMMON/CC/CDA,RDIFF,RGEAR,RGRM,RTIRE
      COMMON/COST/GASCST(10),KWCST(10)
      COMMON/EFCVT/APCVT(8),ARCVT(7),EFF(8,7)
      COMMON/KILOG/WGENG,WGCVT,WGCHGR,WGGRM,WGGRDF
     &,WGDIFF,WF,WPL,WPROP,WS,WGMOTR,WGCLT,WCURB
      COMMON/LIMIT/NTRIPX,ITERMX
      COMMON/MAP/DISCHG(101,6),EFFMTR(81,7),HEMAP(6,6),
     &GREFF(101,11),VCHG(13,12),ATORQ(6),AESPED(6),ARATIO(10)
      COMMON/OMISC/CHOOSE,SMOOTH
      COMMON/MOTOR/MTKWPK
      COMMON/PHY/GRAV,RHO
      COMMON/PRINT/APETT(15),AELETA(15),AELETP(15)
      COMMON/RRATO/NTIME,WGEAR,RCVT,PMOTOR,PMTRTD,PGEAR
      COMMON/RSPLT/ACCEL,SOC,PCVT,CX(15),VAVE,PHEMAX, PHE,PELEC
      COMMON/SCALE/SFX(17),SFG(20),NN
      COMMON/STC/V(831),BET(831),TRIPLN(8),TRIPNO(8)
      COMMON/CHARG/AACV(8),ACR(8)
      COMMON/TIMEC/DLTSTC,DELTHW,TACCEL,TCOAST,TBRAKE,TSTOP,TCYCLE
      COMMON/TRIP/CHARGE(36),EBTOIL(36),HOUT(36),IDOD(36),
     &IVESTC(36),PETSTC(36),SOCSTC(36),REGEN(36)
      COMMON/VARY/ WTL,INOCHG
      COMMON/YEARC/PETYR(15),ELECYR(15),ELEC(15),DISCH(15)
C
C ALPHA
      DATA ALPHA1/1./, ALPHA2/0./, ALPHA3/0./
C BATT
      DATA BTMKUP/.3/
C CC
      DATA CDA/.6/, RDIFF/1./, RGEAR/.08333333/, RGRM/0.2857/
      DATA RTIRE/.3/
C COST
      DATA GASCST/0.32,0.35,0.38,0.41,0.44,0.47,0.5,0.53,0.56,0.59/
      DATA KWCST/.0111, .0125, .0139, .0153, .0167, .0181, .0194,
     &.0208, .0222, .0236/
C KILOG
      DATA WF/510./, WGCLT/0./, WPL/415./
C LIMIT
      DATA ITERMX/5/, NTRIPX/8/
C MOTOR
      DATA MTKWPK/40./
```

```
C OMISC
      DATA CHOOSE/0./,SMOOTH/.TRUE./
C PHY
      DATA GRAV/9.807/, RHO/1.225/
C RRATO
      DATA PMTRID/20000./
C SCALE
      DATA SFX/20*1./, NN/5/
      DATA SFG/20*1./
C STC
      DATA RET/830*0./
      DATA TRIPLN/10000.,30000.,50000.,80000.,130000.,160000.,
     &500000.,800000./
      DATA TRIPNO/130.,85.,57.,54.,12.,7.,3.,1./
C TEST
      DATA AACV/2.265,2.2225,2.1993,2.1827,2.1702,2.1607,2.1524,2.1455/
      DATA ACR/0.,1.017,2.034,3.052,4.069,5.086,6.104,7.121/
C TIMEC
      DATA DLTSTC/1./, DELTHW/30./
      DATA TACCEL/14.0/, TCOAST/64.0/, TBRAKE/74.0/, TSTOP/83./
      DATA TCYCLE/108./
C VARY
      DATA WTL/207./, INOCHG/1/
C
      DATA DISCHG/1.30,1.30,1.30,1.30,1.30,1.30,1.30,1.30,
     &1.3000,1.3000,1.3000,1.3000,1.3000,1.3000,1.3000,1.3000,
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     &1.9820,1.9845,1.9870,1.9895,1.9920,1.9942,1.9964,1.9986,
     &2.0008,2.0030,2.0052,2.0074,2.0096,2.0118,2.0140,2.0159,
     &2.0178,2.0197,2.0217,2.0236,2.0255,2.0274,2.0293,2.0313,
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 DATA ATORQ/0.,19.,47.,94.,140.,178./
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 DATA APCVT/0.,2.85,4.42,9.32,60.,80.,90.,100./
 DATA ARCVT/.333,.667,.5,1.,1.49,2.,2.5/
 DATA EFF/0.,.904,.931,.944,.945,.937,.929,.918,
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 DATA GREFF/.9,.948,.9667,.978,.9815,.9827,.9842,.9851,.9857,.9861,
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16. Abstract

This work demonstrates the use of optimization methods as an effective design tool in the design of hybrid vehicle propulsion systems. Optimization techniques were used to select values for three design parameters (battery weight, heat engine power rating and power split between the two on-board energy sources) such that various measures of vehicle performance (acquisition cost, life cycle cost and petroleum consumption) were optimized. The approach produced designs which were often significant improvements over hybrid designs already reported on in the literature. The principal conclusions are as follows. First, it was found that the strategy used to split the required power between the two on-board energy sources can have a significant effect on life cycle cost and petroleum consumption. Second, the optimization program should be constructed so that performance measures and design variables can be easily changed. Third, the vehicle simulation program has a significant effect on the computer run time of the overall optimization program; run time can be significantly reduced by proper design of the types of trips the vehicle takes in a one year period. Fourth, care must be taken in designing the cost and constraint expressions which are used in the optimization so that they are relatively smooth functions of the design variables. Fifth, proper handling of constraints on battery weight and heat engine rating, variables which must be large enough to meet power demands, is particularly important for the success of an optimization study. Finally, the principal conclusion is that optimization methods provide a practical tool for carrying out the design of a hybrid vehicle propulsion systems.

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