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HYBRID VEHICLE POTENTIAL ASSESSMENT

Volume 3: Parallel Systems

By
S. P. DeGrey

MASTER

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Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

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ELECTRIC AND HYBRID VEHICLE SYSTEM
RESEARCH AND DEVELOPMENT PROJECT
HYBRID VEHICLE POTENTIAL ASSESSMENT
VOLUME III. PARALLEL SYSTEMS

September 30, 1979

MASTER

S. P. DeGrey

Approved by:

F. T. Surber
Manager, Studies and Assessments

T. A. Barber
Manager, Electric and Hybrid
Vehicle System Research and
Development Project

Prepared for
U.S. Department of Energy

by
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

PREFACE

In 1976, Congress passed the Electric and Hybrid Vehicle (EHV) Research, Development, and Demonstration Act of 1976, Public Law 94-413, later amended by Public Law 95-238. The Department of Energy is conducting an EHV development program in compliance with that Law. The EHV System Research and Development Project, one element of this Program, is being conducted by the Jet Propulsion Laboratory (JPL) of the California Institute of Technology through an agreement with the National Aeronautics and Space Administration. This report presents the results of the investigations conducted under the Hybrid Vehicle Potential Assessment Task which is a part of the EHV Systems R&D Project.

Early results of this study were used as the technical basis for the Near Term Hybrid Vehicle Development Program now being carried out by the JPL Electric and Hybrid Vehicle System Research and Development Project.

This report is in ten volumes. Volume I contains an overview of the study and the major findings. Volumes II through X are of technical supplementary reports that describe the details of the study and present the most important data generated by the study elements.

STUDY TEAM MEMBERS

Principal Investigator	F. T. Surber
Hybrid Vehicle Review	K. O. Leschly
Mission Analysis	F. T. Surber G. K. Deshpande
Power Train Analysis	S. P. DeGrey S. G. Liddle Z. Popinski
Cost Analysis	K. S. Hardy R. C. Heft
Impacts Analysis	K. O. Leschly

Volumes Comprising the Hybrid Vehicle Potential Assessment

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5030-345, Vol. I	Summary	F. T. Surber et al.
5030-345, Vol. II	Mission Analysis	F. T. Surber G. K. Deshpande
5030-345, Vol. III	Parallel Systems	S. P. DeGrey
5030-345, Vol. IV	Series Systems	Z. Popinski
5030-345, Vol. V	Flywheel Systems	S. G. Liddle
5030-345, Vol. VI	Cost Analysis	K. S. Hardy
5030-345, Vol. VII	Hybrid Vehicle Review	K. O. Leschly
5030-345, Vol. VIII	Scenario Generation	K. O. Leschly
5030-345, Vol. IX	Power Train Summary, Component Descriptions, HYVEC Vehicle Simulator	S. G. Liddle S. P. DeGrey
5030-345, Vol. X	Electric and Hybrid Vehicle Cost Handbook	R. C. Heft S. C. Heller

CONTENTS

I.	INTRODUCTION -----	1-1
II.	VEHICLE CHARACTERISTICS -----	2-1
	A. Description of Configurations -----	2-1
	B. Control Strategies -----	2-3
III.	DESIGN CONSIDERATIONS -----	3-1
	A. Battery Power vs. Energy -----	3-1
	B. Power-to-Weight Ratio -----	3-4
	C. Sizing the Battery Pack -----	3-6
IV.	RESULTS - OVERALL MISSION SURVEY -----	4-1
V.	RESULTS - MISSION 2 -----	5-1
	A. Vehicle and Battery Weight -----	5-1
	B. Power System Sizing -----	5-1
	C. Range -----	5-2
	D. Fuel Economy -----	5-5
	E. Design Considerations -----	5-9
VI.	RESULTS - MISSION 7 -----	6-1
VII.	CONCLUSIONS -----	7-1
	A. Fuel Economy -----	7-1
	B. Battery Energy and Power Density -----	7-2
	C. Design Considerations -----	7-3

Figures

2-1.	Hybrid Parallel Power Train Configuration "1" -----	7-5
2-2.	Hybrid Parallel Power-Train Configuration "2" -----	7-5
2-3.	Conventional ICE Power-Train Configuration -----	7-6
2-4.	Electric Only Power-Train Configuration -----	7-6

2-5.	Power vs. Time for Segment of FTP-Urban Cycle, Mission 2, Vehicle D, MFG = 10%, Lead-Acid -----	7-7
2-6.	Power Density vs. Energy Density and State-of- Charge for 1985 Lead-Acid Batteries -----	7-8
2-7.	Power vs. Energy Available for 1985 Advanced Batteries -----	7-8
2-8.	Power Demands vs. Vehicle Weight, Mission 1 -----	7-9
2-9.	Gross Vehicle Mass vs. Battery Mass Fraction, Missions 1 through 7, Vehicle Design A -----	7-10
2-10.	Annual Fuel Economy vs. Battery Mass Fraction, Missions 1 through 7, Vehicle Design A, Lead-Acid Batteries -----	7-10
2-11.	Gross Vehicle and Battery Mass, and Total Power vs. Battery Mass Fraction, Mission 2, Designs A, B, C, D -----	7-11
2-12.	Engine and Motor Peak Power, Mission 2 -----	7-12
2-13.	Primary Electric Range vs. Battery Mass Fraction, Mission 2 -----	7-12
2-14a.	Primary Electric Range vs. Battery Mass Mission 2, Nickel-Zinc -----	7-13
2-14b.	Primary Electric Range vs. Battery Mass Fraction, Mission 2, Sodium-Sulphur -----	7-13
2-15.	Fuel Consumption vs. Distance, Mission 2 Lead-Acid Battery -----	7-14
2-16a.	Annual Fuel Economy vs. Battery Mass Fraction, Mission 2, Lead-Acid -----	7-15
2-16b.	Fuel Economy at 192 km vs. Battery Mass Fraction, Mission 2, Lead-Acid -----	7-15
2-17a.	Fuel Economy at 192 km vs. Battery Mass Fraction, Mission 2, Nickel-Zinc -----	7-16
2-17b.	Fuel Economy at 192 km vs. Battery Mass Fraction, Mission 2, Sodium-Sulphur -----	7-16
2-18.	Effect of PFUEL Control Strategy on Annual Fuel Economy, Mission 2 -----	7-17
2-19.	Fuel Economy, FTP-Urban (PELEC) and FTP-Highway (PFUEL) vs. Battery Mass Fraction, Lead-Acid Battery -----	7-18

2-20.	Normalized Energy Usage, FTP Highway, PFUEL-ON Mode, Mission 2, Lead-Acid Battery -----	7-19
2-21.	Percent Time Heat Engine Required in PELEC ON/OFF Mode, vs. Battery Mass Fraction, Mission 2 -----	7-19
2-22.	Gross Vehicle and Battery Mass, and Total System Power vs. Battery Mass Fraction, Mission 7 -----	7-20
2-23.	Engine and Motor Peak Power vs Battery Mass Fraction, Mission 7 -----	7-21
2-24.	Range vs. Battery Mass Fraction, Mission 7, Lead-Acid Battery -----	7-21
2-25.	Fuel Consumed vs. Distance Mission 7, Lead-Acid -----	7-22
2-26a.	Annual Fuel Economy vs. Battery Mass Fraction, Mission 7, Lead-Acid -----	7-23
2-26b.	Fuel Economy at 195 km vs. Battery Mass Fraction, Mission 7, Lead-Acid -----	7-23
2-26c.	Annual Fuel Economy vs. Battery Mass Fraction for PFUEL On/Off and On Control Strategies, Mission 7, Lead-Acid -----	7-24
2-27.	Total System Efficiency at 195 km vs. Battery Mass Fraction, Mission 7, Lead-Acid Battery -----	7-25
2-28.	Percent Electrical Energy at 195 km vs. Battery Mass Fraction, Mission 7, Lead-Acid Battery -----	7-26
2-29.	Percent Time Heat Engine Required in PELEC ON/OFF Mode, Mission 7 -----	7-26

I. INTRODUCTION

This chapter deals primarily with the parallel hybrid vehicle. This vehicle type is characterized by an arrangement of the heat engine and electric motor in the power-train such that a direct mechanical or fluid-mechanical power path from both the motor and engine to the wheels is available. Out of the several possible component arrangements that could satisfy these requirements, a configuration in which the engine and motor are mounted in tandem, driving a 4-speed manual transmission, was selected for extensive computer analysis.

Simulation of all the identified missions (1 through 7) were run for this parallel hybrid configuration. For each mission, the battery mass fraction (MFB) which is defined as the ratio of the battery mass to the gross vehicle weight (expressed in percent) was varied from 5 to 30%. These vehicles were designed such that the total energy usage of the battery before cut-off would be about 80% of the C/3 discharge rate.

Due to the similarity of results for missions with similar acceleration and driving cycle requirements, missions 2 and 7 were selected for additional detailed trade-off studies. Four different motor/battery sizing criteria were examined (Vehicles "A", "B", "C", "D") over a range of MFB from 5 to 30%.

II. VEHICLE CHARACTERISTICS

A. Description of Configurations

A Parallel Hybrid Configuration utilized in this section is generally characterized as having a heat engine and a motor connected within the power-train in such a way that each are able to supply power to the drive shaft and accessories either individually or simultaneously. Hybrid configuration "1" features the motor and heat engine in a tandem arrangement, with the motor closest to the transmission, and clutches between engine/motor and motor/transmission.

In this arrangement, the motor and engine revolve at the same speed, and both power outputs flow through the transmission. A schematic diagram of configuration 1 is shown in Figure 2-1. An alternate configuration, "2" is similar to 1 except the motor is located behind the transmission, and a differential gearbox is added to provide the necessary motor/driveshaft speed ratio. The advantage of configuration 2, shown schematically in Figure 2-2, is the lower power requirement of the transmission and elimination of the inertial effects of the motor on the power-train when operated with heat engine only (alternate arrangement only), while the disadvantage is that the motor is operated in a unfavorable speed range, (efficiency and power) a larger percentage of the time. For a typical acceleration maneuver, configuration 2 would require a larger motor, but a smaller transmission.

Although several control strategies were available within the HYVEC simulation program (see supplementary report #8) the principle control strategy (PELEC/PFUEL) used for the parallel configurations utilizes the motor or the heat engine as the primary power source in the vehicle drive-train depending on the state-of-charge of the battery pack. There are two major modes in the control strategy, the first of these is called the primary electric mode (PELEC). In this mode, the motor supplies all of the vehicular power requirements, including the accessories. In a situation where the electric portion of the power-train is incapable of meeting the power demands either due to a motor, battery, or controller power limitation, the heat engine is turned on to supply the additional power required. If the heat engine is turned completely off when not in use, the strategy is called "Primary Electric-Engine ON/OFF" (PELEC-ON/OFF). If the heat engine is left idling during the time periods when the motor is able to supply all the vehicular power requirements, the strategy is called "Primary Electric-Engine Continuously On" (PELEC-ON). When the batteries are discharged to a certain preset point, the control strategy switches from primary electric mode to the primary heat engine (fuel consuming) mode (PFUEL). This usually occurs at the point of battery discharge when the battery pack maximum power capability is just equal to the maximum power capability of the motor/controller. The power-train is then sized to meet the maximum acceleration performance requirements using the full power of the motor plus the full power of the heat engine.

Discussion of the results is broken down into four sections. The first section describes the configuration and control strategies of the vehicles simulated. The second section outlines some design considerations including battery discharge versus energy available, sizing the power-train components, and sizing the battery pack. The third section describes briefly the results for the single design point vehicle on missions 1 through 7, and in detail the parametric studies of missions 2 and 7. The last section presents some conclusions and design recommendations.

All of the simulations presented in this chapter represent configuration 1. From an overall system performance point-of-view, configuration 1 and 2 are very similiar, and the trends presented for 1 are essentially the same for 2.

The conventional internal combustion engine (ICE) vehicle power-train configuration modeled for baseline performance is shown schematically in Figure 2-3. The power-train consists of a heat engine with accessories, a clutch, and a manual transmission. The electric vehicle (ELEC) shown in Figure 2-4 is similiar to the ICE, substituting an electric motor/controller and batteries for the heat engine/gas fuel tank.

B. Control Strategies

The physical arrangements of the heat engine and electric motor in the hybrid parallel configurations allow considerable flexibility in determining the control strategy. The engine and motor can be operated individually at any point in time, or simultaineously. The decisions as to when and how much power should be supplied by each of the components as a function of parameters such as battery charge level and vehicle power requirements are made by the controller.

The primary heat engine mode is similiar to the primary electric mode, except the motor and engine switch roles. The heat engine supplies the vehicle power requirements and the motor supplies power required beyond the maximum capability of the heat engine. In the primary heat engine on/off mode (PFUEL ON/OFF), the engine is turned off when the net power requirement at the driveshaft is negative, (vehicle decellerating) and when the vehicle velocity is zero. At this time ($V = 0$), the motor supplies the accessory power requirements. In the primary heat engine continuously on mode (PFUEL-ON) the heat engine is on all of the time, and again, the motor is used to supplement the heat engine when needed. The operation of the PELEC-ON/OFF control strategy is illustrated in Figure 2-5 on a segment of the FTP-Urban cycle.

In addition to the primary control strategy outlined above (PELEC/PFUEL) two other parallel hybrid control schemes were considered briefly in this analysis. The first of these is a modification of the PELEC/PFUEL strategy that eliminates the PELEC portion of the strategy. At the beginning of a trip, with batteries fully charged, the heat engine is the primary source of power (PFUEL). The motor is used to satisfy power requirements above the engines' maximum power capability. In this strategy, the engine may be arbitrarily limited to a given percentage of actual maximum power, in an attempt to eliminate operation at unfavorable efficiency points. This control strategy is commonly called heat-engine load leveling.

The last control strategy is similiar to PELEC/PFUEL except the criterion for switching from PELEC mode to PFUEL mode is not based upon the battery state-of-charge, but upon the vehicle velocity.

For example, if the vehicle velocity switch point is set at 40 Km/Hr, the controller would select the primary electric mode for all vehicle velocities at or below 40 Km/Hr, and switch the primary heat engine mode above 40 Km/Hr. Utilization of the heat engine in an on/off mode, or a continuously on mode are options in both of these secondary control strategies.

These secondary control strategies were both considered in several cases for Mission 2. The PFUEL only strategy was rejected due to the high fuel consumption in the initial portion of the trip, and negligible difference in overall fuel economy. The strategy utilizing vehicle velocity as a switch from PELEC to PFUEL was rejected due to the undesirability of turning the heat engine on and off numerous times.

All of the data presented in this chapter represents the PELEC-ON/OFF)/(PFUEL-ON/OFF) control strategy except where otherwise noted. Several figures are presented in the results section showing the effects of using the PFUEL-ON strategy rather than PFUEL ON/OFF strategy.

The ICE vehicle and the electric vehicle are controlled conventionally. Regenerative braking is utilized in the hybrid and the electric vehicle down to the preselected minimum vehicle speed, usually around 10 Km/Hr.

III. DESIGN CONSIDERATIONS

The overall design goals for hybrid vehicles are discussed in Supplementary Report No. 1. Briefly these are: equivalent vehicle performance, minimum fuel consumption and minimum operating cost.

A. Battery Power vs. Energy

One of the fundamental trade-offs in hybrid or electric vehicle design is battery power required versus battery energy available. As soon as the peak power demand at the batteries is defined, the total amount of energy available from the batteries is also defined. The actual amount of energy depends on how the battery is discharged up to that point, i.e., steady state, transient, alternate charge-discharge, but, the trend is always the same. The power versus energy function in the HYVEC battery model for 1985 lead-acid batteries is shown in Figure 2-6. All of the parallel hybrid vehicle power-trains are sized such that the sum of the maximum power capability of the engine and motor is just sufficient to meet the vehicle maximum power requirements. These requirements are determined by the 0-100 Km/Hr acceleration specification for all missions except mission 7. The control strategy PELEC/PFUEL is set to switch from PELEC mode to PFUEL mode when the batteries are discharged to a point where they are just capable of supplying the peak motor power.

This is necessary because even in PFUEL mode, the full motor power is still required in addition to full engine power to meet the maximum acceleration requirements. The four power-energy design points used in this study are shown in Figure 2-6. The actual battery discharge cut-off point represents a battery power capability slightly higher than the motor power in each case. This accounts for the inefficiencies in the controller and motor, assumed to average about 85% from the battery terminals to the motor output (only for the purpose of determining the cut-off).

The trade-off between power and energy is illustrated in Figure 2-7 for lead-acid, nickel-zinc, and sodium-sulphur batteries. Energy available is referenced to the 1985 lead-acid battery C/3 steady discharge rate energy, and the power is referenced to lead-acid maximum power capability at full charge. The advantages of the advanced batteries over lead-acid from a power-system design point-of-view are obvious. As an example, if the peak vehicular power requirement was set at 50%, (of Pb-acid peak) the energy available from Pb-acid, Ni-Zn, and Na-S would be 65%, 135%, and 220% respectively. For the same motor and battery pack weight, the Ni-Zn would supply twice the energy, and the Na-S would supply almost three and one-half times as much energy. These obvious benefits to the operation of the power-train must of course be weighed against the increased cost of the advanced batteries in determining the preference of one battery type over another.

An alternate method of increasing the energy available from the battery would be to increase the size of the heat engine such that the sum of engine and motor peak powers would actually exceed the maximum power requirements of the vehicle. With this sizing criteria, the batteries could be discharged below peak motor power demand, but only to the point where motor and peak engine power again reached the maximum power requirements. Increasing the heat engine size is undesirable due to an efficiency decrease in most cases, and a weight and cost increase in all cases. Also, a primary consideration is to minimize the need for engine supplemental power in the PELEC mode during driving cycle operation, i.e., maintain maximum motor power capability in PELEC mode. The four design points considered for missions two and seven, (Vehicles "A", "B", "C", and "D") shown in Figure 2-6, represent a range of energy density from 34 (A) to 18 (D) Kw-hr/Kg, and power density from 47 (A) to 92 (D) Kw/Kg for Pb-acid battery vehicles. This range of design points is sufficient to show the major trends of this parameter.

The first-order goal in sizing the motor and thus setting the maximum discharge rate is to maximize the total energy available from the battery. This usually results in increased range and fuel displacement. However, other considerations such as sizing the motor to meet the driving cycle power requirements and minimizing the battery mass tend to drive the design cut-off point to higher power levels and less overall energy.

B. Power-to-Weight Ratio

The overall vehicle power-to-weight ratio which is defined as peak engine plus peak motor power divided by gross vehicle weight, is determined by the most severe performance requirement imposed on the vehicle. For missions 1 through 5 the most demanding requirement is an acceleration capability of zero to 100 Km/Hr in fourteen seconds. For most of the mission drive-train gear ratios and wheel diameters selected for baseline simulations, a power-train sized for the 0-100 Km/Hr acceleration results in sufficient power to meet the Federal Test Procedure-Urban (FTP-U) and Highway (FTP-H) driving cycle peak power demands. Values of peak power as a function of gross vehicle weight are shown in Figure 2-8. Curves "A" and "B" represent heat engine only and electric motor only peak power ratings for 0-100 Km/Hr acceleration in 14 seconds. The noticeable difference between the motor and engine power requirements (~20%) is due to the favorable torque/speed characteristics of the motor. This allows a decrease in the overall power-to-weight ratio as the total power split between the engine and motor is increased in the direction of a larger motor. Curves "B" and "C" represent FTP-U and FTP-H peak cycle power points. Even though the value of peak power is only 60% of the peak acceleration requirement, the engine/motor speed is not at the maximum power producing point (~95% max. speed) when this occurs. This effect is even more pronounced in the Aerospace Delivery Van cycle used in mission 7. The constant acceleration ramps used to characterize the Van cycle result in peak power requirements about the same as the FTP-U.

Thus, a mission 7 power-train sized for 0-100 Km/Hr acceleration in 14.0 seconds (specification is only 18 seconds) will have insufficient power at 3 points in the van cycle. The power requirements for gradeability performance are also shown in Figure 2-8, ("D" and "E"). These power requirements are sufficiently lower than the acceleration and the FTP-U so as to never be a driver in sizing the hybrid power-train.

The relative magnitude of the peak power requirements for the acceleration specification, and the driving cycles shown in Figure 2-8 illustrates an important advantage of parallel hybrid vehicles over conventional ICE or electric vehicles.

The parallel hybrid vehicle power-train can be sized such that either the engine or the motor is able to supply most of the driving cycle power demands (E.G. 95% time wise) while operating individually in the power-train, yet, when operated simultaneously provide acceptable acceleration performance. This feature enables significant down-sizing of the engine and motor over the required by ICE, electric, or series hybrid vehicle designs. The benefits of down-sizing such as improved operating efficiency (primarily heat engine), lower weight, and lower cost (primarily motor/controller/batteries) are well known. The disadvantage is the added complexity of a power-train in which two power components must at different times operate independently and simultaneously, with a smooth transition between the two modes.

C. Sizing the Battery Pack

For a given motor/battery peak power design point, varying the mass of the battery pack has the following overall effects on the vehicle design and performance. The gross vehicle mass increases both due to battery/motor weight and propagated chassis weight. The primary electric range increases along with the primary range fuel economy. Vehicle power-to-weight ratio decreases due to the increased power fraction of the motor, and as the motor power increases, the percentage of time that the engine is required to meet driving cycle power requirements decreases. The 200 Km trip length overall fuel economy is not as sensitive as other parameters, as the increased trip length tends to make the electrical energy expended in the primary electric portion of the trip, which is typically the first 25 to 100 Km, a smaller fraction of the total energy consumed. These parameters will be quantified in the mission results section. One of the important considerations in sizing the battery pack in the parallel hybrid power-train design is the power required by the motor to meet the majority of driving cycle requirements. Although the power density of any battery type is constant at a given state-of-charge, the battery power to vehicle weight ratio increases significantly with increasing battery mass fraction. Thus for a given motor/battery power design point, there exists a unique battery pack weight which will enable the motor to supply a certain percentage of driving cycle power requirements, e.g., 95% by time. However, this point usually does not correspond to the lowest operating cost, so that trade-offs must be made in this area.

IV. RESULTS - OVERALL MISSION SURVEY

During the course of mission analysis and trade-off studies, it became apparent that many of the trends exhibited by the variation of a primary parameter, such as battery mass fraction, were consistent from mission to mission. The absolute values of the results vary according to the vehicle weight, but the overall trends are generally consistent. This is especially apparent when comparing vehicle designs from mission to mission where the driving cycle and acceleration performance requirements are similar. Missions two and three have identical driving cycles and performance requirements. Missions one, five and six also have similar driving cycle requirements (FTP-Urban cycles at the beginning followed by FTP-Highway cycles), with mission six only having an acceleration requirement of 18 seconds instead of 14 seconds. The only major difference other than vehicle weight between missions one, two, three, five and six is the reduced acceleration performance of mission six, and mission five starting with only 1 urban cycle rather than 4 and 6 of the other missions. Missions four and seven have significantly different driving cycles. The numerous New York City Taxi cycles in mission 4 and Van cycles in mission 7 place different constraints on the drive-train than occurs with a series of Urban and Highway cycles.

These include markedly increased idle time, and continued high peak power demands throughout the entire trip length. All of the missions were analysed using a similiar set of design constraints on sizing the heat engine and motor, and the same control strategy (PELEC/PFUEL). The vehicle weight is summarized for missions 1 through 7 in Figure 2-9. Annual fuel economy for missions 1 through 7 is shown in Figure 2-10. All of these vehicles represent motors sized such that cut-off occurs at approximately 80% of the C/3 discharge rate (Vehicle "A"). It can be seen in Figure 2-10 that missions 1, 2, 3 and 6 have very similarly shaped curves of fuel economy as a function of battery mass fraction. Mission 5 is displaced downward slightly, and missions 4 and 7 have markedly different trends from the other missions.

Missions two and seven were analysed in considerably more detail in an attempt to ascertain the effects of the motor size/discharge rate as a function of energy available from the battery. The design points considered are identical to those shown in Figure 2-6 and are identified as "A", having 31% of fully charged battery power as the motor peak power design point, "B", 40%, "C", 50%, and "D", 60%.

V. RESULTS - MISSION 2

A. Vehicle and Battery Weight

The variation of gross vehicle weight , battery weight, and total power (engine + motor) are shown in Figure 2-11 as a function of battery mass fraction. These curves represent all four vehicle designs and include the propagated weight in the chassis. The total vehicle mass actually increases very slightly with increased motor/controller power and decreased engine power (A→D), but for mission 2 the increase is so small that only one curve is shown. The total drive-train power is also shown in Figure 2-11. Total power decreases from vehicle "A" to "D" due to the increased fraction of the total power assigned to the motor, which has favorable torque-speed characteristics, allowing less power for the 0-100 Km/Hr acceleration maneuver (see Figure 2-8).

B. Power System Sizing

The motor/engine peak power distribution, shown in Figure 2-12 illustrates the trade-off between motor and engine sizing. For a MFB equal to 20%, the motor power increases from 19 Kw for design A, to 36 Kw for design D, while the engine power decreases from 67 Kw to 45 Kw. Eventually, the engine peak power is reduced to such a degree that it is unable to supply sufficient power to meet driving cycle requirements in the primary engine mode. Although the motor is always available to supply the additional power required, excessive use of the motor in the PFUEL mode decreases the charge state of the battery to a point where the batteries must be recharged with the heat engine.

Otherwise, the power available from the motor would be reduced by the battery power limit to a point where engine plus motor power would not be sufficient to meet acceleration requirements. This mode of operation where the engine is used to recharge the batteries is undesirable due to the conversion efficiencies of the engine, motor/generator, and batteries.

It is interesting to note that for design A, the engine power is essentially constant. In this case, the increased power rating of the motor just compensates for the increased mass of the vehicle in accelerating the vehicle from 0-100 Km/Hr in 14 sec. Also, in all cases for a given vehicle design where the mass of the vehicle is increased by adding additional batteries, the engine size either remains constant (A) or decreases (B, C, D). A certain amount of the penalty of increased vehicle weight is offset by the increased operating efficiency of the engine in the PFUEL mode.

C. Range

Figure 2-13 shows primary electric range as a function of battery mass fraction. The trend to be expected in sizing the motor and battery pack is shown clearly in Figure 2-13. For a given battery power design point, the range increases as a function of battery mass.

The total energy available from a given set of batteries, at a specified state-of-charge is directly proportional to the mass of the battery pack. A doubling of the mass of the battery will result in twice the energy available, but, since the total vehicle weight only increases by the weight of the additional batteries plus some chassis and component weight, the incremental increase in energy required by the vehicle is significantly lower than that added by the batteries. The effects of increasing the motor size, and in this case the battery discharge rate, on range is also shown in Figure 2-13. For 20% battery mass fraction, the range is directly proportional to the rate of discharge. Both on a power and an energy basis. I.E.:

Range (KM)	Energy Available	Peak Discharge Rate (%)
$\frac{A}{D} = \frac{70.6}{34.5} = 2.05$	$\frac{A}{D} = \frac{52.}{27.5} = 1.9$	$\frac{A}{D} = \frac{31}{60} = 0.52$

One of the most important constraints on increasing the mass of the battery pack is not the trade-off between range and vehicle weight, but rather the initial and replacement cost of the battery pack versus the cost of the petroleum displaced, which generally favors minimum battery weight, (see supplementary report #5).

Mission 2 vehicles A through D were also simulated using the advanced batteries, nickel-zinc and sodium-sulphur. These vehicles were sized exactly the same as the lead-acid vehicles, to get a direct comparison of the benefits of the increased energy density on range and fuel consumption. The results in Figures 2-14a and 2-14b show that for a given battery discharge power density, (constant for a given vehicle design) the range is almost directly proportional to energy density, as expected.

Vehicle design D at 5% point (MFB = 15.5%)

	Pb-A	Ni-Zn	Na-S
Range (KM)	25	52	92
Ratio to Pb-A	1	2.1	3.7
Energy (W-Hr/Kg)	18.2	41.3	70
Ratio to Pb-A	1	2.3	3.8

The trade-off between the increased range and fuel displacement of the advanced batteries and the increased initial and replacement cost is the critical item in evaluating the overall worth of the advanced batteries. It is intuitively obvious that for a given vehicle having a travel distribution of 90% trips with total length of 75 Km or less, an increase in range from 75 to 150 Km is going to have a much smaller impact on the annual fuel displacement than for example, an increase of range from 35 to 70 Km.

The increase in advanced battery power density at a given energy density is less dramatic than the increase in energy density at fixed power density. An increase in power density at a given energy density reduces the minimum battery pack required to meet driving cycle requirements if the range is allowed to vary, or increases the motor size and decreases the engine size if range is held constant, which increases the fuel economy in the PFUEL mode. Additional work is required to optimize the design point i.e., trade-off between power and energy, for the advanced batteries.

D. Fuel Economy

The fuel economy of the parallel hybrid vehicles considered in this study is highly dependent on the trip length due to the nature of the control strategy. The distribution of electrical energy is always concentrated in the initial portion of the trip whose length is defined as the primary electric range. This is shown in Figure 2-15 where fuel consumed is plotted vs distance traveled. As the discharge rate is shifted from low to high (A→D) the fuel consumption rate in the electric range decreases, but the range itself also decreases. The overall effects of these trade-offs on long trip fuel economy (192 KM), and annual fuel economy (supplimentary report #5) are shown in Figures 2-16a and 2-16b. As the battery weight is increased, the fuel economy begins to vary from vehicle A to D, but the overall trend is toward increasing fuel economy.

At a 10% battery fraction, fuel economy is similar for all four vehicles. In this case, the trade-off between total energy obtained from the battery (decreasing from A to D) and the size and method of utilizing the heat engine is about even. A smaller heat engine operates at a higher efficiency for most driving conditions, up to a certain limit. Also, it should be noted from Figure 2-12, that for such a small battery pack even doubling the motor size is only changing the overall motor power fraction from 10% to 20%, thus the overall effect is minor. As the battery mass increases, the total battery energy available becomes the dominant parameter in overall fuel economy. For example, at a battery fraction of 20%, the smallest motor (Vehicle A) is large enough to supply sufficient power to the drive-train 90% of the time, and still deliver twice the electrical energy as vehicle D. Even though the fuel economy diverges for vehicles A through D as the battery weight increases, it should be noted that the difference is relatively small up to battery weight of about 25%. At MFB of 20%, the fuel economy varies by 8% at 192 Km, and 22% annually. This is an important factor to keep in mind when considering the relative feasibility of the various vehicle designs.

The fuel economy at 192 Km for nickel-zinc and sodium-sulphur batteries is shown in Figures 2-17a and 2-17b. The trends already shown for the primary electric range are also reflected in the fuel economy. As the electrical energy fraction of the total energy increases

for a given vehicle design and weight, the thermochemical energy decreases, and the fuel economy increases. The fuel economy at 192 Km for vehicle C at 20% battery mass fraction is 20, 29.5, 90 Km/L for Pb-A, Ni-Zn, and Na-S respectively. This represents increases of 42%, 109%, and 540% over the ICE fuel economy at 192 Km for mission 2. An interesting trend is shown in Figure 2-17b where the fuel economy for vehicle B is higher than for vehicle A. The primary electric range of vehicle B at MFB = 20% is 198 Km, thus, the fuel economy represents only operation in the PELEC mode. Since vehicle B is discharging the batteries at a higher rate than A, the total electrical energy is higher, and fuel economy is higher.

The effect of operating strategy in PFUEL mode on annual fuel economy for lead-acid batteries is shown in Figure 2-18. The relative percentage of time decelerating and idling in the FTP-Highway cycle is small, so the effect of operating the engine continuously (PFUEL-ON) versus on/off operation is small, reaching a maximum of 6% for vehicle D.

Figure 2-19 shows the fuel economy for an FTP-Urban cycle in the PELEC-ON/OFF mode, and fuel economy for an FTP-Highway cycle in the PFUEL-ON mode. Fuel economy in the PELEC mode is entirely predictable, reflecting the increasing fraction of electrical energy as battery mass increases. In the PFUEL mode, vehicle A shows the trend expected due to the increased vehicle mass, (as MFB increases) i.e., fuel economy decreases. As the heat engine size decreases, (A→D) the

benefits of reduced idle fuel flow, and increased operating efficiency more than offset the effect of increased vehicle mass. Thus, the fuel economy of vehicle C actually increases as vehicle weight increases. Although not shown in Figure 2-19, this trend reverses if the heat engine is sized too small, as in vehicle D above an MFB of about 20%. This is due to the fact that the engine requires an increasing assist from the motor to meet the driving cycle requirements, and thus must run the motor as a generator, charging the batteries, and dramatically reducing the fuel economy. Also, heat engine efficiency decreases significantly at power levels above about 80% of peak.

The fuel consumed in liters per kilometer per kilogram is shown in Figure 2-20 as a function of battery mass fraction. Even though the actual fuel consumption (Km/L) is decreasing for A and B, and slightly increasing for C, the efficiency of the heat engine system is increasing dramatically with increased battery fraction. The amount of fuel required by vehicle A to move one kilogram of vehicle mass one kilometer is 30% lower at MFB = 25% than for the gas only vehicle. Vehicle C requires 40% less fuel than the gas only vehicle at the same MFB. These trends are a combination of the increased operating efficiency of a smaller engine in a heavier vehicle, and reduced idle fuel flow with reduced engine size.

E. Design Considerations

One of the major design problems in the parallel hybrid vehicle will be designing a power-train that can effect a smooth transition from either motor or engine supplying power to both motor and engine supplying power and back again. The most critical mode is the primary electric mode, during which time the heat engine supplies the difference in power needed to meet driving cycle or acceleration power requirements. Switching the heat engine off and on numerous times is clearly undesirable due to the electric energy required to start the engine, emissions, fuel economy, and accelerated engine wear. Perhaps the best compromise in this area would be to design the power-train so that the motor is large enough to handle 95% of the driving cycle requirements, and use the heat engine only for maximum acceleration maneuvers, such as freeway merging or vehicle passing.

Figure 2-21 shows the percent of time during the primary electric mode operation that the heat engine is required for all four vehicle designs. If an upper limit of 5% was assumed to be acceptable for this particular mission, all vehicle designs falling on or below the 5% line of Figure 2-21 would be acceptable. For any given motor/battery sizing criteria, this constraint results in minimum battery mass fractions corresponding to the 5% line: i.e., Vehicle A, MFB = 25%; Vehicle D, MFB = 15.5%. A dashed line corresponding to the 5% design constraint is shown on Figures 2-12, 2-13, 2-14, 2-16, and 2-17. The final step in selecting the optimized vehicle for mission 2 would be to consider the overall operating costs for vehicles A, B, C, and D, draw the 5% power constraint line and select a vehicle at or below the 5% line which has the lowest operating cost.

The 5% point was selected to illustrate the optimization process. Some additional analysis is needed to determine how much of a power deficiency is acceptable to the driver in FTP-Urban type driving. Again, the heat engine is always available for additional power requirements, but the system would have to be designed to minimize its use in the primary electric mode of operation.

VI. RESULTS - MISSION 7

The same general procedure of parametrically considering the vehicle design possibilities used in mission 2 was used in mission 7. The same four vehicle versions A, B, C, and D, corresponding to motor/battery power design points were analysed over a range of battery weights, from 10% of gross vehicle weight, to 30%. Gross vehicle mass, battery mass, and total power-train peak power are shown in Figure 2-22. Engine and motor power ratings are shown in Figure 2-34, and primary electric range is shown in Figure 2-24. These figures depict trends that are very similar to mission 2. The accumulative fuel consumption as a function of distance travelled is shown in Figure 2-25. Again, the rate of fuel consumed depends primarily on whether the vehicle is operating in primary electric mode, and secondarily on the driving cycle. The overall fuel economy at 195 KM trip length, and the annual fuel economy are shown in Figures 2-26a and 2-26b, for lead-acid batteries.

The general trends of increasing fuel economy as function of increasing battery mass fraction evident in mission 2 are the same for mission 7. The major difference is in the trend of fuel economy at 192 Km as a function of energy available from the battery especially at low battery fractions. The power-energy sizing and cut-off criteria shown in Figure 2-6 was used in mission 7. Absolute energy from the battery decreased from vehicle A to D for a given battery fraction, and in most cases, would result in a decrease in fuel economy.

However, Figure 2-26b indicates that at MFB = 10% vehicle A has about the same fuel economy as vehicle D, and the fuel economy of vehicles B and C is about 20% higher. This trend indicates a critical power level required by the numerous van cycles of mission 7, such that the heat engine in vehicle A is utilized a larger percent of the time at low power levels, thus resulting in low overall fuel economy. As the motor power increases in vehicles B, C, and D, the motor power is sufficient to eliminate most of the unfavorable operating points, and total electrical energy becomes the dominant parameter.

The effect of PFUEL operating strategy is shown in Figure 2-26c. The penalty for continuous engine operation is severe in mission 7 due to the large percentage of idling time. Annual fuel economy penalties at 20% battery fraction are 37%, 41%, 22%, and 28% for vehicles A, B, C, and D respectively.

The vehicle system efficiency and energy split between petroleum and wall-plug electricity are shown in Figures 2-27 and 2-28. These figures illustrate one of the trade-offs occurring as battery mass is increased for vehicle design C. All of the vehicles are basically designed with a control scheme that avoids a situation where the batteries are charged by way of the engine running the motor as a generator. This can only be the case if the heat engine is large enough to provide for the driving cycle power requirements in the primary engine mode. This occurs at a total vehicle power split of about 55% for the engine and 45% for the motor. Vehicle design C at an MFB of 30% has a power split of 40/60.

This resulted in heavy usage of the motor during primary engine operation, and required battery charging by the heat engine. This caused the system efficiency to drop off for vehicle C in Figure 2-27, even though the total electrical energy fraction was increasing (Figure 2-28).

Figure 2-29 shows the percent of time that the heat engine was utilized in the primary electric range. For this particular mission, this data could not be used to determine an appropriate design cut-off point for two reasons. The Van cycle acceleration ramps were simulated as constant acceleration profiles causing artificially high power requirements, and, Van cycles contain a large amount of idling time, so that a percentage of total time is not truly representative of the power capabilities of the system. It is sufficient to say that the general trend would be similar to mission 2.

VII. CONCLUSIONS

A Fuel Economy

The major conclusions regarding fuel economy that can be drawn as a result of the analysis presented in this chapter are: fuel consumption can be essentially eliminated or at least minimized during operation in the primary electric mode, and, the fuel consumption penalty of operating in the primary heat engine mode with increased vehicle weight (due to the added electrical system weight) can be minimized or eliminated by judicious sizing of the heat engine and motor.

These conclusions are only applicable if considered within the constraints presented in this chapter.

B. Battery Energy and Power Density

Increasing battery specific energy is very important up to a certain point, then the returns diminish due to the travel patterns, i.e., increasing a hybrid vehicles primary electric range from 60 to 80 Km by increasing the specific energy of the battery pack by 30% is going to have a lesser effect on petroleum displacement because the frequency of travel between 60 and 80 Km is lower than 40 to 60 Km. Thus, somewhere between the specific energy available from lead-acid and sodium-sulphur batteries, a point of diminishing returns exists. This is not necessarily true for the electric vehicle, where the absolute range is determined by the energy density.

The battery power density and the associated energy trade-off is perhaps a more critical parameter. The power density defines the minimum battery pack mass for a feasible vehicle design, and the overall costs are highly sensitive to the battery mass.

C. Design Considerations

Design optimization of parallel hybrid vehicles involves several important considerations and trade-offs. The most fundamental of these is the overall control strategy for the operation of the power-train.

The basic strategy recommended as a result of study is:

- 1) Maximum vehicle power requirements are supplied by heat engine and motor power applied simultaneously.
- 2) Major portion of electrical energy available in batteries is used during the initial portion of the trip.
- 3) Heat engine sized to supply driving cycle power requirements in primary engine mode.
- 4) Motor sized to supply the majority of driving cycle power requirements in primary electric mode.
- 5) Heat engine is never used to charge the batteries.
- 6) Batteries are never allowed to discharge below the point where capable of supplying peak motor power.

The major unresolved design consideration that is not included in the constraints is the optimum trade-off between battery discharge rate, total battery energy available, and the size of the battery pack.

To answer this question the overall cost of operation must be included in the analysis.

The parallel hybrid configuration has several inherent advantages over the series hybrid or the purely electric vehicle. Drive-train components can be sized and controlled such that the sum of the power produced is the maximum required by the vehicle, the range is limited only by the size of the fuel tank, and all of the power-producing components have a direct mechanical path to the wheels. The only disadvantage is the added complexity of the control system, which should be investigated further.

Figure 2 - 1
Hybrid Parallel Power Train
Configuration "1".

Figure 2 - 2
Hybrid Parallel Power-Train
Configuration "2"

Figure 2 - 3
Conventional ICE Power-Train
Configuration.

Figure 2 - 4
Electric Only Power-Train
Configuration.

Figure 2-5. Power vs. Time for Segment of FTP-Urban Cycle, Mission 2, Vehicle D, MFG = 10%, Lead-Acid

Figure 2 - 6

Power Density vs Energy Density and
State-of-Charge for 1985 Lead-Acid
Batteries.

Figure 2 - 7

Power vs Energy Available for 1985
Advanced Batteries.

Figure 2 - 8

Power Demands vs Vehicle Weight,
Mission 1

Figure 2 - 9
Gross Vehicle Mass vs Battery Mass
Fraction, Missions 1 through 7,
Vehicle Design A.

Figure 2 - 10
Annual Fuel Economy vs Battery Mass
Fraction, Missions 1 through 7,
Vehicle Design A, Lead-Acid Batteries.

Figure 2 - 11 Gross Vehicle and Battery Mass, and Total Power vs Battery Mass Fraction, Mission 2, Designs A, B, C, D.

Figure 2 - 12
Engine and Motor Peak Power,
Mission 2.

Figure 2 - 13
Primary Electric Range vs. Battery
Mass Fraction, Mission 2.

Figure 2 - 14a
Primary Electric Range vs. Battery
Mass Fraction, Mission 2, Nickel-Zinc

Figure 2 - 14b
Primary Electric Range vs. Battery
Mass Fraction, Mission 2, Sodium-Sulphur

Figure 2 - 15 Fuel Consumption vs Distance, Mission 2 Lead-Acid Battery.

Figure 2 - 16a
Annual Fuel Economy vs. Battery
Mass Fraction, Mission 2, Lead-Acid

Figure 2 - 16b
Fuel Economy at 192 km vs. Battery
Mass Fraction, Mission 2, Lead-Acid

Figure 2 - 17a
Fuel Economy at 192 km vs. Battery
Mass Fraction, Mission 2, Nickel-Zinc

Figure 2 - 17b
Fuel Economy at 192 km vs. Battery
Mass Fraction, Mission 2, Sodium-Sulphur

Figure 2 - 18
Effect of PFUEL Control Strategy on
Annual Fuel Economy, Mission 2

Figure 2 - 19 Fuel Economy, FTP-Urban (PELEC) and FTP-Highway (PFUEL) vs. Battery Mass Fraction, Lead-Acid Battery.

Figure 2 - 20

Normalized Energy Usage, FTP
Highway, PFUEL-ON Mode, Mission 2,
Lead-Acid Battery.

Figure 2 - 21

Percent Time Heat Engine Required
in PELEC ON/OFF Mode, vs. Battery
Mass Fraction, Mission 2.

Figure 2 - 22
Gross Vehicle and Battery Mass, and
Total System Power vs. Battery Mass Fraction,
Mission 7

Figure 2 - 23
Engine and Motor Peak Power vs
Battery Mass Fraction, Mission 7

Figure 2 - 24
Range vs Battery Mass Fraction,
Mission 7, Lead-Acid Battery.

Figure 2 - 25
Fuel Consumed vs. Distance Mission 7,
Lead-Acid

Figure 2 - 26a Annual Fuel Economy vs. Battery Mass Fraction, Mission 7, Lead-Acid

Figure 2 - 26b Fuel Economy at 195 km vs. Battery Mass Fraction, Mission 7, Lead-Acid

Figure 2-26c. Annual Fuel Economy vs. Battery Mass Fraction for PFUEL On/Off and on Control Strategies, Mission 7, Lead-Acid

Figure 2 - 27
Total System Efficiency at 195 km vs. Battery
Mass Fraction Mission 7, Lead-Acid Battery

Figure 2 - 28
Percent Electrical Energy at 195 km
vs Battery Mass Fraction, Mission 7,
Lead-Acid Battery.

Figure 2 - 29
Percent Time Heat Engine Required in
PELEC ON/OFF Mode, Mission 7.