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HYBRID VEHICLE POTENTIAL ASSESSMENT

**Volume 9: Power Train Summary, Component
Descriptions, and HYVEC Vehicle Simulator**

By
S. G. Liddle
S. P. DeGrey

September 30, 1979

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Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

U. S. DEPARTMENT OF ENERGY

Division of Transportation Energy Conservation

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**ELECTRIC AND HYBRID VEHICLE SYSTEM
RESEARCH AND DEVELOPMENT PROJECT**

**HYBRID VEHICLE POTENTIAL ASSESSMENT
VOLUME IX. POWER TRAIN SUMMARY,
→ COMPONENT DESCRIPTIONS, AND
HYVEC VEHICLE SIMULATOR**

September 30, 1979

S. G. Liddle
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

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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

Report No.	Subject	Author(s)
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

OVERALL SUMMARY OF CONCLUSIONS -----	1-1
INTRODUCTION -----	1-1
CONTROL CONSIDERATIONS -----	1-1
DESIGN CONSIDERATIONS -----	1-3
FUEL ECONOMY CONSIDERATIONS -----	1-4
CHARACTERIZATION OF POWERTRAIN COMPONENTS FOR ELECTRIC HYBRID VEHICLES -----	2-1
1. Introduction -----	2-1
Heat Engines -----	2-1
Electric Motor, Generator and Controller -----	2-2
Batteries -----	2-3
Transmission -----	2-4
Vehicle, Chassis and Performance -----	2-4
HYBRID VEHICLE SIMULATION PROGRAM "HYVEC" -----	3-1
GENERAL CAPABILITIES -----	3-2
Power-Train Sizing and Vehicle Weight -----	3-2
Driving Cycles -----	3-4
Drive - Train Modeling -----	3-4
Transmissions -----	3-5
Motor/Generator and Controller -----	3-5
Heat Engines and Accessories -----	3-5
Battery Model -----	3-6
APPENDIX -----	4-1

Figures

1.	Engine Map for Pontiac 151 CID Engine -----	2-8
2.	Engine Map for Chevrolet 250 CID Engine -----	2-9
3.	Engine Map for Mercedes 183 CID Diesel -----	2-10
4.	Motor Efficiency - Lucas 40 KW D.C. Series -----	2-11
5.	Battery Characteristics -----	2-12
6.	Power Available vs. Net Energy Supplied - 1985 Lead-Acid Battery Pack, Mass = 100 Kg -----	3-8

Tables

1.	Engine Details -----	2-6
2.	Battery Characteristics -----	2-7

OVERALL SUMMARY OF CONCLUSIONS

Introduction

When the results for all three types of hybrids are compared, certain conclusions about them may be drawn. These conclusions fall into three categories; control considerations, design considerations and fuel economy considerations.

While there are some features of the hybrids which are common to all of them, the detailed design trade-offs and the optimization varies from type to type, from configuration to configuration and from mission to mission.

Control Considerations

The goal of this hybrid program is to reduce petroleum consumption and to use electricity in its place. The travel distribution for the missions indicate that most trips are of relatively short length and that few are long distance trips. It is, therefore, desirable to make as many of the short trips as possible on electricity and to have the capacity to make long trips using petroleum. The hybrid vehicle has this capability providing its operating strategy is properly designed.

It was found on all three types of hybrids that an operating strategy which uses electricity alone or with a flywheel for the first portion of the daily driving cycle and uses the engine only after the batteries are effectively discharged, displaced the greatest amount of petroleum fuel on an annual basis.

It was also found that the use of an ON-OFF engine control scheme resulted in lower petroleum consumption than did a continuously-ON control. The very best fuel economy resulted from turning the engine off whenever its power is not needed. The frequent starting and stopping of the engine by this operating strategy is not practical. The best compromise strategy for the parallel hybrids is for the engine to remain off during the electrical driving phase of the daily driving cycle and to assume the base load once it is turned on. For the series hybrid, the strategy is to have the engine turned off during the initial electrical driving phase and to turn on when the battery is no longer able to meet the load requirements. During the time it is on, it runs at or near its best BSFC condition supplying both the vehicle needs and charging the batteries. When the batteries have been recharged to a reasonable state-of-charge, the engine is shut off and the batteries are used to drive the car.

In both the parallel and series type of hybrids, residual battery power may be used to load-level the heat engine during the time it is providing the base load. While the batteries may not be able to provide power to meet the full load, they may still be able to meet the relatively small power demands for load-leveling.

Design Considerations

These considerations are primarily aimed at component sizing. The methods for sizing are similar for all of the types of hybrids and these similarities are discussed here.

Since the initial portion or phase of the daily driving cycle is to be electrical, the motor and controller must be capable of meeting the maximum driving cycle requirements. In the case of the series hybrid, the motor and controller must be capable of handling the maximum acceleration power load. The generator used for the series hybrid, however, need only provide power to meet the driving cycle requirements. The battery makes up the difference in order to meet the maximum acceleration load.

The engine is sized to meet driving cycle requirements in all three types of hybrid. Peak power requirements are met by the engine with the help of the batteries. In the parallel-flywheel hybrid, the flywheel may be used instead of the batteries for peak power. In the parallel systems, direct charging of the batteries by the engine should be avoided.

The size of the transmission in the parallel hybrids depends on the configuration. The transmission in the parallel-flywheel hybrid is sized to match the engine output. In the parallel hybrid, it is sized to match the output of the motor and the engine since the motor in this case is at the transmission input rather than at its output as in the flywheel hybrid version.

Battery sizing is primarily a function of the power and range requirements of the electrical-power-only phase of the daily driving cycle. In general, there is a minimum battery size that will enable the vehicle to meet the performance criteria. This size is set by the power density-energy density relationship of the battery. Increasing the battery mass above that required for performance increases the range. Range may also be increased by the use of batteries with a superior power-energy relationship.

Fuel Economy Considerations

The control considerations presented earlier touched on fuel economy as it affects electrical power usage. The section discusses some additional points affecting the fuel economy of the hybrid vehicles.

The use of a diesel engine instead of a spark ignition engine will increase the fuel economy of the hybrid vehicle regardless of the type.

The reduction in the relative size of the engine in a hybrid vehicle results in a higher power loading and better specific fuel consumption which in turn offsets the weight penalty of the battery and the associated electrical equipment.

For most of the missions, the full driving cycle fuel economy increases as the battery mass fraction increases. The exceptions to this rule are typified by an unusually large amount of idle time in the driving cycle.

For all hybrids, the operating strategy is the largest single factor affecting the fuel economy of a hybrid vehicle. By properly designing the operating strategy, it is possible for all types of hybrids to show an improved annual fuel economy and the replacement of a substantial amount of petroleum by electricity.

CHARACTERIZATION OF POWERTRAIN COMPONENTS

FOR ELECTRIC HYBRID VEHICLES

1. Introduction

The three types of hybrids considered in this study; series, parallel and parallel-flywheel, have a number of components in common. These include the engine, batteries, motors, controllers, differentials, tires, the chassis and a transmission. For convenience, the characteristics of these common components are presented here rather than in the sections dealing with each type of hybrid. In those cases where a component is used exclusively for a particular type of hybrid such as a flywheel, its characteristics are presented in the appropriate section.

The characteristics of the components presented here are felt to be representative of the expected state-of-the-art in the 1980's.

Heat Engines

Three engines were selected for use in this study as models. Two spark ignition engines, a Pontiac 151 CID 4 cylinder and a Chevrolet 250 CID 6 cylinder engine, were used as well as a Mercedes Benz 4 cylinder 183 CID diesel engine. The engine maps, plots of engine speed, power and fuel flow, are presented as Figure 1 to 3 for the three engines respectively.

In use, the maps are scaled to the engine power level determined by the mission requirements. The Pontiac engine was used for the passenger car missions when the Otto cycle engine was specified. The Chevrolet engine was used for the van missions. The Mercedes engine was used as the diesel engine for all missions. Details of the baseline engines are given in Table 1.

The scaling of the map assumes that the shape of the maximum power line and the brake specific fuel consumption are independent of the peak power rating of the engine.

The engine mass in kg is computed by multiplying the peak power in KW by a factor of 2.35 and adding 22.7 to the product.

Electric Motor, Generator and Controller

One motor map, shown as Figure 4 was used for all motors regardless of the hybrid type and for the generator in the series hybrid. This map, a plot of motor speed, power and efficiency, was scaled as necessary to meet the requirements of each mission.

The baseline motor used for the map is a Lucas d-c series traction motor with a peak output of 40 kw and a 4200 rpm maximum speed. The maximum power curve shown in Figure 4 is characterized by constant torque at low speed, constant power in the middle speed range and a drooping power characteristic at high speed.

The controller efficiency when the motor is used as a generator is assumed to be 99.5%. Its efficiency for the motor as a motor depends on its relative speed. When the ratio of output speed to design speed is less than 0.414, the efficiency is 96% and above that speed, it is assumed to be 99.5%.

The mass of the motor and generator in KG is the peak power in KW divided by 0.4. The controller mass in KG is its peak power rating in KW divided by 0.8.

Batteries

Three different batteries were used in this analysis; 1985 lead-acid, nickel-zinc and sodium-sulphur. Details of the batteries are given in Table 2 and their power density-energy density relationship is shown in Figure 5 on cartesian coordinates rather than the logarithmic coordinates frequently employed. These curves are based on 3 hour discharge rate (C/3). Battery degradation due to cycle life and to depth of discharge effects have not been taken into account. The effect of battery temperature on battery output has not been taken into account due to a lack of adequate data.

Transmission

All of the hybrids investigated used a transmission and for the purpose of this study, a four speed manual transmission was used. The gear ratios in the first three gears were modified for the various hybrids in an attempt to obtain a balance between fuel economy and acceleration. The requirements of the parallel-flywheel hybrid where the transmission serves only the engine is different and the gear ratios tend to be different from the parallel hybrid where the transmission serves both the engine and the motor. The gear ratios are not given here since they vary not only from type to type but also mission to mission and operating strategy to operating strategy.

The design power of the parallel-flywheel is the same as the peak power of the engine. In the parallel hybrid, it is designed to the peak acceleration power which is met by both the engine and the motor feeding power into the transmission input. The series hybrid transmission is matched to the output of the motor. The mass of the manual transmission in KG is calculated by dividing the design power in KW by 1.8.

Vehicle, Chassis and Performance

The basic vehicle and chassis characteristics are independent of the type of hybrid used, the batteries, the engine and the control strategy. These common characteristics were developed in mission analysis and are also listed elsewhere in this report but for convenience they are given in Table 3.

Certain performance standards for each mission must be met by the vehicles analyzed. The standards are listed in Table 4. These figures are minimum values, an actual hybrid system may exceed one or more of them but must, at least, meet all of them. These standards, like the vehicle characteristics were developed outside of the powertrain analysis as part of another section of the assessment task and are presented solely for the reader's convenience.

TABLE 1
ENGINE DETAILS

ENGINE	POWER KW	DISPLACEMENT LITERS	IDLE		MAXIMUM SPEED RPM
			SPEED RPM	FUEL FLOW KG/H	
Pontiac 151 CID	67.5	2.5	800	.68	4400
Chevrolet 250 CID	79.0	4.1	800	1.64	3800
Mercedes 183 CID Diesel	51.5	3.0	800	.55	4000

TABLE 2

BATTERY CHARACTERISTICS

BATTERY	MAXIMUM (C/3 RATE)		EFFICIENCIES	
	POWER DENSITY KW/KG	ENERGY DENSITY KW-H/KG	CHARGE	DISCHARGE
Lead-Acid	.154	.066	.80	.90
Nickel-Zinc	.180	.095	.80	.90
Sodium-Sulphur	.170	.137	.80	.90

Figure 1. Engine Map for Pontiac 151 CID Engine

Figure 2. Engine Map for Chevrolet 250 CID Engine

Figure 3. Engine Map for Mercedes 183 CID Diesel

Figure 4. Motor Efficiency - Lucas 40 KW D.C. Series

Figure 5. Battery Characteristics

HYBRID VEHICLE SIMULATION PROGRAM "HYVEC"

The Hybrid Vehicle simulation program "HYVEC" was developed to support the vehicle/power-train analysis work within the Hybrid Vehicle Potential Assessment Task. The general structure of the program is based on individual modeling of component performance and efficiencies, and power/speed paths from the wheels through the entire drive-train. Driving cycle simulations are calculated sequentially using a finite increment of differential time, usually one second. The component models are utilized as generic rather than specific representations of actual hardware, and as such, are in non-dimensionalized form, allowing considerable flexibility in scaling and in parametric trade-off application. The basic design of the program allows maximum flexibility in sizing of vehicle components, i.e. engine and motor power, flywheel energy and battery mass.

Two features are implemented which allow this flexibility; first, the component performance data is scalable, and, secondly, the total vehicle weight including component and propagated chassis weight is calculated within the program. Vehicle cost considerations are handled within separate programs using input data generated by HYVEC.

The basic HYVEC program was separately modified for each of the three major configurations, parallel, parallel with flywheel, and series. Each of the resultant program versions use the same basic modeling approach and data, but vary widely in the details of the configuration-unique portion of the program, such as the controller logic.

GENERAL CAPABILITIES

Power-Train Sizing and Vehicle Weight

The vehicle sizing routine is set up to determine the size, on a power and weight basis, of the components in the power-train, including the batteries, as well as the chassis weight and total vehicle weight. This is controlled by specifying certain general power-train characteristics such as power-to-weight ratio, battery/vehicle weight ratio, and the fraction of the total vehicle power that is ascribable to each power-producing component. The total power-train is divided into the following elements: heat engine, motor/generator, controller, transmission, batteries, and flywheel. For a given run, each one of the components has a maximum power associated with it as well as a power-to-weight ratio (specific power) such that the entire vehicle weight can be determined by writing the following equations*:

*Parameters defined in Appendix 1

$$MV = MCHAS_N + MPAYL + MENG + MMTR + MCONTR + MBATRY + MFLWHL$$

$$MENG = K_P * MVEH * PFE/ESP$$

$$MMTR = K_P * MVEH * PFM/MSP$$

Similar equations for the other components leads to the final equation for vehicle weight:

$$MV = MCHAS_N + MPAYL + K_P * MV (PFE/ESP + PFM/MSP + KTP/TSP + \frac{PFM * KOL}{CSP} + \frac{PFFW * TFWP}{C * FWSE} + MFB/K_P)$$

Solving for vehicle weight, MVEH:

$$MV = \frac{MCHAS_N + MPAYL}{(1 - K_P (PFE/ESP + \dots + MFB/K_P))}$$

This equation allows solution for vehicle weight explicitly. A hybrid vehicle power-train is almost heavier than its equivalent conventional ICE counterpart. To account for this effect on chassis weight, two quantities are defined.

$$MFPT = \frac{\text{MASS POWER-TRAIN (ICE NOMINAL)}}{\text{MASS CHASSIS (ICE NOMINAL)}}$$

$$KMP = \frac{\text{ADDITIONAL CHASSIS WEIGHT}}{\text{ADDITIONAL POWER-TRAIN WEIGHT}}$$

By using these quantities and equation (1), the vehicle weight is solved for in an iterative fashion.

Driving Cycles

Driving cycle capability includes EPA-Highway, EPA-Urban, SAE-C, SAE-D, Aerospace corp. Delivery Van, Highway-Van, and New York City Emission cycles. Up to 17 sequentially different driving cycles or sets of cycles can be specified by the user.

Drive - Train Modeling

Road Load

The basic model for tire and wheel bearing losses used in HYVEC was compared with several other models and experimental data. Results of the survey established the equation as a reasonable approximation of losses, providing that the proper value for the overall coefficient is utilized.

The basic equation is:

$$F_{rl} = \mu Mv [1 + C_1 V + C_2 V^2]$$

Where units of C_1 and C_2 are $(ft/s)^{-1}$ and $(ft/s)^{-2}$ respectively.

The final equations for all the vehicle power requirements at the wheel are:

Tire and Bearing Losses

$$P_{tb} = M * MV * (1. + C_1 * 0.9113 * V + C_2 * (.9113 * V)^2) * V/367.0978$$

Aerodynamic Drag:

$$P_{aero} = C_d * A_f * (V + V_{wind})^2 * V * (530/(460 + T_{amb}))/77760.$$

Gradient:

$$P_s = S * MV * V/36709.78$$

Vehicle Inertia:

$$P_a = A * MV * V/12960.$$

Transmissions

The basic transmission used in the HYVEC computer programs is a 4-speed manual transmission, with shifting logic based on vehicle speed and power requirements. Clutch coupling/de-coupling losses are included in flywheel version of the program. The flywheel version also included a continuously-variable transmission model that was used in conjunction with the flywheel.

Motor/Generator and Controller

The motor/generators are modeled in terms of power-speed-efficiency maps. Performance characteristics of a typical series traction motor designed for electric vehicle utilization (LUCAS 40-KW) are used in all three programs. Controller/power conditioning losses are calculated using a single point efficiency, applied to all power flow into or out of the batteries.

Heat Engines and Accessories

Heat engine performance was modeled with two forms of data within the program, power-speed-BSFC maps and power-speed-fuel flow maps. Fuel flow maps eliminate the problem of characterization of fuel consumed at very low power levels, as BSFC tends toward infinity as power approaches zero. The calculation of fuel flow for a scaled engine from BSFC utilizes the ratio of the local powers, while calculation from absolute fuel flow utilizes the ratio of peak powers, giving identical results (except at zero or near zero powers).

$$\dot{M}_f = \text{BSFC}_{\text{map}} * \text{PENG} \quad (\text{from BSFC map})$$

$$\dot{M}_f = \dot{M}_{\text{map}} * \text{PENG peak/PENG peak} \quad (\text{from } \dot{M}_f \text{ map})$$

(map)

All of the engine maps used in this study were fuel-flow, except for the Mercedes diesel.

Accessory models available in the HYVEC programs include the following: alternator (average 30-amp load), power steering pump, air conditioning pump, fan, and water pump. The accessory power losses are a function of shaft speed. Accessory loads are typically assigned to the heat engine or the motor, or both depending on the design of the particular configuration and control strategy.

Battery Model

The battery model used in HYVEC utilizes the Ragone power-energy relation to define the maximum discharge rate as a function of net energy supplied by the battery.

As an example, consider a battery pack weighing 100 Kg with power-energy characteristics of the 1985 lead-acid battery (Fig. 8-6).

At zero net energy supplied, the battery is fully charged, and is capable of supplying about 15.5 Kw of power. As energy is supplied by the battery to the power-train, the maximum power capability decreases. A charge-discharge efficiency is applied to energy flowing into the battery in the accounting of net energy.

$$E_{\text{net supplied}} = E_{\text{out}} - E_{\text{in}} * N_{\text{cd}}$$

This model is, by definition of the Ragone power-energy relation, exact in predicting the energy available at a given discharge rate. For example, at a constant discharge rate of 4 kilowatts, 3.8 Kw-Hr of energy can be supplied by the batteries. It is felt that the model also gives a reasonable approximation of power available as a function of energy supplied for transient charge-discharge rate application.

Figure 8-6 Power Available vs Net Energy Supplied - 1985 Lead-Acid Battery Pack, Mass = 100 Kg

APPENDIX

<u>NAME</u>	<u>MEANING</u>	<u>UNITS</u>
MV	GROSS VEHICLE WEIGHT	Kg
MCHAS _N	NOMINAL CHASSIS WEIGHT	Kg
MPAYL	PAYLOAD	Kg
MENG	ENGINE WEIGHT	Kg
MMTR	MOTOR/GNE WEIGHT	Kg
MTRANS	TRANSMISSION WEIGHT	Kg
MCONTR	CONTROLLER/ELECTRICS WEIGHT	Kg
MBATRY	BATTERY WEIGHT	Kg
MFLYWH	FLYWHEEL ASSEMBLY WEIGHT	Kg
Kp	VEHICLE POWER-TO-WEIGHT RATIO	Kw/Kg
PFE	ENGINE POWER FRACTION	-
ESP	ENGINE SPECIFIC POWER	Kw/Kg
PFM	MOTOR POWER FRACTION	-
MSP	MOTOR SPECIFIC POWER	Kw/Kg
TSP	TRANSMISSION SPECIFIC POWER	Kw/Kg
KOL	MOTOR OVERLOAD	-
CSP	CONTROLLER SPECIFIC POWER	Kw/Kg
TFWP	FLYWHEEL MAX. POWER DURATION	Sec
FWSE	FLYWHEEL SPECIFIC ENERGY	Kw-Hr/Kg
MFB	BATTERY WEIGHT/VEHICLE WGT.	-
C ₁	1.4×10^{-3}	(ft/s) ⁻¹
C ₂	1.2×10^{-5}	(ft/s) ⁻²

<u>NAME</u>	<u>MEANING</u>	<u>UNITS</u>
P_{tb}	TIRE AND BEARING	Kw
P_{aero}	AERODYNAMIC	Kw
P_s	SLOPE	Kw
P_a	VEHICLE INERTIA	Kw
μ	OVERALL ROLLING RESISTANCE COEFFICIENT (INCLUDED IN MISSION SPECIFICATIONS)	Kg/Kg
V	VEHICLE VELOCITY	Km/Hr
C_d	DRAG COEFFICIENT	-
A_f	FRONTAL AREA	M^2
V_{wind}	WIND VELOCITY	Km/Hr
T_{amb}	AMBIENT TEMPERATURE	$^{\circ}F$
S	PERCENT GRADE	%
A	VEHICLE ACCELERATION	Km/Hr-s