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HYBRID VEHICLE POTENTIAL ASSESSMENT

Volume 4: Series Systems

By
Z. Popinski

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 IV. SERIES SYSTEMS

September 30, 1979

Z. Popinski

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

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1. INTRODUCTION

Hybrid electric vehicles combine an on-board heat engine with an energy storage system (battery, flywheel) and conversion devices (motor, generator) as major components of the propulsive system. Many powertrain component arrangements and power flow paths are possible. According to the way power is transmitted to the vehicle drive wheels, vehicles may be either parallel and series configurations.

In the Hybrid Vehicle Potential Assessment Task three major powertrain configurations (parallel, parallel with flywheel and series) have been studied. In order to establish the relative merits of each of these configurations detailed simulation studies have been made. This report describes the evaluation of the series configuration. Work on the other two configurations is discussed in two other supplemental reports.

The series configuration has the advantage that the engine is mechanically uncoupled from the wheels and can be operated at its best economy point much of the time. The mechanical energy produced by the engine is converted through a generator into electrical energy which is used to drive the motor or charge the batteries. This configuration offers a good degree of flexibility. It has the disadvantage that substantial losses of energy occur since the mechanical energy from the engine passes through several components before being used to drive the wheels. The energy produced by the engine is reduced by the produce of efficiencies of components connected in series.

Trade-offs involved in the study of the series configuration were directed toward (1) establishing the size of the engine, motor and generator to meet vehicle acceleration performance; (2) determining what level to operate the engine, and (3) determining when to use the battery. These results were then used in the electric range simulation.

2. SERIES CONFIGURATION

A simplified schematic in Fig. 1 shows a series configuration of a heat engine/battery hybrid vehicle. The heat engine drives an electrical generator which then transmits energy to be used to drive the electric motor or to recharge the batteries. The output from the electric motor passes through a transmission and differential to the wheels. If the load demand exceeds the capacity of the heat engine, additional energy is supplied to the motor by the batteries. This configuration provides a number of control options for the vehicle:

- a. Within the electric range, energy for the motor is supplied primarily by the battery with the heat engine operating continuously as a load leveler.
- b. Within the electric range, energy for the motor is supplied primarily by the battery with the heat engine operating in an off-on mode as a load leveler. Heat engine operates continuously during extended range.

c. Energy is continuously supplied to the motor by the heat engine with the battery being charged or discharged depending on the energy required by the motor and the battery state-of-charge.

In the first option, the energy for the motor is supplied by the battery with the heat engine operated continuously at a low power level to drive the engine mounted accessories. Within the electric range, the heat engine is switched to a higher power level to meet unusual load requirements (highway passing). When the battery is depleted to a prescribed minimum level. The battery stops supplying energy to the motor and the heat engine is switched to a higher power level to meet the vehicle power requirements.

In the second option, the energy for the motor is supplied by the battery with the heat engine operated in the on/off mode for load leveling. In this case, all non-engine accessories must be driven electrically. Beyond the electric range, the heat engine is operated continuously to meet vehicle power requirements.

In the third option, the heat engine is operated continuously at a low or intermediate power level and supplies energy to the motor. Depending on the energy requirements of the motor, the battery may act as a load leveler by supplying energy to the motor or may be charged if engine power is available and the battery is below the minimum state-of-charge.

3. CONTROL STRATEGY

The main goal of an acceptable strategy for a hybrid vehicle is to operate it with the least possible fuel consumption during a designated electric range. During this phase, the battery is used as the primary power source. If the battery reaches the point where it cannot satisfactorily perform an acceleration maneuver, the heat engine takes over the task of providing the primary energy.

From an energy standpoint, three driving modes can be differentiated:

- a. Full Throttle Acceleration Mode
- b. Electric Range Mode
- c. Extended Range Mode

Depending on the operating mode of the vehicle, the heat engine can be set at different power levels (Fig. 2). During acceleration maneuver, the engine is set at 90% of its peak power. Since this maneuver is of short duration, the penalty in fuel economy should not effect the total fuel consumption significantly. During the electric range, the heat engine is set at a partial load, typically from 5-15% of the peak power of the engine. During extended range operation with the heat engine supplying the bulk of the required energy, it is important to have the engine working in the best fuel economy range, which was assumed to be at 50% of the peak power.

It is desirable that these three engine power operating levels be located on the locus line of best fuel economy. Fig. 2 shows the characteristic heat engine performance lines in terms of power and engine speed which are non-dimensionalized for convenience of scaling the power and speed to any values needed. It should be realized, that scaling of fuel consumption may lead to serious inaccuracies, especially if the power of the engine differs greatly from the nominal rating of the original engine for which the fuel map has been obtained. Fig. 2 also shows a power profile for the motor and generator. Since the generator converts the mechanical energy of the engine which works predominately at 50% of its power, the generator has been sized for half of the engine power, assuming that overload conditions during the acceleration mode are within the generator tolerance limit.

Chemical battery performance is defined by characteristic curves in terms of the battery specific power (BSP) as a function of battery specific energy (BSE) as shown in Fig. 3. This is an ideal and simplified characterization of the battery which determines the maximum power available from the battery, based on constant discharge and charge rates. The important temperature effect which limits the performance of the battery is not included. The battery state (BST) which is a measure of the available stored energy, is defined by $BST = 1 - \frac{BSE}{BSE_{MX}}$

where BSE is the value of the specific energy at the current location on the performance curve. Values of BST range from 1 for a fully charged battery to 0 for a dead battery. The useful range of the battery extends from the maximum BST (BST_{MX}) to the minimum BST (BST_{MN}), below which value the battery needs charging.

3.1 Acceleration Mode

The full throttle acceleration mode is performed using the heat engine set at a high power level as the main energy source and with an assist from the battery which should be maintained at or above a certain minimum level (i.e., $BST \geq .5$):

Sizing of the essential components is dictated by a satisfactory performance of the vehicle for the acceleration maneuvers in Table 5. The acceleration mode is one of the most demanding driving modes for a vehicle. The vehicle must be able to perform it at any time. (i.e., when merging with traffic, or during a passing maneuver).

3.2 Electric Range Mode

During the electric range mode the vehicle is primarily battery powered with the heat engine supplying the necessary energy to supplement the battery and to drive any engine accessories. During this phase the battery energy is depleted to a predetermined level which must be sufficient to meet the load demands during the acceleration maneuver.

Driving the vehicle over the electric range (50, 75 and 100 Km) is accomplished assuming the battery is initially at the maximum state-of-charge (100%). It is assumed that the battery will be recharged by electric power from the utility industry (i.e., via a wallplug). The heat engine is operated only at partial load, typically from 5-15% of power in order to drive the accessories and to assist the battery. It is assumed that the battery is properly sized when its state-of-charge is depleted to 50% at the end of the electric range.

3.3 Extended Range Mode

At the end of the electric range, the battery state-of-charge is assumed to be depleted to 50% and cannot be used as the primary power source. At this point engine operation is changed to a power level equal to 50% of the maximum engine power. The battery is used as the need arises but is maintained at 50% state-of-charge, either by regenerative braking or utilizing the excess power of the engine. Thus, the range of the vehicle is extended according to the fuel reserve in the tank and the battery is maintained at a state capable of sustaining the successive accelerations when needed.

4. DESIGN CONSIDERATIONS

Design considerations of the series hybrid vehicle involve performing trade-off studies between the conflicting aspects of the vehicle characteristics. These studies are oriented toward optimization of the vehicle. Since it is impossible to define one single all-purpose vehicle, several types of vehicles meeting various applications were defined and evaluated. Of the various applications available, the following two were considered in this assessment of the series hybrid vehicle:

(1) a commuter vehicle (designated Mission I) and (2) a fixed route delivery van (designated Mission VI). A vehicle with two occupants or less accounts for about 92% of business trips and 77% of family business trips. Thus, a commuter and family business car is in great demand and is a logical choice as a candidate for a hybrid electric vehicle. It is designated as Mission I vehicle with a payload of 2 passengers and 50 KG. This mission is described by a driving schedule consisting of 4 urban cycles and 10 highway cycles covering a total distance of 213 KM. The vehicle selected for Mission VI is a fixed route delivery truck/van with 2 passengers and 750 KG maximum payload. The increasing number of vans sold in recent years justify consideration of this vehicle for study as a hybrid vehicle. This mission consists of 6 urban cycles and 8 highway cycles covering a total distance of 204 KM.

4.1 Parametric Trade-off Studies

The hybrid vehicle system consists of many components and optimizing their proper sizes in relation to the total vehicle weight and performance while meeting mission requirements is a formidable task. Evaluation of vehicle performance can be accomplished by considering full throttle acceleration maneuvers, or by using standardized driving cycles, such as the EPA urban and highway cycles.

The performance of a hybrid electric vehicle is characterized by a number of parameters which are helpful in defining the system and are very useful in the design studies. Two parameters which are used in characterizing the total vehicle are total vehicle weight and vehicle power-to-weight ration. These can be used to calculate a "base power" for the vehicle

$$P_B = M K_P$$

where,

P_B = base power of vehicle

M = total vehicle weight

K_P = vehicle power-to-weight ratio

The power of the heat engine and motor is expressed relative to this "base power" by the following equations

$$P_{FE} = \frac{P_{HE}}{P_B}$$

$$P_{FM} = \frac{P_{MTR}}{P_B}$$

Where, P_{HE} = power of heat engine
 P_{MTR} = power of motor
 PFE = engine power fraction
 PFM = motor power fraction

Battery weight is expressed relative to total vehicle weight as follows:

$$MFB = \frac{M_B}{M}$$

Where, M_B = battery weight
 MFB = battery weight fraction

In order to gain insight into the behavior of this complex system, a parametric study of vehicle acceleration was made. The acceleration is simulated for the Mission I vehicle with an Otto engine and lead-acid battery, although the trends should be typical for other mission/engine/battery combinations. The acceleration time is shown in Figure 4 as a function of other vehicle parameters. All curves with the exception of curve (7) show a decreasing acceleration time with an increase in battery state-of-charge. The effect of the motor overload factor on acceleration time is illustrated by comparing curves (5) and (7) which have motor overload factors of 2.0 and 1.5, respectively. As the initial battery state-of-charge is increased on curve (7), the battery power available for acceleration is limited by the capacity of the motor and further increases in battery state-of-charge do not improve the acceleration time.

Comparing curves (1) and (2) leads to an observation that increasing the motor overload factor from 1 to 1.5 reduces acceleration time by about 3% when vehicle performance is not limited by the capacity of the motor. It should be pointed out that momentary overload of the motor improves not only acceleration performance, but also results in a smaller and lighter motor and improves the overall vehicle weight/cost aspects.

The effect of heat engine size on acceleration time is shown clearly by curves 2, 3, and 7 which have engine power fractions of .4, .55, and .6, respectively. Since the full throttle acceleration is performed using the heat engine as the main power source, an increase in engine power fraction reduces acceleration time significantly. As shown in curves (5) and (6), increasing the battery weight fraction from 0.15 to 0.20 reduces the acceleration time by 11% even though the vehicle weight increases from 1510 to 1700 KG. Note that the effects of increasing the engine and/or battery power on acceleration performance are limited by the capacity of the motor.

The effects of vehicle power-to-weight ratio, engine power fraction, battery weight fraction and initial battery state-of-charge are illustrated in Fig. 5. An increase in vehicle power-to-weight ratio is seen to produce a sharp increase in vehicle weight and a decrease in acceleration time.

The effect of the battery weight fraction on the acceleration time and vehicle weight is shown in Fig. 6. As expected, an increase in battery size reduces the acceleration time and increases the vehicle weight. Fig. 7 shows the effect of the engine power fraction on acceleration time. The acceleration performance improves with increasing engine size until it is limited by the capacity of the motor as illustrated by curve (2) which has a motor overload factor of 1.0. With a motor overload factor of 2, the motor capacity is increased, permitting improvements in acceleration time for engine power fractions up to 6. The operational point described by the power-to-weight ratio .07, engine size $PFE = .6$ and overload factor 2. seems to offer optimum operating conditions for the vehicle.

Two frequently used driving cycles are the EPA highway and city cycles. The peak and average power demand for these cycles as a function of vehicle weight are plotted in Fig. 8. It is noted that the peak power required is higher for the urban cycle than for the highway cycle; however, the average power required is higher for the highway cycle. The energy consumption for the highway cycle is about 50% higher than that for the urban cycle for a vehicle weight of 1000 KG; however the energy consumptions for the urban and highway cycles become about equal for a vehicle weight of 5000 KG. Also included in Fig. 8 is a curve for acceleration time which seem to decrease with increasing vehicle weight. This suggests that the power to weight ratio could be decreased slightly for increasing weight to achieve a constant acceleration time.

These average power profiles can be used as a guide for sizing the power source to meet road load power requirements. In addition, the energy consumption curves are indicators of the capacity of the storage device required.

4.2 OPTIMIZATION AND SIZING

The sizing of components was accomplished by requiring that the vehicle meet the acceleration performance requirements. This places the most stringent demand on the powerplant and if it is satisfied, driving cycle road loads can be met by the vehicle. This establishes the size of the engine, motor, generator and battery. For electric range simulation some adjustments of the power level and battery size were needed to reach the desired range and to maintain the battery state at a prescribed minimum level to sustain the acceleration maneuver.

A plot of acceleration time versus initial battery state-of-charge is shown in Fig. 9 for the vehicle parameters selected as a result of the parametric studies. The required acceleration time for the Mission I vehicle is met with an initial battery state-of-charge of 50% which allows utilization of the bulk of the battery energy for the electric range driving and still meet acceleration demands. Fig. 5 confirms that a vehicle power-to-weight ratio of 0.07 is an acceptable compromise value considering the effects of vehicle weight, acceleration time and battery state-of-charge. Fig. 7 indicates that an engine power fraction of 0.6 is an optimum value for sizing the engine. Assuming that the sum of the engine and motor power fractions is equal to 1, this yields a motor power fraction of 0.4. It should be noted that although the motor in a series configuration has to be capable of transmitting the sum of power supplied by the engine/generator and the battery, only a fraction of the engine power corresponding to the product of the efficiencies of the generator and the controller is transmitted to the motor.

With the above parameters established, what remains to be determined is the operating power level of the engine for electric range driving. The engine power level selected for the electric range mode may significantly influence the fuel economy, mainly because of the distribution of the brake specific fuel consumption lines in the low power/speed region. The operating engine power fractions which lead to the best vehicle fuel economy are shown plotted versus the electric range in Fig. 10.

Eventually the same approach which has been used to size the system components was used to optimize the operating conditions for other combinations of engine/battery and for different electric ranges and missions.

Table 1 represents the optimization results based on acceleration performance for the simulated cases for Missions I and VI. Based on these results, preliminary electric range simulation results for ranges of 50, 75 and 100 KM and various combinations of engine/battery for Missions I and VI are summarized in Table 2. These parameters had to be modified in some cases to meet the ranges and the requirement to maintain the state of the battery at 50% throughout vehicle operation.

5. RESULTS

Analysis of the series hybrid configuration were conducted to establish the potential for near-term reduction of the transportation fuel consumption. The vehicles, designed for specific missions, were simulated in their optimized versions. This was done using a computer simulation program which includes models of the major system components: heat engine, electric motor, generator, battery, transmission and controller.

System components were selected after a review of existing hardware, taking into consideration component performance. The factors considered were power rating, efficiency, economy and speed range. This selection process was applied to heat engine, motor and generator. The electric batteries are based on present technology for the Pb-Ac battery and on projections to 1985 for the advanced batteries, Ni-Zn and Na-S, with the performance characteristics being taken from the available literature.

Components were selected on the basis of compatibility with a given configuration, good efficiency and flexibility. Weight propagation of the system components and interactions of individual components were considered. Table 3 shows the simulated cases and combinations of engine and battery types and electric ranges which were studied.

A uniform set of vehicle specifications was used for this study in order to have a common basis for comparison of results for various missions and configurations. The mechanical specifications for all vehicles and missions and the performance requirements are tabulated in Table 4 and 5. A summary of the computer results for the simulated cases for Missions I and VI is shown in Table 6.

5.1 Mission I

The vehicle for mission I was simulated for two types of engines, Otto and diesel, and three types of batteries, Pb-Ac, Ni-Zn and Na-S. The performance characteristics of the engines and the three batteries are shown in Fig. 11 and Fig. 12, respectively. Three electric ranges of vehicle operation were considered, 50, 75 and 100 KM, with an extended range of 200 KM. The distance beyond these ranges, constitutes the extended range performed primarily by the heat engine. During the electric range, the heat engine is operated at low power level and the vehicle is operated primarily on battery energy. The battery is depleted to a state .5 at the end of the electric range and stays at this level to be able to perform the acceleration maneuver.

Fig. 13 shows variation of characteristic performance values over a 200 KM range for an Otto engine and 1985 Pb-Ac battery for electric ranges of 50, 75 and 100 KM. A moderate fuel consumption at constant rate over the electric range is noticable and it increases when the power level of the engine is switched to 50% beyond the electric range. The consumed electric energy increases linearly over the electric range and levels off beyond the range. The fuel economy is constant within the electric range and drops afterwards, when the load and fuel consumption goes up. The system could be operated over the electric range without the heat engine which would result in better fuel economy with battery powering the vehicle. The engine would be turned on when the battery is unable to meet the road load, resulting in substantial fuel savings (see estimated fuel economy in Table 6 for the engine off operation). Both the low and the intermediate engine power levels can be optimized according to the engine fuel map, load requirement and the need to keep the state of the battery at the minimum level.

The results for an Otto engine and Ni-An battery are illustrated in Fig. 14. The trends of the presented values are similar to those presented for the 1985 Pb-Ac battery case.

A comparison of results for all three battery types is shown in Fig. 15. A first look reveals the lower value for expended electrical energy by the lead acid battery and the same value of expended electrical energy for the two more advanced batteries. Considering the weights of the

vehicles for these batteries, one would expect the vehicle with the lead acid battery to require more energy than the two remaining vehicles. However, the first vehicle is assisted by the heat engine being operated at a higher part load condition. Thus, the heat engine provides more energy resulting in a smaller amount of electrical energy being supplied by the battery. This is not reflected in the amount of fuel consumed at the higher power level, but this may be due to engine operation in a region of lower brake specific fuel consumption.

Similar cases for diesel engine and the three battery types are compared in Fig. 16. The fuel economy for the diesel engine case is about 25 KM/L compared with a value of about 20 KM/L for the Otto engine case.

5.2 Mission VI

A series of simulation cases for this mission performed for an Otto engine and three types of batteries is presented in Fig. 17 for an electric range of 50 KM. The vehicle with the Pb-Ac battery is characterized by low electrical energy consumption and high fuel consumption due in part to the engine power level of electrical energy 15%. The vehicle equipped with the Ni-Zn battery consumes the most electrical energy and least amount of fuel. The comparison of these results is obscured to some degree by the spread in the electric range for the cases being compared. Similar results are given in Fig. 18 for an electric range of 100 KM.

Results for a diesel engine are given in Fig. 19 and Fig. 20 for electric ranges of 50 KM and 100 KM, respectively. Trends are similar to those discussed for the Otto engine cases.

To evaluate the effect of battery size on the electric range, vehicle weight and fuel consumption, several cases have been computed by varying the battery weight fraction. The results of these calculations are given in Fig. 21. An increase in battery weight fraction causes an increase in vehicle weight and battery size which increases the electric range. Thus, for given set of parameters, the battery weight fraction can be used to control the electric range of the vehicle. Both the electric and chemical energy consumption increase linearly with battery weight fraction. The fuel economy drops slightly with increasing battery size for the range distance and over the extended range. A strong decrease of the electrical energy economy over the extended range with increasing battery size is noticable. This is due to a minimal consumption of the battery energy over the extended range.

6. SUMMARY AND CONCLUSIONS

6.1 Mission I

The results of simulation studies for Mission I vehicles are summarized in Table 6 for Otto and diesel engines and for three types of batteries. The fuel economy for electric range and extended range operation is shown in Fig. 22 plotted against the electric range. The electric range fuel economy is seen to increase slightly with increasing electric range. The electric range fuel economies for the series hybrid vehicles studied range from 20-30 KM/L for Otto engine configurations and from 40-63 KM/L for diesel engine configurations. The lowest fuel economy values are for Pb-Ac batteries, while the highest values are for Na-S batteries. These numbers compare with a fuel economy of 19 KM/L for pure Otto engine operation for Mission I. Extended range fuel economies are up to 22 KM/L for the Otto engine configurations and up to 25 KM/L for the diesel engine configurations.

The effects of engine and battery type on vehicle weight and fuel economy are shown in Figures 23 and 24 for a 75 KM electric range. In each case, the result for a pure Otto engine baseling is shown for comparison. All series hybrid configurations are considerably heavier than the baseline vehicle. The use of more advanced batteries yields better fuel economy and lighter weight hybrid vehicles. Diesel engine configurations show much better fuel economy than the Otto engine configurations; however, it should be noted that comparisons against a pure diesel engine baseline would be less optimistic.

The electrical economy for electric range and extended range operation is shown in Fig. 25 plotted against the electric range. The electrical economy for the electric range is relatively constant except for the Pb-Ac battery case which shows an increase in electrical economy with increasing electric range. This is probably due to the higher engine power level used for the higher electric range cases with the Pb-Ac battery. For the extended range, the electrical economy decreases significantly with increasing electrical range since the batteries are being used over a larger fraction of the total vehicle range.

6.2 Mission VI

The simulation results for Mission VI vehicles are summarized in Table 6 for Otto and diesel engines and for three types of batteries. The fuel economy for electric range and extended range operation is shown in Fig. 26 plotted against the electric range. The electric range fuel economies for the series hybrid vehicles studied range from 5-7 KM/L for Otto engine configurations and from 6-15 KM/L for diesel engine configurations. The most significant diesel fuel economy advantage is obtained for an electric range of 50 KM. The lowest fuel economy values are obtained for Pb-Ac batteries, while the highest values are for Na-S batteries. These numbers compare with a fuel economy of 6 KM/L for pure Otto engine operation for Mission VI. Extended range fuel economies are up to 7 KM/L for the Otto engine configurations and up to 8 KM/L for the diesel engine configurations. The diesel engine configurations yield better extended range fuel economy than the Otto engine configurations for an electric range of 50 KM; however, these trends are reversed for an electric range of 100 KM.

The effects of engine and battery type on vehicle weight and fuel economy are shown in Figures 27 and 28 for 50 KM electric range and in Figures 29 and 30 for a 100 KM electric range. Again the result for a pure Otto engine baseline is shown for comparison. All series hybrid configurations are considerably heavier than the baseline vehicle. The only hybrid configurations showing a fuel economy advantage over the baseline are the configurations with a diesel engine and advanced batteries for the 50 KM electric range case. In this case, it should be noted that comparisons against a pure diesel engine baseline would be less optimistic.

The electrical economy for electric range and extended range operation is shown in Fig. 31 plotted against the electric range. For both electric and extended range, the electrical economy decreases significantly with increasing electric range.

In summary, the series hybrid vehicle with advanced batteries and an Otto or diesel engine offers some fuel economy advantage over the pure Otto engine for some electric ranges for Mission VI.

6.3 Conclusions and Recommendations

This study has attempted to evaluate the system performance of several hybrid vehicles of the series configuration and to determine the influence of various vehicle parameters. Based on the constraints imposed on the study and the configuration selection process described in this report, the following conclusions can be stated for Missions I and VI.

Mission I (75 KM Electric Range):

- Hybrid configurations are 40-90% heavier than the pure Otto engine baseline.
- Hybrid configurations with Otto engine and advanced batteries (Ni-Zn, Na-S) yield about 50% better fuel economy over the electric range and about 5% better fuel economy for extended range operation.

- Hybrid configurations with diesel engines and advanced batteries (Ni-Zn, Na-S) yield about 200% better fuel economy over the electric range and about 25% better fuel economy for extended range operation.
- Although diesel engine fuel economy results are good, it should be noted that comparisons are made against an Otto engine baseline. Comparisons against a pure diesel engine baseline would be less optimistic.
- Hybrid configurations with Pb-Ac batteries show lower fuel economy than the baseling for extended range operation.
- It is likely that better fuel economy results would be obtained with the use of a larger battery weight fraction.

Mission VI:

- Compared with the pure Otto engine baseline, hybrid configurations are 20-60% heavier for a 50 KM electric range and 30-90% heavier for a 100 KM electric range.
- For a 50 KM electric range, hybrid configurations with Otto engines show no fuel economy advantage over the pure Otto engine baseline for either electric range or extended range operation.

- For a 50 KM electric range, hybrid configurations with diesel engines and advanced batteries (Ni-Zn, Na-S) show about 100% better fuel economy over the electric range and about 25% better fuel economy for extended range operation.
- For a 100 KM electric range, hybrid configurations show little or no fuel economy advantage over the pure Otto engine baseline for either electric range or extended range operation.
- The diesel engine results would be less optimistic if compared with a pure diesel engine baseline.
- It is likely that better fuel economy results would be obtained with the use of a larger battery weight fraction.

It is expected that improvements in fuel economy could be made using the on-off control mode for the heat engine during the electric range. For a given vehicle design with specified battery and vehicle masses, changing the heat engine operating strategy from continuous operation to on-off operation during the electric range has the following overall effects: the electric range decreases; the electric range fuel economy increases dramatically; and the extended range fuel economy at 192 KM increases 5-10% depending on the design.

This is due to the relative inefficiency of operating the heat engine continuously at low power levels, and the inefficiency associated with using the heat engine to charge the batteries (battery charge/discharge efficiency) during the continuous operation mode. The annual fuel economy would probably increase slightly more than the fuel economy at 192 KM due to the concentration of distance traveled in the first part of the trip and the increased efficiency of the on-off control strategy.

Further fuel economy improvements could be made by keeping the heat engine off during the electric range and re-sizing the batteries to meet the energy requirements during the electric range. It is recommended that additional simulation studies be made to get a good estimate for the fuel economy potential of this control mode.

7. NOMENCLATURE

BSE	-	Battery specific energy
BSFC	-	Brake specific fuel consumption
BSP	-	Battery specific power
BST	-	Battery state
E	-	Electric energy
E-H	-	Energy required for highway driving cycle
E-U	-	Energy required for urban driving cycle
K_P	-	Vehicle power to weight ratio
M	-	Total vehicle weight
M_B	-	Battery weight
MFB	-	Battery weight fraction
MOF	-	Motor overload factor
N	-	Engine speed fraction
P_{AV}^{-H}	-	Average power required for highway driving cycle
P_{AV}^{-U}	-	Average power required for urban driving cycle
P_B	-	Base power of vehicle
PFE	-	Engine power fraction
PFM	-	Motor power fraction
P_{HE}	-	Power of heat engine
P_{MTR}	-	Power of battery
POP	-	Operating engine power fraction

POP_{ACC} -	Operating engine power fraction for acceleration
POP_{EL} -	Operating engine power fraction for electric range
POP_{EXT} -	Operating engine power fraction for extended range
P_{PK}^{-H} -	Peak power for highway driving cycle
P_{PK}^{-U} -	Peak power for urban driving cycle
R -	Range
T_{100} -	Acceleration time to reach vehicle velocity of 100 KM/hr

TABLE 1 . HYBRID ELECTRIC VEHICLE OPTMIZATION AND SIZING
BASED ON ACCELERATION PERFORMANCE

MISSION I

M(KG)	ENGINE	BATTERY	Kp	PFE	PFM	MFB	POP	T ₁₀₀ (SEC)
1491	OTTO (7)	2	.07	.6	.4	.12	90	13.8
1304	"	4	.0575	.6	.4	.15	90	14.02
1284	"	6	.056	.6	.4	.15	90	13.9
1491	DIESEL (6)	2	.07	.6	.4	.12	90	13.8
1280	"	4	.065	.6	.4	.12	90	14.19
1281	"	6	.061	.6	.4	.12	90	13.87

MISSION VI

4346	DIESEL (6)	2	.055	.6	.4	.13	90	17.8
3934	"	4	.044	.6	.4	.13	90	17.86
3867	"	6	.042	.6	.4	.13	90	17.9
4346	OTTO (8)	2	.055	.6	.4	.13	90	17.83
3934	"	4	.044	.6	.4	.13	90	17.91
3867	"	6	.042	.6	.4	.13	90	17.94

TABLE 2 . HYBRID ELECTRIC VEHICLE RANGE SIMULATIONS
BASED ON INITIAL ACCELERATION CONTROLLED PARAMETERS

MISSION I

M (KG)	ENGINE	BATTERY	Kp	PFE	PFM	MFB	RANGE NOMINAL/ ACTUAL	POP
1336	OTTO (7)	2	.07	.6	.4	.10	50/48	4
1456	"	2	.07	.6	.4	.14	75/76	8
1474	"	2	.07	.6	.4	.145	100/102	12
1255 1163	"	4	.06	.6	.4	.12	50/66	4
1255	"	4	.06	.6	.4	.12	75/73	6
1338	"	4	.06	.6	.4	.15	100/99	8
1163	"	6	.06	.6	.4	.08	50/54	4
1185	"	6	.06	.6	.4	.09	75/72	6
1281	"	6	.06	.6	.4	.13	100/100	8
1491	DIESEL (6)	2	.07	.6	.4	.12	75/72	6
1320	"	4	.065	.6	.4	.12	75/75	6
1174	"	6	.061	.6	.4	.08	75/73	6

MISSION VI

4345	DIESEL (6)	2	.055	.6	.4	.13	50/57	4
5329	"	2	.055	.6	.4	.22	100/98	4
3862	"	4	.044	.6	.4	.10	50/58	8
4290	"	4	.045	.6	.4	.17	100/98	4
3665	"	6	.044	.6	.4	.09	50/58	6
3933	"	6	.044	.6	.4	.13	100/105	4
4261	OTTO (8)	2	.055	.6	.4	.12	50/54	4
4345	"	2	.055	.6	.4	.13	100/105	15
3547	"	4	.046	.6	.4	.06	50/64	15
3895	"	4	.045	.6	.4	.12	100/107	15
3940	"	6	.045	.6	.4	.05	50/63	15
3634	"	6	.045	.6	.4	.08	100/106	15

TABLE ³ . SUMMARY OF PERFORMANCE SIMULATIONS
FOR SERIES HYBRID VEHICLES

ENGINE	BATTERY	MISSION I			MISSION VI	
		50KM	75KM	100KM	50KM	100KM
OTTO	Pb-Ac, 1985	X	X	X	X	X
	Ni-Zn	X	X	X	X	X
	Na-S		X		X	X
DIESEL	Pb-Ac		X		X	X
	Ni-Zn		X		X	X
	Na-S		X		X	X

TABLE 4. MECHANICAL SPECIFICATIONS FOR SIMULATION
OF HYBRID ELECTRIC VEHICLES

MISSION NO .	I	VI
MISSION TYPE	Commuter	Variable Route Van
Average Payload (KG)	90	750
Baseline Carriage Wt. (KG)	500	1400
Baseline Powertrain to Carriage Wt. Ratio	.45	.45
Frontal Area (m)	1.7	2.7
Drag Coefficient	.40	.60
Rolling Resistance Coefficient	CROL = .010 CROLL = 1.4E-3 CROL2 = 1.2E-5	
Mass Propagation Factor	KMP = 0.22 + 0.28 * EXP (-14. *MFB)	
Wheel Rolling Diam. (m)	.533	.667
Wheel Moment of Inertia (KG -m ²)	.4	1.6
Rear Axle Differential Gear Ratio	3.70	3.08
Effective Rear Axle Differential Efficiency	.95	.96
Manual Transmission (1)	3.75	3.98
Gear Ratios (2)	2.16	2.14
(3)	1.38	1.42
(4)	1	1
Shift Speeds (Km/Hr) (1)	11.	15.
(2)	19.	28.
(3)	24.	43.

TABLE 5. PERFORMANCE REQUIREMENTS FOR SIMULATION
OF HYBRID ELECTRIC VEHICLES

MISSION NO.	I	VI
MISSION TYPE	Commuter	Variable Route Van
PERFORMANCE REQUIREMENTS		
Sustained Speed (Km/hr)	100	100
Accelerations (secs)		
0-50 (Km/hr)	6	7
30-55 (Km/hr)	4	5
60-90 (Km/hr)	9	10
0-100 (Km/hr)	14	18
Gradeability		
5% @ 90 Km/hr; Km	2	2
7% @ 50 Km/hr; Km	.4	.4
20% @ 20 Km/hr; Km	.2	.2
Driving Cycle*	4U 10H	6U 8H
Length (Mm)	213.	204.
* U = EPA Urban Cycle H = EPA Highway Cycle		

TABLE 5 (contd)

MISSION NO.	I	VI
MISSION TYPE	Commuter	Variable Route Van
Manual Trans. Gear (1)	0.96	0.96
Efficiencies (2)	0.97	0.97
(3)	0.98	0.98
(4)	1.00	1.00
Transmission Specific Power (Kw/Kg) (manual)	1.8	
Engine Type	Briggs & Stratton 0 to 14 Kw; Pontiac 151: 15 to 90 Kw Chevy 250: 91 Kw to 135 Kw Chevy 350: 135 Kw and above	
Engine Moment of Inertia (Kg-m ²) (manual trans.)	$J_{eng} = \text{EXP} (1.39 * \ln (P_{E_{max}} \text{ (Kw)} - 8.156)$	
Engine System Specific Power (Kw/Kg)	$ESP = P_{eng} \text{ (Kw)} / (2.196 * P_{eng} \text{ (Kw)} + 22.7)$	
Engine Max. Speed (RPM)	Briggs: 4000, Pontiac: 5000, Chevy 250: 4500, Chevy 350: 4500	
Engine Idle Speed (RPM)	800	800
Baseline Engine Idle Fuel Flow (lb/hr)	Briggs: 1.65 Pontiac: 1.6, Chevy 250: 3.6, Chevy 350: 4.9	
Electric Motor Type	Lucas Series Traction	
Motor Moment of Inertia (Kg-m ²)	$J_{mtr} = \text{EXP} (1.39 * \ln (P_{M_{max}} \text{ (Kw)} (-7.41)$	
Motor Specific Power (Kw/Kg)	0.4	
Motor Max Speed (RPM)	Same as engine for parallel configuration, otherwise: 5000	

TABLE 6

Summary of Fuel and Electrical Economy for Series Hybrid
Vehicle with Otto and diesel Engines (50, 75 and 100 KM)

MISSION I

OTTO ENGINE

BATTERY	PARAMETER	50KM	192KM	75KM	192KM	100KM	192KM
Pb-Ac 1985	M (KG)	1336		1456		1474	
	KM/L	20.	17.	21.5	17.0	23.5	18.0
	KM/KW-HR	17.5	74.	17.5	46.0	22.0	40.0
Ni-Zn	M (KG)	1163		1255		1338	
	KM/L	26.	18.5	27.5	19.5	28	21.
	KM/KW-HR	14.	56.	13.0	34.5	13.	27.5
Na-S	M (KG)			1184			
	KM/L			29.	21.		
	KM/KW-HR			13.	32.		

DIESEL ENGINE

Pb-Ac 1985	M (KG)			1588		
	KM/L			41.5	17.5	
	KM/KW-HR			13.	33.5	
Ni-Zn	M (KG)			1320		
	KM/L			53.5	22.	
	KM/KW-HR			13.	33.	
Na-S	M (KG)			1207		
	KM/L			63.	24.5	
	KM/KW-HR			13.5	35.0	

TABLE 6 (contd)

Summary of Fuel and Electrical Economy for Series Hybrid
Vehicle with Otto and Diesel Engines (50, 75 and 100KM) (continued)

MISSION VI

OTTO ENGINE

BATTERY	PARAMETER	50KM	192KM	100KM	192KM
Pb-Ac 1985	M (KG)	3687		4395	
	KM/L	4.8	5.8	4.85	5.2
	KM/KW-HR	16.5	52.4	8.5	16.
Ni-Zn	M (KG)	3462		3826	
	KM/L	6.0	6.5	6.3	6.5
	KM/KW-HR	9.5	25.4	6.3	11.8
Na-S	M	3355		3605	
	KM/L	6.	7.	6.6	6.8
	KM/KW-HR	14.	28.	6.4	11.2

DIESEL ENGINE

Pb-Ac 1985	M (KG)	4261		5330	
	KM/L	10.	6.7	5.5	3.3
	KM/KW-HR	5.8	18.4	4.0	7.6
Ni-Zn	M (KG)	3760		4290	
	KM/L	13.8	8.2	6.7	4.3
	KM/KW-HR	4.2	12.8	3.6	6.
Na-S	M (KG)	3546		3900	
	KM/L	15.2	8.8	7.8	4.8
	KM/KW-HR	4.8	12.0	3.5	6.4

TABLE 7. COMPARISON OF KM/L FOR HYBRID/OTTO AND DIESEL
OTTO ENGINE ONLY AND HYBRID/ENGINE OFF IN R

MISSION I

	HYBRID/OTTO			OTTO ENGINE ONLY			HYBRID/DIESEL	
BAT.	M	R	EL R EXTD R KM/L	M	EXTD R KM/L	M KG	EL R EXTD R KM/L	
	KG	KM		KG				
Pb-Ac	1336	50	20	17	815	19	1588	41.5
	1456	75	21.5	17				
	1474	100	23.5	18				
Ni-Zn	1163	50	26	18.5			1320	53.5
	1255	75	27.5	19.5				
	1338	100	28	21				
Na-S	1184	75	29	21			1207	63.
								24.5

MISSION VI

Pb-Ac	3687	50	4.8	5.8	2780	6.8	4261	10.	6.7
	4395	100	4.9	5.2			5330	5.5	3.3
Ni-Zn	3462	50	6.	6.5			3760	13.8	8.2
	3826	100	6.3	6.5			4290	6.7	4.3
Na-S	3355	50	6	7			3546	15.2	8.8
	3605	100	6.6	6.8			3900	7.8	4.8

Figure 1. Hybrid Electric Vehicles Series Configuration

Figure 2. Power Profiles for Heat Engine; Motor and Generator

$$BATTERY STATE BST = 1 - (BSE/BSE_{MX})$$

BST = 1, FULLY CHARGED BATTERY

BST = 0, DEAD BATTERY

Figure 3. Performance Characteristics of a Battery

Figure 4. Effect of System Parameters on Vehicle Acceleration for Mission I, Series Configuration. (Otto Engine - 7, Lead-Acid Battery - 2)

Figure 5. Effect of System Parameters on Vehicle Acceleration for Mission I, Series Configuration. (Otto Engine - 7, Lead-Acid Battery - 2)

Figure 6. Effect of Battery Size on Vehicle Acceleration and Weight for Mission I, Series Configuration. (Otto Engine - 2, Lead-Acid Battery - 2)

Figure 7. Effect of Engine Size on Vehicle Acceleration for Mission I, Series Configuration

Figure 8. Peak and Average Power, Energy and Acceleration Time T_{100} for Vehicle of Weight M for Urban and Highway Cycles, Mission I. (Otto Engine - 7, Lead-Acid Battery - 2)

Figure 9. Optimization of Vehicle Parameters Based on Acceleration Performance for Mission I, Series Configuration. (Otto Engine - 2, Lead-Acid Battery - 2)

Figure 10. Heat Engine Power Levels for Electric Ranges 50, 75 and 100 km, POP_{EL} . (Otto Engine - 7, Pb-Ac, 1985 Battery - 2)

Figure 11. Heat Engine Performance Characteristics - Maximum Power

Figure 12. Battery Performance Characteristics

Figure 13. Range Performance Simulations for Mission I, Series Configuration. (Otto Engine -7, Pb-Ac Battery - 2, 50/75/100/200 km Ranges)

Figure 14. Range Performance Simulations for Mission I, Series Configuration. (Otto Engine - 7, Ni-Zn Battery - 4)

Figure 15. Range Performance Simulations for Mission I, Series Configuration. (Otto Engine - 7, 75/200 km Ranges)

Figure 16. Range Performance Simulations for Mission I, Series Configuration. (Diesel Engine - 6, 75/200 km Ranges)

Figure 17. Range Performance Simulations for Mission VI, Series Configuration. (Otto Engine - 8, 50/200 km Ranges)

Figure 18. Range Performance Simulations for Mission VI, Series Configuration. (Otto Engine - 8, 100/200 km Ranges)

Figure 19. Range Performance Simulations for Mission VI, Series Configuration. (Diesel Engine - 6, 50/200 km Ranges)

Figure 20. Range Performance Simulations for Mission II, Series Configuration. (Diesel Engine - 6, 100/200 km Ranges)

Figure 21. Effect of Battery Size MFB for Mission VI, Series Configuration. (Otto Engine - 8, Battery Pb-Ac 1985, 50/200 km Ranges)

Figure 22. Summary of Fuel Economy Results
Mission I - Series Configuration

Figure 23. Electric Range Fuel Economy (Mission I, 75 km Electric Range)

Figure 24. Extended Range Fuel Economy (Mission I, 75 km Electric Range)

Figure 25. Summary of Electrical Economy Results
Mission I - Series Configuration

Figure 26. Summary of Fuel Economy Results
Mission VI - Series Configuration

Figure 27. Electric Range Fuel Economy (Mission VI, 50 km Electric Range)

Figure 28. Extended Range Fuel Economy (Mission VI, 50 km Electric Range)

Figure 29. Extended Range Fuel Economy (Mission VI, 100 km Electric Range)

Figure 30. Electric Range Fuel Economy (Mission VI, 100 km Electric Range)