DR. 1222

ENERGY

CONS-4209-T1(Vol.5)

CONSERVATION

HYBRID VEHICLE POTENTIAL ASSESSMENT

Volume 5: Flywheel Systems

By
S. G. Liddle

MASTER

September 30, 1979

Work Performed Under Contract No. EM-78-I-01-4209

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

U. S. DEPARTMENT OF ENERGY

Division of Transportation Energy Conservation

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

DISCLAIMER

"This book was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof."

This report has been reproduced directly from the best available copy.

Available from the National Technical Information Service, U. S. Department of Commerce, Springfield, Virginia 22161.

Price: Paper Copy \$8.00
Microfiche \$3.50

ELECTRIC AND HYBRID VEHICLE SYSTEM
RESEARCH AND DEVELOPMENT PROJECT
HYBRID VEHICLE POTENTIAL ASSESSMENT
VOLUME V. FLYWHEEL SYSTEMS

September 30, 1979

S. G. Liddle

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

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

RB

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

THE FLYWHEEL - ELECTRIC HYBRID VEHICLE

INTRODUCTION -----	1
CONFIGURATION -----	2
SPECIAL COMPONENTS -----	3
DESIGN CONSIDERATIONS -----	10
RESULTS -----	17
Mission 1 -----	17
Mission 2 -----	20
Mission 3 -----	21
Mission 4 -----	24
Mission 5 -----	26
Mission 6 -----	27
Mission 7 -----	29
SUMMARY -----	30

Figures

1. Flywheel-Electric Hybrid Configuration -----	34
2. Continuously Variable Transmission Efficiency -----	35
3. Operating Strategy 205 Driving Phase -----	36
4. Operating Strategy 205 Regenerative Braking -----	37
5. Operating Strategy 209 Driving Phase -----	38
6. Operating Strategy 209 Regenerative Braking -----	39
7. Operating Strategy 201 Driving Phase -----	40
8. Operating Strategy 201 Regenerative Braking -----	41
9. Operating Strategy 210 Driving Phase -----	42
10. Operating Strategy 210 Regenerative Braking -----	43

11.	Operating Strategy 211 Driving Phase -----	44
12.	Operating Strategy 211 Regenerative Braking -----	45
13.	Operating Strategy 211 Lead-Acid Batteries -----	46
14.	Flywheel Electric Hybrid 211 Strategy -----	47
15.	-----	48
16.	-----	49
17.	Lead-Acid Batteries 211 Operating Strategy -----	50
18.	Mission 1 Lead-Acid Battery -----	51
19.	Mission 1 -----	52
20.	Mission 1 All Strategies Lead-Acid Batteries -----	53
21.	Mission 1 Operating Strategy 205 Battery Lead-Acid ---	54
22.	Mission 1 Operating Strategy 211 Battery Lead-Acid ---	55
23.	Mission 1 211 Strategy Lead-Acid Battery -----	56
24.	Mission 2 All Strategies Lead-Acid Batteries -----	57
25.	Mission 2 All Strategies Lead-Acid Battery -----	58
26.	Mission 2 All Strategies Lead-Acid Battery -----	59
27.	Mission 2 205 Strategy Lead-Acid Battery -----	60
28.	Mission 2 211 Strategy Lead-Acid Battery -----	61
29.	Mission 2 211 Strategy Lead-Acid Battery -----	62
30.	Mission 3 All Strategies All Batteries -----	63
31.	Mission 3 All Strategies All Batteries -----	64
32.	Mission 3 All Strategies All Batteries -----	65
33.	Mission 3 205 Strategy Lead-Acid Battery -----	66
34.	Mission 3 -----	67
35.	Mission 3 Lead-Acid Battery 211 Strategy -----	68
36.	Mission 4 All Strategies Lead-Acid Battery -----	69
37.	Mission 4 All Strategies Lead-Acid Battery -----	70

38.	Mission 4 All Strategies Lead-Acid Battery -----	71
39.	Mission 5 All Strategies Lead-Acid Battery -----	72
40.	Mission 5 All Strategies Lead-Acid Battery -----	73
41.	Mission 5 All Strategies Lead-Acid Battery -----	74
42.	Mission 6 All Strategies All Batteries All -----	75
43.	Mission 6 All Strategies All Batteries Otto Cycle Engine -----	76
44.	Mission 6 All Strategies All Batteries Diesel Cycle Engines -----	77
45.	Mission 6 All Strategies All Batteries All Engines ----	78
46.	Mission 7 All Strategies Lead-Acid Battery -----	79
47.	Mission 7 All Strategies Lead-Acid Battery -----	80
48.	Mission 7 All Strategies Lead-Acid Battery -----	81
49.	Lead-Acid Batteries 211 Operating Strategy -----	82
50.	Lead-Acid Battery 211 Strategy Flywheel-Electric- Heat Engine Hybrid -----	83
51.	Lead-Acid Batteries -----	84
52.	Flywheel-Electric-Heat Engine Hybrid Lead-Acid Battery 211 Strategy -----	85

Table

I	Details of Flywheels -----	33
---	----------------------------	----

THE FLYWHEEL - ELECTRIC HYBRID VEHICLE

INTRODUCTION

This variation of the electric hybrid system is the third to be investigated. It differs from the earlier configurations by the addition of the flywheel system which provides for temporary storage of surplus energy during regenerative braking and supplements the battery and engine outputs during acceleration. Since the flywheel has inherent losses in the form of windage, bearings and seals, it is not suitable for long term energy storage. Although the flywheels energy storage capacity is limited as compared to the battery, its ability to absorb or provide power is well in excess of that of the battery. It is this high power capability that is the reason for its use in the system. As the battery is discharged, its power capacity also declines. When the battery is no longer capable of meeting the power demanded of it, it is considered discharged. The use of the flywheel allows the battery to be discharged beyond its normal limit. This permits either the use of a smaller battery for a given range or greater range for a given battery. The price for this improved battery utilization is the added complexity of a third energy system and its controls, the necessity of a continuously variable transmission and higher first costs.

Throughout this study, the flywheel is assumed to be at full charge at the beginning of the mission and is allowed to be at any charge level at the end of the mission. This is not an absolute requirement but made merely to simplify the calculations. Any initial flywheel energy level could be specified if required.

CONFIGURATION

The arrangement of the components in this flywheel - electric hybrid system is as shown in Figure 1. Unlike the parallel hybrid configuration studied, the motor-generator is connected to the output of the transmission rather than to the input. The advantage of this arrangement is that during regenerative braking, the power goes directly to the motor-generator and to the flywheel with a minimum of loss. If the motor-generator or the flywheel are attached to the engine transmission input, then the regenerative energy must go through it, introducing an additional loss in the system. It would also restrict the choice of engine transmission. For instance, the modern torque converter automatic transmission is very inefficient when the power flow direction is reversed. Some continuously variable transmissions (CVT) are also power directionally sensitive. On the other hand, the use of a transmission between the motor and the axle increases the average motor efficiency at low vehicle speeds and may allow a smaller motor to be used.

In the interim report of this study, a number of configurations were presented and discussed as to their advantages and disadvantages. Only one of the configurations could be analyzed in depth because of time restrictions and the one shown here was chosen primarily because of its lack of transmission restrictions.

The flywheel in this hybrid system is used primarily as a buffer for the electrical system. If the power demand of the vehicle is greater than the capacity of the motor or battery, then the difference is taken from the flywheel. In some operating strategies, if there is more regenerative power available than the battery can absorb, the extra power is diverted to the flywheel. In other strategies, the flywheel has first priority to regenerative braking power with excess power going to the battery. If the battery is discharged to its limit, the flywheel may be used, depending on the operating strategy, to load level the engine directly. It may, also, depending on the strategy, be used to drive the car by itself. The operating strategies used in this study will be presented in detail in a later section.

SPECIAL COMPONENTS

Most of the components used in this system are discussed in another section of this report. However, since the flywheel and its transmission are used only in this version, they are not included in that earlier section.

The flywheel used in this study was assumed to be a S-glass composite wheel operating with a design speed of 25000 rpm. Details may be found in Table I. Actually, two flywheels were used. One was a two kilowatt-hour capacity wheel used with the shared strategies. In general, the vehicles were quite heavy and the additional capacity was needed. As the work progressed, the vehicles became lighter and the flywheel capacity was reduced to one kilowatt-hour. Simulation runs made with both wheels for the same mission indicated that the smaller wheel had a very slight (2%) fuel economy edge over the larger wheel in the lighter vehicles. It did not appear to be enough of a change to justify designing a special flywheel for each mission so the same wheel was used for all of them.

The S-glass composite flywheel was chosen over the steel wheel because of its fracture characteristics which virtually eliminate the need for a contaminant ring. It was also anticipated that the overall system cost would be less for the composite wheel.

It is necessary to use a continuously variable transmission with the flywheel. Power is taken from or added to the flywheel according to the rate of change of the speed ratio of the transmission. This transmission is somewhat idealized in that the specific nature of the speed ratio system is not defined but is characterized only by an efficiency - speed ratio - power map. This map is based on experimental data from an operational CVT and is shown in Figure 2. A clutch is used to isolate the flywheel system from the driveshaft of the vehicle. Its use is dictated by two restraints. One is that many CVT's do not have a true

zero output speed for non-zero input speed. They are all continuously variable but not infinitely variable. So when the vehicle is stopped, the flywheel must be declutched. The second is that when the flywheel system is not being used, the clutch prevents power being lost from the driveshaft to the CVT and reduces the wear of the CVT as well.

OPERATING STRATEGIES

Five different strategies were investigated during the course of this study. Two are shared strategies (the engine and the electrical system share the load in some prescribed manner) and three are unshared (one system at a time carried the load). The unshared strategies, sometimes called either/or strategies, use one system at a time to provide power though the other system may be called upon to load level when the main system cannot meet the power requirements. The flywheel is the main source of load leveling power but under special conditions the engine, the battery and the flywheel may all contribute to meeting the load. A strategy may also be a always-on or an on-off strategy depending on whether the engine is kept running or is shut off when power is not required from it. By definition, the shared strategies are always-on strategies but the unshared strategies may be either. The three unshared strategies in this study are all on-off.

The designations used here for the various strategies are for identification only and do not form a continuous series of numbers. The numerical 2 at the beginning of the designation refers to the flywheel hybrid but the rest of the number was assigned arbitrarily. The specific features of each strategy are outlined in the following descriptions.

(1) 205 Strategy - In this strategy, the power load is continuously shared by the engine and the electrical system with the division of power being a linear function of the battery state-of-charge. In the early part of a mission, the battery is near full charge and carries most of the load. The engine assumes more and more of the load as the battery charge decreases. The flywheel acts as a buffer to the electrical system only. Regenerative braking power is directed first to the battery with the excess going to the flywheel. The engine is not normally used to charge either the flywheel or the battery. Logic flow diagrams for the drive phase and regenerative braking phase of the strategy are presented as Figures 3 and 4.

(2) 209 Strategy - The power load is shared the same as in 205 strategy with both the engine and the electrical system taking part. The basic difference between the 205 and 209 strategies is in the way the regenerative braking power is handled. In the 209 strategy, the power is directed first to the flywheel with the excess going to the battery. In the 205 strategy, the flywheel charge is depleted early in the mission and it is essentially dormant for the rest of the mission.

With the 209 strategy, the flywheel is kept charged and is available to load level the battery throughout the mission. As in the 205 strategy, the engine is not normally used to charge either the flywheel or the battery. Flow diagrams for this strategy are given in Figures 5 and 6 for the driving and braking phases of this strategy.

(3) 201 Strategy - This is the first of the unshared or either-or strategies. In this strategy, the battery takes the main load with the flywheel load leveling until the battery state-of-charge reaches a prescribed minimum. At this point, the flywheel assumes the load with engine load leveling it until it is exhausted after which the engine must provide all of the power. It can happen that the flywheel reaches its minimum state-of-charge before the battery in which case the engine load levels the battery until it is down to its minimum at which time the engine takes the full load. The regenerative braking power is preferentially directed to the battery with the excess going to the flywheel. Figures 7 and 8 are the logic flow diagrams for this operating strategy.

(4) 210 Strategy - The battery in this strategy takes the load during the time either it or the flywheel is above their minimum states-of-charge. When either system reaches its minimum, the engine is started. If it is the flywheel that reaches its minimum state-of-charge first, the engine takes over its job load-leveling the batteries. If it is the battery which reaches its minimum first, then the engine takes over the battery's job and the flywheel continues to do the job of load leveling. Once the engine has started, the minimum state-of-

charge of the flywheel is modified to a value below the original value by about ten percentage points. This allows the flywheel to load-level the engine by a small amount.

The flywheel gets preferential treatment with regards to requirements power with the excess going to the battery. This feature together with the dual minimum states-of-charge makes it possible for the flywheel to load-level the motor, the battery and the heat engine as needed. Logic flow diagrams for the drive and braking phases of this strategy are presented in Figures 9 and 10.

(5) 211 Strategy - This strategy is an extension of the 210 strategy in that the battery drives the vehicle with the flywheel load-leveling it until either the battery or flywheel reaches its minimum state-of-charge. At this time, the engine is started and immediately assumes the role of providing the base power load with either the battery or the flywheel load leveling. Once the engine starts, it may be shut off again if the battery state-of-charge is greater than some pre-determined limit.

In this study, the limit is set at twenty percentage points above the minimum value. When the engine is shut off, the battery takes over the base load until it or the flywheel is discharged to its minimum and the engine restarts. As in the 210 strategy, regenerative braking power

goes to the flywheel first and the excess goes to the battery. When the battery is load-leveling the engine, the flywheel may be load-leveling the battery. If the battery becomes fully discharged the flywheel can load-level the engine directly. The logic flow diagrams for this strategy is shown in Figures 11 and 12.

These strategies represent an evolutionary trend in the development of the control philosophy of a flywheel - electric hybrid vehicle. Prior to this work, very little had been done to determine the best way to use the flywheel in a parallel electric hybrid system. This study makes a sizeable step in that direction.

The last strategy, the 211, appears to be the one best suited to this particular hybrid application, i.e., minimizing petroleum consumption. It is the results for this strategy that will be discussed most in the later sections of this report. It should not be assumed that the 211 strategy is the last word in this area. There are several variations of this strategy which appear promising but it does not produce the lightest vehicle. The 209 strategy vehicles are lighter and some of the 210 strategy vehicles have better fuel economy. At present, the 211 appears to be the best all-round strategy. There is plenty of room for further work in this area.

DESIGN CONSIDERATIONS

Of all the black arts used in hybrid vehicle design, component sizing is the darkest. Because of a non-linear relationship between component size and mass and the mass of the total vehicle, relatively small changes in components can have profound effects on the overall vehicle mass and, hence, on its cost. Since performance and range specifications affect size directly, they must be carefully chosen so as not to impact mass unduly. As an example, in Mission 4, one case called for a 100 km range on battery power only. The resulting weight of the vehicle was 32,908 kg. Reducing the range to 75 km dropped the total mass to 8940 kg and a further reduction in range to 50 km lowered the mass to 5959 kg. A two to one reduction in range resulted in a 5.6 to 1 reduction in vehicle mass for the same performance. A change in operating strategy reduced the motor, battery and engine masses further so that the vehicle masses are 2522, 2568 and 2645 kg for 50, 75 and 100 km range respectively. For the 100 km range vehicle, this represents a 12.5 to 1 reduction in mass for the same performance. This is an extreme case, admittedly, but variations of 2 to 1 are not unusual. Part of the problem in these cases is the definition of range for a hybrid vehicle. It is not the same as range for a conventional heat engine car or a pure electric one. In fact, there is not one definition but many, depending on the mission, configuration and operating strategy of the hybrid vehicle for which it is being defined.

Turning to the specific case of the flywheel - electric hybrid vehicle with the 211 strategy, the sizing problem is aggravated by the fact that the motor, engine and battery can be undersized with any overload being taken up by the flywheel. However, if the components are too small, the flywheel will be called on too often for its relatively small energy storage capacity and it will be discharged quickly. If the components are too large, the flywheel is never used and it becomes an expensive, unnecessary component.

The engine can be sized by running the simulation over the full driving cycle with only the engine and flywheel operational. Starting with an engine so small that the flywheel is depleted before the end of the driving cycle, it is increased in size until the flywheel is able to at least, maintain its minimum charge throughout the driving cycle. The peak engine power per unit mass will be less than would be needed by a heat engine only car but, depending on the mission, will be larger than the average power per unit mass required by the driving cycle.

Figure 13 presents the ratio of average engine power to peak engine power as a function of battery mass fraction for the 211 operating strategy. The missions arrange themselves into two distinct groups. One composed of Missions 1, 2, 3, 5 and 6 show an increase in the ratio of average power to peak power for battery mass fraction (mass of the battery divided by total vehicle mass) up to about 0.20.

Above this value, the curves tend to flatten out and peak. The other two missions show only a slight increase in the value of the ratio as the mass fraction increases. They, too, have maxima in the 0.15 to .30 range. The type of car is not responsible since each group contains both passenger cars and vans. This figure illustrates the sensitivity of hybrid vehicles to the driving or duty cycle they have to operate over.

The flywheel size can be set in several ways. One way is to simply pick a size, then determine the engine size needed to successfully complete the mission. This is the method used to set engine size. The inverse method is to choose an engine size and then find the flywheel size necessary to complete the mission without exhausting its energy. A third method is to vary both engine and flywheel to optimize the fuel economy over some specified driving cycle. Another method is to size it by making it some multiple of the energy required for a maximum effort acceleration up to a specified speed in a given length of time. It was found in this study that for the 211 strategy, a one kw-h capacity flywheel is adequate for all of the vehicles. The two kw-h capacity flywheel is needed only for very heavy vehicles. As a rule of thumb, it is suggested that the energy capacity be about three times the energy needed for a maximum effort acceleration of 0 to 100 km/h in what ever time is specified or one kw-h whichever is greater. It is a good idea to provide some reserve power in the flywheel for emergency use. For this reason, there are several "minimum" states-of-charge for the flywheel. The first limit is for normal driving operations and would be about 50% of full charge. The second limit is used by a couple of strategies.

When the engine starts, the "minimum" is changed from 50% charge to 40% charge to provide a cushion during the change over from battery to engine operation. The third limit is about 10% to 20% depending on the ratio limit of the transmission. All CV transmissions are continuously variable but few are infinitely variable so most of them cannot drive all the way to zero flywheel speed. A minimum speed is, therefore, imposed on the system. The 20% to either 40% or 50% range is reserved for emergency use when the battery is "dead", the flywheel is at its nominal "minimum" charge and the engine is undersized. This emergency range should have sufficient power with the engine for one maximum effort acceleration.

For cars in the 2000 to 4000 kg total mass range, a one kilowatt-hours capacity is adequate for a wide range of driving cycles.

The sizing of the motor is a bit more complicated than the sizing of the engine. It would appear that the largest it has to be is the same as the maximum power of the battery when it is fully charged. The motor could handle all the power that the battery can put out at any time. This, however, is not quite the case. Since the motor is connected to the driveshaft, its speed varies directly with vehicle speed. The size of the motor is dictated by the driving cycle requirements and its own part load characteristics. In the 211 strategy, the flywheel will be called upon for power frequently in the early stages of the mission and will drop in charge rapidly. When it reaches its minimum, the engine

will be started. The battery will be only slightly used and the result is rather poor fuel economy. Increasing the motor size decreases the amount of power demanded of the flywheel early in the electric driving phase and increases the time before the engine starts thus using more of the battery power. The maximum motor size is that one for which the flywheel is no longer called upon for assistance. The battery in this case is used to its maximum. The actual motor size is less than the maximum and depends on the acceptable amount of battery range curtailment. In this study using, the 211 strategy, the motor size is only 3 to 5% less than the maximum to minimize the effect on battery range. The peak power rating of the motor may be 0.6 to 2.5 times the maximum battery power and is a strong function of the battery mass fraction (battery mass/total vehicle mass) as shown in Figure 14.

The figure is a plot of the ratio of peak motor power to peak battery power as a function of equivalent battery mass fraction. Equivalent battery mass fraction is defined as the actual battery mass fraction times the maximum specific power of the battery used and divided by the maximum specific power of the reference battery which for this curve is lead-acid battery with a maximum specific power of 0.154 kw/kg. The remarkable thing about this curve is that all of the data points used to generate it fell within 5% of the line regardless of the engine used, the particular mission, the type of battery or the nominal range.

The size of the battery is primarily a function of the type of battery, the desired range and the power requirements of the mission. Three ranges are used in this study; 50, 75 and 100 km. The range is interpreted in different ways. It can be considered as the distance travelled on battery alone, on battery with flywheel load-leveling, in normal hybrid operations, on battery load-leveled by the engine, by battery and flywheel followed by engine load leveled by battery or battery load-leveled by engine. Each interpretation results in a different battery mass, fuel economy, total vehicle mass and energy usage.

In the 211 strategy, the range is divided into two sections, electric with flywheel and engine with battery. About 65% to 75% of the nominal range is travelled in the battery with flywheel load-leveling mode. The engine is then started and the battery is used to load-level the heat engine. The battery is sized so that this schedule is met. Figure 15 shows the distance traveled on the battery and flywheel only as a function of battery mass fraction. The curves fall into four groups. Missions 4 and 7 are very similar just as they were in Figure 13 for engine size. The second group is the remaining missions, No. 1, 2, 3, 5 and 6, using lead-acid batteries. Missions 3 and 6 using nickel-zinc batteries form a separate group as do the same missions with the sodium-sulphur batteries. These curves are for the 211 operating strategy and the other strategies would have different curves. Curves such as this one provide a convenient means of choosing an initial value of battery mass fraction to start the calculations of simulation.

There is no clear cut relationship between battery mass and fuel economy over the whole mission as can be seen in Figure 16. On five of the missions, the fuel economy increases with an increase in battery mass fraction. The other two missions show a only modest increase in fuel economy with increased battery mass fraction, then a slight decrease as it is increased further. For these two missions there is an optimum battery mass fraction. For the other missions, there may be an optimum but if it exists, it must be above the range of battery mass fractions investigated in this study.

In this configuration, the transmission is required to handle only the engine output power and, hence, is designed to match engine output. Similiarly, the motor controller is sized to match motor output.

The total mass of the vehicles are shown in Figure 17 for the 211 operating strategy. In general, the vehicle mass increases with battery mass fraction. All of the missions except missions 4 and 7 show a trend for the mass to increase at a decreasing rate, flattening out above fractions of 0.40. The two missions, 4 and 7, show the opposite trend with the vehicle mass increasing at an increasing rate. These two missions have shown unusual behavior in Figures 13, 15 and 16.

RESULTS

Mission I

Four different operating strategies were used on this mission. Lead-acid batteries, ranges from 20 Km to 130 Km and gasoline spark ignition engines were used on all simulation runs. The operating strategy plays an important part in the mass and fuel economy of the hybrid vehicle. For instance, on this mission, the hybrid vehicle mass varied from a low of 1136 kg to a high of 2322 kg, mostly as a result of strategy changes. The effect of battery mass fraction and operating strategy on vehicle mass is shown in Figure 18. The fuel economy

over the full driving cycle changes even faster, from a low of 8.36 Km/L to a high of 34.13 Km/L, a factor of four. Changing from a shared (always-on) strategy to an unshared (on-off) strategy doubled the fuel economy and modifications to the unshared strategy account for the remaining improvement. The fuel economy of a hybrid using a strategy like the 211, is not a single number but varies continuously with distance traveled. In the 211 strategy, it could be defined as infinite during the electric drive phase early in the mission and declines continuously with distance travelled after the engine starts. For convenience, all fuel economy figures for this mission and the others are for the full driving cycle, defined as total distance travelled divided by total fuel used. The effect of operating strategy on fuel economy is shown in Figure 19.

The net battery power (total output - input from regenerative braking) is shown as a function of battery mass fraction and the operating strategy in Figure 20. As expected, the electrical energy usage increases as the battery mass fraction increases for all of the operating strategy. The 205 strategy uses more energy than the 211 strategy for all mass functions.

The inter-relationship of battery, flywheel and engine power is illustrated in Figures 21 and 22 for operating strategies 205 and 211 respectively. In these figures, the battery and the flywheel states-of-charge and the fuel used are shown as functions of the distance travelled. With the 205 strategy, both the flywheel and the battery states-of-charge decrease continually with distance increase. Fuel usage increases nearly linearly with distance. With the 211 strategy, the battery decreases rapidly during the first fifty kilometers where it is driving the car with the help of the flywheel. Once the engine starts, its state-of-charge remains nearly constant. The flywheel state-of-charge decreases with distance up to the fifty kilometer mark when the engine starts. Because of its small energy capacity (one kilowatt-hour), the flywheel state-of-charge varies markedly as power is demanded of it. After the engine starts, the flywheel, using regenerative braking power, begins to recover energy.

With the 211 strategy, there will be a reserve in the flywheel and battery even after a very long drive where in the 205 strategy, the engine must handle all the load after about 150 Km and this means the engine must be larger than if it had help from the other systems.

The engine and motor sizes as well as the total vehicle mass are shown in Figure 23 as functions of battery mass fraction. Of particular interest is the fact that there is a minimum in the engine size curve. The heat-engine-only car needs a large engine to handle the acceleration load. With the hybrid, the battery and flywheel take a good part of this load, allowing the engine to get smaller. However, as the battery mass fraction gets larger, the total vehicle mass increases and the engine begins to get larger just to handle the weight. The minimum engine size does not correspond to best fuel economy. In fact, the best fuel economy occurs for a fairly heavy car with engine larger than the minimum.

The heat-engine-only vehicle for this mission has a mass of 814 kg, about two-thirds of the lightest hybrid, and a fuel economy of 18.50 Km/L as compared to 34.13 Km/L for the best hybrid. This vehicle is shown on most figures as a battery mass fraction of zero. With this mission, the hybrid displays better fuel economy despite its greater mass.

Mission 2

Four strategies, two shared and two unshared, are used for this mission. Lead-acid batteries and a spark-ignited gasoline engine were used throughout. Nominal ranges from 20 km to 130 km were studied. As in Mission 1, the shared strategies (205 and 209) generally have greater masses and lower fuel economies than do the unshared strategies (210 and 211), the vehicle masses ranged from 2139 kg to 3482 kg while the unshared strategies have masses of 1768 to 2919 kg, as shown in Figure 24. For comparison, the heat-engine-only vehicle for this mission has a mass of 1356 kg. The fuel economies range from a low of 7.18 km/l to a high 26.83 km/l while the heat engine only car has 13.62 km/l economy. Figure 25 shows the fuel economy as a function of battery mass fraction and operating strategy. It can be readily seen that the operating strategy has a strong effect on fuel economy and that the hybrid may have fuel economy values above and below those of the non-hybrid car.

The use of electrical power is shown in Figure 26 as net power from the battery. The 205 strategy uses more power for a given battery mass fraction than does the 211 strategy. Since it also uses more fuel, it is considerably less energy efficient on this mission than the 211 strategy.

The histories or curves of battery and flywheel states-of-charge as well as engine fuel usage are shown in Figures 27 and 28. The history for the 205 strategy is shown in Figure 27 and it is readily apparent that this mission is similar to Mission 1. Both the flywheel and the battery states-of-charge decrease as distance increases and show no sign of leveling out or increasing. Figure 28 which shows the results for the 211 strategy presents a picture similar to Mission 1 but with the flywheel returning to its fully charged condition before the end of the 180 km trip. The exact distance at which the full charge of the flywheel is achieved is a function of the battery mass fraction. It is apparent that the 211 strategy provides a good reserve of power throughout the driving cycle.

The engine peak power, motor peak power and total vehicle mass are shown in Figure 29. As with Mission 1, the engine peak power has a minimum value near a mass fraction of 0.10, which again does not correspond to the best fuel economy condition.

Mission 3

Nickel-zinc, sodium-sulphur and lead-acid batteries were used in conjunction with this mission. Four operating strategies were used and ranges from 50 to 100 km were used for the lead-acid battery and a 75 km range was used for the other two. As in the earlier missions,

the shared strategies generally have the greatest masses and the lowest fuel economies. The vehicle mass for these strategies range from 2320 kg up to 4807 kg depending on range, type of battery and the specific strategy, as shown in Figure 30. The fuel economy varies over a narrower range from 5.29 km/l to 8.38 km/l. The unshared strategies have vehicle masses ranging from 2049 kg to 2514 kg and fuel economy goes from 16.07 km/l to 18.76 km/l. The fuel economy for the various strategies are shown in Figure 31.

The effect of battery type on full mission fuel economy is surprisingly small. For the 75 km nominal range and using the 211 strategy, the fuel economies are 16.75, 18.63 and 18.76 for cars with lead-acid, nickel-zinc and sodium-sulphur batteries respectively. The advanced batteries are only 11% and 12% better than the lead-acid battery. The fuel economy for the full driving cycle as a function of battery mass fraction is shown in Figure 31. For a given battery mass fraction, the advanced batteries may have substantially better fuel economy than the lead-acid battery but for a given range, the gain is much smaller.

To be more specific, in the case of the 211 strategy, the gain in fuel economy for the advanced batteries is due mainly to the reduced mass of the vehicle. The use of the flywheel makes it possible to utilize the lead-acid battery in such a way that they are nearly the equal of the nickel-zinc and sodium-sulphur batteries as far as the ability to deliver power is concerned. The result is that the battery mass fraction is relatively small for all the batteries so that even a large change in the battery mass is only a minor change in the vehicle as a whole. It might be that those missions requiring a large battery mass fraction would better utilize advanced batteries than this one.

The electrical usage is presented in Figure 32. As with earlier missions the shared 205 and 209 strategies use more electrical power than the unshared 210 and 211 strategies.

Figures 33 and 34 are two "history" curves for Mission 3 using the 205 and the 211 operating strategies, respectively. The 205 strategy presents a picture very similar to that of the earlier missions with both the battery and the flywheel states-of-charge continuously declining through the full driving cycle. The 211 strategy has a curve similar to that of Mission 2 (Figure 28) except the flywheel comes back up to full state-of-charge faster. Beyond 50 km, the flywheel is fully capable of load leveling the engine. With the 211 strategy, battery and flywheel handle all the load for about 40 km and then the engine takes over the load with both the battery and the flywheel load-leveling it.

Once the engine starts, the battery load is sharply reduced and it discharges at a very slow rate. The perturbations in the flywheel charge is partly due to its own internal losses.

In Figure 35, the total vehicle mass, motor peak power and engine peak power is shown as functions of battery mass fraction. The vehicle mass is a linear function of battery mass fraction. Motor peak power increases at a decreasing rate while the heat engine peak power decreases from the heat engine only case (battery mass fraction = 0) to a minimum battery mass fraction of 0.12 and then increases as the fraction increases further. In a heat engine only car, the fuel economy normally decreases as mass increases. When the Mission 3 results shown in Figures 2 and 4 are compared, it is evident for this hybrid, fuel economy increases as vehicle mass increases up to the limit of this study.

Mission 4

This mission is the first commercial service application for the flywheel-electric hybrid vehicle. The three earlier missions were for private passenger cars. The basic vehicle requirements for Mission 3 and for Mission 4 are the same, really only the driving cycle is different. Thus a comparison of the results for these two missions provide an insight into the effect of driving cycle alone. Some of the figures presented when sizing of the components was discussed indicated that the results of Mission 4 deviated markedly from most of the other missions.

It turns out that the taxi application as specified by Mission 4 has the poorest results of any of those studies. Three ranges; 50, 75 and 100 km, were used with lead-acid batteries. As usual, four strategies, two shared and two unshared, were used. The use of shared strategies on this mission results in vehicle mass from 1.5 to 19.4 times as great as that of the heat-engine-only vehicle. The results of the mass calculations are shown in Figure 36. The shared strategies go off the figure while the unshared strategies have masses larger than the non-hybrid vehicle but far less than the shared strategy vehicles, being only 1.4 to 2.3 times as great as the non-hybrid. The fuel economies for shared hybrid are lower by factors of 1.7 to 15.6. Fuel economies for the unshared hybrid are slightly better than for the non-hybrid but only by 4 to 23%. This is only a fraction of the 80% to 100% improvement computed for other missions. The fuel economy for this mission differs drastically from the earlier missions. Figure 37 shows that there is an optimum value of battery mass fraction to maximize fuel economy but that maximum is only 12% greater than the non-hybrid. These results are for the 211 strategy. A 23% gain was computed using the 210 strategy.

The battery power usage is shown in Figure 38 for all of the strategies studied. The usage is greater for this mission than any other mission for all strategies. The fuel economy gains to be gotten from the hybrid on this mission are so small compared to those of other missions that it must be concluded that this mission does not make the best use of the flywheel-electric hybrid concept.

Mission 5

Four strategies were used for this mission but only one range, 75 km, and only lead-acid batteries. As usual, the shared power strategies produced the heaviest cars with the poorest fuel economies. The masses are from 1.5 to 2.1 times that of the heat-engine-only non-hybrid car. These are the lowest factors of any of the missions using the shared strategies. The total vehicle mass is presented in Figure 39.

The shared strategies are considerably better than the unshared with the vehicle mass only 38% greater than the non-hybrid. Shared strategy fuel economy was close to that of the non-hybrid, ranging from 19% less to 4% better. The vehicles using the unshared strategies had fuel economies far better than the shared strategies or the non-hybrid, in fact, the best gains in this flywheel-electric hybrid study. The fuel economy is shown in Figure 40 and, as can be seen, the fuel economy is rising rapidly with increases in battery mass fraction.

Figure 41 shows the electric power utilization which is small compared to the other missions and yet large fuel economy gains were realized.

The "history" figures and the engine, motor size figures presented in the discussion of Missions 1 to 3 have not been included here. Those for this mission are very similar to those of Mission 3 and it was felt they would add nothing new to this discussion. Certainly, this mission is a better application of the hybrid concept than is Mission 4.

Mission 6

This mission was studied in more detail than any other mission using the flywheel-electric hybrid vehicle. Four strategies, three battery types, two heat engines and three ranges were utilized.

As with earlier missions, the vehicles using shared load strategies generally had greater masses than the unshared strategies but unlike the earlier missions, one shared strategy, 209, had a lower total vehicle mass than any of the unshared strategies by 40 to 580 kg. Even with the lower mass, the fuel economy of this shared strategy vehicle is so low compared to the unshared ones that it does not appear to be economically viable. The masses of all the vehicles are shown in Figure 42.

The effect of battery mass fraction on fuel economy is shown in Figure 43 for all of the operating strategies. This mission, like all previous missions with the exception of Mission 4, reveals a trend of increasing fuel economy with increasing battery mass fractions. For a given range, the advanced batteries (nickel-zinc and sodium-sulphur) show only modest increase (4% to 16%) in fuel economy as compared to lead-acid batteries. These results are about the same as found for Mission 3.

The use of a diesel engine instead of the gasoline engine shows only a moderate improvement in fuel economy if both engines are sized to the same peak power. For the 211 strategy, the fuel economy increased 6.4% to 8% when a diesel engine was used instead of the spark ignition engine. The increase was largest for lead-acid batteries and smallest for the sodium-sulphur battery. The best fuel economy was computed for the diesel engine-sodium-sulphur battery combination with 100 km range.

Its fuel economy is 11.43 km/l as compared to the heat engine only non-hybrid fuel economy of 6.64 km/l. The fuel economy results for the diesel engined hybrid is shown in Figure 44.

The electric usage is shown in Figure 45 for all of the strategies. This mission is similar to Mission 3 in the electrical usage pattern.

No "history" curves or motor, engine size curves are included in this discussion. They are very similar to those of Mission 3.

Mission 7

This is the slowest mission of all with an overall average speed of 17 km/h. Mission 4 has an overall speed of 24 km/h and Mission 5 averages 71.5 km/h. This mission has other characteristics similar to those of Mission 4. The fuel economy as shown in Figure 16 exhibits the same behavior with a maximum at 0.12 battery mass fraction. The ratio of the peak fuel economy to that of the heat engine only car is 1.67, which is considerably better than it was for Mission 4.

This mission differs markedly from the other missions in that the shared strategy, (205) vehicles had lower masses than did the unshared strategies. The differences amount to 650 kg for the 50 km range vehicle and 1550 kg for the 100 km range vehicle. If the 209 strategy, which was not used for this mission, followed the same trend that it did on other missions, its vehicles would be lighter still.

However, the fuel economies of these lightweight cars is only about half that of the cars using the 211 strategy and about two-thirds of that of the non-hybrid car. The masses for the car with different strategies are shown in Figure 46 and the fuel economy is presented in Figure 47. The electrical energy usage for the full driving cycle is shown in Figure 48.

While this mission is more suitable to hybrid operation than Mission 4, it is not as attractive as the others from a weight-fuel economy standpoint.

SUMMARY

The most obvious conclusion to come out of this study is that the shared power load strategies are not suitable for hybrid operation. They are, generally, both heavier and have poorer fuel economy than the heat-engine-only vehicle. The unshared power load strategies generally have better fuel economies than the non-hybrid cars but are considerably heavier.

The 211 strategy appears, at present, to be the best one developed so far for the flywheel-electric hybrid but it may still be improved. The sizing of components is an area where considerable improvement may be made. The use of the flywheel permits more freedom in sizing than is allowed the parallel hybrid but the best way to use the flywheel is not clear.

Looking only at weight and fuel economy, it is evident that Missions 4 and 7 are the least suited to flywheel hybrid operation. Missions 1 and 5 appear to be the best suited since they involve the least increases in weight and the greatest increases in fuel economy. The reason for these differences may lie in the ratio of average engine power to peak engine power as shown in Figure 13. Missions 1 and 5 are at the top of the family of curves and show a marked change between the hybrids and the non-hybrids. On the other hand, Missions 4 and 7 are well down on the chart and there is very little difference between the non-hybrids and the hybrids.

Some of the results of the study were presented in Figures 13 and 17 and were discussed in connection with sizing the components. Some additional results are presented in Figures 49 and 52. The engine peak power as a function of battery mass fraction is shown in Figure 49. All of the curves show a minimum in the .09 to .21 range.

Figure 50 shows the motor peak power as a function of battery mass fraction. Most of the missions follow similar trends but Missions 4 and 7 are quite different. They tend to increase rapidly even for high battery mass fractions whereas all the other curves are beginning to level off.

There is another unusual behavior of Mission 4. This is illustrated in Figure 51. The range of the vehicle on battery and flywheel power only is independent of strategy for Mission 3 but, for Mission 4, it is very dependent. There is a two to one ratio between the 210 and the 205 strategies with the 211 strategy in between.

The sum of fuel energy and battery recharging energy, in other words, total input energy to the system is plotted against battery mass fraction in Figure 52. Most of the missions (1-3, 5 and 6) show a decrease in total energy as the mass fraction increases. Missions 4 and 7, show an initial decrease, each going through a minimum around 0.10 to 0.13, then increasing again. Mission 4 shows only a slight decrease in total energy at its minimum as compared to the non-hybrid. At battery mass fractions above .17, the total energy of the hybrid is higher than that of the non-hybrid.

TABLE I
DETAILS OF FLYWHEELS

1 Kilowatt-hour capacity

Design Speed	rpm	25,000
Diameter	mm	585
Mass of Wheel	kg	15.2
Material		S-glass composite
Mass of wheel, housing and drive	kg	30

2 Kilowatt-hour capacity

Design speed	rpm	25,000
Diameter	mm	671
Mass of Wheel	kg	23.0
Mass of wheel, housing and drive	kg	48.5

Figure 1. Flywheel-Electric Hybrid Configuration

Figure 2. Continuously Variable Transmission Efficiency

Figure 3. Operating Strategy 205 Driving Phase

Figure 4. Operating Strategy 205 Regenerative Braking

Figure 5. Operating Strategy 209 Driving Phase

Figure 6. Operating Strategy 209 Regenerative Braking

Figure 7. Operating Strategy 201 Driving Phase

Figure 8. Operating Strategy 201 Regenerative Braking

Figure 9. Operating Strategy 210 Driving Phase

Figure 10. Operating Strategy 210 Regenerative Braking

Figure 11. Operating Strategy 211 Driving Phase

Figure 12. Operating Strategy 211 Regenerative Braking

Figure 13. Operating Strategy 211 Lead-Acid Batteries

Figure 14. Flywheel Electric Hybrid 211 Strategy

Figure 15

Figure 16

Figure 17. Lead-Acid Batteries 211 Operating Strategy

Figure 18. Mission 1 Lead-Acid Battery

Figure 19. Mission 1

Figure 20. Mission 1 All Strategies Lead-Acid Batteries

Figure 21. Mission 1 Operating Strategy 205 Battery Lead-Acid

Figure 22. Mission 1 Operating Strategy 211 Battery Lead-Acid

Figure 23. Mission 1 211 Strategy Lead-Acid Battery

Figure 24. Mission 2 All Strategies Lead-Acid Batteries

Figure 25. Mission 2 All Strategies Lead-Acid Battery

Figure 26. Mission 2 All Strategies Lead-Acid Battery

Figure 27. Mission 2 205 Strategy Lead-Acid Battery

Figure 28. Mission 2 211 Strategy Lead-Acid Battery

Figure 29. Mission 2 211 Strategy Lead-Acid Battery

Figure 30. Mission 3 All Strategies All Batteries

Figure 31. Mission 3 All Strategies All Batteries

Figure 32. Mission 3 All Strategies All Batteries

Figure 33. Mission 3 205 Strategy Lead-Acid Battery

Figure 34. Mission 3

Figure 35. Mission 3 Lead-Acid Battery 211 Strategy

Figure 36. Mission 4 All Strategies Lead-Acid Battery

Figure 37. Mission 4 All Strategies Lead-Acid Battery

Figure 38. Mission 4 All Strategies Lead-Acid Battery

Figure 39. Mission 5 All Strategies Lead-Acid Battery

Figure 40. Mission 5 All Strategies Lead-Acid Battery

Figure 41. Mission 5 All Strategies Lead-Acid Battery

Figure 42. Mission 6 All Strategies All Batteries All Engines

Figure 43. Mission 6 All Strategies All Batteries Otto Cycle Engine

Figure 44. Mission 6 All Strategies All Batteries Diesel Cycle Engines

Figure 45. Mission 6 All Strategies All Batteries All Engines

Figure 46. Mission 7 All Strategies Lead-Acid Battery

Figure 47. Mission 7 All Strategies Lead-Acid Battery

Figure 48. Mission 7 All Strategies Lead-Acid Battery

Figure 49. Lead-Acid Batteries 211 Operating Strategy

Figure 50. Lead-Acid Battery 211 Strategy Flywheel-Electric-Heat Engine Hybrid

Figure 51. Lead-Acid Batteries

Figure 52. Flywheel-Electric-Heat Engine Hybrid
Lead-Acid Battery 211 Strategy