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UCID- 17098, Volume 1

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THE BATTERY-FLYWHEEL HYBRID ELECTRIC POWER SYSTEM FOR NEAR-TERM APPLICATION
VOLUME 1 - SYSTEM DESCRIPTION

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MASTER

April 15, 1976

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Prepared for U.S. Energy Research & Development Administration under contract No. W-7405-Eng-48.

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THE BATTERY FLYWHEEL HYBRID ELECTRIC POWER SYSTEM
FOR NEAR-TERM APPLICATIONS

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FOREWORD

This report documents the results of an investigation of a Battery-Flywheel Power Systems by Lawrence Livermore Laboratory in association with Airesearch Manufacturing Company of California. The report, "The Battery-Flywheel Hybrid Electric Power System for Near-Term Applications," consists of two volumes:

Volume I - System Description

Volume II - System Design

The authors would like to thank the Lawrence Livermore Laboratory and Airesearch staff members for their critique of the report draft and to cite the following individuals for their contributions to this report: Roy A. Renner - LLL Automotive Consultant, for overall technical advice and manuscript review; Dr. John F. Cooper - LLL Electrochemist, for his contributions concerning battery technology; Donna L. Dougherty, Barbara L. Coles and Roslyn D. Scherr, - LLL Energy Resource and Planning Group, for the clerical help required to publish this report.

SECTION I

SUMMARY

A. AN ALTERNATE PROPULSION SYSTEM IS REQUIRED

The transportation sector of the economy uses approximately one-fourth of all energy consumed in the United States.¹ From an energy-use standpoint, this sector is dominated by the highway vehicle system. It alone accounted for about 75% of the transportation energy used in 1973.² This energy demand is almost entirely supplied by petroleum, and thus transportation is a major contributor to our domestic oil imbalance.

Use sectors other than transportation can change the fuels that they use, subject to the constraints of capital equipment inventories. This is not true of transportation at this time. The highway vehicle system will require petroleum for some time; no acceptable power systems are yet available that will use fuels other than petroleum. It is imperative that alternative energy sources, and the propulsion systems to use them, be developed for transportation, in particular for the highway vehicle system.

Electric vehicles are an interesting and challenging alternative to the internal combustion engine powered automobile. If they are successfully developed and introduced, the electric vehicles will be energized by electric power plants which can be fueled by coal or uranium. The electric vehicle can thus be a multi-fuel but non-petroleum automobile.

Although the concept of the electric vehicle has existed for as long as the automobile, it has not found acceptance with the driving public because the available batteries have limited energy and power capacity. This results in a vehicle of dismal performance and limited range. Additionally, battery recharge times are long, so that the vehicles have to be idled for long time periods.

Because of the growing petroleum shortage, electric vehicles are again being investigated with renewed interest. Extensive programs are underway by both industry and government to develop advanced batteries which will have increased power and energy densities. The performance data for advanced batteries as well as the current production lead-acid battery are shown in Figure 1. It is highly unlikely that the more energetic advanced batteries will be available for use in the automobile before 1985. Since it normally takes at least 10 years from its introduction until a new concept achieves full production, the lead-acid battery will be the primary energy source for battery electric vehicles for quite some time.

The limitations of these batteries for automotive propulsion is well known and has led to the concept of the limited range vehicle.* It is known that 75% of vehicle miles travelled consist of trips that are of distances of 50 miles or less and that trips of 20 miles or less make up over 50% of the vehicle miles travelled.⁵ When one examines the percentage of vehicle miles driven by trip purpose as depicted in Figure 2, the short mileage type of trip dominates. Although the data do not indicate the frequencies of these trips, they do indicate that trips to and from work dominate and thus, the majority of these would be round trips once a day.

Assuming costs and performance - acceleration, hill climbing capability - are appropriate, one can see that the limited range electric vehicle can become a partial solution to the petroleum shortage. Electric vehicles energized by lead-acid batteries could achieve the range required for over 50% of the trips travelled by the American public in private automobiles.

In order to improve the probability of the electric vehicle being the vehicle of choice by consumers for urban use, every effort should be made to improve its performance capabilities.

*The internal combustion engine automobile also has a range limitation, but the national infrastructure of service stations and the short time required for refueling provides an illusion of unlimited range.

Fig. 1. Performance characteristics of electric batteries.

Fig. 2. Percentage of vehicle miles driven by trip purpose.
 (Source: Ref. 5)

B. A HIGH PERFORMANCE ELECTRIC VEHICLE POWER SYSTEM

Electric vehicles powered by today's lead-acid batteries will provide respectable range at the expense of high performance. The specific energy of the battery as depicted in Figure 1 is a measure of range. This is more directly portrayed in Figure 3 where energy has been translated into range and power into speed for a vehicle with the listed characteristics.

As can be seen from Figure 3, the range available from a lead-acid battery for the given vehicle is limited to about 50 miles, and that while driving at 20 mph or less*. The range available to a battery electric vehicle is a strong function of the power demand. Acceptable performance, that is appropriate acceleration, hill climbing ability or high speed, further limit range. Thus, one must limit the performance capability of the present electric vehicles to maintain an acceptable range.

To insure that these vehicles are acceptable to the driving public, it will be necessary to maximize the range for the type of urban driving encountered and to provide acceptable acceleration, cruising speed, and hill climbing capability. The latter are necessary so that they can safely compete on the road with vehicles using other propulsion systems. These properties can be achieved by combining the lead-acid battery with a power booster, in principle not unlike that under consideration for the internal combustion engine.

Both range and performance can be improved by replacing some of the batteries in an electric vehicle with an equivalent weight of flywheel. The purpose of the flywheel is to act as a power booster for the battery. The flywheel is a mechanical device and can manage high power demands without reducing its total energy capacity. The range of a vehicle can be increased since the energy capacity of the battery-flywheel combination will be greater than the

* The range of the vehicle can be increased somewhat by increasing the weight of the battery to weight of vehicle, and reducing the resistive forces.

Note:
 Vehicle characteristics
 Curb weight – 2000 lbs
 Frontal area – 20 ft²
 Aerodynamic drag coefficient – 0.60
 Rolling resistance – 35 lbs

Fig. 3. Velocity vs range for existing and proposed battery systems.
 (Vehicle velocity as shown also relates to acceleration and hill climbing ability.
 It is a measure of available power.)

all-battery system. This is largely due to battery load leveling. That is, the battery can operate with a low current (power) demand placed upon it. The flywheel supplies the high power demands. Thus, the addition of the flywheel can provide a vehicle with high performance without suffering the same degradation of range as an all-battery electric vehicle.

A two-passenger all-battery commuter vehicle* with a loaded weight of 2400 lbs and a power system which weighs 1025 lbs is calculated to have the following ranges under the driving conditions listed:

<u>Constant Speed</u>	<u>Range (miles)</u>
30 mph	99
55 mph	36
<u>SAE J227 Driving Cycles**</u>	
Metropolitan	34
Residential	51

The same vehicle can be designed to use the battery-flywheel hybrid power system in which the total weight of the vehicle power system remains constant but where 50 lbs of battery are replaced by a flywheel component subsystem. The following ranges were calculated for this vehicle:

<u>Constant Speed</u>	<u>Range (miles)</u>
30 mph	101
55 mph	42
<u>SAE J227 Driving Cycles**</u>	
Metropolitan	75
Residential	94

*The vehicle was designed for low aerodynamic drag and low rolling resistance.

**The SAE J227 Driving Cycles²⁰ are described in Volume II, Section IV.

It can be seen that there is a rather dramatic improvement in range when operating in accordance with the cycles which represent urban driving.

These possible improvements to the range of the current lead-acid powered electric vehicle surfaced as a result of an investigation of battery-flywheel power systems by Lawrence Livermore Laboratory in association with the Airesearch Manufacturing Company. Our investigation has led to the following conclusions:

- 1) The battery-flywheel power system can provide a near-term electric vehicle which should be more acceptable to the driving public than an all battery electric vehicle. It will provide improved performance, and in an urban environment, increased range--about a factor of two increase.

- 2) The use of the flywheel allows the battery to be operated in a load leveled condition and not be subjected to high power demands. Capacity is thus increased so that an electric vehicle's range is increased while maintaining acceptable performance. Cycle life should also be increased as a result.

- 3) The operating cost of an electric vehicle with the battery flywheel hybrid power system should be less than for an all battery system because of increased overall efficiency.

- 4) The increased efficiency of operation will cause a reduction in energy demand for electric vehicles over and above the petroleum saved by changing from internal combustion engine power systems.

SECTION II

POWER SYSTEM DESCRIPTION

A. THE FLYWHEEL ADDITION

The flywheel subsystem used for the Hybrid Power System study is similar to those designed by Airesearch. The flywheel, typical of the unit shown in Fig. 4, has a fiber composite rim and rotates at a maximum speed of approximately 40,000 RPM. The 50 lb (23Kg) subsystem has an effective energy release of 750 Whrs or an energy density of 15 Whrs/lb (33 Whrs/Kg). The subsystem includes the rotor, containment and vacuum/lube pump. The containment will be maintained at a vacuum of 5 microns to decrease run down losses due to friction and windage. Run down from 40,000 to 20,000 RPM is calculated to take 2.8 hours during which time 75% of the total energy is expended. Energy will be extracted over this maximum to 1/2 maximum RPM range during power system operation.

As discussed previously, a lead-acid battery suffers reduction in available capacity when subjected to elevated discharge rates. It provides highest energy at modest power demands. On the other hand, a flywheel can deliver or re-accept energy at high power levels without affecting its energy storage capacity. This capacity is limited only by the stress-bearing capability of the connected hardware, gearing, shafts, etc. For the electric vehicle, the flywheel addition provides a means of satisfying the power demands of stop-and-go performance requirements that, time-averaged, represent only a modest continuous energy investment at low power levels.

FIGURE 4. COMPOSITE FLYWHEEL UNDER TEST (ARTIST'S CONCEPTION).

For the power system proposed, the flywheel is called upon to augment the battery during periods of high current demand, i.e., starting, acceleration and hill climbing. The battery will supply cruise and control power plus the energy required to replenish flywheel losses. This "split" of energy demand is shown figuratively in Figure 5. With battery power demand stabilized at a low value, specific energy is maintained near maximum resulting in an increased vehicle range. This range increase is not accompanied by the normally associated decrease in performance since the flywheel satisfies the required power demand.

The range of power demand placed on the "load leveled" battery, when installed in a vehicle traversing the SAE J227 Metropolitan and Residential Driving Cycles²⁰ is shown by the shaded bands on Figure 6. The rate of discharge is maintained at greater than 3.1 hr, while the specific power varies up to a maximum of 10.8 watts/Kg. Battery specific energy is thus maintained near the maximum available value.

Another important benefit that the hybrid system offers is increased battery life. Figure 7 shows the adverse effect on battery life due to excessive depth of discharge. In the hybrid system the battery will be discharged at a reduced, stabilized rate with the flywheel supplying peak power demands. Vehicle operating time between deep discharge cycles will be extended with a resultant increase in battery life.

In addition to load leveling the battery, the flywheel's ability to absorb energy (recharge) at high rates is a major contributor to increased range. Vehicle kinetic energy is restored to the flywheel when traversing a downgrade or during any period of deceleration. The battery-flywheel hybrid is thus able to make efficient use of a regenerative braking system to recover energy.

The hybrid vehicle when operating in a commuter environment will necessarily be parked during the working day. Flywheel energy content at the time of parking

Fig. 5. Specific energy as a function of specific power — lead acid battery and fiber composite flywheel.

Fig. 6. Load leveled battery power demand.

Fig. 7. Assumed life of 1980 lead-acid electric car batteries.
(Source: Ref. 9)

can be utilized to charge the battery bank rather than lost to run down. During the 2.8 hour time frame afforded by run down, establishment and control of a charge rate, matched to the existing battery state of charge, appears practical.

B. POWER SYSTEM DESIGN CONCEPT

The hybrid electric propulsion system employs a flywheel as a power booster for the battery in conjunction with an infinitely variable, electro-mechanical transmission. This hybrid system will provide improved vehicle performance and range when compared to a battery-only powered electric vehicle designed for urban driving. The energy storage capacity of the flywheel and the torque capacity of the transmission are sufficient to provide the torque capacity for all of the normal high power transients which occur in normal urban driving. This includes starting, acceleration, high speed passing maneuvers, uphill grades for limited distances, and energy recovery during braking.

This approach provides an efficient power system which will give improved vehicle performance while eliminating the high power demands on the battery which heretofore have had such a deleterious effect on battery performance, life, and cost. The results are increased range, increased acceleration, performance, increased energy economy, and longer battery life.

The proposed power system is shown schematically in Figure 8. The system includes the flywheel, transmission, power control unit, and the traction and flywheel motor/generators. The flywheel is a laminated fiber composite design of high energy density. The transmission is a simple differential planetary gear set infinitely variable from zero to maximum vehicle speed. The micro-processor-based power control unit provides interactive control of power flow

Fig. 8. System schematic diagram.

between the traction M/G, flywheel M/G and the battery. The traction and flywheel motor/generators are separately excited* DC machines developed by Airesearch. Either machine may be utilized in a motoring or generating mode as dictated by the control requirement. The major characteristics of the power system components are listed in Table 1.

To accelerate the vehicle, the traction M/G is supplied with current from the flywheel M/G acting as a generator. The necessary torque for the generator is supplied by the deceleration of the flywheel, which also reacts through the gears to supply additional accelerating torque to the shaft of the traction M/G. The planet carrier shaft (drive shaft) is common to the traction M/G armature. The net torque to the wheels is thus the sum of the electrical torque and the mechanical torque. Thus, the name split-path transmission.

With vehicle velocity constant (no acceleration demand) the battery provides traction motor power plus the power required by the flywheel motor to replenish flywheel run-down losses.

The deceleration case is the reverse of the acceleration case. The traction M/G is operated as a generator and the flywheel M/G acts as a motor to accelerate the flywheel. The flywheel resistive torque is again split between the ring gear and the carrier output shaft so that the two components to torque decelerate the vehicle and store the deceleration energy in the flywheel.

The efficiency of the split-path transmission is an important feature of this system. The combined efficiency will lie between the product of the electrical efficiencies and the mechanical efficiency. Figure 9 shows how this varies as a function of the mechanical torque fraction F for typical values of the component efficiencies. The value of F varies during any transient operation, but for the cases studied, the resulting average values are approximately 0.50, resulting in

*Field and armature windings brought out separately.

TABLE I

MAJOR CHARACTERISTICS OF THE PRELIMINARY
BASELINE SYSTEM

<u>Vehicle</u>		
2-Passenger Commuter		
Vehicle gross weight, lb		2400
Vehicle curb weight, lb		2000
Rolling resistance coefficient		0.012
Vehicle effective drag area, $C_D A$, ft ²		5.9
<u>Propulsion System</u>		
Flywheel	Total energy, w-hr	1000
	Available energy, w-hr	750
	Maximum speed, rpm	40,000
	Loss at maximum speed, w	380
	Total assembly weight, lb	50
<u>Traction</u>		
Motor/Generator	Rated power, hp	11.5
	Maximum speed, rpm	8000
	Nominal efficiency, percent	85
	Weight, lb	75
<u>Flywheel</u>		
Motor/Generator	Rated power, kw	9.9
	Maximum speed, rpm	12,000
	Nominal efficiency, percent	82
	Weight, lb	45
<u>Gearbox</u>		
	Efficiency, percent	96
	Weight, lb	20
<u>Power Control</u>		
<u>Unit</u>	Efficiency, percent	98
	Weight, lb	35
Battery pack weight, maximum, lb		800
Total propulsion system weight, lb		225

$$\eta_o = \eta_{Fw} [F\eta_m + (1-F)\eta_g\eta_{TM}\eta_c]$$

F = fraction transmitted mechanically

η_m = mechanical efficiency = 0.96

η_g = generator efficiency = 0.82

η_{TM} = motor efficiency = 0.85

η_c = controller efficiency = 0.98

η_{Fw} = flywheel efficiency = 0.99

Fig. 9. Power transmission efficiency.

combined efficiencies of over 80%, as shown in Figure 9. Power is thus transmitted with a higher average efficiency than that obtainable with an all-electric drive concept.

To initially charge the flywheel the flywheel M/G can be supplied with power from either the battery or an external source. The motor action accelerates the flywheel to its maximum speed (40,000 RPM) as shown by the "start" point in Figure 10. The traction M/G is held stationary (brakes applied) during initial flywheel run-up. Following flywheel run-up to the maximum operating level, outputs from speed sensors monitoring traction M/G RPM (road speed) and flywheel RPM, are utilized by the Power Control Unit to hold flywheel RPM within the control band prescribed. As vehicle speed increases, flywheel RPM is decreased. Thus the kinetic energy of the vehicle plus the kinetic energy of the flywheel is maintained constant, thereby providing the energy base required to meet acceleration demand with a margin for RPM increase adequate to accept energy during deceleration. On long down-grades flywheel RPM may tend to rise above the "start" point of Figure 10.

At this point the starting resistor will be switched into the armature circuit of the flywheel M/G and the excess energy dissipated. Limited regeneration to the battery, following flywheel run-up to maximum (start point) might be employed. This should be investigated further.

Fig. 10. Flywheel speed control.

C. CONTROL CONCEPT

The control requirement for the hybrid propulsion system differs from that needed for a battery only system. The hybrid concept utilizes two energy sources (battery and flywheel) that must be scheduled either separately or in parallel to provide traction motor drive power. Scheduling is dictated by vehicle operating conditions.

The battery will supply cruise power with the flywheel augmenting the battery during any peak power demand. Flywheel energy, via the flywheel M/G generating, is utilized for the starting acceleration with the battery supplying control power only. Relieved of the peak power demands, battery discharge rate is thus stabilized. During deceleration, vehicle kinetic energy is returned to the flywheel via traction M/G generating, and flywheel M/G motoring, to be reused on the next acceleration.

The battery, essentially a constant potential source, would require current limiting if used to supply traction motor power below base speed.* In the proposed system, flywheel energy, via the flywheel M/G (generating) provides a variable voltage source for the traction M/G (motoring) from start through the base speed range. Field control is utilized above base speed to control traction motor armature current, and hence, vehicle cruise speed. Starting resistors would be utilized for the flywheel M/G until base speed is reached.

Field control requires the use of what is termed a separately excited machine. This machine has separately connected field and armature windings. The more commonly used series machine has its armature and field winding, or windings, in series. Field current in a series machine is therefore equal to and varies with armature current.

With field control, the lower power of the field circuit is controlled rather than the high power armature circuit. Field current of motors in this application

*Motor RPM above which armature current limiting is not required due to back EMF generated.

is less than 60 amps. The much higher armature circuit current (approximately 10 times greater) would require the use of higher rated, more costly components.

Torque change in a field controlled motor is accomplished by varying the strength of magnetic field cut by the rotating armature conductors. Maximum field strength is a function of the field winding material type and amount. Minimum field strength is dictated by the maximum rated motor speed and the requirement of sparkless commutation. Motor speed range is determined by, and inversely proportional to field strength range. This control method provides base to maximum speed and torque variation that is smoothly variable.

Interactive control of the flywheel-battery power split to the traction motor, as well as flywheel RPM scheduling is provided by the microprocessor based power control unit. It is patterned after microprocessor systems developed by LLL.

The Power Control Unit (PCU) required for control of the hybrid power system is described in detail in Volume II, Section III. The major PCU components and the control functions each performs as follows:

Microprocessor (μ P) - The control algorithm is stored in memory for execution based upon operator and/or instrumentation inputs.

Instrument Interface (II) - Provides interface between the μ P and vehicle/power system instrumentation, i.e. flywheel RPM, road speed, etc. The II also provides output to the operators annunciators.

Armature and Field Control (AFC) - Houses field excitation supplies and armature switching circuitry for both the flywheel and traction M/G's.

Control Interface (CI) - Interfaces the μ P with the operator, AFC motor/generator control circuitry and the battery charger.

The ability to re-program the microprocessor allows optimization of the control algorithm for a particular operating environment or if desired to cover as broad an operating base as possible.

SECTION III
VEHICLE PERFORMANCE

A. SPECIFICATIONS AND PERFORMANCE GOALS

The limited range and performance capability of electric vehicles powered by existing lead-acid batteries is well known. This hybrid power system can provide marked improvement in both range and performance. In order to illustrate the improvements that can be realized, we have chosen a two-passenger commuter vehicle as a baseline design. The vehicle specifications for this baseline design are given in Table 2.

TABLE 2

Vehicle Specifications:

Passenger Capacity	2
Test Weight (Curb weight plus payload)	2400 lbs
Curb Weight	2000 lbs
Frontal Area (projected area)	18 sq ft
Drag Coefficient (C_D)	.33
Rolling Resistance Coefficient (lbs/10 ³ lbs vehicle)	.012
Tire Size	13 inch radial
(Rolling Radius Under Load)	(.725 feet)

Baseline vehicle range was calculated using the hybrid power system and compared with the range obtained with lead-acid battery power only.

The power train weight of the hybrid and battery-only systems is maintained at 1025 lbs, of which 850 lbs is allocated to energy source. The hybrid energy

source includes the 50 lb flywheel assembly plus 800 lbs of battery. The hybrid system traction M/G, sized for cruise demand, is approximately half the H.P. rating required for a battery-only powered vehicle of like specifications. The combined weight (120 lbs) of the hybrid system traction, and flywheel M/G's, and transmission is considered equivalent to that of the battery-only system traction motor. The power control unit weights are considered equal for the two power systems.

The lead-acid battery source used as the "model battery" for performance estimates is represented by the maximum performance limit of the "lead-acid band" of Figure 1.

A mechanical fraction of 0.50 is assumed for the hybrid system resulting in a power transmission efficiency of 82% as seen in Figure 9. A 72% efficiency is assumed as a typical value for the battery-only system.

B. HYBRID VEHICLE PERFORMANCE

Vehicle range was calculated for the hybrid and battery-only powered baseline vehicle operated at continuous speed and according to test schedules specified in SAE J227 Electric Vehicle Test Procedures.²⁰ These comparisons are shown in Table 3. Detailed range calculations and driving cycle descriptions may be found in Volume II, Section IV.

TABLE 3

<u>Condition</u>	<u>Range in Miles</u>	
	<u>All-Battery</u>	<u>Hybrid</u>
30 miles/hr continuous	99	101
55 miles/hr continuous	36	42
<u>SAE J227</u>		
Metropolitan Cycle	34	75
Residential Cycle	51	94

As seen in Table 3, a dramatic range increase results through use of the hybrid power system when traversing the SAE J227 driving cycles. The extension of electric vehicle range due to the flywheel's ability to meet high power demands, absorb energy on deceleration and extend battery range through load leveling is evident.

Calculated acceleration and gradeability performance for the hybrid powered baseline vehicle is shown in Table 4. Detailed calculations may be found in Volume II, Section IV.

TABLE 4
Acceleration and Gradeability

<u>Acceleration</u>	<u>Elapsed Time</u>
0-33 mph	6 sec
0-55 mph	13 sec
25-55 mph	8.5 sec
<u>Gradeability</u>	
55 mph* from rest on a 5% grade	21 sec

*Velocity could be maintained for a distance of 1.5 miles.

Electric commute vehicles with the hybrid range and acceleration shown in Tables 3 and 4, should prove consumer acceptable and could compete safely on the road with vehicles utilizing other propulsion systems.

As a further test, the hybrid system was theoretically "installed" in an existing electric vehicle. The Sundancer⁴ developed by ESB Inc. was used as the test bed vehicle. A battery weight of 50 lbs was removed and the flywheel assembly "installed" for the hybrid performance calculations.

The Sundancer was road tested over a velocity profile prescribed by the SAE J227 metropolitan driving cycles. The road test results are compared to those calculated for the "hybrid Sundancer" in Table 5.

TABLE 5
ESB Inc. Sundancer⁴

	<u>As Built</u>	<u>LLL/Airesearch Hybrid</u>
Battery:	EV 140 Experimental	Lead-Acid "Model"*
Efficiency:	65%	70 - 83%
Range: Metropolitan Cycle	50 - 55 mi (Road Test)	93 - 148 mi (Calculated)

*Maximum limit of "lead-acid band" in Figure 1.

As noted in Table 5, the Sundancer range is approximately doubled when powered by the hybrid system and a low efficiency is assumed.

The all-battery, as built, Sundancer range was calculated as 51 miles when traversing the SAE J227 metropolitan driving cycle. Characteristics for the EV 140 experimental battery were used in the calculations. Calculation method is upheld since this calculated range falls within the range band obtained during actual Sundancer road tests.

C. COST OF OPERATION

Operational costs for any electric vehicle will depend on the current cost of power available for battery recharge as well as the energy consumption of the vehicle itself. Since the electrical rates and recharge equipment efficiencies will be the same for all EV'S, the differences in fleet operating costs will be the energy consumed by the vehicle. Therefore, we calculated the energy consumption of both the hybrid vehicle and the battery-only vehicle as a baseline for comparison .

Energy consumption or its reciprocal energy economy is defined in SAE J227 Sect. 4.4.1 for battery-electric drive systems (excluding recharge equipment) as

driving range in a defined drive mode divided by the total energy available from the propulsion battery at the C/8 drain rate.²⁰

The C/8 drain rate is further defined as the ampere-hour capacity at the 8-hour discharge rate, expressed as C/8. For the "model" lead-acid battery data, the C/8 rate occurs at 16.4 Wh/lb.

Further assumptions include:

1. All batteries are charged equally by the same procedures.
2. The batteries are fully charged and in new condition.

On this basis, Table 6 gives the comparison of estimated energy economy for the two cases, based on ranges calculated for the drive modes.

TABLE 6
Comparison of Estimated Energy Economy, Miles/KWh

<u>Drive Mode</u>	<u>Battery-Only Vehicle</u>	<u>Hybrid Battery Electric Vehicle</u>
30 mph Continuous	7.1	7.6
55 mph Continuous	2.6	3.2
Metropolitan Area Drive Cycle	2.4	5.7
Residential Area Drive Cycle	3.7	7.2

The hybrid power system can thus provide both increased range and energy economy for an electric vehicle operated in an urban environment.

SECTION IV APPLICABLE VEHICLES

The battery flywheel hybrid power system is applicable to a number of different types of battery powered electric vehicles. Before listing vehicle applications, let us review the principal operating characteristics of the hybrid power system. These are:

1. The flywheel provides all transient power demands within its storage capability for acceleration to speed, traffic maneuvers, and grade climbing.
2. The battery provides power for steady speed cruise, replenishment of flywheel losses, and system control.
3. The flywheel stores and reuses energy recovered by regenerative braking.

With these characteristics in mind, it is clear that to realize the potential of the hybrid power system the electric vehicle use pattern must contain significant transient power requirements.

Figure 11 shows that a preponderance of vehicle trips are under 50 miles length, representing about 75% of vehicle-miles traveled, largely under urban or suburban stop-and-go traffic conditions. It is here that the hybrid power system can make its greatest contribution. With the flywheel addition, two-passenger battery-powered commute vehicles can reach arterial and freeway speeds, maneuver handily in stop-and-go traffic, and yet attain a respectable range capability and economy.

There appears to be no particular technological limit to the size of the battery-powered vehicle which would benefit economically from the hybrid power system if the use pattern shows a substantial transient power requirement. For example, if the battery and flywheel weight of the vehicle discussed in Section III were doubled, the payload could more than double since the weight bearing structure and trim need not be doubled in weight. The four-passenger commute vehicle is therefore an

Length of trips		
Trip length (one-way miles)	Trips	Vehicle miles
Under 5	54.1%	11.1%
5-9	19.6	13.8
10-15	13.8	18.7
16-20	4.3	9.1
21-30	4.0	11.8
31-40	1.6	6.6
41-50	0.8	4.3
51-99	1.0	7.6
100 and over	0.8	17.0
Total	100.0%	100.0%

Percent of total trips
Percent of vehicle miles

Fig. 11. Percent of vehicle miles and total trips by trip length
(Source: Ref. 5)

equally attractive application for the hybrid power system.

Commercial electric vehicles are seen as a potential for the hybrid power system. This class of vehicles includes:

1. Light delivery trucks/vans such as postal vans, food supply trucks, and parcel delivery vans.
2. Urban taxi fleets and airport shuttles.
3. Mini-bus fleets, for urban areas and feeder systems to metropolitan or rapid transit facilities.

Typical Commute Vehicle

To provide an example of a typical commute vehicle with a hybrid power system installed the available U.S. manufactured "small" cars in the curb weight range of 2000 lbs were surveyed. The General Motors "Chevet" was chosen and is shown in Figure 12.

The test vehicle can be modified by removing the internal combustion engine and the auxiliary equipment as well as the fuel tankage. A total of approximately 1000 lbs can be removed to provide for the weight of the battery/flywheel propulsion system.

A more desirable arrangement may be possible with the addition of a trans-axle drive. While some foreign manufactured vehicles are currently equipped, small U.S. manufactured vehicles are expected to be available within 1 to 2 years with this type of drive system. This transaxle drive can reduce the vehicle weight by elimination of the drive shaft. The normal transmission portion of the transaxle would also be removed from the drive line.

The addition of the flywheel-hybrid propulsion system will not impose excessive loads on the selected vehicle. The system addition can be made in both the front and rear of the vehicle if necessary to provide weight distribution the same as before modification.

Fig. 12. Typical installation (General Motors Chevette shown).

Propulsive and braking forces will not differ significantly from those related to a conventional design. The addition of gyrodynamic loads imposed by a spinning flywheel has been analyzed by Airesearch and is not considered to be a design factor as long as the stored energy in the flywheel is no more than 3 Kw hr with the flywheel spin axis as shown in Figure 12. As a general rule of thumb, it has been calculated that approximately 1 Kw hr of flywheel capacity can be carried in a rigidly mounted arrangement with any flywheel spin axis orientation for each 1000 lbs of vehicle unloaded weight. The energy storage capacity of the flywheel can be increased to 2 Kw hr/1000 lbs with a vertical spin axis and to 1.5 Kw hr/1000 lbs with a longitudinal spin axis. In addition, these flywheel capacities can be increased substantially if a suspension (passive, active, or gimbal-type) is provided for the flywheels. The 1 Kw hr/1000 lbs of vehicle weight can be applied to any vehicle of less than 30,000 lbs curb weight.

SECTION V
KEYS TO HYBRID POWER SYSTEM DEVELOPMENT

A. FLYWHEEL DEVELOPMENT

On the basis of preliminary design done to date and the results of the Airesearch R&D program on composite flywheels, a multiring, 1 Kw-hr composite flywheel was selected for the design study.

A development test unit should be designed, fabricated, and tested to determine the mechanical losses of the flywheel unit. Significant progress has been made to date to reduce the losses created by bearings, seals, and rotor windage. These concepts must be evaluated and further optimized in the flywheel test unit.

B. TRANSMISSION DEVELOPMENT

The candidate electromechanical transmission design is based on already developed components used in propulsion systems or similar power transmission systems. Several components have a critical influence on the energy savings of the propulsion system and require further evaluation. The flywheel M/G operates at maximum speed when the vehicle is at rest. A development test M/G must be designed, fabricated, and tested to measure the idle losses and devise means to minimize these losses. Bench test of gear box bearings and lubrication systems must also be conducted to prove out loss calculations on the selected gear system.

C. CONTROLLER DEVELOPMENT

Optimization

To determine the optimum control algorithm for the vehicle operated in accordance with Test Procedure SAE J227, or any other driving cycle, the vehicle

control system must be modeled and computer simulation studies conducted.

A key factor that must be determined is the Power Control Unit controlled power split between battery and flywheel. The goal is to minimize the battery current demand in order to maximize vehicle range, while managing flywheel charge and discharge so that battery and flywheel energy depletion occur simultaneously. This would insure that the system always functions as a hybrid and never on battery or flywheel alone. Since the battery and flywheel power demand will differ with each driving cycle, the power split must be optimized through simulation to cover as broad an operating base as possible.

Redundancy

The reliability of critical command path components, as identified through operational performance and safety analysis studies, must be determined.

Operator safety must be considered as a prime impetus for the implementation of redundancy. The decision as to whether redundancy is warranted will be based upon the degree of operational reliability and/or safety improvement to be realized at the expense of increased complexity, weight and cost.

D. BATTERY DEVELOPMENT

Required Characteristics

Although a sufficient amount of battery characteristic data exists in the literature for the initiation of preliminary design studies, this data is not sufficient for an in-depth evaluation of the true, achievable performance and economics of flywheel-battery hybrid vehicles. A large amount of the available data are conflicting, particularly with respect to cost and life expectations. It will be important to undo these conflicts and obtain a clear understanding of lead-acid battery characteristics required for design and performance evaluation of the hybrid power system. Table 7 shows a preliminary listing of the data that must be determined.

TABLE 7

Battery Characteristics Required

Ampere-hour capacity as a function of discharge rate and battery temperature.

Terminal voltage as a function of load current.

Internal resistance

Capacity as a function of cycle life for various depths of discharge

Charge and discharge efficiency as a function of rate and internal temperature

OEM costs as a function of quantities

Salvage value

If the required characteristic data is not available, a battery testing program designed to obtain the data required must be initiated.

Regenerative Battery Charging

Energy recovery directly into the battery during regenerative braking has been discounted in most past studies because of the deleterious effect of high recharging currents and/or the low overall recovery efficiency. The flywheel in the hybrid system will provide the energy sink for regenerative braking. Flywheel RPM may reach maximum during regenerative braking on extended down grades. At this point, starting resistors will be switched into the flywheel motor circuit to dissipate braking energy. Limited regeneration to the battery under this condition will be investigated as a means of conserving energy otherwise dissipated by the starting resistors.

Optimized Design

The flywheel is called upon to supply all high energy demands resulting in a lower, stabilized energy level demanded of the battery. Relieved of the high peak current requirement, the maximum current density required per cell is reduced. Any reduction in plate area, with accompanying reduction in mass, made possible through the reduced peak current requirement, will result in an increased specific energy (Wh/Kg).

A battery design optimized for use with the hybrid power system appears feasible and should be investigated.

E. SAFETY ANALYSIS

To insure that the hybrid power system is safe for vehicle operation, a detailed fault analysis must be made. This should insure that proper design emphasis is placed on areas with high failure probability or areas that induce severe secondary failure. Since the flywheel is the component of prime concern, its location on the vehicle must be considered in any analysis from the standpoint of accidental impact or flywheel failure. The method of flywheel housing attachment to the vehicle frame must also be considered.

F. PROOF OF PRINCIPLE

Although all components called for by the Hybrid Power System design concept are state-of-the-art with considerable operation experience from other applications, there still remains the integration into an operating system. The proof-of-principle should be demonstrated through a comprehensive operational test program designed to establish clearly the performance characteristics, and thus the incremental economy benefits of the Hybrid Power System package as a

separate entity, compared to a Battery Electric Power System as the base case. This can be accomplished if two comparable (even identical except for the power train) vehicles, each carrying one of the two power packages, are operated over the same set of test circumstances and procedures. The previously mentioned SAE J227 Electric Vehicle Test Procedure could be used as a yardstick but may not be an exclusive one.

Some benefits that may derive from use of the Hybrid Power System may not be immediately visible at first glance, and even may be difficult to assess. Range over a specific course, time to specific or peak velocity, are discernible characteristics comparable to the results of equivalent tests on other equipment even at other times. But how does one evaluate the benefit to the life expectancy of a set of batteries under even well-documented use conditions? Or as compared to another set under different use conditions? Can this process be simulated? Is it amenable to component testing only? This must be addressed with the required action initiated, since benefit to the battery is a prime claim of this system.

In its infancy today, the Hybrid Power System needs to prove that it has a contribution to make to electric vehicle technology. To tap its potential, a development program should consist of the following:

1. Power System Test - Initial prototype debugging and component assessment, optimization of accessories and instruments etc., under simulated load conditions. The Power system should consist of the following:
2. Vehicle Integration and Demonstration - Upon successful completion of dynamometer tests, the power system could be tested using a dynamometer. road verification of the SAE J227 Electric Vehicle Test Procedure Calculations. Vehicle performance utilizing the hybrid power system could then be compared to a battery only vehicle. To this end, it might be appropriate to convert an existing EV to demonstrate the improvement.

SECTION VI

EFFECT OF THE HYBRID POWER SYSTEM ON ENERGY AND PETROLEUM DEMAND

A. PROJECTED AUTOMOTIVE FUEL DEMAND

The battery-flywheel hybrid power system is suitable for many different types of vehicles as has been discussed earlier. However, the primary thrust of this document is to indicate its utility in a commuter vehicle of the future. Therefore, in projecting the energy and petroleum savings that might be possible with this type of power system, the commuter vehicle will provide the model.

For our baseline automobile fuel demand projection we used the Brookhaven National Laboratory Reference Energy System.⁶ Fuel demands through the year 2000 are shown in Table 9. Please note that this is all gasoline and hence, all from crude petroleum. The data base reflects higher energy prices which are likely to occur and some naturally occurring conservation which results. It is therefore an appropriate moving baseline against which the effect of various new technology changes such as the battery-flywheel vehicle can be tested.

The number of miles that the average automobile is driven each year has been 10,000 miles.¹¹ It is assumed that this will continue. On the basis of this and the annual vehicle miles traveled shown in Table 9 one can project the number of vehicles on the road. This is shown in Table 8. In addition, the per automobile fuel consumption is projected.

TABLE 8
Projected Fuel Consumption Per Automobile

Year	No. of Autos	Annual Fuel Consumption* (10 ⁶ bbl/yr Petroleum)	Annual Fuel Consumption Per Automobile (bbl/yr)
1980	125,800,000	1884	15.0
1985	146,700,000	1984	13.5
1990	163,900,000	2147	13.1
2000	205,000,000	2431	11.9

*Although 1 barrel of petroleum produces about 1/2 barrel of gasoline, we have put gasoline in petroleum barrel equivalents. The assumption made is that 42 gals of gasoline ("1 bbl") equates to 1.1 bbl of petroleum. The 10% is to allow for petroleum refining losses.

TABLE 9.

PROJECTED AUTOMOTIVE GASOLINE DEMAND

	1980			1985			1990			2000		
	f_i	e_i	D_i	f_i	e_i	D_i	f_i	e_i	D_i	f_i	e_i	D_i
DIRECT FUEL USE												
Methane												
Jet Fuel												
Gasoline	1.0	.20	9.947	1.0	.20	10.477	1.0	.20	11.338	1.0	.20	12.837
Distillate Oil												
Residual Oil												
Coal												
Other												
ELECTRICITY												
TOTAL FUEL DEMAND, D, 10 ¹⁵ BTU			9.947	1.1%/yr		10.477			11.338	1.3%/yr		12.837
BASIS 10 ⁹ Vehic. Mi.												
Local		{ 705.		3.2%/yr	{ 859.			{ 971.		2.3%	{ 1244.	
Intercity		{ 553.			{ 608.			{ 668.			{ 806.	
Fraction of Vehic. Mi.												
Local Travel			.560			.585			.592			.606
P.M. (Passenger Miles)				2.8%/yr	2670.					2.2%/yr	3669.	
BASIC ENERGY DEMAND, E, 10 ¹⁵ BTU			1.990			2.095			2.268			2.567
FUEL EFFICIENCY												
(BTU/V-M) MPG, Local	(9,328)	13.4		(8,333)	15.0		(8,064)	15.5	(6,944)		18.0	
(BTU/V-M) MPG, Intercity	(6,097)	20.5		(5,459)	22.9		(5,252)	23.8	(5,208)		24.0	
Avg. MPG		16.5			18.3			18.9			20.4	

D_i Fuel Demand
 e_i Engine Efficiency
 f_i Fraction Efficiency

B. ELECTRIC VEHICLE INTRODUCTION RATE PROJECTION

There have been a number of projections for electric vehicle introduction. Most of them project this introduction to be modest and gradual. This is probably true for a number of reasons. The initial electric vehicles will be of limited performance and will be introduced at a time (between now and 1980) when the general public has not yet experienced serious gasoline shortages and the resultant higher fuel prices. Thus, the electric car, even as a commuter vehicle, will face very stiff competition from the high performance internal combustion engine vehicle. However, as we proceed into the post 1990 period, Figure 13 shows the gap between demand and domestic oil supply growing dramatically. Fuel price during this post petroleum era will be increasing at the same time the performance of the electric vehicle is improving. Thus, the electric vehicle will become more attractive - particularly for commuter use. As shown in Sections II and III, the addition of a flywheel power booster to a battery electric vehicle will enhance its performance and reduce the cost of its operation, thus making electric vehicles so designed even more attractive. Table 10 shows several projections for electric vehicle introduction.

TABLE 10
Estimated Electric Vehicle Population

	<u>1985</u>	<u>1990</u>	<u>2000</u>
High Estimate ¹²	1×10^6	5×10^6	25×10^6
Low Estimate ¹³	0.2×10^6	1.8×10^6	18×10^6

While EV's will be introduced prior to 1985, (indeed, some are on the road now) it is not expected that they will be available in appreciable quantities until 1985. Of course the availability of a vehicle with more acceptable performance like the battery-flywheel hybrid, could increase the introduction rate.

Fig. 13. Domestic oil resources are inadequate.
(Source: Ref. 3)

For the purpose of estimating the energy/petroleum benefits to be achieved, we have assumed that the EV of the future will be a battery-flywheel hybrid.

C. IMPACT ON PETROLEUM/ENERGY CONSUMPTION

It should be clear from Figure 2 that most of the miles driven by the automobile are driven in the least efficient mode, local or urban driving. It is just this use that the commuter car powered by the battery-flywheel hybrid power system is designed to provide. Table 11 indicates the petroleum savings possible if the battery-flywheel hybrid vehicle becomes the EV of the future.* This petroleum savings will aid in reducing the need for foreign imports. At \$13/bbl this could amount to a 4.3×10^9 savings in foreign oil payments in the year 2000.

TABLE 11
Possible Petroleum Savings by Battery-Flywheel Vehicle

Year	No. of Local Miles/yr** (10^9 mi/yr)	No. vehicles Equivalents	Local Fuel Demand (10^6 petro. bbl/d)***	No. of Battery Flywheel Veh.	Petroleum Saved 10^6 bbl/d
1980	705	70,500,000	3.41	-	-
1985	859	85,900,000	3.72	1,000,000	0.04
1990	971	97,100,000	4.06	5,000,000	0.21
2000	1244	124,400,000	4.48	25,000,000	0.90

We believe the SAE J227 Metropolitan Driving Cycle to be a fair representation of commuter driving. We have shown that the battery-flywheel vehicle provides

* We have used the optimistic estimate from Table 10.

** Refer to Table 8.

***Again as in Table 8, 42 gals of gasoline are considered equivalent to 1.1 bbl of petroleum.

increased range over this cycle. This increased range represents higher efficiency and should amount to an overall energy saving. Of course, we have compared the hybrid to the battery-only EV with both utilizing the lead-acid battery. Future batteries will give different results. All should profit by the hybrid power system but the results will be battery dependent. Table 12 indicates this savings.

TABLE 12
Energy Savings by Battery-Flywheel EV Compared to Battery EV

Year	EV Energy Demand (10^{15} BTU/yr)	Improved Efficiency Battery-Flywheel Hybrid*	Energy Savings (10^{15} BTU/yr)
1980	-	121%	-
1985	0.06	121%	0.03
1990	0.32	121%	0.18
2000	1.39	121%	0.76

We must emphasize that this is a savings in addition to the petroleum savings of Table 11. To determine the EV energy demand we used the fact that these vehicles, driven in the urban environment are more efficient than ICE vehicles when the efficiency is calculated from the energy source to use on the road. Battery EV's using electricity derived from coal have an efficiency of 11% in urban driving while ICE's using gasoline from petroleum are 8% efficient in urban driving.¹⁴

*The SAE J227 Metropolitan Driving Cycle was assumed.

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