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CURRENT STATUS OF ALTERNATIVE AUTOMOTIVE POWER SYSTEMS AND FUELS

VOLUME IV - ELECTRIC AND HYBRID POWER SYSTEMS

U.S. ENVIRONMENTAL PROTECTION AGENCY
Office of Air and Waste Management
Office of Mobile Source Air Pollution Control
Alternative Automotive Power Systems Division
Ann Arbor, Michigan 48105

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VOLUME IV - ELECTRIC AND HYBRID POWER SYSTEMS

Prepared by

The Environmental Programs Group

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Prepared for

U.S. ENVIRONMENTAL PROTECTION AGENCY
Office of Air and Waste Management
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FOREWORD

This report, prepared by The Aerospace Corporation for the Environmental Protection Agency (EPA), Alternative Automotive Power Systems Division, summarizes available nonproprietary information on the technological status of automotive power systems which are alternatives to the conventional internal combustion engine, and the technological status of nonpetroleum-based fuels derived from domestic sources which may have application to future automotive vehicles.

The status of the technology reported herein is that existing at the end of 1973 with more recent data in selected areas. The material presented is based principally upon the results of research and technology activities sponsored under the Alternative Automotive Power Systems (AAPS) Program which was originated in 1970 and which is administered by the Alternative Automotive Power Systems Division of EPA. Supplementary data are included from programs sponsored by other government agencies and by private industry. Additional information on technology and development programs is known to the government but cannot be documented herein because the data are proprietary.

One purpose that the AAPS Program serves is to provide a basis of knowledge and perspective on what can and cannot be accomplished with the use of alternative propulsion and fuels technology and to disseminate this information to Congress, Federal policy makers, industry, and the public. Thus, the publication of information such as that contained herein is in keeping with this element of the mission of the AAPS Program. This is the first of a series of reports on alternatives that are intended to be published annually.

The results of this study are presented in four volumes and three main topical areas:

Volume I. Executive Summary

Volume II. Alternative Automotive Engines

Volume III. Alternative Nonpetroleum-Based Fuels

Volume IV. Electric and Hybrid Power Systems

Volume I, the Executive Summary, presents a concise review of important findings and conclusions for all three topical areas. Thus, an overview of the study results may be obtained by reading Volume I only. Volumes II, III, and IV contain detailed, comprehensive discussions of each topical area and are therefore of interest primarily to the technical specialist. Each of these three volumes also contains Highlights and Summary sections pertaining to the topical area covered in the volume.

This volume, Volume IV, presents available information pertaining to the current technological status of electric and hybrid power systems that may have application to future automotive vehicles.

A brief review of important findings and conclusions is presented in the Highlights and Summary sections. The report body is divided into two parts: Part I -- Electric Vehicles and Part II -- Hybrid Heat Engine/ Battery and Hybrid Heat Engine/Flywheel Vehicles. Section 1 of Part I reviews the electric vehicle history, Section 2 defines the power plant configurations, and Section 3 reviews vehicle performance characteristics. Sections 4 and 5 discuss current and projected status of electric vehicles, respectively. Section 1 of Part II defines a hybrid vehicle and lists various EPA-sponsored studies, Section 2 discusses the basic hybrid concept and vehicle powertrain operating modes, and Section 3 shows how vehicle specifications influence design approaches. Section 4 describes system and component design requirements and the analytical and test results achieved for hybrid heat engine/battery vehicles. Section 5 provides a similar discussion for hybrid heat engine/flywheel vehicles. Section 6 briefly describes other energy storage concepts, and Section 7 summarizes the development status of hybrid vehicles. Appendix A presents the Air Pollution Control Office vehicle design goals for a six passenger automobile.

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HIGHLIGHTS

HIGHLIGHTS

Electric and hybrid power systems are unique alternatives to heat engines for automotive propulsion. The extensive use of electric vehicles would shift the burden of controlling exhaust emissions from motor vehicles to stationary electric generating plants supplying energy for recharging batteries where the treatment of stack exhaust could be more easily controlled. Furthermore, the current use of petroleum-based fuels for automotive propulsion could be diminished, and personal transportation energy needs could be supported to a large degree by coal or nuclear resources.

The most common form of system operation that has been studied for hybrid heat engine/battery and hybrid heat engine/flywheel vehicles relies on the heat engine to supply energy for vehicle cruise and for recharging the battery or flywheel. The additional power for vehicle acceleration is supplied by the battery or flywheel. With this form of heat engine operation, the hybrid concept offers the possibility of reduced mobile emissions. A shift of exhaust emissions to stationary electric generating plants, as in the case of electric vehicles, would be possible only if the energy for recharging the battery or flywheel were available from an external stationary power source, and the heat engine was then used just for supplying emergency power or for extending vehicle range on an infrequent basis.

A status review has been made of automotive electric and hybrid power systems in this country and, where information was available, in foreign nations. A number of prototype vehicles have been built with private capital, and, in some cases, federal funding has been used to evaluate and test these systems. In particular, the results derived from EPA-funded programs were reviewed in context with the design goals established by the

Alternative Automotive Power Systems (AAPS) Program for personal passenger cars. The following highlights present the essential elements of this review. In addition to the technical problems noted, estimated high manufacturing costs will likely be an inhibiting factor in widespread application of these systems.

Electric Vehicles

1. In electric car designs, lead-acid batteries have been used in most cases, and the direct current electric brush motor with silicon-controlled rectifier time-ratio controls is used by an overwhelming majority of vehicle designers.

2. Currently, a major problem with electric vehicles is the limitation on the amount of energy and power that can be delivered by a given size battery; this limitation has a direct effect on vehicle range and acceleration.

3. In general, the majority of electric vehicles do not perform up to heat engine vehicle capabilities--particularly with respect to maximum acceleration, speed, range, and hill-climbing ability, as well as to passenger space and accommodations such as air conditioning and heating. The usual maximum speed is 30 to 50 miles per hour, and range is usually limited to 50 miles under conditions of optimum cruise speed.

4. An additional problem with the electric vehicle is the power and time needed for recharge of the batteries. Vehicle usage will be limited unless provisions are made for exchange of depleted batteries for fresh batteries. The capability of residential electrical grids to supply large power levels during daytime for a large number of electric vehicles also may be a problem.

5. In selecting batteries for electric vehicles, a dominant parameter has been purchase cost. Consideration also must be given to battery replacement costs and operating costs. For these reasons, lead-acid batteries are almost universally used.

6. No one battery has been developed yet to satisfy the combined design requirements for low cost, long lifetime, high energy density (for vehicle range), high power density (for vehicle acceleration), and ease of maintenance.

7. For near-term applications, nickel-zinc batteries offer higher energy density possibilities, but cost and nickel availability are drawbacks for supplanting lead-acid batteries (nickel-cadmium batteries are even more expensive). For far-term applications, the zinc-chlorine and alkali-metal/high temperature battery systems, with significant increases in energy and power density capabilities, appear promising if development goals are achieved.

8. Work on batteries for electric vehicles is accelerating abroad. The major activities are in the Federal Republic of Germany, Japan, the United Kingdom, and the U.S.S.R. In each case, the government is either formally participating in or is influencing the direction of the work.

9. Excluding the special-purpose applications of golf carts, electric fork lifts, and delivery vans, no major production of electric passenger vehicles is expected for the next 10 years. This picture could change, should there be a major gasoline shortage, a restriction on operating conventional vehicles in some areas due to air quality constraints, or a breakthrough in battery technology that would allow much improved vehicle performance and range.

Hybrid Heat Engine/Battery and Hybrid Heat Engine/Flywheel Vehicles

1. The range limitations of electric vehicles are not found in the hybrid heat engine vehicle concept. The hybrid vehicle under discussion uses a small heat engine to provide road cruising power, with acceleration power requirements provided by a battery in the case of an electric energy storage hybrid, and by a flywheel in the case of an inertial energy storage hybrid. By so restricting the operation of the heat engine, early studies anticipated significant reductions in exhaust emissions without the need for complex, costly exhaust treatment devices, but results to date have not verified this expected performance.

2. The EPA contracted with several companies in the 1969 to 1972 period to perform evaluations of hybrid battery and flywheel systems. This effort encompassed the analysis and test of hybrid systems and associated components.

3. Elements of the TRW electromechanical transmission (heat engine/battery hybrid) were assembled into a breadboard prototype unit and tested as a complete integrated system. Powertrain efficiency was found to be below predicted values (though possibly correctable through redesign), and exhaust emissions were reduced to or below the level

of the original 1976 Federal exhaust emission standards[1] only by the application of an exhaust emission control system involving exhaust gas recirculation, tricomponent catalysts, etc.

4. The Minicar, Inc., hybrid heat engine/battery powered car was deficient in meeting performance goals, and exhaust emissions were not reduced to acceptable levels.

5. Petro-Electric Motors has an operable hybrid heat engine/battery powered automobile that is undergoing test and evaluation at EPA laboratories under the Federal Clean Car Incentive Program.

6. The Aerospace Corporation analytical study of hybrid heat engine/battery powered vehicles showed that, with a spark ignition engine, exhaust emissions could meet the original 1976 Federal exhaust emission standards only by the use of aftertreatment devices in the exhaust, along with engine modifications. In comparison to the conventional automobile, no improvements in fuel economy were found. Similar conclusions were arrived at by Lockheed in its analysis of a hybrid heat engine/flywheel system.

7. The General Motors Stir-Lec I automobile (hybrid heat engine/battery) achieved very good fuel economy, but proved to be very limited in acceleration and peak speed. Exhaust emissions (except for NO_x) were reduced, but not enough to meet Federal 1976 standards.

8. Tyco concluded that a commercial state-of-the-art SLI (starting-lighting-ignition) lead-acid battery was unsuited for hybrid vehicle use because of life limitations, although required power levels were achieved. Research tests with a revised design showed substantial improvements in meeting required EPA lifetime.

9. It was also demonstrated by TRW/Gould that while a commercial state-of-the-art SLI lead-acid battery approached required EPA design power levels, it lacked the required lifetime. In a research battery design, TRW/Gould achieved the required power density, but lifetime goals were still not met.

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[1] Hydrocarbon (HC) = 0.41 gm/mi
Carbon monoxide (CO) = 3.4 gm/mi
Oxides of nitrogen (NO_x) = 0.40 gm/mi

10. Lockheed concluded that 4340-grade steel was the most cost-effective material for a flywheel in a disc configuration. E-glass and S-glass materials were found to be best suited for bar-type flywheel geometries. In tests to failure, the steel wheel exceeded specified peak speeds, while the glass materials fell short of design goals.

11. The Johns Hopkins University Applied Physics Laboratory tested advanced flywheels in filamentary and composite rod/bar configurations with mixed results. Single-strand boron filaments, small graphite/epoxy composite rods, and small R-glass/polyester composite rods exceeded the energy storage design goal of 30W-hr/lb, but the larger 1-pound S-glass/epoxy and graphite/epoxy composite bars failed to achieve this design goal; this was attributed to inadequate material processing techniques.

12. Sundstrand determined that a combination of mechanical, hydromechanical, and hydrostatic transmissions is a practical means of providing power for the flywheel, heat engine, and drive wheel links in a hybrid heat engine/flywheel powered car. Computer simulation of vehicles driven over the Federal Emissions Test Driving Cycle showed no fuel economy advantage for the hybrid-powered automobile when compared with a conventionally powered automobile. Mechanical Technology, Inc., in its transmission study, arrived at conclusions similar to Sundstrand.

13. Although not all of the goals were met, the EPA-funded programs resulted in some technology advancements, a much clearer definition of critical problem areas, and the establishment of preferable system operating modes. While the hybrid vehicle has proven to be technically feasible, it is a complex costly system when configured to match the performance of conventional internal combustion engine powered vehicles.

SUMMARY

SUMMARY

Electric and hybrid power systems are unique alternatives to heat engines for automotive propulsion. A status review has been made of such systems in this country and, where information was available, in foreign nations. A number of prototype vehicles have been built with private capital, and, in some cases, federal funding has been used to evaluate and test these systems. In particular, the results derived from EPA-funded programs were reviewed in context with the design goals established by the Alternative Automotive Power Systems (AAPS) Program for personal passenger cars.

S. 1 ELECTRIC VEHICLES

Because of the growing concern over air pollution, interest in electric vehicles was renewed in the late 1960's and early 1970's, principally for delivery vans and trucks in Great Britain and for compact and subcompact cars in Japan. The primary consideration was that extensive use of electric vehicles could shift the burden of controlling exhaust emissions from motor vehicles to stationary electric generating plants supplying energy for re-charging batteries, where the treatment of stack exhaust could be more easily controlled. Furthermore, the current use of petroleum-based fuels for automotive propulsion could be diminished, and personal transportation energy needs could be supported to a large degree by coal or nuclear resources. This renewed interest has not culminated in any extensive production of electric cars for numerous reasons. One overriding reason is the continued limited range of this vehicle--about 50 miles with lead-acid batteries (the only economically viable electric energy storage device available today). Another is that, even with lead-acid batteries, the projected purchase cost of electric vehicles is still significantly higher than that of the gasoline-powered vehicle.

S.1.1 Power Plant Description

The basic power plant in electric vehicle designs consists of one or more electric motors and controllers, perhaps a transmission or other gears, and a battery system. Lead-acid batteries have been used in most cases, and the direct current electric brush motor is used by an overwhelming majority of vehicle designers and fabricators. In some systems, regenerative braking is used which causes the motor to operate as a generator, permitting recharging of the battery as the car decelerates. Figure S-1 illustrates the main components of an electric car drivetrain in schematic form, and Figure S-2 depicts similar components as installed in the General Motors Electrovair II electric car.

S.1.1.1 Design Features--Batteries

Currently, a major problem is the limitation on the amount of energy and power that can be delivered by a given-size battery; this limitation has a direct effect on vehicle range and acceleration. Evidence of this problem is seen in the restricted operation of contemporary electric vehicles as illustrated in Table S-1. This is a partial list of electric vehicles built to prototype level of design or to commercial design specifications for small quantity production in the United States. Analytical studies have shown that battery requirements for powering a full-performance family car are a specific energy density of about 135 watt-hours per pound to satisfy vehicle range, and a specific power density of about 95 watts per pound to satisfy vehicle acceleration. Current battery capabilities (Table S-2) approach the power density requirement but fall far short of the energy density requirement. In a compact electric car, travel distances comparable to a heat engine car (without refueling) cannot be approached even with a battery system weighing about one-third of the vehicle curb weight.

When promoting a new battery for development, with intended application to electric vehicles, the technical comparison is most often based on specific energy density. As electric vehicle programs proceed, other factors, implicit in the design of battery systems, must be considered. One

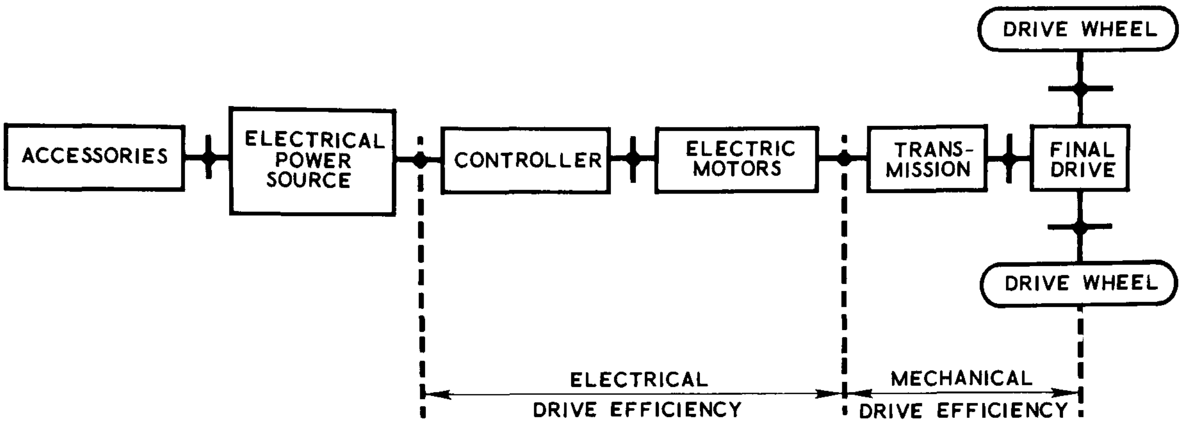

Figure S-1. Electric Car Drivetrain Showing the Main Components

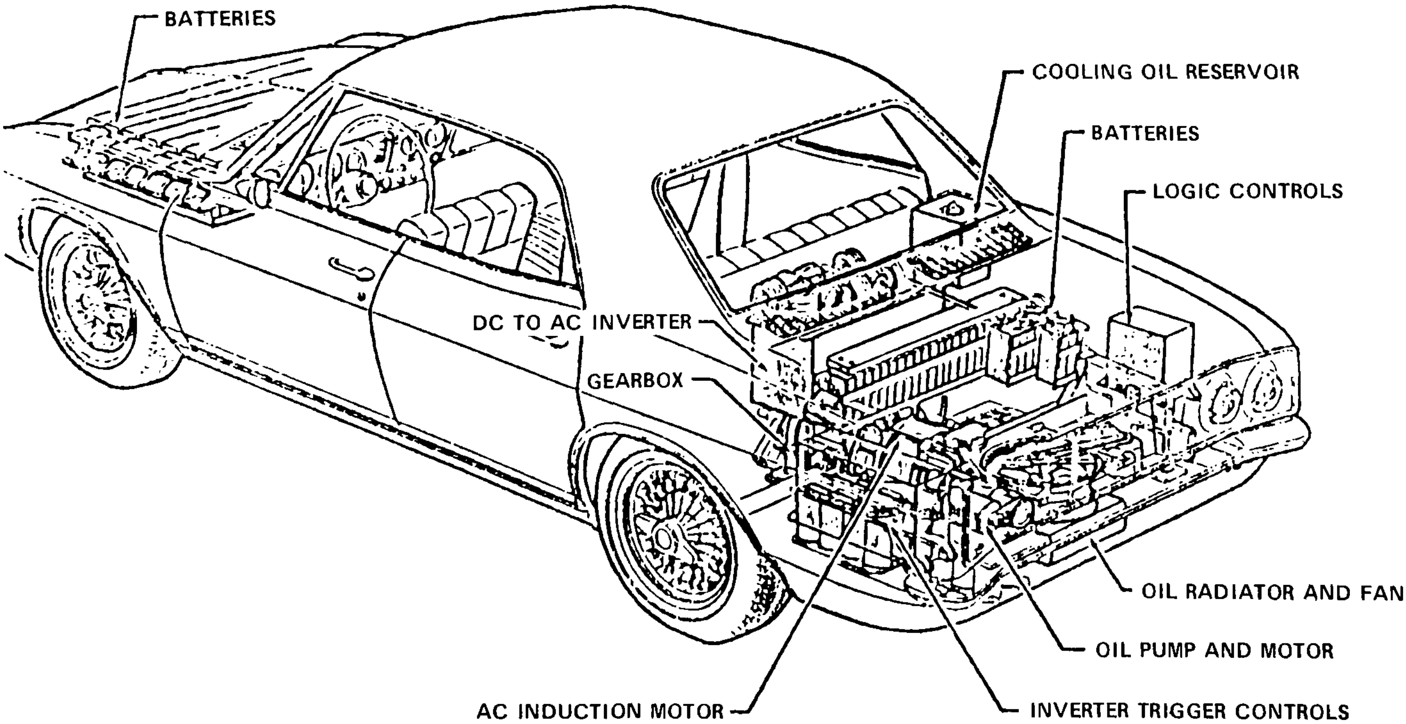

Figure S-2. Phantom View of General Motors Electrovair II Showing the Location of Major Experimental Components

Table S-1. Electric Vehicle Summary Data for Operating Passenger Models in the United States

Car Name and Manufacturer	Vehicle Curb Weight, pounds	Drive Motor(s)	Maximum Speed, miles per hour	Energy Source and Capacity	Range, miles
COMUTA Ford	1,200	Two 5 hp Series dc	40[a]	Lead-acid 48V (384 lb)	39 @ 25 mph[b]
GM 512 General Motors	1,250	8-1/2 hp Series dc (54 lb)	40[a]	Lead-acid 84V (329 lb)	47 @ 30 mph[b]
SUNDANCER 2 ESB	1,600	8 hp Series dc (83 lb)	60+[a]	Lead-acid 86V (750 lb)	70 to 75 on SAE Residential[b]
MARQUETTE Westinghouse	1,730	Two 4-1/2 hp dc (45 lb)	25[b]	Lead-acid 72V (800 lb) 8 kW-hr	50[b]
HENNEY KILOWATT Union Electric	2,135	7.1 hp Series dc	40[b]	Lead-acid (800 lb) 8 kW-hr	40[b]
YARDNEY	1,600	7.1 hp Series dc	55[b]	Silver-zinc 12 kW-hr (240 lb)	77[b]
ALLECTRIC West Penn Power Co.	2,160	7.1 hp 72Vdc	50[c]	Lead-acid 72V (900 lb) 9 kW-hr	50[b]
"MINI" General Electric	2,300	dc Motor 10.9 hp	55[b]	Lead-acid and Nickel-cadmium	100 @ 40 mph[b]
American Motors and Gulton Ind.	1,100	--	50[b]	Lithium-nickel fluoride (150 lb) and Nickel- cadmium (100 lb)	150 with regeneration[b]
ESB Renault	--	--	40[b]	Lead-acid (72V)	25 to 35[b]
Rowan Electric	1,300	Two dc Compound	40[c]	Lead-acid	100[b]
ALLECTRIC II West Penn Power Co.	2,300	7.1 hp dc	50[c]	Lead-acid (900 lb)	50[b]
Super-electric Model A Garwood & Stelber Ind.	--	Two 2 hp	52[b]	Lead-acid (520 lb)	--
CORTINA ESTATE CAR	3,086	40 hp 100V (150 lb)	60[b]	Nickel-cadmium (900 lb)	39.9 @ 25 mph[b]
COMET Ford	3,800	85 hp	70[b]	Sodium-sulfur (1,086 lb)	--
CITY CAR PINTO	3,200	40 hp	50[b]	Lead-acid (956 lb)	39 @ 40 mph[b]
MARS II Elect. Fuel Prop. Inc.	3,640	15 hp dc	55[a] 60 to 65[c]	Lead-acid 96V (1,700 lb) 30 kW-hr	70 to 120[b]
ELECTROVAIR General Motors	3,400	100 hp ac induction	80[b]	Silver-zinc 530V (680 lb) 19.5 kW-hr	40 to 80[b]
ELECTROVAN General Motors	7,100	125 hp ac induction	70[c]	Hydrogen-oxygen fuel cell 180 to 270 kW-hr	100 to 150[b]
CARMEN GHIA Allis Chalmers	3,440	--	--	Lead-acid 120V (1,534 lb)	60 @ 60 mph[b]
SIMCA Chrysler	--	--	--	Lead-acid (1,400 lb)	40[b]
Elect. Fuel Prop. Inc.	3,400	--	85[b]	Lead-acid cobalt	150 to 175[b]
FALCON Linear-Alpha	--	25 hp ac induction motor	60[b]	Lithium-nickel fluoride (360 lb)	75 @ 30 mph[b]

[a]Test data
[b]Basis of data not verifiable
[c]Design goals

Table S-2. Characteristics of Currently Available Secondary Batteries

Battery Type	Specific Energy Density W-hr/lb	Energy Density, W-hr/in^3	Specific Power Density, W/lb	Approx. Relative Cost	Remarks
Lead-Acid	20	2.0	100	1	Standard
Nickel-Iron	13	1.2	60	3	Excellent life; poor maintenance; nickel supply limited
Nickel-Cadmium	12	1.1	80	20	Good cycle life; cadmium supply limited

W-hr/lb = Watt-hours per pound
W-hr/in^3 = Watt-hours per cubic inch
W/lb = Watts per pound

objective of system design would be to reduce vehicle weight and to minimize influences such as drag, frontal area, acceleration, and peak cruise speed, which would allow a reduction in battery energy usage.

An additional problem with the electric vehicle is the power and time needed to recharge the batteries. Ordinarily, recharge time will exceed discharge time so that extensive vehicle usage will be limited unless provisions are made for exchange of depleted batteries for fresh batteries. The capability of residential electrical grids to supply large power levels during daytime for a large number of electric vehicles may also be a problem. Possible solutions are slow charging during evening hours and higher efficiency for charge acceptance of batteries.

In selecting batteries for electric vehicles, a dominant parameter has been purchase cost. Cost is influenced by the basic raw material cost and the demand/availability ratio assignable to the raw materials. In addition to original purchase cost, consideration must be given to battery replacement cost and operating cost. For this reason, lead-acid batteries are almost universally used. For high-temperature batteries, cycle life and, especially, time at operating temperature are important factors for determining frequency of battery replacement.

No one battery has been developed yet to satisfy the combined design requirements for low cost, long lifetime, high energy density, high power density, and ease of maintenance. Some of the batteries and battery systems that are of interest are described briefly in the following paragraphs.

In recent years, the applicability of the lead-acid battery for propelling electric highway vehicles has improved considerably. Most of the progress in lead-acid systems has been made in the small and intermediate sizes such as for automobile starting, golf cart propulsion, and fork lift propulsion and power, where high production volume is possible. Little further improvement in lead-acid battery performance is expected, except in lifetime.

The nickel-iron system has been proposed as a low-cost replacement for the lead-acid battery. Intensive work by Westinghouse has improved battery life and introduced new maintenance concepts, but this battery appears best suited for industrial applications because of cost, poor low-temperature performance, poor charge retention, and the need for frequent service. Except for lifetime, the nickel-iron battery is not competitive in most respects with lead-acid batteries.

Nickel-cadmium batteries, when referenced to lead-acid batteries, have about the same performance, longer cycle life, and cost considerably more.

In contrast to the aforementioned current battery systems, there are other systems under development with characteristics that theoretically are more capable of meeting the cited battery requirements. As an example, for near-term applications, nickel-zinc batteries offer higher energy density possibilities, but cost and nickel availability are drawbacks for supplanting lead-acid batteries. A specific energy density of 30 watt-hours per pound and a specific power density of 150 watts per pound seem possible.

Metal-gas batteries provide energy densities in the 30 to 60 watt-hours per pound range, depending on the reactants selected. The use of air in these batteries is advantageous for obvious reasons (e.g., no on-board storage required), but they require the addition of scrubbers for carbon dioxide removal, an air blower, and a water makeup system, which negate much of the gain. Also, a low-cost suitable air electrode has not been discovered. Work on the nickel-hydrogen battery has increased, but work on other metal-gas batteries (e.g., zinc-oxygen or zinc-air) has declined.

Alkali-metal/high-temperature batteries are theoretically capable of meeting the goals that have been established for full-performance vehicles. Demonstrations of high power density and high energy density have been made, although not always in the same cell. For the far-term period (1985 to 2000), such systems are most favored, but in most cases they are still undergoing research for proof-of-principle.

The sodium-sulfur system, first announced by Ford, is receiving international attention. The major United States program on the sodium-sulfur battery is Ford's, although TRW Systems, General Electric, and others have also worked on it. All sodium-sulfur ceramic electrolyte projects face the same key problem today; namely, deterioration of the beta-alumina electrolyte after 1000 to 2000 hours at working temperatures. In addition, economic success will ultimately depend on finding inexpensive ways to produce the desired ceramic and to fabricate large batteries.

The lithium-sulfur system has been under development for a number of years at Argonne National Laboratory, with a smaller effort at Atomics International. Test results show the system has the desired charge and discharge rate characteristics for a vehicle battery, although the life is limited and sulfur utilization has been too low to allow high energy densities to be sustained. Obtaining low-cost materials compatible with this battery environment continues to be a major problem.

The lithium-chlorine system was the first one investigated by General Motors. It showed high power densities, but was hampered by difficult corrosion problems at the 700-degree-centigrade operating temperature. Later, a modified system was investigated by Sohio.

Organic electrolyte batteries offer the possibility of high energy densities at ordinary temperatures and are attractive for this reason; however, power densities are low. To date, no long-cycle-life, rechargeable organic electrolyte cell has been built.

Zinc-halogen cells have been investigated in two laboratories. The Zito Company reports long cycle life for an aqueous zinc-bromine cell, but the energy density is too low to be of interest. A different concept has been demonstrated by Occidental Petroleum that uses a zinc-chlorine battery in which chlorine is stored as a solid hydrate at 8-degrees centigrade or below. For far term applications, this battery appears promising if development goals are achieved.

Work on batteries for electric vehicles is accelerating abroad. The major activities are in the Federal Republic of Germany, Japan, the United Kingdom, and the U.S.S.R. In each case, the government is either formally participating or influencing the direction of work. In at least five other countries (France, Switzerland, Sweden, Italy, and Czechoslovakia), vehicle battery projects are known to be under way. The most dramatic achievement of the past year was the use of a sodium-sulfur battery to power a small van. This was accomplished by the Electricity Council Research Centre at Capenhurst in the United Kingdom.

S.1.1.2 Design Features--Motors and Controls

A wide selection of motor design and controller combinations has been used in past and present electric cars. The controllers vary in complexity from the use of simple carbon-pile resistance stacks employed on early streetcars to complex three-phase, silicon-controlled rectifier time-ratio controls used in some of the advanced experimental alternating current motor drives.

The overwhelming majority of electric vehicle builders use the brush direct current motor. Brushes are easy to replace and are capable of lasting 50,000 vehicle miles. For motor control, the chopper circuit (generally using silicon-controlled rectifiers) provides an efficient means for transforming a fixed battery voltage to a smoothly varying effective voltage matching the power requirement of the motor at all operating speeds.

To date, there has been no mass production of motors or motor controllers that are suitable for family-size vehicles. Because of this status, these powertrain elements presently have a high cost, and it is this high cost that is the greatest hurdle to their widespread use in automotive vehicles. In addition, electric motors, particularly direct current motors, have not been developed to provide combined optimization of efficiency, weight, size, and cost for vehicle propulsion. Part-load efficiency is very important because during a typical urban driving cycle the motor is expected to operate at part-load most of the time; this efficiency will be lower than that available when operating at design load.

S.1.2 Vehicle Performance Characteristics

In general, most electric vehicles do not perform up to heat engine vehicle capabilities, particularly with respect to maximum acceleration, speed, range, hill-climbing ability, and passenger capacity. The usual maximum speed varies between 30 and 50 miles per hour. When a compact car weighing about 2,000 pounds is converted to an electric vehicle weighing 3,000 pounds (including 1,000 pounds of batteries), it cannot travel more than 30 to 50 miles between charges in stop-and-go driving. If greater battery weight is added to increase the range, the handling characteristics such as steering and braking are further degraded, in addition to having poor acceleration and an uncomfortable ride. It is therefore concluded that a general-purpose, all-electric family car is not possible with present lead-acid batteries.

Though some improvement can be made in aerodynamic drag by streamlining, and in road drag by using radial ply tires, the basic power to move and accelerate vehicles of certain weight and cross-section area remains essentially fixed. Reducing drag to a minimum while increasing drive system efficiency to a maximum are the only steps outside of battery development that can be taken if the ratio of drivetrain weight to total weight is to be maintained at feasible levels. Unfortunately, these actions can provide only minor improvement.

When energy requirements of electric vehicles are compared to conventional cars, a careful examination must be made of the efficiencies of the various steps of energy flow. But to avoid making assumptions regarding the efficiency of elements in the vehicle powertrain, road test data for a given vehicle must be used. As one example, in a comparison of energy expenditures between electric and gasoline engine powered vehicles used in postal delivery service, the electric vehicle showed some advantage for this special application. If these results were extrapolated to passenger cars, it should be noted that for equivalent weight vehicles, the gasoline engine powered car has superior driving range, cruise speed, acceleration, and passenger/luggage accommodations. In favor of the electric car, however, is the prospect that energy for propulsion can be derived directly from non-petroleum based sources such as nuclear power or abundant supplies of coal. Eventually, these sources can also be available indirectly through production of synthetic fuels for heat engine powered cars.

While an electric vehicle has fewer moving parts than an internal combustion engine powered vehicle, no definitive data are available for passenger cars that can establish a statistical base for maintenance requirements and cost.

In regard to safety, general requirements for an electric vehicle will be comparable to those for a similar heat engine vehicle. Spill-proof battery caps must be used; in the event of an accident, there must be provision to avoid hazards from spilled electrolyte. There must be redundancy in design to minimize shock hazard, and short-circuit protection must be maintained.

S.1.3 Current and Projected Status

Electric delivery trucks or vans and electric utility vehicles have been built in increasing numbers in Great Britain for the past decade, and are now estimated to exceed 75,000 vehicles. Small electric cars and electric utility vehicles are currently being produced in Japan in greater numbers than in the United States, largely because of the ban on heat engine vehicles in Osaka during the 1970 World's Fair. Many demonstration and prototype models have been built in the United States, but, excluding electric golf carts and electric fork lifts, no major production of electric vehicles is currently under way.

Excluding the special-purpose applications of golf carts, electric fork lifts, and delivery vans, no major production of electric passenger vehicles is expected for the next 10 years. Only very low production of vehicles for use by electric utilities and an increasing number of individual conversions to electric propulsion are expected to be the extent of passenger cars on city streets during this time.

In addition, the electric car would have to be sold at a price comparable to the heat engine car for general acceptance. This would require subsidies or tax incentives, as well as mass production methods to reduce fabrication costs. Of importance also is an acceptable cost for battery replacement and the assurance of low electric power rates to control vehicle operating costs. This picture could change, should there be a major gasoline shortage, a restriction on operating conventional vehicles in some areas due to air quality constraints, or a breakthrough in battery technology that would allow much improved vehicle performance and range.

S.2 HYBRID HEAT ENGINE/BATTERY AND HEAT ENGINE/FLYWHEEL VEHICLES

The problem of adequate operating range for electric vehicles has been already noted. Until low-cost, high-capacity batteries become available to permit operating ranges for electric cars that are nearly comparable to those for gasoline engine-powered cars, other concepts must be examined in the search for a low-pollution vehicle that could satisfy personal transportation needs. One such concept that has received the attention of automobile designers in the last 5 years is the hybrid vehicle--a vehicle combining various power delivery systems in the powertrain to use each form of power most effectively. The most common form of system operation that has been studied relies on a small, nearly constant power heat engine to supply energy for vehicle cruise and for recharging a battery or flywheel. The additional power for vehicle acceleration is supplied by the battery in the case of an electric energy storage hybrid, and by the flywheel in the case of an inertial energy storage hybrid. With this form of heat engine operation, the hybrid concept offers the possibility of reduced mobile emissions. A shift of exhaust emissions and energy source to stationary electric generating plants, as in the case of electric vehicles, would be possible only if the energy for recharging the battery or flywheel was available from an external stationary power source, and the heat engine was then used just for supplying emergency power or for extending vehicle range on an infrequent basis.

To evaluate various hybrid concepts, the EPA under the AAPS Program assumed the task of planning a hybrid vehicle prototype development program. Implementation of a 3-year program began in 1970 with participation of several companies offering the required technical expertise. Emphasis was placed on achieving the original 1976 Federal emission standards without the use of engine add-on control devices (e.g., catalytic converters). The hybrid vehicle development program was terminated because of funding limitations imposed in Fiscal Year 1971 and because it was found that operating a spark ignition engine in a hybrid mode still required the same types of exhaust aftertreatment needed on conventional systems. This latter fact was of overriding importance in terminating further work on hybrids.

It should be noted that many of the study guidelines that resulted in specific powertrain design constraints for these programs have since been under revision. Revised guidelines for vehicle range, acceleration performance, cruise speed, exhaust emissions, and fuel economy could result in modifications to system designs as well as to study conclusions.

S.2.1 General Concept Designs and System Operation

Hybrid vehicle powertrain concepts can be grouped into two broad classes (Figure S-3). The first class, series configuration, is characterized by the principle that all energy flowing from the heat engine to the

In contrast to the electric system, the hybrid heat engine/ flywheel design provides higher energy densities resulting in system weights and volumes that are a smaller fraction of the allowable value for the total propulsion system.

S. 2. 3 Hybrid Heat Engine/Battery Vehicle

S. 2. 3. 1 System Designs

Two major hybrid heat engine/battery system concepts funded under the AAPS Program were the TRW Systems, Inc., electromechanical transmission system (Figure S-4) and the Minicar, Inc., heat engine/battery vehicle (Figure S-5). This included the building of a breadboard prototype system by TRW and a vehicle-mounted prototype system by Minicar. Under the EPA Federal Clean Car Incentive Program, Petro-Electric Motors installed a heat engine/battery powertrain in a 1972 Buick Skylark. Another AAPS-funded study was performed by The Aerospace Corporation to provide an analytical evaluation of hybrid heat engine/battery vehicles. This effort did not include building a breadboard or prototype device. In addition, General Motors built its own prototype system called Stir-Lec (modified Opel-Kadett). Figure S-6 shows the major components as located in the vehicle, and Figure S-7 is a schematic diagram of the hybrid power system.

S. 2. 3. 2 System Design Requirements and Achievements

TRW performed computer simulation studies to evaluate the automotive propulsion systems on the basis of total weight, volume, and efficiency over the Federal Emissions Test Driving Cycle. The system modeling used manufacturer's data for major components and included analysis of generators, traction motors, power conditioning unit, gearing, and batteries. A dynamometer demonstration breadboard was also built as proof-of-principle hardware. Poor correlation was found between computer-predicted results and breadboard testing results. A reduction in overall powertrain efficiency (road demand/engine output) from the predicted 76.7 percent to a nominal test value of 50 percent is the most encompassing

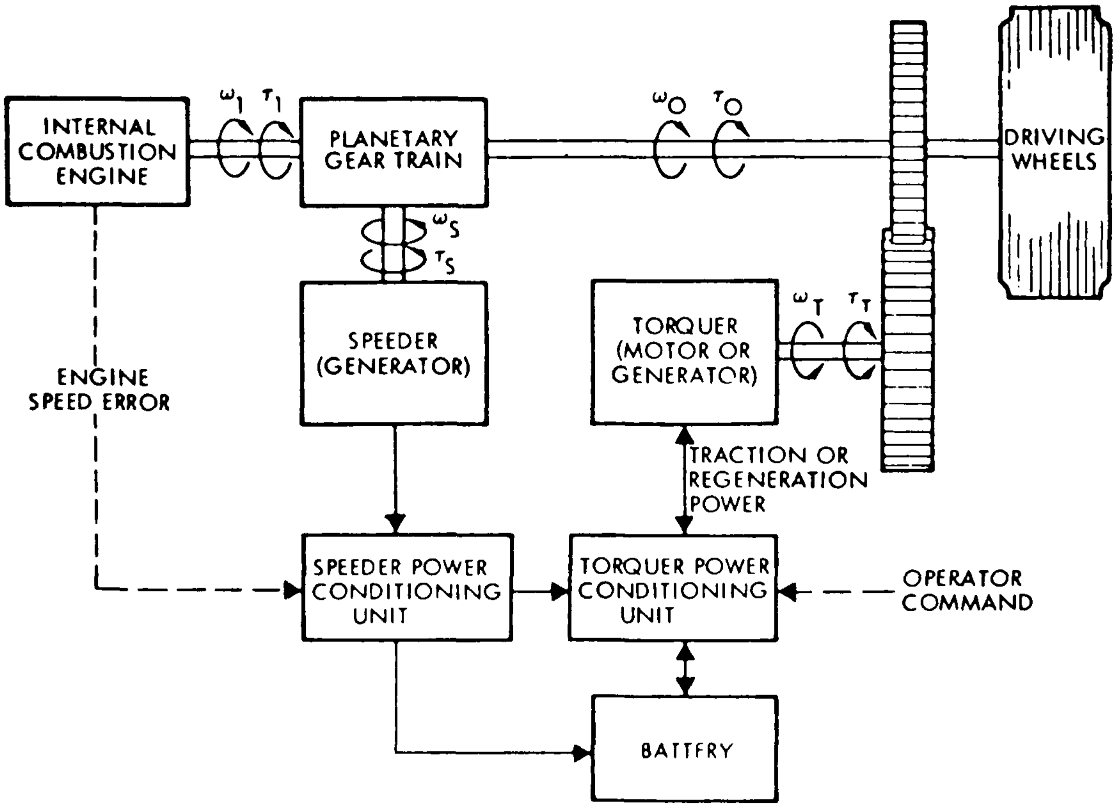

Figure S-4. Schematic, TRW Electromechanical Transmission Mode I Operation

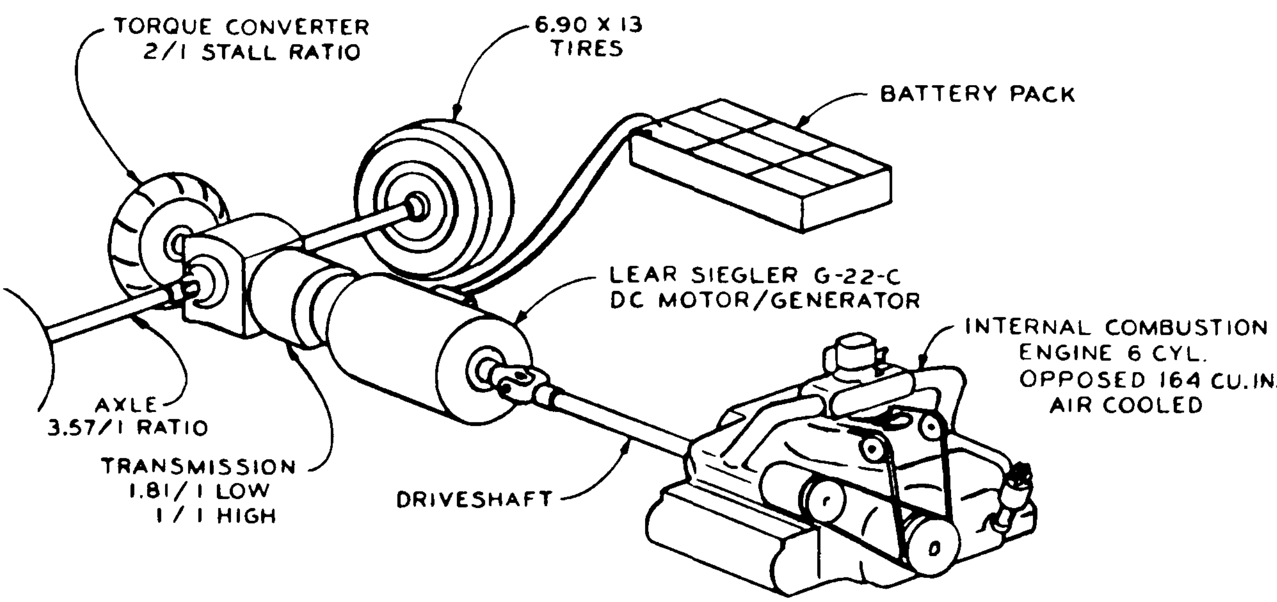

Figure S-5. Minicar Drivetrain

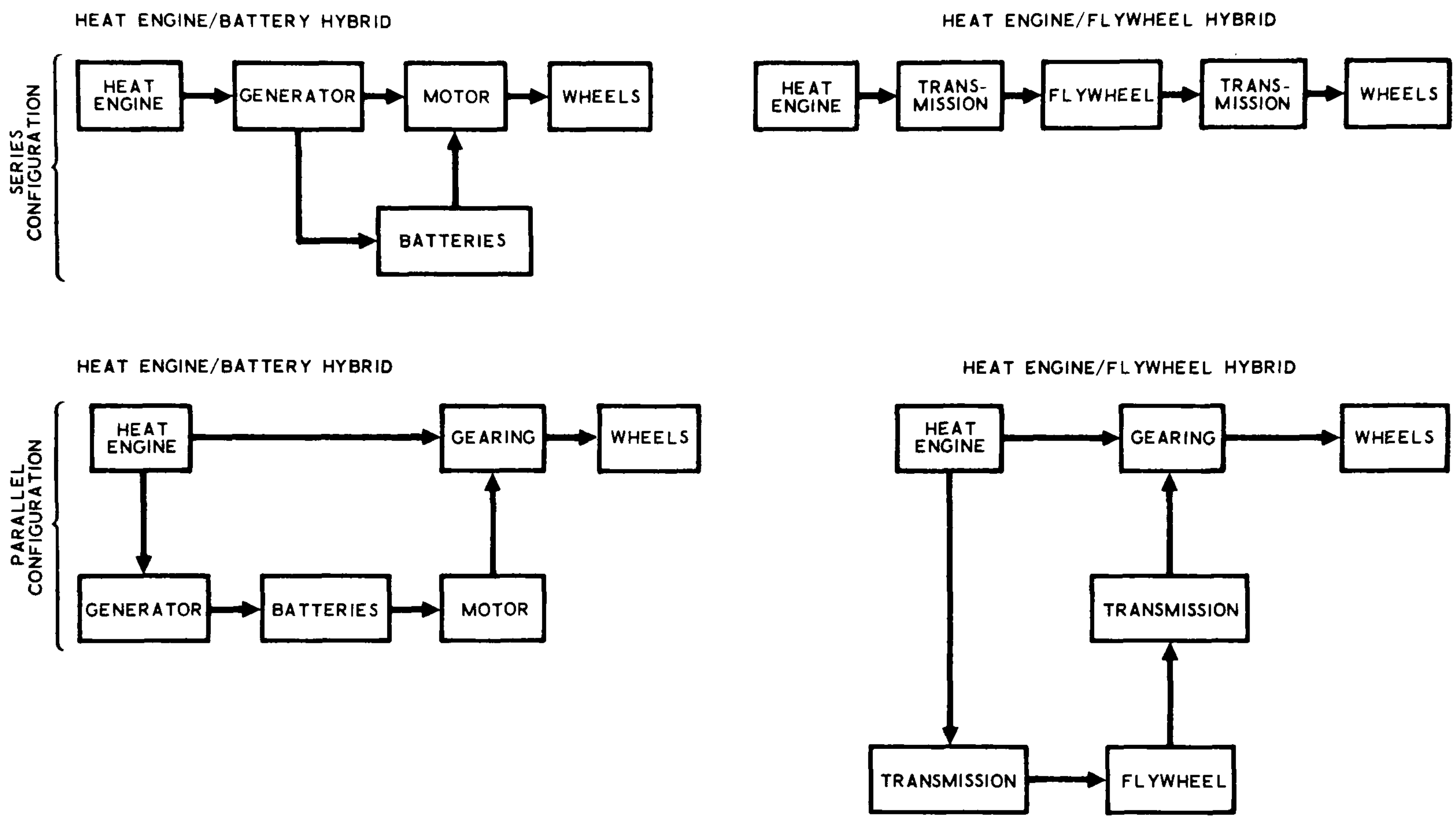

Figure S-3. Simplified Schematics, Heat Engine Hybrid Vehicle Powertrain Concepts rear wheels first passes through an intermediate energy conversion device or devices.[1] The second class, parallel configuration, is characterized by the principle that some of the energy flowing from the heat engine passes directly to the rear wheels, with the balance of the energy directed in a parallel path through an energy conversion device or devices.[1]

Different operating modes have been considered for the hybrid vehicle powertrain. The majority of designs are based on the unimodal concept, whereby a portion of the heat engine energy is used continually to replace energy drained from the on-board energy storage device (battery or flywheel). Another design is the bimodal operating scheme, whereby the vehicle is driven in an all-battery (or all-flywheel) mode or all-engine mode. The bimodal vehicle would normally be driven in the battery/flywheel mode with recharging provided by a source external to the vehicle; the engine in this case is used merely to extend vehicle operating range whenever required.

S.2.2 Design Impact of Vehicle Specifications

Early in the AAPS program, vehicle specifications for each of a number of urban automotive applications were developed jointly by EPA and the several contractors involved in the hybrid system study effort. In general, the propulsion system weight limitations impose upper bounds on the ability of the system to furnish power and energy required to operate the vehicle for extended durations at the specified road performance levels.

Certain power plants are not applicable to the hybrid electric family car under the propulsion system weight allocation defined by the EPA specification, and only the spark ignition engine (reciprocating or rotary) and gas turbine engine result in realistically achievable values for battery power and energy densities. It should be noted, however, that more recent development work could result in some modifications to these conclusions; e.g., Stirling engine weight and size have been reduced markedly from former levels.

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[1] Generator, motor, and battery in electric system, or flywheel and transmission in inertial system.

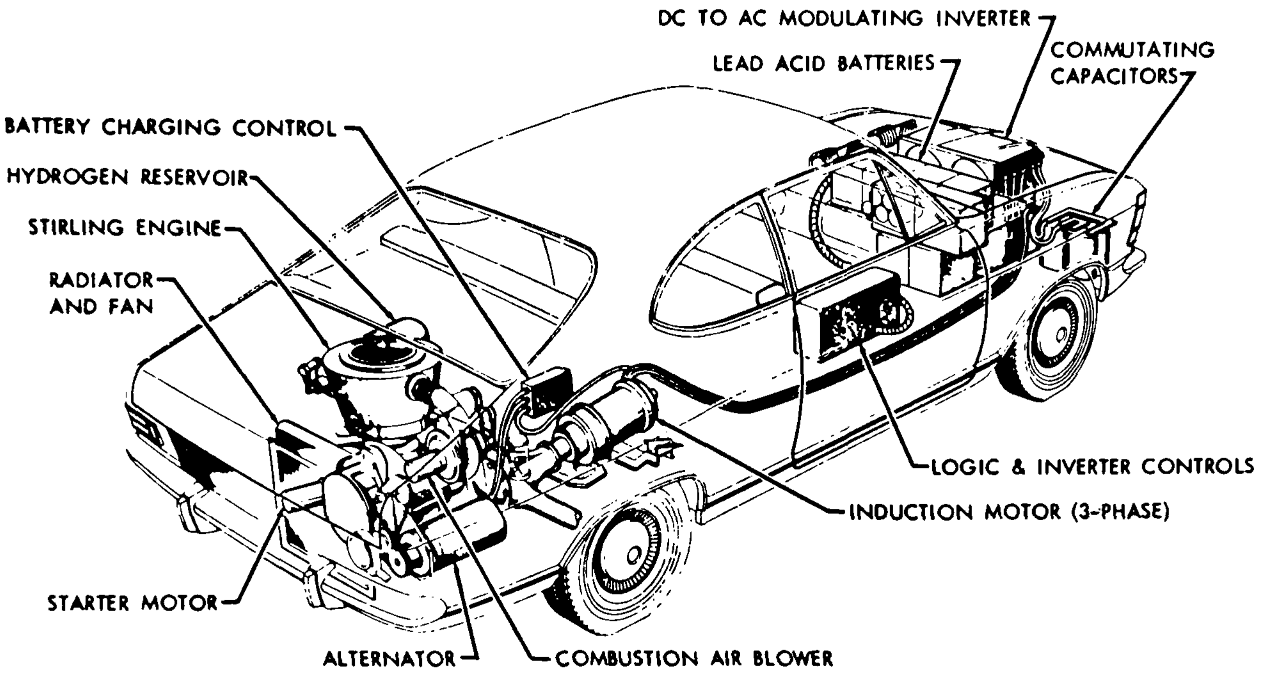

Figure S-6. Phantom View of General Motors Stir-Lec I

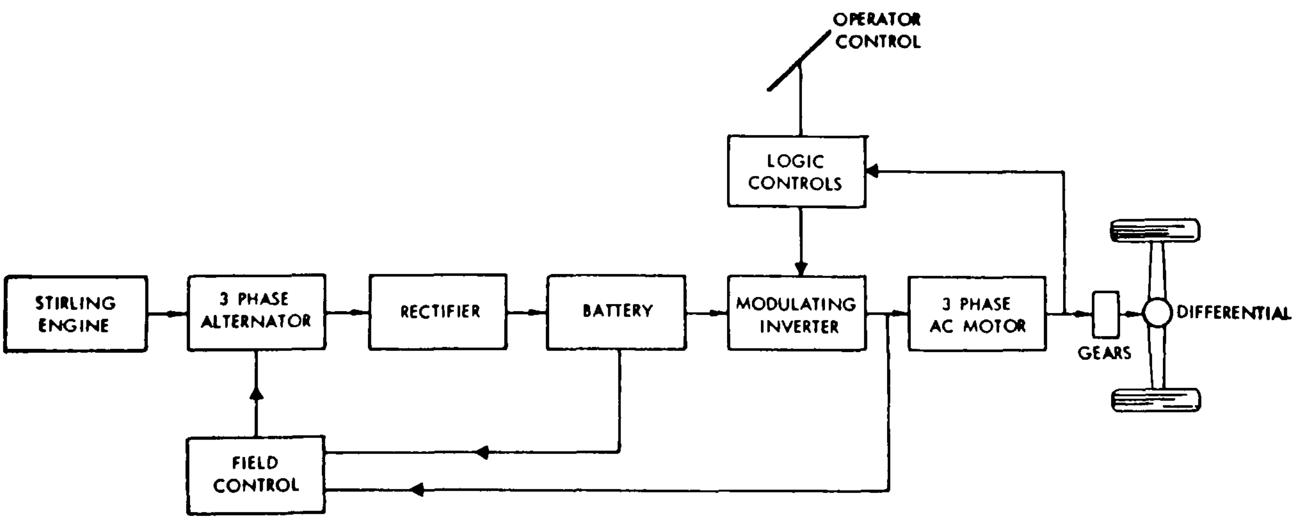

Figure S-7. Schematic, General Motors Stirling-Electric Hybrid System departure. The test program allowed the major contributors to system losses to be identified. TRW stated, "In most cases, the losses can be reduced significantly by design refinement."

A Chevrolet Vega engine modified for intake manifold fuel injection was used for the heat engine element in the TRW powertrain system. The emission control system proved very effective in terms of hydrocarbon and oxides of nitrogen control. The combined use of the hydrocarbon accumulator and three-component catalyst resulted in HC emissions ranging from 34 to 73 percent of the original 1975 Federal emission standards. The NO_x results ranged from 15 to 80 percent of the original 1976 standards. The CO standard was met with a seven percent margin on one occasion, but was exceeded during all other tests.

The first configuration tested by Minicar did not provide sufficient electric power to reduce emissions significantly. After many improvements, a final prototype configuration, the Hybrid C-1, was built. Its electric system provided up to 27 horsepower at the drive wheels, which was short of the 40-horsepower goal. Operating performance did not match that of many equivalent-size standard vehicles, and emissions were not reduced to acceptable levels. The results of measured emissions over the Federal Emissions Test Driving Cycle were HC = 3.15 grams per mile, CO = 29.6 grams per mile, and NO_x = 1.0 grams per mile.

The Petro-Electric hybrid automobile was delivered to EPA in February 1974 and is currently undergoing test and evaluation.

The Aerospace Corporation study was aimed at determining the feasibility of using a hybrid heat engine/electric propulsion system as a means of reducing exhaust emissions from street-operated vehicles. Analytical results from computer calculations are as follows:

a. The study indicated that only the spark ignition engine and the gas turbine engine offer reasonable weight margins for the battery system. After all component weights were subtracted from the 1500 pounds allocated powertrain weight, the weight available for batteries requires that they deliver a power density of just over 200 watts per pound and an energy density of just over 20 watt-hours per pound for the spark ignition engine powered parallel hybrid.

b. Fuel economy estimated for the family car series configuration was 11 miles per gallon and for the parallel configuration was 12.5 miles per gallon. These estimates are based on a fully warmed-up vehicle driven over the Federal Emissions Test Driving Cycle. The results are equivalent to the mileage expected for a conventional, similar-size 1970 car.

c. For a parallel configuration with spark ignition or gas turbine engines, most emissions were predicted to be reduced to levels below the original 1975-1976 Federal emissions standards. The one exception was oxides of nitrogen from the spark ignition hybrid. The spark ignition engine utilized lean operation, an oxidation catalyst, and exhaust gas recirculation.

d. An estimate of vehicle system costs for the family car, as ratioed to a conventional car, ranged from about 1.15 for a hybrid spark ignition engine system to 2.25 for a hybrid Stirling engine system. The conclusion drawn was that the hybrid vehicle would require a significant increase in expenditures by the consumer for first costs.

For General Motors' Stir-Lec I car, a readily available 8 horsepower Stirling engine was used to drive a three-phase alternator delivering rectified power for recharging batteries. Battery power was delivered to a three-phase alternating current motor through a modulating inverter. The total weight of the Stir-Lec I powertrain was 1,189 pounds, which compared with 498 pounds for the standard Opel Kadett powertrain; a total vehicle weight was 3,200 pounds compared with the standard weight of 1,990 pounds for the Opel Kadett.

At about 30 miles per hour on a level road, the General Motors Stir-Lec I vehicle achieved a fuel economy of 30 to 40 miles per gallon. Battery capabilities limited the range to about 30 to 40 miles at 55 miles per hour. Acceleration from 0 to 30 miles per hour took about 10 seconds. It achieved a top speed of 30 miles per hour with engine power only and a top speed of 55 miles per hour if battery power was added. General Motors noted that HC and CO emissions (in grams per horsepower-hour) were low, but NO_x emissions were much higher than expected for this engine; 1976 Federal standards were exceeded for all three species. The expectations were that engine modifications could provide major reductions in NO_x levels.

S.2.3.3 Component Design Requirements and Achievements

S.2.3.3.1 Motors, Generators, and Control System

There were no EPA contracts awarded for development of rotating electrical equipment and associated controls. Therefore, the discussion is limited to general design considerations and the state of the art of these components as related to hybrid vehicles.

The motor overload capability is very important in the parallel hybrid configuration. At cruise velocity, all the power is mechanically transferred from the heat engine to the wheels. Since the motor is not supplying continuous power for cruise, it can be sized for supplying transient power only, resulting in a small, lightweight unit. On the other hand, the series hybrid configuration requires that the motor be sized for the more rigorous requirement of continuous cruise power and is much heavier than the parallel system motor. Allowable temperature rise is the long-term constraint which must be met by sufficient sizing or adequate cooling system.

The motor control system for the series configuration hybrid electric vehicle is identical to that for the all-electric vehicle. However, a simple separate control of the generator field is required in the series configuration hybrid to modulate the power output from the heat engine for a fixed engine speed and convert it to electrical energy to be delivered to the motor. The motor controller for the parallel configuration hybrid system, by contrast, is more complex than the series hybrid because it requires special logic to control the electric motor which is augmenting power from the heat engine.

S.2.3.3.2 Batteries for Hybrid Vehicles

As part of the hybrid heat engine/electric vehicle program, two investigations were initiated to study the application of lead-acid batteries to hybrid vehicles. Contracts were awarded to Tyco Laboratories, Inc., and to TRW Systems (with Gould as subcontractor[2]) to fill a need for data on such batteries when operated under the unique conditions imposed by the hybrid vehicle. Preliminary results of investigations by The Aerospace Corporation and TRW Systems were used to establish battery operating requirements as documented in the EPA Statement of Work.

In the initial effort, each contractor studied the applicability of commercial lead-acid batteries to the hybrid vehicle under simulated operating conditions. It was concluded that commercial SLI (starting-lighting-ignition) batteries of conventional design were unsuitable because of their short life. However, the results did indicate that, with certain design modifications, lifetimes might be satisfactory.

Based upon these test findings, along with measured and calculated power losses in the battery, TRW/Gould concluded that, with limited optimization, an advanced design SLI battery could be developed to deliver 150 watts per pound for 75 seconds. Additionally, TRW/Gould projected that with more extensive optimization, which would include the use of lower resistivity materials and a new grid design, the battery could be redesigned to produce 200 watts per pound for 75 seconds, and this could be achieved without any major changes in existing manufacturing methods or cost.

In its lead-acid research battery design for the hybrid vehicle, Tyco Laboratories used a quasi-bipolar arrangement. Under the same test conditions as the commercial SLI battery, the research battery lasted for 1,000 high-rate hybrid test cycles, compared with 350 of the same test cycles achieved by the commercial battery. Since the hybrid operation is expected to involve 500 such high-rate cycles, this achievement of triple the life is significant; however, the contract duration did not permit verification of overall cycle life and calendar life.

Based on tests of the SLI battery, TRW/Gould made selective changes to the SLI cell design and, for a research battery design, was able to increase specific power density to 150 watts per pound for 75 seconds and

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[2] Gould supplied the batteries tested by TRW.

204 watts per pound for 20 seconds. The higher power density was obtained by using a greater number of thinner plates per unit volume and by using higher conductivity lead alloy grids and conductors. Tests of the new design indicated cell lifetimes of 8,000 to 12,000 charge and discharge pulses consisting of 30 low rate shallow pulses for each high rate pulse. The conventional SLI battery lasted for 6,859 pulses under the same test conditions.

TRW/Gould also designed and built several bipolar cells for the hybrid vehicle. Cycle life of the best bipolar positive plate was 6,000 pulses, with 600 deep discharge cycles to 1.0 volt. This was judged by TRW/Gould to be as good as could be expected from a high-quality conventional battery. Based upon the bipolar single-cell test results, TRW/Gould conservatively estimated that a prototype battery could be built which would have a specific power density of 164 watts per pound and a power density of 21 kilowatts per cubic foot for a 75-second discharge. Such a battery could be available in 2 years and in production in 4 years. Projections by TRW/Gould indicate a specific power density of 300 watts per pound could be achieved in about 5 years.

In a study supported by EPA under an interagency agreement, the U.S. Army Electronics Command tested nickel-zinc battery cells for the hybrid vehicle. Power densities up to 300 watts per pound for 5 seconds were achieved. These tests demonstrated that this battery could be designed to provide adequate specific energy density (watt-hours per pound) and specific power density (watts per pound) for the hybrid vehicle application, but that considerably more development would be needed to obtain satisfactory life.

S.2.3.3.3 Heat Engines

Systems studies by TRW have shown that even conventional engines operating in the hybrid mode can have lower emissions and improved fuel economy in comparison with these same types of engines in conventional automobiles.[3] Since the engine in a hybrid vehicle need provide

[3]Lockheed Missiles and Space Company in its hybrid heat engine/flywheel vehicle study arrived at similar results.

only the maximum power required for cruising (and not acceleration), it can be smaller than the engine for the conventional automobile. Engine power is expected to be 90 to 110 horsepower for a full-size passenger car.

Based on engine weight and volume and allowable propulsion system weight and volume, The Aerospace Corporation determined that only the gas turbine and the spark ignition reciprocating and spark ignition rotary engines were feasible for installation in a hybrid heat engine/battery automobile. Recent reductions in Stirling engine weight and volume might revise the conclusions related to this engine.

In engine testing supported by EPA under an interagency agreement, the Bureau of Mines Fuel Combustion Research Group measured emissions of two conventional 350-CID engines under simulated hybrid operating conditions. The results indicated that the emission levels of the original 1976 Federal emission standards would not be achieved by these engines operating in the hybrid mode without exhaust aftertreatment.

S.2.4 Hybrid Heat Engine/Flywheel Vehicle

S.2.4.1 System Designs

Work was performed by Lockheed Missiles and Space Company in the investigation of inertial energy storage under two separate contracts. The first, Flywheel Feasibility Study and Demonstration, had as its objectives the analytical determination of the feasibility of the flywheel hybrid as a low-emission propulsion system for urban vehicles and the demonstration and performance evaluation of full-scale flywheels for hybrid applications. The second, Flywheel Drive Systems Study, as applied to the family car, was directed toward advancing the development of flywheel systems technology.

In the Lockheed concept, the drivetrain consists of a heat engine coupled to the flywheel and the vehicle wheels through a planetary/hydrostatic power-splitting transmission. The heat engine provides cruise power, drivetrain losses, accessory power, and flywheel recharging power; the flywheel provides the power required for vehicle acceleration.

The configuration selected by Lockheed for the family car flywheel was an 18.6-inch-diameter conical section with a constant radius flare at the periphery. This disc-shaped flywheel configuration was fabricated of 4340 steel and tested during the feasibility study. Flywheel selection was predicated on the use of available materials, and it was designed to operate in a partial vacuum within a burst containment structure. The energy storage capacity of the flywheel is 0.5 kilowatt-hours at a design speed of 24,000 revolutions per minute. The weight of the flywheel alone is 86 pounds, which constitutes approximately 46 percent of the weight of the complete flywheel assembly.

Concurrent with the work done by Lockheed, an experimental and analytical study of high specific energy density flywheel systems for use in automotive propulsion systems was conducted by Johns Hopkins University (Applied Physics Laboratory). This study had two objectives: (a) the proof-of-principle demonstration of the use of filamentary or composite materials of high uniaxial tensile strength in rotor configurations that would have very high specific energy densities (i.e., 30 watt-hours/pound), and (b) the theoretical evaluation of the performance of such flywheels alone and in combination with heat engines. Figure S-8 illustrates the general arrangement of components in the Johns Hopkins heat engine/flywheel hybrid concept.

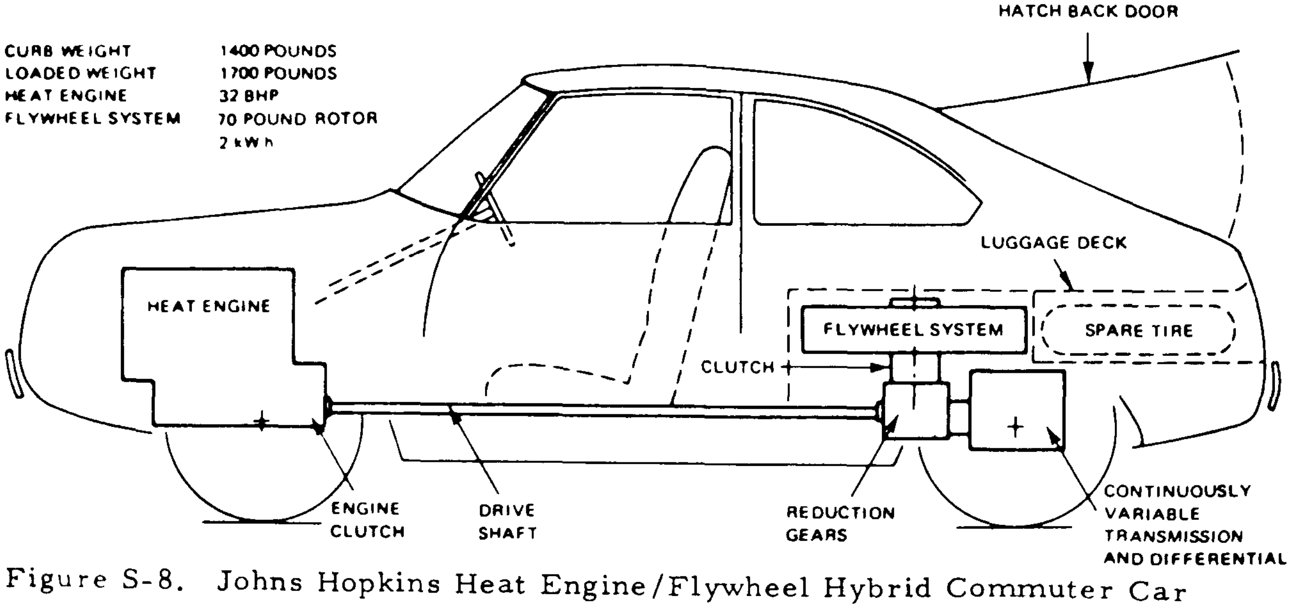

Figure S-8. Johns Hopkins Heat Engine/Flywheel Hybrid Commuter Car

S.2.4.2 System Design Requirements and Achievements

The main conclusions reached by Lockheed with regard to the flywheel/hybrid vehicle were as follows:

a. A comparative analysis of heat engine emissions for a hybrid flywheel drive contrasted with a conventional three-speed automatic transmission shows that without a catalyst, the flywheel drive offers HC, CO, and NO_x emission reductions. With a catalyst, HC and CO emissions were generally equivalent between hybrid and conventional drives; the flywheel drive offered a significant reduction for only NO_x emissions.

b. Fuel economy over the Federal Emissions Test Driving Cycle for the flywheel transmission is predicted to be roughly equivalent to that of a conventional transmission.

c. The estimated cost of ownership, size, and weight of a family car flywheel drive falls within established EPA goals.

The primary conclusions reached by Johns Hopkins with regard to the flywheel/hybrid vehicle were as follows:

a. The heat engine/flywheel hybrid propulsion systems satisfy the vehicle performance requirements.

b. The spark ignition engine is the near-term choice for the heat engine.

c. The gas turbine engine seems to offer the greatest promise for the future because of its low specific weight, its potential for minimizing emissions, and its operating speed, which is close to that of the flywheel.

S.2.4.3 Component Design Requirements and Achievements

S.2.4.3.1 Flywheel

Concurrent with the overall vehicle applicability and configuration tradeoff studies, preliminary flywheel design studies were conducted by Lockheed prior to fabricating and testing candidate flywheels. Six basic flywheel geometries were investigated in the studies. These included the pierced uniform disc, an unpierced uniform disc, a constant-stress disc, a truncated conical disc, a rim-type flywheel, and the bar-type configuration. Only those materials that could be obtained in mill-run quantities were considered. The most cost-effective were found to be E-glass, S-glass, and 4340-grade steel. The filamentary composites, however, seemed readily applicable only to the bar-type flywheel geometry. The 4340-grade steel was felt to be an excellent candidate for low-cost flywheels in a disc configuration.

In tests to failure, the steel disc-shaped flywheel was accelerated until disintegration occurred at 35,590 revolutions per minute. This represented a peripheral velocity of 3,170 feet per second, a specific energy density of 26.1 watt-hours per pound, and a total stored energy of 1.1 kilowatt-hours, which exceeded the design specification by a factor of about two, and accordingly provided a margin of safety.

Disintegration of the glass composite bar-shaped flywheel of unidirectional construction occurred prior to reaching a design speed of 20,000 revolutions per minute. The maximum energy storage capacity at failure (15,070 revolutions per minute) was 0.568 kilowatt-hours, as compared with the design point of 1.0 kilowatt-hours.

Lockheed conclusions regarding the steel flywheel were as follows:

a. The production cost of complete family car flywheel assemblies was projected to range from $85 to $115, depending on flywheel configuration.

b. All the elements of a practical family car flywheel assembly are available without further technology development.

c. Early estimates of flywheel system losses as provided to the transmission contractors were proved by hardware testing to be highly conservative. Flywheel windage, bearing, seal, and vacuum pump losses were substantially lower than earlier predictions.

d. Prevention of flywheel burst due to overspeed can be obtained by allowing the flywheel to grow plastically into the containment ring. Total containment of a flywheel burst at energy levels representative of what might be the case for a full-size vehicle was not successfully demonstrated with lightweight, low-cost materials.

Experimental work conducted by Johns Hopkins University was directed toward a demonstration of the "superflywheel" concept in which energy densities of 30 watt-hours per pound could be achieved. Spin tests of small-diameter composite rods (up to 0.25 inches) and filamentary single strands were conducted in which the several candidate materials exceeded the specific energy density goal of 30 watt-hours per pound. Follow-on tests of 30-inch-long, 1-pound rods or bars achieved 82 to 94 percent of the desired goal.

Johns Hopkins reached the following conclusions regarding the testing of filamentary and composite rods and bars.

a. Spin tests demonstrated the ability to achieve 48 watt-hours per pound (without failure) with boron single strand filaments; at burst, 36 watt-hours per pound was achieved with small graphite/epoxy composite rods, and 31 watt-hours per pound was achieved with small R-glass/polyester composite rods.

b. The larger 1-pound composite bars did not meet the desired 30 watt-hours per pound. The best sample S-glass/epoxy achieved 28 watt-hours per pound, while the graphite/epoxy achieved 26 watt-hours per pound.

c. Tensile tests indicated that the graphite/epoxy material was substandard. While the S-glass/epoxy bars achieved satisfactory stress levels in tensile tests, numerous surface defects may have contributed to the inability of this material to meet 30 watt-hours per pound requirements. With improved processing techniques, Johns Hopkins felt confident that energy densities in excess of 30 watt-hours per pound could be achieved.

S.2.4.3.2 Transmissions

Under AAPS Program sponsorship, two studies were conducted on transmission designs for a parallel configuration flywheel hybrid system by Sundstrand Aviation and Mechanical Technology, Inc. Both studies examined the development of total energy transfer systems from the hybrid engine to the drive wheels, and the management of the energy storage system.

Sundstrand selected a combination mechanical, hydromechanical, and hydrostatic transmission system for linking the engine-flywheel-drive wheels together. This transmission is made up of a five-element differential, several hydraulic units (variable and fixed displacement), clutches, controls, and associated gearing.

At the conclusion of its study, Sundstrand stated that:

a. A combination of mechanical, hydromechanical, and hydrostatic transmissions is a practical means of providing power for the flywheel, heat engine, and drive wheel links.

b. The selected transmission provides an infinitely variable ratio between the flywheel and the vehicle wheels, and a nonlinear ratio (fixed by vehicle speed) between the heat engine and flywheel. Although the engine speed is not independent of the flywheel speed, it does operate near its minimum specific fuel consumption (pound fuel/horsepower-hour) line.

c. The specified spark ignition heat engine with the selected transmission has a greater computed fuel consumption over the Federal Emissions Test Driving Cycle than that of a typical three-speed automatic transmission. Cruise fuel consumption is greater than for the three-speed automatic below 50 miles per hour and less above this speed.

d. The theoretical fuel economy benefits that can be gained from the flywheel energy storage concept over a "light-duty" cycle, such as the Federal Emissions Test Driving Cycle, are minimal because of the small amount of energy available for storage and reuse. In fact, when the "cost" of storage in terms of power loss is included, there is no benefit. The more "severe" the acceleration/braking duty cycle relative to maximum vehicle capability, and the heavier the vehicle, the greater are the benefits derived from the flywheel energy storage concept.

The study performed by Mechanical Technology arrived basically at the same conclusions as Sundstrand. Mechanical Technology proposed a power-splitting transmission. This transmission is an infinitely variable, stepless unit that obtains torque multiplication and control by hydraulic principles.

In a calculated comparison between the efficiencies of power-trains for flywheel hybrid and the standard automobile for cruise operation, the flywheel/hybrid powertrain was found to be substantially lower, even though the transmission efficiency for the hybrid transmission was estimated to be higher. The fuel economy of the hybrid automobile, compared with the standard automobile, is poor up to a cruise speed of 50 miles per hour, but at higher speeds it has superior fuel economy.

S.2.5 Assessment of Hybrid Powertrain Application to Automobiles

At the time of program suspension, EPA funds expended on the hybrid vehicle development program had resulted in some major technology advancements, a much clearer definition of critical problem areas, and the establishment of preferable system operating modes. These results are indicative of information acquired in the very early phases of development, namely, proof-of-principle. Some forms of hybrid systems could represent an intermediate step between current automobile powerplants and a future system that relies totally on an energy storage device for delivering power to the drive wheels.

The powertrain has been tested as an integrated system for only the heat engine/battery hybrid, not for the heat engine/flywheel hybrid. Test results showed that the concepts were technically feasible and could operate over the desired power and speed range. System efficiencies were lower than desired and exhaust emissions from the spark ignition engines could only approach the original 1976 Federal emission standards by means of the application of a catalytic converter, exhaust gas recirculation, and lean operation. This additional complexity compromises one of the original hopes for the hybrid vehicle; i.e., that these engine changes would not be required. The EPA contractors claimed that with further development some system deficiencies could be corrected.

In regard to heat engine/battery hybrids, tests of commercial lead-acid batteries showed relatively poor life at the performance required for this application. Battery redesigns and advanced concepts for lead-acid cells resulted in the achievement of power and energy levels that represent a major increase over standard batteries for this application, leading to optimism regarding the ability of these designs to meet most of the established performance specifications. However, cycle life, while greatly improved, is still short of specified goals.

For heat engine/flywheel hybrids, both conventional steel disc-shaped flywheels and advanced material concept bar-shaped flywheels were tested to destruction. The conventional design met the specified goals for energy storage level before failing. Results with the advanced filamentary and composite rod/bar configurations were mixed, with a number of test samples failing at rotational speeds short of planned levels. Fabrication problems with the advanced concepts and difficulties in avoiding undesirable stress concentrations led to early failure.

Only a limited investigation was made of the estimated consumer purchase cost for a hybrid vehicle. Based on preliminary coarse estimates, the purchase cost of hybrid vehicles is expected to be significantly higher than that of current automobiles, particularly for hybrid vehicles with advanced concept engines (e.g., gas turbines). However, an analysis of lifetime costs for the hybrid vehicle has not been performed wherein vehicle first cost, maintenance cost, engine fuel cost, and battery replacement[4] or flywheel replacement[5] cost could be assessed.

Some additional system design considerations are worth mentioning at this point. First, some of the vehicle performance specifications adhered to during the EPA contractor studies could be relaxed for evaluation of a special-purpose rather than a general-purpose car. Allowing a reduction in acceleration levels and peak cruising speeds is expected to yield marked reductions in the required level of battery or flywheel power density. This result stems from two sources: (a) reduced power required and (b) additional weight and volume available because of reductions in the size of the heat engine and transmission and, for the hybrid battery vehicle, reductions in the size of the generator and electric drive motor.[6] Thus, rather than considering a hybrid vehicle designed to replace general-purpose personal passenger cars in use in the United States, the objective rather would be to determine just what percentage of all the various transportation needs could be fulfilled by this special-purpose, limited-use type of vehicle.

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[4] Depending on cycle life.

[5] Depending on fatigue life.

[6] Particularly for the series configuration.

Second, consideration could be given to the multimode form of hybrid vehicle operation. As an example, recharging of the energy storage device (battery or flywheel) could be accomplished wholly or in part by an external stationary power source rather than solely by the on-board heat engine. This bimodal design would permit independent operation whereby the vehicle is powered either by the battery (or flywheel) alone or by the heat engine alone. The most important impact could be the transfer of the energy resource base from petroleum-based fuels to coal or nuclear power, because electric generating plants would now supply all or part of the recharge energy. Conservation benefits that would accrue to the limited supply of petroleum-based fuels are obvious.

The hybrid vehicle has been proven to be a valid functioning system, both by analysis and limited experimental tests, although not all of the original program goals were met. At the inception of the EPA hybrid vehicle program, emphasis was placed mainly on reduction of exhaust emissions to the then promulgated 1976 Federal standards. If the program were to be reactivated, the vehicle designs would have to strike a balance between fuel economy and exhaust emissions, and system performance would have to be re-evaluated in light of the revised standards.

PART I

ELECTRIC VEHICLES

1. INTRODUCTION

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The electric car came into prominence in the early decades of the 20th century. Initially, it seemed to offer many advantages over the gasoline-powered car: it was quieter, issued no detectable fumes, accelerated more smoothly and, even at 15 mi/hr, exceeded the speed of gasoline-powered cars. However, in time, the gasoline engine underwent successive design changes that increased power output and resulted in smoother vehicle acceleration. Larger fuel tanks extended the driving range well beyond that achievable with the battery-powered electric car. The electric car's share of the market diminished, and it eventually became a novelty when the gasoline-powered automobile claimed the major share of the consumer market. This change was brought on largely by the economic advantages occasioned by Henry Ford's mass production techniques, the reliability of the spark ignition engine, and the use of muffled engine exhausts.

Because of concern with air pollution, interest in electric vehicles was renewed in the late 1960's and early 1970's, principally for delivery vans and trucks in Great Britain and for compact and subcompact cars in Japan. More recently, the diminishing domestic petroleum-based energy resources have placed further emphasis on reconsideration of the electric car. The primary arguments for renewed interest in these cars are (a) that air pollutants can be removed from the exhaust of millions of individual automobiles and transferred to stationary power plants where treatment of the exhaust from stacks could be more easily controlled, and (b) that more abundant nonpetroleum-based energy resources can be used for transportation (i.e., shifting the energy base from oil to coal or nuclear power).

This viewpoint has not culminated in any extensive production of electric cars for numerous reasons. One reason is the continued limited range of this vehicle -- about 50 miles with lead-acid batteries (the only economically viable electric energy storage device available today for this application). Another reason is that, even with lead-acid batteries, the projected purchase cost of electric vehicles is still significantly higher than the gasoline-powered vehicle.

Nonetheless, with projected improvements, the electric vehicle can be viewed as a potential contributor to the national inventory of transport vehicles. As such, this report reviews electric vehicle development world-wide, but with emphasis on domestic requirements. Following a description of the design features, and performance characteristics of the primary elements in the electric vehicle powertrain, the status of technology is reviewed,and the potential for national transportation needs is assessed. In this context, the succeeding discussion is addressed to electric powered personal passenger cars and not to special performance vehicles such as milk trucks, postal vans, buses, etc.

2. POWER PLANT DESCRIPTION

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The basic power plant consists of one or more electric motors and controllers, perhaps a transmission or other gears, and a battery system. In electric car designs, lead-acid batteries have been used in most cases and the direct current electric brush motor is used by an overwhelming majority of vehicle designers and fabricators. It is self-commutating and requires only variable voltage to obtain a wide speed and torque range. Several types of direct current motors employed include (a) series wound, (b) separately excited (c) compound wound, and (d) the permanent magnet motor. The alternating current induction motor has also been tried, but the requirement for multiphase conversion of power from the battery to produce variable voltage and frequency for the motor introduces excessive complexity and weight and, therefore, is currently lagging as a potential design approach.

In some systems regenerative braking is used; this causes the motor to operate as a generator and recharges the battery as the car decelerates. It provides equivalent and sometimes greater braking than that provided by compression braking from conventional heat engines, and is especially useful to control vehicle velocity while descending mountain roads. One study (Ref. 2-1) estimated the average energy recovery at 7 percent.

2.1 POWER PLANT CONFIGURATIONS

Electric vehicles built and proposed to date have used a variety of power plant configurations. Electric cars that were built on the chassis of production models of heat engine cars were generally forced to place the batteries where room was already available and to use one large electric motor coupled to the transmission and mounted where the heat engine is normally located. On the other extreme is a specially designed electric car using unsprung, gear motors mounted to each wheel and having a specially designed cavity for battery containment, which provides for quick change of the batteries.

Between these two limits are many configurations which have been use or proposed. The following list gives some typical examples, beginning with minimum modification of a present heat engine car and progressing to specially designed cars.

a. Motor front mounted in heat engine position and using remainder of existing drivetrain. Batteries mounted in trunk and around motor.

b. Motor front mounted in heat engine position, but coupled to synchromesh transmission without clutch.

c. Motor front mounted in heat engine position, but coupled to drive shaft without a transmission.

d. Single rear motor either coupled to transmission or directly to the differential of a transaxle rear mounted heat engine car.

e. Two motors driving individual wheels with no differential gear. The motors are frame mounted and drive the wheels through non-slip belts that allow for vertical wheel motion. Batteries are mounted principally in front trunk area.

f. Two frame-mounted, high-speed motors driving belts that drive individual wheel-mounted planetary reduction gears. Batteries are in a longitudinal well that is loaded from the rear of the car.

g. Two wheel-mounted, unsprung gear motors driving rear wheels. Flexible power cables permit vertical wheel motion with respect to the frame. Batteries under seat and in trunk.

h. Four unsprung, wheel-mounted minimum-size gear motors. Batteries under passenger floorboard.

A typical electric car drivetrain that replaces the drivetrain of a heat engine is shown in Figure 2-1.

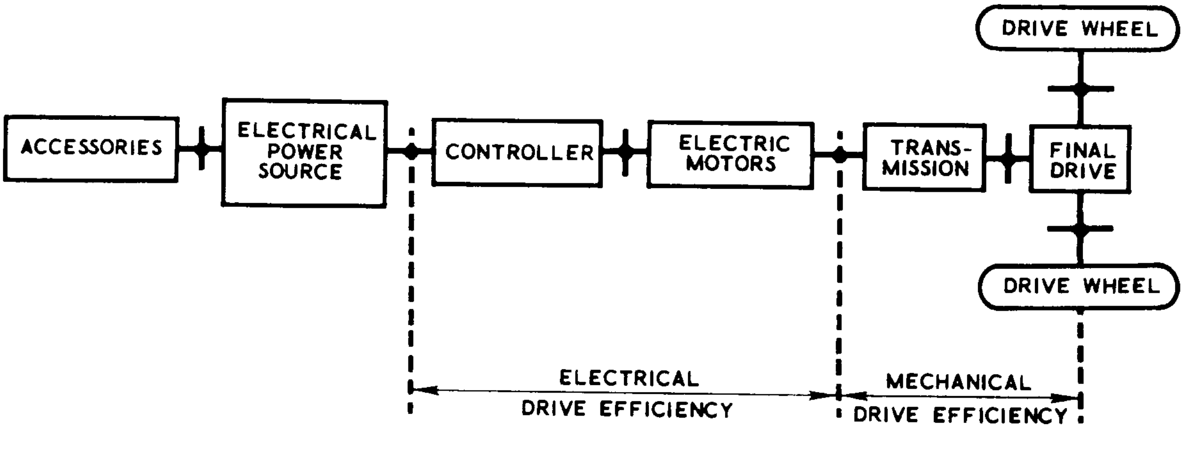

Figure 2-1. Electric Car Drivetrain Showing the Main Components

2.2 DESIGN FEATURES

2.2.1 Batteries

Various studies such as the one by A. D. Little (Ref. 2-2) have indicated that a high performance electric vehicle will need 200 to 300 W-hr of installed battery capacity per ton-mile. A chart showing design requirements for electric vehicles as established in the A. D. Little study is given in Table 2-1. Comparisons between these derived values and specified values for existing electric vehicles give reasonable correlation. One objective of system design would be to reduce vehicle weight and to minimize influences such as drag, frontal area, acceleration, and peak cruise speed, which would allow a reduction of battery energy usage in the form of Watt-hours/vehicle ton-mile.

2.2.1.1 Battery Design Factors

When promoting a new battery for development, with intended application to electric vehicles, the parameter most often compared is specific energy density (W-hr/lb). As electric vehicle programs proceed, other factors, implicit in battery system design, must be considered. These are discussed below.

2.2.1.1.1 Cost

In selecting batteries for electric vehicles, the dominant parameter has been cost, and for this reason, lead-acid batteries are almost universally used. Cost is influenced by the basic raw material cost and demand/availability ratio assignable to the raw materials. In addition to the cost and availability of primary electrode materials, consideration must be given to the cost of electrode preparation, the container and seal costs if the electrolyte is corrosive, the cost of the electrolyte, and battery replacement and operating costs. Cycle life, and especially time at operating temperature for high-temperature batteries, is an important factor for determining battery replacement frequency. A potential problem with some batteries, especially those that use gas electrodes (e.g., zinc-oxygen/air or the nickel-hydrogen) is the need for noble metal catalysts. Another cost-related

Table 2-1. Electric Vehicle Specifications (Ref. 2-2)

Parameters	Units	Family Car	Commuter Car	Utility Car	Delivery Van	City Taxi	City Bus
Assumptions							
1. Acceleration to	mi/hr	60	60	30	40	40	30
2. Acceleration in	seconds	15	30	10	20	15	15
3. Range	mi	200	100	50	60	150	120
4. Seats or payload	lb	6	4	2	2,500	6	10,000
5. Loaded weight[a]	lb	4,000	2,500	1,700	7,000	4,000	30,000
6. Curb weight	lb	3,500	2,100	1,400	4,500	3,500	20,000
7. Weight assignable to propulsion, energy storage, controls	lb						
a. conventional construction		1,250	750	500	1,400	1,250	5,000
b. lightweight construction		1,750	1,050	700	2,000	1,750	7,000
8. Frontal area	ft^2	25	18	18	42	25	80
9. Drag coefficient		0.35	0.25	0.25	0.85	0.35	0.85
10. Elec. transmission efficiency	%	82	77	72	79	76	85
Derived Parameters							
11. Maximum power delivered by motors	kW	70	22	12	49	36	135
	hp	94	30	16	66	48	180
12. Maximum output of power source	kW	85	29	17	62	47	159
13. Maximum velocity	mi/hr	100	80	65	56	77	55
14. Delivered energy	kWh	100	20	8	45	75	300
15. Stored energy	kWh	122	26	11	57	99	353
16. Weight of motors, transmission, and controls	lb	348	118	82	259	210	615
17. Weight assignable to power source	lb						
a. conventional construction		902	632	418	1,141	1,040	4,385
b. lightweight construction		1,402	932	618	1,741	1,540	6,385
Power Source Requirements							
18. With conventional construction							
energy density	W-hr/lb	135	41	26	50	96	81
power density	W/lb	94	46	40	55	45	36
19. With lightweight construction							
energy density	W-hr/lb	87	28	18	33	64	55
power density	W/lb	60	31	28	36	30	25
20. Watt-hr/ton mile[b]	--	305	208	259	271	330	196

[a] The loaded weights given for the cars and taxi are not the maximum that they are capable of carrying but rather reflect typical usage.

[b] Derived from Ref. 2-2 data above by calculation of

$$\frac{1000 \times \text{Stored energy (kWh)}}{(\text{Vehicle loaded weight (lb)}/2000) \times \text{Range (mi)}}$$

selection criterion is the ability to reclaim and reprocess the basic battery materials.

2.2.1.1.2 Energy and Power Density

In the electric vehicle, the energy storage and drive system is usually allocated a portion of the total volume and curb weight. These values, along with battery energy and power capabilities, result in important parameters that are used in estimating a vehicle's range and drivability. These are: specific energy density (W-hr/lb), energy density (W-hr/in.^{3}), and specific power density (W/lb).

In consideration of energy density, a distinction must be made between that now achieved with commercially available batteries and that which is projected on the basis of either theoretical reactions or small-scale, single-cell tests.

While some batteries might have excellent specific energy densities, their energy density might be low if (a) considerable thermal insulation is needed, (b) low molecular weight electrodes are used, or (c) gaseous reactants are used, as in the fuel cell or the metal-gas battery.

2.2.1.1.3 Operating Temperature

Battery systems which have high-temperature electrode couples or undergo a phase change (melt) when heated from room temperature to operating temperature, can have significant parasitic losses and can consume considerable energy and time for start-up.

2.2.1.1.4 Voltage Characteristics

Since the vehicle drive motor will be more efficient if operated over a narrow voltage range, those battery systems that achieve their high energy densities with a high voltage variation must be penalized by the cost of additional power conditioning components or by a lower drive system efficiency. Increased power conditioning will impact cost, also. Of further concern is the degradation of cell voltage with time which will affect battery performance and system design.

2.2.1.1.5 Charge/Discharge Rate

An inherent problem with the electric vehicle is the energy and time needed to recharge the batteries. Ordinarily, recharge time will exceed discharge time so that extensive vehicle usage will be limited unless provisions are made to exchange depleted batteries for fresh batteries. This simply involves a trade-off between cost and convenience. The capability of residential electrical grids to supply large power levels during daytime for a large number of electric vehicles may also be a problem. Possible solutions are slow charging during evening hours and higher-efficiency for charge acceptance of batteries.

High-rate batteries are probably not needed, since the large installed capacity of an electric vehicle will usually have the capability to supply high currents for moderately short periods.

2.2.1.1.6 Corrosion

Most high-energy batteries, and especially those containing Group I metals (lithium, sodium, potassium) and sulfur, have formidable corrosion problems. Molten sulfur attacks every metal, although some alloys and refractory metals are corroded at low enough rates to allow their consideration as container materials. Some electrode and electrolyte materials attack the separators, react with impurities (including those in the grain boundaries), and react violently with water.

It is likely that corrosion and the resultant materials problems will be the limiting factor in the development of high-energy batteries.

2.2.1.1.7 Material Conservation

Battery materials which can easily be reclaimed and reused at the end of battery life are desirable; they should be plentiful and, if possible, not a secondary extraction material such as cadmium, which is a biproduct of zinc smelting. Increased demand of such a material would severely disrupt present markets.

2.2.1.1.8 Safety

Because electrode materials that are most reactive provide the highest specific energy densities, safety can be a problem during maintenance or in the event of an accident. The effect of internal cell failures on battery operation (such as a separator rupture) should be minimized during design studies to avoid an unstable condition.

2.2.1.2 Battery State of the Art

Currently, a major problem is the limitation on the amount of energy and power that can be delivered by a given size battery. Evidence of this problem is seen in the restricted operation of contemporary electric vehicles as illustrated in Table 2-2 (Ref. 2-3). This is a partial list of electric vehicles built to prototype level of design or to commercial design specifications for small quantity production in the United States. Analytical studies (Ref. 2-2) have shown that battery requirements for powering a full performance family passenger car are: a specific energy density of about 135 W-hr/lb and a specific power density of about 95 W/lb. Table 2-3 shows that current battery capabilities fall far short of the energy goals. A summary of characteristics for battery systems that have been suggested for future electric vehicles is given in Table 2-4.

2.2.1.2.1 Improved Conventional Batteries

In recent years, the lead-acid battery has improved considerably (Ref. 2-2) in directions relevant to electric vehicle highway applications. Most of the progress in lead-acid systems has been made in the small- and intermediate-size area, where high-production volume applications exist such as for automobiles, golf carts, and forklifts. But of note is that the hybrid vehicle in an automotive oriented study for EPA, where high power density for acceleration was specified, TRW Systems, Inc., and Gould showed that a modern SLI (starting, lighting, ignition) battery capable of 18.7 W-hr/lb under a slow rate could deliver 94 W/lb for 25 seconds (Ref. 2-4). (By contrast, a decade ago battery power densities of 40 to 50 W/lb were considered to be the best available). TRW Systems/Gould and another EPA

Table 2-2. Electric Vehicle Summary Data for Operating Passenger Models in the United States (based on Ref. 2-3)

Car Name and Manufacturer	Vehicle Curb Weight, pounds	Drive Motor(s)	Maximum Speed, miles per hour	Energy Source and Capacity	Range, miles
COMUTA Ford	1,200	Two 5 hp Series dc	40[a]	Lead-acid 48V (384 lb)	39 @ 25 mph[b]
GM 512 General Motors	1,250	8-1/2 hp Series dc (54 lb)	40[a]	Lead-acid 84V (329 lb)	47 @ 30 mph[b]
SUNDANCER 2 ESB	1,600	8 hp Series dc (83 lb)	60+[a]	Lead-acid 86V (750 lb)	70 to 75 on SAE Residential[b]
MARQUETTE Westinghouse	1,730	Two 4-1/2 hp dc (45 lb)	25[b]	Lead-acid 72V (800 lb) 8 kW-hr	50[b]
HENNEY KILOWATT Union Electric	2,135	7.1 hp Series dc	40[b]	Lead-acid (800 lb) 8 kW-hr	40[b]
YARDNEY	1,600	7.1 hp Series dc	55[b]	Silver-zinc 12 kW-hr (240 lb)	77[b]
ALLECTRIC West Penn Power Co.	2,160	7.1 hp 72Vdc	50[c]	Lead-acid 72V (900 lb) 9 kW-hr	50[b]
"MINI" General Electric	2,300	dc Motor 10.9 hp	55[b]	Lead-acid and Nickel-cadmium	100 @ 40 mph[b]
American Motors and Gulton Ind.	1,100	--	50[b]	Lithium-nickel fluoride (150 lb) and Nickel- cadmium (100 lb)	150 with regeneration[b]
ESB Renault	--	--	40[b]	Lead-acid (72V)	25 to 35[b]
Rowan Electric	1,300	Two dc Compound	40[c]	Lead-acid	100[b]
ALLECTRIC II West Penn Power Co.	2,300	7.1 hp dc	50[c]	Lead-acid (900 lb)	50[b]
Super-electric Model A Garwood & Stelber Ind.	--	Two 2 hp	52[b]	Lead-acid (520 lb)	--
CORTINA ESTATE CAR	3,086	40 hp 100V (150 lb)	60[b]	Nickel-cadmium (900 lb)	39.9 @ 25 mph[b]
COMET Ford	3,800	85 hp	70[b]	Sodium-sulfur (1,086 lb)	--
CITY CAR PINTO	3,200	40 hp	50[b]	Lead-acid (956 lb)	39 @ 40 mph[b]
MARS II Elect. Fuel Prop. Inc.	3,640	15 hp dc	55[a] 60 to 65[c]	Lead-acid 96V (1,700 lb) 30 kW-hr	70 to 120[b]
ELECTROVAIR General Motors	3,400	100 hp ac induction	80[b]	Silver-zinc 530V (680 lb) 19.5 kW-hr	40 to 80[b]
ELECTROVAN General Motors	7,100	125 hp ac induction	70[c]	Hydrogen-oxygen fuel cell 180 to 270 kW-hr	100 to 150[b]
CARMEN GHIA Allis Chalmers	3,440	--	--	Lead-acid 120V (1,534 lb)	60 @ 60 mph[b]
SIMCA Chrysler	--	--	--	Lead-acid (1,400 lb)	40[b]
Elect. Fuel Prop. Inc.	5,400	--	85[b]	Lead-acid cobalt	150 to 175[b]
FALCON Linear-Alpha	--	25 hp ac induction motor	60[b]	Lithium-nickel fluoride (360 lb)	75 @ 30 mph[b]

[a]Test data
[b]Basis of data not verifiable
[c]Design goals

Table 2-3. Characteristics of Currently Available Secondary Batteries

Battery Type	Characteristics				Remarks
	Specific Energy Density, W-hr/lb	Energy Density, W-hr/lb	Specific Power Density, W/lb	Approximate Relative Cost	
Lead-Acid	20	2.0	100	1	Standard
Nickel-Cadmium	12	1.1	80	20	Good cycle life; cadmium supply limited
Nickel-Iron	13	1.2	60	3	Excellent life; poor maintenance; nickel supply limited

contractor, Tyco Laboratories, Inc. (Ref. 2-5), indicated that lead-acid batteries could be developed to deliver power densities as high as 300 W/lb. There has been no comparable effort to develop lead-acid batteries for an all-electric vehicle which would require greater emphasis on energy delivery capability (Watt-hours/pound).

The nickel-iron system has been proposed as a low-cost replacement for the lead-acid battery. Intensive work by Westinghouse has improved battery life and introduced new maintenance concepts, but this battery appears best suited for industrial applications. The batteries have excellent lifetimes, with many batteries having exceeded 20 years in normal service. It is not affected by overcharge or complete discharge, but does generate hydrogen on charge and has poor charge retention. It offers little, if any, performance advantage over lead-acid.

A good candidate battery for the electric vehicle in the near-term period (1975 to 1985) is the nickel-zinc system. A specific energy

Table 2-4. Batteries for Future Electric Vehicles (Refs. 2-6 through 2-9)

System	Projected Maximum Performance			Opt'g Temp., °C	Open Cell Voltage	Problem Areas
	Specific Energy Density, W-hr/lb	Energy Density, W-hr/in^3	Specific Power Density, W/lb			
Improved Conventional Batteries						
Lead-Acid	20 (76)[a]	2.0	150	20	2.05	Low energy density
Nickel-Iron	25 (121)	1.5	60	20	1.37	Low charge efficiency, hydrogen evolution, maintenance
Nickel-Zinc	30 (146)	2.0	150	20	1.71	Cost, life
Metal-Gas						
Iron-Air	50	2.5	20	20	N.A.	Cathode corrosion, life recharge, mechanical replacement, noble metal catalyst needed
Zinc-Air	60 (614)	2.5	35	20	1.65	Zinc deterioration, life cost, complexity, recharge, mechanical replacement, noble metal catalyst needed
Nickel-Hydrogen	40 (177)	N.A.	100	20	1.36	Volume, life, hydrogen, noble metal catalyst needed, cost
Zinc-Oxygen	60	2.5	30	20	N.A.	Life (zinc and air electrode), cost, noble metal catalyst needed
Alkali Metal-High Temperature						
Sodium-Sulfur	100	8.1	100	300	1.8 to 2.1	Corrosion, life (sodium and sulfur highly reactive), startup
Lithium-Sulfur	100 (700)	6.7	400	400	N.A.	Corrosion, cost, materials (lithium and sulfur highly reactive), startup
Lithium Chlorine	50 (1,050)	5.0	150	650	3.46	Corrosion, cost, materials (lithium and chlorine highly reactive), startup
Metal-Halide						
Zinc-Bromine	30 (196)	N.A.	N.A.	N.A.	1.8	Low energy density
Zinc-Chlorine	50 (209)	N.A.	60	N.A.	2.12	Early state of development, problem areas not yet fully defined

[a]( ) designates theoretical value

density of 30 W-hr/lb and a specific power density of 150 W/lb seems possible. Battery life, presently 100 to 200 cycles, has been a drawback, but work is under way on new separator systems to correct the problems of degradation of the zinc electrode and penetration of the plate separator system by zinc dendrites. The other major question is whether costs can be eventually competitive with the lead-acid battery.

The energy density of the nickel-cadmium battery is about the same as the lead-acid battery and it has superior life, but its cost is much greater.

2.2.1.2.2 Metal-Gas Batteries

These batteries provide energy densities in the 30 to 60 W-hr/lb range, depending on the reactants selected. The use of air in these batteries is advantageous for obvious reasons (e.g., no onboard storage required), but they require the addition of scrubbers for CO_2 removal, an air blower, and a water makeup system, which negate much of the gain. With either air or oxygen, an oxygen electrode catalyst is required. No catalysts exist that are inexpensive enough for car batteries. Reduced noble metal loadings or nonnoble catalysts might be usable if hydrogen gas is used. However, the volume required for hydrogen gas storage presents a problem, and hydride storage systems are heavy and either complex or expensive, depending on the hydride selected for use. In addition, the usual problems associated with zinc, cadmium, and iron electrodes in conventional batteries appear in these cells. Prototype batteries have been built and tested by Gulf-General Atomics (circulating electrolyte), Sony (pulverized zinc fuel), and General Motors (mechanically rechargeable). The pumped circulating systems are complex. Gulf-General Atomics concluded that their system was unattractive economically, and General Motors has declared the mechanical recharging approach to be impractical.

The nickel-hydrogen system is receiving considerable development emphasis for aerospace industry applications. It is believed that long lifetimes, adequate for the electric vehicle, can be achieved with this system, but problems remain with regard to cost, safety, and energy density.

2.2.1.2.3 Alkali Metal - High-Temperature Batteries

These systems are theoretically capable of meeting the goals that have been established as necessary for full-performance vehicles. High temperatures (300 to 700°C) allow the use of relatively resistive solid ionic conductors and molten salts as electrolytes, and permit rapid charging and discharging. Demonstrations of high power and energy densities have been made, although not always in the same cell. Life is 500 to 1,000 complete discharge cycles in 1,000 to 2,000 hours of operation for almost all systems. Life time limitations are generally associated with materials problems.

The sodium-sulfur system, first announced by Ford Motor Company (Ref. 2-10) is receiving international attention. The concept uses a beta-alumina solid electrolyte that conducts sodium ions at reasonable rates at the operating temperature of 350°C or slightly above. The major United States program on the sodium-sulfur battery is Ford's, although TRW Systems, General Electric, and others have also worked on this cell. Ford has tested single cells and a small, 200-W, 24-cell battery. The latter reportedly ran for 2,000 cycles and 7 months total hot life--the longest life reported to date. The battery delivered 43 W-hr/lb and 93 W/lb, exclusive of insulation. A little recognized fact is that in the Ford battery design, power and energy density must be optimized separately. Thus, a 500-W battery optimized to delivery 135 W-hr/lb would produce 46 W/lb, while one designed for high power would put out 40 W-hr/lb but 150 to 250 W/lb (Ref. 2-10), again exclusive of insulation. The largest foreign programs are in the United Kingdom (British Railways Board, The Electricity Council), Japan (jointly between Yuasa and Toshiba), France (CGE), and Switzerland (Battelle-Geneva). British Railways has tested both tubular and flat-plate cells and has a 1 kW battery operational. The Electricity Council has built a 960-cell, 50 kW-hr battery and began road tests in a Bedford van in November 1972. The battery is rated at 15.5 kW average output, has a peak power capability of 29 kW, and weighs 1,760 lb. The energy density is, therefore, 28 W-hr/lb and the power density at peak output is 16.5 W/lb. The energy density is expected to ultimately reach 91 W-hr/lb with life in excess of 1,000 cycles. The Japanese work on this system is part of their government-sponsored electric vehicle program. The objective is to have a battery-powered vehicle in operation by 1975. Yuasa is testing single cells and seven-cell units. Lifetimes in the order of 1,000 hours (166 cycles) are common. The energy density delivered is about 50 W-hr/lb. The French and Swiss are concentrating their efforts on operation of single cells. All sodium-sulfur projects face the same key problem today; namely deterioration of the beta-alumina electrolyte after 1,000 to 2,000 hours at working temperatures. This deterioration is ascribed to a variety of causes and has led to a number of proprietary "fixes", but no substantial increases in life have been reported. This is the major technical hurdle to be overcome before a successful battery can be demonstrated. Economic success will ultimately depend on finding inexpensive ways to produce the desired ceramic and to fabricate large batteries.

A different approach to the sodium-sulfur system is being pursued by Dow Chemical Company. Sodium ion-conducting glass is used as the electrolyte in the form of hollow fibers with very thin walls (typically 85-micron O.D. × 35-micron I.D.). Thousands of these tubes are collected in bundles to form a cell, using a glass header and aluminum for the container and current collector. Dow has a proprietary method of treating the current collector to prevent formation of a passivating film. Energy densities ranging from 80 W-hr/lb for small cells to 135 W-hr/lb for large cells are predicted. Dow has attempted to develop a 40 Ah cell under a contract cosponsored by the Navy, Army, EPA, and DOT. This development effort may have been premature in view of the limited amount of life data and glass compatibility experience Dow has in hand. It did prove valuable, however, in that it focused attention on problem areas that will require work. This approach appears to have the best low-cost potential among the various high-temperature batteries under development.

The lithium-sulfur system has been under development for a number of years at Argonne National Laboratory, with a smaller effort at Atomics International. Test results show the system has the desired charge and discharge rate characteristics (Table 2-5) for a vehicle battery,

Table 2-5. Lithium/Sulfur Laboratory Program Goals and Cell Performance--Argonne National Laboratory

Performance Designation	Single Cell Performance						Comments
	Area cm^2	Ah/ cm^2	A/cm^2	Volts	Cycles	Life, hr	
Goals	350	0.4	0.4	1.6	1,000	26,000	0.3-cm-thick cathode
Status	2	0.70	2.0	1.7	>1,250	>6,500	1.9-cm-thick cathode
	13	0.74	0.2	1.5	130	500	1.3-cm-thick cathode, sealed cell
	30	0.40	0.3	1.5	250	800	0.3-cm-thick cathode

although the life is limited and sulfur utilization has been too low to allow high energy densities to be sustained. Unsealed cells have been cycled for 1,500 cycles during 7,000 to 8,000 hours of operation, but these were essentially tests of the positive electrode, as the lithium electrode had to be replaced several times to correct internal shorting problems. Shorting arises due to a "dewetting" of the anode and subsequent formation of lithium globules between the electrodes. In sealed cells, this results in failure in 500 to 800 hours and 130 to 250 cycles. High sulfur electrode capacity losses (as much as 75 percent in the first 60 cycles) may be correctable using a new "mixed cathode" construction, but the required capacity densities (1 Ah/cm^2) have not been sustained. The system has some severe materials problems. In laboratory cells, niobium housings fail due to corrosion, and molybdenum is now being used. Static diffusion block tests show chromium is virtually the only low-cost material that might be corrosion-resistant, assuming it can be plated and maintained void-free on a lower cost base metal. Electrical insulators are also a problem. Current emphasis is one use of these batteries for central station service to accommodate power peaks.

Currently, Argonne National Laboratory is placing emphasis on the lithium-aluminum alloy/ferric-sulfide battery. Although this battery does not have the energy density potential of the lithium-sulfur or sodium-sulfur batteries, it has a less severe materials degradation problem and should cost less.

The lithium-chlorine system was investigated by General Motors and later, in a modified form, by Sohio. The former investigation showed high power densities, but was hampered by difficult corrosion problems at the 700°C operating temperature. The latter investigation progressed to a 264 W-hr, 12-cell battery that was tested for 100 cycles. This battery delivered 24 W-hr/lb without insulation. Due to the particular method of storing lithium and chlorine, the outlook for high energy densities is not promising.

2.2.1.2.4 Other Approaches

Organic electrolyte batteries offer the possibility for high energy densities at ordinary temperatures and are attractive for this reason. Literature research shows that primary cells can deliver 100 to 200 W-hr/lb at low discharge rates (over a period of 100 hours or more). High rate cells have been built but have limited wet-stand capability due to solubility of the cathode materials used. To date, no long cycle life, rechargeable organic electrolyte cell has been built. Much basic research is necessary on electrode reactions in nonaqueous media and on electrolyte properties. Since the most promising approaches involve soluble cathodes, work on an ion-selective separator would improve the chances for success.

Zinc-halogen cells have been investigated in two laboratories. The Zito Company reports long cycle life for an aqueous zinc-bromine cell, but the energy density is too low (20 W-hr/lb) to be of interest. A different concept has been demonstrated by Occidental Petroleum which uses a zinc-chlorine battery in which chlorine is stored as a solid hydrate at 8°C or below. The system developed has progressed to where a mechanically rechargeable 1,800-lb battery has been installed in a Vega for testing. The energy density is 30 W-hr/lb, but Occidental claims to be working on improvements that will increase this value to 75 W-hr/lb, giving the car a range of 200 miles. A joint venture between Occidental and Gulf and Western Industries was recently announced to develop this battery for both vehicle and utility industry use.

Fuel cells, which enjoyed a resurgence in development effort in the 1960's, are usually mentioned whenever electric cars are discussed. Their obvious advantages of high efficiency, silent operation, and harmless exhaust products, especially where hydrogen and oxygen are the reactants, have been well discussed by Escher (Ref. 2-11) and others. The major problem that has prevented commercial exploitation of the fuel cell has been cost, which can be directly related to the use of noble metal electrode catalysts, particularly for the oxygen or air electrodes. Since these electrodes are common to metal-air and metal-oxygen cells as well, a breakthrough in low-cost electrode catalysts could make either fuel cells or metal-gas batteries more attractive for electric vehicles.

2.2.1.3 Development Activities

Battery technology for electric vehicles has not advanced rapidly in the United States for a number of reasons. Private investment is almost nonexistent because of the lack of any market potential, while government research and development funds are limited and the electric vehicle has not had a high priority. The inability to find a battery that could compete with the lead-acid except at a prohibitive cost has also slowed progress.

Work on the nickel-hydrogen battery has increased, but work has declined on other metal-gas batteries (e.g., zinc-oxygen or zinc-air) and on the nickel-zinc battery.

Only long-range, high-energy battery research is receiving any significant federal support. The Ford Motor Company in collaboration with the University of Utah and Rensselaer Polytechnic Institute has been working on a sodium-sulfur battery under a $700,000 contract for FY 1973 from the National Science Foundation (NSF). This proof-of-concept effort is directed toward electric utility needs and would find application to automotive needs if a lightweight, low-volume concept evolves successfully. Stanford Research Institute received $100,000 from NSF in FY 1973 to work on lead-lead oxide cells for primary application to the electrochemical industry. Following a $300,000 contract from NSF in FY 1973, work continues at Argonne National Laboratory on the lithium-sulfur battery at a contract value of about $1 million for FY 1974, with the objectives being redirected to utility load leveling and peaking applications. This program, which had been jointly funded by NSF and Atomic Energy Commission (AEC) in FY 1974, is now funded solely by AEC as of February 1974. Overall, NSF expects to have about $900,000 available in FY 1974 for advanced battery research.

The Electric Power Research Institute, Palo Alto, California, is also funding work at a $1 million level for FY 1974, on sodium-sulfur batteries at TRW Systems and General Electric, lithium-sulfur batteries at Atomics International, and zinc-chlorine batteries at Energy Devleopment Associates. Although some of this effort might apply to electric vehicles, the primary goal is for energy storage satisfying utility load leveling and peaking needs.

On the other hand, work on batteries for electric vehicles is accelerating aboard. Table 2-6 summarizes these programs. The major activities are in the Federal Republic of Germany, Japan, the United Kingdom, and the U.S.S.R. In each case, the government is either formally participating or influencing the direction of work. In at least five other countries

Table 2-6. Foreign Battery Research and Development (R&D) Efforts for All Types of Electric Vehicles, by Countries (Ref. 2-6)

Country	Formal National Program	Estimated Budget	Comments
Federal Republic of Germany	No	$650,000 per year	Direction influenced by government
Japan	Yes	$14 million (1971-75)	Includes vehicle development
United Kingdom	No[a]	$950,000 (1973)	1/2 million electrics in use - 30 companies making electric vehicles
U.S.S.R.	Yes	Unknown	Experimental and prototype vehicles tested
Others			
France	--	--	--
Sweden	--	--	--
Italy	--	--	--
Czechoslovakia	--	--	--
Switzerland	--	--	--

[a]Strong government support of R&D

(France, Switzerland, Sweden, Italy, and Czechoslovakia) vehicle battery projects are known to be under way. The most dramatic achievement of the past year was the use of sodium-sulfur battery to power a small van. This was accomplished by the Electricity Council Research Center at Capenhurst in the United Kingdom.

2.2.2 Motors and Controls

A wide selection of motor design and controller combinations have been used in past and present electric cars. The controllers vary in complexity from the use of carbon-pile resistance stacks employed on early streetcars to three-phase, silicon-controlled rectifier (SCR) time-ratio controls used in some of the advanced experimental alternating current motor drives. No specific approach has yet been universally adopted, but the brush direct current motor controlled with a pulse-width modulation (PWM) SCR system was overwhelmingly used for electric vehicles during 1973, followed by the step voltage, parallel-series switching system.

Of the many motor types available, only a small number can be considered for vehicle drive applications. Many, such as the stepper motor and hysteresis motor, are designed for special-purpose application much different than an electric car. Others, such as the alternating current induction motor and the alternating current reluctance motor, require very complex controllers that must handle large currents for the amount of torque generated. These two types of motors must be supplied with both variable voltage and frequency. Because of the controller complexity and the poor motor efficiency, these motors are not considered optimum for electric vehicles.

Despite the high power density of the alternating current induction motor, its requirement for advanced controller technology is a severe limitation. This was demonstrated by General Motors when they used this motor for a converted Corvair, the "Electrovair". Its requirement for three separate circuits providing both variable voltage and frequency caused the controller weight to be greater than the motor weight. Two versions of the Electrovair were built. The first required a total controller weight of about 480 lb, compared to 160 lb for the motor. The Electrovair II controller combined some functions by building voltage and frequency controls in the same component. This unit weighed about 240 lb, including the cooling system. Subsequent electric cars built by General Motors used a brush direct current motor.

The Electrovair cars (Figure 2-2) were designed and tested by General Motors to evaluate performance and design features. The Corvair engine was removed and replaced by an electric drive consisting of a silver-zinc battery weighing about 600 lb, an alternating current induction motor, and

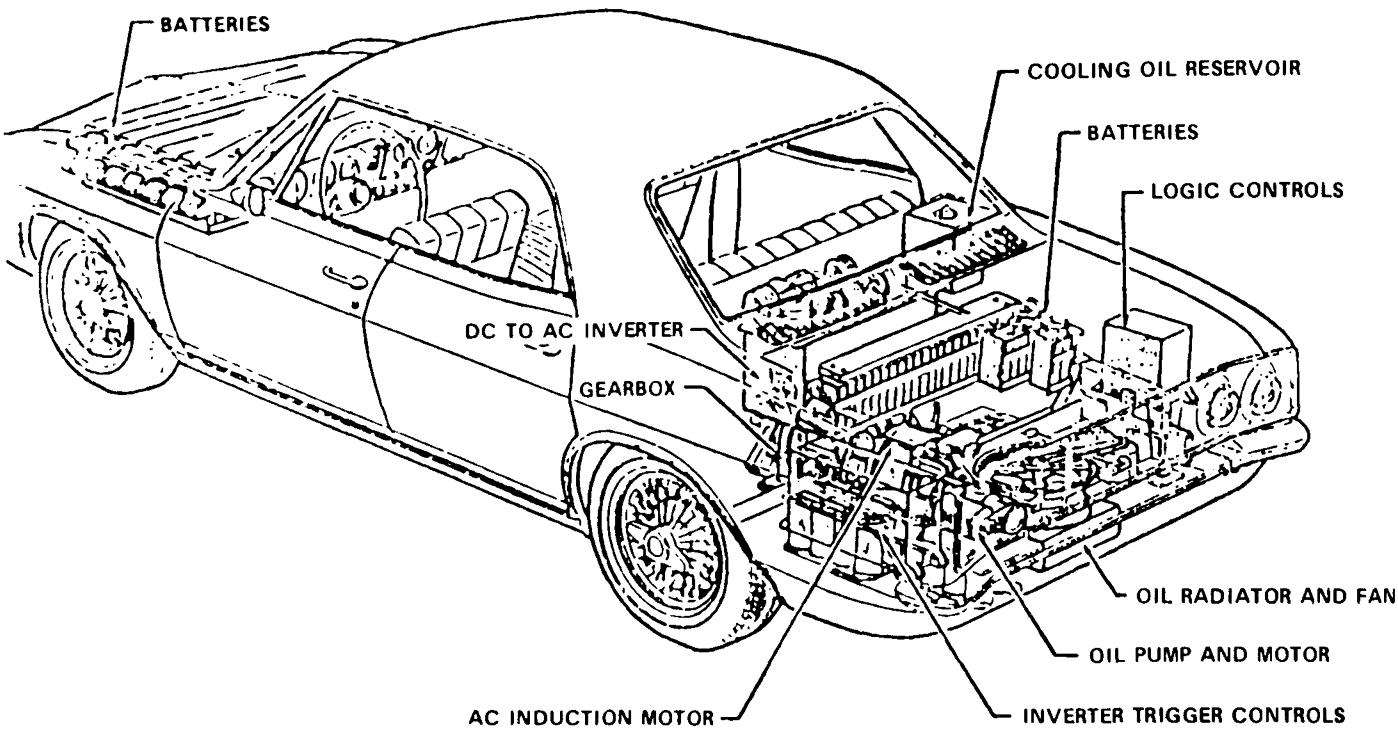

Figure 2-2. Phantom View of the General Motors Electrovair II Showing the Location of Major Experimental Components (Ref. 2-12).

associated controls. The Electrovair I weighed about 3,600 lb and demonstrated an acceleration capability of 0 to 60 mi/hr in about 15 seconds, which is comparable to the wide-open throttle acceleration of a production Corvair with automatic transmission. The motor was coupled to the rear differential through a fixed-speed reducer, and the full torque was provided by the motor without a gear shifting transmission. The driving range at 60 mi/hr cruising speed was 70 miles before recharging was required.

The electric power delivery system to the drive wheels consists of a chopper (or modulator) to convert the fixed battery voltage to a smoothly variable direct current voltage, an inverter to convert this variable direct current to three-phase alternating current voltage with rectangular waveform, and an induction motor. Thus, by controlling the chopper and inverter simultaneously, the voltage and frequency of the motor can be varied smoothly (Ref. 2-12).

2.2.2.1 Design Factors

2.2.2.1.1 Cost

Neither motors that are suitable for family size vehicles nor controllers to regulate them have been mass-produced to date. Because of this, these powertrain elements presently have a high cost, and it is this high cost that is the greatest single hurdle to widespread use in automotive vehicles. The mass-produced costs must not exceed 20 percent of today's costs for the same devices presently used in aircraft or other special applications requiring high quality control in manufacture. A single compound wound, compensated motor of the type that could drive a family car is listed in the General Electric catalog as costing $2,300 to $3,200, depending on the features. The controller is an additional cost. It will thus require a large production base to make an electric family car economically viable.

2.2.2.1.2 Drive Motors

Electric motors, particularly direct current motors, have not been developed to provide combined optimization of efficiency, weight, size, and cost for vehicle propulsion. It is possible that they might be designed with lighter weights than those in the market today with equal reliability and lifetimes because weight has not been a prime consideration. Some gains may be effected by installing improved (low hysteresis loss) core materials, replacing all the frame with the lightest weight materials at minimum structural rigidities that will maintain gaps and bearing integrity, and using high energy density fields (new rare earth cobalt permanent magnet materials). The usual motor frame structure is very thick, heavy, and strong. The weight saved could be used to increase the motor core cross-sections, reducing core hysteresis losses and magnetizing currents. Also, increasing the copper cross-sections will decrease the resistance I^2R copper losses. Motor efficiency at design load could thus possibly be increased from 75 to 90 percent at the same weight per unit horsepower. With proper design, the working portion of the motor can be larger for a given size and weight, as compared to floor-mounted models where weight is unimportant.

Currently, efficiency can be traded off against motor weight. For a given design power level, the weight per unit horsepower can be decreased if the efficiency is allowed to decrease (Figure 2-3, Ref. 2-7). Extrapolation from present technology indicates that power densities of 5.5 to 8 lb/hp should be achieved at a reasonable efficiency and cost by merely optimizing the design for the particular application and using lightweight materials whenever possible (Figure 2-4). Based on these figures, a 4,000 lb electric car capable of cruising at 80 mi/hr would require a motor weighing almost 400 lb (rated at 60 hp).

The following list describes motors that are candidates for electric vehicle propulsion and their characteristics.

a. The series wound motor has its field winding connected in series with the motor armature so the field strength is a function of load current. This provides a very steep speed-torque characteristic at light loads, which becomes fairly flat at overloads. The series motor has high starting torque capability because the field is strengthened as the load increases, thereby compensating for the demagnetizing effect of armature reaction. The series motor speed can be controlled by varying the applied voltage, but since changes in load can cause relatively large changes in speed, precise control is difficult. For example, if the maximum speed on level terrain is reached through application of full battery voltage to the series motor, as soon as the vehicle reaches an incline or a headwind, it will always slow down (series field strength increases) rather than draw additional power from the batteries to maintain speed. This motor is also difficult to control for power transfer during regenerative braking.

b. The shunt wound motor has its field connected in parallel across the motor armature. This provides a field strength independent of load current and directly proportional to applied voltage. This results in a fairly flat speed-torque characteristic. It is important that this type of motor have compensating windings to nullify the degradation that would result from armature reaction.

   Without compensation, the demagnetization effect on the field poles of armature reaction will cause field weakening. Then, the motor draws more current, producing an avalanche effect, which further weakens the field.

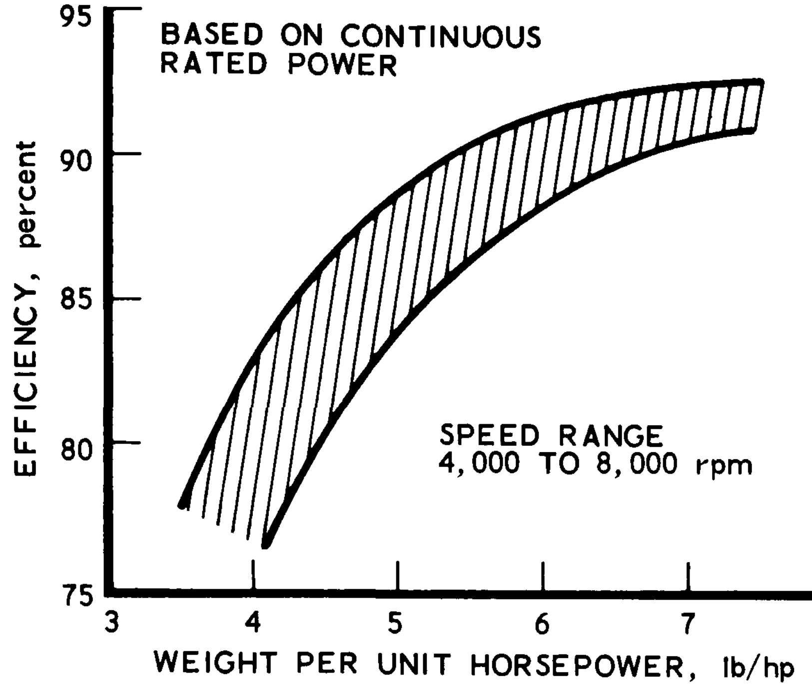

Figure 2-3. Typical Maximum Efficiency for Direct Current Motors as a Function of Weight per Unit Horsepower (Ref. 2-7)

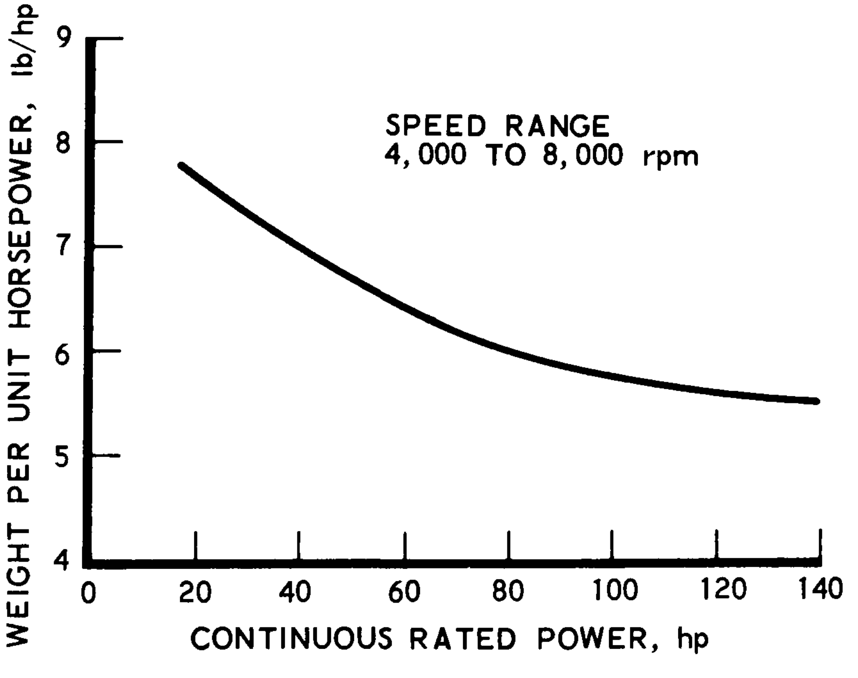

Figure 2-4. Typical Weight per Unit Horsepower as a Function of Rated Power for Direct Current Motors Including Forced Air Cooling (Ref. 2-7)

To obtain good speed control with this type of motor, it is necessary to provide an independent power control for the separately excited field to obtain controlled field strength. Then, voltage to the armature can be varied in order to vary motor speed.

With constant field strength despite armature reaction, this motor will draw additional current at a given voltage on occasions of increased load (with the vehicle on an incline or encountering a headwind) to help maintain the same velocity. In addition, field weakening is sometimes used to increase speed up to three times base speed. During field weakening, the motor can operate at constant power, providing higher speeds. The power to operate the separately excited field is from 1 to 10 percent of the rated motor power. Accurately controlled regenerative braking is available when this motor is equipped with a separately excited field.

c. The compound wound motor provides both a shunt field and a series field so that performance will fall somewhere between a shunt and a series speed-torque characteristic, depending on the ratio of field strengths selected. If additional speed and regenerative braking control are desired, the parallel winding can be separately controlled as in a separately excited motor, rather than the usual shunt connection across the single-line input.

d. The permanent magnet motor has permanent magnet pole pieces in place of field windings. Field strength is constant and is not affected by armature reaction as in a wound field motor. This is due to the low permeance coefficient of the permanent magnet material. This provides a straight line speed-torque characteristic with relatively low no-load speed and high starting torque. By varying the applied armature voltage, precise speed control is obtained. Since this motor does not have a wound field, there are no field losses. This means that for an equivalent rating, it is more efficient at all equivalent power levels and speeds. This motor has strong potential for electric vehicles, but is not yet fully developed, because the permanent magnet material has not been available in sizes and field strengths needed for electric cars.

e. The brushless direct current motor has often been used in fractional horsepower space applications, but has not yet been fully developed for electric vehicle use. The integral horsepower brushless direct current motor will use rare earth cobalt permanent magnets and Hall effect detectors to trigger the SCRs for commutation. The brushless motor is self commutating. Load demand is met by variation of average current, and velocity demand is met by a change of effective voltage through the PWM system.

f. The synchronous alternating current motor energized from a battery requires a controller incorporating both voltage control and frequency conversion. The voltage and frequency control can be achieved either in a separate chopper followed by an inverter or combined in a modulating inverter. The alternating current synchronous motor will come to a stop if its maximum torque is exceeded. A rotor position sensor can be incorporated into the motor which will force the motor to operate like the brushless direct current motor.

g. The alternating current induction motor operating at a fixed frequency is not practical for variable-speed applications. However, when driven by a variable-frequency inverter or cycloconverter, torque-speed characteristics similar to direct current motors can be obtained. The induction motor has the advantage in specific power when compared to direct current motors at the required electric vehicle horsepower levels. The requirement for a complex device to control frequency and voltage has restricted its use in electric vehicles.

The overwhelming majority of electric vehicle builders use the the brush direct current motor. Brushes are easy to replace and are capable of lasting 50,000 vehicle miles. Power input to the motor is usually through a single circuit requiring only variable voltage; this greatly simplifies controller complexity and weight. Some builders found it worthwhile to use a two-circuit direct current motor providing control of both armature and field circuits. This provides an increase in load, velocity, and regeneration control available from the low-power second circuit of a separately-excited field.

2.2.2.1.3 Control Systems

In a comparison tradeoff of drivetrain designs, it is very important to include control system cost and weight. In terms of performance and versatility, the selection of an adequate low-cost control system is as significant as motor selection. Because all of the contending electric motors need variable voltage applied for varying speed, control and regulation must include the modification of a fixed-voltage source (the batteries). This can be achieved by means of a chopper circuit, a variable resistance in the armature circuit, or a step-voltage change combined with field control.

The chopper circuit (generally using SCRs) provides an efficient means for transforming a fixed battery voltage to a smoothly varying effective voltage matching the requirement of the motor at all speeds of operation and providing a smoothly varying speed. The chopper system provides pulse frequency variation, PWM, or a combination of the two. While the chopper sees a varying impedance for the motor (depending on motor speed), it presents a relatively constant high impedance to the battery when used with proper filtering elements. This allows the reduction of high current pulses in the battery. Also, compared to pure direct current control, the chopper introduces losses due to high-frequency operation. These losses can be partially reduced by special motor design and adequate filtering. Since the forward voltage drop of the high-current SCR is about 1 V, 0.5 kW would be lost in the SCR at 500A. This power loss presents a heat dissipation problem. The higher the maximum system voltage,the lower the proportionate loss of the SCR controller system at a given motor power.

The main disadvantage of the chopper is the high cost of the power switching components and the associated control circuitry. However, if industry has the incentive for high production levels, it is estimated that at some period beyond 1975, the price of the high-current, high-voltage SCR should be reduced sufficiently to make it economically viable. Recent price reductions have already made them practical for experimental vehicles. However, the SCR protection circuit and the current-smoothing filters will still remain significant cost factors.

A variable resistance in the armature circuit is a simple type of controller that was used on streetcars and some early electric cars. Though simple, this type of control introduces high losses because of the voltage drop across the resistance, and is an inefficient method of voltage control for a vehicle required to operate over a wide speed range.

Step voltage systems have been used in which multiple-pole relays switch batteries from parallel to series in steps as vehicle speed increases. This may be undesirable, because the discrete velocity increments may prevent one vehicle from following another vehicle at the same velocity, and the relays are constantly working under load, thereby shortening the operating life. To provide adequate voltage matching over a wide speed range, several stages of voltage switching are required to obtain reasonable motor efficiency and avoid excessive loading of the battery. The number of switching steps may be reduced by combining field control with voltage switching (i.e., by using armature current sensing to provide feedback information for controlling the field). This would control current surges and corresponding jerks.

A comparison of operational characteristics using the three types of controllers is given in Table 2-7.

Table 2-7. Comparison of Motor Controllers (Ref. 2-7)

Item	dc Chopper	Variable Resistance	Step Voltage with Field Control
Types of Motor Controlled	All dc motors	All dc motors	Only separately excited, stabilized or compound wound
Velocity Range	Zero to maximum speed	Start only	Wide with three steps or more
Smoothness of Velocity Change	Very smooth	Jumpy	Initial jump 0.5 mph then smooth
Controller Protection	Solid state only-circuit breakers and fuses too slow	Circuit breakers and fuses sufficient	Circuit breakers and fuses
Controller Cost (1975)	High	Low	Medium
Controller Efficiency	Medium	Very Low	High with controller logic
Special Sensors and Control Logic	Complex	Simple	Complex
External Smoothing Filter	Heavy filter req'd	Not required	Not required
Starting Torque	High but inefficient	Medium and very inefficient	High with inefficient over-excitation
Velocity Stability	Stable with shunt motor, decreasing with load on series motor	Somewhat unstable varying with load	Stable up to torque limit
Torque at High Speed	High	Low	Medium-limited by field weakening ratio
Power Conditioning Characteristics	Modulation of full power used by motor	High switching currents with much dissipation	With small signal field control, high contactor currents at switch closing but zero contactor currents on switch opening.[a]

[a] Before a change of armature voltage takes place, the field is momentarily increased to the point where armature current reaches zero. The feedback from the current sensor then allows the armature relay to open. The usual problem of interrupting direct current is thus avoided.

Of greater complexity are the controllers for the brushless direct current and the alternating current induction motors. Controllers for alternating current motors must provide not only variable voltage, but also variable frequency to the motor. At present, three-phase, variable-frequency and variable-voltage inverters at power levels associated with electric vehicles are very expensive and heavy, because they are complex (twelve SCRs or more are needed, with at least six having high current ratings). The voltage control may be incorporated into the inverter or a separate chopper may be used.

2.2.2.1.4 Power

In the interest of saving weight, the power levels of electric vehicles are limited. A review of prototype electric cars shows that the usual motor used in vehicle application is driven at or above its rating to save weight. This results in increased heating requiring a forced air cooling system (or even oil cooling) due to the lower efficiency of the smaller motor. A forced cooling system can almost convert the peak power rating into continuous power rating. Hence, the rated continuous power of the motor does not seriously constrain the short-term power capability during acceleration. However, due to commutation limits, the overload capability decreases with velocity.

With this approach, the efficiency is usually 65 to 75 percent for the motor alone, as opposed to efficiencies of 90 percent with heavier motors having a higher weight per unit horsepower. The principal power dissipation is in core and copper losses, which is an unfortunate conversion of electrical energy into waste heat. The heat serves no useful purpose, except in some designs it can be vented into the vehicle interior in winter.

The batteries also constrain the power levels realized by an electric power plant. This arises from the limitation of the power per unit weight available in batteries. Similarly, the limitation on energy storage also constrains power levels. This results because battery discharge efficiencies are a function of the power level. Thus, at high discharge rates, the efficiency is low (just as it is at high charge rates), and the available energy for the motor is reduced for a given battery.

2.2.2.1.5 Weight

A literature survey on electric vehicles shows that many electric car designers build smaller and lighter weight specialty vehicles to keep power requirements low. It becomes necessary to design the vehicle with the objective of minimum weight of all structural and panel parts to permit sufficient allocation of weight to the batteries. The "Sundancer" was totally designed as a minimum weight, very low aerodynamic drag electric car with a major allocation of weight to batteries. It was built for ESB, Inc., by McKee Co. to offer maximum range with today's batteries (Ref. 2-13).

A study by Minicars, Inc., for EPA (Ref. 2-3) projects all designs for electric cars as being in a low performance class (similar to a VW 1200) because of low battery power levels available in the allocated weight. This study also points out that these limited performance vehicles can met the real requirements of average urban driving, but are range limited for suburban driving.

Electric drive systems have also been used on slow, heavy vehicles that make many short duration stops. The town delivery truck or van and the local bus are good examples. There is usually no attempt to reduce frame weight to compensate for heavy battery weight with these vehicles. Indeed, the overall loaded weight is so large that even the heavy batteries do not represent over 30 percent of the overall weight.

The family car lies midway between these trends. To date no prototype has been designed or built that would accommodate six to eight people. Compact vehicles have been designed for two to four passengers, and buses have been designed for 20 people and more. A family car such as the eight to nine passenger heat engine powered station wagon weighing 4,000 to 5,000 lb with about 25 ft^2 of frontal area has much larger power requirements than those that have been practically achieved in the lighter electric cars. To reach this power level would require power plant weight and volumes required for electric buses.

2.2.2.1.6 Materials

The major material in an electric motor is reasonably high permeance core material, such as 4 percent Silicon Steel or Armco 24. Other materials, such as Permendur, are capable of higher magnetic flux density before saturation, but the cost generally precludes their use for large motors. Although large direct current motors normally have steel or iron frames around the field yoke material, these frames could be built from aluminum or other lightweight material, since only rigidity, not magnetic permeability is required for the frame structure as long as the yoke is present.

The raw materials used in a system to be mass produced must be readily available in large quantities as a primary mining or refinement process. Excluding batteries, all the metals to be used in the electric vehicle are available in quantity, with the possible exception of copper. Aluminum is a possible substitute for copper; it has a better conductance per unit weight than copper, but also a lower density. Thus, when a motor is designed for the same electrical (I^2R) losses using aluminum conductors, the unit will be lighter but larger, than when using copper.

The least available material in a permanent magnet motor using rare earth cobalt is the cobalt. Rare earth metals, samarium and praseodymium, are plentiful in the earth's crust. Silicon for the SCRs is plentiful.

2.2.2.1.7 Pressure and Temperature Effects

Electric vehicles are expected to be relatively insensitive to pressure changes. Brushes cannot commutate as well under reduced pressure due to a reduction in the potential insulation gradient of rarified air. Arcing can thus occur at lower voltages. In addition, brush wear increases with less air molecules to act as a surface contact lubricant. Neither of these effects is of disturbing magnitude up to 10,000 ft altitude, which is the usual maximum height of mountainous roads. Even the highest peaks which contain roads (such as Pikes Peak) would not justify special design of a brush-commutation system.

Air density and the motor cooling system temperature impacts design, particularly under load. The temperature rise of the motor that would result from climbing a mountain could be a serious constraint on all electric vehicles. A motor would have to be sized for mountain climbing application commensurate with its cooling system. Cold temperatures can be a severe problem for the battery system, which has a very serious degradation in available energy at below-freezing temperatures.

2.2.2.1.8 Cooling Requirements

In the initial running period, the power output capability is restricted by the degree of thermal lag that determines transient temperatures in the motor. After continuous operation, the power is limited by heat emission rates of the motor and its cooling system. Cooling must be provided to ensure that the temperature rise does not exceed the temperature rating which is dependent on the type of material used for insulation. Running the motor above this rating will shorten its operating life due to insulation deterioration and subsequent shorts. Motor burnout due to operation at excessive temperature is a common failure with motors used in electric cars.

2.2.2.1.9 Transmissions

A method to change the gear ratio between the motor and the drive wheel is advisable for hill climbing and start-and-stop driving. Though direct current motors can provide their highest torque at zero velocity, the disadvantage of high current required to accelerate one with a fixed high gear ratio must be considered against the losses and added weight of a transmission.

2.2.2.2 Operating Characteristics

2.2.2.2.1 Power Control

Most electric vehicles built to date have used either step voltage series-parallel switching or a PWM system. The step voltage approach is becoming less popular as SCRs for a PWM system become less expensive. In step voltage control, there are a small number of discrete voltage settings.

This results in power surges when changing control levels. A major shift from step voltage to the PWM has occurred in the past year because PWM systems provide a smoothly varying, controlled velocity and torque. Until last year, voltage switching schemes had been used in a large variety of electric cars such as the Sundancer (Ref. 2-13). This car, shown in Figure 2-5, weighs about 2,000 lb (test weight including 750 lb of lead-acid battery). It has a constant speed driving range of 50 mi at 50 mi/hr, and 140 mi at 30 mi/hr. (The urban driving range was between 50 and 80 mi.) The electric drive control uses both voltage switching and series resistance control. Figure 2-6 shows another electric car, the Mars II, which used a similar drive scheme (Ref. 2-14). However, R. R. Aronson, President of Electric Fuel Propulsion, Corp., which manufactured the Mars II, indicated in 1971 that his future electric cars would be controlled by the SCR direct current PWM system.

2.2.2.2.2 Vehicle Range Limitations

Currently, a major problem with electric vehicles is the limitation on the amount of energy and power that can be stored in a given size battery. Evidence of this problem is seen in contemporary electric vehicle operating characteristics. In a compact electric car, travel distances comparable to a heat engine car (without refueling), can only be approached with a battery system weighing about one-third of the vehicle curb weight. The magnitude of this problem becomes evident when the energy storage capacity of gasoline is compared with batteries. For example, at 14 mi/gal, a heat engine requires about 145 lb of fuel and tank to store the energy for a 280 mi trip. At a typical 0.5 kW-hr/mi for battery energy usage of an electric car, about 140 kW-hr is required to be stored in the battery for the same trip. Thus, for the same travel per unit weight, the battery must store about 970 W-hr/lb. Present lead-acid batteries achieve only about 15 to 20 W-hr/lb. So, while it is not necessary to match the storage efficiency of gasoline in all vehicle applications, it is quite evident why electric cars are overweight with batteries to achieve any reasonable range.

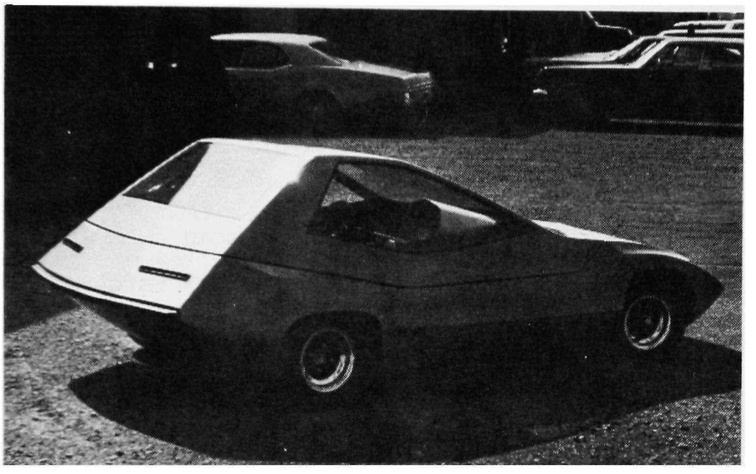

Figure 2-5. "Sundancer" Rear Quarter View (Ref. 2-15)

Figure 2-6. View of 1968 Mars II Electric Car (Ref. 2-17)

2.2.2.2.3 Special Requirements and Procedures

The all-electric vehicle must have a battery state-of-charge indicator to advise the driver of the remaining vehicle usable range. It must also include an on-board battery charger with a standard plug for 115Vac outlet limited to a 2 kW charge rate. This could be used in emergency for a boost charge.

Residential recharging requires about 8 hours, since home electrical outlets will limit charging to about 2.2 kW into the charger on a 20-A circuit. Special wiring such as used for electric stoves could cut this time, but charging efficiency is lower at higher rates.

An alternative to recharging is a battery replacement system that could be used for a portion of the electric automobile population that required very rapid restoration of energy. The exhausted battery pack is rolled out from a storage well under the vehicle and a freshly charged battery pack is inserted. The time required is about the same as the usual gasoline refueling period. The exhausted battery pack is recharged while the vehicle continues on its trip (Ref. 2-15).

The standard driving foot pedals, steering wheel, and ignition key that closes a line relay are used. When the foot throttle is raised, regenerative braking can be used to decelerate the vehicle at a rate similar to that available from a heat engine. Hydraulic brakes and an effective emergency parking brake are also required.

Current limiting provisions independent of throttle position are of prime importance for safety. The inexperienced driver may push the throttle to the floor with the wheel against the curb. The armature resistance of vehicle-size motors is too low to prevent a destructive surge of current with application of full voltage while the motor is not turning. The PWM system must incorporate a current sensor and control logic which prevents buildup of currents above four to five times rated current. In the step voltage control system, a current limiting line relay may be inserted with a latching circuit to its closing coil. This relay is opened at a predetermined maximum current, and can be reset by a turn of the ignition key to the momentary start position. In case the throttle is fully depressed at the same time the latching relay is being reset, the relay will chatter but no destructive currents can flow.

Each system must have circuit breakers and/or fuses mounted as close to battery terminals as practical. By having a switch at the driver's position which can remotely reset or trip the circuit breakers in case of inadvertent over-loads, the vehicle need not significantly decrease velocity before the breakers are reset and power is reapplied.

3. VEHICLE PERFORMANCE CHARACTERISTICS

3. VEHICLE PERFORMANCE CHARACTERISTICS

A typical approach to building electric cars has been to use the frame and entire structure of the conventional heat engine powered car and merely replace the heat engine with an electric motor mounted in the same location. A manual shift transmission is often retained, and the usual drive shaft and differential remains. In this case, batteries are often packed in all available space. Trunk space is often sacrificed, and heavy duty brakes, shock absorbers, and springs are installed to compensate for the additional weight. In many cases, such as the Mars II, the resulting weight distributions caused adverse handling characteristics (Ref. 3-1).

Currently, if high acceleration performance is designed into the all-electric vehicle to attempt to approach that of the baseline heat engine vehicle, then the range becomes very limited (about 30 to 40 mi between charges for 1,000 lb of battery load). However, if both high performance and long range are desired, the battery weight will result in the vehicle weight being much larger than a heat engine powered car of similar performance, and indeed electric cars may never fully match the heat engine powered car performance until advanced battery systems are available.

3.1 POWER, SPEED, AND TORQUE

Analytical studies have been conducted on the expected performance of electric vehicles, but those who subsequently built prototypes discovered that actual performance (including range) did not measure up to the predictions based on analysis of total drivetrain efficiency, battery performance, aerodynamic drag, and friction drag of tires. Tire drag was often higher than anticipated since the resulting vehicles are extremely overweight with batteries compared to the base heat engine vehicle. To alleviate the problem, tires are over-inflated to reduce friction. Radial ply tires have also been used to reduce friction somewhat (Ref. 3-1).

In general, the majority of the electric vehicles do not perform up to heat engine capabilities, particularly with respect to maximum acceleration, speed, range, and hill climbing ability. The usual maximum speed lies in the range from 30 to 50 mi/hr. Hill climbing results in a dramatic reduction in maximum speed. For example, a 5 percent grade would usually cause a 50 percent drop in velocity, and a 15 percent grade can generally be ascended only if a variable gear ratio transmission system has been included.

The range is always constrained by the total energy carried in the vehicle, and also varies in each vehicle with the cruise velocity, number of stops required, and the total weight. Aerodynamic drag is not a significant factor at the lower speeds. Differences in the vehicle frontal area become a factor above 30 mi/hr and important above 50 mi/hr. The range variation due to velocity is very large. The range at maximum speed can be one-half the range at the optimum speed (Ref. 3-2). In addition, the range is approximately inversely proportional to the number of stops. Comparison of vehicles from a curb weight of approximately 1,200 to 4,800 lb shows that range is strongly affected by the weight with the ratio of the vehicle weight to the battery weight being the controlling factor.

A typical vehicle is the converted American Motors Hornet, "The Electro-Sport." This vehicle had a curb weight of 5,180 lb including about 2,200 lb of batteries. It reached a speed of 69 mi/hr, accelerated from 0 to 30 mi/hr in 9.8 seconds and from 0 to 50 mi/hr in 26.4 seconds. Its range at different continuous speeds was:

Speed, mi/hr	Range, mi
50	56.7
40	73.4
30	87.3
20	101.6

It was able to climb an 8.4 percent grade at 21 mi/hr. At a constant cruise speed, the energy taken out of the battery varied from 0.277 to 0.458 kW-hr/mi.

With a severe urban driving cycle involving four start-stops per mile, it traveled 31.2 mi (125 stop-start cycles) at an average speed of 20 mi/hr with an energy requirement of 0.7 kW-hr/mi (Ref. 3-2). Note that, with four stops per mile, the energy usage increased by about a factor of 2.5 compared to continuous driving at the same average speed.

In another evaluation, over 50 Mars II vehicles were built by converting Renault-10 sedans. Actual performance of these cars did not match earlier predictions. Reference 2-17 predicted acceleration of 0 to 40 mi/hr in 10 seconds, a top speed of over 70 mi/hr, and ranges of 70 mi at 70 mi/hr and 150 mi at 40 mi/hr. The curb weight of the heat engine powered baseline design for the Renault-10 is 1,800 lb, while the electric version weighed 4,100 lb. The test results (Ref. 3-1) state: "Most of the shortcomings ascribed to the Mars II stem directly from its excessive weight and adverse weight distribution due to the batteries." It also lists the actual test top speed at 55 mi/hr and ranges of 84 mi at 45 mi/hr, 91 mi at 37 mi/hr, and 125 mi at 31 mi/hr. The minimum acceleration time for 0 to 40 mi/hr was actually 21 to 22 seconds, neglecting time for shifting. The large weight was a result of 1,800 lb of batteries employed in an effort to achieve high performance and long range.

3.1.1 Power and Energy Storage

When a compact car weighing about 2,000 lb is converted to an electric vehicle weighing 3,000 lb (including 1,000 lb of batteries), it cannot travel more than 30 to 50 mi between charges in stop-and-go driving. If greater battery weight is added to increase the range, the handling characteristics such as steering and braking are degraded, in addition to having poor acceleration and an uncomfortable ride. It is thus concluded that a general-purpose, all-electric family car is not possible with present lead-acid batteries.

If the battery weight is limited to 500 lb and the range between battery charges is 200 mi, then a compact car must carry about 100 kW-hr for stop-and-go driving (estimated to require energy expenditures of about

0.5 kW-hr/mi). This would require a battery energy density of 200 W-hr/lb. Only further research can develop this capability, which is a very great increase over the present level of 15 W-hr/lb of lead-acid batteries.

Though some improvement can be made in aerodynamic drag by streamlining and in road drag by using radial ply tires, the basic power to move and accelerate vehicles of certain weights and cross-section area remains essentially fixed. Reducing drag to a minimum, while increasing drive system efficiency to a maximum are the only steps outside of battery development that can be taken if the ratio of drivetrain weight to total weight is to be maintained at feasible levels. Unfortunately, these actions can only provide minor improvement.

3.1.2 Speed and Torque

As discussed previously, it is not practical to achieve the same torque and speed characteristics in an electric vehicle as in a heat engine vehicle. However, it is possible to make improvements in the use of electric motor capabilities.

The present peak operating speeds of electric motors sized to drive road vehicles are approximately the same as their heat engine counterparts. Although this feature is convenient for those firms converting cars by simple replacement of the heat engine with an electric motor, these speeds are not optimum for packaging of the powertrain in electric vehicles. For example, if a 3,000 rpm motor is replaced by a motor rated for 12,000 rpm at 20 hp, its power density would improve from about 7-1/2 to 4-1/2 lb per continuous horsepower. Reference 2-2 indicates that 12,000 and 24,000 rpm direct current motors could achieve 1.54 lb per peak horsepower and 1 lb per peak horsepower, respectively.

3.2 EMISSIONS

Gases can evolve from the battery system depending on the type of battery and the packaging design. Lead-acid batteries containing antimonial lead grids give off gases on charge, discharge, and on standing idle. These gases are largely hydrogen and oxygen, but small amounts of antimony hydride, arsenic hydride, carbon monoxide, and chlorine may also be present. Sulfuric acid can also be lost through vents and enter the atmosphere in the form of sulphates.

Outside of the battery, the direct emissions from an electric vehicle are primarily heat and a possible trace of ozone from the opening of current-carrying relays. The operation of SCRs in PWM does not generate ozone, however.

Overall emissions must also include those produced by the electric plant that generates the energy to charge the battery. Both the type of emissions and the total emissions must be evaluated to determine the benefits that accrue to the pollutant levels in the atmosphere when energy is expended at a large, fixed single source as opposed to many small, mobile sources.

3.3 FUEL (ENERGY) ECONOMY

When energy requirements of electric vehicles are compared to conventional cars, a careful examination must be made of the efficiencies of the various steps of energy flow. Thus, as pictured in Figure 3-1, starting with the required power or energy delivered to the wheels, we have to consider the efficiency of each stage in the system. But to avoid making assumptions regarding efficiency of elements in the vehicle powertrain, road test data for a given vehicle must be used. Some of the available test reports quote only total range at a given speed, some measure Watt-hours to the motor, and some base range on total energy storage. Efficiencies, such as battery discharge efficiency and motor efficiency, are a function of the operating cycle, the temperature, etc. For example, Reference 3-1 found a 4 to 1 variation in range between 0 and 80°F operating temperatures. For this reason, it is very difficult to obtain a consistent set of performance characteristics from different tests.

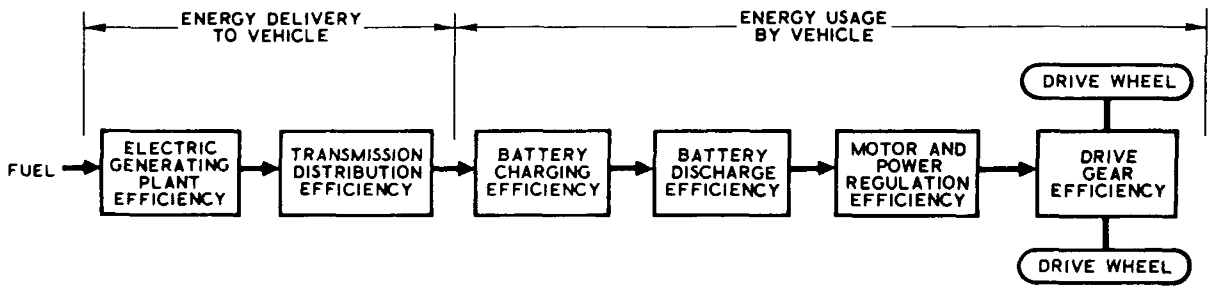

Figure 3-1. Electric System Energy Flow Diagram

Some basis for comparison between electric and spark ignition internal combustion engine powered vehicles is offered by test data acquired by the United States Postal Service during evaluation trials of intracity mail delivery service trucks in Cupertino, California (Ref. 3-3). The Harbilt electric vans designed for this type of service are powered by two 36-V, lead-acid batteries and can reach a peak speed of 40 mi/hr while ascending a 2 percent grade. The conventional postal vehicle is a Jeep powered by a four cylinder, internal combustion gasoline engine. The postal routes ranged from 8 to 15 mi with 100 to 300 stops.

Calculations of energy expenditure (Ref. 3-3) showed the electric vehicle using an average of 1.3 kW-hr/mi and the Jeep using the equivalent of an average 5.1 kW-hr/mi (after converting from gasoline consumption figures in miles per gallon). To truly offer a compatible comparison, the electric power plant generating efficiency and the transmission efficiency between the power plant and the battery charging station for the electric vehicle must be taken into account. Based on an average nationwide efficiency of 35 percent for the electric generating plant and 91 percent for transmission and distribution (Refs. 3-4 and 3-5), the electric vehicle is then actually using energy at the rate of about 4.1 kW-hr/mi.

The electric vehicle indeed shows some advantage in energy consumption for this special application; a gasoline engine powered vehicle is at a disadvantage under conditions of low-speed stop and start driving coupled with significant periods of engine idle. However, the advantage shown might be reduced (or eliminated) if the Jeep engine was derated so that vehicle performance was lowered to that of the electric vehicle; i.e., fuel economy of the Jeep could possibly be improved if the engine were redesigned for this particular application.

If this comparison were extrapolated to passenger cars, it should be noted that for equivalent weight vehicles, the gasoline engine powered car has superior driving range, cruise speed, acceleration, and passenger/luggage accommodations. In favor of the electric car, however, is the prospect that propulsion energy can be derived directly from non-petroleum based sources (e.g., nuclear power or abundant supplies of coal). (Eventually, these sources can also be available indirectly through production of synthetic fuels for heat engine powered cars.)

3.4 NOISE LEVELS

Aside from brush whine, the only noise sources expected from an all-electric are gears, wind noise, and tires. In some designs noise has also come from power transformers, but, in general, the electric drive is the quietest mode of transportation available.

3.5 ODOR

Relay switching in the step voltage system will cause a slight odor of ozone. Even this odor is avoided in the PWM system. Odors from electric generating stations will occur separately from the vehicle.

3.6 MAINTAINABILITY

While an electric vehicle has fewer moving parts than an internal combustion engine powered vehicle, no definitive data are available for passenger cars that can establish a statistical base for maintenance requirements and costs. Some indications of relative differences may be available from the large fleet of electric trucks and vans operating in Great Britain. However, extrapolation of those data to passenger cars could prove erroneous if the duty cycle and powertrain design requirements for those trucks are markedly different than for cars.

3.7 SAFETY

General safety requirements for an electric vehicle will be comparable to those for a similar heat engine vehicle. There will be additional requirements for circuit breakers with provision to reset the breakers in the event of an inadvertent overload at high speed. Spillproof battery caps must be used; in the event of an accident, there must be provision to avoid hazards from spilled electrolyte. Provision must also be made for opening the battery circuit for maintenance. There must be redundancy in design to minimize shock hazard, and short-circuit protection must be maintained.

In early work at General Motors on all-electric vehicles (Electrovair I), they elected to ground mid-battery voltage to minimize the shock hazard. It was subsequently determined that by not grounding the battery to the vehicle, the risk of shock and the risk of cable shorting upon impact are reduced. Though the drive batteries were not grounded to the chassis, in a later vehicle the accessory battery used the frame for the negative terminal. To achieve isolation between the drive batteries and the accessory battery, a high impedance charging unidirectional circuit was used.

3.8 DRIVABILITY

The Cornell Aeronautical Laboratory evaluation of an electric vehicle (Ref. 3-1) reports poor drivability due to the distribution of battery and motor weight in the front hood and rear trunk regions. The yaw moment of inertia is thus considerably greater than its heat engine counterparts. To alleviate this problem, the design of an original electric (as opposed to the conversion of a heat engine car) must include mounting most of the batteries in the mid-car region under the floor or seats of the car. The increased weight causes greater steering and braking effort, but usually not so great as to require power steering or power braking.

As noted in previous sections, the electric vehicle also has a low acceleration capability (except perhaps at very low speeds) and a limited top speed.

4. CURRENT STATUS OF TECHNOLOGY

4. CURRENT STATUS OF TECHNOLOGY

4.1 CURRENT USE

Electric delivery trucks or vans and electric utility vehicles have been built in increasing numbers in Great Britain for the past decade and are now estimated to exceed 75,000 vehicles. Small electric cars and electric utility vehicles are currently being produced in Japan in greater numbers than in the United States, largely because of the ban on heat engine vehicles in Osaka during the 1970 World's Fair. In the United States, an initial production of fewer than 300 vehicles has been accomplished by both Vanguard and Electric Fuel Propulsion Corp. Battronic is producing 100 cars for the Electric Vehicle Council and is building over 300 truck vehicles. Many demonstration and prototype models have been built, but, excluding electric golf carts and electric fork lifts, no major production of electric vehicles is under way in the United States.

Under a $14 million, 5-year program initiated in FY 1971, Japan is developing an electric car for use in city-bound transportation (Ref. 4-1). Aside from this program, they have produced about 1200 road qualified electric cars from 1966 to 1972 of which about 280 were used in EXPO-70, about 520 used for golf courses, and the majority of the remainder used in commercial and industrial applications. Table 4-1 lists the performance characteristics of electric vehicles built to prototype level of design in Japan, including trucks, vans, passenger cars, and buses.

4.2 CURRENT RESEARCH AND DEVELOPMENT

Motors holding great promise, but not yet developed to the point of qualification for electric vehicles, are the disc-armature motor that is being developed at the University of Warwick and the samarium cobalt permanent magnet brushless motor designed by General Electric under a contract through Wright-Patterson Air Force Base. These 1972 to 1973

Table 4-1. Performance of Japanese Prototype Electric Vehicles in 1973 (Ref. 4-2)

Parameters	Cargo		Passenger Cars (and Vans)		Buses
	Lightweight	Compact	Lightweight	Compact	Large-Size
Passenger + Loading Capacity, kg	two persons + 200	two persons + 1,000	four persons (or two persons + 100)	five persons (or three persons + 300)	60 to 80 persons
Approximate Gross Vehicular Weight,[a] kg	1,100	3,500	1,000	2,000	15,000
Maximum Speed, km/hr	more than 70	more than 70	more than 80	more than 80	more than 60
Mileage per One Recharge,[b] km	130 to 150	180 to 200	130 to 150	180 to 200	230 to 250
Acceleration (0 to 30 km/hr) in seconds	less than 5	less than 5	less than 4	less than 3	less than 8
Climbing Ability (speed of climbing an inclination of 6 deg), km/hr	more than 40	more than 40	more than 40	more than 40	more than 25
Company Responsible for Development	Toyo Kogyo	Nissan	Daihatsu	Toyota	Mitsubishi

[a]The weight of a battery shall be less than 30 percent of the gross vehicular weight. The energy density of a lead storage battery shall be 60 W-hr/kg. However, this is based on constant output for 5 hours.

[b]The mileage per one recharge is based on a value in continuous running at a constant speed of 40 km/hr.

developments are demonstrating that high-speed motors mounted in the drive wheel with epicyclic or planetary gears are possible. Samarium and/or praseodymium cobalt magnets represent a breakthrough in large motor field sources, since they are high in both field intensity and field density. That is, they provide high torque per ampere and the high coercive strength to resist change of the high torque per ampere. They cannot be demagnetized at any motor currents at temperatures below approximately 700°C. Hitachi Magnetics Corporation, in joint venture with General Electric, announced an even better rare earth cobalt magnet that could supply almost twice the torque per ampere as present motors with wire-wound fields.

A comparison for various materials of permanent magnet characteristics along with approximate dates of introduction are shown in Table 4-2.

Today's heat engine car requires a mechanical linkage between the engine (which is frame mounted) and the wheel axle (which moves up and down relative to the frame). Unsprung motors can be directly (or spur gear) coupled to a wheel. That is, in an advanced concept, a torque motor armature becomes the wheel center or a high-speed motor armature directly drives a reduction gear within the wheel hub. The electric vehicle can use multiple electric motors without overall efficiency penalty. However, a modest increase in weight will occur per unit torque and power when distributed among four motors. But, this may be offset by the weight saving due to elimination of drive shaft, differential, and transmission. There may also be an increase in vehicle cost and repair expense with this design.

Individual drive wheel motors can be sufficiently lightweight to avoid undue tire wear despite their unsprung vertical inertia. Therefore, the following wheel-mounted motor configurations may prove to be feasible:

a. Four annular torque motors mounted in the wheels, eliminating all reduction gears. The loss in power per unit weight of this type of motor is partially compensated by weight saving of all gears and couplers.

Table 4-2. Comparison of the Permanent Magnet Field Materials

Parameter	Material			
	Alnico V	Ferrite V	Samarium Cobalt	Rare Earth Cobalt
Manufacturer	General Electric Company	Indiana General Corporation	Hitachi Magnetics Corporation	Hitachi Magnetics Corporation
B-H Maximum Product in Millions Gauss-Oersteds	5.25	3	18	50
Year Introduced	Late 1940s	1954	Late 1960s	1973
Characteristics	Coercive strength only 600 Oersteds	High coercive strength about 3,000 Oersteds low flux density	An isotropic--difficult to radially magnetize	Isotropic also for radial magnetization
Comment	Subject to demagnetization in large motors	Low torque per ampere	High torque per ampere; will not demagnetize	Highest torque per ampere; lowest weight
Projected Approximate Large Quantity Cost[a]	$6/lb	$1/lb	$12/lb	$25/lb

[a]Based on 100,000 magnets per year, current technology, from manufacturer's catalog and personal communication.

b. Four disc-type torque motors using rare earth cobalt permanent magnet fields with almost linear torque-speed curves. These motors are mounted in the wheels.

c. Four printed circuit disc motors of bipolar or homopolar configuration with a permanent magnet field mounted in the wheels.

Although battery capability is recognized as the greatest single block to a practical family electric car, improvements can and must be made to the motor and controller systems to better utilize the power that next generation batteries will make available. Motor performance can be improved by designs using lightweight materials. Very few technology improvements have been accomplished in the controllers since the late 1960's, which marked the advent of the SCR chopper in pulsewidth modulation mode driving a direct current series field wound motor. During the past four years, the power handling capability of SCR systems has improved several fold, while costs have been reduced to about one-fourth of initial costs.

In addition to the new rare earth cobalt permanent magnet motors now being produced in developmental quantities, an advanced motor concept that may supply the highest power density is the cryogenic motor, which uses super-conductors for high-strength magnetic fields without iron core materials. Its extensive development is at least a decade away. Besides the need for long-term insulated containment of the cryogenic fluid (such as liquid helium), development is required for a safe method of dissipating the large amount of energy stored in the conductors if superconductivity is lost.

5. PROJECTED STATUS OF ELECTRIC VEHICLES

5. PROJECTED STATUS OF ELECTRIC VEHICLES

5.1 REQUIRED DEVELOPMENT

In addition to the essential development of batteries with higher energy and power density, other technology development is required for mass-produced, all-electric family cars. This includes:

a. The development of low-cost manufacturing techniques for motors and controls is necessary.

b. Development of lightweight components is required. Motors have small bearing tolerances for maintenance of magnetic air gaps that require rigid end bearing mounts. The weight saving from less material and lighter weight but more compliant material can possibly be made by using the rigidity of the mount structure to maintain bearing alignment.

c. The development of a standardized structure for the battery pack mount, despite differences in manufacturer and external appearance, would enhance usability of electric cars.

Recent evaluations of domestic transportation needs (Ref. 5-1) call for battery development with an energy density goal of 100 W-hr/lb, a power density goal of 100 W/lb, a life of 1,000 cycles, and a cost goal of $1/lb. Also called for are motor/control packages of less than 5 lb/kW and costing about $1/lb. From an initial expenditure of $10 million over a 3 to 5 year period, an overall program for electric vehicle development is estimated to cost $250 million, resulting in a preproduction prototype vehicle at the end of 15 to 20 years.

5.2 PROJECTIONS FOR ELECTRIC CARS

Excluding the special-purpose applications of golf carts, electric fork lifts, and delivery vans, no major production of electric passenger vehicles for a first-use car is expected for the next 10 years. Small production for use by electric utilities and an increasing number of individual conversions to electric propulsion will be the extent of passenger cars on city streets for this period.

Often, families will retain a larger car or station wagon for trips and entire family use, and use a second compact car for work or shopping use. The all-electric vehicle as a second commuter car is currently marginally acceptable at best. Even for this type vehicle, mass production is not expected within the next 5 years.

In addition, the electric car would have to be sold at a price comparable to the heat engine car for general acceptance. This would require subsidies or tax incentives, and mass production methods to reduce fabrication costs. Of importance also is an acceptable cost for battery replacement and the assurance of low electric power rates to control vehicle operating costs. A major gasoline shortage, a restriction on driving heat engine vehicles in some areas due to emissions, or a breakthrough in battery technology allowing much improved performance and range could cause increased acceptance of the electric car.

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PART II

HYBRID HEAT ENGINE/BATTERY AND HEAT ENGINE/FLYWHEEL VEHICLES

1. INTRODUCTION

1. INTRODUCTION

The problem of adequate operating range for electric vehicles has been discussed in Part I of this volume.

Lacking the availability of low-cost, high-capacity batteries to permit operating ranges for electric cars that are comparable to gasoline engine powered cars, other concepts have been examined in the search for a low-pollution vehicle that could satisfy personal transportation needs. One concept that has received the attention of automobile designers in the last 5 years is the hybrid vehicle - a vehicle combining various power delivery systems in the powertrain to use each form of power more effectively.

The hybrid powertrain concept for automobiles originated in 1917 when the Woods Dual Power automobile was manufactured in limited quantities. This spark ignition heat engine/battery hybrid vehicle had a peak speed of 20 mi/hr and was capable of operating in three distinct modes: all electric, engine only, or hybrid with both engine and batteries supplying power. Regenerative braking was also available.

A modern version of the hybrid vehicle was considered to offer potential improvements in air quality and also serve as an intermediate step between the gasoline engine powered car and the all-electric powered car. First, the hybrid vehicle range was considered to be no more limited than the gasoline engine powered car because the heat engine on board this vehicle, in conjunction with a full-size fuel tank, provided a reservoir of energy equivalent to that of the gasoline engine powered car. Second, only a small nearly constant power engine would be required to provide road cruising power, with acceleration power requirements provided by a battery in the case of an electric energy storage hybrid and by a flywheel in the case of an inertial energy storage hybrid. (Other forms of energy storage have also been considered.) It was expected that a fixed power engine could be optimized for reductions in both exhaust pollutants and fuel consumption.

To evaluate various hybrid concepts, the EPA under the AAPS Program assumed the task of planning a hybrid vehicle prototype development program. Implementation of a 3-year program began in 1970 with the participation of several companies offering the required technical expertise. Emphasis was placed on achieving original 1976 Federal emission standards without the use of engine add-on control devices (namely, catalytic converters).

The programs were formulated with three basic types of efforts for both electric and inertial hybrid systems: systems analysis, systems development, and component development. Over a 3-year period from 1970 to 1973, approximately $2 million was expended in contracts for analysis and test of hybrid systems and components. The work was administered by two government agencies, Department of Health, Education and Welfare (DHEW) and Environmental Protection Agency (EPA), each chartered at the time to perform investigations of this nature.[1] The program was terminated because of funding limitations imposed in FY 1971, and because it was found that operating a spark ignition engine in a hybrid mode still required the same type of exhaust aftertreatment needed on conventional systems. At the same time, the EPA was also forced to curtail and/or suspend active programs designed to evaluate some other alternative systems for powering automobiles. Since then, EPA has concentrated on the prototype development of systems offering a greater near-term (1975 to 1985) potential, namely gas turbine and Rankine cycle engines.

This report summarizes results from the contractor development programs, reviews the technical achievements in context with prior goals, and offers a prognosis for the future potential of hybrid powertrains for automobiles. In this regard, many of the study guidelines that resulted in specific powertrain design constraints have been under revision since the

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[1] The EPA was created by an act of Congress in April 1970. Responsibility for the DHEW program was assumed by EPA at the time of its inception.

period when the EPA studies were being conducted. Revised guidelines for vehicle range, acceleration performance, cruise speed, exhaust emissions, and fuel economy could result in modifications to system designs and to study conclusions.

The report is based largely on documentation that had been prepared by DHEW and EPA contractors and published at the conclusion of each separate study effort. Other hybrid vehicle studies not federally funded are also briefly reviewed.

A brief listing of the EPA contractors and their assigned work effort is given below.

a. Hybrid Heat Engine/Battery System Development

   1. TRW Systems, Inc. System analysis, system construction, and integrated system breadboard tests
   2. Minicar, Inc. - Powertrain fabrication, installation in automobile, and dynomometer tested
   3. The Aerospace Corporation - Systems analysis including component sizing, performance, and costs
   4. Petro-Electric Motors - Leasing of a prototype vehicle to the government for test and evaluation

b. Hybrid Heat Engine/Flywheel System Development

   1. Lockheed Missiles and Space Co. Systems analysis including component sizing and performance estimates
   2. Johns Hopkins University, Applied Physics Laboratory (APL) Systems analysis and performance estimates

c. Component Development

   1. Lockheed Missiles and Space Co. Flywheel analysis, design, construction, and test
   2. Johns Hopkins University (APL) Advanced concept flywheel analysis, design, construction, and test
   3. TRW Systems, Inc. and Gould Battery Company - Lead-acid battery redesign and test

4. Tyco, Inc. - Lead-acid battery advanced concept design and test

5. Bureau of Mines, U.S. Dept. of Interior - Laboratory tests for establishing performance map for V-8 spark ignition engine

6. Sundstrand Aviation - Transmission design evaluation and performance analysis

7. Mechanical Technology, Inc. - Transmission design evaluation and performance analysis.

2. GENERAL CONCEPT DESIGNS AND SYSTEM OPERATION

2. GENERAL CONCEPT DESIGNS AND SYSTEM OPERATION

2.1 BASIC CONCEPT

The basic integrated heat engine hybrid vehicle concept is designed to permit near steady-state engine operation while it is supplying vehicle cruise power; vehicle acceleration power is supplied from an energy storage device that is recharged by the engine. The term near steady-state refers to slowly varying engine power demands. In addition, the engine operating speed and/or power levels could be restricted to a narrow range or set at a fixed point, depending on vehicle performance requirements. By virtue of this scheme, hybrid vehicle proponents envisioned that the engine designer could be aided in conceiving a design optimized for minimum exhaust emissions (and possibly minimum fuel consumption as well) that would not require the use of add-on devices such as catalysts or thermal reactors. Furthermore, under acceleration power demands, engine hesitation, "stumble," or power lag is quite often associated with present day techniques for control of exhaust emissions, particularly during cold start. With acceleration power demand removed from the engine and transferred to an energy storage device, smooth engine operation (and thereby smooth vehicle operation) is expected. It is also conceivable that the heat engine size can be reduced with engine auxiliaries (pumps, fans, etc.,) need only be sized for steady-state operation; further size reduction could be possible if the required range in values for engine operating speed and/or power were to be limited.

Other heat engine hybrid concepts involve independent operation of the heat engine and the energy storage device whereby recharge of the energy storage device is performed by energy sources external to the vehicle; i.e., a recharging station or electrical outlet in the garage at each residence. This nonintegrated version of the hybrid vehicle has not been assessed, as has the integrated version, for application to personal passenger car needs of the nation. Hence, only the integrated version will be discussed in this report.

2.2 POWERTRAIN CONCEPTS

Hybrid vehicle powertrain concepts can be grouped into two broad classes as shown in simplified form in Figure 2-1. The first class, series configuration, is characterized by the principle that energy flowing from the heat engine to the rear wheels first passes through an intermediate energy conversion device or devices. This means of decoupling the engine from the rear wheels provides a large degree of flexibility in engine operating modes. Although there are several energy storage concepts for a hybrid vehicle, EPA contracted to evaluate just two--battery and flywheel. It is these two concepts that are included in the succeeding discussion. (As differentiated from the static battery, the flywheel stores energy and also transfers it kinetically. Hence, the system configurations will differ somewhat.)

In the case of a series configured heat engine/battery hybrid, the heat engine drives an electrical generator that transmits energy to the electric drive motor and thence to the wheels. A portion of the generator energy is directed to recharging the batteries as needed. For a series configured heat engine/flywheel hybrid, the heat engine drives the flywheel through a transmission and the flywheel drives the rear wheels through another transmission.

The second class, parallel configuration, is characterized by the principle that some of the energy flowing from the heat engine passes directly to the rear wheels with the balance of the energy directed in a parallel path through an energy conversion device or devices. This engine coupling to the rear wheels is far more limited in terms of engine flexibility than for the series configuration, but the transmission losses are less and the overall system efficiency is higher. Furthermore, the nonenergy storing components that are driven by the engine in the parallel configuration are required to supply acceleration power only whereas in the series configuration they are required to supply cruise plus acceleration power. Hence, the size and weight of components in the parallel configuration are reduced from that for the series configuration. This is particularly true for the electric drive

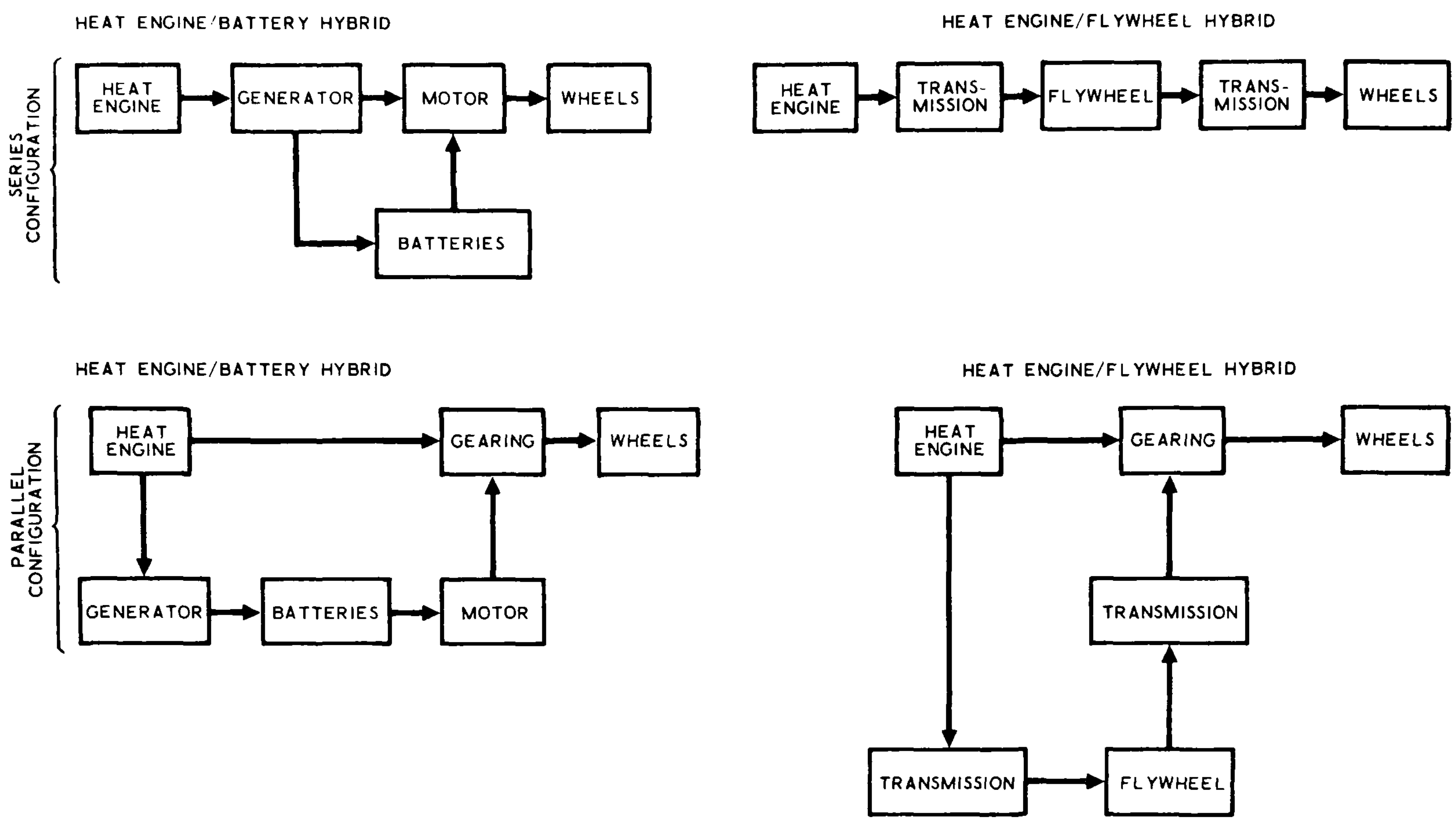

Figure 2-1. Simplified Schematics of Heat Engine Hybrid Vehicle Powertrain Concepts

motor which can operate at three to four times rated power for brief periods (acceleration periods).

In the case of a parallel configured heat engine/battery hybrid, the heat engine power in the parallel energy flow path drives a generator to recharge the batteries that are used to provide acceleration power to the electric motor that is differentially geared to the heat engine drive shaft. For a parallel configured heat engine/flywheel hybrid, the heat engine power in the parallel energy flow path drives the flywheel through a transmission; the flywheel then delivers power to the vehicle drive shaft through a transmission and differential gear system.

2.3 REGENERATIVE BRAKING

The regenerative braking mode of operation for hybrid vehicles (as well as for all-electric or all-flywheel vehicles) has the potential to be a significant contributor to powertrain efficiency. The advantage expected from this mode of operation is a reduction in fuel consumption compared to conventionally powered cars. Because of the energy storage device inherent in the hybrid powertrain concept, kinetic energy can be recovered and stored during vehicle deceleration and used for supplementing power needs during the next period of vehicle acceleration. Analytical studies have predicted that up to 30 to 40 percent of vehicle kinetic energy could be recovered by various regenerative braking schemes, but adequate experimental evidence is lacking. One study (Ref. 2-1) showed an average energy recovery of only 7 percent.

2.4 VEHICLE POWERTRAIN OPERATING MODES

Different operating modes have been considered for the hybrid vehicle powertrain. The majority of designs discussed in this part of the report are based on the single ("hybrid") mode concept, whereby a portion of the heat engine energy is used continually to replace energy drained from the on-board energy storage device (battery or flywheel). Other designs have resulted in a form of trimodal operating scheme whereby the vehicle can be driven alternatively in the (a) "hybrid" (engine on-board recharging) mode, (b) all-battery (or all-flywheel) mode, or (3) all-engine mode. A somewhat simpler version of this design is the bimodal operating scheme whereby the vehicle is driven only in an all-battery (or all-flywheel) mode or all-engine mode. The vehicle would normally be driven in the battery (or flywheel) mode with recharging provided by a source external to the vehicle; the engine in this case is used merely to extend vehicle operating range whenever required.

2.5 ENGINE OPERATING MODES

Several forms of heat engine operating modes can be conceived for the single "hybrid" mode of vehicle operation. These modes are discussed first for the series configuration and then for the parallel configuration. In either case, a design can be evolved to ensure either partial or full recharging of the on-board energy storage device.

2.5.1 Series Configuration

With the series configuration arrangement, a number of modes of operation are conceivable. Several of the more significant modes are shown in Figure 2-2 and discussed in the following paragraphs in terms of the mode of heat engine operation.

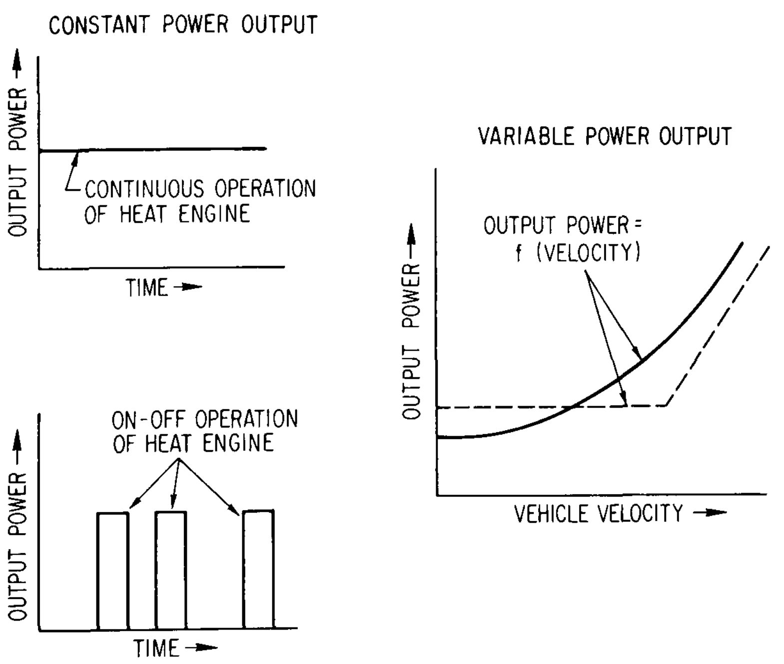

Figure 2-2. Various Heat Engine Operational Modes - Series Configuration

2.5.1.1 Constant Speed (rpm) and Power Output

2.5.1.1.1 Heat Engine Operated Continuously

In this mode of operation, a severe problem arises in relation to sizing the heat engine. If the heat engine is sized only to produce the total energy required in the time duration of a given driving cycle (including inefficiencies of the power plant system), then the heat engine may not provide the proper continuous high-speed power demand for highway operation. This results in discharge of the energy storage device at high speeds (if the heat engine size is too small). Conversely, if the heat engine is sized for the maximum continuous power demand for highway operation, excessive energy loss to a dissipation heat-sink occurs at lower power demands.

This mode of heat engine operation is of course attractive from the standpoint of heat engine exhaust emissions and/or fuel economy per se, in that it should be possible to select an operating point (i.e., rpm, air-fuel ratio, etc.) most amenable to reduced emissions and/or improved fuel economy. However, its apparent inflexibility with regard to heat engine sizing removes it from consideration as a viable series mode of operation for matching the performance of current automobiles. However, this mode may still be suitable for vehicles with reduced top speeds and/or revised specification requirements.

2.5.1.1.2 On-Off Operation of Heat Engine

As an alternative to continuous operation, it is possible to operate a constant power output heat engine in an on-off mode. Here, the heat engine would be sized to meet the continuous high-speed power demand for highway operation, and would operate intermittently during urban driving conditions. The heat engine could be turned on or off in response to vehicle power demands or state of charge of the energy storage device.

However, this mode of operation can result in very high energy losses during those periods when the drive motor power demand is low and a good portion of heat engine power output must be dissipated because the energy storage device simply cannot accept power at the rate being supplied.

2.5.1.2 Variable Power Output

2.5.1.2.1 Heat Engine Operated Continuously

Many of the deficiencies of the constant-power output mode of operation can be avoided by allowing the power output of the heat engine to vary. In this case, the heat engine can be sized for the maximum continuous power requirement and be allowed to operate at lower power levels for those periods of vehicle driving cycles that require less power. If heat engine speed is also allowed to vary to produce this variation in power output (as in conventional internal combustion engines), it is envisioned that the control system can effectively vary throttle setting response times so that engine speed and power changes take place at a controlled rate in such a manner that no true vehicle acceleration demands are imposed on the heat engine in the conventional sense.

The matching of all possible vehicle duty cycle energy requirements may not be possible. To overcome this difficulty, the heat engine power output might be scheduled as a function of vehicle velocity (heat engine produces more power as road load increases) with a throttle "bias" feature in the heat engine fuel control system to increase or decrease the baseline heat engine power output schedule (Figure 2-3) in accordance with an input signal related to the state-of-charge of the energy storage device.

2.5.1.2.2 "Step-Mode" Operation

Another technique for varying heat engine power output is to schedule power output in discrete steps. Figure 2-4 illustrates one such approach, wherein three power output levels are used. A low level could be scheduled for a low-velocity range (e.g., 0 to 30 mi/hr), an intermediate level for velocities between the low-velocity range and vehicle top speed, and a peak level for cruising at maximum continuous power conditions.

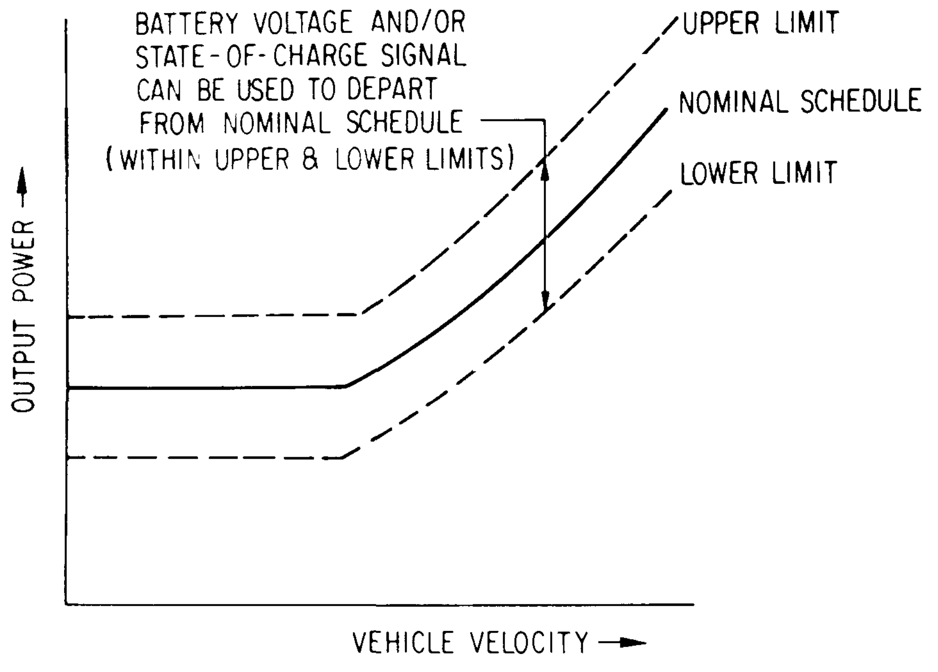

Figure 2-3. Heat Engine Variable Power Output Mode "Biased" Throttle Setting Feature

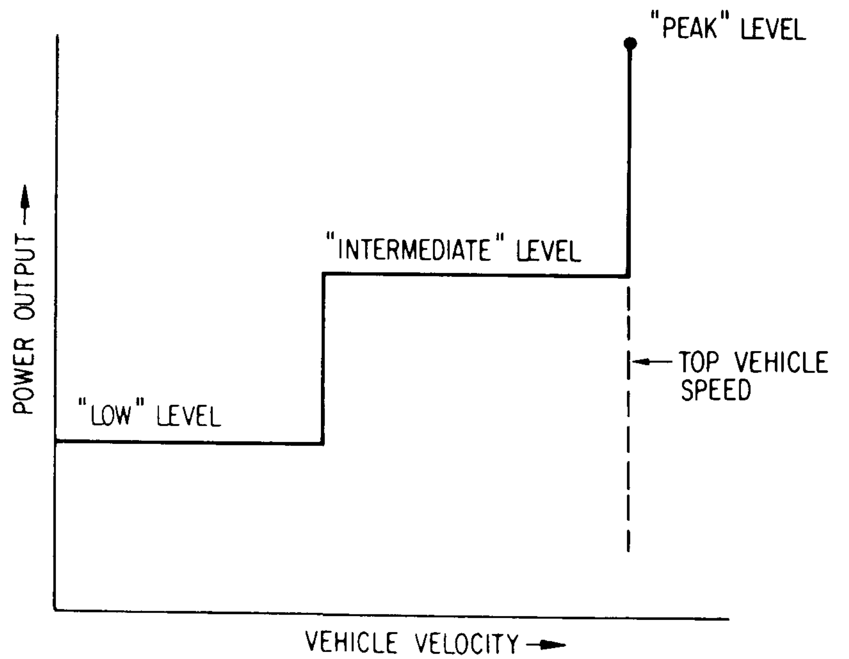

Figure 2-4. Heat Engine Variable Power Output Mode -- Step Mode

2.5.2 Parallel Configuration

The possible heat engine operating modes are much more limited for the parallel configuration than for the series configuration. This restriction is imposed by the direct mechanical link between the heat engine and the rear wheels. Therefore, the continuous, variable power output mode is the only simple form of engine operation that is considered to be feasible.

3. DESIGN IMPACT OF VEHICLE SPECIFICATIONS

3. DESIGN IMPACT OF VEHICLE SPECIFICATIONS

3.1 GENERAL REQUIREMENTS AND CONSIDERATIONS

Early in the Alternative Automotive Power Systems (AAPS) Program, vehicle specifications for each of a number of urban automotive applications were developed jointly by EPA and the several contractors involved in the hybrid system study effort. Lockheed Missiles and Space Co. (LMSC), for example, in their flywheel hybrid feasibility study report (Ref. 3-1), published a specification summary for the vehicles being considered, as shown in abbreviated form in Table 3-1. A similar set of specifications, based partly on an early study by Battelle Memorial Institute (Ref. 3-2), was published by The Aerospace Corporation in Reference 3-3. These early specifications were modified as new requirements were identified during the study efforts. The final form of the EPA specifications for the family car (six-passenger automobile) appeared as shown in Appendix A. It may be observed that the grade velocity requirement changed from 65 mi/hr, as shown in Table 3-1, to 70 mi/hr, as indicated in Appendix A. The impact of these and other specifications is discussed in subsections that follow.

Most of these modifications were minor. The basic vehicle performance requirements did not change significantly from the initial values, which were based on matching hybrid system performance to the acceleration, speed, and grade ability of conventional, contemporary vehicles. Likewise, the propulsion system sizing and operational requirements for the hybrid vehicle were designed to match similar features in conventional vehicles. The rationale for this approach was to enhance public acceptance of hybrid systems by providing operational, safety, and convenience features comparable to those of existing systems.

In addition to the above constraints, certain criteria pertaining to the state, level, and method of energy storage and transfer were adopted. In the battery hybrid system studied by The Aerospace Corporation (Ref. 3-3) for example, the batteries were required to be returned to the initial

Table 3-1. Vehicle Specifications

Item	Family Car	Commuter Car	Remarks
Stops/Mile	a	0.02 to 5[b]	Number of stops that vehicle makes per mile necessitated by traffic or commercial constraints
$\bar{V}$ operation, mi/hr	a	4 to 62[b]	Length of trip/route divided by time vehicle is on trip/route ≅ $\ell_{range}/\Delta t_{range}$
V_{max}, mi/hr	a	70	Maximum sustained cruise velocity
v grade @ grade, mi/hr @ %	65 @ 5	33 @ 12	Maximum sustained velocity on the specified grade
Grade length, mi	Continuous	4	--
$\bar{a}$ max, mi/hr/second	4.44 to 60 mph	5	Maximum acceleration achievable [proportional to V (0 to cruise)/Δt (to reach cruise)]
Δt stop, seconds	a	60 to 300[b]	Length of time vehicle is stopped (V - 0) while all accessories are operating. Stop necessitated by traffic or commercial considerations (such as loading/unloading passenger from bus) only.
ℓ_{range}, mi	200	1 to 50[b]	Length of a trip or duty cycle. Maximum value of one trip if it is given as a variable is the maximum length of a trip/duty cycle possible without supplementing vehicle energy system. Note: For the flywheel-only city bus, ℓ_{range} may be achieved by one duty cycle with "recharge" between duty cycles. The ratio of recharge time to duty cycle time shall not exceed 7 percent.
W_p, lb	--	--	Payload weight for commercial vehicles
Number of Seats	6	2	Occupant capacity (passengers and driver) for noncommercial vehicles
W_c, lb	4,300 max	1,400	Curb weight
W_ℓ, lb	5,300 max	1,700	Fully loaded total vehicle weight
W_s, lb	1,600 max	600	Weight assignable to all propulsion system components including energy storage, controls, etc.
Vol_s, ft^3	35	16	Maximum volume assignable to propulsion system components including energy storage controls, etc.
Δt power, seconds	45	60	Time from start-up to usable power output
A, ft^2	$A \times C_d$ - 13	18	Frontal cross-sectional area suitable for the calculation of aerodynamic drag
C_d		0.35	Drag coefficient
Jerk, mi/hr/second^2	a	5 max	--

[a]Not specified.

[b]The range (a to b) means a continuous variable bounded by a and b. Any calculations made should be dense enough over the range (a to b) to show the effect of the variable.

NOTES:

1. Any calculations of rolling resistance due to tires should be made on the basis of currently available tires and include the effect of tire width. Decreasing rolling resistance due to tires by assuming a type of tire that has unsafe traction characteristics by virtue of low rolling resistance is not allowed.

2. With respect to the city bus, the average acceleration ($\bar{a}$ max) must not be achieved by any instantaneous accelerations or rate of acceleration that would cause passenger discomfort.

3. Any resulting weight distribution that results in possible handling characteristics significantly different from the normal expected by drivers of the vehicles should be noted specifically.

4. Any decrease in gross vehicle weight achieved, for example in the lighter family car and the commuter car, must not compromise safety considerations.

5. Operation of the vehicle should not be compromised by ambient weather considerations. Ambient weather is defined as -25° to 110°F.

6. Noise aspects of the various components should be considered.

state-of-charge by the end of the vehicle driving cycle.[2] In the hybrid heat engine/flywheel studied by LMSC (Ref. 3-4), the flywheel energy level had to be controlled to maintain a constant total kinetic energy in the vehicle/flywheel system. Other constraints were adopted or imposed to reduce the variety of possible design options or applications to a manageable number. These and other constraints adopted during the hybrid vehicle program are discussed in further detail in Sections 4 and 5 which treat system and component requirements applicable to each of the design configurations investigated by the individual contractors.

In this section the specifications on vehicle emissions, vehicle performance, and power plant sizing exemplified by the EPA requirements in Appendix A are discussed with respect to their influence on the overall design of the hybrid vehicle powertrain.

3.2 ROAD PERFORMANCE REQUIREMENTS

The road performance specifications (start up, acceleration, and grade velocity performance) for the family car are given in Paragraph 8 of Appendix A. Although these specifications are in general agreement with the performance capabilities of conventional full-size passenger cars, an exception is the 85 mi/hr maximum cruise velocity specification--a lower speed than the maximum velocity achievable in most conventional family cars. However, this higher velocity may be regarded as being less of a cruise performance specification than the consequence of sizing the engine to meet high performance acceleration objectives. In the hybrid system, the acceleration requirements are met through power supplied by the electrical or inertial components of the drive system.

The determination of performance goals in terms of power required at the vehicle wheels is based on the velocity-time schedules for the maneuvers specified in Paragraph 8 of Appendix A. In general, these characteristics determine the vehicle propulsion system peak power requirements, fix the size of the heat-engine power plant, and influence the selection of appropriate power profiles the heat engine must deliver. Figure 3-1 (from

[2]The Federal Emissions Test Driving Cycle.

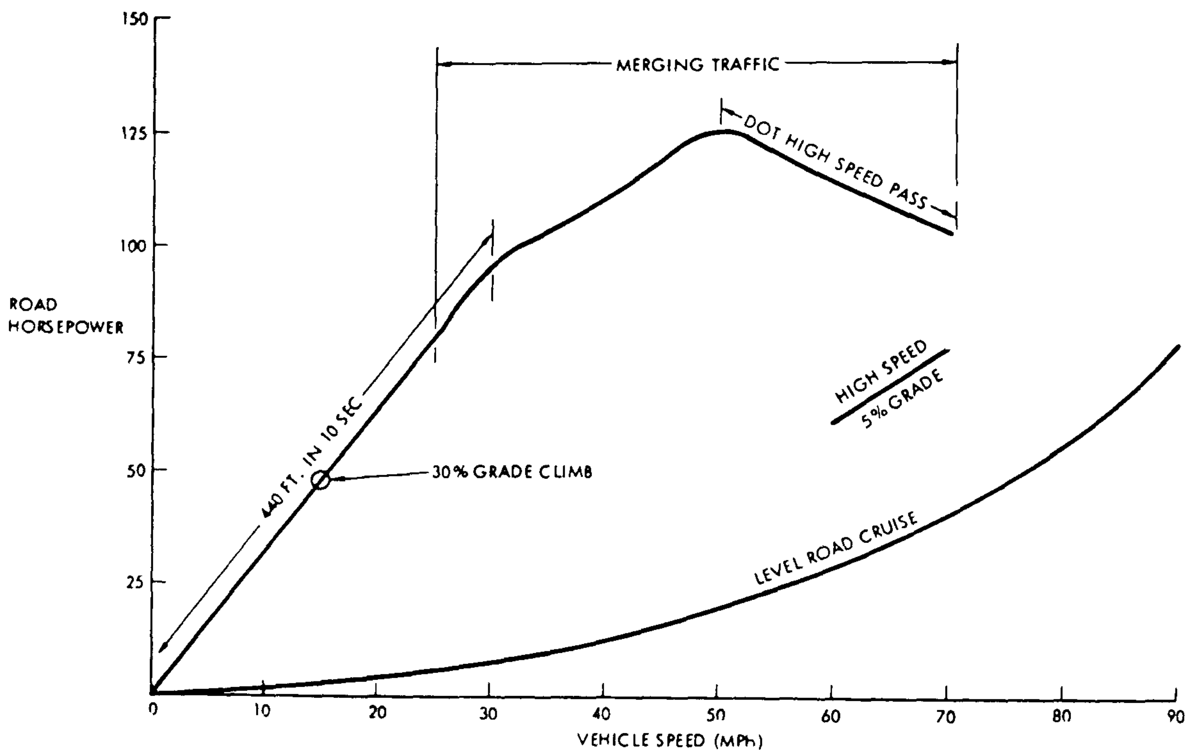

Figure 3-1. Wheel Power Demands for a 4,000-lb Car (Ref. 3-5)

Ref. 3-5) shows the typical road load power requirements for a 4,000-lb vehicle. The maximum power output demand results from the acceleration maneuver requirement; the gradability requirement is not a determining factor. To cruise at 85 mi/hr, approximately 65 road horsepower are needed and the powertrain must be capable of providing short-duration power bursts at the wheels in excess of 100 hp. When powertrain losses and the additional power required for passenger comfort and convenience features are considered, the heat engine must be capable of providing a maximum continuous power output of from 85 to 100 hp.

Increased vehicle weight increases the road power requirements over the values shown in Figure 3-1. A 5,500-lb vehicle, for example, increases the cruise power requirement at 85 mi/hr by 10 percent and increases the total system peak power requirement by about 35 percent.

In the hybrid concepts examined, the difference between the power required for vehicle propulsion and the power supplied by the heat engine must be furnished by the flywheel or the electric-motor components of the hybrid powertrains. Hence, with the selection of an appropriate heat engine power profile and with overall drivetrain gear ratios established, the characteristics shown in Figure 3-1 yield the requirements for the flywheel or electric motor peak torque and power outputs. Additionally, the selection of a representative vehicle-use duty cycle establishes the requirements for installed energy storage capacity, considering the need to operate the heat engine at low power output levels to minimize emissions.

3.3 WEIGHT AND VOLUME LIMITATIONS

Weight and volume specifications for the family car are covered in Paragraphs 1 through 6 of Appendix A. The weight specifications encompass requirements for the vehicle chassis, the propulsion system, and the vehicle gross weight. The volume requirement calls for standard engine packageability features and limits the allowable propulsion system volume to 35 ft^3. This specification impacts the design or selection of drivetrain components and immediately eliminates some heat engines as viable candidates for certain hybrid vehicle applications. Many engines require a significant portion of the allotted 35 ft^3, thereby imposing severe volume requirements on other components. Weight and volume trends for the various heat engine candidates as a function of horsepower may be seen in Section 4.3.4.

In general, the propulsion system weight limitations impose upper bounds on the ability of the system to furnish power and energy required to operate the vehicle for extended durations at the specified road performance levels (Figure 3-1). The criticality of these specifications depends in part upon the state of the component technology for the particular hybrid system being considered.

For the hybrid battery system, the propulsion system weight specification is critical in that it severely impacts the battery design requirements and limits the selection of available heat engine alternatives. The situation may arise as described in Ref. 3-3 as follows: once battery power and energy requirements are defined, the power density and energy density requirements can be established by the specified powertrain weight less the weight of all other powertrain components and subsystems. Component and subsystem weights will increase with increasing severity in specified requirements for acceleration and peak cruise speed. Hence, for a fixed powertrain weight allocation, a high-performance car will result in a reduction of weight available for batteries and, correspondingly, this will increase the severity of battery design requirements.

The design implications for the series hybrid battery family car are illustrated in Figure 3-2, showing the relationship between the powertrain weight allocation and the required battery power density and energy density for different heat engines. Certain power plants are not applicable to the family car under the propulsion system weight allocation defined by the specification, and only the spark ignition engine (reciprocating or rotary) and gas turbine engine result in realistically achievable values for battery

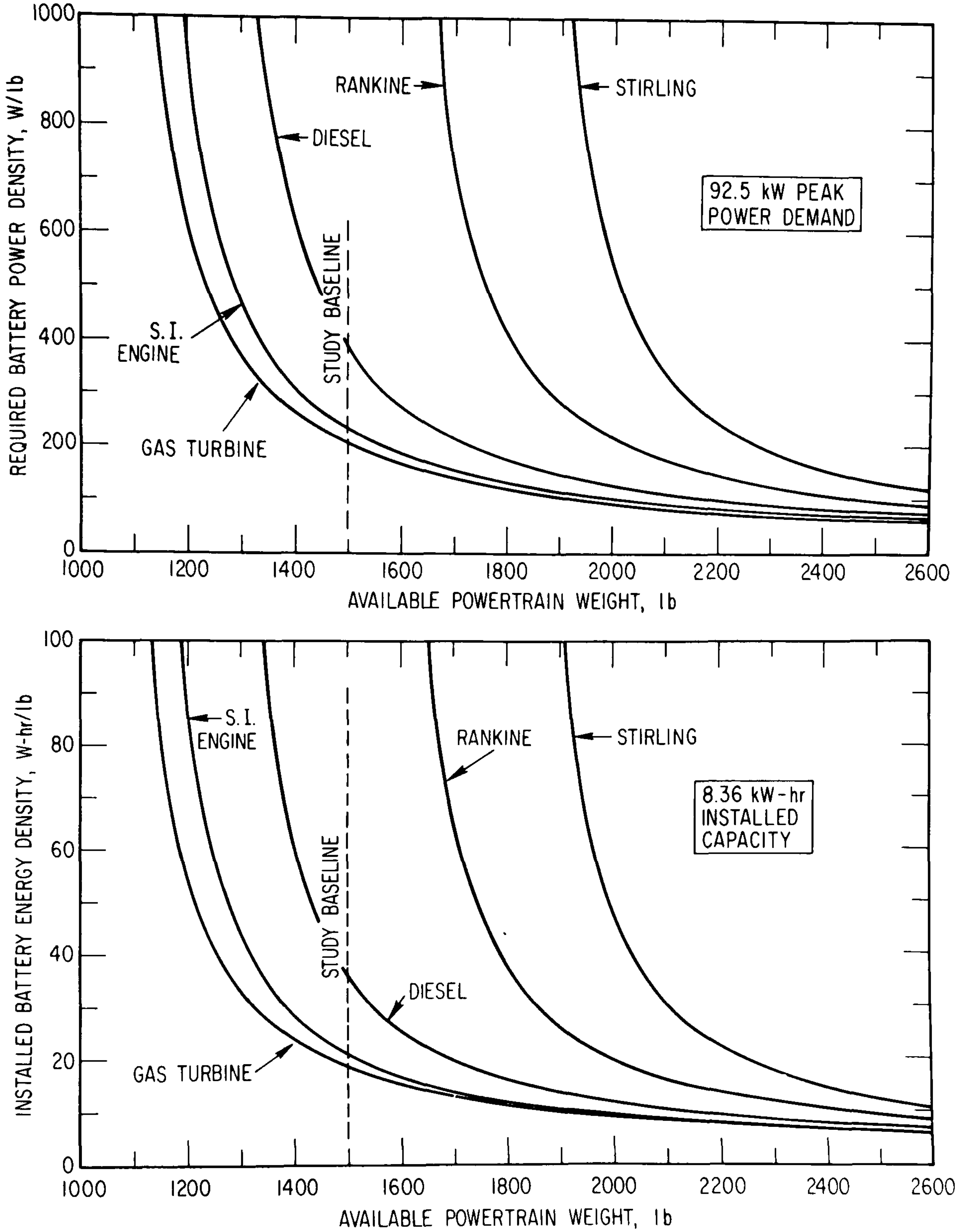

Figure 3-2. Effect of Powertrain Weight on Battery Requirements - Family Car Series Configurations (Ref. 3-3)

power and energy densities. It should be noted, however, that more recent development work could result in some modifications to these conclusions; e.g., Stirling engine weight and size has been reduced markedly from former levels. (See expanded discussion in Volume II, Alternative Automotive Engines.)

In contrast to the battery system, the hybrid heat engine/flywheel design provides higher energy densities resulting in system weights and volumes that are a smaller fraction of the allowable value for the total propulsion system. Thus, a broader range of heat engines may be considered feasible for use with this design.

3.4 FUEL ECONOMY AND EXHAUST EMISSIONS

Paragraph 10, Appendix A discusses fuel economy. Although no specific goals are identified, the best possible performance consistent with the objectives for exhaust emissions as delineated in Paragraph 7 is obviously desired. The fuel economy objective may impact the design of the hybrid system in a number of ways: the choice of series versus parallel drivetrain configurations; the selection of heat engine type, mode of operation, and power output profile; and the type of transmission. These and other alternatives also become design considerations in connection with the specifications covering vehicle exhaust emissions.

A number of different engine operating modes may be considered for the hybrid vehicle. For the series configuration, the choices are relatively broad as compared with the parallel configuration. The engine may be operated at fixed rpm and fixed power output, at fixed rpm and variable power output, and at variable rpm and variable power output, or at mixed conditions over the vehicle speed range. Engine operating mode selection will be influenced by considerations of fuel economy, emissions, and transmission and control system design complexity.

Fuel consumption characteristics differ among the various heat engine candidates, and part load performance in some systems such as the gas turbine is relatively poor. Fuel consumption in the spark ignition engine is highly variable and depends on the specific operating condition of the engine. This is shown by the performance map of Figure 3-3. Normal road load operating conditions for a conventional automobile and for the parallel hybrid vehicle with conventional transmission are represented by the cruise profile curve superimposed on the illustration. The fuel economy implications of the choice of engine operating mode may be recognized by noting that the specific fuel consumption (SFC) parameter will be minimized by operating at or near the lower envelope of the rpm curves. Therefore, efficient engine operation in the series hybrid vehicle may be achieved by removing the carburetor power enrichment device and setting the engine throttle wide open. In the parallel hybrid configuration, operation along the minimum SFC envelope would involve the use of a multiple step, wide gear-ratio or continuously variable transmission.

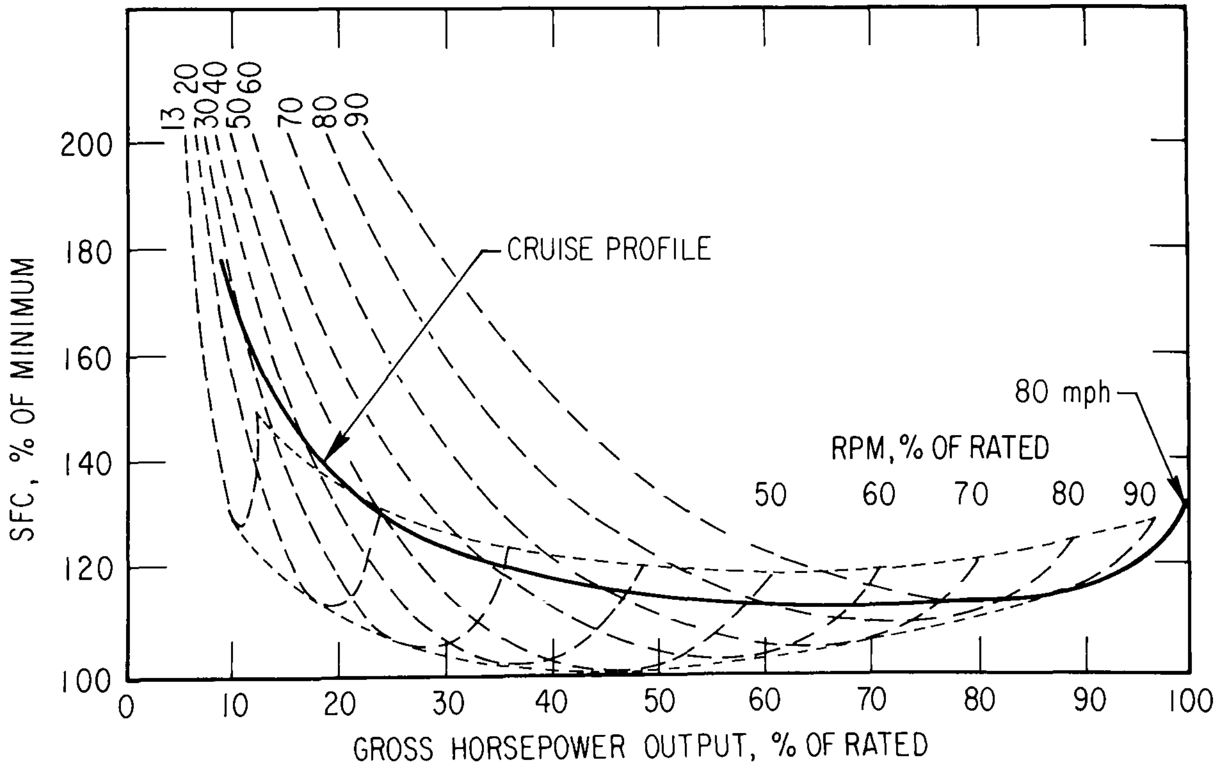

Figure 3-3. Spark Ignition Engine SFC Map, Normalized (Ref. 3-3)

As previously noted, many of the fuel economy design considerations--primarily engine selection and operating mode--apply also to exhaust emissions. Fixed, near-constant, or slowly variable quasi-steady-state engine operation offer the best potential for meeting the specified exhaust emission goals by eliminating design constraints associated with transient or widely varying engine operating conditions. Trends in the steady-state emissions at various loads for conventionally designed spark ignition engines are presented in Figure 3-4.

Many approaches to optimizing engine emissions are possible. For the spark ignition engine, these include variation of spark timing, combustion chamber design, air-fuel mixture preparation, water injection, and the use of external control devices. Air-fuel ratio is a significant emissions parameter in all of the heat engine candidates being considered. Ultralean conditions indicate the potential of achieving low NO_x levels while also controlling HC and CO to acceptable levels. Operational problems at lean conditions tend to be minimized in the hybrid operating mode. Nevertheless, ultralean design for the spark ignition engine may involve carburetor and intake manifold design modifications, the use of precombustion chambers or stratified charge devices, changes in transmission gear ratio range and step size to minimize drivability problems, and the use of mixed fuels to improve fuel flammability properties and to ensure proper air-fuel distribution from cylinder to cylinder.

3.5 IMPLICATIONS OF REVISED VEHICLE SPECIFICATIONS

Reduced levels of vehicle acceleration and highway cruise speeds can be expected to lead to reduced consumption of automotive fuel. Hence, with the current emphasis on conservation of domestic energy resources along with improvements in air quality, revisions to the original hybrid vehicle specifications could be expected to have some value in easing the rigorous design requirements imposed on elements of the vehicle powertrain. For example, a reduction in peak cruise speed from 80 to 55 mi/hr would require less than half the power formerly needed at the rear wheels. The

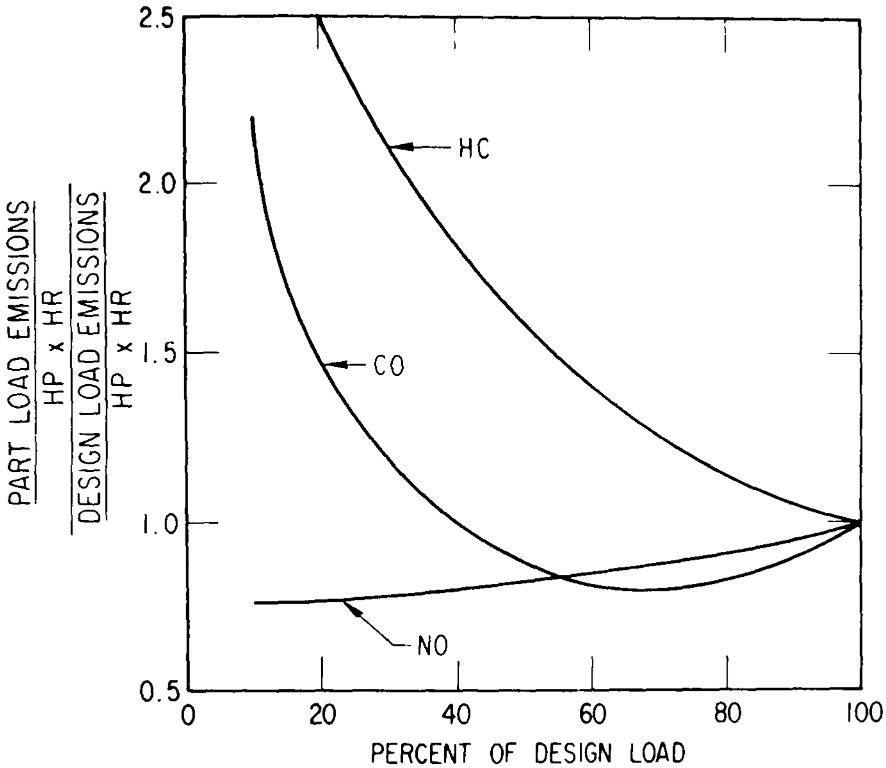

Figure 3-4. Emissions Effect of Spark Ignition Engine Load Variation (Ref. 3-3)

resultant decrease in the size of the heat engine (and in the size of the motor in the series configuration) would provide more space and weight for batteries with an expected significant decrease in battery power and energy density requirements.

Further reductions in engine size would be possible if vehicle range requirements were also relaxed. This would result in mobile recharging of the battery by the heat engine and stationary recharging of the battery from electrical outlets in residences and commercial buildings. If this concept were extended, a bimodal car might be envisioned that operated either on an all-electric or all-heat engine system depending on the power required and/or the type of road and traffic encountered. With lower vehicle speeds and acceptance of reduced performance, the bimodal car might be a more competitive passenger vehicle now than in the past.

Such revisions to vehicle specifications could have some impact on the conclusions reached by the various EPA contractors during the hybrid vehicle program. How significant this impact might be is unknown at this time.

4. HYBRID HEAT ENGINE/BATTERY VEHICLE

4. HYBRID HEAT ENGINE/BATTERY VEHICLE

4.1 SYSTEM DESIGNS AND OPERATION

Two major hybrid heat engine/battery system concepts funded by the EPA were: the TRW Systems, Inc. electromechanical transmission system and the Minicar, Inc. heat engine/battery vehicle. This included the building of a breadboard prototype system by TRW and a vehicle-mounted prototype system by Minicar. Under the EPA Federal Clean Car Incentive Program, Petro-Electric Motors has built a hybrid heat engine/battery system and installed the powertrain in a 1972 Buick Skylark. In addition, General Motors built their own prototype system called Stir-Lec. Other heat engine/battery system prototypes have also been built; these are not discussed in detail, but are listed for general information only.

An additional EPA-funded study was performed by The Aerospace Corporation to provide an analytical evaluation of hybrid heat engine/battery vehicles. This effort did not include building a breadboard or prototype device; however, brief tests were conducted on a separately excited direct current motor to ascertain the magnitude of speed and load variation that is possible with field control as a function of applied voltage.

Each of the EPA contractors studied the trade-off of system and component designs and costs and have presented somewhat different solutions. Since performance requirements and driving cycles were identical, the difference among various designs can be found in efficiency and cost factors that are influenced by varying design complexities.

4.1.1 TRW Systems, Inc.

TRW considered four system designs (Ref. 2-1) and elected to develop one of these: a parallel configuration, electromechanical transmission (EMT) system. The prototype EMT system (Figure 4-1) operates as follows:

a. The spark ignition, reciprocating heat engine (modified Volkswagen engine) drives the sun gear of a planetary gear train. The carrier gear transmits power to the speeder (generator) while the ring gear transmits power to the drive shaft.

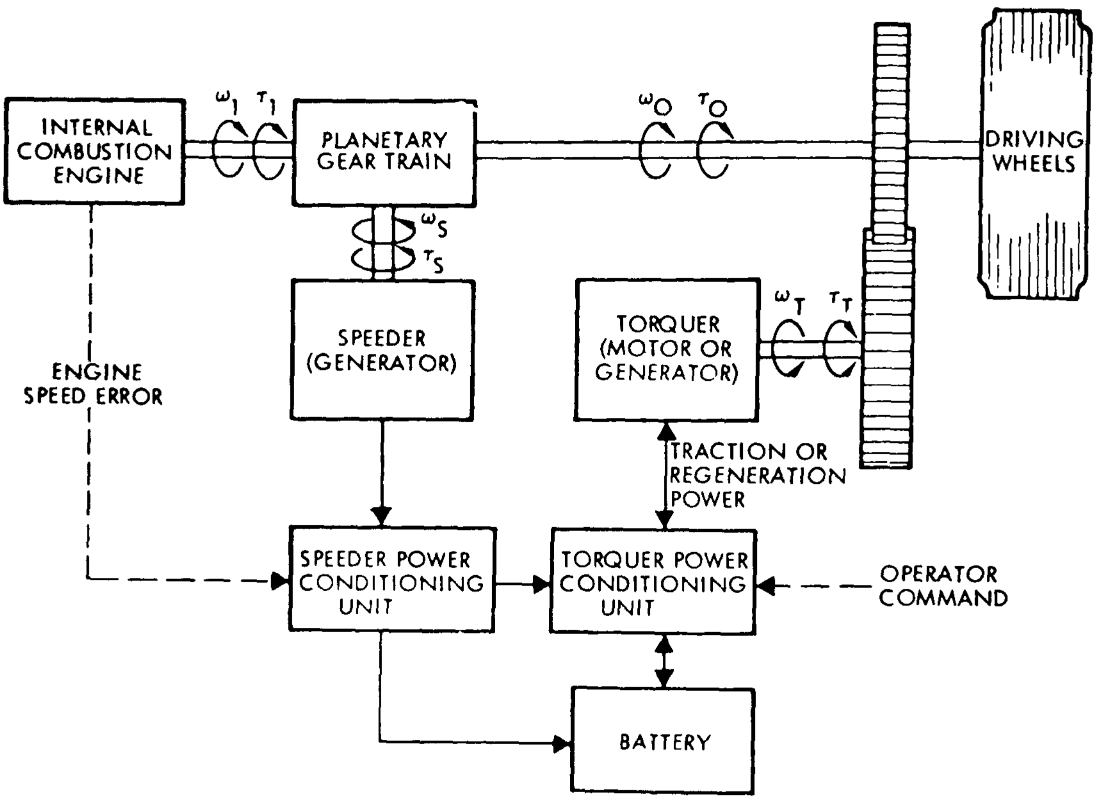

Figure 4-1. TRW Electromechanical Transmission Mode I Operation (Ref. 2-1)

b. Power is divided as a function of demand and speed required at the wheel. When the vehicle is at rest all the power goes to the speeder. As the vehicle gains velocity, the speeder decreases in speed at an inverse ratio to the wheel shaft speed.

c. During the increase in speed to 40 mi/hr, the generator continues to turn, but does not necessarily generate power. Since under some circumstances the demand at the wheel shaft exceeds the constant heat engine power rating, the torquer (a series wound direct current motor) is used to augment the power to the wheel shaft through direct gearing to this shaft.

d. When the demand at the wheel shaft is less than the power rating of the heat engine, the speeder provides wheel velocity adjustment and absorbs the excess power and converts it to electrical energy sending it through the power conditioning unit to the battery.

e. The power conditioning unit has two major functions: controlling the speeder velocity and power conversion rate and controlling the torquer to provide traction or regenerative power.

f. The torquer can either augment the power at the wheels by adding torque in the forward direction or it can reverse the torque direction and act as a generator converting the regenerative braking energy into electrical energy and charging the batteries.

g. A Mode II operation is used for velocities above 40 mi/hr whereby the speeder is locked out by a brake at its input shaft and the heat engine is coupled directly to the wheel shaft. The heat engine is therefore required to change its speed directly with the increase of vehicle velocity above 40 mi/hr. The direct current torquer may still augment or regenerate energies in Mode II.

4.1.2 Minicar, Inc.

The principal technique used by Minicar for reducing emissions was to prevent rapid changes in power output from a modified Chevrolet Corvair engine. This was accomplished by augmenting engine power with power from a separately excited motor during vehicle acceleration. The engine is run at a lean air-fuel ratio and a throttle spring and dashpot mechanism prevent rapid changes in power. Exhaust gas is used to heat the intake manifold to enhance air-fuel mixing. With a heated manifold the engine could operate at an air-fuel ratio of 18:1, but 16.5:1 was used in vehicle performance tests (Ref. 4-2).

A parallel configuration was selected. In this configuration the electric motor/generator was mounted about a common drive shaft from the engine. Total power was delivered to an automatic transmission and thence to the drive wheels. Intake manifold pressure was used to regulate the field current in a three-step control system. In addition, a relay was used for permitting combinations of parallel-series connection of the batteries to provide step voltage changes to the armature. A sketch of the drivetrain is given in Figure 4-2.

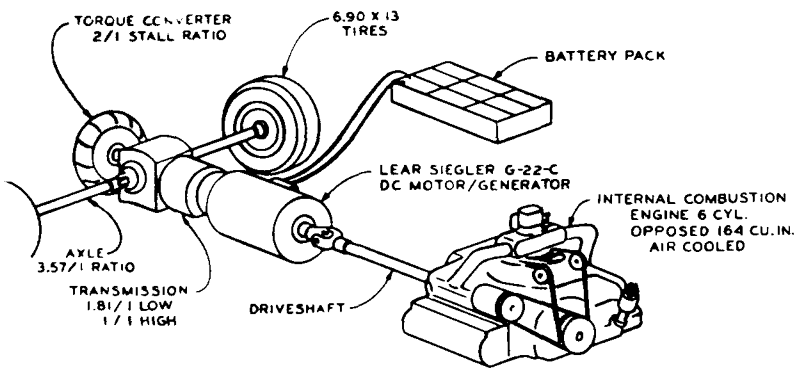

Figure 4-2. Minicar Drivetrain
(Ref. 4-2)

4.1.3 The Aerospace Corporation

The Aerospace Corporation study (Ref. 3-3) was aimed at determining the feasibility of using a hybrid heat engine/battery propulsion system as a means of reducing exhaust emissions from street operated vehicles. Several classes of vehicles and several design configurations were considered in the study, however, only automobile designs are discussed in this report. Following a review of associated technologies, requirements for electrical and mechanical components were determined. In summary, the design and system operation portion of the study included the following:

a. Energy Flow Paths--Both series and parallel configurations were analyzed for a lightweight commuter car and a full-size, six-passenger automobile. Operation of these vehicles was simulated over the Federal Emissions Test Driving Cycle. Engine/generator charging of the batteries was regulated to ensure a full battery charge at the end of the driving cycle. Heat engine power levels were adjusted to meet vehicle cruising requirements in addition to battery charging requirements.

b. Types of Components--The components investigated for use in the heat engine/battery hybrid were:

Motors:

alternating current induction

direct current externally excited

direct current series wound
direct current compound wound
torque motors
direct current brushless

Generators:

direct current
alternating current (alternators)

Power Conditioning and Control:

pulse-width modulation
frequency modulation
variable-frequency inverters
cycloconverters
integrated circuits
relays/switches
current limiters
circuit breakers and fuses
filters (inductor-capacitor)
storage battery system

Heat Engines:

spark ignition
diesel
gas turbine
Rankine
Stirling

Batteries[3]:

lead-acid
nickel-cadmium
nickel-zinc

c. Design Rationale--Significant vehicle design point conditions that affected power plant sizing and operational capability included vehicle top speed, gradability (in terms of percent grade, velocity on the grade, and grade length), vehicle weight, and aerodynamic drag area and drag coefficient.

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[3]Other batteries were considered, but were eliminated in a screening process based primarily on near-term development status and future performance potential.

The only limitations imposed upon the powertrain were the assigned powertrain weights and volumes. A final requirement was that the acceleration, grade, and speed capabilities of each vehicle with a hybrid power plant installed were to be equal to that of a contemporary automotive vehicle. The rationale for this requirement was that such performance would enhance public acceptance of the hybrid vehicle and would also avoid the prospect of poor traffic safety.

Designs for electric motor drive systems had the following goals for performance characteristics: (a) high starting torque, (b) sufficient accelerating torques over the specified speed range, (c) high overall operating efficiency, (d) simple inexpensive speed control, and (e) simple, inexpensive, and efficient regenerative braking. Designs for the battery system included considerations of power density (W/lb), energy density (W-hr/lb), and cost.

d. Performance Estimates--Vehicle performance estimates were summarized in the form of figures for battery power and energy density, vehicle exhaust emissions, vehicle fuel economy, and a listing of component weights for each system design. Computer calculations included analytical models of performance for each major component.

4.1.4 Petro-Electric Motors

Early in 1971, Petro-Electric Motors, New York City, entered into a contract agreement with EPA for development of a hybrid heat engine/battery vehicle under the Federal Clean Car Incentive Program. Under this program, the contractor initially assumes development cost and risk, and is permitted to maintain car ownership and design patent rights. Following delivery of a prototype vehicle for test and evaluation, EPA can contract for vehicle lease and eventually purchase a limited number of vehicles. A prototype Petro-Electric hybrid automobile was delivered to EPA in February 1974 and is currently undergoing test and evaluation.

The Petro-Electric hybrid powertrain has been installed in a 1972 Buick Skylark, 4-door sedan with a curb weight of approximately 4,150 lb. This parallel configuration consists of the following major components:

a. An RX-2, 70 in.^{3}, 130-hp Wankel rotary engine, Model 12A combined with a thermal reactor and exhaust gas recirculation for exhaust emissions control (273 lb)

b. Eight 12-V lead-acid batteries rated at 90 Ah (10 hr rate) with a maximum 600 A draw (300 lb)

c. A 20 hp (60 hp maximum) separately excited, shunt field, direct current motor/generator rated for 115 A, 120 V (240 lb)

d. A 1973 Chevrolet Vega manual transmission

The engine is mechanically coupled to the transmission and the motor/generator (same shaft). Electrical power flows back and forth between the motor/generator and the batteries, in one direction for battery recharge and in the other direction for augmenting engine power to the transmission. (Regenerative braking is also used for recharging the batteries.) The vehicle operator pedal position controls motor/generator field current for the battery recharging mode or power augmentation to the transmission. Engine power range is restricted to levels designed to result in low levels of fuel consumption and exhaust emissions. During periods of high power demand, further depression of the accelerator pedal frees the engine from its normal constant manifold vacuum operating mode and allows increased engine power output.

4.1.5 General Motors Corporation

In 1969, a Stirling-Electric Hybrid car (Stir-Lec I) was developed by General Motors without government funding. A phantom view and block diagram of the system are shown in Figures 4-3 and 4-4, respectively (Ref. 4-3). As Figure 4-4 shows, this is a series powertrain. The Stirling engine (see Section 4.3.4) drives a three-phase alternator, the output of which is rectified to charge the batteries. The controller includes a modulated inverter to provide variable frequency and voltage to the three-phase induction motor. The drive system is similar to the all-electric Electrovair II that was demonstrated in 1966. The induction motor is coupled to the differential pinion shaft through a planetary gear set with a speed reduction of 3.45 to 1 for an overall ratio of 13.4 to 1. Cooling water at 8 psig is used to limit the stator winding maximum temperature to 275°F; the rotor is air cooled.

The battery pack consisted of 14 automotive-grade lead-acid batteries connected in series. The cells carry a 44 Ah rating at the 20-hr discharge rate for a total energy capacity of 6.6 kW-hr. To increase battery life, the depth of discharge, however, is limited to about 75 percent of this capacity.

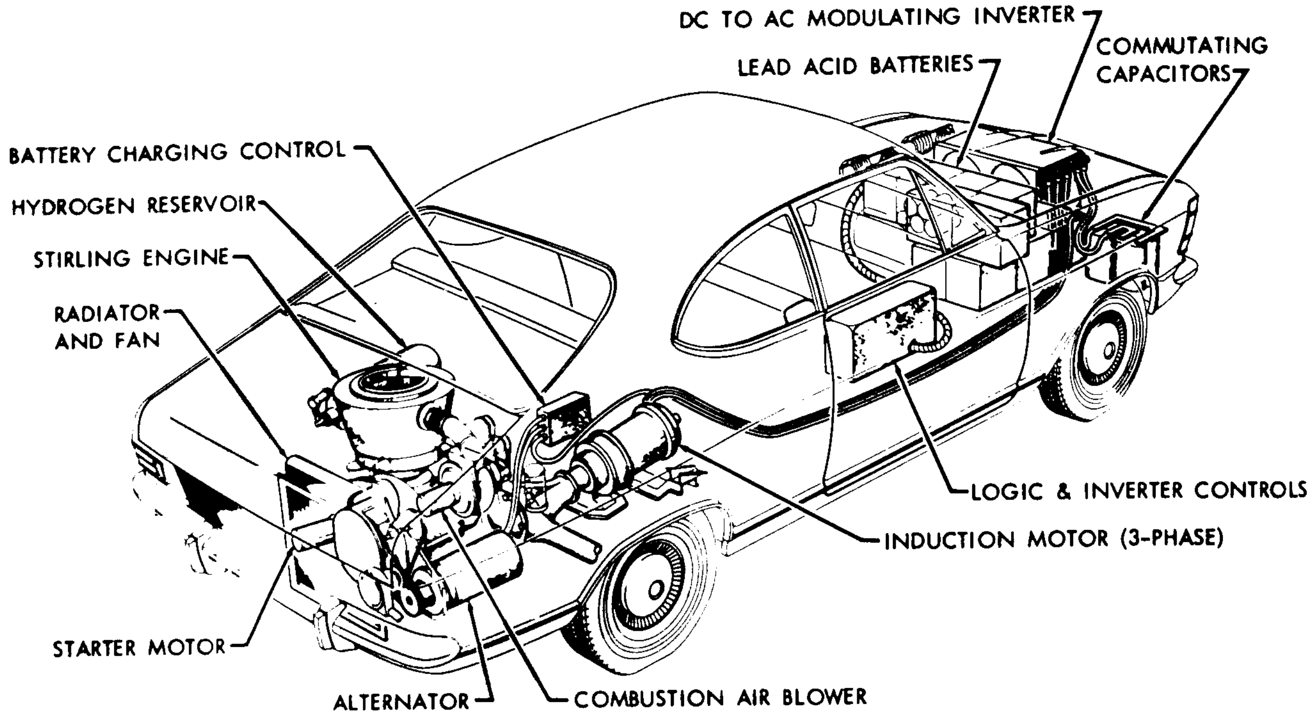


Figure 4-3. Phantom View of GM Stir-Lec I (Ref. 4-3)

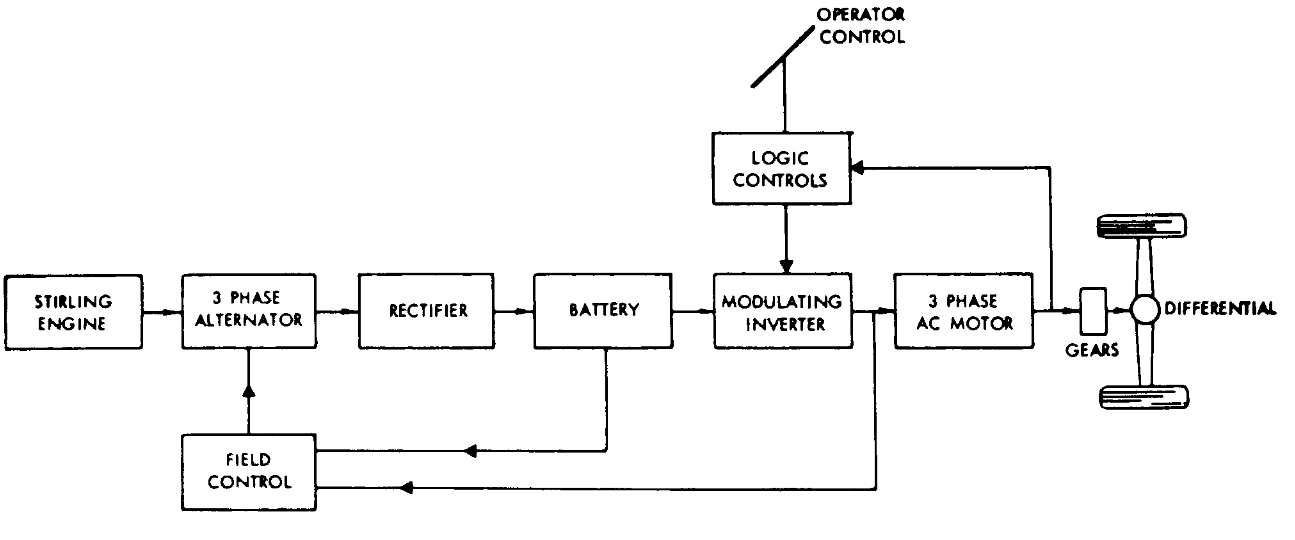


Figure 4-4. Block Diagram of GM Stir-Lec I Hybrid System (Ref. 4-3)

The modulating inverter provides variable voltage and frequency to the induction motor for smooth torque control at all speeds. It converts the nearly constant direct current battery voltage into three-phase alternating current power. It contains 18 SCRs and six power diodes; ram air is used for cooling.

4.1.6 Other Electric Hybrids

Following are brief descriptions of the salient features and characteristics of several other electric hybrid vehicles which have been examined by a number of organizations.

4.1.6.1 General Motors No. 512 Hybrid Gasoline-Electric (Figure 4-5) (C.1969)

Dimensions:	66 in. length, 56 in. height, 52 in. width
Curb weight:	1,250 lb
Gasoline engine:	12 in^3 displacement, engaged at 10 mph, drives through electromagnetic clutch at steady speeds, drives 90V alternator.
Electric:	Series motor delivers power to drive wheels up to vehicle speed of 10 mi/hr. Also used for acceleration power.

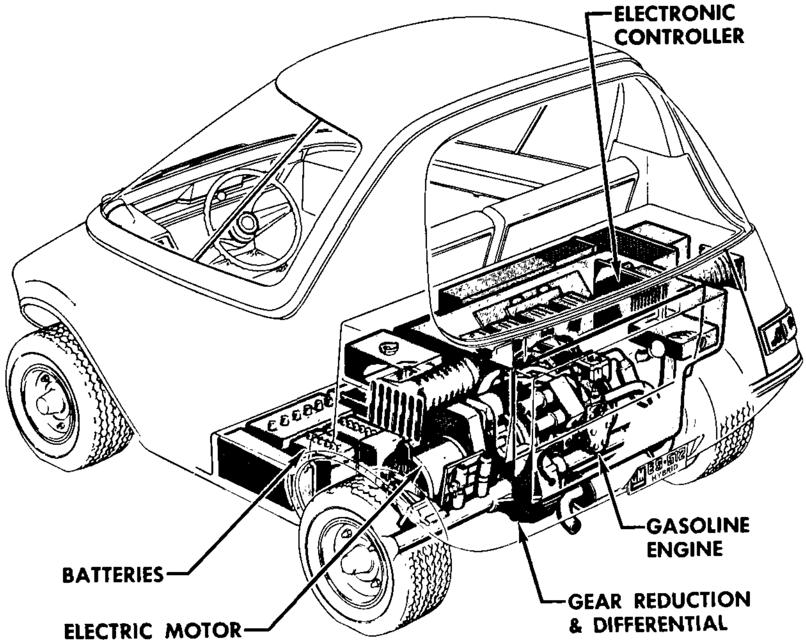


Figure 4-5. General Motors No. 512 Hybrid Gasoline-Electric

4.1.6.2 Toyo Kogyo Company, Limited, EX005 (Hybrid Car)--Prototype (Figure 4-6) (C.1970)

Characteristics:	This hybrid car is propelled by an electric motor that is powered by lead-acid batteries. In addition, it has a small rotary engine to generate electricity for battery recharging.
Total length:	93 in.
Total width:	58 in.
Total height:	63.5 in.
Curb weight:	1,000 lb
Load capacity:	Four persons
Maximum speed:	25 mi/hr
Generator:	3 kW
Battery:	Lead-acid battery (96V) 12V in eight sets
Motor:	1 kW in two sets
Engine type:	Rotary engine, one rotor, air-cooled engine of 200 cm^3

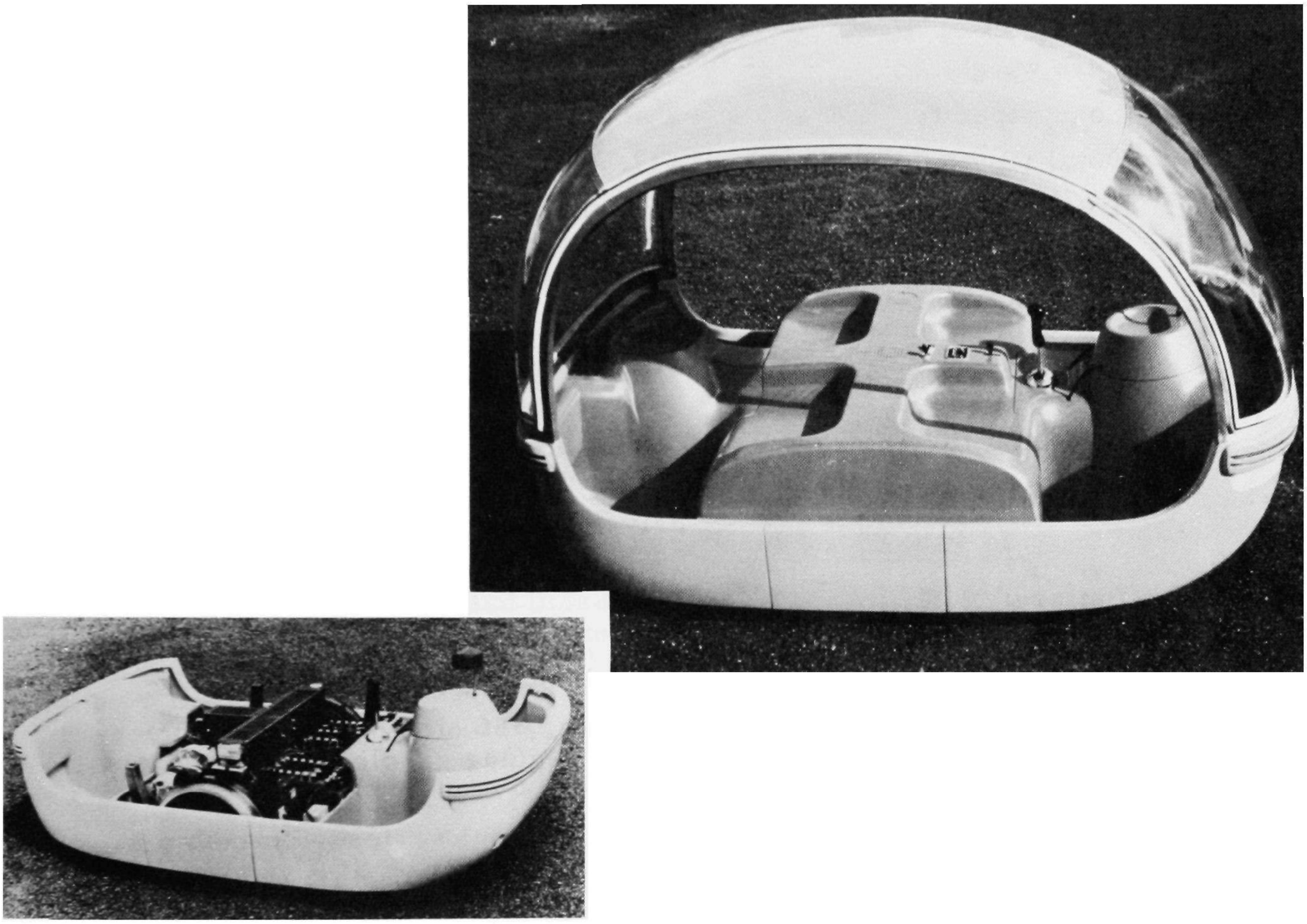


Figure 4-6. Toyo Kogyo Wankel/Electric Car

4.1.6.3 Daihatsu Kogyo Company, Limited Fellow Max Hybrid Commercial Car (Figure 4-7) (C. 1970)

Body type:	Modified L38V
Curb weight:	1,874 lb
Load capacity:	Two persons
Total length:	117.7 in.
Total width:	51.0 in.
Total height:	52.4 in.
Tread of the front:	44.1 in.
Tread of the rear:	43.3 in.
Wheelbase:	82.3 in.
Minimum turning radius:	165.4 in
Motor:	Direct current series, 5.3 kW, 55V dc, drives rear wheels during vehicle acceleration[4]
Battery:	Lead-acid battery, 100 Ah/5-hr in six sets, 72V
Control:	SCR chopper
Gasoline engine:	ZM type, 356 cm^3 of piston displacement, regular gasoline, drives front wheels
Generator for charge:	Direct current series, controlled at constant current by SCR chopper
Maximum speed:	Gasoline engine: more than 62 mi/hr (on highway) 37 to 50 mi/hr (in the suburbs); charge at will battery motor: 40 mi/hr

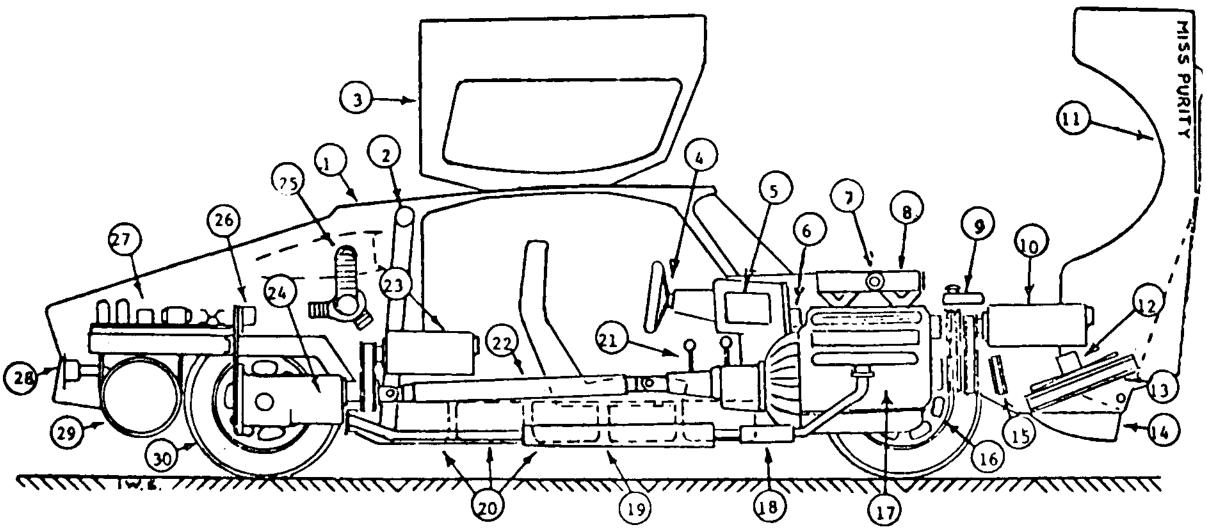
[4] During vehicle cruise or deceleration, rear wheels drive motor as a generator

Figure 4-7. Daihatsu Kogyo Fellow Max Hybrid Car

4.1.6.4 The University of Toronto, Canada, Faculty of Applied Science and Engineering (Figure 4-8)

The University of Toronto built this trimodal vehicle "Miss Purity" for entry into the 1971 Clean Air Car Race.

Body:	Polyester/fiberglass, flooring and firewall are aluminum.
Chassis:	Front end - 1970 Chevelle; remainder specially built, aluminum wheels.
Generator:	16 hp, 140V, 90 A alternating current with solid-state cyclic interrupt switch.
Battery:	Lead-acid 96 Ah, 12V in ten sets; one additional for lights and field current.
Motor:	16 hp, direct current shunt motor 100V, 120 A, base speed 3,700 rpm, external fan cooled, PWM controller, speed control and pedal switching are in the field circuit.
Engine:	Chevrolet 302 -CID V-8, 11:1 compression ratio, uses platinum catalytic muffler, propane fueled (has a liquid/gas expansion valve).
Transmission:	Two-speed gearbox and clutch with transaxle provides ten ratios to engine and five to the electric motor.



1. FIBREGLASS BODY
2. SAFETY ROLL BAR
3. GULL-WING DOOR
4. SAFETY STEERING WHEEL
5. ELECTRIC LOGIC CIRCUITS
6. EXPANSION VALVE
7. CARBURETOR
8. SECONDARY PLENUM
9. RADIATOR HEADER TANK
10. D.C. GENERATOR AND DRIVE
11. FOREBODY (RAISED)
12. ELECTRIC FANS
13. RADIATOR
14. AIR SCOOP
15. OIL COOLER
16. ALUMINUM WHEELS
17. V-8 ENGINE
18. CATALYTIC MUFFLER
19. MAIN MUFFLER
20. BATTERIES
21. STICK SHIFTS
22. ENGINE DRIVESHAFT
23. D.C. MOTOR AND DRIVE
24. CORVAIR TRANSAXLE
25. EQUIPMENT FANS
26. AMP-HOUR METER
27. CHOPPER CONTROL
28. PROPANE FILLER
29. PROPANE TANK
30. RADIAL PLY TIRES.

Figure 4-8. University of Toronto Car

4.2 SYSTEM DESIGN REQUIREMENTS AND ACHIEVEMENTS

4.2.1 TRW Systems, Inc.

4.2.1.1 Design Requirements

TRW performed computer simulation studies to evaluate the automotive propulsion systems described in Section 4.1.1 on the basis of total weight, volume, and efficiency over a driving cycle based upon urban traffic flow conditions.[5]

The system modeling used manufacturer's data for major components and included analysis of: generators, traction motors, power conditioning unit (PCU), gearing, and batteries. Power, current, voltage, speed, torque, and efficiency were computed over the driving cycle for a constant battery charge and without accessories. The results are given in Table 4-1.

Table 4-1. Electromechanical Transmission Electrical Systems Characteristics on the LA-4 Driving Cycle (Ref. 2-1)

Parameters	Predicted Values	
Overall Efficiency, percent	76.7	
Total Weight, W, lb	386.0	
Control Complexity	Dual Loop	
Components	Rated kW	Weight, lb
Speeder (forced cooled)	10.0	40
Torquer	22.4	160
PCU	22.4	95
Rectifier	10.0	Not Reported

[5]Designated as the LA-4 driving cycle; the basis for the current Federal Emissions Test Driving Cycle.

The EMT motor, unloaded during cruise, was rated on the basis of power augmentation required for vehicle acceleration over the LA-4 driving cycle. The EMT system performance capabilities were determined initially by analysis and then confirmed by dynamometer tests. Table 4-2 lists the ratings of the components established for a parallel configuration. Note that without a multiple gear ratio between the motor and wheels, some of the component ratings were exceeded. Use of a variable gear ratio lowers the peak motor torque required, improves efficiency, and relaxes the battery power density requirements.

The generator power rating is established by its cooling system. Three cooling systems were considered: internal fan self cooled, external forced air cooled, and oil spray with heat exchanger. The external forced air system was selected for variable speed operation in the parallel configuration. The rating of the EMT generator (based on the absorption of full engine power at rest) was conservative, although its speed varied over a 10 to 1 range as the vehicle speed varied from 0 to 42.5 mi/hr.

4.2.1.2 Performance Results

A dynamometer demonstration breadboard was built as "proof-of-principle" hardware. Poor correlation was found between computer predicted results and breadboard testing results. A reduction in overall power-train efficiency (road demand/engine output) from the predicted 76.7 percent to a nominal test value of 50 percent is the most encompassing departure. The test program allowed the major contributors to system losses to be identified. Gelb, et al stated (Ref. 4-1) that: "In most cases the losses can be reduced significantly by design refinement."

The EPA Specifications for velocity, acceleration, and length of run before refueling were met in driving cycle simulation calculations. Equivalent level road speed to 85 mi/hr could be achieved, but an actual velocity time trace taken from the LA-4 driving cycle was used in the analysis. The cycle has a peak velocity of 47 mi/hr.

Table 4-2. Rating and Required Performance of Electrical Components, LA-4 Driving Cycle, Parallel Configuration (Ref. 2-1)

Component	Rating	Requirements	
		Gear Ratio Fixed	Gear Ratio Variable
Traction Motor			
RMS Power, hp	30	17.2	17.2
RMS Current, A	145	235	144
Current Maximum, percent rated	300	N/R	300
RMS Torque, ft lb	22.5	55.3	27
Motor Power Control Unit			
Power, kW	22.5	8.9	8.9
Average Current, A	145	182	119
Peak Current, A	600	800	450
Generator			
Average Power, kW	N/R	N/R	N/R
RMS Power, kW	10	4.6	4.1
Average Current, A	50	34.7	31
Peak Current, A	100	100	98

N/R - Not Reported

Table 4-3 lists the measured efficiency of components for simulated operation during breadboard tests of a 3,000-lb vehicle on the LA-4 driving cycle. These results are compared with TRW claims for efficiences obtainable with redesigned elements in the system.

Table 4-3. Average Component Efficiency, LA-4 Driving Cycle (Ref. 2-1)

Component	Measured Efficiency, Percent	Estimated Redesign Efficiency, Percent
Gearbox	75	>85
Speeder	70	90
Speeder PCU	95	N/R
Torquer (drive)	67	>80
Torquer PCU (drive)	88	N/R
Torquer (regeneration)	52	N/R
Torquer PCU (regeneration)	90	N/R
Battery (at utilization)	64	N/R

N/R - Not Reported

Other improvements in system efficiency seemed possible. Accordingly, TRW conducted a parametric analysis to determine the effect of gear ratio, battery impedance, regeneration, and gear efficiency on overall system efficiency. The results are given in Table 4-4.

Table 4-4. Effects on Overall System Efficiency, LA-4 Driving Cycle (Ref. 3-5)

Configuration	Percent Increase or Decrease			
	Use of Variable Gear Ratio	Battery Impedance Changed from 86 to 172 ohms	Absence of Regeneration	Gear Efficiency Changed from 98 to 87%
Series	+15	-7	-10	-7
Parallel	+13	-1.5	-13	-9

As can be seen from Table 4-4, the use of a variable gear ratio would increase the overall efficiency due to a better match between road demand and available power at various vehicle speeds.

An increase in internal impedance of the battery decreased the system efficiency for both configurations, but the parallel configuration was affected far less than the series configuration.

If regenerative braking is omitted, the vehicle kinetic energy is lost during vehicle deceleration; this results in a decrease in overall efficiency.

The planetary differential gear coupled with other gears may achieve net gear efficiency values from 94 to 98 percent. With use of the present 75 percent efficiency planetary differential, the net gear efficiency falls from the 94 to 98 percent range down to the 87 to 90 percent range with the resultant overall efficiency penalty shown.

The results of exhaust emission measurements for several of the cold start tests are shown in Table 4-5. The data show the actual grams of HC, CO, and NO_x for the three-bag results and are summarized in the next-to-the-last column in the form of gm/mi. The final column presents some pertinent remarks about each test.

Table 4-5. Breadboard Hybrid System Emission Test Results, Federal Test Procedure (Ref. 3-5)

Test Date	Cold Start Bag, gm			Hot Start Bag, gm			Stabilized Bag, gm			Emissions, gm/mi[b]			Remarks[a]
	HC	CO	NO_x[a]	HC	CO	NO_x[a]	HC	CO	NO_x[a]	HC	CO	NO_x[a]	
12/22/71	1.63	55.3	0.52	0.24	1.08	0.16	0.77	14.7	0.12	0.21	5.22	0.06	poor hot start excessive enrichment
12/27/71	1.25	55.3	0.87	0.25	2.20	0.54	0.38	4.3	0.21	0.14	3.92	0.12	--
12/28/71	1.72	59.5	0.28	1.27	22.1	0.54	0.41	4.41	0.33	0.25	5.65	0.10	too slow choke relief
12/30/71	1.68	41.9	3.22	0.40	6.60	0.21	0.38	4.3	0.32	0.18	3.47	0.24	--
1/3/72	2.56	49.6	3.88	0.40	2.66	0.44	0.90	9.54	0.43	0.30	4.33	0.31	very poor hot start
1/4/72	17.5	45.2	0.66	0.21	2.43	2.66	0.95	6.95	0.50	1.15	3.69	0.31	no hydro-carbon accumulator
1/6/72	2.84	46.8	3.48	0.84	1.63	0.56	0.50	2.64	0.58	0.29	3.20	0.32	no detect-able NH_3
										0.41	3.4	3.1	1975 Fed. Standards
										0.41	3.4	0.40	1976 Fed. Standards

[a] NO_x as NO_2

[b] No fuel economy data available

The emission control system consisted of a hydrocarbon accumulator and a three-component catalyst. The accumulator was designed to store hydrocarbon emissions during cold-start and feed these pollutants to the catalyst after a predetermined level of engine and catalyst warm-up. The catalyst was designed to simultaneously control hydrocarbon, carbon monoxide, and nitric oxide emissions with precision settings for engine air-fuel ratio. A Chevrolet Vega engine modified for intake manifold fuel injection was used for the heat engine element in the powertrain system. The emission control system proved very effective in terms of hydrocarbon and oxides of nitrogen control. The combined use of the hydrocarbon accumulator and three-component catalyst resulted in hydrocarbon emissions ranging from 34 to 73 percent of the original 1975 Federal emission standards. When the hydrocarbon accumulator was bypassed, the total HC emissions were 2.8 times greater than the standards. The NO_x results ranged from 15 to 80 percent of the 1976 standards. The lower values were associated with earlier tests where the choke control during the cold start was more erratic and the engine exhaust NO_x did not come up as rapidly as it did in later tests. The most troublesome pollutant was CO. The CO standard was met with a 7 percent margin on one occasion; the standard was exceeded during all other tests. Examination of the bag data shows the cold start CO to be the major factor in the total CO emissions.

4.2.2 Minicar, Inc.

4.2.2.1 Design Requirements and Performance Results

The first configuration tested by Minicar did not provide sufficient electric power to significantly reduce emissions. The electric system was to have supplied 40 percent of the required power, but actually supplied no more than 10 percent. One reason for this was that at idle the generator voltage was less than battery voltage; therefore, the batteries were charged during this period.

A special motor/generator was ordered that could generate 48V during high idle speed (about 1000 rpm) provided the generator field was overexcited. With an automatic transmission, excessive creeping occurred when the engine idled at speeds above 600 rpm so a two-step voltage system was used. At low speeds, 24V was available by use of a parallel connection. At higher speeds, a step change to series-connected 48V was made with concurrent field control.

After many improvements, a final prototype configuration, the Hybrid C-1, was built. Its electric system provided up to 27 hp at the drive wheels which was short of the 40-hp goal (Ref. 4-4). The operating performance did not match that of many equivalent size standard vehicles.

The adjustable orifice dashpot for heat engine power lag functioned properly as a throttle delay, but optimum delay for both acceleration and deceleration engine transients was not found.

The field control as a function of manifold vacuum was not a closed feedback system; indeed, three steps were used. The torque and commanded speed of the shunt motor was, therefore, only grossly controlled and did not accurately augment power to keep heat engine power at a constant level.

The C-1 system was tested with the electric system providing up to 27 hp. Emissions were not reduced to acceptable levels (Ref. 4-4); the results of measured emissions over the Federal Emission Test Driving Cycle were HC-3.15 gm/mi, CO-29.6 gm/mi, and NO_x-1.0 gm/mi.

4.2.3 The Aerospace Corporation

4.2.3.1 Design Requirements

Selected examples of performance requirements for hybrid vehicles with a spark ignition heat engine are illustrated in Table 4-6 for a family car and a commuter car for the parallel system. The values shown are for both full-load and part-load operations. Physical and performance characteristics for the spark ignition powered parallel configuration electrical subsystems are shown in Table 4-7.

Table 4-6. Parallel Configuration, Subsystem Estimated Performance--Spark Ignition Engine (Ref. 3-3)

Sizing Criteria \ Vehicle	Family Car		Commuter Car
	Direct Current Chopper	Step Voltage & Field Control[a]	
Vehicle Specification Requirements			
Maximum Cruise Speed (V_{max}), mi/hr	80	80	70
Velocity on Grade, mph @ %	40 @ 12	40 @ 12	33 @ 12
Road Horsepower @ V_{max}, hp	58	58	20
Road Horsepower @ V_{grade}, hp	61	61	21
Selected Baseline Subsystem Efficiencies for Design-Point Sizing			
Final Drive (Differential), %	95	95	95
Automatic Transmission, %	90	90	90
Electric Drive Motor (Torquer), %	90	90	90
Control System, %	97	99.5	99.5
Generator, %	90	90	90
Accessory Power Requirements			
All Accessories, hp	12.6	12.6	5.7
No Air Conditioning, hp	6.7	6.7	1.7
Maximum Heat Engine Power Output Required, hp	84	84	31
Selected Baseline Subsystem Efficiencies for Part-Load Operation During Emission Driving Cycles			
Final Drive (Differential)	95	95	95
Automatic Transmission	90	90	90
Electric Drive Motor (Torquer)	80	80	80
Control System	97	99.5	99.5
Generator	80	80	80

[a]This column used for final analysis results

Table 4-7. Parallel Configuration, Characteristics of Selected Electrical Subsystems--Spark Ignition Engine (Ref. 3-3)

Subsystem \ Vehicle	Family Car		Commuter Car
	Direct Current Chopper	Step Voltage & Field Control	
Electric Drive Motor			
Type	Direct Current Series	Direct Current Shunt-Wound	Direct Current Shunt-Wound
Rated Voltage, V	220	220	220
Rated Horsepower, hp	38	38	12
Volume, ft^3	3.0	3.4	1.2
Weight, lb[a]	232	250	83
Efficiency @ Rated Load, %	90	92	92
Motor Controller			
Volume, ft^3	1.5	0.023	0.023
Weight, lb	100	12.5	9.5
Efficiency @ Rated Load, %	95	99+	99+
Generator			
Type	Alternating Current	Alternating Current	Alternating Current
Maximum Speed, rpm	12,000	12,000	12,000
Rated Output, kW	8.1	7.5	4.5
Volume, ft^3	0.08	0.07	0.06
Weight, lb	19	18	12
Efficiency @ Rated Load, %	90	90	90
Alternating Current Rectifier			
Volume, ft^3	0.1	0.1	0.05
Weight, lb	9	9	5
Efficiency @ Rated Load, %	99+	99+	99+
Generator Controller			
Volume, ft^3	0.009	0.009	0.009
Weight, lb	2	2	2
Cables, Low Level Electronics, Accessories, Cooling System, and Miscellaneous			
Weight, lb	55	50	38

[a]Without forced air cooling system.

A summary of subsystem weight and volume requirements for all heat engines considered is given in Table 4-8 for the family car parallel mode. This table also shows the value assigned as available for vehicle propulsion system weight and volume. After all powertrain weights and volumes were subtracted from the propulsion system weight and volume allowances, the balance was allocated to the battery subsystem. The parallel configuration provides a greater weight allocation for batteries.

4.2.3.2 Performance Results

Analytical results from computer calculations are as follows:

a. Battery power and energy density required for the commuter and family cars are given in Table 4-9. (The battery depth of discharge for each of the heat engines investigated in the study was 5 percent or less for the vehicle operating over the DHEW Driving Schedule[6] and batteries recharged by the end of the cycle.) The total powertrain weight was set at 1,500 lb by EPA. The peak power demand was determined to be 92.5 kW. Then after all other component weights were subtracted from the 1,500 lb, the weight allocation to the batteries requires that they deliver a power density of just over 200 W/lb for the spark ignition engine powered parallel hybrid. Based on the current draw limitations defined by conventional lead-acid battery polarization curves, to meet the required power drain during maximum vehicle acceleration, installed battery capacity was established at 8.36 kW-hr. The weight allocation requires an energy density of just over 20 W-hr/lb for the same case. A small, but significant, reduction in power density and energy density is possible for a gas turbine powered hybrid. The study indicated that only the spark ignition engine and the gas turbine engine offer reasonable weight margins for the battery system.

b. Fuel economy determined for the family car series configuration was 11 mpg and for the parallel configuration was 12.5 mpg. These estimates are based on a fully warmed-up vehicle driven over the DHEW Driving Schedule. The results are equivalent to the mileage expected for a conventional similar size 1970 car.

c. Figure 4-9 shows the successful reduction of emissions over the DHEW Driving Schedule with a parallel configuration hot start to levels below the original 1975/1976 Federal emission standards. The one exception is NO_2 from the spark ignition hybrid. The spark ignition engine used lean operation, an oxidation catalyst, and exhaust gas recirculation. A cold start correction factor of 1.2

[6] DHEW Driving Schedule (now Federal Emissions Test Driving Cycle)

Table 4-8. Preliminary Weight and Volume Summary of Powertrain--Family Car Parallel Mode (Ref. 3-3)

Powertrain Subsystems \ Heat-Engine Class	Spark Ignition		Diesel		Gas Turbine		Rankine		Stirling	
	Wt.[a]	Vol.[b]	Wt.	Vol.	Wt.	Vol.	Wt.	Vol.	Wt.	Vol.
Electrical Drive Motor	250.0	3.40								
Controller (Motor)	12.5	0.02								
Generator	18.0	0.07								
Alternating Current Rectifier	9.0	0.10	→							
Generator Controller	2.0	0.01								
Fuel Tank (Full)	154.0	3.08								
Rear Axle Drive	80.5	0.48								
Heat Engine	319.0	10.90	445.0	14.30	280.0	8.65	755.0	12.20	1025.0	21.00
Gearing (Heat Engine to Generator)	2.0	0.02	2.0	0.02	2.0	0.02	2.0	0.02	2.0	0.02
Radiator (Full)	27.1	0.36	27.1	0.36	0	0	0	0	0	0
Exhaust	27.1	0.44	27.1	0.44	27.1	0.44	27.1	0.44	27.1	0.44
Starter	10.0	0.08	10.0	0.08	10.0	0.08	0	0	0	0
Transmission	59.0	0.42	59.0	0.42	59.0	0.42	59.0	0.42	59.0	0.42
Drive Line	70.0	0.15	70.0	0.15	70.0	0.15	70.0	0.15	70.0	0.15
Subtotal	1040.2	19.53	1166.2	22.93	974.1	16.92	1439.1	20.39	1709.1	29.19
Assigned Value	1500.0	28.0	1500.0	28.0	1500.0	28.0	1500.0	28.0	1500.0	28.0
Available for Batteries	459.8	8.47	333.8	5.07	525.9	11.08	60.9	7.61	0	0

[a]Weight in lb
[b]Volume in ft^3

Table 4-9. Resultant Hybrid Vehicle Battery Requirements--Baseline Case (Ref. 3-3)

Vehicle Class/Mode / Area	Family Car		Commuter Car	
	Series	Parallel	Series	Parallel
Peak Power Demand, kW (From Design Driving Cycle)	92.5	92.5	28	28
Installed Energy Capacity, kW/hr (From Design and/or Federal Emissions Test Driving Cycle)	8.36	8.36	4.40	4.40
Weight Available for Batteries, lb				
- Spark Ignition	398	460	101	145
- Diesel	240	334	53	99
- Gas Turbine	453	526	170	211
- Rankine	0	61	0	32
- Stirling	0	0	0	0
Power Density Required, W/lb				
- Spark Ignition	232	201	279	193
- Diesel	385	277	527	284
- Gas Turbine	204	176	165	133
- Rankine	--	1520	--	875
- Stirling	--	--	--	--
Energy Density Required, W-hr/lb				
- Spark Ignition	20	18.1	43.8	30.3
- Diesel	35	25	83	44.5
- Gas Turbine	18.4	15.9	25.9	20.9
- Rankine	--	137	--	137
- Stirling	--	--	--	--

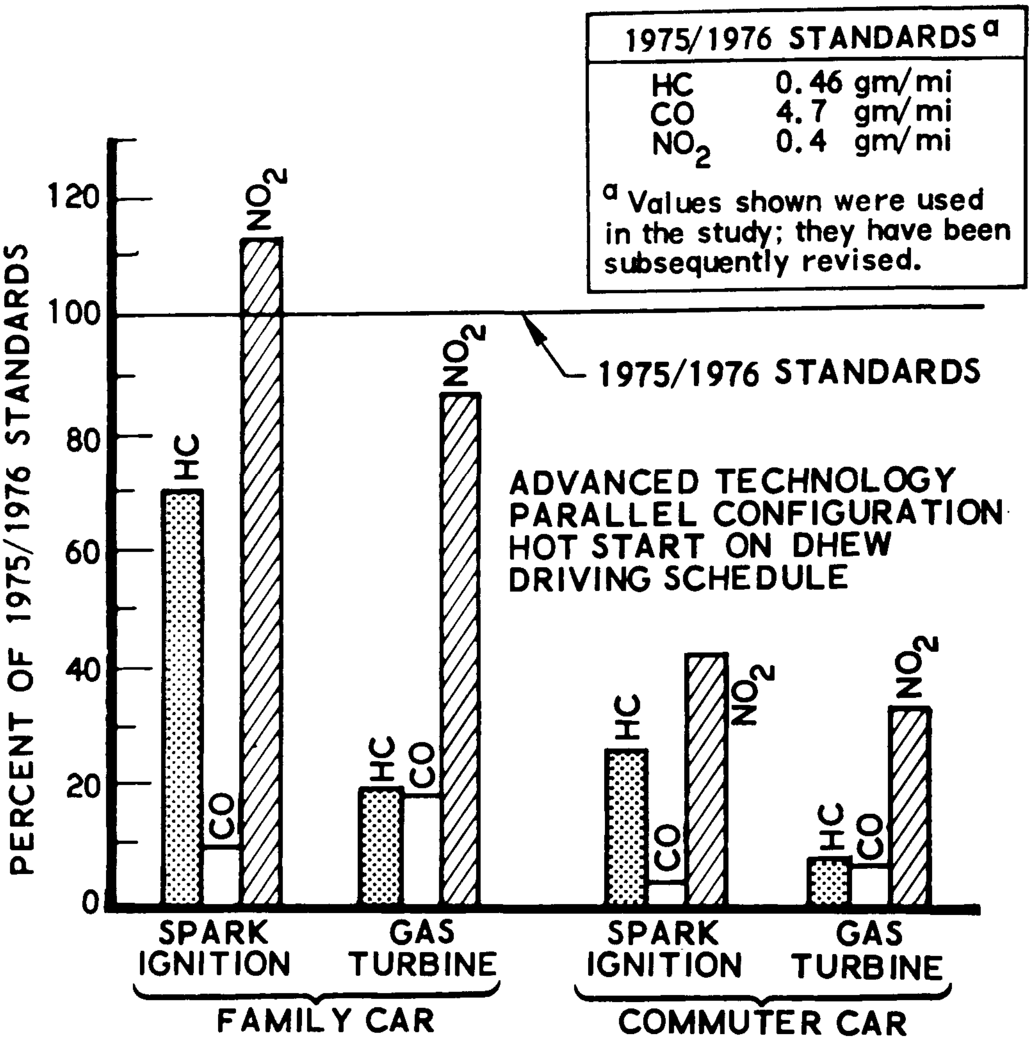


Figure 4-9. Comparative Calculated Emission Levels of the Family and Commuter Cars (Ref. 3-3)

for HC and CO should be applied to the hot start values. The NO_2 correction factor is 0.95, however.

Figure 4-10 compares the emission levels over the DHEW Driving Schedule (now Federal Emissions Test Driving Cycle) of the conventional vehicle (cold start) with hybrids (hot start) for different engine and exhaust control schemes: variable air-fuel ratio from rich to lean, air-fuel ratio maintained at 15 to 16 with exhaust gas recirculation, and air-fuel ratio maintainted at 22 with catalyst and exhaust gas recirculation.

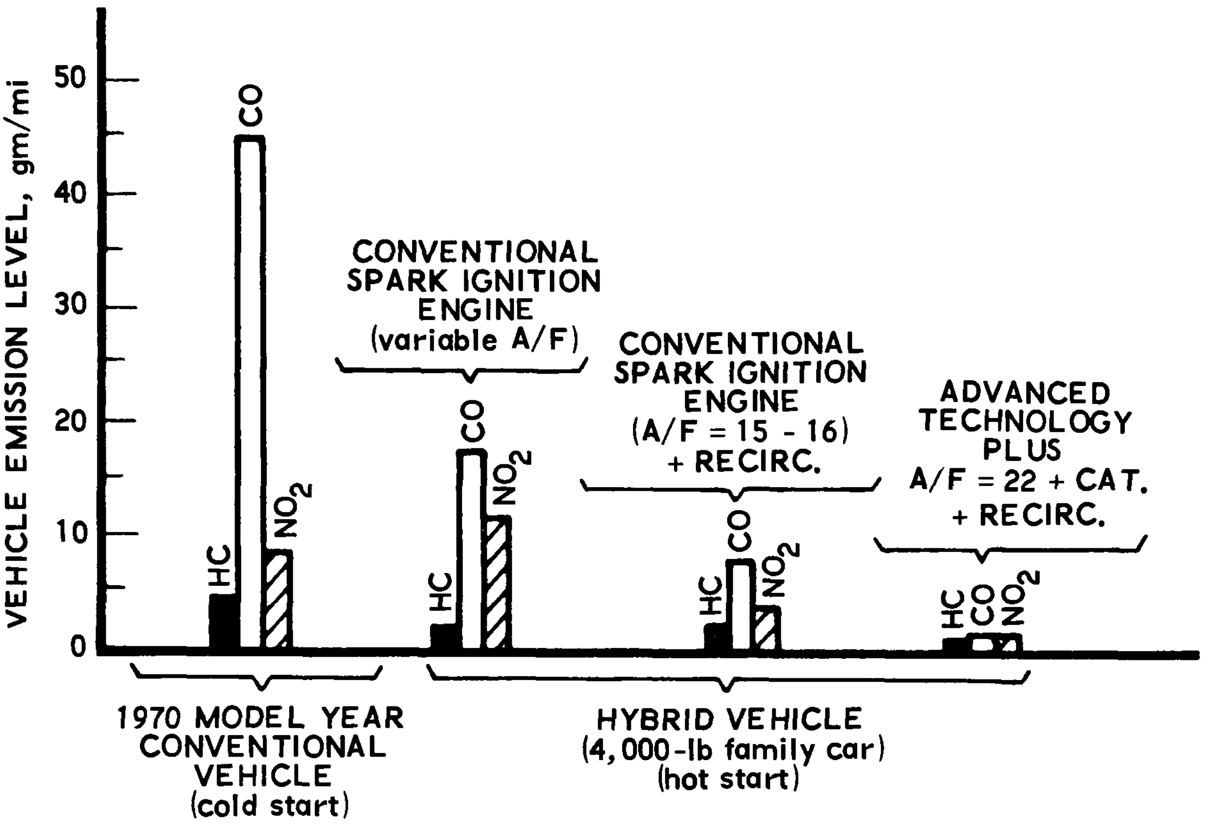


Figure 4-10. Calculated Vehicle Emission Comparison, Conventional Operation Versus Hybrid DHEW Driving Schedule (now Federal Emissions Test Driving Cycle) -- Spark Ignition Engine (Ref. 3-3)

The first case, with simply varying engine air-fuel ratio, did not show reductions in NO_x; about a 50 percent reduction in HC and CO occurred. Similar results were found in Reference 4-5.

The last case, advanced technology (with lean operation, oxidizing catalyst, and exhaust gas recirculation), is required to meet the original 1976 Federal emission standards.

d. A summary of engine costs and vehicle system costs is given for the family car in Table 4-10. The conclusion drawn was that the hybrid vehicle would require a significant increase in expenditures by the consumer for first costs. Design requirements and unique mass production techniques might reduce these figures somewhat.

Table 4-10. Summary of Engine Costs and Vehicle System Costs (Ref. 3-3)

Heat Engine	Approximate Relative Engine Cost	Approximate Relative Vehicle Cost
Conventional Car	Not Applicable	1
Hybrid Spark Ignition	1	1.4 to 1.6
Hybrid Diesel	1.5	1.5 to 1.7
Hybrid Gas Turbine	2	1.6
Hybrid Rankine	3.75	2
Hybrid Stirling	5	2.25

4.2.4 General Motors Corporation - Stir-Lec I

4.2.4.1 Design Requirements

A readily available 8-hp Stirling engine was used. It was originally designed for the Army as a portable power unit. The 450-lb Stirling engine uses a small amount of hydrogen as the working fluid at pressures up to 1,000 psi (full rated power). The engine idles at a working fluid pressure of about 260 psi. The drive system includes a motor of about 20 hp over a 3 to 1 speed ratio range. Motor speed at 55 mph is 12,500 rpm. The motor and gear box weighed only 85 lb. Though the three-phase alternator had a 25 hp nominal rating at a designed speed range of 5,000-500 rpm, in this application it produced a maximum power output of 6.75 hp. The battery pack and racks weigh 490 lb, the inverter weighs 82 lb, and the control electronics weighs 24 lb. The weight of the Stir-Lec I powertrain is 1,189 lb, which compares with 498 lb for the standard Opel Kadett powertrain. A total vehicle weight is, therefore, 3,200 lb compared to the standard weight of 1,990 lb for the Opel Kadett.

4.2.4.2 Performance Results

At about 30 mi/hr on a level road the vehicle achieves a fuel economy of 30 to 40 mi/gal. Battery capabilities limit the range to about 30 to 40 mi at 55 mi/hr. In the all-electric mode, the range varied from 15 to 30 mi depending upon the type of driving cycle. Acceleration from 0 to 30 mi/hr takes about 10 seconds. It achieves a top speed of 30 mi/hr with engine power only and a top speed of 55 mi/hr if battery power is added. In Figure 4-11 the vehicle emissions data are shown both with and without preheating of burner inlet air to 1,200°F. The HC and CO emissions are low, but the NO_x emissions are much higher than expected for this engine. General Motors stated that engine modifications could be expected to provide major reductions in the NO_x levels.

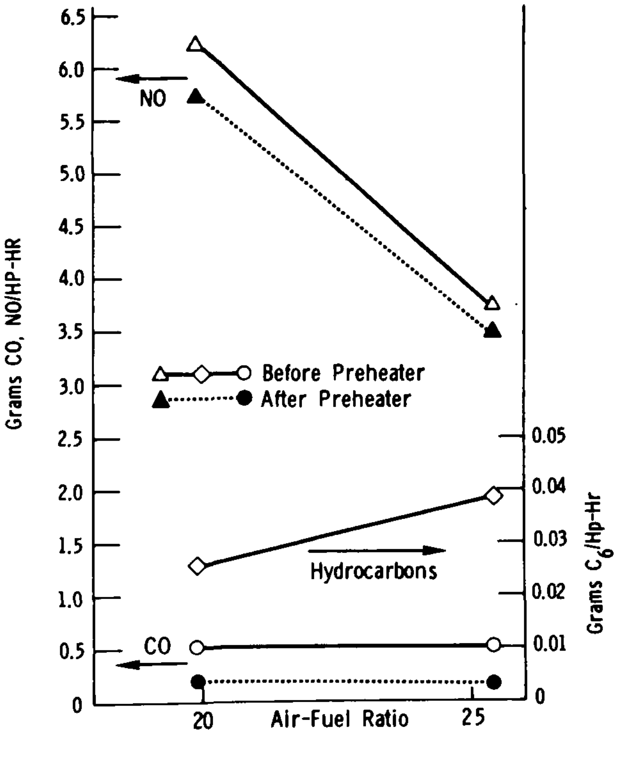


Figure 4-11. Stir-Lec I Engine Mass Emissions

4.3 COMPONENT DESIGN REQUIREMENTS AND ACHIEVEMENTS

4.3.1 Motors and Generators

There were no EPA contracts awarded for development of rotating electrical equipment. Therefore, this section discusses general design considerations and the state of the art of these components as related to hybrid vehicles. A more extensive discussion for the electric vehicle was given in Section 2 of Part I.

4.3.1.1 Design Considerations

The motor/generator performance requirements are considerably greater for the series configuration than for the parallel configuration. All the heat engine mechanical energy must be converted to electrical energy and then back to mechanical torque at the drive wheels in the series configuration. In various parallel arrangements mechanical energy is transferred directly to the drive wheels with the differences between the mechanical level transmitted and the demand level being absorbed or supplied through the motor/generator. This allows a lower continuous duty rating for the parallel system motor/generator with corresponding lower weight and lower electrical losses than for the series system.

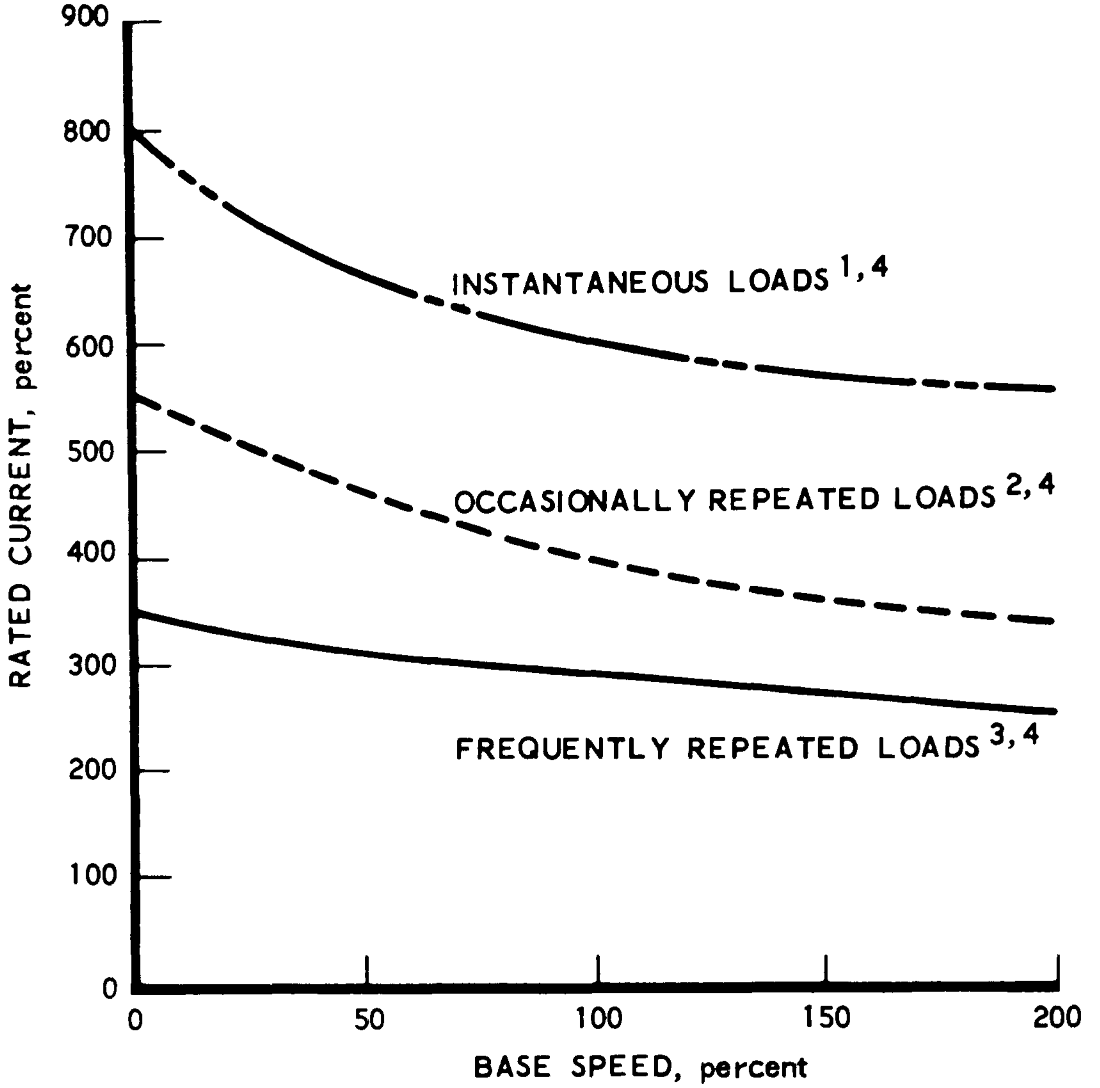
It can be seen, therefore, that the series hybrid configuration design can be quite similar to the all-electric vehicle design for battery, controller, and motor systems. The overall difference lies in the method of charging the batteries: the all-electric vehicle must use a charger that accepts electrical energy from a power transmission line and delivers the energy, at the proper voltage and current, to a battery system before energy is removed from the batteries. By contrast, the series hybrid converts mechanical energy from a heat engine to electrical energy with a generator that provides the proper voltage and current to both the battery system and the drive motors. The fact that all the energy is stored before use in the former case but during use in the latter case allows the series hybrid to function with less energy storage capacity.

4.3.1.2 Motor Rating and Overloads

Figure 4-12 shows the overload capability of compensated brush direct current motors suitable in size for hybrid or electric vehicle use. These overload limits are established both by commutation constraints (which become more severe at higher speeds) and by thermal conditions. Notice that the "Frequently Repeated" curve in Figure 4-12 allows one minute overload of 2-1/2 to 3-1/2 times design rated continuous duty load. This could provide adequate acceleration of an all-electric or hybrid electric car to highway speeds. Bursts of power for up to 5 seconds allow 3-1/3 to 5-1/2 times overload which is "Occasionally Repeated".

The overload capability is very important in the parallel hybrid configuration. At cruise velocity, all the power is mechanically transferred from the heat engine to the wheels. Since the motor is not supplying continuous power for cruise, it can be sized for supplying transient power, resulting in a small, lightweight unit. It was thus determined in Reference 3-3 for a 4,000-lb passenger car, that a 38-hp motor, rated for continuous duty would, at a factor of three overload, provide 114 hp for acceleration to maximum vehicle speed. It can also provide a starting torque for one minute of 3-1/2 times the rated current torque. Since the curves in Figure 4-12 assume continuous duty at 100 percent of rated load before the overloads occur, the temperature rise of the motor in the parallel hybrid configuration would be lower since the motor is not continuously loaded.

On the other hand, the series hybrid configuration requires that all continuous and overload power be provided by the electric motor. This motor must be sized for the more rigorous requirement of continuous cruise power and is much heavier than the parallel system motor. Reference 3-3 thus calls for the use of a continuous duty rating of 61 hp in a 4,000-lb passenger car for this configuration. This is the minimum input power required to provide vehicle cruise at 80 mi/hr.



1. Instantaneous loads are defined as 0.5 seconds duration or less, repeated not oftener than once every minute.
2. Occasionally repeated loads are defined as 5 seconds duration or less, repeated not oftener than once every 5 minutes.
3. Frequently repeated loads are defined as 1 minute duration or less, repeated not oftener than once in a period of 20 times the duration.
4. Curves are for assumed continuous duty at 100 percent of rated load prior to onset of overload. They apply regardless of whether speed is obtained by armature voltage or shut field control, and they also apply for regenerating operations.

Figure 4-12. Overload Capability Compensated Direct Current Motors (Ref. 4-6)

The size and rating of both hybrid motors were imposed by the specifications under the EPA design guidelines of 80 mi/hr cruise and equivalent acceleration and gradability of 1970 type family-size heat engine passenger cars. Relaxation of the specifications could have a marked effect on major components. If the cruise speed specification were reduced from 80 to 55 mi/hr for the family car, the series hybrid configuration motor continuous input rating could be reduced from 61 to 22 hp. This would result in a much smaller motor and more space for batteries. Note, however, that the gradability requirement would have to be reduced to correspond to the lower power rating. Since peak acceleration (requiring 114 hp) could only be obtained for five seconds in a five minute interval with the smaller motor, the acceleration specification would also have to be relaxed.

To summarize, the most rigorous duty demanded of a motor or generator establishes its size and in turn its weight, peak power, and maximum torque capabilities. Allowable temperature rise is the long-term constraint that must be met by sufficient sizing or adequate cooling system.

4.3.2 Control System

4.3.2.1 Comparison of Motor Controller

The motor control system for the series configuration hybrid electric vehicle is identical to that for the all-electric vehicle. However, a simple separate control of the generator field is required in the series configuration hybrid to modulate the power output from the heat engine for a fixed engine speed and convert it to electrical energy to be delivered to the motor. A more complex control logic will have to be inserted for a heat engine-generator system with variable engine speed that is designed for transmitting higher levels of power to the motor to enable the vehicle to operate at high speed on level roads or at sustained speeds on grades.

The motor controller for the parallel configuration hybrid system, by contrast, is more complex than the series hybrid because it requires special logic to control the electric motor that is augmenting power from the heat engine. That is, the road power demand less the mechanical power provided by the heat engine must be supplied by the electric motor. A sensor and logic system must, therefore, be capable of accepting foot throttle position information and heat engine power output information to provide the difference. Therefore, it is a heavier, costlier system by virtue of the increased logic, but it is lighter and cheaper on the basis of reduced power handling requirements.

4.3.2.2 Generator Control

A battery charge rate sensor and generator control is needed for both the series and parallel hybrid systems. (The all-electric vehicle has no generator and, hence, no generator controller.) In the series hybrid, power is being continuously converted from mechanical torque from the heat engine to electrical energy at the generator output. The logic for the series hybrid is simpler because it need only sense the battery back voltage and regulate generator field strength accordingly (as is done with current conventional 12-V alternator, regulator systems).

The parallel hybrid, however, must contain logic to control the field strength in the generator so that batteries are charged only when surplus power is available from the heat engine. That is, in the parallel system, batteries will never be charged at the same time that electrical energy is being delivered by the generator to the motor and this occurs only when heat engine power is less than road demand (typically in a vehicle acceleration mode).

4.3.2.3 Regeneration Mode

In the all-electric vehicle, braking force is supplied when kinetic energy is converted back to electrical energy through the motor/generator and directed to recharging the battery system. The braking drag is limited, therefore, by both the short-term over-current rating of the motor and the charge acceptance rate capability of the batteries. In both hybrid configurations, the heat engine-generator system may be charging the batteries at the same time braking drag is required. The simultaneous supply of electric energy from both the heat engine-generator and motor-generator during regenerative braking can exceed the charge acceptance rate of the battery system. In addition, the battery is kept near a full charge in the hybrid mode. Therefore, both the state of charge of the battery and its charge acceptance rate are two severe constraints to utilization of regenerative braking energy in the hybrid vehicle.

4.3.3 Batteries for Hybrid Vehicles

4.3.3.1 Battery Requirements

As part of the hybrid heat engine/electric vehicle program, two investigations were initiated to study the application of lead-acid batteries to hybrid vehicles. Contracts were awarded to Tyco Laboratories, Inc. (Ref. 4-7) and to TRW Systems, Inc. with Gould as subcontractor[7] (Ref. 4-8). These contracts were awarded to fill a need for data on lead-acid batteries when operated under the unique conditions imposed by the hybrid vehicle (i.e., the battery is charged by an engine-driven generator and is used only to supply pulse power needs during acceleration) as contrasted with the all-electric vehicle battery that supplies all vehicle power demands.

Before the start of the battery investigations, independent contracts had been awarded by EPA to The Aerospace Corporation and TRW Systems for studies of hybrid heat engine/battery system vehicles. The preliminary results of these investigations (Refs. 3-3 and 2-1) were used to establish battery operating requirements shown in Table 4-11 (Ref. 4-9).

[7] TRW Systems, Inc. tested batteries supplied by Gould.

Table 4-11. Hybrid Vehicle Battery Preliminary Requirements (Ref. 4-9)

Parameters	Specification		
Power	55 kW discharge for 25 seconds, twice within 60 seconds 30 kW recharge for 90 seconds after above two discharges		
Voltage, V	200 to 220 open circuit 150 minimum		
Life	5-years; 200,000 cycles		
Number of Cycles	Rate, kW		Discharge Energy Per Cycle W/hr
	Discharge	Charge	
500	55	30	380
3000	55	30	130
3000	55	30	80
Balance of 200,000	10	5	30
Weight, lb			
Maximum	550		
Goal	450		
Cost	$550		
Operation	Safe No undue care or maintenance		

4.3.3.2 Commercial Lead-Acid Batteries

Prior to the Tyco and TRW/Gould programs, there was a considerable amount of published information on the discharge and charge current rates and cycle life characteristics for starting-lighting-ignition (SLI) and golf cart type battery applications to electric vehicles. However, there was little information that could be used to predict performance of these batteries during hybrid vehicle operation.

In the initial effort, each contractor tested commercial SLI batteries to establish a reference performance case. Test battery characteristics, test conditions, and test results are presented in Table 4-12.

In the Tyco reference tests, the battery cells were to have been cycled at conditions representative of those in the preliminary hybrid specification--55 kW discharge and 30 kW charge; however, test equipment limitations reduced the rates slightly to 48 kW discharge and 26 kW charge.

A maximum of 350 of these high-rate cycles were sustained by the positive plates prior to failure. Positive plates averaged 72 percent capacity loss after 300 cycles. The capacity loss and positive plate failures were caused by plate expansion and consequent poor paste adhesion, particularly in the positive battery terminal region. An individual cell plate was used in tests against oversized counterelectrodes. The SLI test battery results showed that negative plates lost only 30 percent of their capacity after 500 cycles and also confirmed the positive plate problems that were revealed in the cell tests.

In the TRW Systems/Gould tests of conventional SLI batteries, a life of 221 high-rate cycles (55 kW, 25 seconds) plus 6638 low-rate cycles (10 kW, 10.8 seconds) was obtained.

It was demonstrated by these tests that a commercial SLI battery of conventional design was unsuited for hybrid vehicle use due to life limitations although it did have required power and rate performance when new.

Table 4-12. Performance Tests of Current Batteries

Parameters	Contractor: Tyco Laboratories, Incorporated	Contractor: TRW Systems/Gould	
Battery	96 Ah	61 Ah, 22 F Gould 22F-GP-G1	
Size, in.			
Length	Not specified	9-7/16	
Width	Not specified	6-7/8	
Height	Not specified	7-5/8	
Volume, $in.^3$	Not specified	480	
Weight, lb	55	35.9	
Specific Energy Density, W-hr/lb	20.9	18.7	
Energy Density, W-hr/$in.^3$	Not available	1.52	
Cell			
No. of positive plates (plate thickness, in.)	7 (0.060)	5 (0.073)	
No. of negative plates (plate thickness, in.)	8 (0.050)	6 (0.053)	
Plate Size, in.	5.2 by 6.1	Not specified	
Test Conditions (Scaled to full-size hybrid battery)		Cycle Type 1	Cycle Type 2
Discharge Rates	47.4 kW rate, 25 seconds	10 kW rate, 10.8 seconds	55 kW rate, 25 seconds
Charge Rates	25.9 kW rate, 61 to 67 seconds Complete discharge at C/5 rate every 100 cycles for capacity determination	5 kW rate, 22 seconds	30 kW rate, 50 seconds
Test Results Maximum Cycle Life	350 cycles 72 percent capacity loss after 300 cycles	6638 Type 1 + 221 Type 2 6859 cycles total (30 cycles of Type 1, one cycle of Type 2, and repeat) No capacity retention measurements	

4.3.3.3 Research Battery Designs for Hybrid Vehicles

4.3.3.3.1 Lead-Acid Batteries

4.3.3.3.1.1 Tyco Laboratories, Incorporated

Tyco Laboratories (Ref. 4-7) used a quasi-bipolar arrangement (Figure 4-13) in its lead-acid battery design for the hybrid vehicle. Vertical lead strips are placed on both sides of an insulating substrate, and these strips are then connected at the top, above the electrolyte level. The positive (lead oxide) paste is applied on one side, and the negative (lead) mass is applied on the other side. A number of these plate assemblies when stacked together (each separated by a thin polyethylene sheet) form a battery. Because the plate assemblies are relatively thin, a high voltage can be obtained in a short length. Capacity is obtained by adding parallel battery modules. Plastics are used extensively in the battery to reduce weight and prevent loss of strength due to corrosion during life.

Under the same test conditions as the commercial SLI battery, a quasi-bipolar battery lasted for 1,000 cycles, compared with the 350 cycles achieved by the commerical battery. Capacity loss after 300 and 1,000 cycles averaged 8 and 48 percent, respectively, compared to a 72 percent capacity loss for the SLI battery after 300 cycles. In contrast to the plate failure of the commerical battery, after 1,000 cycles the positive plate was in good condition, while the nagative plate did have some blistering and shedding.

4.3.3.3.1.2 TRW Systems, Inc./Gould

Based on the tests of the modern SLI battery, TRW Systems, Inc./Gould (Ref. 4-8) made selective changes to the SLI cell design and was able to increase power density to 150 W/lb for 75 seconds and 204 W/lb for 20 seconds. The higher power density was obtained by using a greater number of thinner plates per unit volume and by using higher conductivity lead alloy grids and conductors. Tests of the new design indicated cell lifetimes of 260 to 390 high-rate cycles plus 7,740 to 11,610 low-rate cycles. Under the same test conditions, the commercial SLI battery lasted 221 high-rate cycles plus 6,638 low-rate cycles.

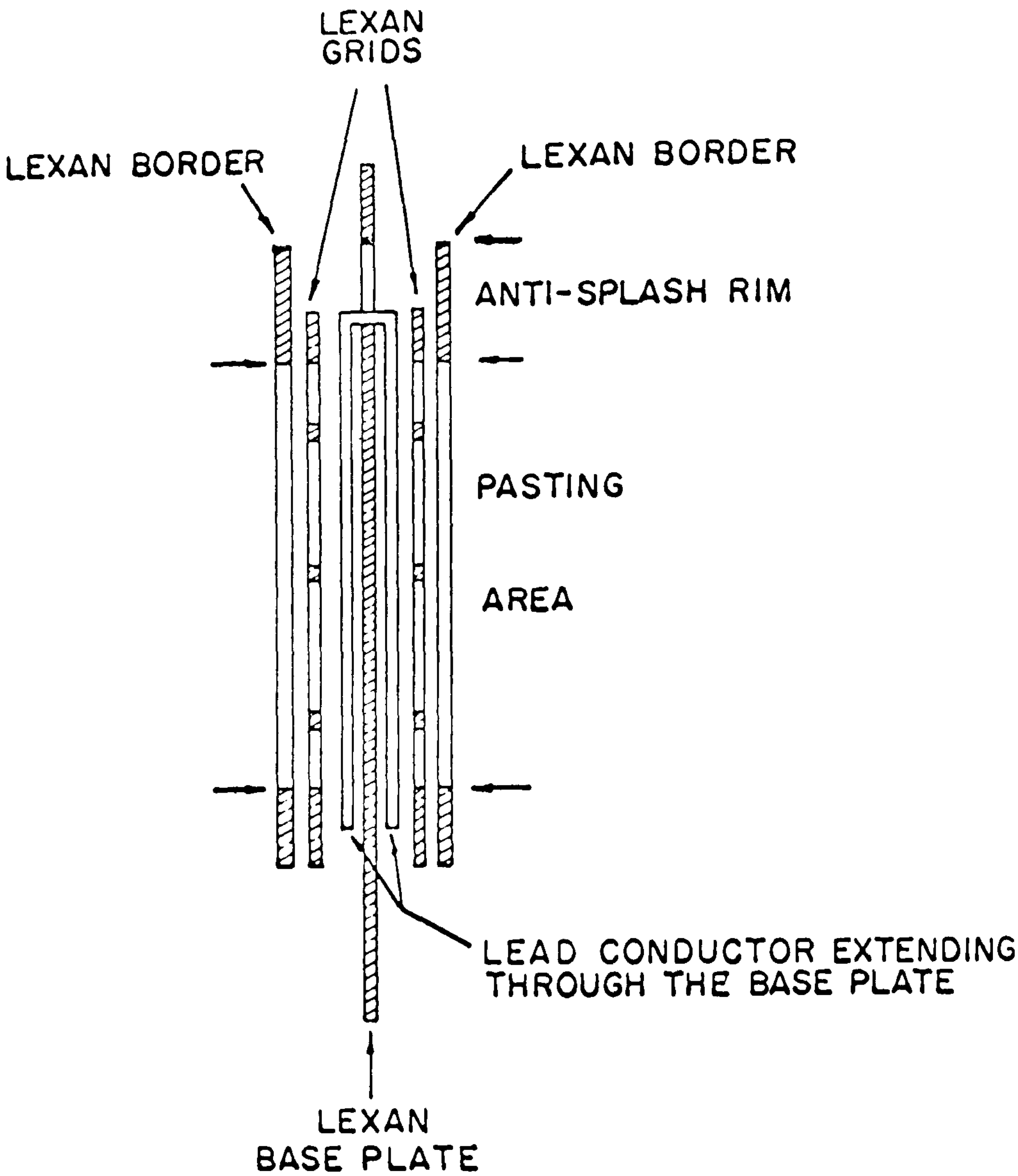


Figure 4-13. Section Through the Various Components of the Quasi-bipolar Plate Prior to Thermoforming (Ref. 4-7)

TRW/Gould also designed and built several bipolar cells for the hybrid vehicle. Cycle life of the best bipolar positive plate was 6,000 cycles that included 60 deep discharge cycles to 1.0 V. This was judged by TRW/Gould to be equivalent to what could be expected from a good conventional positive plate.

4.3.3.3.2 Other Batteries

4.3.3.3.2.1 Nickel-Zinc

In a study supported by EPA under an interagency agreement, the U.S. Army Electronics Command (Ref. 4-10) tested nickel-zinc battery cells for the hybrid vehicle. Cells for testing were received from Eagle-Picher, General Electric, Energy Research Corporation, and NASA Lewis Research Center. An individual cell rated at 24 Ah yielded up to 26,000 Ah total output, which is calculated in Ref. 4-10 as being equivalent to 3/8 of the cycle life called for in Ref. 3-3.

The principal failure mode observed with the nickel-zinc cells was degradation of the cellulose cell plate separator material. Inorganic separators (designed for another application) were supplied by NASA Lewis Research Center, but in the thicknesses available proved to be unsatisfactory for this application. The nickel electrodes were unaffected by the testing, while the zinc electrodes showed a low (10 to 20 percent) shape change.

Power densities up to 300 W/lb for five seconds were achieved. The nickel-zinc battery tests demonstrated that the nickel-zinc battery could be designed to provide adequate specific energy density (W-hr/lb) and power density (W/lb) for the hybrid vehicle application, but that considerably more development would be needed to obtain satisfactory life.

4.3.3.3.2.2 Nickel-Hydrogen

Metal-gas batteries, particularly nickel-hydrogen, could find application in the hybrid vehicle. Prototype nickel-hydrogen cells have been built with specific energy densities above 30 W-hr/lb and specific power densities of more than 200 W/lb, and are considered feasible (Ref. 4-11).

The nickel electrode in the nickel-cadmium battery has proven to be relatively trouble-free; the hydrogen electrode of the hydrogen-oxygen fuel cell has also proven to be reliable (Ref. 4-12). The combination of the two could be expected to have good life and performance if the experience with fuel cells can be reliably extrapolated to batteries. Over 2,000 complete discharges have been made with nickel-hydrogen cells without any significant degradation. It has been also shown that the cells can accept charge and can discharge over a wide range of current levels.

The main concerns in the development of the cell would be large volume, safety, and cost. Safety problems may arise from the potential leakage of hydrogen through seals and cases, although such leakage is generally associated with high-pressure and high-temperature systems that are not required in the hybrid application.

4.3.3.4 Impact of Vehicle Requirements on Battery Design

Figure 4-14 (Ref. 3-3) shows the characteristics of the most severe operating cycle in the DHEW Driving Schedule (now Federal Emissions Test Driving Cycle) based upon a 4,000-lb family automobile. In this case, severity is defined by the duration of discharge, ampere hours delivered, and peak battery current. The battery power density needed to meet this demand is about 100 W/lb and the ampere hours delivered are 0.62 Ah.

Based upon these findings, it appears that the lead-acid battery will be adequate for the hybrid to negotiate the DHEW Driving Schedule on a repetitive basis provided its cycle life can be improved. A reduction in the requirements specified for vehicle peak acceleration (0 to 60 mi/hr in 13.5 seconds) and top speed (80 mi/hr) will also make the lead-acid battery more suitable for the hybrid vehicle. Further battery weight reductions might be achieved by use of advanced battery systems.

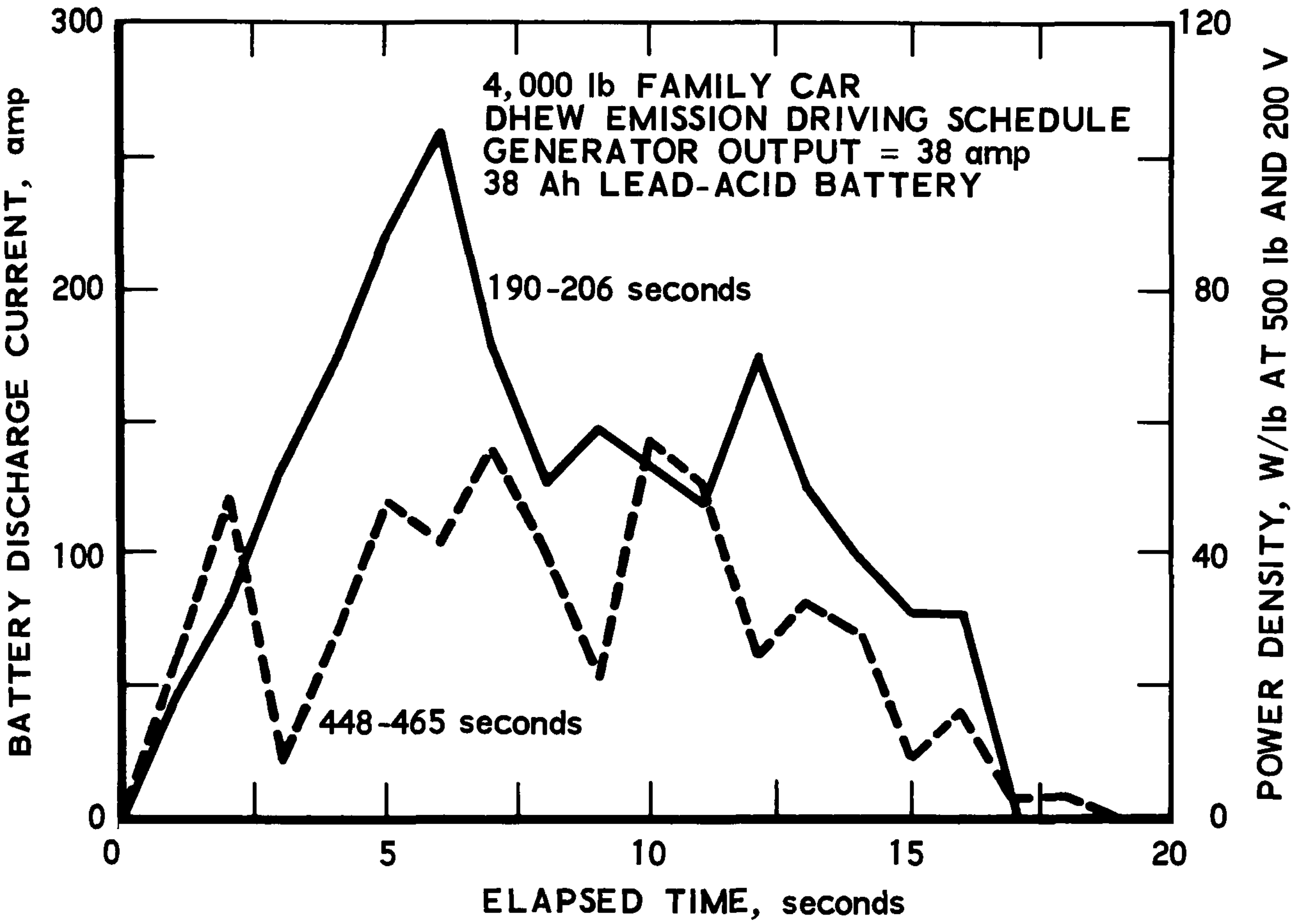


Figure 4-14. Battery Peak Discharge Currents and Associated Power Density (Ref. 3-3)

4.3.4 Heat Engines

4.3.4.1 Introduction

System studies by TRW Systems (Ref. 2-1) have shown that even conventional engines operating in the hybrid mode can have lower emissions and improved fuel economy in comparison with these same types of engines in conventional automobiles.[8] Since the engine in a hybrid vehicle need only provide the maximum power required for cruising (and not acceleration), it can be smaller than the engine for the conventional automobile.

[8] Lockheed Missiles and Space Company (LMSC) in its hybrid heat engine/flywheel study arrived at similar results (Ref. 3-1).

Engine power is expected to be 90 to 110 hp for a full-size passenger car (Refs. 3-1 and 3-3). Because rapid transient power requirements for acceleration are met by an energy storage device, such as a flywheel or battery. the engine operates at or near steady-state conditions. Under these conditions, the engine may be designed with unique features and operating characteristics in an attempt to achieve significant reductions in exhaust emissions and fuel consumption.

4.3.4.2 Candidate Heat Engines

A number of heat engine types have been considered by EPA contractors for use in hybrid vehicles: the Otto cycle (spark ignition engine), the Diesel cycle (compression ignition engine), the Brayton cycle (gas turbine engine), the Rankine cycle ("steam" engine), and the Stirling cycle. These engines are discussed in the following paragraphs.

4.3.4.2.1 Otto Cycle

The sequence of operations in the reciprocating spark ignition engine involves four piston strokes: intake, compression (during which ignition and combustion of the charge occur), power or expansion, and exhaust. A rotating lobe in the Wankel engine undergoes a similar operating sequence. Typically, a carburetor supplies an air-fuel mixture to the engine intake at a near-constant, near-stoichiometric ratio over a broad range of engine operating conditions. Engine output to meet load requirements is controlled by throttling the air flow, which in turn controls the fuel flow to the engine. At a fixed throttle setting, the engine delivers a relatively constant torque, and its output power is roughly proportional to engine speed (rpm).

4.3.4.2.2 Diesel Cycle

The diesel cycle employs a four-stroke sequence of engine operations made up of an air-only intake stroke, a compression stroke that raises the air temperature above the autoignition point of the fuel, followed by combustion of an injected fuel charge, a power or expansion stroke, and an exhaust stroke. Fuel under high pressure is delivered to the cylinder through individual cylinder nozzle injection valves by an injection pump driven by the camshaft. Unlike the spark ignition engine, the charge mixture is not regulated and overall air-fuel ratios ranging from 20 to 75 or higher may be encountered over the normal engine operating range. Load and speed control are achieved by adjusting the amount of fuel injected.

4.3.4.2.3 Brayton Cycle

In the basic Brayton cycle, inlet air is compressed and heated at constant pressure in a combustion process; combustion products are expanded through a power turbine and discharged to the atmosphere, eventually reaching equilibrium with the environment. The engine design arrangement can be either single-shaft or dual-shaft (free turbine). In the single-shaft arrangement, a turbine supplies power to both the compressor and the load. In the dual-shaft arrangement, separate turbines supply power for the load and for the compressor.

Cycle efficiency and engine fuel economy can be improved by: (a) increasing the maximum cycle temperature, (b) improving component efficiencies, and (c) using a regenerator to recover some of the rejected heat. Optimum cycle efficiencies are obtained at high compressor pressure ratios (8 to 12) without regenerators, and at low compressor pressure ratios (4 to 6) with regenerators (Ref. 4-13).

The most advanced operational gas turbine is Chrysler's sixth generation gas turbine engine for automobiles that is being developed further under an EPA-sponsored contract. The Chrysler design is a low pressure ratio, free turbine, regenerative engine with a compressor pressure ratio of 4:1, maximum turbine speed of 45,700 rpm, and first stage turbine inlet temperature of 1,850°F.

4.3.4.2.4 Rankine Cycle

The Rankine cycle engine is an external combustion power plant using water or other working fluids. In this cycle, the working fluid is vaporized and superheated at high pressure in a boiler. The fluid is then expanded in a power absorbing reciprocating piston or rotating turbine; the exhaust is condensed and the liquid is pumped back to the boiler.

In the water-base vehicular engine, steam design pressures and temperatures of about 1,000 psia and 1,000°F are planned. Organic working fluid systems under development range in pressure from 700 to 1,000 psi with temperatures of about 600°F.

The EPA has sponsored four Rankine cycle development programs. These programs are:

a. Water-base Rankine--reciprocating expander and turbine expander.

b. Organic Rankine--reciprocating expander and turbine expander.

Components for these engines have been under test since January 1973 (Ref. 4-14).

4.3.4.2.5 Stirling Cycle

The Stirling cycle engine is a closed-cycle external combustion engine with a reciprocating expander. The working fluid can be any gas. Ideally, the Stirling cycle consists of two constant volume processes joined by an isothermal expansion and an isothermal compression process.

The Stirling cycle has a very high efficiency approaching the Carnot cycle efficiency; the basic problem has been excessive weight and volume. Improvements have been made in recent years in reducing both weight and volume. Several European companies (N.V. Philips of Holland, and United Stirling of Sweden) have worked on Stirling engines for automobiles. Currently, N.V. Philips and Ford Motor Company are in the process of designing a 170-hp Stirling engine for a Torino automobile. Changes that have lead to the compactness and reduced weight of the engine include the use of a swash-plate (for converting reciprocating motion of the piston to rotary drive shaft motion) and the use of high pressure (200 atm) gaseous hydrogen as the working medium (Ref. 4-15).

4.3.4.3 Fuel Consumption, Weight, and Volume Characteristics

Specific fuel consumption (SFC), weight, and volume characteristics for each of the candidate heat engine types are shown in Table 4-13 for the hybrid family car and in Table 4-14 for the hybrid commuter car.

Table 4-13. Family Car Heat Engine Characteristics (Ref. 3-3)

Heat Engine	SFC, lb/hp-hr	Weight, lb	Volume, ft^3
Spark Ignition Engine - Reciprocating Piston	0.50	335	11.8
Spark Ignition Engine - Rotary Piston	0.50	216	5.8
Compression Ignition Engine	0.43	493	15.1
Brayton Cycle Engine	0.57	310	10.4
Rankine Cycle Engine (Positive Displacement)	0.87	846	13.5
Stirling Cycle Engine (Rhombic Drive)	0.42	1,153	22.8

Table 4-14. Commuter Car Heat Engine Characteristics (Ref. 3-3)

Heat Engine	SFC, lb/hp-hr	Weight, lb	Volume, ft^3
Spark Ignition Engine - Reciprocating Piston	0.56	180	6.1
Spark Ignition Engine - Rotary Piston	0.56	116	4.0
Compression Ignition Engine	0.45	228	8.9
Brayton Cycle Engine	0.65	125	3.9
Rankine Cycle Engine (Positive Displacement)	0.93	322	5.5
Stirling Cycle Engine (Rhombic Drive)	0.43	432	8.6

These characteristics are representative of information available at the time the study reported in Ref. 3-3 (C. 1970). The SFCs for the spark ignition and compression ignition engines represent the minimum point in the engine operating map; the SFCs for the Brayton, Rankine, and Stirling engines represent the design or full-load point in the entire operating map. It is noted that these data may be compared on an equal basis without great error since the SFC characteristic for design-optimized systems used in the hybrid application would tend to be relatively flat over a wide load range.

The weights and volumes for each engine type represent technology current at the time of the hybrid study. Values shown for the rotary piston spark ignition engine were estimated from Curtiss-Wright data, appropriately adjusted to reflect a consistent set of automotive accessories for all engines. Weights and SFCs for the compression ignition engine are based on turbocharged, divided-chamber designs. Weight and volume values for the Rankine cycle reflect positive displacement expander systems. The Stirling cycle characteristics are representative of engines using Rhombic drive devices. As noted earlier, more recent designs using swash-plate mechanisms and double-acting pistons are lighter and more compact.

A broader view of the tabulated results may be obtained by referring to the plots of Figures 4-15, 4-16, and 4-17, where the data are grouped by heat engine characteristic and are plotted over a range of engine horsepower. The SFC plot, Figure 4-15, shows that the Stirling and compression ignition engines provide the lowest fuel consumption over the horsepower range. The spark ignition engine ranks second on this basis, with SFCs ranging 25 to 12 percent higher for low to high horsepower applications. The weight plot, Figure 4-16, shows that the rotary piston spark ignition engine is the lightest of the heat engine candidates for all hybrid vehicles. The Brayton cycle is second best in this category for the commuter car. The reciprocating piston spark ignition engine is

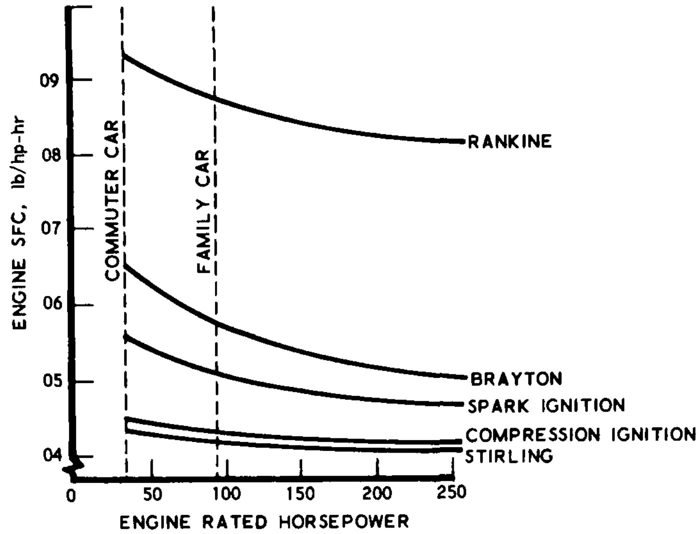


Figure 4-15. Heat Engine SFC Comparison (Ref. 3-3)

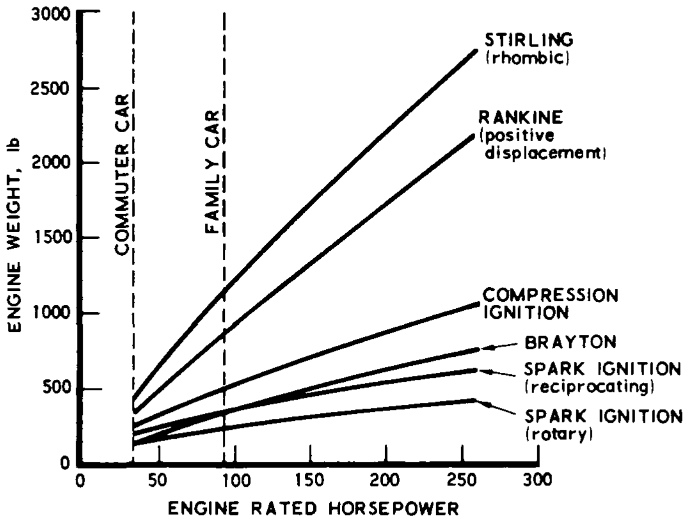


Figure 4-16. Heat Engine Weight Comparison (Ref. 3-3)

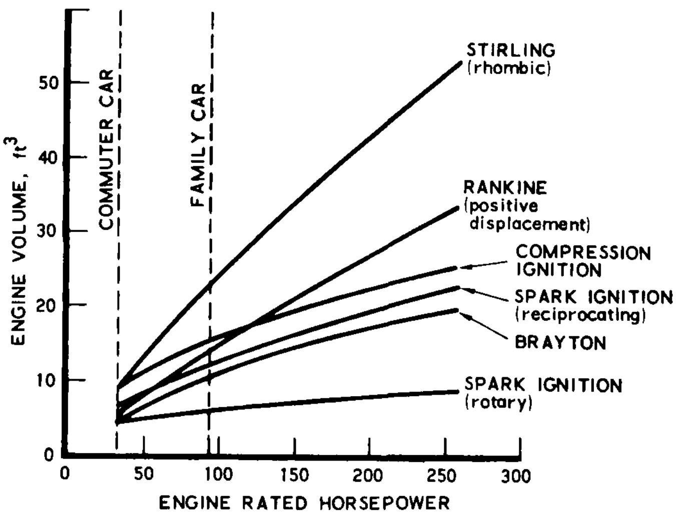


Figure 4-17. Heat Engine Volume Comparison (Ref. 3-3)

competitive with the Brayton cycle for the family car and is superior to the Brayton cycle for higher horsepower applications. The Stirling (rhombic drive technology) and Rankine (positive displacement) engines run significantly heavier than other heat engine types and, in view of the criticality of weight in relation to battery power density requirements, these systems would appear to be unsuitable for hybrid use without further development.

4.3.4.4 Emissions

Hydrocarbon (HC), carbon monoxide (CO), and oxides of nitrogen (NO_x) emission are given as design-load specific mass emissions for each of the five engine types in Figure 4-18 (Ref. 3-3). These charts allow a comparison of specific mass emissions for each engine category for both 1970 state of the art and projected technologies. The values indicated do not provide a direct correlation to vehicle emission, since the latter depend on the part-load operating cycle and its attendant emission characteristics.

The spark ignition engine values may be compared with results obtained by the Bureau of Mines using standard 350-CID engines in a test program conducted for EPA with the goal of supplying information for a hybrid vehicle engine design (Ref. 4-16). At steady-state conditions with exhaust control equipment consisting of a catalytic converter and exhaust gas recirculation (EGR), minimum HC and CO emissions were obtained at air-fuel ratios between 16 and 17. At these conditions, the emissions in gr/bhp-hr were:

HC	0.2 to 0.4
CO	1.5 to 2.5
NO_x	1.0 to 1.5

The HC compares quite well with the engine design load values in Figure 4-17 for projected technology. Both CO and NO_x exceed the projected technology levels by a factor of two or more. Nonetheless, at the

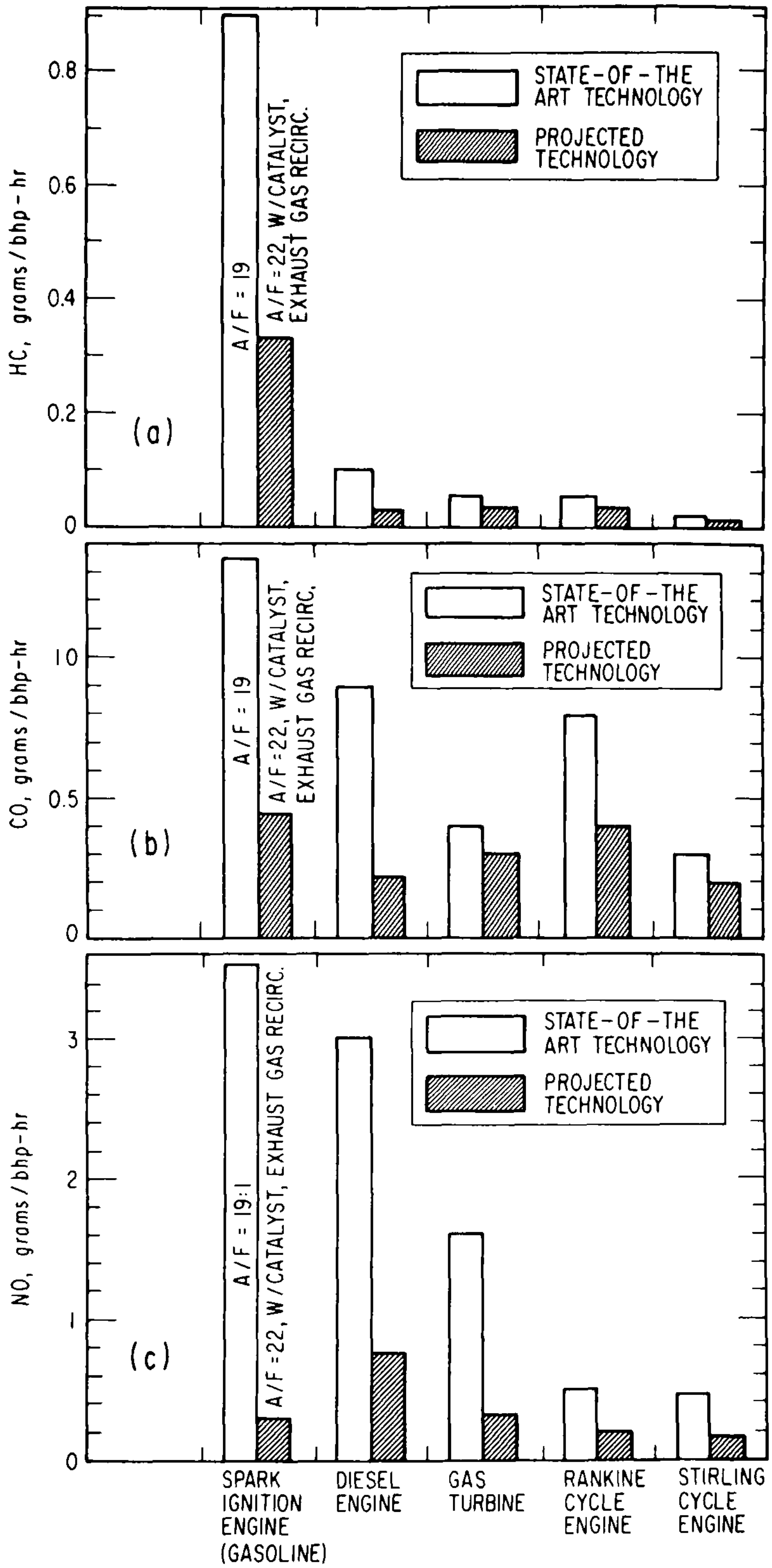


Figure 4-18. Heat Engine Exhaust Emissions at Design Load (Ref. 3-3)

Notes: NO_x values are expressed as NO; to be comparable to Federal emission standards (NO_2), values should be multiplied by 1.53. Also, "state-of-the-art" represents that prevailing in 1970.

measured levels, it would appear that, if this engine were operated in a hybrid vehicle, the 1976 interim Federal emission standards could be met. But the referenced work estimates that EGR alone would not be sufficient to reduce NO_x enough to meet the original 1976 Federal emission standards.

Diesel engine emissions compare favorably with spark ignition engine emissions for the 1970 technology case. High-pressure, high-temperature combustion in the diesel may, for the projected technology, limit the reduction in NO_x to a level somewhat higher than that achievable with the spark ignition engine operating at ultralean conditions.

Satisfactorily low levels of both HC and CO are achievable in current Brayton cycle systems. The major problem in gas turbine design for low emissions relates to NO_x. The EPA AAPS Brayton program is currently supporting the development of new lean-combustion burner designs that show promise of meeting 1976 emission objectives.

The emission levels shown for the Rankine cycle engine were based largely on General Motors research engines, Doble automobile tests, Williams system steam data, and burner data from various sources. The most critical emission specie of the Rankine engine is NO_x. Possible techniques for reducing NO_x are being examined in the EPA AAPS Rankine cycle program that is supporting the investigation and development of new burner types and control techniques such as EGR.

The Stirling engine provides very low emission levels. The CO and HC levels are presently below the 1976 standards and various methods, such as exhaust gas recirculation, are being tested to reduce NO_x emissions.

4.3.4.5 Hybrid Operation

A number of possible engine operating modes for the hybrid vehicle were discussed in Section 2.4. As a rule, the selection of mode will depend on a number of considerations, among which are the requirements for vehicle performance under urban and highway operating conditions, vehicle exhaust emissions and fuel economy. These conditions, in turn, will interact with the choice of drivetrain arrangement, series or parallel.

In general, the fixed speed, fixed power output mode does not provide the necessary flexibility required to meet vehicle energy requirements. Two other modes of hybrid operation for the engines under consideration are feasible. One is the constant rpm and variable power output mode. This mode is frequently used in engine/generator power units and may be applied to the series configuration of the hybrid vehicle for all of the heat engines under consideration. It may be particularly suitable for the gas turbine (single-shaft design), with variable turbine nozzle or compressor inlet guide vanes to maintain control over turbine inlet temperature and air-fuel ratio. Generally, the parallel hybrid configuration will require variable rpm and variable power operation.

The variable rpm and variable power output mode at optimum throttle setting suggests an interesting possibility: attainment of an optimum SFC level over the complete engine load range. The low SFC may favorably influence vehicle exhaust emissions provided that the air-fuel ratio requirements for low SFC can be maintained compatible with the requirements for low emissions.

4.3.4.6 Engine Feasibility for Hybrid Vehicles

Based on engine weight and volume and allowable propulsion system weight and volume, only the gas turbine, spark ignition reciprocating and spark ignition rotary engines are considered feasible for installation into a hybrid heat engine/battery automobile (Ref. 3-3). The other engines would impose excessive performance requirements on other components because of reduced weight and volume available on board the vehicle. This is particularly true for battery systems, where performance requirements, in the form of power and energy density, are much higher than any future expectations for advanced battery designs. Recent reductions in Stirling engine weight and volume might permit use of this engine in a hybrid, but the desirability of such use has not been examined in sufficient depth to revise the conclusions cited.

It is of interest to note that all performance and physical characteristics for these engines are based upon designs that meet the rapid response and wide range in engine speed and power required for current conventional automobiles. Engines designed specifically for a hybrid automobile may possibly be reduced in size and weight. Improvements in exhaust emissions and fuel economy might also result from a new design. Verification of these projections is not currently available.

5. HYBRID HEAT ENGINE/FLYWHEEL VEHICLE

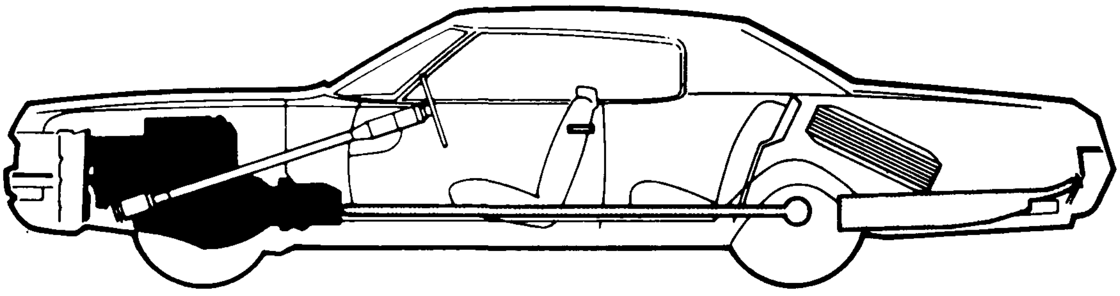
5. HYBRID HEAT ENGINE/FLYWHEEL VEHICLE

5.1 SYSTEM DESIGNS AND OPERATION

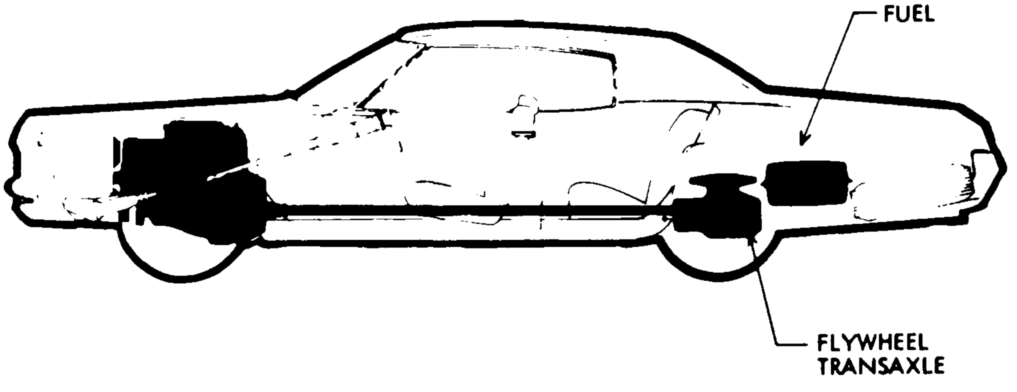
5.1.1 Lockheed Missiles and Space Co., Inc.

Work was performed by Lockheed Missiles and Space Co. (LMSC) in the investigation of inertial energy storage under two separate contracts. The first, Flywheel Feasibility Study and Demonstration (Ref. 3-1), had as its objectives the analytical determination of the feasibility of the flywheel hybrid as a low-emission propulsion system for urban vehicles (family car, commuter car, delivery van, and intracity bus) and the demonstration and performance evaluation of full-scale flywheels for hybrid applications. The second, Flywheel Drive Systems Study (Ref. 3-4), as applied to the family car, was directed toward advancing the development of flywheel systems technology including: (a) the experimental development of final designs of flywheel auxiliary equipment (housings, bearings, seals, etc.), (b) the experimental demonstration of positive energy containment in burst tests of flywheels, (c) safety analyses, (d) use of engine emission data supplied by the U.S. Bureau of Mines (Ref. 4-16) in analyses of hybrid vehicle emissions, and (e) systems coordination for the transmission studies (see Section 5.3.2) conducted by Mechanical Technology, Inc. (MTI) and Sundstrand (Refs. 5-1 and 5-2, respectively).

Two conceptual drivetrain arrangements (Figure 5-1) were examined by Lockheed for the heat engine/flywheel family car. The first replaces the conventional hydrokinetic transmission with the flywheel drive transmission in an engine-mounted configuration. In the second arrangement, the conventional transmission was replaced by a torque damper and the flywheel drive transmission was incorporated into an independent rear suspension transaxle package. Since it resulted in packaging advantages, Lockheed favored the latter configuration.



Drivetrain Arrangement for Engine-Mounted Flywheel/Transmission



Drivetrain Arrangement for Transaxle Flywheel/Transmission

Figure 5-1. Lockheed Conceptual Drivetrain Arrangements (Ref. 3-1)

The drivetrain (Figure 5-2) consists of a heat engine coupled to the flywheel and the vehicle wheels through a planetary/hydrostatic power splitting transmission.

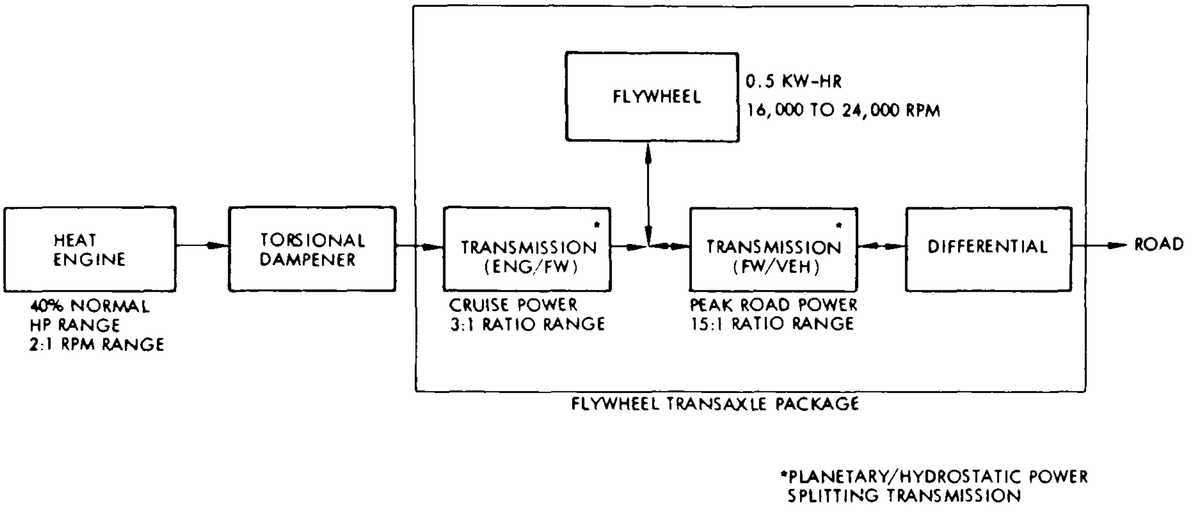


Figure 5-2. Lockheed Transaxle Flywheel/Hybrid Transmission Configuration (Ref. 3-1)

The heat engine provides cruise power, drivetrain losses, accessory power, and flywheel recharging power. An internal combustion, spark ignition, reciprocating engine was selected by LMSC for use in the flywheel/hybrid passenger car for operation under variable speed (2:1) and load conditions.

The flywheel provides the power required for vehicle acceleration. Flywheel charging is accomplished by the heat engine and by regenerative braking of the rear wheels during deceleration. The flywheel was fabricated of 4340 steel and was sized on the basis of the vehicle kinetic energy at maximum speed. The preliminary configuration selected by Lockheed for the family car flywheel (Figure 5-3) was a 20.4-in.-dia conical section with a constant radius flare at the periphery. This flywheel configuration was fabricated and tested during the feasibility study (see Section 5.3.1). However, the incorporation of the burst containment structure dictated a reduction in flywheel diameter to comply with automotive

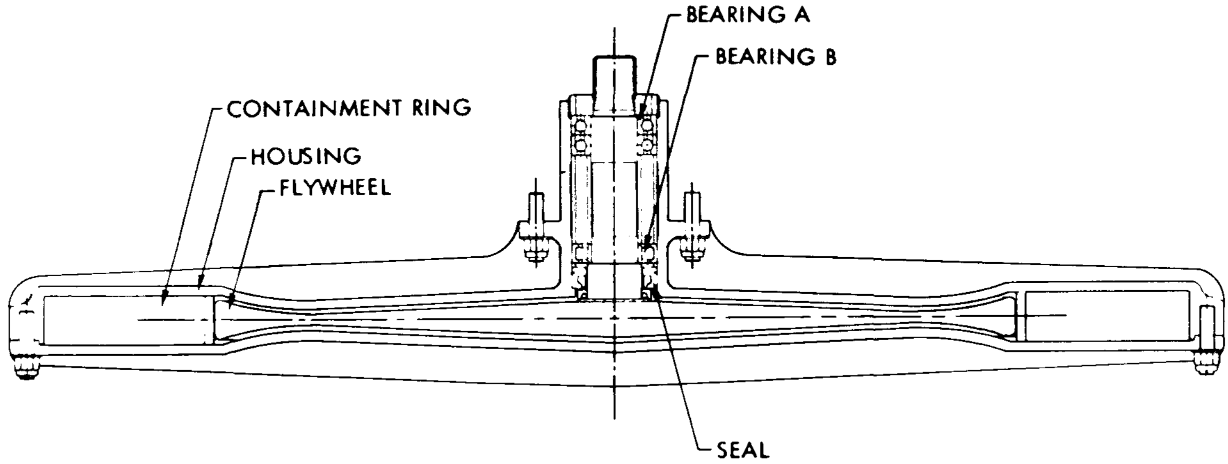


Figure 5-3. Preliminary Lockheed Flywheel Design -- Family Car (Ref. 3-4)

space requirements. Accordingly, the baseline flywheel configuration (Figure 5-4) was selected and mounted in the transaxle configuration (Figure 5-1). The energy storage capacity of the flywheel is 0.5 kW-hr at a design speed of 24,000 rpm. The weight of the flywheel alone is 86 lb, which constitutes approximately 46 percent of the weight of the complete flywheel assembly.

Flywheel selection was predicated on the use of available materials and near-term (5 to 10 years) technology. This precluded the use of the more advanced materials investigated by Johns Hopkins University (Ref. 5-3) for flywheel application. In addition, Lockheed imposed certain design constraints as screening criteria within the general volume and weight limitations imposed by the EPA Vehicle Design Goals, Appendix A. These constraints included the following: (a) the flywheel assembly maximum weight should not exceed 50 percent of the 1,600 lb specified for the entire propulsion system, (b) the flywheel assembly volume should not exceed 50 percent of the total 35 ft^3 volume specified for the propulsion system, (c) the flywheel assembly radius should not exceed 2 ft and the assembly height should not exceed 1 ft, (d) a speed constraint of 24,000 rpm based

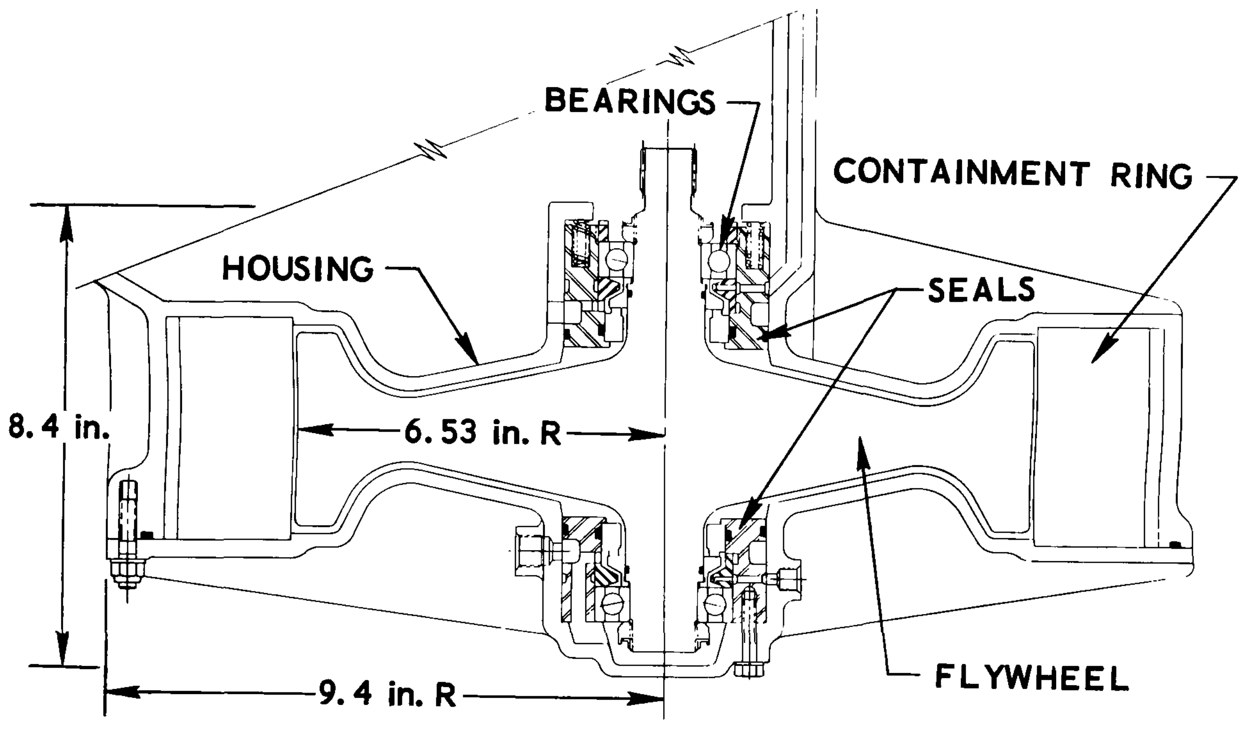


Figure 5-4. Lockheed Baseline Flywheel (Ref. 3-4)

on the availability of relatively inexpensive seals and bearings, and (e) the flywheel assembly cost should not exceed \$0.50/W-hr of energy storage capacity. The flywheel assembly was assumed to incorporate a housing suitable for maintaining the required vacuum, bearings, and seals. Flywheel assembly cost was estimated at three times flywheel material cost plus \$3.00/lb for the housing.

The flywheel was designed to operate in a partial vacuum of 0.01 atm (7.6 mm Hg) to reduce windage losses since rim speeds would be supersonic. Lockheed determined that the flywheel gyrodynamic forces in the family car were only a minor consideration. It was further concluded that the choice of flywheel spin axis orientation (i.e., vertical, longitudinal, transverse) can be based primarily on vehicle packaging considerations. The effect of these forces on a vehicle operating on icy roads was not investigated and would require further study.

Two flywheel drive transmission configurations (Figure 5-5) were considered by Lockheed. The double transmission (series configuration) was preferred to the single transmission (parallel configuration) because it offered greater control flexibility by allowing the heat engine speed to be controlled independently of either flywheel speed or vehicle speed. The power-splitting transmission favored by Lockheed is a combination of a mechanical-differential and hydrostatic transmission.

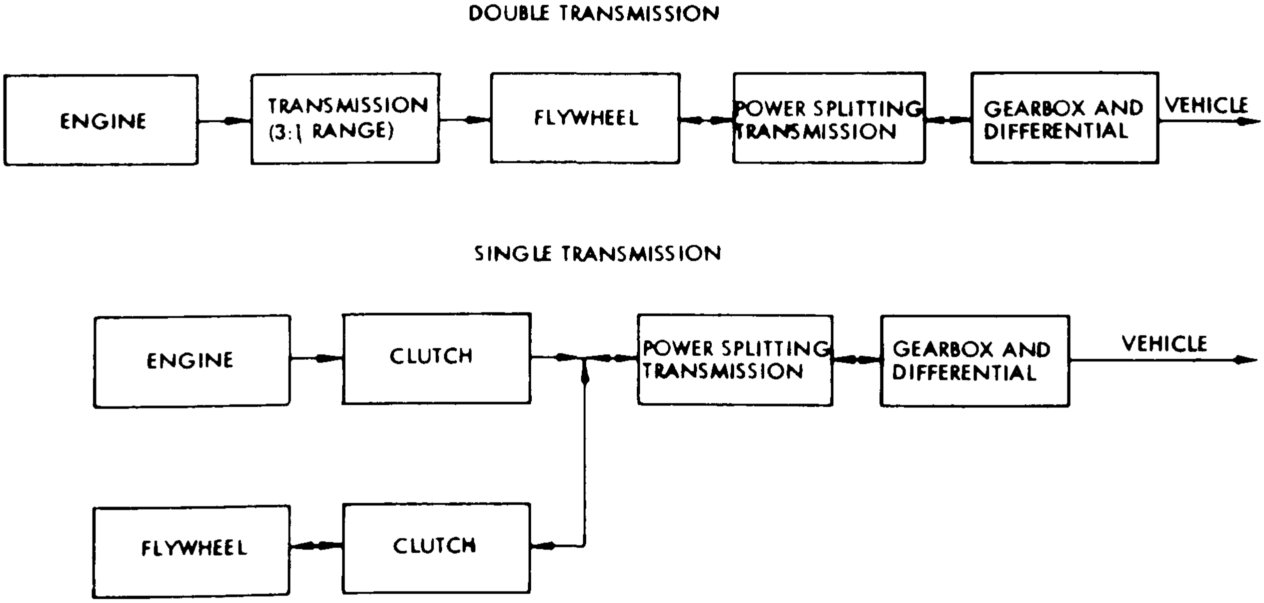


Figure 5-5. Lockheed Power-Splitting Transmission Configurations (Ref. 3-1)

The basic control concept proposed by Lockheed (total kinetic energy) is intended to control the heat-engine output so as to hold the sum of the kinetic energies of the flywheel and the vehicle at a constant value. This value is essentially equal to the kinetic energy of the fully loaded vehicle at maximum cruise velocity (where flywheel kinetic energy can be zero). The actual levels of vehicle and flywheel kinetic energies are monitored and summed. The difference between this sum and the constant reference value constitutes an error signal to the engine to recharge the flywheel. Recharging continues until the actual summed kinetic energies match the predetermined value. According to Lockheed, this system will account for energy reclaimed by regenerative braking and minimize the size of the flywheel.

5.1.2 Johns Hopkins University, Applied Physics Laboratory

Concurrent with the work done by Lockheed, an experimental and analytical study of high specific energy flywheel systems for use in automotive propulsion systems was conducted by Johns Hopkins University, Applied Physics Laboratory. This study had two objectives: (a) proof-of-principle demonstration of the use of filamentary or composite materials of high uniaxial tensile strength in rotor configurations that would have significantly higher specific energies (i.e., 30 W-hr/lb) and (b) theoretical evaluation of the performance of such flywheels alone and in combination with heat engines, in four classes of vehicles: family car, commuter car, delivery van, and intracity bus.

Vehicle evaluation studies by Johns Hopkins indicated that the city bus was the only one of the four classes that could meet performance specifications using a flywheel-only propulsion system. Heat-engine/flywheel hybrid propulsion systems would satisfy the performance requirements for all four classes.

The near-term heat engine choice was the spark ignition engine, but the gas turbine engine was considered to offer the greatest promise for the future because of its low specific weight, its potential for minimizing emissions, and its higher operating speed, which is close to that of the flywheel.

The general details of a hybrid propulsion system selected by Johns Hopkins for a commuter car is shown in Figure 5-6. This car has a curb weight of 1,400 lb and a loaded weight of 1,700 lb. A series configuration powertrain is envisaged by Johns Hopkins with the heat engine mounted in the front of the car and the flywheel-transmission system mounted

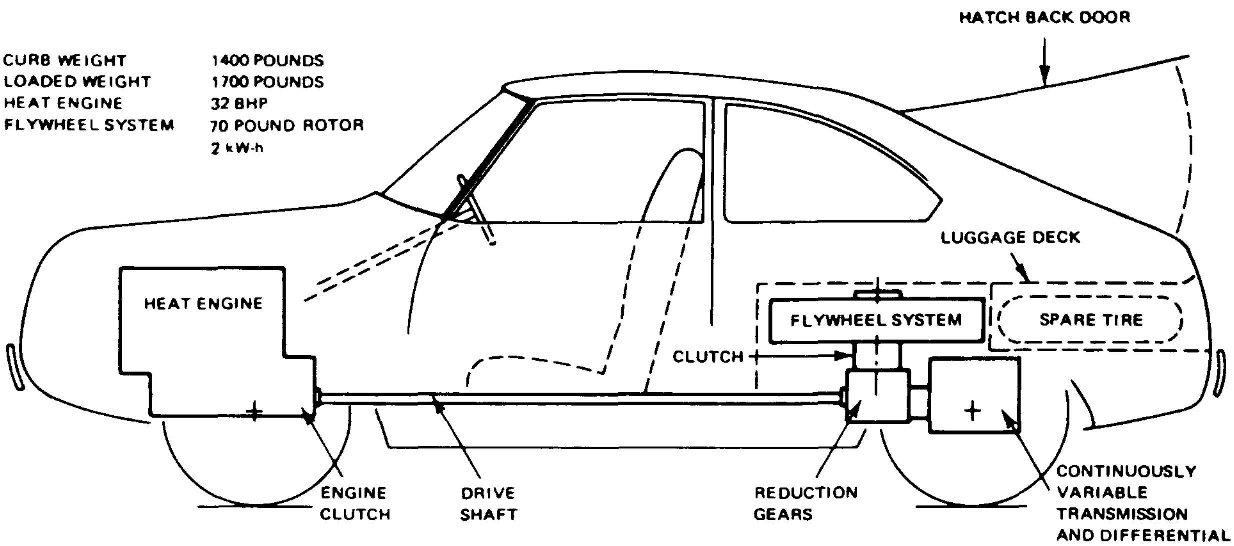


Figure 5-6. Johns Hopkins Heat Engine/Flywheel Hybrid Commuter Car (Ref. 5-3)

in the rear, essentially equalizing the weight distribution. The continuously variable transmission is integrated with the differential. All of the power-train components in the rear of the car are rigidly connected to one another and are shock mounted on the spring mass. The rear wheels are independently suspended. This arrangement provides space for a disc flywheel of 2 kW-hr or a bar of approximately 1.5 kW-hr, although the use of a system with this amount of energy will depend on the ability to contain the rotor, acceptable vehicle handling characteristics, and the development of low-friction bearings and seals.

In evaluating each of the four types of vehicles, Johns Hopkins made the following assumptions:

a. Composite discs would be superior to bars with respect to packaging volume and would have approximately the same specific energy (these were assumed for the applications studies).

b. The heat engine would be operated in an on-off mode in supplying energy to the flywheel; all drive wheel power is supplied by the flywheel in the proposed series configuration.

c. A 72 percent overall transmission efficiency (engine-to-flywheel-to-drive wheels) for all driving modes.

A continuously variable transmission of the power-splitting type was felt by Johns Hopkins to best satisfy the requirements for a hybrid vehicle. (Lockheed recommended the same type transmission.)

The drivetrain schematic is shown in Figure 5-7. The power required for accessories (power steering, power brakes, air conditioning, fans, pumps, and lights) is taken from the central gearbox, and an input shaft is provided for externally supplying power to charge the flywheel in the event of a rundown or while the vehicle is parked. To conserve the stored energy, the clutch of the flywheel is disengaged whenever the vehicle is parked. When the flywheel and drive clutches are engaged, power can be transmitted from the gearbox to the drive wheels, or vice versa (for regeneration).

The operator controls are analogous to those on present vehicles. An "ignition" switch engages the flywheel clutch, a selector lever positions the transmission for drive, neutral, or reverse, and accelerator and brake pedals command vehicle accelerations and decelerations. (A conventional parking brake, not shown, would be provided.) A central control box called the power programmer, translates operator commands into the desired mechanical responses.

5.2 SYSTEM DESIGN REQUIREMENTS AND ACHIEVEMENTS

5.2.1 Lockheed Missiles and Space Company, Inc.

5.2.1.1 Design Requirements

Propulsion system performance requirements, based on Revision C to the EPA Vehicle Design Goals (see Appendix A), were calculated in terms of tractive effort to provide a common basis to the contractors for

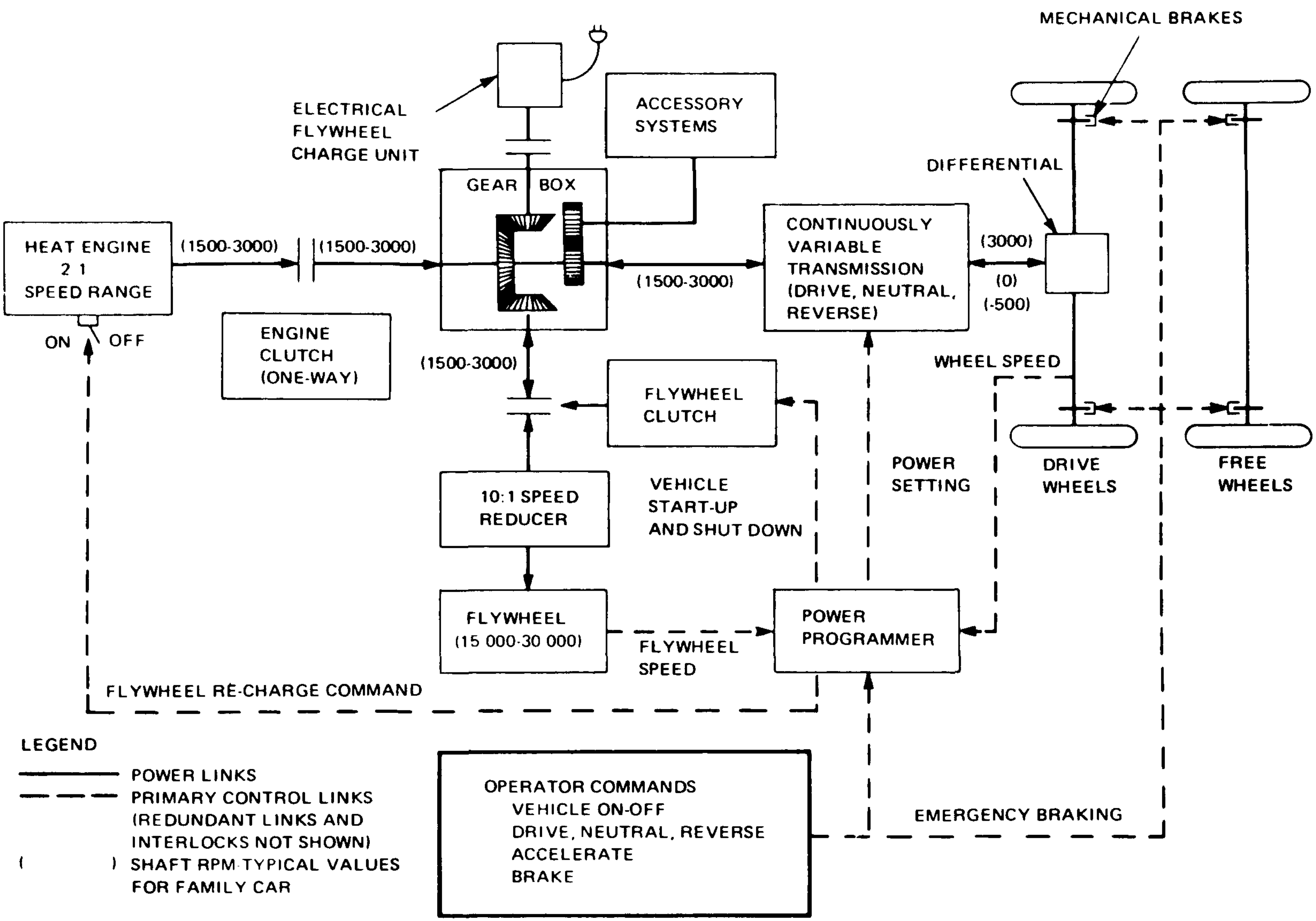


Figure 5-7. Johns Hopkins Flywheel Hybrid Power Control System (Ref. 5-3)

transmission design. Average values of vehicle weight were assumed (i.e., test weight of 4,300 lb and gross weight of 5,000 lb); both are 300 lb below the maximum allowable. The tractive effort profile for vehicle acceleration and cruise requirements is shown in Figure 5-8.

The heat engine was sized on the basis of a sustained 70 mi/hr on a 5 percent grade. This requires 93 road hp, which, when combined with drivetrain losses (10 percent) of 10.3 hp and accessory power requirements of 5 hp brings the total required to 108 hp. The vehicle performance requirements of Appendix A could, therefore, be met as follows: from a standing start, the heat engine power rises to a constant value of 108 hp at 26 mi/hr, remains at this value to 70 mi/hr, and then declines from 70 to 85 mi/hr. To match current automotive capabilities, however, Lockheed increased the low-speed tractive effort requirement from 1,523 lb to one-half the test weight, or 2,150 lb. This level of tractive effort provides a capability for acceleration from 0 to 15 mi/hr in 6 seconds on a 30-percent grade.

5.2.1.2 Performance Results

A comparison of several types of family car transmissions studied by Lockheed in both the single and double configuration (See Figure 5-5) is presented in Table 5-1. The efficiency is calculated for operation of the family car over a DHEW[9] Urban Dynamometer Driving Schedule with the assumption that all braking is regenerative. The best transmission on the basis of highest efficiency (which minimizes emissions) and the lowest cost was the power-splitting transmission. The weight and volume of the power-splitting transmission, although greater than for the hydrostatic transmission, were not considered excessive by Lockheed.

As part of the Flywheel Feasibility Study (Ref. 3-1), a conventional spark ignition heat engine was selected by Lockheed on the combined basis of comparative costs, brake specific fuel consumption (BSFC),

[9] Department of Health, Education, and Welfare (predecessor to EPA).

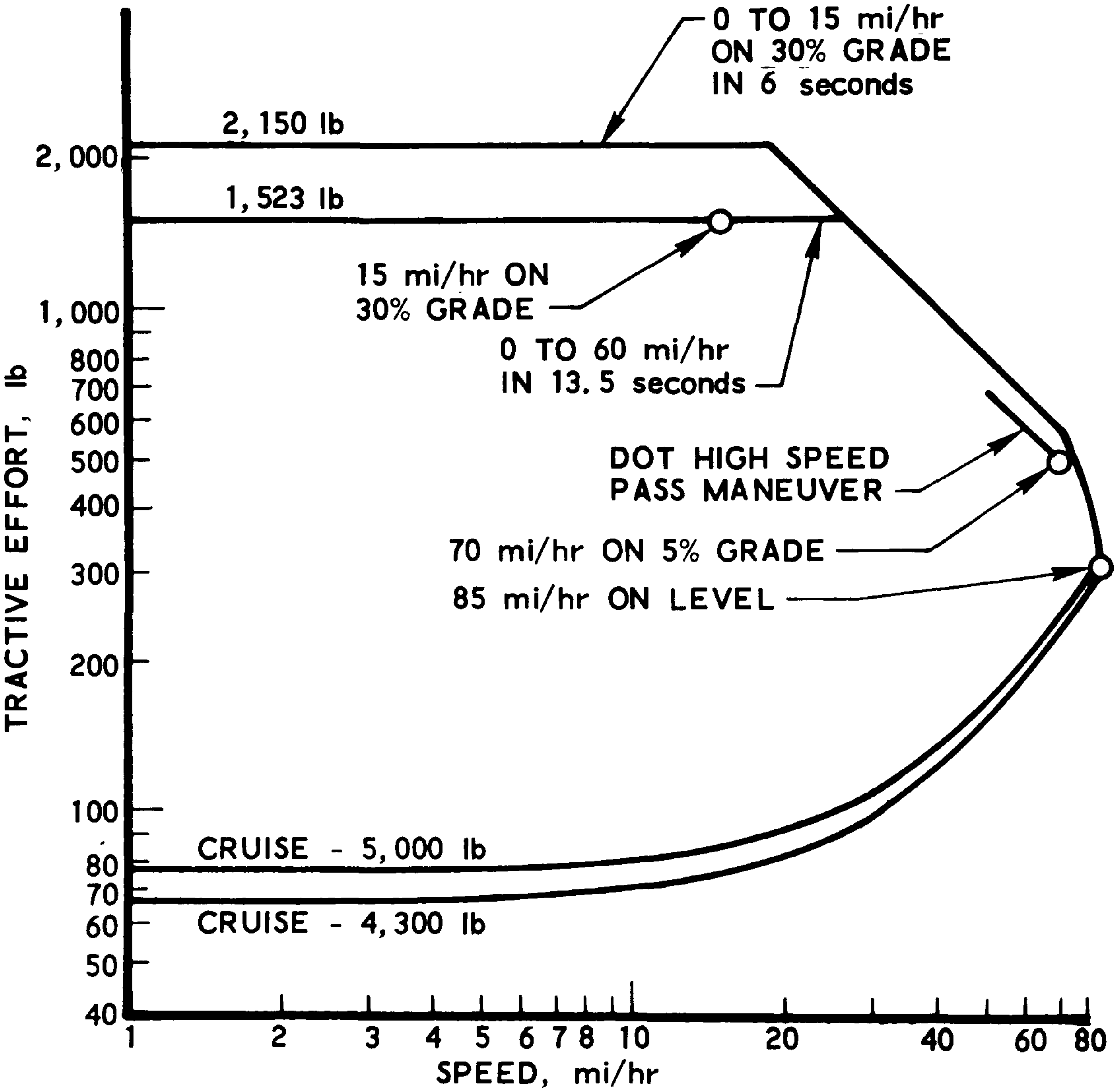


Figure 5-8. Lockheed Minimum Tractive Effort as a Function of Speed Requirements for Flywheel Drive System (Ref. 3-4)

Table 5-1. Lockheed Family Car Transmission Comparison (Ref. 3-1)

Item	Electric		Hydrostatic		Power Splitting	
	Single	Double	Single	Double	Single	Double
DHEW Schedule Efficiency (Normalized)	0.588	0.369	0.745	0.626	1.000	0.835
Volume, ft^3	3.4	4.0	3.3	3.7	3.7	5.1
Weight, lb	488	536	280	289	311	391
Cost, $	641	689	403	469	261	341

weight, and volume. A summary of these parameters, together with the analytically derived emissions and BSFC are presented in Table 5-2 for each engine type considerd by Lockheed. Vehicle emissions calculated by Lockheed in the Feasibility Study for the family car were based on EPA-supplied parametric curves of best and worst emissions as a function of horsepower. From these, emissions were calculated for the best and worst cases for each of the candidate heat engines during simulated operation over the DHEW Urban Driving Schedule. The effect of cold starts was not included and the results were regarded as very preliminary. Fuel consumption, designated as Cruise Specific Fuel Consumption, is based only on the trend curve developed from single values of BSFC plotted as a function of horsepower as obtained from a survey of engine manufacturer's data. Such horsepower and BSFC values are frequently for wide-open throttle operation; hence, these results were regarded as extremely preliminary because they represent a single wide-open throttle BSFC case for the heat engine required power level of 108 hp.

In contrast, during the Flywheel Drive Systems Study (Ref. 3-4) Lockheed calculated BSFC on the basis of an EPA-supplied BSFC map for a medium-sized V-8 engine and EPA-furnished accessory

Table 5-2. Lockheed Family Car Powertrain Comparison (Ref. 3-1)

Item	1970 Family Car	Engine Plus Power Splitting Transmission							
		Spark Ignition		Diesel		Turbine		Rankine	
Volume, ft^3	16	21.0		24.2		8.5		37.2	
Weight, lb	817	1,034		1,390		672		1,492	
Cost, $	958	1,050		1,771		5,749		1,476	
Vehicle Cruise Specific Fuel Consumption, lb/hp-hr	0.47	0.486		0.424		0.919		0.774	
Calculated Hot Start Vehicle Emissions, gm/mi[a]		Best	Worst	Best	Worst	Best	Worst	Best	Worst
HC	3.25	0.083	0.695	0.278	0.487	0.016	0.127	0.229	0.347
CO	36.9	1.42	2.57	0.308	11.6	0.503	5.84	1.88	2.85
NO_x	3.22	0.591	1.11	1.39	4.52	1.94	3.43	0.434	0.650

[a] Includes air conditioning and other accessories. Does not include any cold start allowance or catalyst exhaust treatment. Engine specific emissions provided by EPA.

power loads. A number of computer runs were made over the DHEW Urban Driving Schedule to determine fuel economy for various drive configurations and engine speed curves. Results of these runs showed that average fuel economy values over the urban driving cycle ranged from 7.3 to 13.7 mpg for the hybrid heat engine/flywheel vehicle, depending on assumed values for transmission efficiency and the operating regime over the engine BSFC map. Comparable figures for the conventional passenger car with automatic transmission ranged from 11 to 12 mpg, depending on the assumed transmission efficiency.

Subsequent emission calculations made by Lockheed, as a part of the Flywheel Drive Systems Study (Ref. 3-4), were based on emissions data provided by the U.S. Bureau of Mines (Ref. 4-16). These data were taken on two 350-CID engines at various engine speeds, percent power, air-fuel ratios, spark advance, EGR rates, and with and without an Engelhard oxidizing catalyst (type unspecified).

Results of the computer simulations over the DHEW Urban Driving Schedule are shown in Table 5-3 for both a conventional three-speed automatic transmission and a flywheel/hybrid vehicle. Results are predicated on both vehicles being equipped with an oxidizing catalyst and with EGR. Cold start effects are not included because of a lack of data.

Table 5-3. Lockheed Vehicle Exhaust Emission Comparison (Ref. 3-4)

Drive System[a]	Calculated Hot Start Emissions, gm/mi		
	HC	CO	NO_x
Conventional Three-Speed Automatic Transmission	0.39	0.95	3.98
Hybrid Heat Engine/ Flywheel Vehicle	0.38	1.12	1.21

[a]4,300 lb family car spark ignition engine with oxidation catalyst and EGR. Engine specific emissions from U.S. Bureau of Mines data.

The main conclusions reached by Lockheed with regard to the flywheel/hybrid vehicle were as follows:

a. A comparative analysis of heat engine emissions for a hybrid flywheel drive contrasted with a conventional three-speed automatic transmission shows that without a catalyst the flywheel drive offers HC, CO, and NO_x emission reductions. With a catalyst, HC and CO emissions were generally equivalent between hybrid and conventional drives; the flywheel drive offered a significant reduction only for NO_x emissions.

b. Fuel economy over the DHEW Urban Driving Schedule for the flywheel transmission is predicted to be roughly equivalent to that of a conventional transmission.

c. The estimated cost of ownership, size, and weight of a family car flywheel drive falls within the established EPA Vehicle Design Goals.

5.2.2 Johns Hopkins University, Applied Physics Laboratory

The analytical studies made by Johns Hopkins for each of the four types of vehicles were predicated upon the EPA-supplied vehicle performance parameters. These are summarized in Appendix A. Both flywheel only and hybrid configurations were considered. For each vehicle class, an appropriate driving "cycle" is represented as the sum of a number of discrete cruise, acceleration, and deceleration phases in terms of the percentage of time spent in each (Figure 5-9).

The operating mode of the flywheel-hybrid vehicle essentially decouples engine operation from the time sequence of vehicle operation. The engine is either on (at full load and nearly fixed speed) to charge the flywheel, or off. For passenger cars, the high rotor energy density allows energy storage for at least seven accelerations from 0 to 60 mi/hr, which, with regeneration, allows the vehicle to negotiate with ease a trip on any of the cycles without the possibility of the energy use rate being greater than the charge rate. Therefore, the time sequence of the modes is immaterial, and the resulting performance and emission estimates are based on average horsepower and velocity for the various phases.

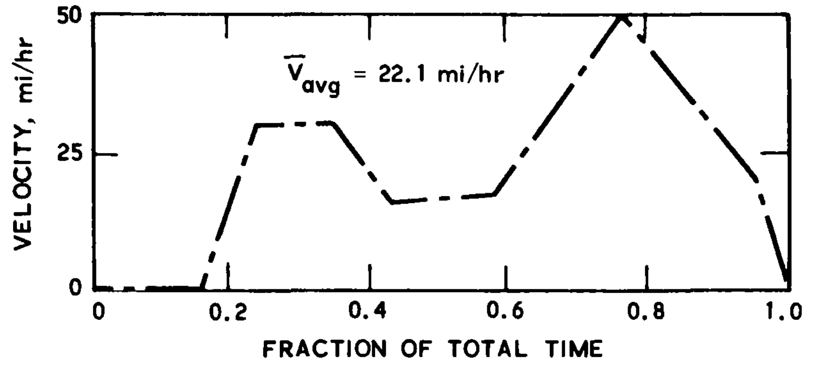


Figure 5-9. Johns Hopkins University Driving Cycle (Ref. 5-3)

The analytical results for the family car and commuter car are summarized in Tables 5-4 and 5-5. The heat engine was sized to permit cruise at the design speed with all accessories operating. Emissions, fuel economy, and ranges are quoted without the air conditioner operating. Fuel economy figures were calculated by Johns Hopkins from BSFC data reported in Reference 5-4. Note that the flywheel subsystem weight (which includes a protective housing in addition to the flywheel) is a significant percentage greater than the weight of the flywheel alone.

Emissions were calculated on the basis of EPA-supplied data in the form of a band of brake specific emissions (lb/hp-hr) applicable for several types of engines.

The spark ignition engine hybrid commuter car was selected by Johns Hopkins for the purpose of investigating the influence of variations in various parameters. The base case refers to the spark ignition engine hybrid reported in Table 5-5 without the air conditioner operating. As examples, when the flywheel rotor weight W_r is increased, Figure 5-10 shows that fuel economy decreases and total emissions increase due to the increased curb weight. The upswings in the hydrocarbon (HC) and carbon monoxide (CO) emissions for the smaller rotors are due to the effects of start-up emission penalties.

Table 5-4. Johns Hopkins Results for Family Car Without Air Conditioner Operating (Ref. 5-3)

Performance Parameters	Flywheel Only	Hybrids		
		Gas Turbine	Otto	Steam
Gross Engine Horsepower	NA	91.0(200.0)[a]	94.0	91.0
$W_{fw}/W_{(fw+e)}$	1.0	0.62(0.52)	0.31	0.27
Flywheel Rotor Weight, W_R, lb	584	353(389)	163	138
$W_{fw} - W_R$, lb	239	159(143)	92	85
Fuel Economy at V_{max}, mpg	NA	9.2(11.8)	11.8	10.0
Flywheel Only Range at 40 mi/hr, mi	42.3	25.6(21.0)	12.2	10.0
Flywheel Only Range on Grade, mi	5.5	3.3(2.7)	1.5	1.3
No. of Accelerations per Flywheel Charge	49	30(24)	13	11
Flywheel Charge Time, minutes	NA	7.7(2.9)	3.5	3.0
Cycle Performance				
Fuel Economy, mpg	NA	11.3(14.4)	14.4	12.2
HC Emission Ratio[b]	NA	0.02(0.01)	0.31	0.46
NO_x Emission Ratio[b]	NA	1.97(1.97)	1.73	0.88
CO Emission Ratio[b]	NA	0.20(0.15)	0.58	0.57
Flywheel Cycles per 100 Miles	4.5	7.4(9.0)	16.0	18.9
Flywheel Only Range, mi	22.4	13.5(11.1)	6.2	5.3
Percentage of Time Engine On	NA	21.1(9.6)	21.1	21.1

[a] Numbers in parenthesis are for a gas turbine engine sized for same fuel economy as Otto engine.

[b] Emissions ratioed to the original 1976 Federal emission standards.

NA = Not Applicable

W_{fw} = weight of flywheel subsystem, lb

$W_{(fw+e)}$ = weight of flywheel subsystem plus engine, lb

W_R = weight of rotor, lb

Table 5-5. Johns Hopkins Results for Commuter Car Without Air Conditioner Operating (Ref. 5-3)

Performance Parameters	Flywheel Only	Hybrids		
		Gas Turbine	Otto	Steam
Gross Engine Horsepower	NA	32.2(109)[a]	33.2	32.2
$W_{fw}/W_{(fw+e)}$	1.0	0.53(0.33)	0.41	0.25
Flywheel Rotor Weight, W_R, lb	217	103(64)	74	35
$W_{fw} - W_R$, lb	112	72(45)	61	49
Fuel Economy at V_{max}, mpg	NA	10.9(25.5)	25.5	17.8
Flywheel Only Range at 40 mi/hr, mi	38.3	18.5(11.5)	13.1	6.2
Flywheel Only Range on Grade, mi	4.9	2.3(1.4)	1.6	0.8
No. of Accelerations per Flywheel Charge	42	20(12)	14	6
Flywheel Charge Time, minutes	NA	6.4(1.2)	4.6	2.2
Cycle Performance				
Fuel Economy, mpg	NA	13.0(30.6)	30.6	21.2
HC Emission Ratio[b]	NA	0.01(0.01)	0.11	0.20
NO_x Emission Ratio	NA	0.76(0.76)	0.67	0.34
CO Emission Ratio	NA	0.10(0.08)	0.22	0.24
Flywheel Cycles per 100 Miles	4.7	9.9(15.8)	13.8	28.9
Flywheel Only Range, mi	21.5	10.2(6.3)	7.3	3.5
Percentage of Time Engine On	NA	23.1(6.8)	23.1	23.1

[a]Numbers in parentheses are for a gas turbine engine sized for same fuel economy as Otto engine.

[b]Emissions ratioed to the original 1976 Federal emission standards.

NA = Not Applicable

W_{fw} = weight of flywheel subsystem, lb

$W_{(fw+e)}$ = weight of flywheel subsystem plus engine, lb

W_R = weight of rotor, lb

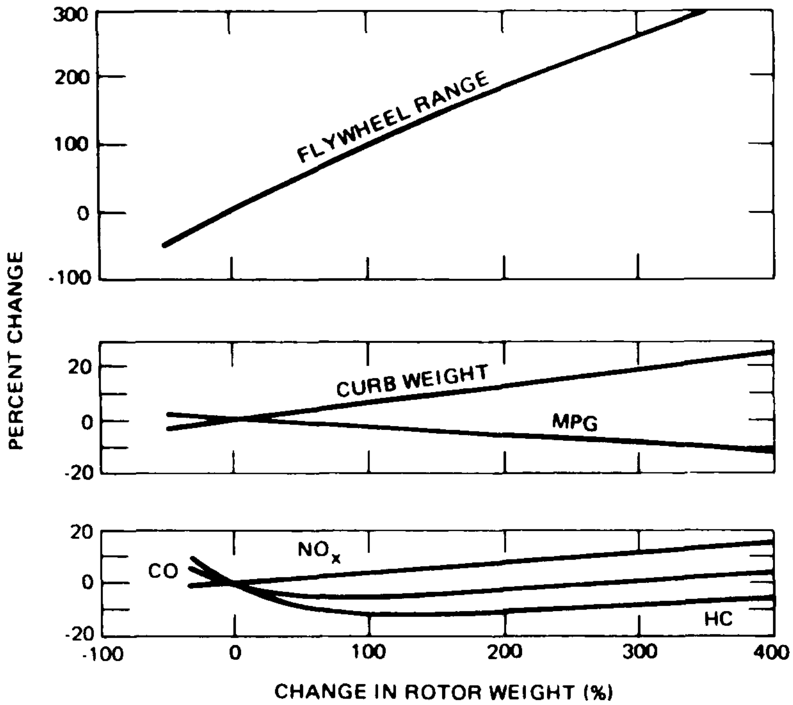


Figure 5-10. Effect of Flywheel Rotor Weight for Otto Hybrid Commuter Car, Johns Hopkins (Ref. 5-3)

The effects of the drivetrain efficiencies and the external resistance (drag and tire friction) on fuel economy are shown in Figure 5-11. The emissions on a gm/mi basis will vary inversely with fuel economy. Increasing the regeneration efficiency by 20 percent (from 50 to 60 percent) is seen to result in a 12 percent increase in fuel economy. The direct linear effects of drive and charge efficiencies are equivalent: a 10 percent increase in either results in a corresponding 10 percent increase in fuel economy. Because of the nature of the driving cycle assumed (small percentage of high speed cruise time) the effects of drag variations are not pronounced. A 20 percent drag decrease results in a 6.2 percent increase in fuel economy.

Conclusions reached by Johns Hopkins regarding the flywheel only or flywheel/hybrid vehicles were as follows:

a. The heat engine/flywheel hybrid propulsion systems satisfy the performance requirements for all four classes of

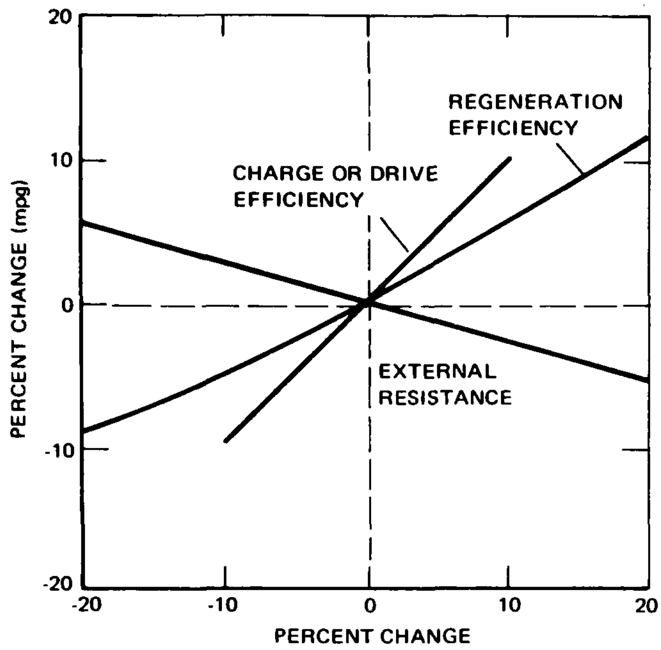


Figure 5-11. Effect of Drivetrain Efficiencies and External Resistance for Otto Hybrid Commuter Car, Johns Hopkins (Ref. 5-3)

vehicles (i.e., family car, commuter car, delivery van, and intracity bus).

b. The spark ignition engine is the near-term choice for the heat engine.

c. The gas turbine engine was believed to offer the greatest promise for the future because of its low specific weight, its potential for minimizing emissions, and its operating speed, which is close to that of the flywheel.

d. The Johns Hopkins University hybrid system emission analyses were considered inconclusive because of the lack of data at the time of their study on the operation of engines at single design points or over a very limited speed range.[10]

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[10] Since that time, data on a spark ignition engine was acquired by the Bureau of Mines (Ref. 4-16).

5.3 COMPONENT DESIGN REQUIREMENTS AND ACHIEVEMENTS

5.3.1 Flywheel

5.3.1.1 Lockheed Missiles and Space Co., Inc.

Concurrent with the overall vehicle applicability and configuration tradeoff studies conducted by Lockheed (Ref. 3-1), flywheel design studies were conducted prior to fabricating and testing candidate flywheels (Ref. 3-4). Six basic flywheel geometries were considered in the Lockheed preliminary design studies for automobiles and buses. These included the pierced uniform disc, an unpierced uniform disc, a constant-stress disc, a truncated conical disc, a rim-type flywheel, and the bar-type configuration. Although this volume of the report addresses hybrid automobile technology, the work performed by Lockheed on flywheels for buses is of significance and will be included in discussions in this section.

Only those materials that could be obtained in mill-run quantities were considered for the flywheel design studies. Eleven materials were chosen on the basis of high strength and/or low cost, as shown in Table 5-6. Recommended working stress was derived from studies for a hybrid flywheel design life of 10 million cycles. To facilitate a quantitative comparison, Lockheed calculated a normalized cost as follows: material cost was divided by the working-stress-to-density ratio and then divided by the resulting value for the least expensive material. Thus, the normalized cost represents the cost for each material to provide an equivalent energy storage capability for a given flywheel configuration. These normalized costs, shown in the right-hand column of Table 5-6, indicate that the most cost-effective materials are E-glass, S-glass, and 4340-grade steel. The filamentary composites, however, seem to be readily applicable to only the bar-type flywheel geometry. These filamentary composites might be used in a rim-type flywheel, but in Lockheed's opinion the web attachment and balancing requirements appeared to present significant problems. The 4340-grade steel was felt to be an excellent candidate material for application to low-cost flywheels in a disc configuration.

Table 5-6. Flywheel Materials Studied by Lockheed (Ref. 3-1)

Material	Density (ρ) ($lb/in.^3$)	Poisson's Ratio (ν)	Ultimate Tensile (F_{tu}) ksi	Yield Tensile (F_{ty}) ksi	Working Stress (σ) ksi	$\frac{\sigma}{\rho}$ ($\times 10^6$)	Material Cost ($/lb)	Normalized Cost ($/lb)
18NI-400 (Maraging Steel)	0.289	0.26	409	400	260	0.900	2.25	5.30
18NI-300 (Maraging Steel)	0.289	0.30	307	300	200	0.692	2.25	6.89
4340 Steel	0.283	0.32	260	217	130	0.459	0.60	2.78
1040 Steel	0.283	0.30	87	58	36	0.127	0.30	5.00
1020 Steel	0.283	0.30	68	43	25	0.088	0.30	7.23
Cast Iron	0.280	0.30	55	37	20	0.071	0.30	8.94
2021-T81 (Aluminum)	0.103	0.33	62	52	26	0.252	0.53	4.45
2024-T851 (Aluminum)	0.100	0.33	66	58	35	0.350	0.50	3.03
6Al-4V (Titanium)	0.160	0.32	150	140	82	0.512	4.00	16.55
E-Glass	0.075	0.29	200	–	67	0.890	0.42	1.00
S-Glass	0.072	0.293	260	–	87	1.210	0.75	1.31

The design capacity of the family car was placed at 0.5 kW-hr based on a required 0.395 kW-hr capacity. Similarly, the design capacity of the bus flywheel was set at 1.0 kW-hr capacity based on a required capacity of 0.604 kW-hr.

A total of 24 hybrid flywheel designs were found to be suitable based on the design constraints. These are summarized in Table 5-7, where it will be seen that 11 were suitable for application to the family car with an energy storage capacity of 500 W-hr. The optimum design for the family car from the standpoint of minimum assembly cost, size, and weight is the constant-stress disc of 4340-grade steel. The cost shown represents the projected assembly cost in automotive quantities after amortization of necessary tooling. On the basis of this preliminary screening, the decision was made by Lockheed to fabricate two 46-lb, 24,000 rpm flywheels from 4340-grade steel in the exponential geometry.

Similarly, the acceptable hybrid flywheel configurations for the city bus are seen in Table 5-7 to cover essentially the same range of geometries and materials as for the family car with the exception of the two filamentary composite flywheels. Again, the optimum flywheel for the city bus appeared to be the 4340-grade steel flywheel in the constant-stress disc configuration. However, it was decided by Lockheed that little additional information would result from fabrication and test of the 1.0 kW-hr flywheel in essentially the same configuration and of the same material as chosen for the 0.5 kW-hr flywheel, Therefore, the decision was made to fabricate a bar flywheel of S-glass filamentary composite bonded with epoxy having a 1 kW-hr capacity.

The intial constant-stress disc configuration was an exponential disc design. The early dropoff of both the radial and tangential stresses in this design indicated that more mass could be added to the periphery of the wheel, increasing the stresses throughout most of the flywheel and thereby improving the overall efficiency. Accordingly, a small rim was added, approximately 0.5 in. thick and tapering back into

Table 5-7. Flywheel Configurations Studied by Lockheed (Ref. 3-1)

Capacity (kw-hr)	Material	Geometry	Flywheel Speed (rpm)	Flywheel Weight (lb)	Assembly Weight (lb)	Assembly Volume	Assembly Cost ($)
0.5	4340	Pierced Disc	21,749	111.7	124.8	0.75	240.44
0.5	4340	Solid Disc	22,821	57.6	74.9	0.39	155.65
0.5	1040	Solid Disc	13,453	206.6	222.0	1.39	232.40
0.5	2021-T81	Solid Disc	13,394	105.0	127.9	1.95	235.65
0.5	2024-T851	Solid Disc	21,940	75.8	91.5	1.45	160.70
0.5	4340	Conical	23,410	52.0	69.1	0.20	145.18
0.5	2021-T81	Conical	18,698	92.1	112.3	1.0	201.08
0.5	2024-T851	Conical	22,970	66.2	82.5	0.75	148.17
0.5	4340	Constant-Stress	24,000	42.4	59.5	0.12	127.51
0.5	2021-T81	Constant-Stress	24,000	75.2	90.9	0.56	166.50
0.5	2024-T851	Constant-Stress	24,000	56.62	73.52	0.43	135.63
1.0	4340	Pierced Disc	17,308	225.9	242.0	1.52	454.85
1.0	4340	Solid Disc	21,746	115.1	133.7	0.78	262.86
1.0	1040	Solid Disc	10,678	413.1	433.1	2.78	431.52
1.0	2021-T81	Solid Disc	13,394	210.1	233.0	3.89	402.60
1.0	2024-T851	Solid Disc	17,714	151.5	171.7	2.89	287.88
1.0	4340	Conical	22,873	99.5	119.3	0.4	238.26
1.0	2021-T81	Conical	18,097	180.2	199.5	2.0	344.30
1.0	2024-T851	Conical	20,857	130.8	149.8	1.49	293.22
1.0	4340	Constant-Stress	24,000	83.8	104.8	0.22	213.66
1.0	2021-T81	Constant-Stress	24,000	150.3	166.0	1.10	286.00
1.0	2024-T851	Constant-Stress	24,000	110.0	127.9	0.83	218.56
1.0	E-Glass	Bar	15,132	87.6	136.5	9.90	260.59
1.0	S-Glass	Bar	19,199	63.3	108.9	7.63	274.54

the flywheel. With this design, the configuration was nearly conical from the hub out to a radius of 7.25 in. For ease in manufacture, it was decided to let this part of the configuration become conical, with a constant radius flare from that point to the rim. The final diameter, as fabricated, was 20.466 in. with a maximum disc thickness of 0.576 in. This is the same configuration as shown in Figure 5-3 and discussed in Section 5.1.1 for the family car hybrid/flywheel vehicle.

Tests on the first steel flywheel were conducted to verify windage losses and to determine the energy density at disintegration speed. Various levels of pressure in the test pit were used to determine the windage losses of the flywheel. The flywheel was driven by an air turbine; driving torque was estimated at various speeds from the power output curves of the turbine and the turbine inlet line air pressure. (An alternate means of determining torque was by use of a disc brake.) A comparison of the power losses calculated from measurements of torque and speed with the losses calculated using an EPA-supplied empirical equation is shown in Table 5-8.

In the test-to-failure, the flywheel was accelerated until disintegration occured at 35,590 rpm. This represented a peripheral velocity of 3,170 fps, an energy density for the flywheel rotor of 26.1 W-hr/lb, and a total stored energy of 1.1 kW-hr which exceeded the design specification by a factor of about two and accordingly provides a margin of safety. Lockheed indicated that failure may have been initiated at an occlusion on the surface of the flywheel.

Table 5-8. Lockheed Comparison of Power Loss Calculations (Ref. 3-1)

Flywheel Speed, rpm	Test Pit Pressure, psia	Loss (Calculated from Turbine Characteristics), hp	Loss (Calculated from EPA Equation), hp
14,110	8.35	14	15.3
12,530	14.7	13	17.3

Power density, spindown, and acoustic noise tests were conducted on the second steel flywheel. Power density measurements verified that at least 5,000 W/lb of usable power could be extracted from the 20.4 in. flywheel at various speeds. Spindown tests were conducted by taking the flywheel to 24,000 rpm and uncoupling it from the turbine. The test pit was evacuated to 0.2-mm Hg for this test. After 20 minutes of spindown, flywheel speed was down to 8,700 rpm, at which time the pit was vented to the atmosphere. At this low pressure the flywheel windage losses are essentially nonexistent, and the bearing and the brake disc were the major sources of drag (approximately 3 hp between 24,000 and 20,000 rpm). Bearing losses were high because of oil-flooding of the bearings.

Two glass flywheels were fabricated using the same bar-type configuration, but different layup procedures. Both were constructed of Ferro Corporation S-1014 glass fiber with 828/1031/NMA resin. Resin content was 22 percent by volume. The fabricated weight and dimensions were not reported by Lockheed for the bar-type flywheels. However, analysis of the test results indicates that the flywheel weight was approximately 77 lb. Design speed for the bar-type flywheels was 20,000 rpm with an energy storage capacity of 1.0 kW-hr.

The No. 1 glass flywheel of unidirectional construction was tested to demonstrate energy density, power density, spindown, and disintegration speed. Disintegration occurred prior to reaching the design speed of 20,000 rpm. The maximum energy storage capacity at failure (15,070 rpm) was 0.568 kW-hr as compared to the design point of 1.0 kW-hr. Lockheed reported that the massive disintegration that occurred after failure made it difficult to determine the failure mode. The break in the hub was stated to have the appearance of a tensile failure, indicating that a high transverse force was involved. This might have been attributable to transverse delamination.

During the energy density test of the No. 2 flywheel, disintegration occurred at 14,690 rpm. Again, the flywheel and hub were completely destroyed, although the added transverse fibers did serve to hold most of the longitudinal fibers together. Similar to the first flywheel, the hub had the appearance of a tensile failure. Lockheed reported that the failure may have occurred by means of the fiberglass moving longitudinally out of the hub.

Lockheed conclusions regarding the steel flywheel for use in the family car were as follows:

a. The production cost of complete family car flywheel assemblies was projected to be $100, plus or minus $15 depending on flywheel configuration.

b. All the elements of a practical family car flywheel assembly are available without further technology development.

c. Early estimates of flywheel system losses as provided to the transmission contractors were proved by hardware testing to be highly conservative. Flywheel windage, bearing, seal, and vacuum pump losses were substantially lower than earlier predictions.

d. Prevention of flywheel burst due to overspeed can be obtained by allowing the flywheel to grow plastically into the containment ring. Total containment of a flywheel burst at energy levels representative of what might be the case for a full-size vehicle were not successfully demonstrated with lightweight, low-cost materials. Containment of a burst at 0.86 hp-hr was demonstrated with a 192-lb steel ring and at 0.46 hp-hr with a 167-lb composite ring.

5.3.1.2 Johns Hopkins University, Applied Physics Laboratory

Experimental work conducted by Johns Hopkins University was directed toward a demonstration of the "superflywheel" concept in which energy densities of 30 W-hr/lb for flywheel rods or bars could be achieved. Spin tests of small diameter composite rods (up to 0.25 in.) and filamentary single strands were conducted in which the several candidate materials exceeded the flywheel rod energy density goal of 30 W-hr/lb. Follow-on tests of 30-in.-long, 1-lb rods or bars achieved 82 to 94 percent of the desired goal.

The results of the 30-in.-long, small diameter rod tests conducted at Johns Hopkins are summarized in Table 5-9. The 4- and 8-mil boron single strand filaments were tested prior to the installation of a diffusion pump in the test chamber vacuum system and were tested at 8×10^{-2} Torr and 4.7×10^{-2} Torr, respectively. All other tests were conducted at a nominal pressure of 1×10^{-3} Torr (1 Torr = 1 mm Hg abs).

The boron filaments were tested in a spin fixture powered by a motor having a rated speed of 39,000 rpm. This was insufficient to fail the boron filament rods, all of which were intact after spindown. The indicated energy densities for these materials are at the maximum indicated rpm and do not represent the energy density at failure. All other materials were tested to failure with higher speed drive systems.

Results from these tests indicated that the flywheel rod energy density goal of 30 W-hr/lb could be achieved with composite rods; valuable information was acquired on the selection of materials for subsequent tests of 1-lb bars. In reviewing the failure mode of the small rods, Johns Hopkins stated that a significant portion of their kinetic energy was dissipated by microfracture or vaporization of the matrix material.

Based upon the test results of the small rods, a joint decision was made by Johns Hopkins and EPA to fabricate the 1-lb bars or two materials: S-glass fiber in an epoxy matrix and a graphite/epoxy composite. The S-glass fiber was selected because of its low cost ($1.00/lb) and known characteristics. The filamentary graphite was selected over the filamentary boron because it has equivalent strength and potential for future price reduction (Johns Hopkins stated current prices of about $200/lb, but indicated an order of magnitude reduction would be possible in the near future for the graphite). The EPA/Johns Hopkins selection of the two markedly different materials (S-galss and graphite) was made to compare the strength levels and modes of failure.

Bars of each composite material were obtained from Hercules, Inc. Fabrication of the bars by molding (which would obviate the need for any surface machining) was considered, but was not used because of high

Table 5-9. Summary of Composite Materials, Rod Tests, Johns Hopkins (Ref. 5-3)

Test	Drive System[1]	Mounting System[2]	Max. Speed (rpm)	Max. Stress[3] (ksi)	E/W[3] (W-h/lb)	Remarks
AVCO Boron Filaments			W_r = 0.00035 and 0.00014 pound			
4-mil	Diehl	Tube	38 000	424	48	Rod did not fail; speed limited by motor
8-mil	Diehl	Tube	34 000	340	38	
General Technology Corp. Boron/ Magnesium 20-Mil Preform			W_r = 0.00075 pound			
1	Diehl	Epoxy	31 500	254	33	No failure; speed limited
Hercules Graphite/Epoxy 1/8-Inch Square			W_r 0.027 pound			
1	S/I	RTV	24 500	105	20	
2	G/S	RTV	19 000	66	12	
3	G/S	Epoxy	31 300	180	33[4]	
Fothergill & Harvey Graphite/Epoxy 1/16 Inch Square			W_r = 0.0066 pound			
1	S/I	RTV	22 400	91	17	
2	S/I	RTV	22 800	94	18	
3	S/I	RTV	22 400	91	17	
4	S/I	RTV	28 900	151	28	
5	S/I	RTV	26 200	124	23	
6	S/I	RTV	22 100	88	16	
7	G/S	Epoxy	33 000	195	36[4]	
PPG/BBI Type 525 E-Glass/Polyester (48% Fiber Volume) 0.098 Inch in Diameter			W_r = 0.015 pound			
1	G/S	Epoxy	23 600	116	19	
2	G/S	Epoxy	23 400	118	18	
3	G/S	Epoxy	24 000	123	19	
4	G/S	RTV	~19 800	~84	~13	Counter stopped just before rod failure
5	G/S	RTV	24 000	123	19	
6	G/S	RTV	23 200	115	18	
PPG/BBI Type 1055 E-Glass/Polyester (58% Fiber Volume) 0.098 Inch in Diameter			W_r = 0.016 pound			
1	G/S	Epoxy	27 000	165	24	
2	G/S	RTV	26 700	160	24	
PPG/BBI R-Composition Glass/Polyester (55% Fiber Volume) 0.098 Inch in Diameter			W_r = 0.015 pound			
1	G/S	Epoxy	28 900	177	28[4]	
2	G/S	Epoxy	30 700	194	31[4]	
3	G/S	RTV	<18 000	<65	<11	Failure before strobe synchronization
4	G/S	RTV	26 400	149	23	
Columbia Products (Shakespeare) E-Glass/ Epoxy, 0.250 Inch in Diameter			W_r = 0.091 pound			
1	S/I	RTV	14 400	41	7	Some indications rod pulled out of holder
2	S/I	RTV	14 600	42	7	

Table 5-9. Summary of Composite Materials, Rod Tests (Continued)

Test	Drive System[1]	Mounting System[2]	Max. Speed (rpm)	Max. Stress[3] (ksi)	E/W[3] (W-h/lb)	Remarks
Corning Glass Rods, 0.106 Inch in Diameter, 30.9 Inches Long			W_r	0.026 pound		
1	G/S	Acrylic	9 240	29	3	
2	G/S	Acrylic	9 480	28	3	
3	G/S	Acrylic	9 780	26	3	Failed awav from point of max. stress
4	G/S	Acrylic	9 900	32	4	d. o.
5	G/S	Acrylic	9 540	30	3	
6	G/S	Acrylic	10 260	36	4	
PPG Glass Rods in Steel Holder			W_{glass} = 0.0015 pound; W_{steel} = 0.32 pound			
1	G/S	Acrylic	25 100	165	14	E/W based on equivalent full circular brush (see text)

1 Drive System:

- S/I: Speed increaser
- G/S: Globe motor with spindle
- Diehl: Diehl motor

2 Mounting System:

- RTV: Dow Corning Silastic 734, room temperature vulcanizing
- Epoxy: Armstrong epoxy
- Acrylic: Acrylic cement
- Tube: Stainless steel tube support with epoxy cement

3 Stress and specific energy calculations assume constant rod cross-section, uniform mass distribution, and 30-inch length (spin diameter) except where noted; 1 ksi 1000 lb/in^2.

4 For the graphite/epoxy and R-glass/polyester materials, the better results were obtained with the Globe motor and epoxy mounting system.

tooling costs. The bars, therefore, were fabricated by laying up the composite tape to the required thickness and forming a plate from which the bars of square cross section were cut. Curing problems associated with the scotch ply tapes resulted in the S-glass/epoxy plate final form being less than the desired thickness. As a result, the square bars cut from the plate weighed only 3/4 lb instead of the desired 1 lb.

Results of the tests are shown in Table 5-10. The first test JH-1 was, as indicated, a facility check-out run using an available E-glass bar. Because of the leaks in the vacuum system (believed by Johns Hopkins to be attributable to the turbine drive spindle seal), it was not possible to achieve the desired vacuum levels. The vacuum achieved for each test is shown in Table 5-10, where it will be noted that the highest pressure, 25×10^{-2} Torr, was experienced on test No. JH-4. Johns Hopkins expressed the opinion that this was satisfactory for the short duration test, however, since the bending stresses induced in the rod by aerodynamic drag were less than 50 psi.

It will also be noted that all bars in spin tests failed to meet the expected stress levels (260,000 psi for S-glass; 200,000 psi for graphite) and the energy storage capacity of the flywheel bar of 30 W-hr/lb. Tensile tests of the two materials indicated that although the S-glass met or exceeded the expected stress level, the graphite/epoxy samples achieved an average stress of only 164,000 psi (84 percent of expected). Johns Hopkins indicated that the most probable reason for the lower tensile strength of the graphite/epoxy was the fact that the prepregnated tape, which was not that normally used by Hercules because of scheduling problems, resulted in only a 53 percent fiber volume instead of the expected 59 percent.

In the opinion of Johns Hopkins, differences between the stress levels achieved in the tensile tests and those achieved in the spin tests were attributable to several factors. Among these are: maintaining fiber alignment and fiber content, and achieving more uniform properties.

Table 5-10. Test Results for 1-lb Bar: Speed, Stress, and Specific Energy at Failure, Johns Hopkins (Ref. 5-3)

Parameters	Test Number					
	JH-1[a]	JH-2	--	JH-3	JH-4	JH-5
Material	E-Glass/ Polyester	S-Glass/ Epoxy	S-Glass/ Epoxy	Graphite/ Epoxy	Graphite/ Epoxy	S-Glass/ Epoxy
Cross Section	13/16-in.-dia	0.57-in.-square	0.56-in.-square	0.79-in.-square	0.78-in.-square	0.57-in.-square
Weight, lb	1.10	0.73	0.72	1.00	0.99	0.72
Speed, rpm	19,900	29,100	b	28,000	28,200	27,200[c]
Stress						
ksi	89	204	b	136	137	178
percent[d]	--	79	b	68	69	69
E/W, W-h/lb	13.2	28.2	b	26.1	26.5	24.7
Vacuum, Torr	1.8×10^{-2}	6.3×10^{-2}	b	17×10^{-2}	25×10^{-2}	19×10^{-2}

[a]Facility and instrumentation checkout

[b]No test--facility failure

[c]Test aborted at this speed. Rod subsequently failed at 24,700 rpm

[d]Percent of expected value quoted by Hercules

High-speed photographs of the failure mode for each of the two types of rods tested revealed a significant feature of filamentary flywheel failure compared to metal flywheels. The photographs showed that both types of rods were essentially destroyed in less than 1 ms and before motion of the containment ring was detected. Analysis of the relative rates of rod destruction and containment ring response by Johns Hopkins revealed that only 1 to 2 percent of the kinetic energy of the rod was transferred to the containment ring, with the remainder of the energy being dissipated by pulverization of the rod itself. In contrast, a steel disc rotor will generally fracture into several large fragments with transfer of nearly all energy to the containment ring.

The following conclusions were reached by Johns Hopkins regarding the testing of filamentary and composite rods and bars:

a. Spin tests demonstrated the ability to achieve 48 W-hr/lb (without failure) with boron filaments; at burst, 36 W-hr/lb was achieved with small graphite/epoxy composite rods, and 31 W-hr/lb was achieved with small R-glass/polyester composite rods.

b. The larger 1-lb composite rods did not meet the desired 30 W-hr/lb. The best sample S-glass/epoxy achieved 28 W-hr/lb while the graphite/epoxy achieved 26 W-hr/lb.

c. Tensile tests indicated that the graphite/epoxy material was substandard. While the S-glass/epoxy bars achieved satisfactory stress levels in tensile tests, numerous surface defects may have contributed to the inability of this material to meet 30 W-hr/lb requirements. With improved processing techniques, Johns Hopkins felt confident that energy densities in excess of 30 W-hr/lb could be achieved.

d. Analysis of the failure modes of both the filamentary and composite materials tested showed that only 1 to 2 percent of the kinetic energy of the rod was transferred to the containment ring.

5.3.2 Transmission

The transmission converts energy output of the engine to useful levels of torque at the vehicle wheels. Ideally, the transmission should have the following characteristics:

a. High efficiency over the normal operating range
b. Control simplicity for optimum performance
c. Low volume for compactness
d. Low noise
e. Low specific weight
f. Reverse-power and braking capability
g. Capability of absorbing road shocks
h. Low power consumption during engine start and at idle

The operational and economic feasibility of a hybrid system depends in large part on the above features and on a reasonable low cost for the transmission.

The selection or design of a transmission for a hybrid system will depend primarily on the type of hybrid powertrain arrangement, the energy storage method used, and the relative speed between various powertrain elements. In a heat engine/flywheel hybrid, the transmission links three main components: engine, flywheel, and drive wheels. Figure 5-12 shows the power connection for both a parallel and series hybrid configuration. In the parallel system shown, power can be delivered to the drive wheels directly from the engine or through a flywheel. Because the flywheel spins at very high speeds, unique forms of wide speed range transmissions are required.

In a heat engine/battery hybrid, the electric drive motor acts as the transmission for the series configuration. Hence, the discussion in this section addresses the subject of unique transmission for heat engine/flywheel hybrid vehicles only.

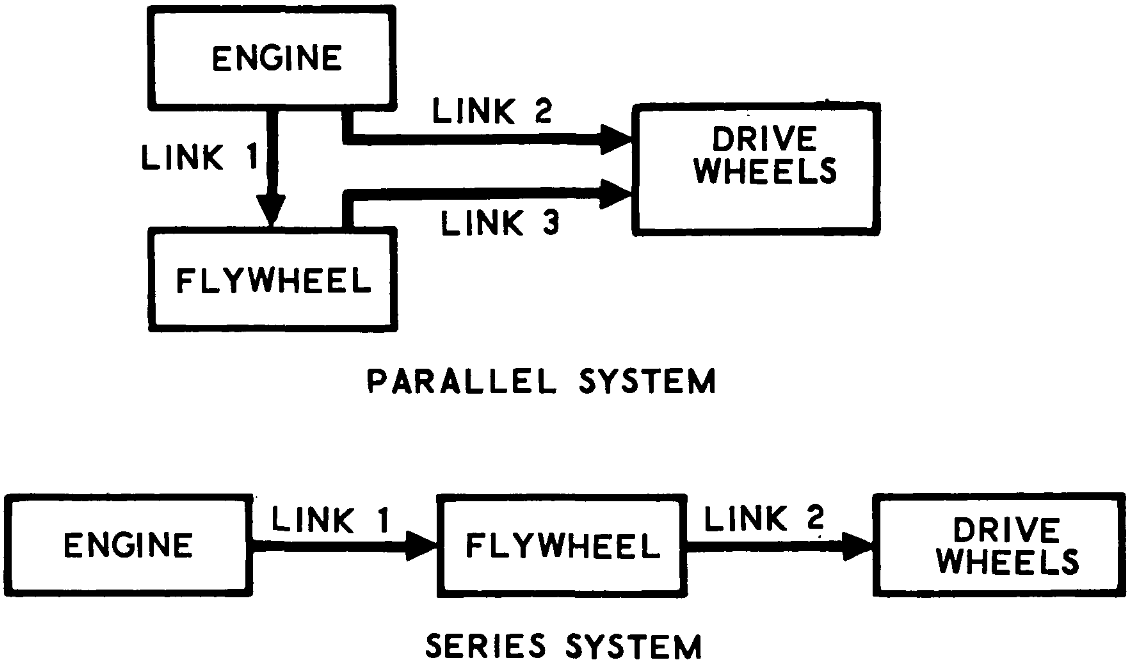

Figure 5-12. Parallel and Series Configurations for Energy Flow in Hybrid Vehicles (Ref. 5-2)

5.3.2.1 Parallel Configuration Operation

Under EPA sponsorship two studies were conducted on transmission designs for a parallel configuration flywheel hybrid system. These studies were conducted by Sundstrand Aviation (Ref. 5-2) and Mechanical Technology, Inc. (MTI) (Ref. 5-1). Both studies examined (a) the development of total energy transfer systems from the hybrid engine to the drive wheels and (b) the management of the energy storage system.

As shown in Figure 5-12, for parallel operation, two types of transmissions are required. From flywheel to the load an infinitely variable transmission is needed (Ref. 5-2). A standard three-speed transmission is adequate between the engine and the load for all engines considered, except for a single-shaft gas turbine. It requires a continuously variable speed transmission - a transmission that has not been fully developed.

5.3.2.1.1 Sundstrand Aviation Study

The Sundstrand study assessed the practicality of a transmission for use in a heat engine/flywheel hybrid system for a full-size family car. In this study, a number of possible types of links between the engine, flywheel, and drive wheels were analyzed: mechanical, hydrostatic, and hydromechanical.

An infinitely variable hydromechanical transmission was selected between the flywheel and the drive wheels. For the engine-flywheel transmission, the engine speed was fixed at each power level to ensure operation near minimum SFC or minimum emission levels. A fixed speed ratio between the engine and the flywheel was not sufficient and hence a transmission was required. Sundstrand selected a combination mechanical, hydromechanical, and hydrostatic transmission system for links 1, 2, and 3, respectively (Figure 5-12). This transmission, called Baseline 8A, is made up of a five-element differential, several hydraulic units (variable and fixed displacement), clutches, controls, and associated gearing. By controlling the displacement of the variable hydraulic unit, it is possible to control the reaction torques in the five-element differential. By controlling these torques, it is possible to control the direction of power flow and hence extract energy from the flywheel and supply this energy to the "output" or take energy from the "output" and supply it to the flywheel, as required.

In considering the Federal Emissions Test Driving Cycle it was discovered that with the Baseline 8A transmission the engine was not running continuously at minimum fuel consumption conditions. But the required engine speed versus vehicle speed characteristics for minimum SFC could be very closely approximated by putting a clutch on the input, such that at light accelerator pedal loads below 50 mi/hr, the engine input comes into the variable hydraulic unit (V-unit), and at heavy accelerator pedal loads below 50 mi/hr, or at any load above 50 mi/hr, the engine input comes directly into the differential gear set. This arrangement, the alternate 8C transmission, shown in Figure 5-13, allows the engine to run at a slower and more economical speed at the slower road speed and lighter load conditions, but allows higher engine speed operation (when the engine would otherwise be power limited) at the higher load and/or higher road speed conditions.

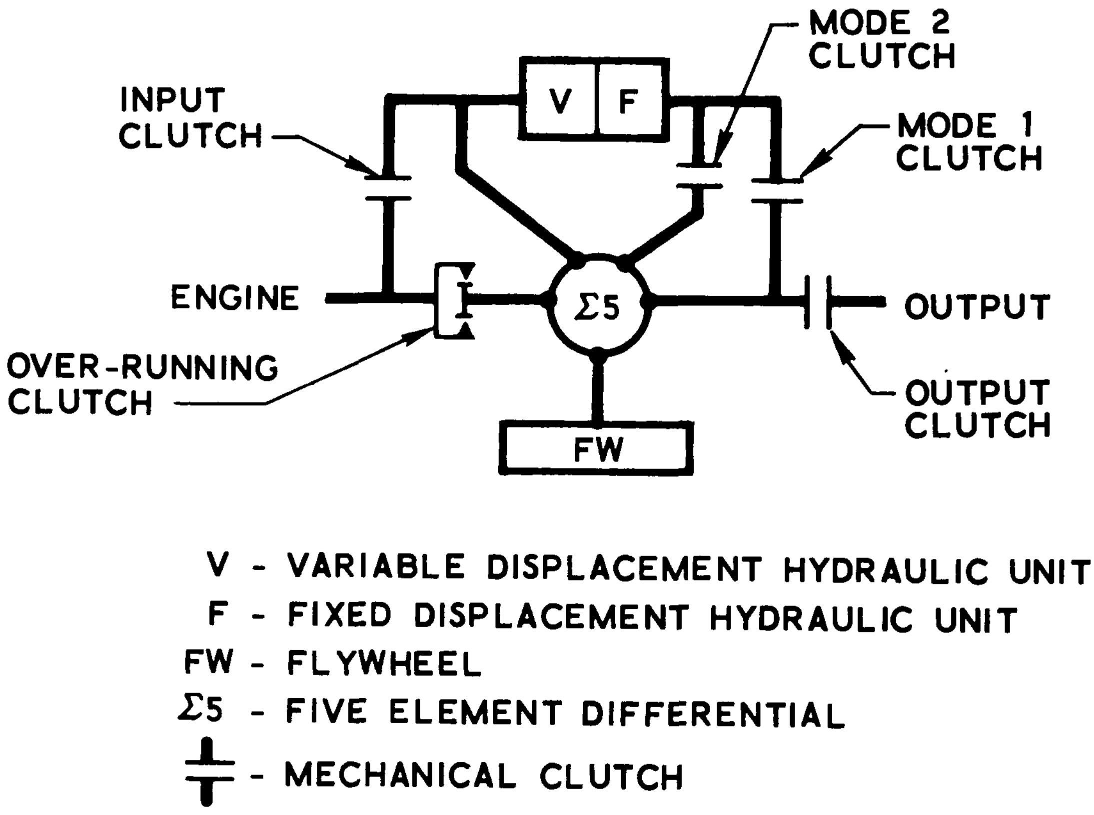

Figure 5-13. Sundstrand Alternate 8C Transmission (Ref. 5-2)

On the basis of fuel consumption calculations utilizing ideal energy storage versus ideal non-energy storage transmission systems operated over the Federal Emissions Test Driving Cycle, Sundstrand concluded that the amount of energy available for storage and reuse, as regenerated on deceleration by a light vehicle operated over the Federal Emissions Test Driving Cycle, was relatively small. This fact was reflected in Federal Emissions Test Driving Cycle fuel consumption calculations made for the Baseline 8A and Alternate 8C transmission and for a typical three-speed automatic. These results, shown in Table 5-11, indicate that the Baseline 8A system has a poorer fuel economy than the Alternate 8C system, and that both of these have poorer fuel economy than the standard transmission when transmission losses are estimated and included in the energy computation ("real" case).

The results of constant speed fuel consumption calculations for the two hybrid storage/transmission systems compared with results for a typical three-speed transmission are shown in Table 5-12. As expected, transmission 8C has fuel economy that is superior to transmission 8A up to approximately 50 mi/hr. It can also be seen that the three-speed automatic transmission has better fuel economy below 50 to 60 mi/hr. Above this value, the two hydromechanical flywheel transmissions exhibit superior fuel economy. These results largely reflect the fact that the flywheel transmissions are configured to permit the engine to operate at or near minimum SFC at higher speeds.

In conclusion, Sundstrand stated that:

a. A combination of mechanical, hydromechanical, and hydrostatic transmissions is a practical means of providing power for the flywheel, heat engine, and drive wheel links.

b. The selected transmission provides an infinitely variable ratio between the flywheel and the vehicle wheels, and a nonlinear ratio (fixed by vehicle speed) between the heat engine and flywheel. Although the engine speed is not independent of the flywheel speed, it does operate near its minimum SFC line.

Table 5-11. Sundstrand Transmission Evaluation -- Federal Emissions Test Driving Cycle (Ref. 5-2)

Transmission	Results, mpg		
	Flywheel Energy Storing Transmission		Nonenergy Storing Three-Speed Automatic Transmission
	Baseline 8A	Alternate 8C	
"Real" (with estimated transmission losses)	7.96	9.26	11.14
"Ideal" (zero transmission losses, flywheel losses are included)	9.78	12.66	11.99
Note: Vehicle weight 4,300 lb			

Table 5-12. Sundstrand Estimate of Constant Speed Fuel Consumption (Ref. 5-2)

Constant Speed, mi/hr	Results, mpg		
	Baseline 8A	Alternate 8C	Three-Speed Automatic
20	9.82	12.62	15.58
30	11.41	12.47	17.86
40	14.42	15.59	17.92
50	16.04	16.80	16.92
60	16.59	16.59	14.30
70	16.25	16.25	11.91
80	13.32	13.32	10.34
Note: Vehicle weight 4,300 lb			

c. The specified spark ignition heat engine with the selected transmission has a greater computed fuel consumption over the Federal Emissions Test Driving Cycle than that of a typical three-speed automatic transmission. Cruise fuel consumption is greater than for the three-speed automatic below 50 mi/hr and less above this speed.

d. The theoretical fuel economy benefits that can be gained from the flywheel energy storage concept over a "light duty" cycle such as the Federal Emissions Test Driving Cycle is minimal because of the small amount of energy available for storage and reuse. In fact, when the "cost" of storage in terms of power loss is included, there is no benefit. The more "severe" the acceleration/braking duty cycle relative to maximum vehicle capability and the heavier the vehicle, the greater are the benefits derived from the flywheel energy storage concept.

5.3.2.1.2 Mechanical Technology, Inc. Study

The study performed by MTI basically arrived at the same conclusions as Sundstrand. Mechanical Technology proposed a power splitting transmission (Ref. 5-1). This transmission is an infinitely variable, stepless unit that obtains torque multiplication and control by hydraulic principles. It is intended for use in a medium-size automobile.

The unit differs from the torque converter or fluid coupling hydrodynamic-type transmissions in that the power in the hydraulic circuit is transferred by fluid static pressure at low flow rates, whereas the hydrodynamic unit uses high flow rates and the inertial motion of the fluid to transfer power. Basically, the transmission system consists of a flywheel planetary gear train, hydraulic variable displacement elements, connecting drive gears, an output planetary gear train, and a control system.

As shown in schematic form, Figure 5-14, three planetary gear trains are used in the assembly to (a) provide a power path for the flywheel, (b) direct the output power when the vehicle is in the high-ratio range, and (c) provide a low-ratio range power path.

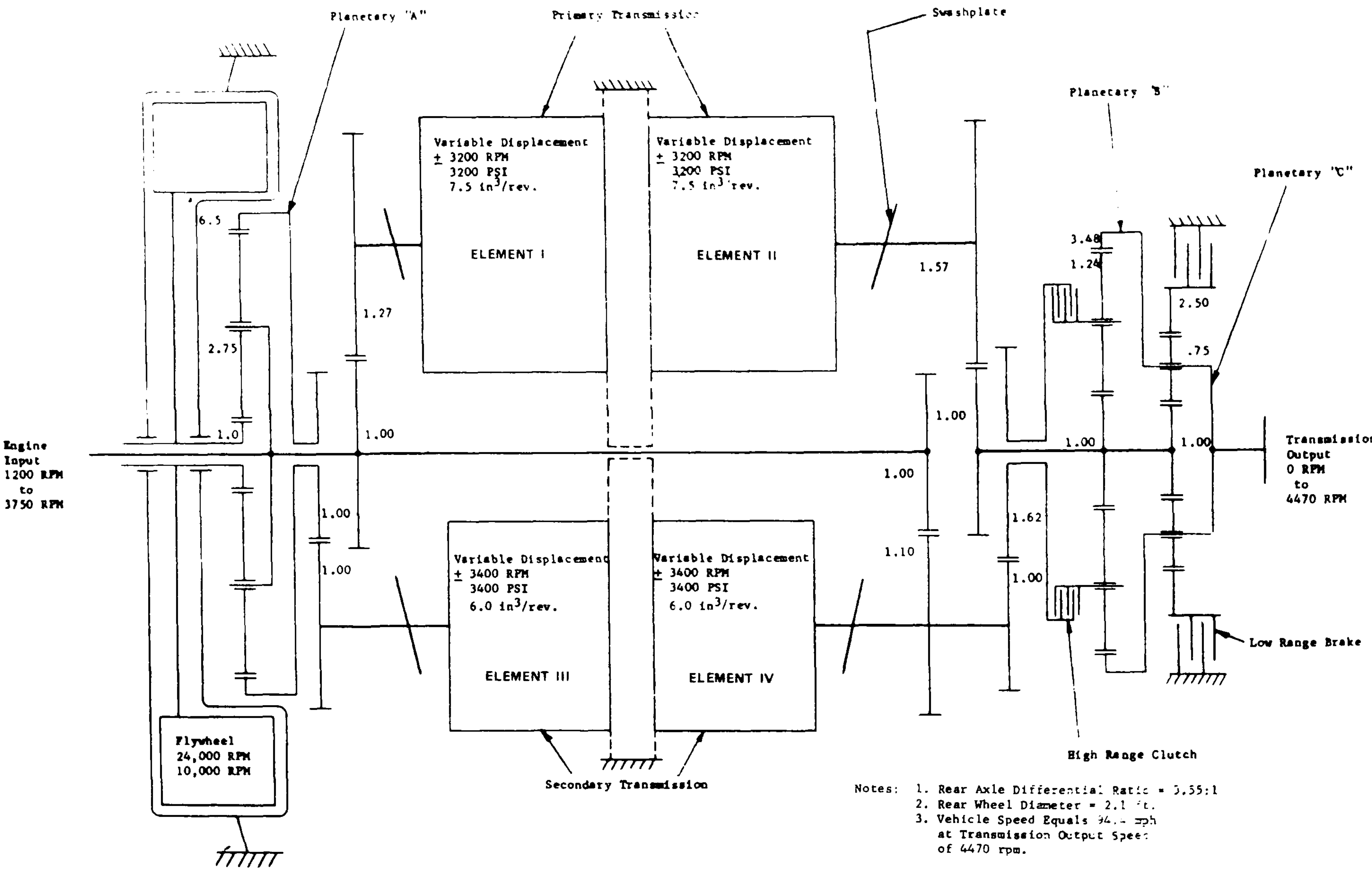

Figure 5-14. Schematic of the MTI Recommended Transmission Design (Ref. 5-1)

The overall transmission consists of two separately controlled split-path hydrostatic links: the primary path that establishes a given ratio between the engine and vehicle for optimum torque-speed loading of the engine in a steady-state mode, and the secondary path that controls the direction and magnitude of power flow to and from the flywheel during vehicle velocity transient. In each of the primary and secondary sections, the hydrostatic transmission consists of two identical positive displacement units - Elements I and II for the primary and Elements III and IV for the secondary circuits.

The output torque is a function of the hydraulic pressure and the displacement of the hydrostatic units. If the torque increases, the displacement or pressure of the units must increase.

The secondary or flywheel drive section operates over a relatively small speed ratio and only operates for short bursts of power. The major power to and from the flywheel is transmitted by the planetary. The hydrostatic drive functions on both sides of the mechanical drive serve only as a positive speed control.

Figure 5-15 shows a comparison between the efficiencies of powertrains for flywheel hybrid and the standard automobile for cruise operation. As shown, the efficiency of the flywheel/hybrid powertrain is substantially lower even though the transmission efficiency for the hybrid transmission is higher (Figure 5-16). The fuel economy of the hybrid automobile compared to the standard automobile is poor up to a cruise speed of 50 mi/hr, but at higher speeds it has superior fuel economy.

5.3.2.2 Series Configuration Operation

In the series configuration for the hybrid heat engine/flywheel vehicle as discussed in Reference 5-3, the engine drives the flywheel and the flywheel drives the car. In such a scheme, an infinitely variable transmission is required between the engine and the flywheel as well as between the flywheel and the load. Mechanical Technology, as did Sundstrand, selected a hydromechanical infinitely variable transmission for this configuration.

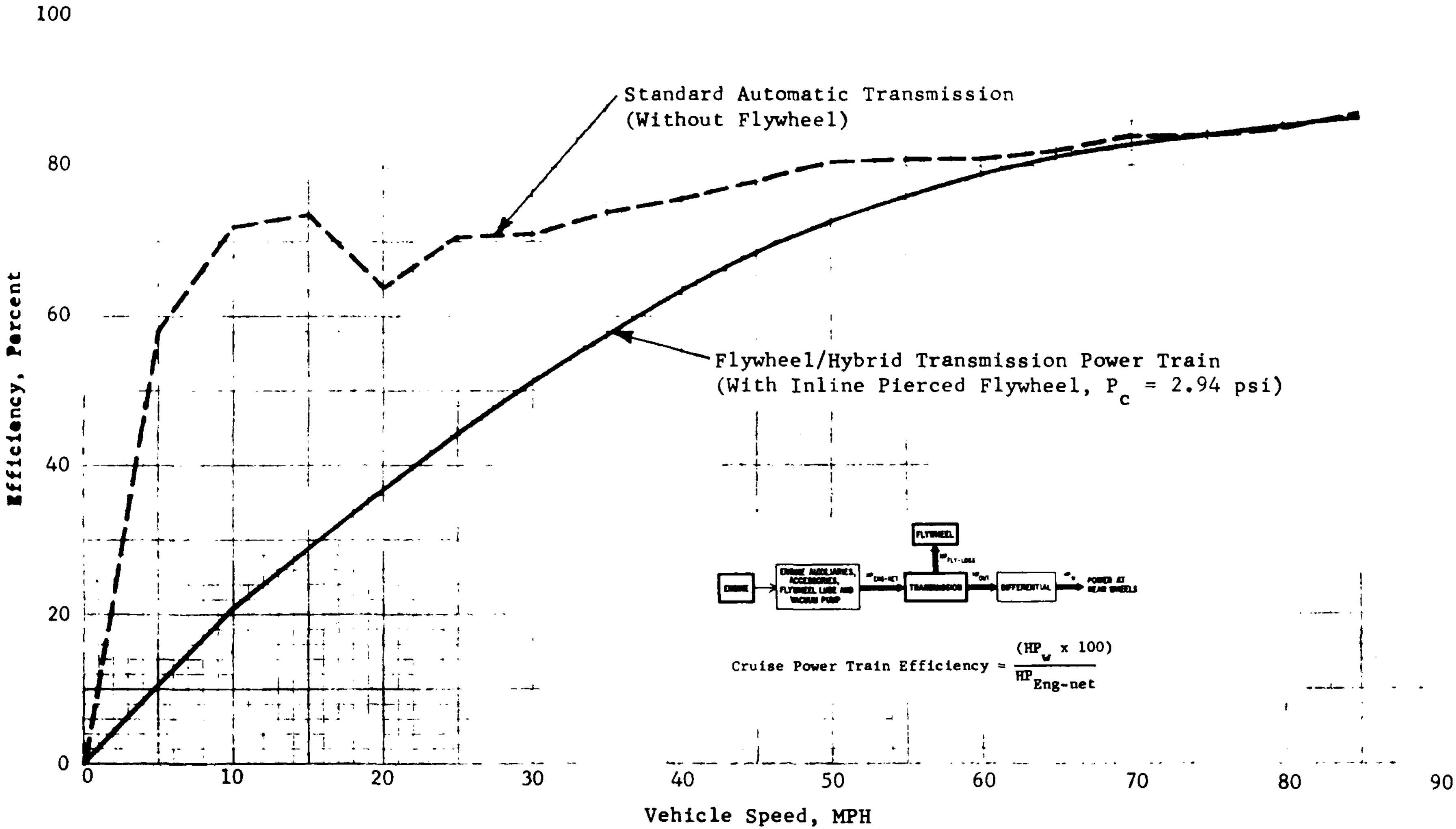

Figure 5-15. MTI Powertrain Efficiency Comparison at Cruise Power (Ref. 5-1)

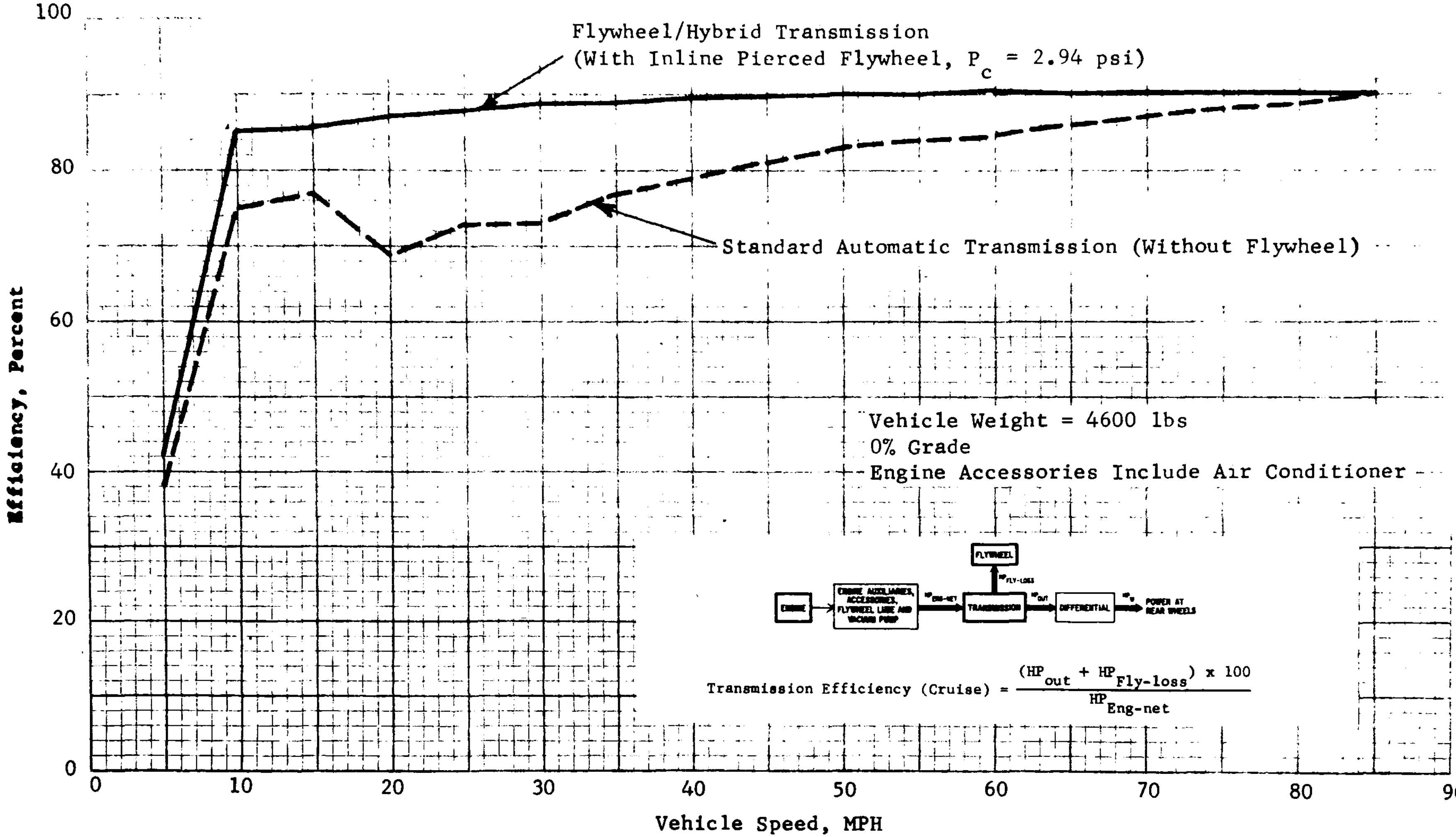

Figure 5-16. MTI Comparison of Transmission Efficiencies at Cruise Power (Ref. 5-1)

5.3.2.3 Other Transmission Designs

There are several other types of transmissions that have been evaluated. In an EPA-sponsored program "Automobile Gas Turbine Optimization Study" several contractors studied transmission systems for use with gas turbine automotive power plants. The single-shaft gas turbine requires an infinitely variable speed transmission. Traction and belt transmissions are two types of infinitely variable speed transmissions that are discussed in Reference 5-5 and summarized in Reference 4-13. These transmissions, which are candidates for use in the hybrid vehicle, are briefly discussed below.

5.3.2.3.1 Traction Transmission

Traction transmissions are not currently commercially available for large power output devices. A recent company development effort in this area by Tracor, Inc. has resulted in the design of a special metal traction device for transmitting torque at the high power levels associated with automotive drives (Ref. 5-5).

The Tracor design uses toroidal discs and rollers, special hydrostatic thrust bearings, and a specially prepared lubrication oil (Monsanto's Santotrac 30). Roller position is controlled so that the transmission can operate in a speed step-up, or in a speed step-down, or in a direct-drive mode. According to Tracor, the favorable features of the traction transmission include low noise, high-speed operation (up to 10,000 rpm input speed), compact size, a wide speed range capability, and comparatively low cost.

The estimated efficiency of the Tracor traction transmission serving a 250-hp engine is shown in Figure 5-17. Over a wide range of vehicle speed, the transmission efficiency is between 85 and 90 percent, somewhat lower than the performance of the hydromechanical system shown in Figure 5-16.

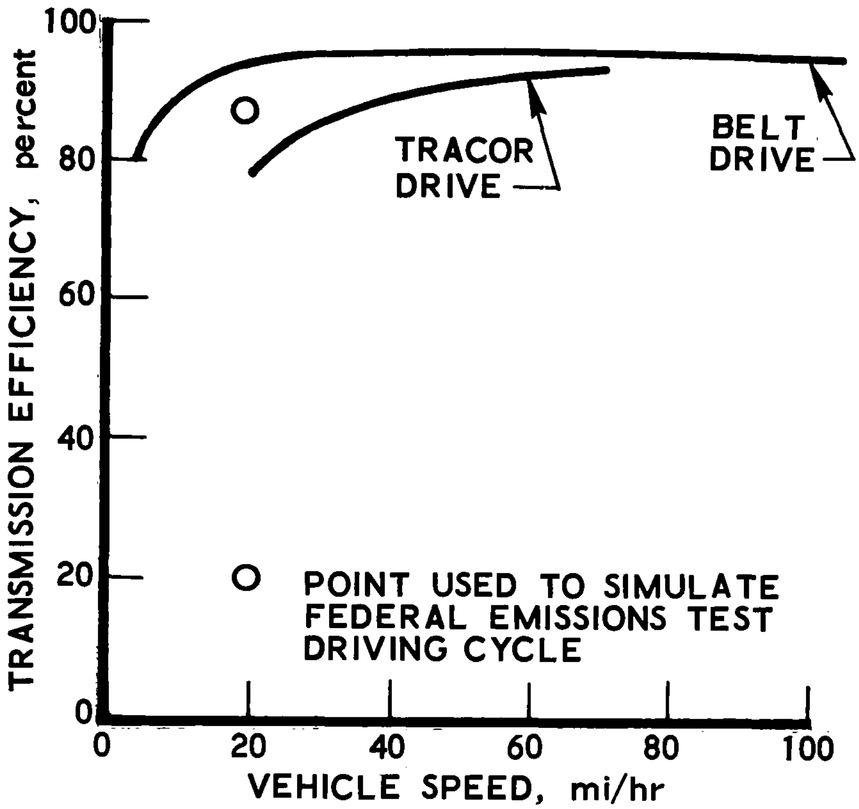

Figure 5-17. Transmission Efficiency at Cruising Conditions for Different Drives, Single-Shaft Gas Turbine Engine (Refs. 5-5 and 5-6)

5.3.2.3.2 Belt Transmission

The belt drive used for high-torque transmissions benefits from a recent development in high-strength rubberized composites and is based on a unique bent-axis concept that affords nearly optimum design. Estimated efficiency versus speed performance of this type of transmission is presented in Figure 5-17. As can be observed, the belt drive transmission has very high efficiency (substantially higher than the toroidal traction drive). In general, the belt drive transmission is presently limited to lower absolute speeds than the toroidal traction system. Further development of this system would be required to match its characteristics with the operating speed range and torque characteristics for several of the candidate heat engines considered for use in the hybrid system.

5.3.3 Heat Engines

The discussion on this subject can be found in Section 4.3.4 for heat engine/battery hybrid vehicles. Though equally applicable to heat engine/flywheel vehicles, it will not be repeated here.

6. OTHER ENERGY STORAGE CONCEPTS

6. OTHER ENERGY STORAGE CONCEPTS

6.1 HYDRAULIC ACCUMULATOR SYSTEM

Some recent studies of hydraulic accumulators with application to hybrid engines are reported in Refs. 6-1 and 6-2. Reference 6-1 reports on a simple, basic accumulator system built and tested in the laboratory. For straight hydraulic power transmission, pump-to-motor, an efficiency of 80 to 85 percent is estimated in simulated steady, high-speed cruise. Reference 6-2 also reports on studies involving a laboratory accumulator hybrid engine system. References 6-3 and 6-4 report on studies of methods of improving accumulator efficiency by reducing the thermal losses. Basically, the approaches involve the use of metallic or fibrous materials in the high-pressure gas to act as heat sink regenerators. Condensible gases greatly improve the efficiency. Either method tends to maintain isothermal conditions in the gas during compression and expansion cycles. Reference 6-3 indicates reduction of losses to less than 2 percent using a foam fill. Reference 6-4 reports performance improvements of 15 to 40 percent using fine copper strands. Any accumulator design that reduces the magnitude of the gas pressure change with volume change results in improved accumulator performance.

While some of these studies of hydraulic accumulators concern simple laboratory hybrid engine systems, none considers the performance, size, weight and practicality of such a system installed in a vehicle. A preliminary analytical evaluation of a vehicular system proposed by the U.S. Navy, Pacific Missile Range (PMR) is reported in References 6-5 and 6-6. Although several types of heat engines are applicable in the system, the example studied involved a Rankine cycle. The system was assumed to be installed in a 4,000-lb automobile.

6.2 ELECTRICAL CAPACITOR STORAGE SYSTEMS

These systems, at least with current state-of-the-art capacitor technology, would have to be very large in volume to store the necessary energy. Practical energy densities in capacitors are about one ten thousandth that of a good battery. Because of high internal energy leakage rates, energy storage in very high voltage capacitors could only be for brief periods. Even if they could be built, the power transfer efficiencies would probably be very low.

6.3 PNEUMATIC ENERGY STORAGE SYSTEMS

These systems (not involving a liquid system, as in a hydraulic accumulator) are inherently inefficient because of the large work required to pump gases to high pressures.

6.4 THERMAL ENERGY STORAGE SYSTEMS

These systems are subject to the same large thermodynamic efficiency losses suffered by the heat engine during initial energy generation. No other temporary energy storage schemes have been proposed.

6.5 FUEL CELL/BATTERY SYSTEMS

These systems have been proposed, but these are subject to the limitations imposed by the large volume, high cost, and limited lifetime of current fuel cell systems.

7. ASSESSMENT OF HYBRID POWERTRAIN APPLICATION TO AUTOMOBILES

7. ASSESSMENT OF HYBRID POWERTRAIN APPLICATION TO AUTOMOBILES

7.1 TECHNOLOGICAL AND ECONOMIC STATUS

At the time of program suspension, EPA funds expended on the hybrid vehicle development program had resulted in some major technology advancements, a much clearer definition of critical problem areas, and the establishment of preferable system operating modes. These results are indicative of information acquired in the very early phases of development--namely, proof-of-principle. To date, the major portion of a full prototype development program for hybrid personal passenger cars has never been performed. Some forms of hybrid systems could represent an intermediate step between current automobile power plants and a future system that relies totally on an energy storage device for delivering power to the drive wheels.

7.1.1 Major Technical Accomplishments

Both heat engine/battery and heat engine/flywheel hybrid systems have been analyzed extensively. Operation of these systems for powering an automobile on grades, at highway speeds, and in urban traffic has been simulated on computers. This effort has resulted in the definition of performance requirements and size and weight for components and subsystems that make up the powertrain system. Exhaust emission levels and fuel consumption levels were then determined analytically for various degrees of design sophistication, and performance specifications were established for critical components such as batteries, flywheels, and control systems.

Two heat engine/battery hybrid systems were built and tested. One was a complete laboratory breadboard model and the other was installed in a research automobile. In both cases, exhaust emissions were measured and component, subsystem, and system efficiencies were determined on the basis of experimental data acquired in system tests.

Dual development programs were initiated for the energy storage devices. These programs for development of batteries and flywheels were divided into near-term and advanced concepts. The programs progressed beyond the design stage to the point where laboratory models were tested to evaluate the concepts. Data were acquired that showed how well each design met the previously established specifications.

Concepts for flywheel transmission systems were analyzed and designs were formulated to meet speed and power requirements. Performance of these designs was simulated in analytical studies of vehicle operation in stop-and-go driving and highway cruising.

7.1.2 Technical Development Status

7.1.2.1 Systems

The powertrain has only been tested as an integrated system for the heat engine/battery hybrid, not for the heat engine/flywheel hybrid. Test results showed that the concepts were technically feasible and could operate over the desired power and speed range. System efficiencies were lower than desired and exhaust emissions from the spark ignition engines could only approach the original 1976 Federal emission standards by means of the application of a catalytic converter, exhaust gas recirculation, and lean operation. This additional complexity compromises one of the original hopes for the hybrid vehicle; i.e., that these engine changes would not be required. The contractors claimed that with further development some system deficiencies could be corrected.

In assessing the results objectively it must be recognized that the systems involved the use of contemporary hardware for components. These powertrain elements had not been designed specifically for application to a hybrid vehicle and, therefore, marginal performance levels might be expected. This is particularly true for the heat engines and electric motors. Test results might have been more encouraging had these systems benefited from a comprehensive component development program aimed at optimization of performance levels for hybrid powertrains. An effort of this type was initiated to develop more efficient lead-acid batteries.

Based on reasonably attainable performance for near-term design of components and energy storage devices, only three heat engines were found to be feasible for installation in engine compartments of current automobiles converted to a hybrid system. These power plants are the spark ignition reciprocating engine, the spark ignition rotary engine, and the gas turbine engine. Diesel, Stirling, and Rankine cycle engines proved to be too heavy and too bulky. However, as these engines undergo successive development stages this conclusion may have to be revised, particularly for new versions of the Stirling engine. An automobile designed specifically for hybrid operation might also relieve the problem of differences between required space/weight and allowable space/weight for the powertrain.

7.1.2.2 Components

Tests of commercial lead-acid batteries showed relatively poor life at the performance required for this application. Battery redesigns and more advanced concepts for lead-acid cells resulted in the achievement of power and energy levels that represent a major increase over standard batteries for this application, leading to optimism regarding the ability of these designs to meet most of the established performance specifications. However, cycle life, while greatly improved, is still short of specified goals. Resolution of this deficiency would require further development work for both lead-acid and other battery types. Changes in heat engine operating modes might result in reduced requirements in battery specifications.

Both conventional steel disc-shaped flywheels and advanced material concept bar-shaped flywheels were tested to destruction. The conventional design met the specified goals for energy storage level before failing, but the advanced concepts failed at rotational speeds short of planned levels. Fabrication problems with the advanced concepts and difficulty in avoiding undesirable stress concentrations led to early failure. Resolution of some of these problems by EPA contractors appeared to be possible, but suspension of the hybrid vehicle program prevented verification of the proposed corrective action.

7.1.3 Economic Status

Only a limited investigation was made of the estimated consumer purchase cost for a hybrid vehicle. The limitation to establishment of a more precise figure was caused by the lack of a definitive system designed specifically for mass production and by the paucity of data for costs of mass produced components such as advanced concept flywheels, large electric drive motors, and sophisticated electronic control systems. (The greatest potential for cost reduction was found to reside with the control system.) Based on preliminary coarse estimates, the purchase cost of hybrid vehicles is expected to be significantly higher than that of current automobiles, particularly for hybrid vehicles with advanced concept engines (e.g., gas turbines). However, an analysis of lifetime costs for the hybrid vehicle has not been performed wherein vehicle first cost, maintenance cost, engine fuel cost, and battery replacement[11] cost would be assessed.

7.1.4 Critical Problem Areas

Some critical problems which must be addressed before a successful prototype hybrid vehicle is developed are:

a. Achievement of battery performance goals in terms of power density, energy density, cycle life, and low cost.

b. Achievement of advanced concept flywheel goals in terms of energy density and cycle life.

c. Demonstration of low-cost flywheel transmissions meeting performance requirements in terms of efficiency, power extraction, and durability over the entire operating range.

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[11] Assuming flywheel fatigue life exceeds vehicle life, no flywheel replacement cost is involved.

d. Development of lightweight, production type electric drive motors and generators that have high efficiency at part-load operation as well as at design load operation.

e. Design of an efficient, low cost, versatile, control system and demonstration of its capabilities.

f. Development of a heat engine designed specifically for hybrid mode operation and determination of any improvement in exhaust emissions and fuel consumption.

g. Integration into a system of all improved components in a gradual, step-wise fashion and verification of system performance and durability.

The aforementioned goals for technical achievement would necessarily have to be coupled with a continual reassessment of hybrid power train production and operating costs. Failure to achieve any one of the stated goals within a carefully planned prototype development program for a battery or a flywheel hybrid would seriously jeopardize successful development of this vehicle.

7.1.5 Alternative Vehicle Design Goals

Some additional system design considerations are worth mentioning at this point. First, some of the vehicle performance specifications adhered to during the EPA contractor studies could be relaxed for evaluation of a special purpose rather than a general purpose car. Allowing a reduction in acceleration levels and peak cruising speeds is anticipated to yield marked reductions in the required level of battery or flywheel power density. This result stems from two sources: (a) reduced power required, and (b) additional weight and volume available because of reductions in the size of the heat engine and transmission and, for the hybrid battery vehicle, reductions in the size of the generator and electric drive motor.[12] Thus, rather than considering a hybrid vehicle designed to replace general-purpose personal passenger cars in use in the U.S., the objective rather would be to determine

[12] Particularly for the series configuration.

just what percentage of all the various transportation needs could be fulfilled by this special-purpose, limited-use type of vehicle.

Second, consideration could be given to the multimode form of hybrid vehicle operation. As an example, recharging of the energy storage device (battery or flywheel) could be accomplished wholly or in part by an external stationary power source rather than solely by the on-board heat engine. The bimodal design would permit independent operation whereby the vehicle is powered either by the battery (or flywheel) alone or by the heat engine alone.

The multimode form of operation would of course require relaxation of the specification for vehicle range. (However, the heat engine would continue to be available for providing range extension whenever required.)

The most important impact could be the transfer of the energy resource base from petroleum-based fuels to coal, because electric generating plants would now supply all or part of the recharge energy.

7.2 PROGNOSIS FOR CONTRIBUTING TO NATIONAL PERSONAL TRANSPORTATION NEEDS

Validity of any prognosis made for future application of an alternative automobile power plant is highly dependent on the availability of clarifying information on system performance and cost. In this regard, the necessary background data on hybrid vehicles is still quite limited and, therefore, the estimates given herein will bear further scrutiny (and possible revision) as additional data may be acquired in the future.

The hybrid vehicle has been proven to be a valid functioning system both by analysis and limited experimental tests, although not all of the original program goals were met. At the inception of the EPA hybrid vehicle program emphasis was placed mainly on reduction of exhaust emissions to the then promulgated original 1976 Federal emission standards. If the program were to be reactivated, the vehicle designs would now have to strike a balance between fuel economy and exhaust emissions and system performance would have to be re-evaluated in the light of the revised standards.

System efficiency requires further improvement to match original goals, and such improvement appears to be quite possible. Vehicle performance is marginal when configured with a conventional chassis and off-the-shelf hardware modified to reflect improvements that evolved from the EPA component development program. Although tests confirmed a major reduction in exhaust emissions compared to 1970 model conventionally powered cars, the primary objective of providing very low exhaust emission levels without exhaust after-treatment devices has not been met. The prospects for further improvement are not good unless the heat engine is designed specifically to operate in the hybrid mode. Furthermore, fuel consumption levels were no better than those for conventionally powered cars even with regenerative braking; again, some improvement might be possible with a new type of engine.

An automobile designed specifically for hybrid operation and for packaging of advanced design components and subsystems could fulfill all performance specifications although durability (in particular battery and flywheel cycle life) is still in doubt.

The purchase cost of a hybrid vehicle is currently estimated to be excessive, particularly when equipped with advanced engine systems. This is a major deterrent to further system development. However, the economic evaluation of hybrid vehicle lifetime cost was not performed. In addition, relaxation of vehicle specifications could result in significant reductions in vehicle cost.

Hybrids of the type studied by EPA do not look promising as yet for the general passenger vehicle. They might prove to be suitable for limited-use, special-purpose cars. The bimodal hybrid vehicle might warrant further evaluation in light of its ability to derive a major portion of its energy from nonpetroleum sources and, thereby, offer benefits to urban air quality. This form of vehicle operation might enhance the viability of hybrid electric and hybrid flywheel vehicles as a contender for meeting a significant portion of public transportation needs while meeting energy conservation and environmental goals.

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APPENDIX A

APPENDIX A. Air Pollution Control Office
Advanced Automotive Power Systems Program
"Vehicle Design Goals – Six Passenger Automobile"
(Revision C – May 28, 1971)

The design goals presented below are intended to provide:

A common objective for prospective contractors.

Criteria for evaluating proposals and selecting a contractor.

Criteria for evaluating competitive power systems for entering first generation system hardware.

Advisory criteria in such areas as rolling resistance, vehicle air drag etc. are included to assist the contractor.

The derived criteria are based on typical characteristics of the class of passenger automobiles with the largest market volume produced in the U. S. during the model years 1969 and 1970. It is noted that emissions, volume and most weight characteristics presented are maximum values while the performance characteristics are intended as minimum values. Contractors and prospective contractors who take exceptions must justify these exceptions and relate these exceptions to the technical goals presented herein.

1. Vehicle weight without propulsion system - W_o.

   W_o is the weight of the vehicle without the propulsion system and includes, but is not limited to: body, frame, glass and trim, suspension, service brakes, seats, upholstery, sound absorbing materials, insulation, wheels (rims and tires), accessory ducting, dashboard instruments and accessory wiring, battery, passenger compartment heating and cooling devices and all other components not included in the propulsion system. It also includes accessories such as, the air conditioner compressor, the power steering pump, and the power brakes actuating device.

   W_o is fixed at 2700 lbs.

2. Propulsion system weight - W_p.

   W_p includes the energy storage unit (including fuel and containment), power converter (including both functional components and controls) and power transmitting components to the driven wheels. It also includes the exhaust system, pumps, motors, fans and fluids necessary for operation of the propulsion system, and any propulsion system heating or cooling devices.

The maximum allowable propulsion system weight, W_{pm}, is 1600 lbs. However, light weight propulsion systems are highly desired. (Equivalent 1970 propulsion system weight with a spark ignition engine is 1300 lbs.)

3. Vehicle curb weight - W_c

$W_c = W_o + W_p$

The maximum allowable vehicle curb weight, W_{cm}, is 4300 lbs. (2700 + 1600 max. = 4300)

4. Vehicle test weight - W_t.

$W_t = W_c + 300$ lbs. W_t is the vehicle weight at which all accelerative maneuvers, fuel economy and emissions are to be calculated. (Items 8c, 8D, 8e).

The maximum allowable test weight, W_{tm}, is 4600 lbs. (2700 + 1600 max. + 300 = 4600).

5. Gross vehicle weight - W_g

$W_g = W_c + 1000$ lbs. W_g is the gross vehicle weight at which sustained cruise grade velocity capability is to be calculated. (Item 8f). The 1000 lbs. load simulates a full load of passengers and baggage.

The maximum allowable gross vehicle weight, W_{gm}, is 5300 lbs. (2700 + 1600 max. + 1000 = 5300).

6. Propulsion system volume - V_p

V_p includes all items identified under item 2. V_p shall be packagable in such a way that the volume encroachment on either the passenger or [illegible] compartment is not significantly different than today's (1970) standard full size family car. The propulsion system shall not violate the vehicle ground clearance lines as established by the manufacturer of the vehicle used for propulsion system/vehicle packaging. Additionally, the propulsion system shall not violate the space allocated for wheel jounce motions and vehicle steering. Necessary external appearance (styling) changes will be minor in nature. V_p shall also be packagable in such a way that the handling characteristics of the vehicle do not depart significantly from a 1970 full size family car.

The maximum allowable volume assignable to the propulsion system, V_{pm}, is 35 ft.^{3}.

7. Emission Goals

The vehicle when tested for emissions in accordance with the procedure outlined in the November 10, 1970 Federal Register shall have a weight of W_t. The emission goals for the vehicle are:

Hydrocarbons*	-	0.14 grams/mile maximum
Carbon monoxide	-	4.7 grams/mile maximum
Oxides of nitrogen**	-	0.4 grams/mile maximum
Particulates	-	0.03 grams/mile maximum

*Total hydrocarbons (using 1972 measurement procedures) plus total oxygenates. Total oxygenates including aldehydes will not be more than 10 percent by weight of the hydrocarbons or 0.014 grams/mile, whichever is greater.

**measured or computed as NO_2.

8. Start up, Acceleration, and Grade Velocity Performance.

a. Start up:

The vehicle must be capable of being tested in accordance with the procedure outlined in the November 10, 1970 Federal Register without special driver startup/warmup procedures.

The maximum time from key on to reach 65 percent full power is 45 sec. Ambient conditions are 14.7 psia pressure, 60°F temperature.

Powerplant starting techniques in low ambient temperatures shall be equivalent to or better than the typical automobile spark-ignition engine. Conventional spark-ignition engines are deemed satisfactory if after a 24 hour soak at -20°F the engine achieves a self-sustaining idle condition without further driver input within 25 seconds. No starting aids external to the normal vehicle system shall be needed for -20°F starts or higher temperatures.

b. Idle operation conditions:

The fuel consumption rate at idle operating condition will not exceed 14 percent of the fuel consumption rate at the maximum design power condition. Recharging of energy storage systems is exempted from this requirement. Air conditioning is off, the power steering pump and power brake actuating device, if directly engine driven, are being driven but are unloaded.

The torque at transmission output during idle operation (idle creep torque) shall not exceed 40 foot-pounds, assuming conventional rear axle ratios and tire sizes. This idle creep torque should result in level road operation in high gear which does not exceed 18 mph.

c. Acceleration from a standing start:

The minimum distance to be covered in 10.0 sec. is 440 ft. The maximum time to reach a velocity of 60 mph is 13.5 sec. Ambient conditions are 14.7 psia, 85° F. Vehicle weight is W_t. Acceleration is on a level grade and initiated with the engine at the normal idle condition.

d. Acceleration in merging traffic:

The maximum time to accelerate from a constant velocity of 25 mph to a velocity of 70 mph is 15.0 sec. Time starts when the throttle is depressed. Ambient conditions are 14.7 psia, 85° F. Vehicle weight is W_t, and acceleration is on level grade.

e. Acceleration, DOT High Speed Pass Maneuver:

The maximum time and maximum distance to go from an initial velocity of 50 mph with the front of the automobile (18 foot length assumed) 100 feet behind the back of a 55 foot truck traveling at a constant 50 mph to a position where the back of the automobile is 100 feet in front of the front of the 55 foot truck is, 15 sec. and 1400 ft. The entire maneuver takes place in a traffic lane adjacent to the lane in which the truck is operated. Vehicle will be accelerated until the maneuver is completed or until a maximum speed of 80 mph is attained, whichever occurs first. Vehicle acceleration ceases when a speed of 80 mph is attained, the maneuver then being completed at a constant 80 mph. (This does not imply a design requirement limiting the maximum vehicle speed to 80 mph.) Time starts when the throttle is depressed. Ambient conditions are 14.7 psia, 85° F. Vehicle weight is W_t, and acceleration is on level grade.

f. Grade velocity:

The vehicle must be capable of starting from rest on a 30 percent grade and accelerating to 15 mph and sustaining it. This is the steepest grade on which the vehicle is required to operate in either the forward or reverse direction.

The minimum cruise velocity that can be continuously maintained on a 5 percent grade with an accessory load of 4 hp shall be not less than 60 mph.

The vehicle must be capable of achieving a velocity of 65 mph up a 5 percent grade and maintaining this velocity for a period of 180 seconds when preceded and followed by continuous operation at 60 mph on the same grade (as above).

The vehicle must be capable of achieving a velocity of 70 mph up a 5 percent grade and maintaining this velocity for a period of 100 seconds when preceded and followed by continuous operation at 60 mph on the same grade (as above).

The minimum cruise velocity that can be continuously maintained on a level road (zero grade) with an accessory load of 4 hp shall be not less than 85 mph with a vehicle weight of W_t.

Ambient conditions for all grade specifications are 14.7 psia 85° F. Vehicle weight is W_g for all grade specifications except the zero grade specification.

The vehicle must be capable of providing performance (Paragraphs 8c, 8d, 8e 8f) within 5 percent of the stated 85° F values, when operated at ambient temperatures from -20° F to 105° F.

9. Minimum vehicle range:

Minimum vehicle range without supplementing the energy storage will be 200 miles. The minimum range shall be calculated for, and applied to each of the two following modes: 1) A city-suburban mode, and 2) a cruise mode.

Mode 1: Is the driving cycle which appears in the November 10, 1970 Federal Register. For vehicles whose performance does not depend on the state of energy storage, the range may be calculated for one cycle and ratioed to 200 miles. For vehicles whose performance does depend on the state of energy storage the Federal driving cycle must be repeated until 200 miles have been completed.

Mode 2: Is a constant 70 mph cruise on a level road for 200 miles.

The vehicle weight for both modes shall be, initially, W_t. The ambient conditions shall be a pressure of 14.7 psia, and temperatures of 60° F, 85° F and 105° F. The vehicle minimum range shall not decrease by more than 5 percent at an ambient temperature of -20° F.

For hybrid vehicles, the energy level in the power augmenting device at the completion of operation will be equivalent to the energy level at the beginning of operation.

10. System thermal efficiency:

System thermal efficiency will be calculated by two methods:

A. A "fuel economy" figure based on 1) miles per gallon (fuel type being specified) and 2) the number of Btu per mile required to drive the vehicle over the 1972 Federal driving cycle which appears in the November 10, 1970 Federal Register. Fuel economy is based on the fuel or other forms of energy delivered at the vehicle. Vehicle weight is W_t.

B. A "fuel economy" figure based on 1) miles per gallon (fuel type being specified) and 2) the number of Btu per mile required to drive the vehicle at constant speed, in still air, on level road, at speeds of 20, 30, 40, 50, 60, 70, and 80 mph. Fuel economy is based on the fuel or other forms of energy delivered at the vehicle. Vehicle weight is W_t.

In both cases, the system thermal efficiency shall be calculated with sufficient electrical, power steering and power brake loads in service to permit safe operation of the automobile. Calculations shall be made with and without air conditioning operating. The ambient conditions are 14.7 psia and temperatures of 60° F, 85° F and 105° F. Calculations shall be made with heater operating at ambient conditions of 14.7 psia and 30° F (18,000 Btu/hr).

11. Air Drag Calculation:

The product of the drag coefficient, C_d, and the frontal area, A_f, is to be used in air drag calculations. The product C_dA_f has a value of 12 ft^2. The air density used in computations shall correspond to the applicable ambient air temperature.

12. Rolling Resistance:

Rolling resistance, R, is expressed in the equation $R = W/65\ [1 + (1.4 \times 10^{-3}V) + (1.2\ 10^{-5}V^2)]$ lbs. V is the vehicle velocity in ft/sec. W is the vehicle weight in lbs.

13. Accessory power requirements:

The accessories are defined as subsystems for driver assistance and passenger convenience, not essential to sustaining the engine operation and include: the air conditioning compressor, the power steering pump, the alternator (except where required to sustain operation), and the power brakes actuating device. The accessories also include a device for heating the passenger compartment if the heating demand is not supplied by waste heat.

Auxiliaries are defined as those subsystems necessary for the sustained operation of the engine, and include condensor fan(s), combustor fan(s), fuel pumps, lube pumps, cooling fluid pumps, working fluid pumps and the alternator when necessary for driving electric motor driven fans or pumps.

The maximum intermittent accessory load, P_{aim}, is 10 hp (plus the heating load, if applicable). The maximum continuous accessory load, P_{acm}, is 7.5 hp (plus the heating load if applicable). The average accessory load, P_{aa}, is 4 hp.

If accessories are driven at variable speeds, the above values apply. If the accessories are driven at constant speed, P_{aim} and P_{acm} will be reduced by 3 hp.

14. Passenger comfort requirements:

Heating and air conditioning of the passenger compartment shall be at a rate equivalent to that provided in the present (1970) standard full size family car.

Present practice for maximum passenger compartment heating rate is approximately 30,000 Btu/hr. For an air conditioning system at 110° F ambient, 80° F and 40% relative humidity air to the evaporator, the rate is approximately 13,000 Btu/hr.

15. Propulsion system operating temperature range:

The propulsion system shall be operable within an expected ambient temperature range of -40° to 125° F.

16. Operational life:

The mean operational life of the propulsion system should be approximately equal to that of the present spark-ignition engine. The mean operational life should be based on a mean vehicle life of 105,000 miles or ten years, whichever comes first.

The design lifetime of the propulsion system in normal operation will be 3500 hours. Normal maintenance may include replacement of accessable minor parts of the propulsion system via a usual maintenance procedure, but the major parts of the system shall be designed for a 3500 hour minimum operation life.

The operational life of an engine shall be determined by structural or functional failure causing repair and replacement costs exceeding the cost of a new or rebuilt engine. (Functional failure is defined as power degradation exceeding 25 percent or top vehicle speed degradation exceeding 9 percent).

17. Noise standards: (Air conditioner not operating)

a. Maximum noise test:

The maximum noise generated by the vehicle shall not exceed 77 dbA when measured in accordance with SAE J986a. Note that the noise level is 77 dbA whereas in the SAE J986a the level is 86 dbA.

b. Low speed noise test:

The maximum noise generated by the vehicle shall not exceed 63 dbA when measured in accordance with SAE J986a except that a constant vehicle velocity of 30 mph is used on the pass-by, the vehicle being in high gear or the highest gear in which it can be operated at that speed.

c. Idle noise test:

The maximum noise generated by the vehicle shall not exceed 62 dbA when measured in accordance with SAE J986a except that the engine is idling (clutch disengaged or in neutral gear) and the vehicle passes by at a speed of less than 10 mph. the microphone will be placed at 10 feet from the centerline of the vehicle pass line.

18. Safety standards:

The vehicle shall comply with all current Department of Transportation Federal Motor Vehicle Safety Standards. Reference DOT/HS 820 083.

19. Reliability and maintainability:

The reliability and maintainability of the vehicle shall equal or exceed that of the spark-ignition automobile. The mean-time-between failure should be maximized to reduce the number of unscheduled service trips. All failure modes should not represent a serious safety hazard during vehicle operation and servicing. Failure propagation should be minimized. The power plant should be designed for ease of maintenance and repairs to minimize costs, maintenance personnel education, and downtime. Parts requiring frequent servicing shall be easily accessable.

20. Cost of ownership:

The net cost of ownership of the vehicle shall be minimized for ten years and 105,000 miles of operation. The net cost of ownership includes initial purchase price (less scrap value), other fixed costs, operating and maintenance costs. A target goal should be to not exceed 110 percent of the average net cost of ownership of the present standard size automobile with spark-ignition engine as determied by the U.S. Department of Commerce 1969-70 statistics on such ownership.

GLOSSARY

GLOSSARY

Acronyms and Units of Measurement

ac	alternating current
Ah	Ampere hour
Ah/cm^2	Ampere hour per square centimeter
BSFC	brake specific fuel consumption (pounds of fuel per engine brake horsepower-hour)
Btu	British thermal unit
CI	compression ignition
CID	cubic inches of piston displacement (reciprocating piston engines)
CO	carbon monoxide
dc	direct current
DHEW	Department of Health, Education, and Welfare (predecessor to EPA in studying the control of automotive emissions)
DOT	Department of Transportation
EGR	exhaust gas recirculation
EMT	electromechanical transmission
FETDC	Federal emissions test driving cycle (used in Federal emissions test for certification of light-duty vehicles)
HC	hydrocarbon
hp	horsepower
kW	kilowatts
MTI	Mechanical Technology, Inc.

NO_x	oxides of nitrogen
PCU	power conditioning unit
PWM	pulse-width modulation
rms	root mean square
SCR	silicon controlled rectifier
SFC	specific fuel consumption
SI	spark ignition
V	Volts
W	Watts
W/lb	Watts per pound
Wh	Watt hours
Wh/lb	Watt hours per pound

Technical Terms

alkali-metal battery	A storage battery in which the anode consists of an alkali-metal such as lithium or sodium.
bipolar cell	An electrode structure in which the anode of one cell and the cathode of the adjoining cell are combined to form a single member.
breadboard prototype	An experimental arrangement of selected components to prove the feasibility of a given design and to facilitate changes when necessary.
carbon-pile resistance stacks	A variable resistor consisting of a stack of carbon disks mounted between fixed and movable metal plates that serve as terminals of the resistor. The resistance value is reduced by applying pressure to the movable metal plate.
Carnot cycle	An ideal cycle that is used to establish the maximum thermal efficiency of a heat engine operating between two temperature limits.
catalytic converter	As applied to automotive heat engines, a device relying on a catalyst process that is used to induce or accelerate oxidizing or reducing chemical reactions in the engine exhaust with the objective of lessening pollutant emissions to the atmosphere.
chopper circuit (for motor control)	An electronic solid-state circuit generally using silicon controlled rectifiers to "chop" continuous direct-current voltage into undulating voltage with an essentially square waveform for control of power delivered to an electric motor.
direct current brush motor	Any motor that accepts power from a direct current source and uses carbon or composition brushes both to carry current to the armature and to mechanically commutate current as the armature rotates.
fuel cell	An electrochemical energy-producing device employing inert electrodes to which are fed liquid or gaseous reactants, and from which the reaction products are continuously removed.

heat engines	A general term applied to a class of engines that use heat to raise the temperature/pressure of a working fluid to provide power (i.e., those that convert heat energy into mechanical energy or motion). As opposed to those that use chemical reactions (i.e., batteries) to provide power. Examples of heat engines are: reciprocating or rotary piston, diesel, gas turbine, Rankine cycle, and Stirling.
hydromechanical transmission	The hydromechanical or power-splitting transmission is a combination of mechanical differential gearing and a hydrostatic transmission.
hydrostatic transmission	The hydrostatic transmission consists of a hydraulic pump with a fluid connection to a hydraulic motor.
hysteresis motor	A small synchronous motor that starts in the hysteresis mode whereby a magnetic field is induced into the rotor (secondary field) which then interacts with the primary field to produce torque. Usually used for light constant-speed duty.
induction motor	An alternating-current motor in which the change of current in the primary, stator winding induces eddy currents in the passive secondary rotor which interacts to produce torque.
inverter	A solid-state electronic or electromechanical device that converts direct current power into alternating current power.
noble metal	A metal such as gold, silver, or platinum that has high resistance to corrosion and oxidation.
organic electrolyte	An electrolyte embodying an organic (carbon containing) solvent contrasted with normal electrolyte that uses water as a solvent.
Otto cycle	A four-step process for internal combustion engines in which the first step consists of intake of an air-fuel (explosive) charge into the cylinder, the second step consists of compression and ignition of the charge, the third step consists of expansion of the gasses, and the last step is expulsion of the combustion products from the cylinder.

powertrain	The complete power generation and transmission system that provides energy to the drive wheels of an automotive vehicle.
pulse-width modulation (PWM)	A method for electric power control relying on the ratio of "voltage time on" to "voltage time off."
quasi bipolar	A term devised to describe a bipolar lead-acid battery that uses the normal lead or lead alloy current collectors in conjunction with an alternative paste support material.
Rankine cycle engine	An external combustion engine in which a high-pressure working fluid is converted to superheated vapor by the heat from combustion gases and then is expanded in a piston- or turbine type device to produce work.
reluctance motor	A synchronous motor similar in construction to an induction motor, in which the member carrying the secondary circuit has salient poles, without permanent magnets or direct current excitation. It starts as an induction motor, but operates normally at synchronous speed. (The rotor seeks minimum reluctance, whence the name reluctance motor.)
series-wound motor	A direct-current motor in which excitation is supplied by a winding or windings connected in series with or carrying a current proportional to that in the armature winding. Has a high starting torque, variation in speed with load, and dangerously high speed with no load.
shunt-wound motor	A direct-current motor in which excitation of the field circuit is supplied by a winding connected in parallel with the armature circuit.
silicon controlled rectifier	An electronic semiconductor device used principally to provide control of high direct current power levels to an electric motor.
stepper motor	A motor that rotates in short and essentially uniform angular movements rather than continuously. The angular steps, usually 30, 45, and 90 deg, are obtained electromagnetically rather than by ratchet and pawl mechanisms as in stepping relays.

Stirling cycle engine	An external combustion, closed cycle, piston-type device that uses a gaseous internal working fluid, usually hydrogen or helium. Cyclical heating and cooling varies the pressure of the fluid within a closed volume, the pressure variations being transmitted to a piston, thereby developing output power.

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16. ABSTRACT

A summarization has been made of the available nonproprietary information on the technological status of automotive power systems which are alternatives to the conventional internal combustion engine, and the technological status of non-petroleum-based fuels derived from domestic sources which may have application to future automotive vehicles. The material presented is based principally upon the results of research and technology activities sponsored under the Alternative Automotive Power Systems Program which was originated in 1970. Supplementary data are included from programs sponsored by other government agencies and by private industry. The results of the study are presented in four volumes; this volume presents the current technological status of electric and hybrid power systems.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Electric Cars Hybrid Heat Engine/Battery Cars Hybrid Heat Engine/Flywheel Cars Batteries Flywheels	Design Concepts Operating Modes Performance Exhaust Emissions Technology Status	
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