Among the items requiring further investigation are methods for studying various aspects of network operation without large-scale simulations, restrictions on cycle size due to the physical layout of interchanges, effects of vehicle performance limitations, and exact control system requirements for operation of an automated-vehicle network.

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Electrical Systems for Hybrid Vehicles

R. C. LaFRANCE AND R. W. SCHULT

Abstract—**This paper is a digest of the electrical system section of a report [8] on the feasibility of using a hybrid heat engine/electrical propulsion system as a means of reducing exhaust emissions from street-operated vehicles. The electrical system is composed of an electric traction motor, a generator, control system, and batteries. Batteries are not covered in this paper, but the remainder of the items will be treated here. First, the electrical system parameters or characteristics that have the greatest impact on the total system are considered; next, details of the advantages and disadvantages of various approaches are summarized; and, finally, development efforts are recommended.**

VEHICLE SPECIFICATIONS

THE Air Pollution Control Office (formerly APCO, now Division of Advanced Automotive System Development of the Environmental Protection Agency) specifications for the four vehicles to be examined for potential applicability of the heat engine/electric hybrid powerplant concept are shown in Table I. Significant vehicle design point conditions most likely to affect powerplant sizing and operational capability include vehicle top speed, gradeability (in terms of percent grade, velocity on the grade, and grade length), vehicle weight, and aerodynamic drag area and drag coefficient. The only limitations imposed upon the powertrain were the assigned powertrain weights and volumes. A final requirement was that the acceleration capability of each vehicle with a hybrid power plant installed was to be equal to that of a contemporary automotive vehicle. Therefore, as stipulated by the specifications of Table I, any resulting hybrid vehicle must match the acceleration, speed, and gradeability characteristics of conventional contemporary vehicles. The rationale for this requirement is that such performance will enhance public acceptance of the hybrid vehicle and will also avoid the propsect of poor traffic safety.

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INTRODUCTION

A hybrid electric vehicle utilizes a heat engine to supply steady-state power and an electric motor to supply transient power. Power is transmitted to the wheels directly from electric drive motors in a series powertrain configuration, but the heat engine is mechanically linked to the drive wheels in addition to the electric motor in a parallel configuration. The mechanical link can be one of several gearbox/transmission arrangements. It is a further principle of the parallel configuration that the power mechanically transmitted from the heat engine to the drive wheels be sufficient only to maintain vehicle cruise speeds, and that power required for acceleration of the vehicle be supplied by an electric drive motor which

TABLE I
APCO HYBRID VEHICLE SPECIFICATIONS

Vehicle Characteristics	Family Car	Commuter Car	Intracity Bus Low Speed	Intracity Bus High Speed*	Delivery/Postal Van Low Speed	Delivery/Postal Van High Speed*
Maximum cruise velocity (mi/hr)	80	70	40	60	40	65
Cruise velocity for maximum range (mi/hr)	66.5	59.4	40	60	40	65
Velocity on grade at grade (mi/hr at percent)	40 at 12	33 at 12	6 at 20	10 at 10	8 at 20	8 at 20
Grade length (mi)	8	4	0.5	0.5	0.5	0.5
Range (mi)	200	50	200	200	60	60
Curb weight (lb)	3,500	1,400	20,000	20,000	4,500	4,500
Loaded weight (lb)	4,000	1,700	30,000	30,000	7,000	7,000
Assigned power train weight (lb)	1,500	600	6,000	6,000	1,700	1,700
Assigned power train volume (ft^3)	28	16	175	175	42	42
Aerodynamic drag area (ft^2)	25	18	80	80	42	42
Drag coefficient, C_d	0.5	0.35	0.85	0.85	0.85	0.85
Acceleration	Equal to contemporary automotive vehicle					

*Recommended Aerospace values

derives its energy source from a battery and/or a generator, also driven by the heat engine.

The components investigated for use in the electric drive and control systems included the following.

Motors:
- ac induction
- dc externally excited
- dc series wound
- dc compound wound
- torque motors
- dc brushless

Generators:
- dc
- ac (alternators)

Power Conditioning and Control:
- pulsewidth modulation
- frequency modulation
- variable-frequency inverters
- cycloconverters
- integrated circuits
- relays/switches
- current limiters
- circuit breakers and fuses
- filters (inductor–capacitor)

It was felt appropriate to add two more vehicle classes to be examined in addition to the four classes specified by the APCO. As can be noted in Table I, both the delivery/postal van and the intracity bus have very low (40 mi/h) top speeds and severe (20 percent) grade requirements. While these characteristics may be very adequate for many municipalities (e.g., San Francisco, Calif.), they would not appear to be most appropriate for urban areas with large freeway networks on which these vehicles are required to operate (e.g., Los Angeles, Calif.). Therefore, a high-speed version of the delivery van and bus was added to the basic group of vehicles listed in Table I. The top speeds of the delivery van and the bus were selected as 65 and 60 mi/h, respectively. No gradeability requirement was set for these two additional vehicles; the resulting gradeability was determined from sizing for maximum velocity. Aside from top speed and gradeability, the other specifications of Table I apply to the two additional vehicles.

SYSTEM SYNTHESIS

There are many different design approaches to the development of an electrical system for the hybrid vehicle. The series versus the parallel powertrain configuration is a major division of the concepts. One form of the series configuration is shown in Fig. 1, in which all of the energy of the heat engine flows through the generator and the motor to the wheels. Part of the energy used for peak power requirements is supplied by the battery. The battery is then recharged during cruise and its energy utilized for starting and acceleration. In Figs. 2–4 three different design approaches are shown for the parallel configuration. The first two have been built and tested. In addition, the electric motor, battery, and control system portions of the third approach have been built and tested in a prototype wheelchair propulsion system.

Fig. 2 is a block diagram of a parallel configuration. The power from the heat engine is transferred to a planetary differential gearing arrangement, which transmits a portion of the energy directly to the wheels. The remainder, not required for propulsion, is converted to electrical energy in the generator and stored in the battery. During periods of start and acceleration, power is drawn from the battery for the motor/generator to help the heat engine drive the wheels. During deceleration, the motor/generator becomes a generator and feeds energy back into the battery. At low vehicle speeds, the heat engine operates at very nearly constant power and speed. (For more details, see [3].)

In Fig. 3 [1], [2] another approach to a parallel system design is shown. It also has a direct drive to the wheels, but not through a differential. The motor/generator is mounted on the same shaft as the heat engine, with its rotor a part of the drive

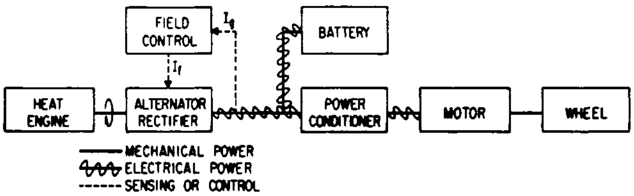

Fig. 1. Electrical control schematic–series configuration.

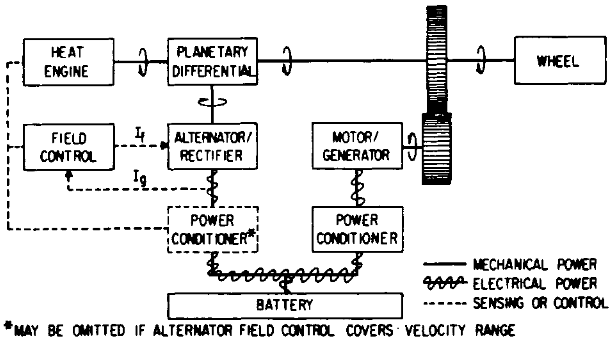

Fig. 2. Single-motor parallel configuration.

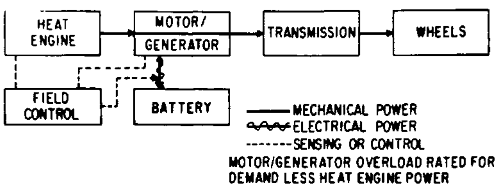

Fig. 3. Single-motor parallel configuration concept–variable-velocity heat engine with in-line augmenting electric motor/generator.

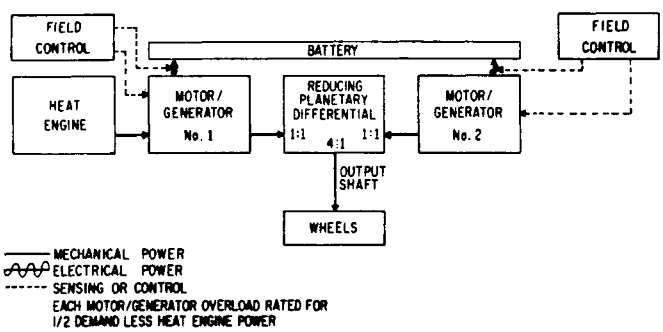

Fig. 4. Dual-motor parallel configuration concept.

shaft. During periods of start and acceleration, the motor/generator acts as a motor and assists the heat engine in driving the wheels. During cruising and deceleration, the motor/generator operates as a generator and feeds energy back into the battery. Gear shifting is required and the heat engine must operate at variable speed and power output.

Fig. 4 shows a dual-motor concept. One form of this system was developed as a completely electrical drive for wheelchairs, fork-lift trucks, golf carts, etc. Each motor/generator can and does help drive the wheels under heavy loading situations, such as start and acceleration. The manufacturer states that the control system complexity is considerably reduced when compared to other parallel configurations.

In summary, it can be said that the electric motors can be smaller in the parallel configuration than in the series configuration, due to the fact that they are used only during peak loading situations. The parallel arrangement appears to have the potential of greater efficiency because a large portion of the energy does not flow through the electrical system but is channeled directly to the wheels. The principal loss is friction in the mechanical system, and the electrical loss is reduced below the series configuration of Fig. 1.

Another major division in design concepts is the ac versus dc motor approach. The ac motors are smaller, lighter, and easier to cool, but they require a variable-frequency power supply that must be derived from dc power if a storage battery is to be used in the system. If an ac generator is used in the system, regardless of the type of motor used, rectification of this power source is necessary for recharging the battery. The ac power can be made available by passing battery power through an inverter. Either induction or synchronous motors can be used, and being considerably smaller than equal-power-output dc machines, they are more easily adaptable to mounting as a part of the wheel assembly. If dc motors are utilized, a decision must be made relative to the field configurations, that is, the manner of separately exciting the main field current and the relative benefits derived from compensating and interpole windings. The operating characteristics must be analyzed to determine specific design details affecting overall efficiency, weight, size, complexity, cost, development status, etc. Low-weight components are important since the power required to propel the vehicle depends on its weight.

The selection of system voltage is primarily based on the weights of the electrical components. Higher voltages result in lower weights for distribution wiring, motors, generators, and controls. For the commuter and family cars, a 220-V system was selected to limit currents so that they do not exceed 500 A. For the bus and van, a 440-V system was recommended to supply higher power requirements and still not exceed 500 A. The voltages and currents are based on the case of the series powertrain configuration where the motor provides total power to the wheels. The motor under consideration has active independent field control for meeting power requirements over the entire vehicle speed range. In the parallel powertrain configuration, requirements are somewhat lower since this motor will deliver only acceleration power.

Subsystem Technology: Motor Characteristics and Control

Designs for electric motor drive systems should have 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, e) simple, inexpensive, and efficient regenerative braking.

The most common approach to the design of electrically propelled vehicles in the United States has been to use dc series motors utilizing chopper circuits for their control, either pulse frequency or pulse duration. Although this approach appears reasonable for some classes of vehicles and driving cycles, it is not optimum for all types. Hence, this section will be devoted

TABLE II
COMPARISON OF MOTOR CONTROLLERS

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.*

*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 DC current is thus avoided.

to an analysis of the motor characteristics for a number of different design approaches that could be used for the hybrid vehicle electric propulsion system.

The motor-induced voltage varies with speed; it is very small at low speed and increases as the motor speed increases. Exceeding this voltage results in high currents leading to overheating of the motor. The armature applied voltage must be varied to match the induced voltage of the motor at all speeds. This can be achieved by means of a) a chopper circuit, b) variable resistance in the armature circuit, or c) step-voltage change and field control.

The chopper circuit 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. Also, while the chopper sees a varying impedance from 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. The main disadvantage of the chopper is the high cost of the power switching components and the associated control circuitry. Also, compared to pure dc control, the chopper introduces losses due to high-frequency operation. These losses can be partially reduced by special motor design and adequate filtering.

The use of variable resistance in the armature circuit introduces high losses associated with the voltage drop in the resistance and is an inefficient method of voltage control for a vehicle required to operate over a wide speed range.

Motor voltage control can also be achieved by step-voltage switching of the battery cell groups from parallel to series as the vehicle speed is increased. However, 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. This method is schematically illustrated in Fig. 5, showing how voltage switching is accomplished by speed sensing and relays [4].

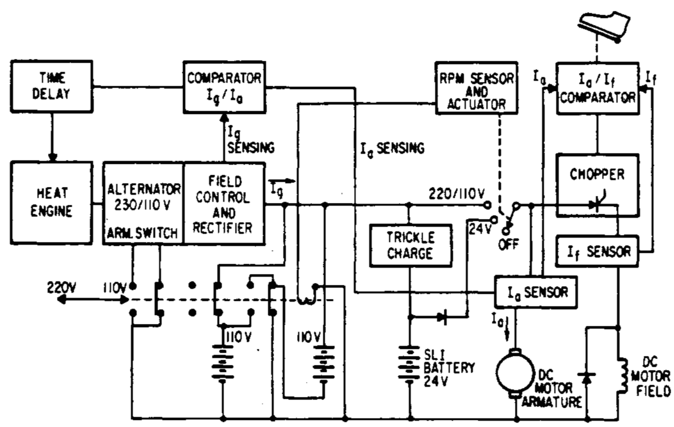

Fig. 5. Separately excited dc motor with step-voltage control.

A comparison of operational characteristics utilizing the three types of controllers are given in Table II. Additional comparisons can be found in [5], which discusses actual field testing of electric cars.

SUBSYSTEM EVALUATION AND COMPARISON

Electric Drive Motor Systems

A comparison of electric motor systems must consider:

1) operating characteristics and suitability to demand requirements
2) control system complexity and cost

3) operating limits including a) surge currents, b) commutating current limit, c) temperature rise limit, and d) velocity limit set by centripetal strength and commutation speed
4) power density (lb/hp) and efficiency
5) motor cost and availability
6) system weight
7) reliability and maintainability.

Series, separately excited, compound, and brushless dc motors as well as ac induction types were evaluated on the basis of parameters 1)–7). Detailed explanations follow.

Operating Characteristics Compared

The series-wound dc motor is basically a torque-demand system with velocity as a function of both applied voltage and load (torque applied). At a given voltage, a change in velocity will occur with a change of load. At a constant load, the velocity will vary approximately in proportion to the applied voltage. Its use is principally in applications requiring high starting torque.

The separately excited dc motor is basically a velocity-demand system. With constant field excitation, torque demanded at a given velocity will automatically be met up to the commutation limit. It is used extensively in industry where starting loads are not high but relatively high constant speed is required under varying loads (or at constant load). Velocity can be widely varied, however, by changing the applied voltage and/or by changing the field excitation. Velocity variation through "field weakening" in a standard motor is limited to about 3:1; but in conjunction with changing the applied voltage to the armature, this variation can be extended to a wider speed range.

The compound motor has both the series and shunt field windings to provide the automatic high starting torque of the series motor and high-speed constant velocity with variable load that is characteristic of the shunt motor. A small penalty of increased weight and increased complexity of the control system results from use of this motor.

The torque motor is listed as a candidate where low-speed precise velocity control is important. The large number of commutation segments and large diameter yield a weight penalty that makes it noncompetitive at this time.

The brushless dc motor is listed as a candidate, but it is presently constrained by cost, and further development is required in the power ranges of the hybrid vehicles. To date, it is known to have been built up to 20 kW, but present SCR technology makes this motor practical for any size vehicle. It is created essentially from the redesign of a shunt motor by providing brushless commutation with armature position sensors driving SCR switches. Its operation is thus similar to that of the ac synchronous motor controlled with a variable-frequency feedback system.

The ac 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 dc motors can be obtained. The controlled slip mode of operation is described in [6]. The induction motor has the advantage in specific power compared to dc motors at the vehicle horsepower levels. Its overwhelming utilization in industry and its simple construction make it a strong contender for future vehicles.

Control System Complexity and Cost

In a comparison tradeoff of the drive train, it is very important to also include the cost and weight of the control system. In terms of performance and versatility, the selection of an adequate control system is as significant as the selection of the motor. All of the contending electric motors need variable voltage applied. Step voltage has been used by which multiple-pole relays switch batteries from parallel to series in steps. This is undesirable because velocity increments may prevent a vehicle from following another vehicle at the same velocity; the relays are constantly working under load, thereby shortening the operating life, and the generator must feed constantly changing voltage levels, which complicates its control logic. A step-voltage system augmented by field control can be made more desirable by using armature current sensing to provide feedback information for controlling the field. This would control current surges and the corresponding jerks.

A much improved variable-voltage system is being used more generally for low-speed vehicles, whereby smoothly varying effective voltage may be applied to the motor. This dc chopper system provides pulse frequency, pulsewidth, or a combined pulsewidth and frequency modulation. The result is smooth control of power supplied to the motor. At present, the cost is high. 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. However, the SCR protection circuit and the current-smoothing filters will still remain significant cost factors.

Since the forward voltage drop of the high-current SCR is about 1 V, it can be seen that, at 500 A, 0.5 kW would be lost in the SCR, which represents a heat dissipation problem. The higher the maximum voltage of the system, the lower the proportionate loss of the SCR controller system at a given motor power.

There is one other problem with the SCR effective-voltage controller when it is used with a series field winding. The field magnetic material must be laminated with higher permeance steels to prevent relatively high core losses at the chopper frequency. An attempt to reduce motor losses by decreasing the chopper frequency can cause motor noise and vibration if the size of the current-smoothing filters is not allowed to increase. A fully compensated motor has very low inductance in the armature. Therefore, an external inductor filter is needed to smooth the motor current at the chopper frequency.

Of greater complexity are the controllers for the brushless dc and the ac induction motors since they 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 the hybrid vehicles are very expensive since they are complex (12 SCR's or more are needed, with at least 6 having high current ratings). The voltage control may be incorporated into the inverter or a separate chopper may be used.

The more complex and expensive controllers have not yet been fully developed; therefore, an engineering risk still appears at this time. The estimated order of increasing complexity and cost is as follows:

1) step-voltage relay-operated controller
2) step voltage augmented with field control and armature current sensing
3) pulsewidth modulation SCR chopper
4) chopper with both frequency and pulsewidth modulation
5) SCR controller with position sensor for dc brushless motor
6) multiphase inverter with variable frequency and voltage control.

Design Goals

As indicated, ac and dc generators have been developed to a fairly high degree for aircraft and automotive applications, and it is apparent that little development is required in this area. The ac generator (with rectifiers) is preferred for the hybrid vehicle because of higher efficiency, lighter weight, and low cost. Some effort should be expended, however, to improve the part-load efficiency.

Electric motors, on the other hand, particularly dc motors, have not been developed to optimize efficiency, weight, size, and cost for vehicle propulsion. It is believed that dc electric motors can be designed with higher efficiencies and lighter weights than those on the market today, and with equal reliability and lifetimes. Reasonable weight and efficiency goals, which it is expected can be achieved for the various classes of vehicles, are tabulated in Table III for the series configuration. Efficiency can be traded off against motor weight as has been indicated.

For a given design power level, the weight per unit horsepower can be decreased if the efficiency is allowed to decrease (see Fig. 6). Power densities of 5.5–8 lb/hp should be achievable at a reasonable cost by merely optimizing the design for the particular application and utilizing lightweight materials whenever possible (see Fig. 7). The efficiencies of these devices would range between 90 and 94 percent at design load depending upon the size of the motor. The weight per unit of horsepower may be further reduced by the use of ac motors, inverters, and liquid cooling. Part-load efficiency is also very important because during a typical driving cycle the motor operates at part-load most of the time.

It is further estimated that the efficiencies of the controllers and the motor in the regenerative mode (with the motor acting as a generator when the vehicle is decelerating) can be improved quite markedly, thus increasing the overall efficiency of the vehicle. The field power of the separately excited motor is typically 5 percent of the full-load power of the motor. Since the controller directly changes only the field current, its efficiency is high when compared to the total motor power being altered. It appears reasonable to believe that regenerative efficiencies on the order of 25–40 percent should be achievable. These values represent the combined efficiencies of drive motor performance as a generator, the driving cycle effect on battery-charge acceptance, the battery charging, and the mechanical friction.

TABLE III
DC Electric Motor Weights (Including Forced Air Cooling)

Vehicle, hp	Weight, lb	Power Density, lb/hp	Maximum Efficiency, %
Commuter, 21	160	7.6	92
Family, 61	390	6.4	92
Van			
Low Speed, 30	180	6.0	92
High Speed, 80	430	5.4	94
Bus			
Low Speed, 100	870	8.7	94
High Speed, 175	1050	6.0	94

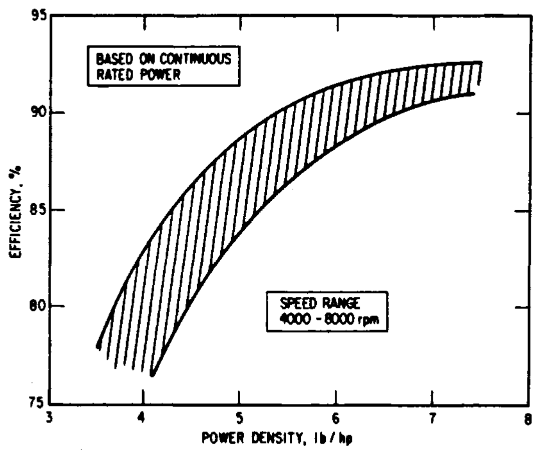

Fig. 6. Typical power density versus maximum efficiency for dc motors–family and commuter cars.

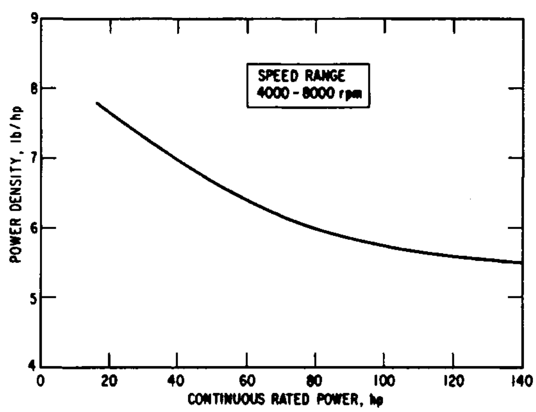

Fig. 7. Typical density versus horsepower for dc motors including forced air cooling–family and commuter cars.

Overall system efficiencies of the different parallel powertrain approaches for various vehicles and driving cycles should be investigated to determine which one will have the greatest possibilities for high efficiency and low pollution levels. One such system, not analyzed in depth nor tested, is the one shown in Fig. 4. Comparison with the other two parallel systems after testing may demonstrate that it has a higher figure of merit.

Application of Electric Hybrid System to Bus Drive

In the automobile, packaging would have to be carefully engineered into a practical system that does not fill the trunk space. The technology in subsystems such as motors, generators, batteries, and controllers would need refining to obtain efficient operation for lighter and smaller packages. In the van, weight and size must also be controlled to provide for payload.

Today's bus provides considerable room between wheel wells and in the back with the practice of raising passenger seating above the wheel wells. A drive system weight up to 6000 lb is not considered excessive when compared to the total bus weight. This greater relative weight and size allowance on the bus means that special reduced size or weight subsystems are not essential (see [7]). Therefore, the bus electric hybrid system could be built today using presently available components. The only original work necessary would be a systems engineering effort to cover layout, matching subsystems, optimizing performance, analyzing reliability, and final design.

Recommended Subsystem Development

Certain areas require further development effort in the electrical system (exclusive of batteries, which are not included here). These efforts consist of the following.

1) Develop lightweight efficient dc motors optimized for efficiency and weight for the automotive application. Both shunt and series types are required.

2) Develop lightweight efficient controllers for shunt motors. Very little development appears necessary in the area of series choppers.

3) Develop small and compact vehicle-borne logic and control circuits to optimize electrical/heat engine performance. Inputs to the logic circuit would be generator current, battery-charge current, motor-armature current, engine speed, battery voltage, and accelerator-pedal position. Based on these inputs the logic circuit would determine the desired optimum heat-engine power setting. Under these conditions, maximum utilization of energy available from regenerative braking could be achieved.

4) Investigate the various parallel system approaches to the design of hybrid cars. Two parallel concepts already built have been evaluated; however, the efficiency of a third type (Fig. 4) using two motors requires further evaluation. Two versions of this configuration need to be investigated, one using armature voltage and/or external excitation as a speed-control mechanism.

5) Determine and compare the efficiencies and heat rejection systems of dc and ac motors and associated control systems, particularly for the large vehicles.

6) Compare in more detail the cost of various approaches.

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