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Hybrid Vehicle for Fuel Economy

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A HEAT ENGINE/ELECTRIC drive train has been evaluated as a means of improving the fuel economy of various types of automotive vehicles. Computer simulation studies and dynamometer tests on a prototype system indicate that improvements in CVS-Hot fuel economy (miles/gallon) of from 30% to 100% can be realized with this system in a vehicle of identical weight and performance characteristics. Preliminary test data also indicates that these fuel economies may be realizable while meeting the 1975/76 Federal Emission Standards (1.5HC, 15CO, 3.1NO_x) with the use of external emissions controls such as catalytic converters. Although similar in configuration to a standard parallel hybrid drive train, the control strategies and energy flow of this system are considerably different from any known hybrid drives. This system does not appear to be of equal merit for all classes of vehicles, but gives the greatest fuel economy improvements when applied to delivery vans, buses, and large passenger cars. There are certain drawbacks to this particular hybrid system, principally in increased initial cost as compared to conventional systems, but this cost differential may be reduced as improved electrical components are developed and as automotive production and marketing techniques are applied to the electrical components. Other potential limitations of this hybrid system are reduced driving range at very low speeds and reduced capability to supply vehicle auxiliaries at standstill. In general, the replacement of a conventional drive train by this particular hybrid train will not increase the vehicle curb weight.

From almost the beginning of the Automotive Age, various combinations of drive systems have been tried in order to achieve vehicle performance characteristics superior to those that can be obtained using a single type of drive. These efforts have been made in the name of many worthwhile goals, such as increased vehicle acceleration capability, audible noise reduction, operation of an engine or turbine at optimum efficiency, reduction of noxious emissions, and improved fuel economy. These efforts have so far not led to any commercial

ABSTRACT

A heat engine/electric hybrid drive train is proposed as a means for improving CVS-Hot fuel economy by an estimated 30% to 100% in various types of automotive vehicles. This drive train, classified as a parallel hybrid, has been analyzed by and emissions characteristics, and has been compared with existing internal combustion engine drive trains and other types of hybrid drives. A prototype system has been assembled and evaluated on a dynamometer test stand and has corroborated the computer analysis and applications, although several experimental hybrid buses and rapid transit vehicles are being evaluated at the present time (1,2,3). For private vehicle applications, hybrid drive systems have generally been found to offer insufficient improvement in meeting one or more of the goals stated above to justify the added cost and complexity compared to a singular drive system, particularly compared to the conventional Otto cycle internal combustion engine drive system. Two extensive EPA-sponsored studies of heat engine/electrical hybrid systems have been published (4,5) and generally concur in this conclusion, as does the more recent JPL Report.(6)

It is therefore with some trepidation that the subject of this paper, a heat engine/electric hybrid drive system, is proposed as a viable drive train for modern automotive vehicles of many varieties. However, this proposition has been developed - and to large extent, confirmed - on premises somewhat different from those upon which the EPA studies were based:

1. The critical fuel situation in the U.S. and most Western countries has placed increased emphasis on improved fuel economy for all types of vehicles since the initiation of the EPA studies of Reference 3 and 4. Recent large increases in gasoline prices have led to the conclusion that a sizable increase in initial vehicle cost (resulting from the use of a hybrid drivetrain) can be justified if a sufficient improvement in vehicle fuel economy is realized.
2. Studies performed during the development of this system have shown that the relative size and power rating of the hybrid drive train components with respect to the vehicle weight and performance rating have an important influence on vehicle fuel economy. Hybrid drive trains may not improve fuel economy for vehicles of every size, weight, and application category. Stated in another way, hybrid drive trains are not "scalable" as a function of vehicle size or weight as are singular drive trains.
3. The modus operandi or control philosophy of a hybrid can have a profound influence on both fuel economy and emissions. Past hybrid developments have tended to use the heat engine primarily as a battery charger; the subject hybrid reverses

It is hoped that the validity of these principles will be amplified by subsequent sections of this paper.

SYSTEM DESCRIPTION

A block diagram of the system illustrating functional performance and energy flow paths is shown in Figure 1. This drive system is intended to replace the engine-transmission system in conventional vehicles with the result of increasing the vehicle CVS-Hot fuel economy (miles/gallon) from 30% to 100% at 1975/76 Federal emission levels using the CVS-Hot cycle while maintaining approximately equivalent accelerating, braking, and passing characteristics. The hybrid-electric system consists of the following major components:

1. A different internal combustion engine, considerably smaller in displacement, and, hence, horsepower capability, than the engine in the original drive train.
2. An electric motor/generator (one unit) which may be on a common shaft with the engine output shaft or connected to the engine output shaft by means of a gear, belt, or chain system. The motor/generator may be of the DC commutator, DC homopolar, synchronous, or induction types.
3. A means of controlling power flow between the motor/generator and battery. This may be an electronic controller using power thyristors or transistors, contactor controller using battery switching techniques, or similar devices. The controller must be capable of two-way power flow and should have high energy efficiency.
4. An energy storage device. This may be any device capable of handling the high bursts of power required by the drive train during acceleration and braking and of supplying the energy needs for low-speed driving and the operation of vehicle auxiliaries at low speeds and standstill. At the present time, batteries are the most practical energy storage device, with the nickel-cadmium battery having almost ideal characteristics for this application but suffering a cost penalty. Flywheels, fuel cells in combination with batteries, closed loop cryogenic expander systems, are other possibilities.
5. A differential and a drive shaft. In general, it is desired to use the original drive shaft and differential

parallel hybrid with engine on-off control, and bears some similarity in configuration with two other recent hybrid developments. (9),(10)

In addition to these major power components, other components required by the hybrid drive train include: control circuitry for the proper operation of the power controller; modified engine throttle and carburetor; sensors for converting vehicle speed, battery voltage and charge level, component temperatures, etc., to electrical signals suitable for use in control and protection systems; protection systems for both engine and electrical system emission controls; and an overall vehicle control system.

Two modifications of the above system (Figure 1) have capabilities for improved system performance but usually add some cost penalties:

1. The use of an automatically-controlled decoupler to permit the engine to be detached from the electrical motor drive shaft when the vehicle is operating in an all-electric drive mode or in a braking mode. It has been shown that the use of such a clutch will result in a further improvement in fuel economy (see Figure 5).
2. The use of an electrically-controlled gear changing system. This will often result in a reduce electrical system weight and an improved electrical system efficiency.

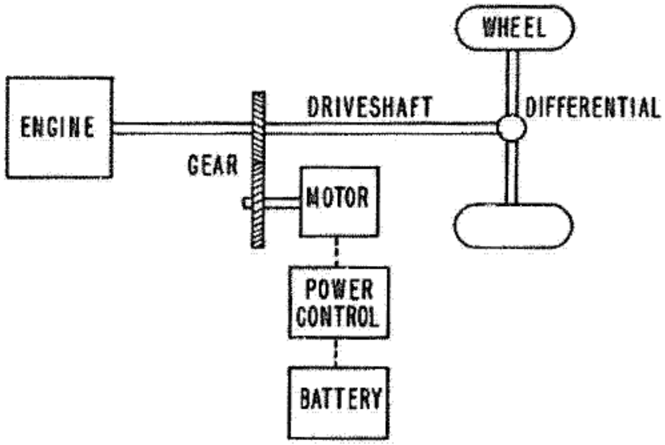


Fig.1 -Ford parallel hybrid

SYSTEM OPERATION

The system has six modes of operation. The first five modes are shown in Figure 2. Mode I is all electric at speeds below 10 to 15 MPH. In Mode II the

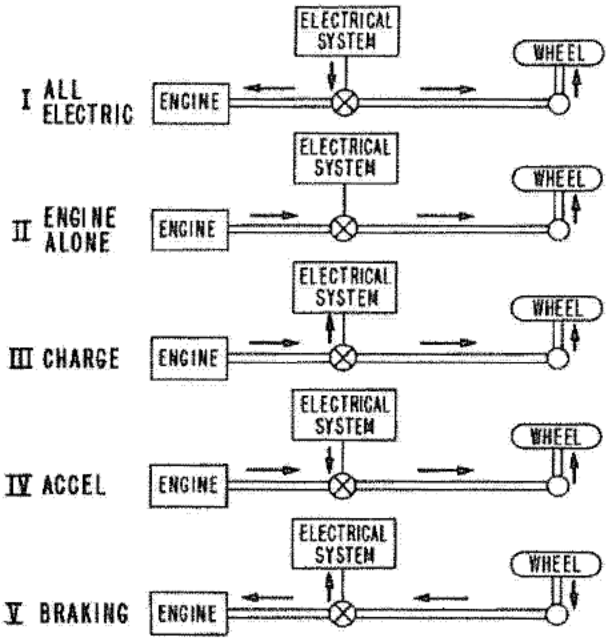
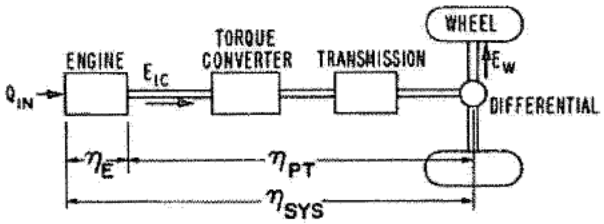


Fig.2 -Five hybrid modes of operation

electrical system. Mode III is the battery charging mode. The engine still drives the rear wheels; however, excess energy is used to charge the battery. When acceleration demands exceed the power input of the engine, the motor provides the needed additional power. This is shown as Mode IV. Mode V is regenerative breaking. The deceleration energy of the vehicle is used to charge the battery. Fuel is shut off to the engine during the all electrical mode and during braking. The battery state of charge is maintained between fairly narrow limits by the control system around a state of charge of about 75% of full charge. This strategy prevents deep discharge cycles on the battery. The sixth mode is at vehicle standstill, during which condition both the engine and electrical motor are inoperative or "dead". Required vehicle auxiliaries are supplied electrically at standstill.

The objective of this system is to provide an increase in fuel economy over a conventional automotive drive system while maintaining equivalent acceleration performance. Comparisons between the hybrid system and conventional systems have been stressed in all studies. The manner in which this comparison is viewed from an overall systems standpoint is important in understanding the significance of this particular hybrid configuration and its operation.

Figures 3 and 4 show that the fuel



ENGINE EFFICIENCY $\eta_E = \frac{E_{IC}}{Q_{IN}}$

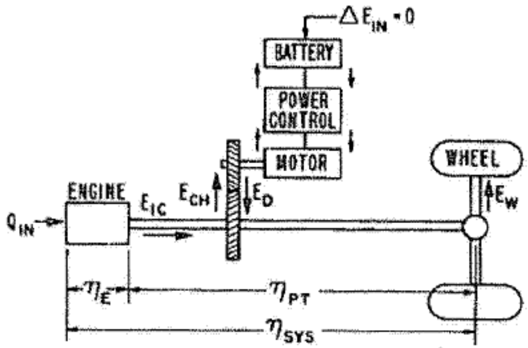
POWERTRAIN EFFICIENCY $\eta_{PT} = \frac{E_W}{E_{IC}}$

SYSTEM EFFICIENCY $\eta_{SYS} = \frac{E_W}{Q_{IN}}$

MILES / GALLON $MPG = \frac{E_W(Q_{IN}/GAL)}{Q_{IN}(E_W/MILE)}$

$$\boxed{MPG = \frac{\eta_E \ \eta_{PT}(Q_{IN}/GAL)}{(E_W/MILE)}}$$

Fig.3 -Average fuel economy for a conventional vehicle in terms of system efficiencies



ENGINE EFFICIENCY $\eta_E = \frac{E_{IC}}{Q_{IN}}$

ELECTRICAL SYSTEM EFFICIENCY $\eta_{EL} = \frac{E_D}{E_{CH}}$

POWERTRAIN EFFICIENCY $\eta_{PT} = \frac{E_W}{E_{IC}}$

SYSTEM EFFICIENCY $\eta_{SYS} = \frac{E_W}{Q_{IN}}$

MPG (MILES/GALLON) $\boxed{MPG = \frac{\eta_E \eta_{PT}(Q_{IN}/GAL)}{(E_W/MILE)}}$

Fig.4 -Average fuel economy for a hybrid vehicle in terms of system efficiencies and energies

$\eta_E \ \eta_{PT}$ (Q/Gal)

where η_E is the average engine brake termal efficiency, η_{PT} is the average transmission efficiency, (Q/Gal) is the energy content per gallon gasoline consumed and (E_W/Mile) is the total energy requirement at the drive wheels per mile necessary to accelerate the vehicle and to overcome vehicle friction and aerodynamic drag. The quantities in this expression represent average values over a prescribed driving cycle. It should be noted that the average powertrain efficiency is defined as the ratio of total positive engine shaft work to total positive energy requirement at the drive wheels. Stated in another way, this represents the fraction of total engine work used to propel the vehicle. For the hybrid drive train state of charge is assumed to be the same at the beginning and end of the drive cycle, thus the net energy input to the transmission from the battery is zero.

The task facing the hybrid system can now be clearly seen. In order to provide an increase in fuel economy over a conventional system the quantity $\eta_E \ \eta_{PT}$ /(E_W/Mile) must be increased. The present hybrid system will be described in terms of how it strives to maintain high average engine efficiency, high average transmission efficiency and low work requirements at the drive wheels while maintaining the equivalent acceleration performance of the conventional system it replaces.

A. High Average Engine Efficiency

1. Small engine - The engine used in the conventional system is replaced by a much smaller engine in the hybrid system. The smaller engine operates at higher load factors, resulting in increased efficiencies. The hybrid engine is sized to meet vehicle cruise requirements up to a specified road speed. This enables the vehicle to be propelled by the engine alone for extended cruise periods. This corresponds to Mode II in Figure 2.
2. Fuel off during idle and deceleration - Approximately 20% of the CVS-H fuel consumption is used during idle and braked deceleration for the conventional vehicles with automatic transmission considered in this study. Elimination of idle and braked deceleration fuel flow in the hybrid configuration results in significant improvements in average engine efficiency.

geared directly to the drive wheels the fuel is shut off at low vehicle speeds and the vehicle is propelled by the electrical system. This corresponds to Mode I in Figure 2. The fuel savings must be weighed against the electrical energy dissipated that must be replaced by charging the battery later in the driving cycle. Since this charging is done at a higher engine efficiency, this mode has a positive effect on the average engine efficiency. However, this charging has an adverse effect on the average transmission efficiency since a lower fraction of the engine work shows up as useful work at the drive wheels. The total gasoline used to replace the battery energy expended during this mode can actually exceed the amount of gasoline used in a conventional vehicle in accelerating up to the corresponding vehicle speed. The energy requirements of this mode can be substantially improved by lowering the work required to motor the engine by opening the throttle, collapsing the valves or by de-clutching the engine. Other approaches include gear changes or use of motors with better low-speed efficiencies.

4. Charging the battery at high-engine efficiency - When the battery requires charging from the engine as represented by Mode III in Figure 2, the basic strategy is to provide the charging energy at the most efficient engine operating point. This contributes to a high overall engine energy efficiency; however, this effect must be weighed against the effect on transmission efficiency since the optimum engine efficiency will not in general correspond to the most efficient charging torque level for the electrical system. Additional trade-offs appear when the effect of engine torque on emissions is discussed in a later section.

5. Accelerate at high-engine efficiency - When the vehicle acceleration demands exceed the power capacity of the engine, the electrical system is used to provide the extra needed power. torque level at which the electrical system is called upon corresponds to a high-engine efficiency point. The effect on transmission efficiency must also be considered since a lower engine torque requires more electrical energy.

B. Transmission Efficiency - The transmission in a hybrid drive train is the portion of the system that transmits useful work from the engine to the drive wheels. Since all the energy needed to propel the vehicle ultimately comes from the engine (assuming the battery ends the drive cycle at the same state of charge) the basic objective of the transmission is to minimize the amount of engine energy used for other purposes. This is achieved as follows:

   1. Engine geared directly to rear wheels for primary source of propulsion - When the electrical system is not in use, the energy from the engine is transmitted directly to the rear wheels through the differential. This is Mode II in Figure 2. The instantaneous transmission efficiency during this mode is essentially equal to the differential efficiency. The engine is sized to provide sufficient torque in this mode for extended high-speed cruise.
   2. Use of electrical system only when needed - To keep the use of the electrical system to a minimum, the motor is used only when needed. The two modes requiring the motor are the all electric mode at low speed (Mode I) and during heavy accelerations (Mode IV).
   3. Use of regenerative braking - During braking the kinetic energy of the vehicle is used to charge the battery. This is described as Mode V in Figure 2. This has a substantial effect on transmission efficiency by reducing the charge energy required from the engine.

C. Drive Wheel Energy - In converting a conventional vehicle to a hybrid configuration the total energy requirements at the drive wheel must also be considered in assessing the potential fuel economy gains. The primary factors that could reduce fuel economy are an increase in the vehicle weight and an increase in the

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