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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 means of computer simulation studies to evaluate its fuel economy, performance, 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 predictions. Problems and limitations of this system are discussed.

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 this philosophy and makes minimum use of the electric system.

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 of the vehicle.

The system can be classified as a

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.

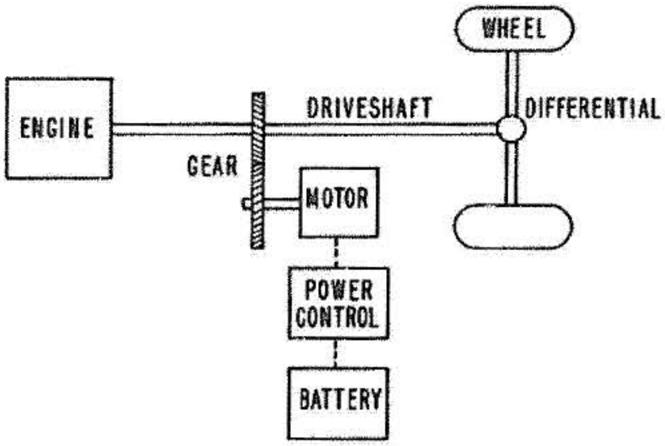


Fig.1 -Ford parallel hybrid

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 engine is the primary source of propulsion and there is no energy in or out of the 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.

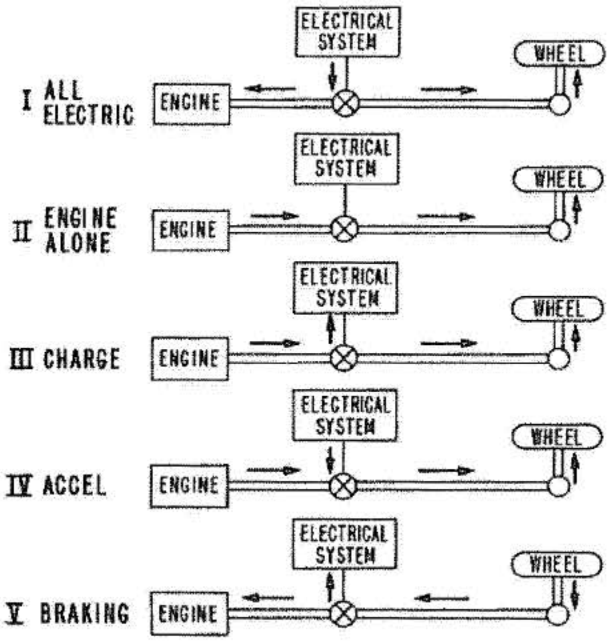
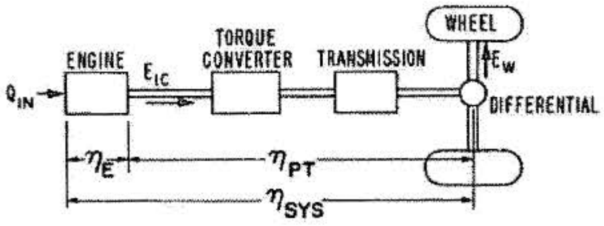


Fig.2 -Five hybrid modes of operation

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 economy for both a conventional and hybrid system can be expressed as follows:



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

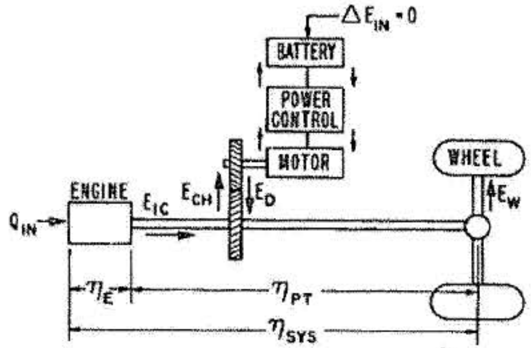
POWERTRAIN EFFICIENCY $\eta_{PT} = \frac{E_W}{E_{IC}}$

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

$$MPG = \frac{\eta_E\ \eta_{PT}\ (Q/Gal)}{(E_W/Mile)}$$

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.
3. Fuel off during low speed operation - Since the engine is

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. This is described as Mode IV in Figure 2. In general the engine 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 rotational inertia due to higher rotational speeds of the engine and motor. System weights will vary considerably with the vehicle acceleration requirements. For the hybrid configurations considered in this study small weight savings were realized. These differences were generally not enough to change the inertial weight class of the vehicle and were not considered in the fuel economy projections. The effects of increased rotational inertias were also seen to be minimal for the configurations investigated.

METHOD OF ANALYSIS

A computer program was developed to simulate all elements of the drive train for the six basic modes of operation over an arbitrary drive cycle. The required power at the drive wheel is computed from the drive cycle data, the vehicle friction, aerodynamic drag, inertial acceleration and rotational inertias. The corresponding power levels are computed throughout the drivetrain based on rotational speeds and torques and component performance characteristics.

Motor/generator and controller efficiencies are computed from efficiency tables in terms of torque and RPM. The efficiency tables used for the D.C. system are based on experimental data from reference (7). Similar tables for a brushless synchronous motor system are based on experimental data from reference (8). Battery efficiency is computer from equivalent circuit models for specific battery types as described in Reference (16).

The engine is sized to provide sufficient power for extended cruise without the electrical system. Fuel flows are computed in terms of engine speed and torque. In general, automatic calibration fuel island data is used with simulated exhaust system, fan on, alternator operated at one-half charge and power steering pump loaded. Engine motoring torque is computed as a function of engine RPM from experimental data.

Axle ratio between the engine and drive wheels and gear ratio between the motor and engine are varied in the analysis until a suitable compromise is reached between fuel economy, top speed, acceleration, maintaining battery charge and, in some cases, emissions.

Comparisons with conventional drivetrains are made by applying the same basic technique of starting at the rear wheels and describing each element individually. Transmission efficiencies are computed for each gear from output speed. Automatic transmission shift schedules are determined from driveshaft RPM and manifold vacuum. Manifold vacuum must be implied from engine torque which cannot be computed until the proper gear is determined. The engine torque and transmission shift schedule must, therefore, be matched iteratively.

The approach is similar to techniques described in Reference (11) for conventional vehicles and in Reference (16) for electric vehicles.

DYNAMOMETER TESTS

Early in the course of the computer simulation and other analytical studies of the hybrid concept, the need for some experimental evidence to support the computer predictions of fuel economy and performance was recognized. Also, emission measurements and engine strategy for emission control were required. The first step in such experimental evaluations has been the testing of an engine-electric drivetrain with a dynamometer and inertia wheel as loading devices. Ultimate evaluation of any alternate engine or other drivetrain component must of necessity by made through a long series of vehicular tests under typical or prescribed driving conditions. However, for systems so far removed from conventional automotive practice as a hybrid drivetrain, dynamometer testing appears essential before vehicular testing is initiated. The principal goals of the hybrid dynamometer tests were:

1. To test the computer predictions of fuel economy, performance, and emissions using a production engine.
2. To establish that the fuel economy improvement is attainable at acceptable emission levels. This required that near optimum engine strategy regarding spark, air-fuel ratio, and exhaust gas recirculation be developed. This was done by dividing the speed torque plane in a grid pattern, studying each area in the grid and summing the total for hybrid operation. This process is called engine mapping in subsequent discussions.
3. To determine that the on-off fuel control required by the hybrid was practical at acceptable performance, emissions and cost. This was determined using a carburetor and minor modifications.
4. To determine that the selected battery was adequate.
5. To determine that the engine is

basically suited to the unique or unusual operations in this concept, such as:

- a. Motoring the engine between 0 and 800 RPM as required by the direct coupling to the wheels. Normally an engine is cranked and immediately accelerated to an idle speed of 700 RPM or more.
- b. Operation at high torque most of the time.
- c. Higher than normal total use and long duration of high torque at high speed.

The experimental hybrid drivetrain was configured as in the block diagram of Figure 1 with two exceptions: The electric motor was on a common shaft with the engine, and the driveshaft was directly coupled to a dynamometer and inertia wheel to simulate the vehicle road, aerodynamic, and inertial loads. The principal components used were:

1. Engine: Ford 2.3L, 4-cylinder, '74 production engine, modified for fuel off operation.
2. Motor: Westinghouse, 40HP, 240 V., 1750 RPM industrial shunt motor; blower cooled.
3. Controller: SCR chopper for motor armature control during motoring and regenerative braking (designed and assembled at Ford); separate power supply for field control.
4. Battery: 140 cells connected in series of Marathon, type 20D120, NiCd; auxiliary forced-air cooling to maintain cells at approximately 20 C; plus required monitoring equipment.
5. Loading Device: Absorption dynamometer of 150 $lb\text{-}ft^2$ inertia and a flywheel of 360 $lb\text{-}ft^2$ inertia.

The combined inertias of the rotating members of the experimental system are equivalent to a vehicle of 7500 lb. inertia weight based upon an engine RPM/vehicle MPH (N/V) ratio of 53.5. Conventional gas analysis equipment was used to measure emissions under conditions of steady state engine operation. Measurements of exhaust CO, CO_2, HC, O_2 and NO_x and intake CO_2 were made. Fuel flow was measured by weight.

Since the hybrid application requires operating an engine under conditions considerably different from those associated with conventional vehicles, preliminary evaluation and modification of the 2.3L engine was necessary:

1. The engine was modified to permit fuel to be turned off during deceleration and at speeds below 15 MPH. This was accomplished by means of a small solenoid valve to block fuel flow in the idle jet, removal of the throttle stop to permit full closure of the throttle plate, a means of admitting air below the throttle, and PCV modification.
2. A sequence control was required for minimum emissions and quality performance during engine fuel turn-on and turn-off. For example, during turn-off, the following sequence was used: (a) close throttle, idle solenoid, and PCV valve, (b) open by-pass air valve around throttle to permit air without fuel into intake manifold, (c) turn-off ignition, with elapsed time between these events.
3. Removal of some engine auxiliaries; for example, the engine alternator is not required in a hybrid drive; air conditioner was not used. The power steering pump was connected and driven.
4. Low-speed engine friction: In a conventional vehicle, the engine is operated below the idle speed (about 800 RPM) for only a few seconds during start-up. In the hybrid, much longer operation may be required. The low-speed friction torques of the 2.3L engine were measured.
5. Low-speed lubrication was evaluated.
6. The EGR valve and plumbing were enlarged to permit large EGR flow at wide-open throttle operation.

Another interesting problem for which there was almost no precedent was the measurement of HC emissions during the frequent engine off/on transitions that the engine passes through during a typical driving cycle. Since CVS equipment for this measurement was not available a technique using diluted samples from the engine-off period was developed and considered to give reasonable accuracy. This method was used to predict the emissions discussed in later sections of this paper.

The resulting experimental system proved to be very "driveable" with smooth transitions between the various operating modes. The system was "driven" through several of the standard test driving cycles with ease and accuracy after a few learning cycles by the operator.

In order to experimentally verify the calculated values of fuel economy that had been obtained from the various computer simulations described above, several dynamic runs over both CVS-H and SAE (17) driving cycles were performed on the experimental hybrid system mounted on a dynamometer test stand. The SAE driving cycle is a simplified version of the CVS-H cycle developed mainly for the electric vehicle tests. Many comparisons of the two driving cycles have shown that both result in approximately the same fuel consumption for both ICE and electric vehicles. Since the "driving" of an experimental drivetrain on a dynamometer test stand over the SAE cycle is much simpler than over the CVS-H cycle, and since the control of the system was not fully automated but required considerable manual control, the SAE cycle was chosen as the means for comparing calculated with measured fuel economy of the hybrid drivetrain. It was found that after only a few tries, manual control was able to follow the required speed and acceleration variations specified by the SAE cycle almost perfectly. The actual efficiencies of the components in the electric branch of the hybrid and the actual road load simulated by the dynamometer were fed into the computer model to obtain the calculated fuel economy. The engine throttle positions were likewise made to correspond between the measure and calculated test runs. The results are summarized below:

TABLE I

COMPARISON OF MEASURED AND CALCULATED DYNAMIC FUEL ECONOMY OF HYBRID

Simulated vehicle inertia weight	7500 lbs
Length of test run	3 SAE cycles (3 miles)
Calculated fuel economy	15.2 mpg
Measured fuel economy	15.8 mpg

FUEL ECONOMY STUDIES WITH AUTOMATIC ENGINE CALIBRATIONS

A variety of studies was conducted by applying the computer program to hybrid and conventional versions of the same vehicle using fuel island data for stock engines with automatic calibrations. The hybrid electrical systems were sized to provide approximately equivalent acceleration performance. The results of these studies are summarized in Figure 5. The purpose of this section is to discuss the reasons for the fuel economy improvement resulting from a hybrid system and to discuss the effects of fundamental system changes on fuel economy.

A. Reasons for Fuel Economy Improvement Resulting from a Hybrid System - The Econoline Van and the Mark IV configurations received the most emphasis in these studies. Figures 6 and 7 present summaries of comparisons made between typical hybrid and conventional versions of the Econoline Van and Mark IV, respectively. The computations were done for the CVS-H drive cycle and both comparisons are based on equivalent acceleration performance between the respective hybrid and conventional configurations. Both hybrid systems represent typical configurations with automatic engine calibrations, DC motor and controller and normal idle throttle engine motoring friction during fuel off modes.

In Figure 6 a 4500 lb. conventional van with 300 CID engine

Vehicle	Hybrid Power Train		Calculated Fuel Economy[c] (MPG)		% Improvement Hybrid/ICE
	Engine	Motor	Hybrid	ICE	
Van[a]	1.1 with closed throttle	DC	18.5	14.4[d]	28
Van	1.1 with wide-open throttle	DC	18.8	14.4	31
Van	1.1 , valves closed	DC	19.5	14.4	35
Van	1.1 , clutch	DC	20.0	14.4	39
Van	2.3 diesel	DC	22.0	14.4	53
Van	2.3 diesel, clutch	DC	23.7	14.4	65
Van	1.1 , clutch	Disc[e]	23.8	14.4	65
Van	2.3 diesel, clutch	Disc	28.4	14.4	97
Mark IV[b]	2.3 (ICE), clutch	DC	18.7	10.5[f]	73
Mark IV	2.3 (ICE), clutch	Disc[e]	21.9	10.5	109

(a) 4500 lb. Inertia Wt.
(b) 5500 lb. Inertia Wt.
(c) All fuel economy calculations based upon vehicle driving the Federal CVS-H cycle; no net change in battery state-of-charge.
(d) Calculated for unemissionized, 240 CID engine. Calculations based upon the 1975, emissionized 300 CID engine used on 1975 vehicles resulted in a fuel economy of 13.4 MPG.
(e) Axial air-gap reluctance motor developed by Ford. (See References (8) and (16)).
(f) Calculated for 1974 460 CID engine with automatic calibration.

Fig.5 -Calculated fuel economy comparisons

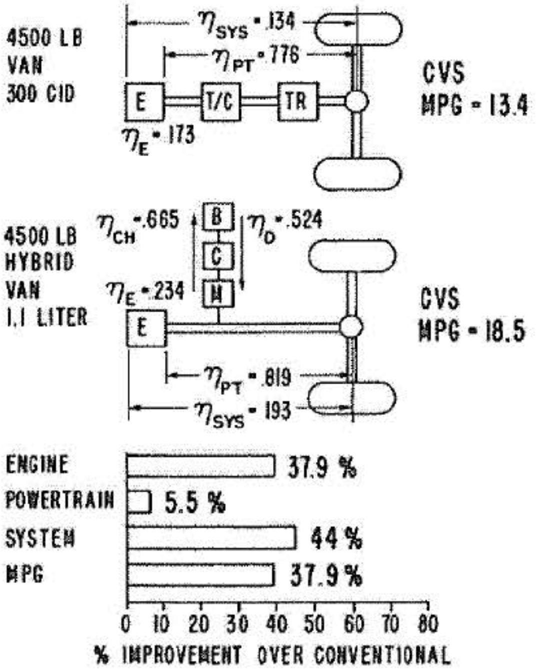


Fig.6 -CVS-H fuel economy and efficiency comparison between hybrid and conventional econoline van

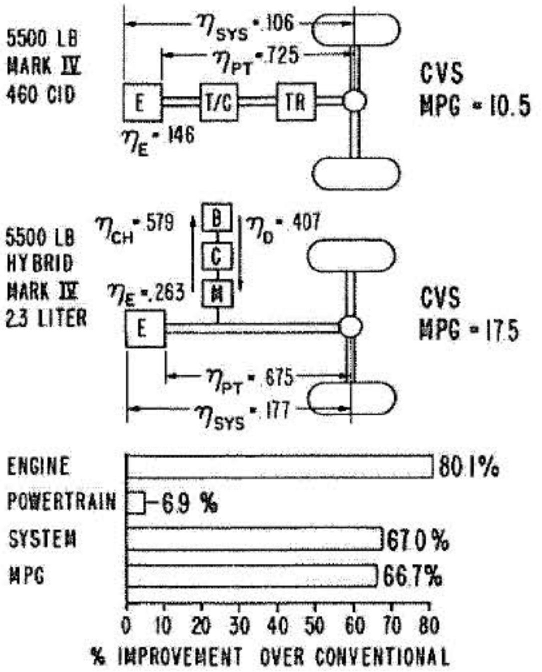


Fig.7 -CVS-H fuel economy and efficiency comparison between a hybrid and conventional Mark IV

and automatic transmission is compared to a 4500 lb. hybrid van with a 1.1 liter engine, DC motor with 130 ft. lb. peak torque and 45 KW of NiCd batteries. Acceleration and battery charging are both done at wide-open throttle and fuel is shut off at engine speeds below 1000 RPM and during braking. Gearing between the engine and rear wheels gives a ratio of engine RPM to vehicle speed in MPH (N/V) of 100, while the ratio of electric motor RPM to engine RPM is 1.75. The weight summary of this substitution is shown in Table II. The performance predictions (acceleration) for this same vehicle are given in Table III.

In Figure 7 a 5500 lb. conventional 1974 Mark IV with 460 CID engine and automatic transmission is compared to a 5500 lb. hybrid Mark IV with a 2.3 liter engine, DC motor with 260 ft. lb. peak torque and 80 KW of NiCd batteries. Accelerations are done at wide-open throttle, while battery charging is done at optimum fuel consumption. Fuel is shut off at engine speeds below 800 RPM and during braking. Engine RPM to vehicle MPH is 58.66, and electric motor RPM to engine RPM is 2.27.

TABLE II

VEHICLE WEIGHT EXCHANGE

Production Systems - 1975 Nantucket	Curb Weight (lbs)
Delete:	
. 300 CID Engine	631
. C-4 Automatic Transmission	155
. Exhaust System	56
. Fuel System (22 gal. base tank)	29
. Battery and Alternator	54
	925 lbs.
Add:	
. 1.1L Engine	243
. Exhaust System	25
. Fuel System (13.3 gal. base tank)	18
. Motor	120
. 2-spd. Trans. (Provision -- not included in fuel economy)	80
. Controller	70
. Battery and Cooling (Ni-Cad System)	170
. 12V Inverter	5
	731 lbs.

NOTE: Structural and other small component changes may alter this weight comparison.

The comparisons shown in Figures 6 and 7 illustrate the following important characteristics regarding fuel economy comparisons

TABLE III

Performance (g)	TED(h) (sec)	0-10 sec (ft)	0-60 mph (sec)	25-60 mph (sec)
1.1L Hybrid Wide Open Throttle(b)(e)	13.3	358	19.7	15.1
1966 240 CID - E-100 (b)	12.5	385	17.1	12.9
Memo: 1974 240 CID E-200 (c)	13.3	364	19.0	14.4

(b) Non-emissionized.
(c) Emissionized.
(e) CVS-CH at 4500 lb. test weight, 25 HP motor, a 50 KW battery, and maximum speed of 81 mph.
(g) Computer projections developed by Powertrain Research, PP&R, Ford Motor Company.
(h) "Time Exposed to Danger"; this is the time required to gain 150 ft. on a vehicle traveling at 55 mph.

between hybrid and conventional vehicles over the CVS-H drive cycle:

1. For both the van and Mark IV configurations the improvement in the hybrid fuel economy is approximately equal to the improvement in overall engine efficiency.
2. Average hybrid transmission efficiencies are comparable in magnitude to the transmission efficiencies of the conventional system with automatic transmission and torque converter.
3. The effect of higher rotating inertias on the required work at the drive wheels for the hybrid configurations is not a significant factor in the fuel

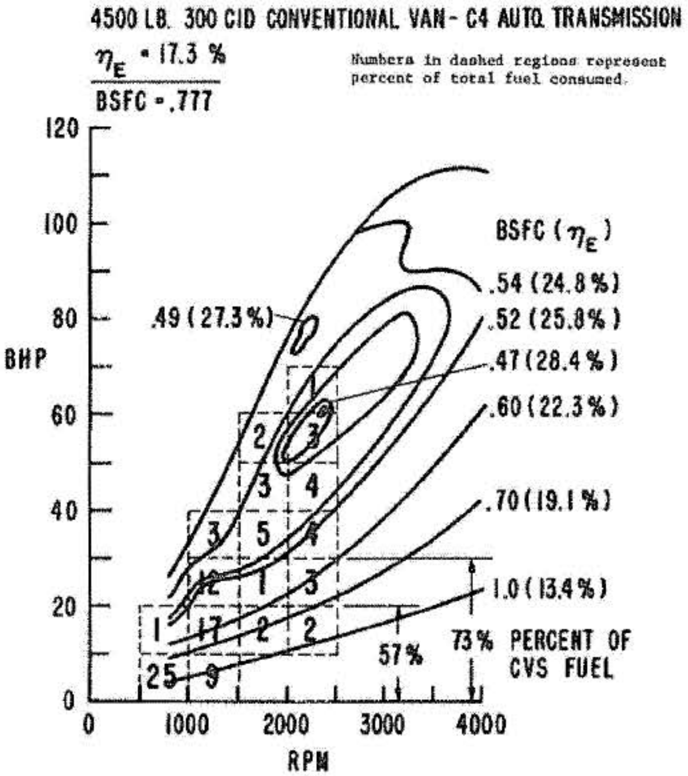


Fig.8 -CVS-H fuel economy utilization for 4500 lb conventional econoline van

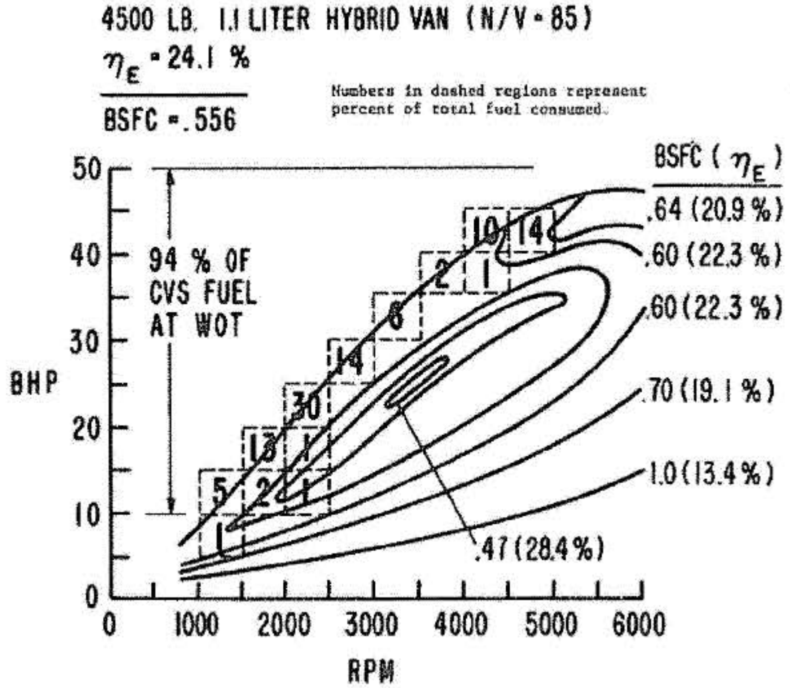
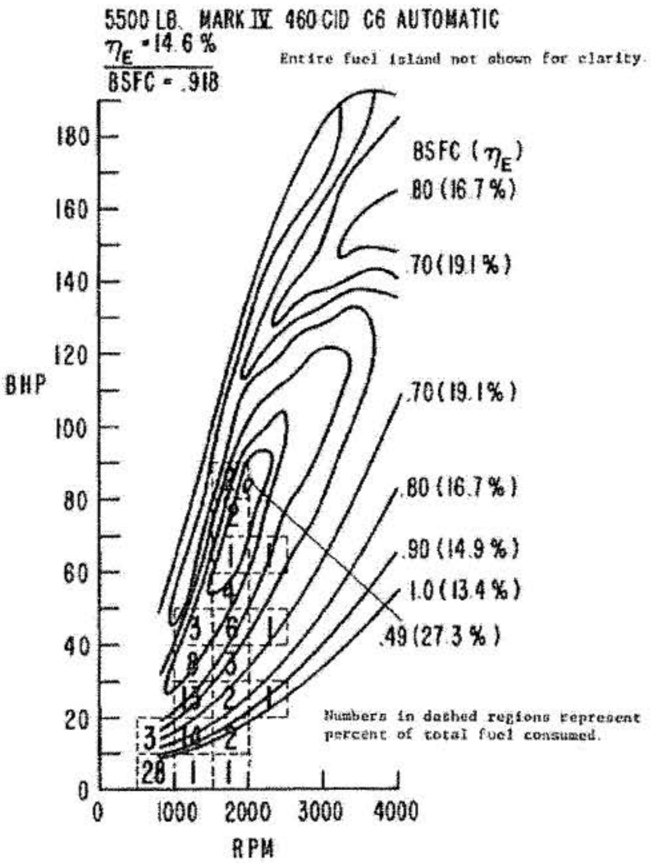


Fig.9 -CVS-H fuel utilization for a 4500 lb hybrid econoline van (N/V=85)

economy, resulting in fuel economy penalties of less than 2%.

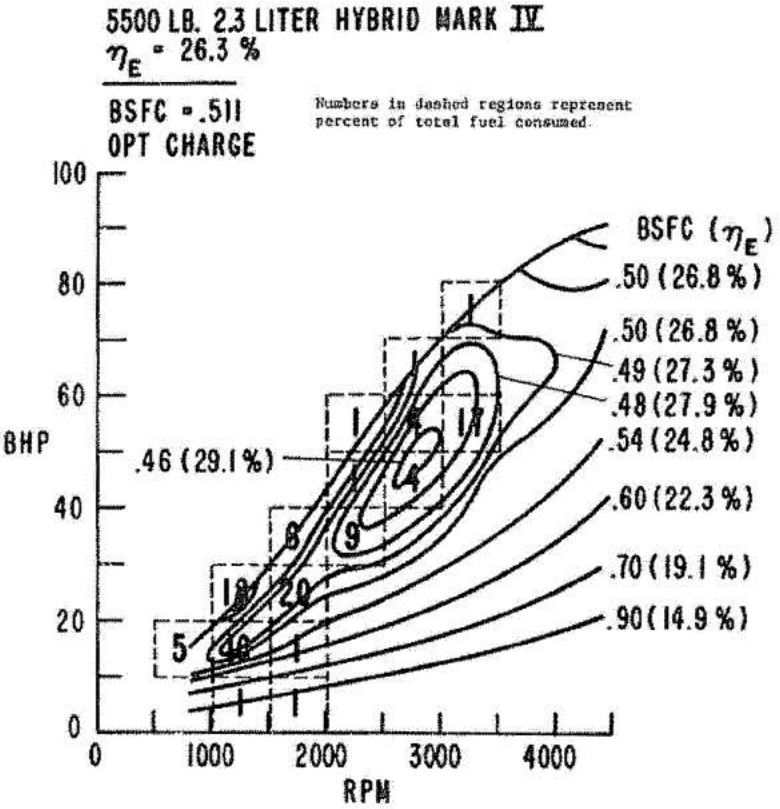
Another important feature of these comparisons is the much greater fuel economy improvement shown for the hybrid Mark IV (66.7%) over that shown for the van (37.9%). Fuel economy is stated in miles per gallon. The reasons for this difference are shown in Figures 8 through 11 which show distributions of fuel utilization over the CVS driving cycle for the conventional and hybrid versions of the van and the Mark IV. The percentages of total fuel consumed at various engine operating points are indicated by the numbers enclosed by the dashed square regions. This information is superimposed on the engine fuel island curves which show contours of constant engine efficiency and brake specific fuel consumption in terms of engine RPM and brake horsepower for an automatic engine calibration. The conventional van does not offer as much improvement potential. In addition, it was necessary to charge at wide open throttle with the hybrid van, while in the case of the Mark IV charging was done at optimum fuel consumption resulting in a higher average engine efficiency. The



Entire fuel island not shown for clarity.

Numbers in dashed regions represent percent of total fuel consumed.

Fig.10 -CVS-H fuel utilization for a 5500 lb conventional Mark IV



Numbers in dashed regions represent percent of total fuel consumed.

Fig.11 -CVS-H fuel utilization for a 5500 lb hybrid Mark IV (optimum fuel charge)

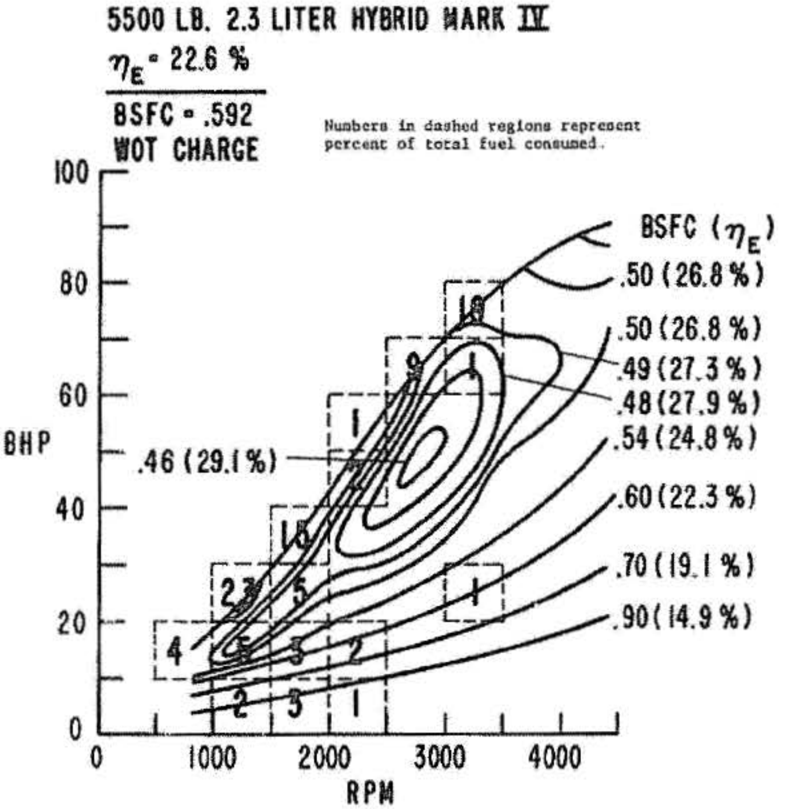


Fig.12 -CVS-H fuel utilization for a 5500 lb hybrid Mark IV (WOT charge)

difference in engine efficiency due to charging strategy is also shown in Figure 12 which shows the reduction in hybrid Mark IV engine efficiency of approximately 14% that would result from charging at wide-open throttle.

It is important to understand the reasons why the average engine efficiency is improved with the hybrid configuration. The key point is that the hybrid engine is operated at more efficient operating points. This results in an improved overall engine efficiency when averaged over the drive cycle. This improvement has two sources. The first is the elimination of all fuel consumed at idle, during braking and during the low speed all-electric mode. The equivalent driving modes for the conventional van and Mark IV account for 25% to 30% of the fuel consumed for the CVS-H cycle. The second source of improvement is the higher load factors and wider throttle openings required by a smaller hybrid engine. This gain must be carefully weighed against the higher frictional losses at the higher engine speeds encountered with the hybrid.

EMISSION AND FUEL ECONOMY PREDICTIONS

The studies described in the previous section indicate that a substantial improvement in fuel economy can be achieved from a hybrid with a conventional automatic engine calibration for spark timing, EGR and air fuel. The experimental program described previously was undertaken to map the emissions and fuel consumption of a 2.3 liter engine. One objective of this program was to provide data for use in computing hybrid emissions and fuel economy over the CVS-H cycle for the Mark IV configuration previously described in Figure 7.

The first step in computing the hybrid emissions was to divide the engine speed torque region into a grid composed of 10 ft. lb. torque increments and 300 RPM speed increments. The hybrid computer program was used to define the time spent in each cell as the engine was used in a hybrid Mark IV driven over the CVS-H cycle. The next step was to map the 2.3 liter engine over the entire speed torque region from 950 to 3350 RPM with the engine operating with a 1974 production calibration for spark timing, EGR and air fuel. All engine mapping was performed with fan off, alternator off, power steering pump loaded and with simulated vehicle exhaust system. These data were used to define the initial emissions and fuel distributions for the baseline configuration. The next step was to select regions of high emissions from the automatic calibration results and to perform additional experiments to reduce emissions. These results were then used with the hybrid computer program to obtain revised emissions and fuel economy predictions for the baseline hybrid configuration.

A. Automatic Calibration Results - NO_x, CO, HC and fuel data were obtained from mapping the 2.3 liter engine with automatic calibration. Figure 13 shows the projected engine energy distribution for the hybrid Mark IV over the CVS-H cycle. Energy distributions are shown as percentages of the total positive engine shaft work over the cycle. These energy values are used with the emission and fuel data obtained experimentally to obtain the CVS-H emission and fuel economy projections for the hybrid Mark IV with automatic engine calibration.

The start/stop value for HC results from shutting fuel off on braked decelerations and starting the engine when it reaches 800 RPM.

Figure 13 clearly shows two regions of high energy usage. One is along the line of maximum torque resulting from hard accelerations. The other region is a band of intermediate torques used to charge the battery. The particular strategy assumed for the baseline hybrid used the optimum fuel engine torque at a given speed to charge the battery. Optimum fuel torques were determined from the automatic engine calibration. The regions of high emissions and fuel utilization were seen also to be located in bands of maximum torque and optimum fuel torque; however, the distributions differ markedly from the energy distributions. The effects of power enrichment were readily seen by the high concentrations of CO and HC at maximum torque. The effect on fuel consumption is similar but not as great. Power enrichment had the opposite effect on the NO_x distributions, tending to lower the distributions at maximum torque.

B. Emission Reduction at Selected Operating Points - Having determined from the automatic calibration results that most of the CVS-Hot emissions and fuel are contained in two narrow bands of torque, the next step was to

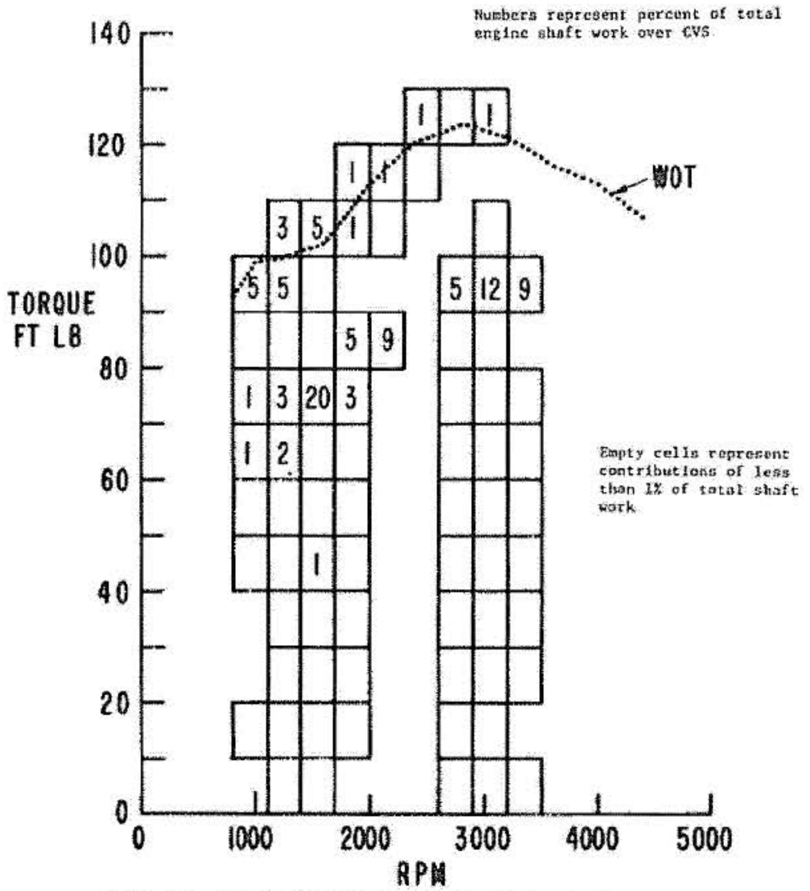
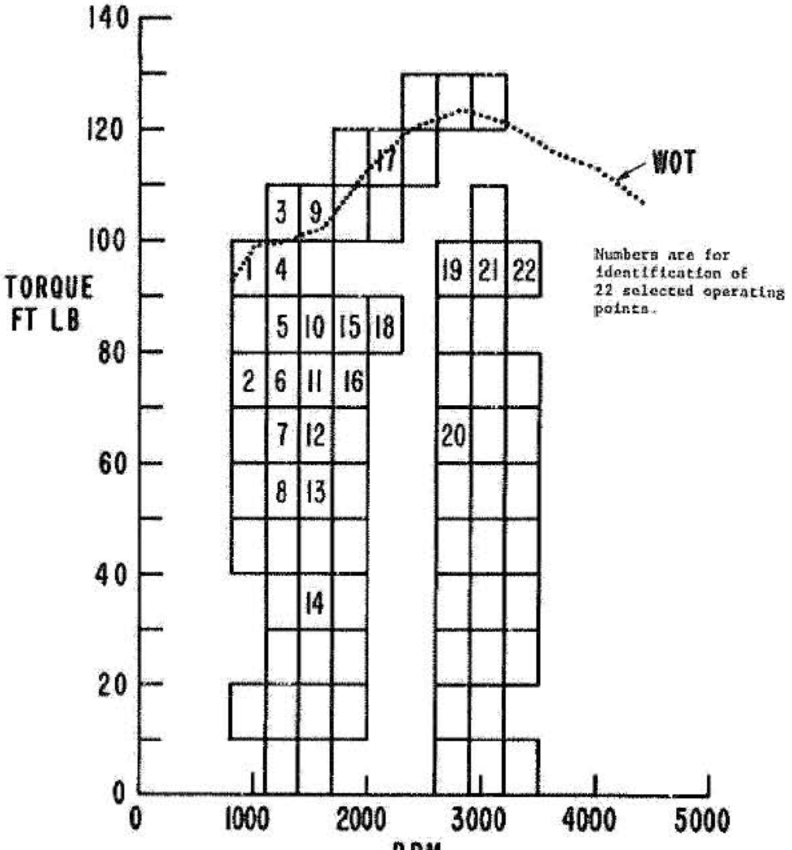


Fig.13 -Distribution of engine energy over the CVS-H cycle for a 5500 lb Mark IV with a 2.3 l engine (optimum fuel charge)



Numbers are for identification of 22 selected operating points.

Fig.14 -22 operating points selected for additional data (2.3 l engine)

acquire additional data in these regions at lower emission levels. Figure 14 shows the 22 operating points at which additional data was taken.

The general approach was to reduce CO at high torques by eliminating power enrichment and to control NO_x at high torques with EGR and spark retard. Points at or very near maximum torque were obtained with wide-open throttle, optimum or near optimum spark and little or no EGR. At intermediate to high torques the throttle was kept open to reduce pumping work, large EGR rates were maintained, and torque was reduced by retarding the spark. Very little additional data was taken at low torques, since NO_x reduction at intermediate and high torques was considered to be higher priority. An operating point is considered to be at the midpoint of a cell having the dimensions 300 RPM by 10 ft. lb. In arranging the data, all values within the cell were assumed to be at midpoint.

The CVS-H emissions and fuel economy projections corresponding to the lowest measured NO_x at each of the 22 operating points shown in Figure 14

	HC	CO	NO_x	MPG
5500 lb Hybrid Mark IV . Fully automatic engine calibration . CVS-H	1.36	44.6	3.28	17.82
5500 lb Hybrid Mark IV . 22 pt NO_x reduction . CVS-H	1.38	14.5	2.14	18.59
5500 lb Conventional Mark IV . (strategy A)(11); CVS-H	.94	5.98	1.69	10.9
5500 lb Conventional Mark IV . (strategy B)(11); CVS-H	1.30	5.64	6.64	11.7

TABLE IV

NOTE: For comparison, the Interim Federal Emission Control Requirements (49 states) are shown below.

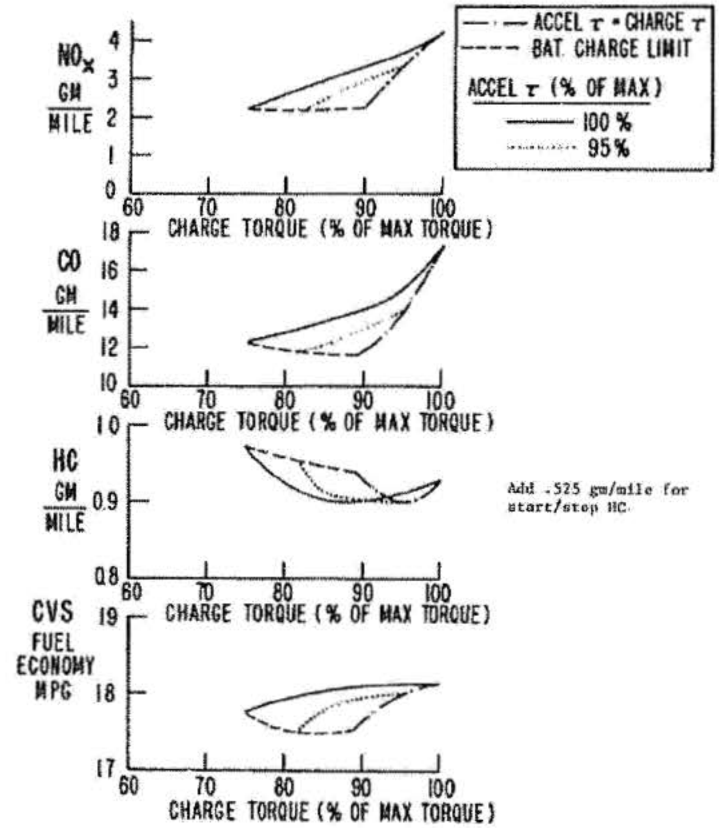
	HC	CO	NO_x
1975/6 CVS-CH Federal Standards	1.5	15	3.1
1977 CVS-CH Federal Standards	1.5	15	2.0

with automatic calibration data assigned to other points is presented below. Also shown for comparison are the fully automatic calibration results from the previous section and computer CVS-H results from Reference (11) for two engine calibration strategies.

The primary emphasis in collecting the data was to adequately describe the regions of high emissions and fuel for the baseline hybrid configuration. The 22 operating points accomplished this purpose. After most of the data had been taken, it was decided that additional information gained by examining emission and fuel trends for different hybrid configurations would be very helpful in evaluating the future potential of hybrids. In order to accurately identify trends, a consistent variation in emissions and fuel with speed and torque was needed. Some additional data was collected and previous data was re-examined. This data revealed consistent trends with torque for NO_x, HC and BSFC at each speed. Considerable scatter was observed for the CO data, which was more sensitive to fluctuations in air fuel ratio. In general, the air fuel ratio varied from 14.0 to 14.6. Initial attempts to describe the entire engine operating region by fitting the data at each speed as a function of torque proved unsuccessful due to lack of consistency with speed variations. The data were again re-examined and some previously discarded data points were included. Plots of emissions and fuel with speed as well as torque were made. As a result of this re-examination, emissions and fuel distributions were approximated over the entire engine operating region. The purpose of these approximations was to provide a reasonable representation of the measured data that clearly shows observed trends with speed and torque. The approximations do not necessarily represent the lowest possible NO_x; however, they do represent projected emissions and fuel values at low NO_x levels with realistic distribution in speed and torque.

C. Emission and Fuel Economy Trends Due to Configuration Changes - The "low NO_x" emission and fuel data obtained experimentally were used to obtain CVS-H fuel and emission projections for various configuration changes.

Figure 15 shows the effects of varying acceleration and charging torque for a 5500 lb. Mark IV. In general, a reduction in either charging or acceleration torque results in lower NO_x and CO, lower fuel economy and a tendency toward higher HC. These changes are due to the lower NO_x and CO values and higher BSFC and HC values occurring at lower torques. The battery charge limit clearly shows the limiting torque values needed to keep the battery charged over the CVS-H cycle.

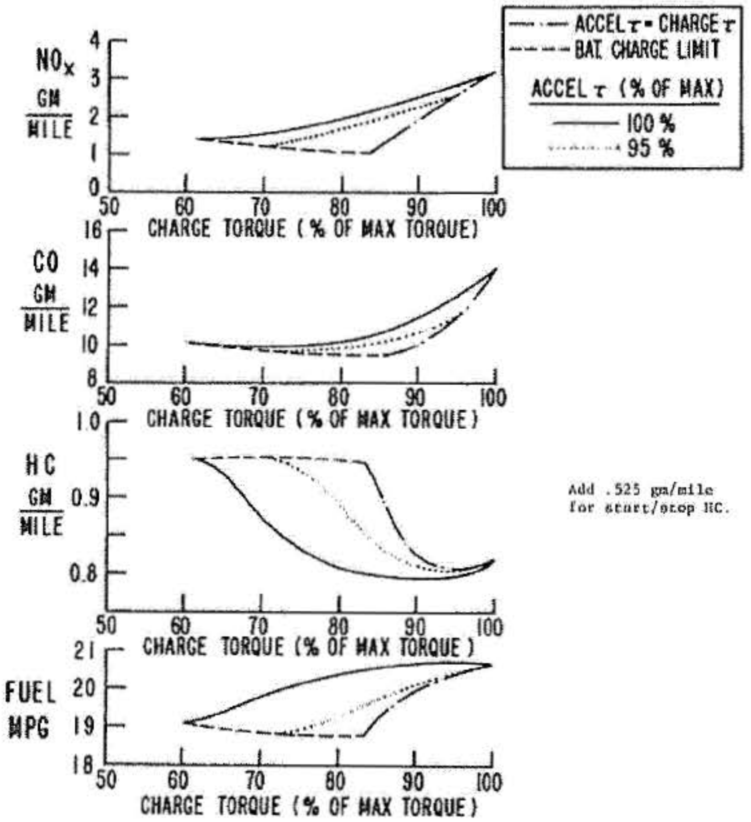


Add .525 gm/mile for start/stop HC.

Fig.15 -CVS-H fuel and emissions trade-offs for various charge and acceleration torque strategies for a 5500 lb hybrid Mark IV

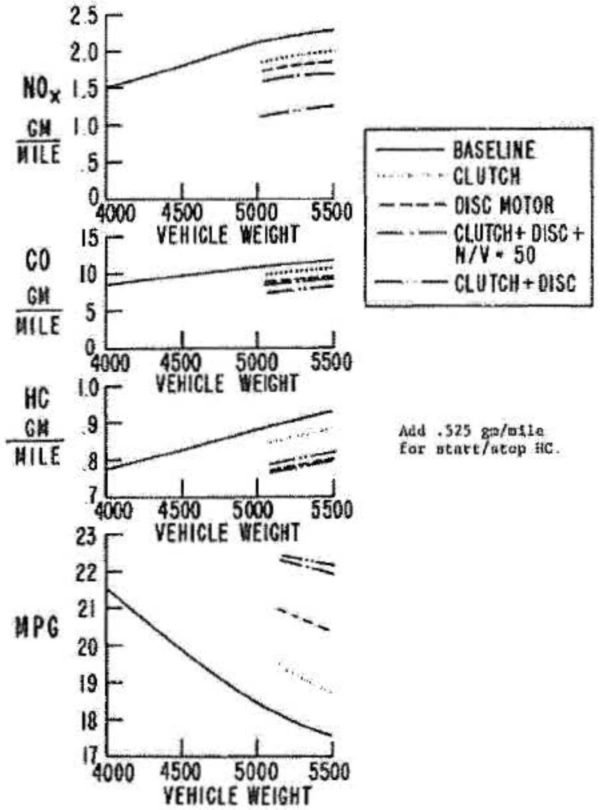
Figure 16 shows the same information for a 4500 lb. vehicle with all other characteristics the same as before. The battery charge limit is shifted toward lower torque values with a significant reduction in NO_x to values approaching 1.0 gram/mile on CVS-H. Substantial reductions are also observed for CO and HC. Substantial increases in fuel economy are observed due to the lower total energy required.

Figure 17 shows the effect of vehicle weight on a configuration having charge and acceleration torque levels of 90% of maximum. The effects of an engine clutch and disc motor are also shown. In general, the effects of a clutch, disc motor and lower inertial weight result in lower emissions and higher fuel economy due to the reduced charging demands on the



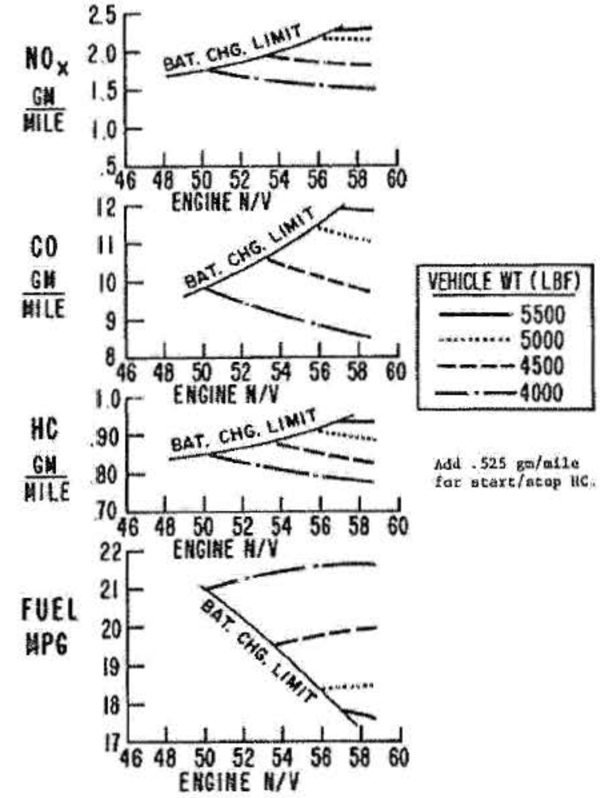
Add .525 gm/mile for start/stop HC.

Fig.16 -CVS-H fuel and emissions trade-offs for various charge and acceleration torque strategies for 4500 lb vehicle



Add .525 gm/mile for start/stop HC.

Fig.17 -Effects of vehicle weight, clutch, and disc motor on CVS-H fuel and emissions for a 5500 lb hybrid Mark IV



Add .525 gm/mile for start/stop HC.

Fig.18 -Effect of engine to drive wheel gearing on CVS-H fuel and emissions for Mark IV with various inertial weights

engine which increased transmission efficiency and reduced high torque operation.

Figure 18 shows the effects of N/V for inertial weights ranging from 4,000 lbs to 5,500 lbs. The ratio of motor speed to engine speed was held constant at 2.27. At the lower weights a reduction in N/V increases NO_x, CO, and HC and lowers fuel economy. The dominant effects are lower engine powers available for charging and lower electrical efficiencies at a given road speed as N/V is reduced. This results in a higher fraction of the engine energy used for high torque charging and a reduction in transmission efficiency. These trends tend to reverse as the weight is increased. At 5,500 lbs. NO_x actually decreases and fuel economy increases as N/V is reduced to the battery charge limit.

SUMMARY AND CONCLUSIONS

An engine/electric parallel hybrid drivetrain has been proposed as a means for improving the fuel economy of vehicles presently powered by conventional ICE drivetrains. The proposed system bears some similarity to several previously studied systems whose evaluation has not appeared very promising. The proposed system is shown to be capable of overcoming many of the deficiencies of the earlier systems through proper matching of hybrid engine to vehicle weight, through use of a single electrical machine for both motoring and regenerative operation, through design of the electrical branch of the hybrid on the basis of short-time power requirements rather than energy requirements, and through maximum exploitation of engine control to achieve both efficient operation and relatively low emission levels. Many analytical studies and corroboration by dynamometer testing have shown that present CVS-H fuel economies (miles/gallon) of existing engine power vehicles can be improved by 30% to 100% while meeting 1975/76 Federal Emission Control requirements with the use of catalytic converters. The percent improvement in fuel economy achievable is largely a function of vehicle weight and performance specification with the larger increases occurring on the larger, high-powered vehicles.

At the present time, nickel cadmium batteries appear to be a feasible choice for the energy storage device in the electrical branch of the hybrid. As a result, substitution of a hybrid drivetrain for a conventional drivetrain would result in a cost penalty on initial vehicle cost.

It is shown that the principal reasons underlying the fuel economy increase realized by this particular hybrid configuration are:

1. The engine used in the hybrid is operated in regions of minimum specific fuel consumption during a much greater portion of its operating time than in conventional drives. The engine is sized more for steady-state (constant speed) driving conditions than for vehicle acceleration requirements. The electrical system serves a function somewhat analogous to that of an infinitely variable transmission and also adds power during vehicle acceleration and stores power during braking.
2. The elimination of the idling condition on the engine. This is a major source of low fuel economy during city driving.
3. The use of regenerative braking.

It should be noted that there are a number of open issues concerning the viability of this hybrid configuration that must be resolved before any thoughts of production can be entertained. Some of these issues, such as the initial cost penalty, meeting more restrictive NO_x standards, low-speed all-electric operation, and obtaining a suitable energy storage device, have been pointed out in the body of this paper. There are other problems which can be solved only through prototype development and lengthy testing of the drivetrain. These include:

1. Drivetrain packaging in a real vehicle.
2. Battery maintenance.
3. Engine lifetime under increased loading (the engine load factor required for the 2.3L hybrid Van operation is .335; for the conventional van, it is .125.)
4. Supplying power to vehicle auxiliaries.
5. Developing the best vehicle control system to achieve driveability comparable to existing vehicles.
6. Driveshaft, differential, and rear wheel performance during regenerative braking.
7. For some applications, such as those requiring driving long distance on upgrades or at very low speeds, larger battery energy capacity than that indicated in this paper is desirable.

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