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ABSTRACT

The design specifications and the results of the performance and emissions testing are reported for a series Hybrid Electric Vehicle(HEV) which was developed by a team of midshipmen and faculty at the United States Naval Academy. A 5-door Ford Escort Wagon with a manual transmission was converted to a series drive hybrid electric vehicle. The propulsion system is based on a DC motor which is coupled to the existing transmission. Lead-acid batteries are used to store the electrical energy. The auxiliary power unit(APU) consists of a small gasoline engine connected to a generator. All components are based upon existing commercial technology.

INTRODUCTION

A series Hybrid Electric Vehicle(HEV) has been developed by a team of midshipmen and faculty at the United States Naval Academy for use in the Hybrid Electric Vehicle Challenge which took place during June of 1993. This competition, involving thirty universities from North America, was jointly sponsored by Ford Motor Company, the SAE International, and the U. S. Department of Energy. A 5-door Ford Escort Wagon with a manual transmission has been converted to a series drive hybrid electric vehicle. The propulsion system is based on a DC motor which is coupled to the existing transmission. Lead-acid batteries are used to store the electrical energy. The auxiliary power unit(APU) consists of a small gasoline engine connected to a generator. The AMPhibian is designed to be an economically feasible HEV, for use in near term applications. To accomplish this, all components are based upon existing commercial technology. Further, this vehicle was designed to retain, to the greatest degree possible, the basic driving characteristics of a conventional gasoline powered vehicle.

DESIGN OBJECTIVES

The challenge involved many aspects including cost effectiveness, acceleration, range, safety, and emissions, which were incorporated into the vehicle design.

COST - Since the AMPhibian was designed to be economically feasible, minimizing cost was considered to be a major design goal. All design decisions were made only after the associated costs were analyzed. To help attain this goal, all components were based upon existing, available technology.

PERFORMANCE AND EMISSIONS - The major performance and emissions design goals for the AMPhibian include 1) the ability to travel 64 Km as a zero emissions vehicle(ZEV) using battery power alone, 2) operating in hybrid mode, the ability to travel 320 Km while meeting the transitional low emissions vehicle(TLEV) air pollution standards, 3) achieve a time of under 15 seconds when accelerating from 0 to 70 Kph, and 4) climb a minimum of a 15% grade. The vehicle was also to maintain driving characteristics as similar to that of conventional gasoline powered vehicles as possible(e.g. one brake pedal, shift gears normally, etc.).

RELIABILITY AND DURABILITY - The AMPhibian should have reliability and durability similar to that of a conventional gasoline powered vehicle. Using existing components not only helps to limit the costs, but also to help ensure reliable and durable operation of the vehicle.

SAFETY - Occupant safety was a prime concern. The frontal impact zone and original vehicle bumpers were maintained to provide sufficient collision protection. The original power-assisted braking system also remained intact to ensure proper braking. A fire suppression system was added to the vehicle and battery compartments, as well as to the engine bay to minimize the chances of injury and equipment damage. Due to the additional vehicle weight, the roof structure was augmented to provide additional protection in case of a vehicle roll-over. Finally, the competition rules required the use of a five point harness system for both the driver and passenger.

WEIGHT - One major disadvantage of electric vehicles has traditionally been the large weight due to the propulsion batteries required to provide the energy storage capability for extended range. An advantage of the HEV concept is to allow for less energy storage capability of the batteries by replacing some of these batteries with a small auxiliary power unit(APU) which provides the equivalent amount of energy with less weight. However, battery weight is still considered to be a major concern, requiring the team to consider all options for reducing vehicle weight. The AMPhibian was designed to weigh less than the gross vehicle weight rating(GVWR) of the 1992 Escort LX Wagon plus an additional 10%. This results in a maximum allowable vehicle mass of 1729 kg. Further, to maintain acceptable handling, the side-to-side bias must remain within 5% of neutral, and the front-to-rear bias must not drop below about 40%/60%.

PASSENGERS AND CARGO - The HEV carries one driver and one passenger, along with a volume of cargo(50 cm by 100 cm by 25 cm). The total combined weight of people and cargo is a minimum of 180 kg.

BATTERY CHARGING - The HEV charging system was designed to recharge the battery pack in six hours. This should reduce daytime charging demand on electrical utilities. Daytime charging, if necessary, could be accomplished using the APU. The charging system accepts either 110V or 220V, 60 Hz AC power.

STYLING - Vehicle styling changes were minimized to maintain continuity with existing vehicle designs. No external glass or body sheet metal was modified except to provide additional ventilation.

VEHICLE DESIGN

The relationship of the design goals was studied, and compromises were made to provide near optimal system design, given the severe budgetary and time constraints. This process resulted in the selection and design of the major vehicle components. The following discussion details the design decisions and vehicle specifications which are summarized in table 1.

POWERTRAIN - The AMPhibian is propelled using a series drive configuration. That is, the only component that is mechanically connected to the drive-train of the vehicle is the electric motor. This arrangement is depicted in fig. 1, a more detailed electrical schematic is shown in fig. 2. This arrangement was considered to be superior to the parallel drive arrangement, in which both the electric motor and the APU can propel the vehicle, for the following reasons. The series drive would require less structural change to install, and thus provide a lower cost. The parallel drive system would also require a more sophisticated control system to minimize driveability problems such as those associated with the transition from electric vehicle(EV) mode to hybrid electric vehicle(HEV) mode. This would, again, result in higher cost, and, possibly, reliability problems due to the added complexity.

The conversion to a series drive system required the removal of the standard Escort engine. Since the Escort has front-wheel drive, the standard engine is mounted

Table 1. Summary of Components used in the U. S. Naval Academy's Hybrid Electric Vehicle.

Chassis:	'92 5-door Escort LX
Stock GVWR:	1572 kg
Converted GVWR:	1729 kg
Maximum Carrying Capacity(passengers and cargo):	180 kg
DC Motor:	General Electric model 5BT1346B50
Motor Controller:	Curtis PMC 1221B-1074
Batteries (propulsion):	10 arranged in series, 12VDC Trojan 5SH(P)
Bus Voltage:	120 VDC
APU Engine:	Briggs and Stratton Vanguard V-twin, 13.4 kW @3600 RPM, two cylinder
APU Alternator:	Fisher Technology, Inc., 13.5 kW, 150 Vpeak
Tires:	Goodyear Invicta GL P175/65R14, low rolling resistance
Estimated Vehicle Cost:	$26,000
Conversion Component Net Cost: (exc. safety items, credit for 1.9l engine)	$14,000

transversely in a transaxle arrangement. Thus, the transaxle was left intact so that a new axle would not need to be designed. The electric motor was attached directly to the existing bell-housing and flywheel. This arrangement also allows full use of the existing transmission, thus allowing for variable gear ratios. This was considered an advantage since it would allow the electric motor to be operated closer to its preferred operating speed over varying vehicle speeds.

Prior vehicle testing and simulation indicated that the vehicle would require a power of approximately 9 kW in order to maintain a steady 80 Kph. Acceleration from a stand still to 72 Kph in less than 15 seconds would require a peak power of 32 KW(at approximately 35 Kph) for a short

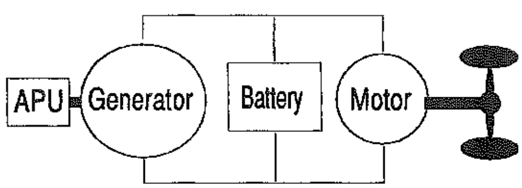

Fig. 1. Series Drive Diagram for the U. S. Naval Academy's Hybrid Electric Vehicle.

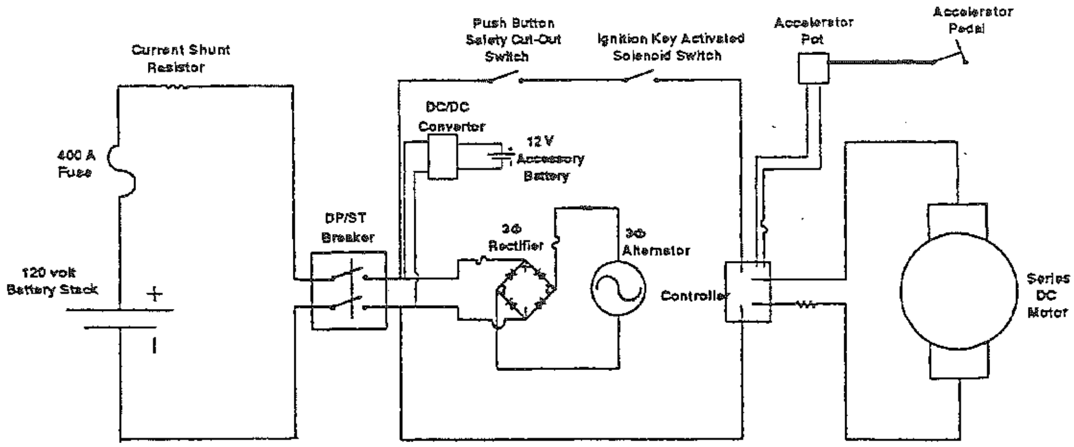

Fig. 2. Electrical Schematic for the U. S. Naval Academy's Hybrid Electric Vehicle.

duration. Motor controller cost and availability became the critical design factor for the selection of both the type of motor and the system operating voltage. The use of an AC motor was investigated due to its inherently higher power density compared to a DC system. However, it was rejected due to the cost, availability, size, and weight of the associated motor controller. A series connected, 15.2 kW(@ 90 VDC) DC motor was chosen instead since DC motor controllers are more widely available, less costly, and lighter in weight. The combination DC motor and controller weighs approximately 82 kg, the engine that was removed weighed 113 kg, thus resulting in a net weight savings of 31 kg. Although the steady state rating is less than the peak incurred during the acceleration, the motor can provide a peak power 2-3 times its steady state rating for short duration. A controller rated at 120 VDC(160 V peak) was chosen, thus this determined the system operating voltage.

BATTERY SELECTION - The AMPhibian has two battery power systems. One system is at 12V and one at 120V. The 12V system is used to power the 12V lighting and accessories. The 120V primary battery powers the prime mover and supplies power to recharge the 12V battery.

The battery selection was overwhelmingly driven by cost considerations. Secondary considerations included: 1) the HEV Challenge constraint of 400V or less battery stack voltage, 2) the motor controller rating of 120V, 3) the HEV Challenge constraint of no more than 20 kW-hr capacity at a 3 hr discharge rate, 4) the gross vehicle weight rating constraints and 5) practical considerations. In general, an inexpensive, small, lightweight battery having high specific power and high specific energy is desired for use in the AMPhibian. Additional considerations included the desire to maximize voltage thereby minimizing power losses due to the lower operating currents. Also, to help to maximize electrical energy storage capacity, and, therefore, ZEV capabilities, the battery ampacity rating should be maximized. Since the maximum rating for the motor controller is 120V, 120V was selected. An order-of-magnitude calculation of the costs of batteries having characteristics superior to those of conventional lead-acid batteries lead the design team to limit selection considerations to off-the-shelf lead-acid batteries. For example, Nickel-Iron batteries were found at a cost of $1800 per six volt battery or $36,000 for a 120V battery stack. Nickel-Cadmium were found at a cost of $964 per six volt battery or $19,280 for a 120V battery stack. Both estimates far exceeded AMPhibian budget constraints; therefore only lead-acid batteries were considered.

The task of battery selection was complicated due to the general lack of published, comprehensive, technical battery performance data covering an extensive number of battery models and manufacturers which had been verified by an independent source. This limited information resulted in the selection of the Trojan 5SH(P) battery. The Trojan 5SH(P) battery is a deep-cycle, wet-celled, 12V battery. The "L" type terminals were selected for this application. With the primary battery selected, the 12V system needed to be defined and selected.

Several approaches were considered to power the 12V system. This included the extremes of using the existing 12V system, as is, or converting all 12V components to 120V. Engineering judgment indicates the latter option is not practical. One approach for providing power to the 12V system was to utilize the output of one twelve volt battery from the 120V stack. This approach has the advantage of simplicity. One disadvantage of this approach is that, using the existing 12V components which are grounded to the chassis, means that the battery stack is no longer electrically isolated from the chassis and, thus, the chance of injury in the event of failure is increased. Another problem, is that, since the batteries are connected in series, if the battery used for the 12V system fails, the whole battery stack will become inoperable. The chance of battery failure can be reduced by inserting a higher amp-hr rated battery into the 120V stack to compensate for the added use. The disadvantage is that this local change to the series of batteries imparts an unknown on the primary battery stack performance (i.e., internal impedance and resistance). This lead to the decision to have two separate battery systems, a 120V primary system and separate 12V system.

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