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ABSTRACT

Various aspects of the design and evaluation of hybrid/electric vehicles are considered with emphasis on the consequences of utilizing advanced electric driveline components such as AC motors/electronics and ultracapacitors. Special attention is given to series hybrid drivelines, because they benefit much more directly than parallel hybrid drivelines from the recent large improvements in the specific weight and volume of electric drive motors/electronics. The results of the present study indicate that series hybrid vehicles with an electric range of 90-100 km and good acceleration performance (0-88 km/h acceleration times of less than 12 seconds) can be designed with a powertrain weight and volume comparable to that of a parallel hybrid of the same performance. The driveline efficiencies of the series and parallel designs for both city and highway driving differ by less than 15 percentage ponts. The control of the series hybrid driveline is expected to be significantly simpler than that of the parallel hybrid system and in addition, meeting the California ULEV emission standards should be less difficult for the series hybrid design, because the start of its engine can be delayed until the catalyst is warm without affecting vehicle driveability.

Simulation results for series hybrid vehicles on the FUDS and the Federal Highway cycles indicate that their fuel economy (miles per gallon) operating in the hybrid mode will be 25-50% greater than conventional ICE vehicles of comparable interior size. Hybrid/electric vehicles using ultracapacitors to load level the engine in the driveline showed even a greater potential improvement in fuel economy. Load leveled operation of the engine may make it less difficult to use high specific power engines, such as two-stroke and gas-turbine engines, in light duty vehicles having stringent emission control requirements.

INTRODUCTION

Hybrid/electric vehicles, which utilize both an electric driveline and an engine to provide the power and energy for propulsion, have been studied for the last 20 years. Hybrid propulsion systems are used primarily to overcome the range limitation of pure electric vehicles powered by batteries alone. A number of hybrid vehicles have been built and tested to demonstrate the viability of various hybrid powertrain approaches. Much of the engineering activity on hybrid vehicles occurred between 1978 and 1984 as part of the response of the United States to the oil crises of 1973 and 1979.

In recent years, interest in hybrid vehicles has been relatively low and most of the work on vehicles using electric

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drivelines has been concerned with pure electric designs. Some work on hybrid vehicles was continued after 1984 and that work will be included in the review of hybrid vehicles given in the next section. Since 1990, there has been increased interest in hybrid vehicles due primarily to the California Initiative that requires 2% of the vehicles sold in California to be electric vehicles by 1998. In light of this renewed interest in hybrid vehicles by the auto industry worldwide, this paper is intended to update hybrid vehicle development and design options reflecting the recent advances in electric driveline component technology and the requirement for ultra-low-emission vehicles (ULEV) in California. Both series and parallel hybrid driveline configurations will be considered. The basic features of each are identified in subsequent sections of this paper.

REVIEW OF PAST/PRESENT HYBRID VEHICLE PROJECTS

This review will include both past and present projects and serve as an introduction to the more detailed discussion of hybrid vehicle design options in later sections of the paper. A summary of hybrid vehicle projects is given in Table 1.

PAST PROJECTS - The term "past projects" means studies and vehicle fabrication/test activities that have been completed and are not part of ongoing programs. The review will be concerned primarily with U.S. Department of Energy programs, as they are completely documented and can be easily referenced. Much of the DOE-supported work in the 1978-1984 period was done by the Jet Propulsion Laboratory (JPL), JPL/ General Electric Co., and the Aerospace Corporation. As presented in References 1-6, JPL and Aerospace performed detailed studies of various hybrid vehicle missions and design options, including in-depth computer simulations of vehicle operation on complex representations of urban and highway cycles. The hybrid vehicle designs treated had acceleration performance comparable to diesel engine-powered conventional ICE vehicles. That performance was considerably better than that of the pure electric vehicles which were being designed at that time. The JPL/Aerospace studies concluded that the parallel electric/heat-engine driveline approach yielded much lighter, smaller, and less expensive hybrid drivelines than the series utilizing a heat-engine-driven generator and thus the parallel hybrid driveline was recommended for the relatively high performance hybrid vehicles studied. It was recognized that the parallel drivelines were more complex and more difficult to control than the series drivelines.

Various approaches to the design of hybrid vehicles were also evaluated as part of the JPL/General Electric (GE) Near-Term Hybrid Vehicle program conducted in 1978-1982. The results of those studies and vehicle design, fabrication, and test activities are given in References 7-12. The JPL/GE studies done in Phase I (prior to the vehicle design and fabrication phase of the program) indicated that for the power-to-weight ratio (0.04375 kW/kg) required to meet the acceleration time goals of the program, the Hybrid Test Vehicle (HTV) should utilize a parallel driveline configuration. The state-of-the-art of electric drivelines (motors and electronics) in 1978 precluded the packaging of the 80-90 kW electric driveline required by a series hybrid design in the space available in the HTV. In addition, the weight of the 90 kW series hybrid driveline would have been much greater than that of the parallel hybrid driveline that utilized a 33 kW DC motor and a 55 kW, 4-cylinder gasoline engine.

A sketch of the HTV hybrid driveline is shown in Figure 1 (taken from Reference 8). As discussed in References (8 and 9), the HTV was built and dynamometer-tested on the FUDS and Federal Highway cycles demonstrating electric only, engine only, and load-shared combined operation under micro-processor control. The JPL dynamometer test results (Reference 9) showed that the HTV had a high potential for large petroleum savings for realistic user missions and had acceleration performance comparable to conventional diesel-powered ICE vehicles. The emissions test data (Reference 9) indicate that the HTV could have been engineered to meet the 1980 emission standards, but likely not the ultralow emissions standards of the late 1990s in California.

As discussed in References 13-15, there have also been studies directed toward the design and fabrication of series hybrid/electric vehicles. Such vehicles had the relatively low performance typical of the pure electric vehicles of 1975-1985 and an engine-generator sized to provide the average power (5-10 kW) needed for the FUDS or C cycles. Those designs yield relatively small range extension at freeway and highway speeds that require much higher power (see Figure 2). The weight and size of those series hybrid drivelines confirmed the estimates of the JPL/Aerospace/GE studies cited previously.

PRESENT PROJECTS - There are presently a number of active hybrid/electric projects around the world, including both parallel (References 16-19) and series (References 20-23) designs. Some of these projects (see Table 1) utilize state-of-the-art electric driveline components, engines, and microprocessor controllers. The presently active hybrid projects represent the base from which future projects utilizing advanced electric driveline and engine technologies will evolve. Such design options for hybrid vehicles are discussed in later sections of this paper.

USER-PATTERN CONSIDERATIONS

The key user-pattern information required to design a hybrid vehicle is the statistics of daily usage (fraction of days for which the total daily travel is less than selected values), as that permits the specification of the all-electric range of the vehicle on a rational basis. The energy (kWh) required by the vehicle to travel this distance is an important factor in sizing the battery. The second factor in sizing the battery is the maximum power (kW) required from the electric driveline during vehicle acceleration. If the electric range specified for a hybrid vehicle is significantly less than that used for a pure electric vehicle, it is likely that the battery in the hybrid vehicle will be sized by peak power, not energy storage, requirements. This is even more likely to be the case in the future than it was in the past, because the acceleration time requirements for electric/hybrid vehicles are becoming more stringent.

The results of a study of the impact of use-pattern on the design of electric and hybrid vehicles are given in Reference 24. The daily vehicle use was analyzed using a Monte Carlo random-trip generator model for various percentiles of car owners based on annual mileage. Calculated cumulative probability daily travel statistics for percent of days and percent of vehicle miles on electricity are given in Figure 3. For example, note from the figure that for the 50th-percentile owner, if the useable electric range of a vehicle is 64 km (40 miles), the vehicle would be used as a pure electric vehicle on 90% of the days representing about 90% of the miles traveled per year; further, a 96 km (60 mile) range on electricity would permit the 90th-percentile owner to operate the vehicle on electricity alone for 80% of the days and 80% of the total miles per year. For a hybrid vehicle, it seems reasonable to define useable electric range as the distance the vehicle can travel primarily on electricity before the battery reaches 80% depth-of-discharge (DOD). Prior to 80% DOD, the engine would not be needed to recharge the battery.

HYBRID DRIVELINE CONFIGURATION OPTIONS

There are three basically different hybrid driveline options: (1) the series hybrid (Figure 4) in which all the torque to the wheels is from the electric motor and the engine powers a generator for recharging the batteries and supplying electrical energy after the batteries are discharged to a specified level, (2) the parallel hybrid (Figure 5) in which both the electric motor and the engine provide torque to the wheels either separately or together and the motor can be used as a generator to recharge the batteries when the engine can produce more power than is needed to propel the vehicle, (3) the split hybrid (Figure 6) in which the front wheels (or rear wheels) are driven by an electric driveline and the other wheels are driven by torque from the engine. This paper is concerned primarily with the series and parallel configurations although, as indicated in Table 1, split hybrid designs have been built and operated successfully. The split hybrid can be considered a

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