**SAE TECHNICAL PAPER SERIES**

**950493**

# The Effects of APU Characteristics on the Design of Hybrid Control Strategies for Hybrid Electric Vehicles

**Catherine Anderson and Erin Pettit**
AeroVironment

**Reprinted from: Design Innovations in Electric and Hybrid Electric Vehicles (SP-1089)**

SAE The Engineering Society For Advancing Mobility Land Sea Air and Space® INTERNATIONAL

**International Congress and Exposition**
**Detroit, Michigan**
**February 27 - March 2, 1995**

SAE routinely stocks printed papers for a period of three years following date of publication. Direct your orders to SAE Customer Sales and Satisfaction Department.

Quantity reprint rates can be obtained from the Customer Sales and Satisfaction Department.

To request permission to reprint a technical paper or permission to use copyrighted SAE publications in other works, contact the SAE Publications Group.

**GLOBAL MOBILITY** DATABASE

*All SAE papers, standards, and selected books are abstracted and indexed in the Global Mobility Database.*



**ISSN 0148-7191**


Persons wishing to submit papers to be considered for presentation or publication through SAE should send the manuscript or a 300 word abstract of a proposed manuscript to: Secretary, Engineering Activity Board, SAE.

950493

# The Effects of APU Characteristics on the Design of Hybrid Control Strategies for Hybrid Electric Vehicles

**Catherine Anderson and Erin Pettit**
AeroVironment

## ABSTRACT

A hybrid control strategy is an algorithm that determines when and at what power level to run a hybrid electric vehicle's auxiliary power unit (APU) as a function of the power demand at the wheels, the state of charge of the battery, and the current power level of the APU. The design of this strategy influences the efficiency of the overall system. The strategy must balance the flow of power between the APU, the battery, and the motor, with the intent of maximizing the average fuel economy without overstressing the battery and curtailing its life.

The development of a system's powertrain components and the design of an optimum control strategy for that system should be concurrent to allow tradeoffs to be made while the designs are still fluid. An efficient optimization process must involve all aspects of the system, including costs, from the beginning.

In this paper, we explore the methodology behind the design of a hybrid control strategy. We also discuss the APU and battery design characteristics that are crucial to the strategy design, focusing on the interdependence of these design characteristics within the entire system. Finally, we propose a process for the development of an optimized hybrid powertrain and the corresponding control algorithm.

## INTRODUCTION

A "hybrid" vehicle usually refers to one that incorporates a minimum of two independent power sources to supply the drivetrain. One of the primary advantages of this dual power supply system is it allows flexibility in power distribution between sources. This versatility enables greater optimization of the vehicle powertrain to meet the required performance of the system. In order to profit from such system flexibility, one must integrate into the system an intelligent control strategy that uses each component to the overall system's best advantage.

A hybrid control strategy is an algorithm that determines how power in a hybrid powertrain should be distributed as a function of the vehicle parameters (e.g., speed and battery component characteristics. One must develop this strategy carefully as part of the vehicle design process from the beginning. While the strategy determines the best operating points for the components, the range of available component characteristics provides the limits within which the strategy must operate.

This paper explores the iterative process of concurrent powertrain component and control strategy design with an emphasis on optimizing the system as a whole. We focus primarily on the auxiliary power unit and the characteristics of the powertrain components that drive the strategy design.

## HYBRID VEHICLE CONCEPT

Hybrid vehicles can be divided into two main categories: *parallel,* in which both systems are used to mechanically drive the wheels; and *series*, where the power supply systems are coupled directly to a power bus which then transfers power to the wheels.

**SERIES SYSTEM -** The philosophy behind a series hybrid vehicle lies in its combination of a primary and a secondary energy conversion. In the primary conversion, an APU converts a highly transportable, stable chemical fuel to mechanical energy (or directly to electrical energy in certain cases) and, subsequently, to electrical energy. The most frequently considered APUs for hybrid systems include various internal and external combustion engines and fuel cells. This primary conversion device can be decoupled from the wheel power demand (unlike the engine in a conventional car) as a Load Leveling Device (LLD), which acts as an energy buffer, is included in the system. This LLD alternately stores energy (either directly from the primary conversion at low wheel power requirements or from the kinetic energy of the decelerating vehicle) and provides the propulsion motor with energy when the demand exceeds the APU power output. Some LLDs that have been proposed for use in hybrid vehicles include batteries, supercapacitors, hydraulic and/or pneumatic storage devices, and flywheels.

The secondary conversion, occurring in the inverter and motor, transforms the electrical energy from either source into the mechanical energy that drives the vehicle. Figure 1 is a

Since all the power sources and sinks are directly coupled by a DC power bus, control of the entire system can be achieved by simply commanding the APU output. The accessory and wheel loads pull required power off the bus with the LLD supplying the balance of power in the system.

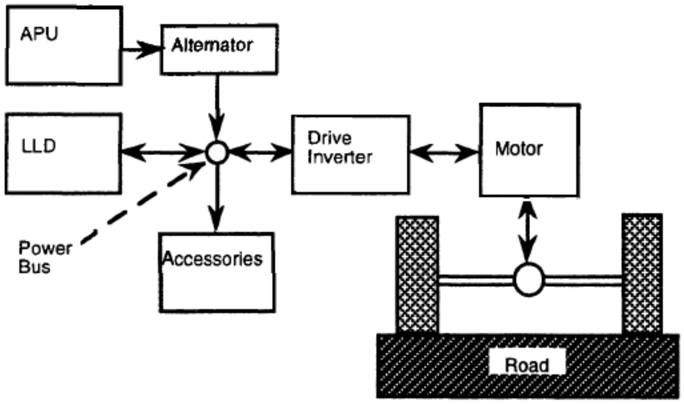


**Figure 1**: Series hybrid vehicle component configuration.

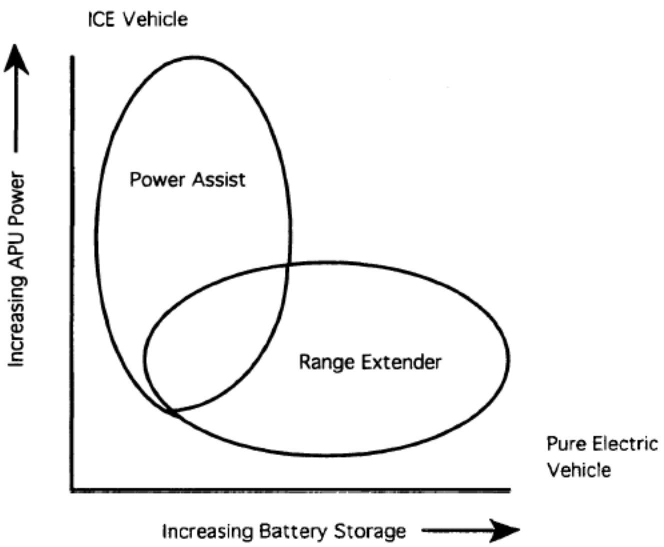


**Figure 2:** Comparison Chart of Power Assist and Range Extender Series Hybrid Vehicles

In addition, the series hybrid design may fall into one of two categories: "power assist" or "range extender" (see figure 2). A power assist hybrid uses the LLD to manage the power output from the APU to maximize efficiency and emissions in the APU. The usable storage capacity of the LLD is quite small (on the order of 1-5 kWh), and the APU must be capable of providing the maximum sustained power the vehicle is expected to need, with the LLD providing peak powers and transients. A range extender hybrid uses a very small APU with a substantial LLD such that the vehicle will perform

a range extender is small compared with the power demand, it is most often run at its maximum power level, and hybrid control strategies are fairly simple.

The primary disadvantage of the series hybrid system in most cases is the extra inefficiencies included in converting the mechanical power output from the APU into electrical power and then back into mechanical power. Often, however, the increased flexibility of the system offers more optimized components that overcome this disadvantage.

**PARALLEL SYSTEM**- In a parallel hybrid vehicle, there is a direct mechanical connection between the APU and the wheels through a transmission. As shown in figure 3, the electric propulsion system may either drive the same set of wheels as the APU through the transmission (Option 1), or drive the other set of wheels directly (Option 2).

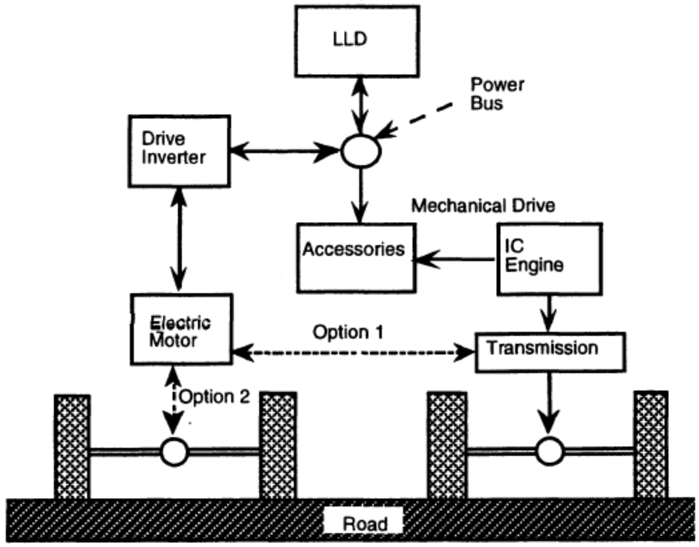


**Figure 3**: Parallel hybrid vehicle component configuration.

The main advantages of the parallel configuration over the series is that the power from the engine is used directly by the drivetrain with no alternator or inverter losses. However, because the APU is directly coupled to the wheels, the APU speed is determined by the vehicle speed and the transmission ratio. This direct coupling limits the flexibility of hybrid strategy design, and (without a novel clutched transmission) forces the APU to idle when the vehicle is at rest.

A parallel hybrid does have an efficiency advantage when the vehicle spends a majority of its driving time at a substantial cruise, but a vehicle that is operated on a "city driving" profile will lose this transmission efficiency advantage to inefficiencies in the APU engine. In addition, if the front and rear axles of the vehicle are driven by different power sources, the vehicle may exhibit changes in handling characteristics as the power distribution between the sources is adjusted.

The thought processes presented in this paper are sufficiently general that they can be applied to any type of versatile layout: the power assist hybrid. For simplicity, we use the example of a generalized IC engine and Pb-Acid battery for the APU and battery, respectively, as a focus for the discussion.

## HYBRID CONTROL STRATEGIES

There are two distinct extremes in the spectrum of control strategies. One is a system that uses a "thermostat" algorithm to command the APU (i.e. the APU is turned on to a constant power level when the SOC of the LLD is below a certain lower threshold, and off when the SOC exceeds an upper threshold). In this mode, the LLD must accommodate all the transient power requirements. Although the APU may be operating at its most efficient point, the losses in the LLD from excessive cycling may surpass the savings from an optimized APU. For the example wheel power curve shown in figure 4, figure 5 shows the corresponding APU and LLD power requirements generated by a thermostat mode.

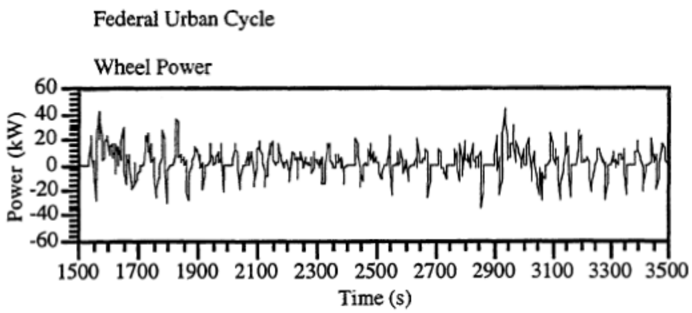


**Figure 4**: The power required at the wheels for a segment of the federal urban drive (LA4).

The other extreme commands the APU to follow the actual wheel power whenever possible (similar to a conventional automobile). Using this strategy, the LLD cycling will diminish, and the losses associated with charge and discharge will be minimized. The APU, however, must then operate over its entire range of power levels and perform fast power transients, both of which can adversely affect engine efficiency and emissions characteristics. Figure 6 shows the APU and LLD power requirements generated by this "following" mode for the same wheel power curve shown in figure 4. It should be noted that this is the mode a parallel hybrid vehicle always uses.

For most of the APUs and LLDs under consideration, neither of these strategies would be the optimum strategy. The ideal hybrid control strategy is one that minimizes the combined inefficiencies of both the APU and the LLD while meeting the desired performance and the emission limits (as well as any other specific system characteristics that are being used as measures of design merit). The optimum strategy is highly dependent on the characteristics of the powertrain components and the planned use of the vehicle. Unfortunately as one attempts to optimize a system, the characteristics of the components begin to conflict, driving the strategy in different directions.

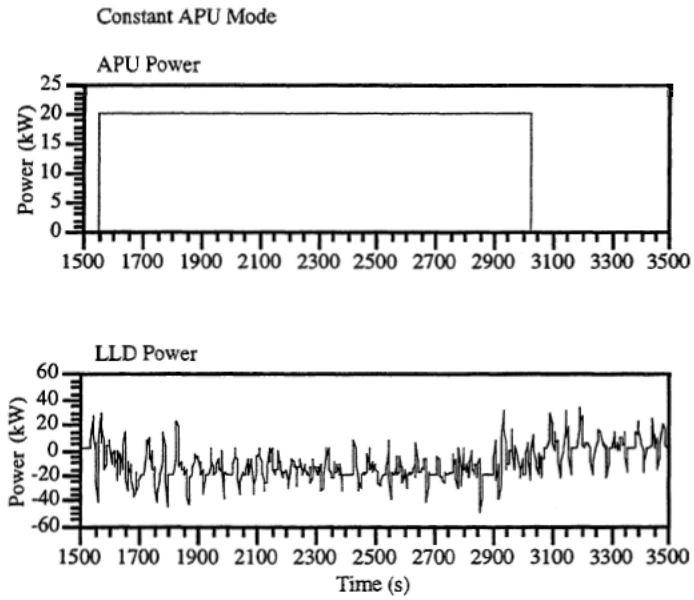


**Figure 5**: The APU and LLD power outputs that satisfy the wheel requirements using a constant APU thermostat strategy.

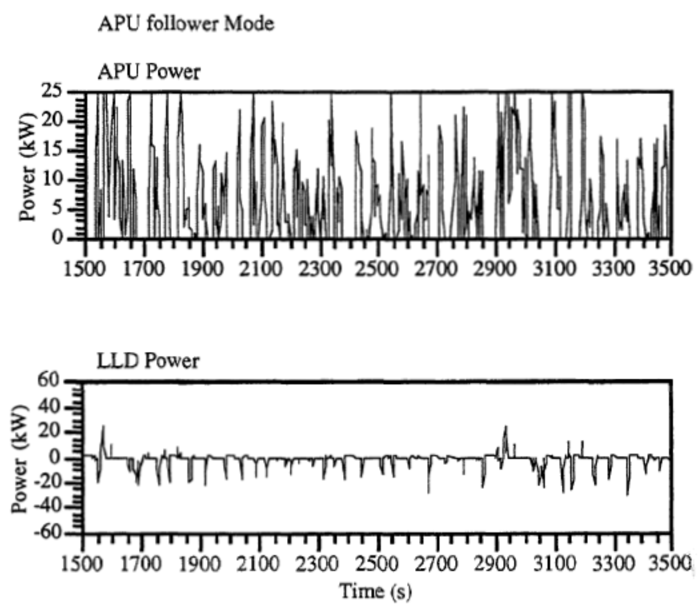


**Figure 6**: The distribution of power for a load following APU.

## COMPONENT CHARACTERISTICS AND DESIGN TRADE-OFFS

**LLDs** - The LLD (in this case a battery) must be the most accommodative element in the powertrain. When there is a large power demand or production from the wheels (as during hard acceleration or braking), it must supply or accept the power required. In a hybrid application, the battery pack generally has lower capacity than it would have for a pure

DOCKET ALARM

# Explore Litigation Insights

Docket Alarm provides insights to develop a more informed litigation strategy and the peace of mind of knowing you're on top of things.

## Real-Time Litigation Alerts

Keep your litigation team up-to-date with **real-time alerts** and advanced team management tools built for the enterprise, all while greatly reducing PACER spend.

Our comprehensive service means we can handle Federal, State, and Administrative courts across the country.

## Advanced Docket Research

With over 230 million records, Docket Alarm's cloud-native docket research platform finds what other services can't. Coverage includes Federal, State, plus PTAB, TTAB, ITC and NLRB decisions, all in one place.

Identify arguments that have been successful in the past with full text, pinpoint searching. Link to case law cited within any court document via Fastcase.

## Analytics At Your Fingertips

Learn what happened the last time a particular judge, opposing counsel or company faced cases similar to yours.

Advanced out-of-the-box PTAB and TTAB analytics are always at your fingertips.

## API

Docket Alarm offers a powerful API (application programming interface) to developers that want to integrate case filings into their apps.

**LAW FIRMS**

Build custom dashboards for your attorneys and clients with live data direct from the court.

Automate many repetitive legal tasks like conflict checks, document management, and marketing.

**FINANCIAL INSTITUTIONS**

Litigation and bankruptcy checks for companies and debtors.

**E-DISCOVERY AND LEGAL VENDORS**

Sync your system to PACER to automate legal marketing.