DESIGN INNOVATIONS IN

Electric

AND

Hybrid Electric Vehicles

SAE INTERNATIONAL® SP-1089

Design Innovations in Electric and Hybrid Electric Vehicles

SP-1089

GLOBAL MOBILITY DATABASE

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

Published by:
Society of Automotive Engineers, Inc.
400 Commonwealth Drive
Warrendale, PA 15096-0001
USA
Phone: (412) 776-4841
Fax: (412) 776-5760
February 1995

ISBN 1-56091-639-7
SAE/SP-95/1089
Library of Congress Catalog Card Number: 94-74742

Printed in USA

PREFACE

The papers in this SAE special publication, Design Innovations in Electric and Hybrid Electric Vehicles (SP-1089), cover technology for both electric and hybrid electric vehicles. As is well accepted, to have a good hybrid electric vehicle requires first having a good electric vehicle. Major manufacturers have initiated the effort required to take electric vehicle technology from the laboratory through the required development steps to provide an automotive product. This work will provide a foundation for the development of hybrid electric vehicles.

Unique engines, unique operating strategies and unique packaging solutions will all be the hallmark of successful hybrid electric vehicles. Over the past several years, the hybrid-electric vehicle concept has been gaining attention as a possible way to reduce emissions and increase fuel efficiency compared to a conventional vehicle. Hybrid-electric vehicles contain a hybrid power supply system - one that incorporates a minimum of two independent power sources to supply the drivetrain. The main advantage of this concept is it permits flexibility in power system design and power distribution between sources. This versatility enables greater flexibility in designing the powertrain to meet the required performance of the vehicle. The challenge is to combine the different power sources such that the advantages outweigh the increased cost of this configuration. These papers cover some of the latest technical developments related to the engine aspect of hybrid-electric vehicle development. Topics included in this year's session are: development of hybrid-electric vehicle design code; optimization of vehicle and engine control strategies; and novel engines for hybrid-electric vehicles.

Also critical to the automotive products of the future is the engineering talent required to produce the innovative designs. One of the programs aimed at exciting students to the new automotive opportunities is the HEV Challenge. This program is well represented by papers in this book. Experience has shown that the HEV Challenge is not only motivating students, but also surfacing innovative automotive engineering solutions to difficult problems. We are pleased to be able to share some of this excitement through this publication.

All of these subjects and the design methodologies required to achieve them, are covered by papers in this collection. We hope that this year's papers will trigger your imagination and provide the foundation for innovative developments that will help electric and hybrid electric vehicles play an important role in our transportation system.

Bradford Bates
Ford Motor Co.
Chairman, Electric Vehicle Committee

Frank Stodolsky
Argonne National Laboratory

Session Organizers

TABLE OF CONTENTS

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 (power demand, battery state of charge (SOC), component temperatures, etc.) and of 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 schematic of the energy flow within the vehicle.

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.

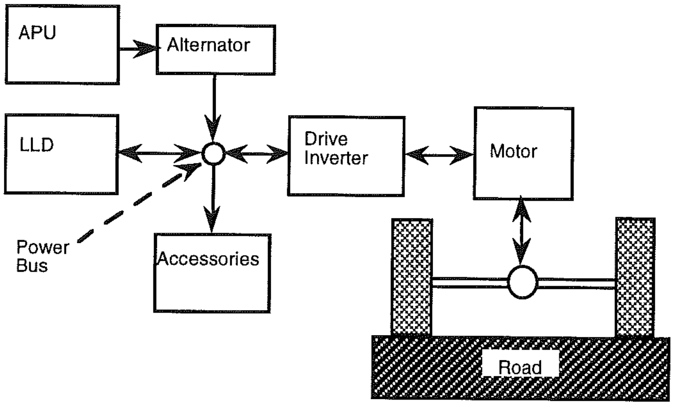

Figure 1: Series hybrid vehicle component configuration.

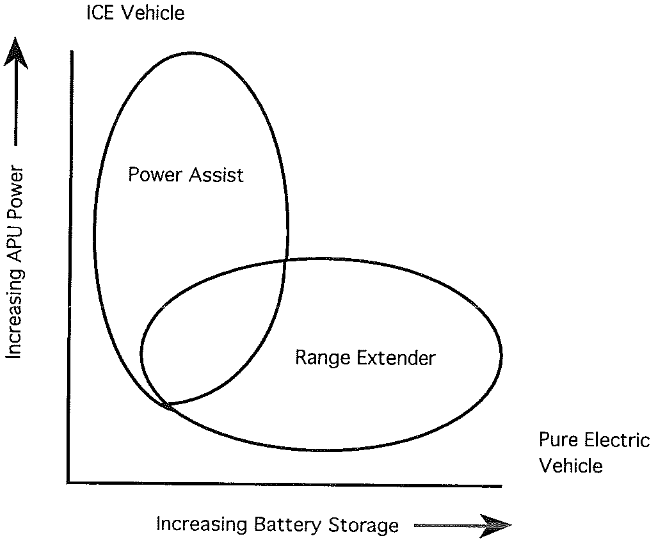

Figure 2: Comparison Chart of Power Assist and Range Extender Series Hybrid Vehicles

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 similarly to a pure electric vehicle, with the additional small power source simply extending the range. Since the APU for 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).

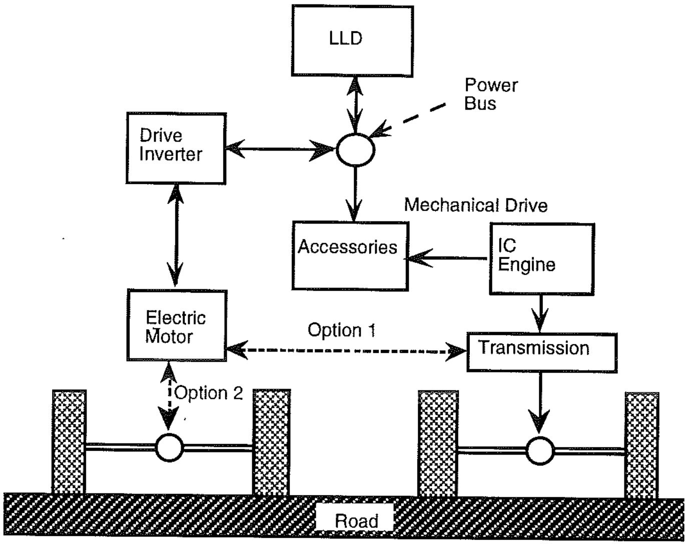

Figure 3: Parallel hybrid vehicle component configuration.

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 vehicle. To fully explore the flexibility allowed by the hybrid system, we focus on the design of a strategy for the most 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.

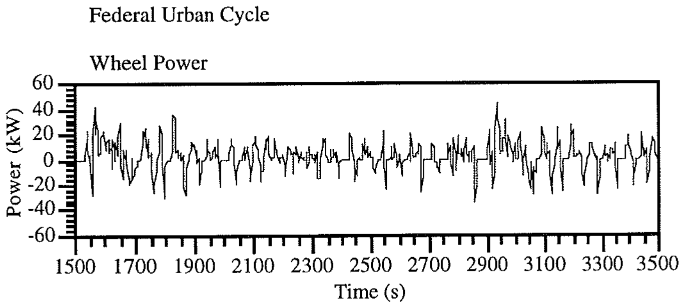

Figure 4: The power required at the wheels for a segment of the federal urban drive (LA4).

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.

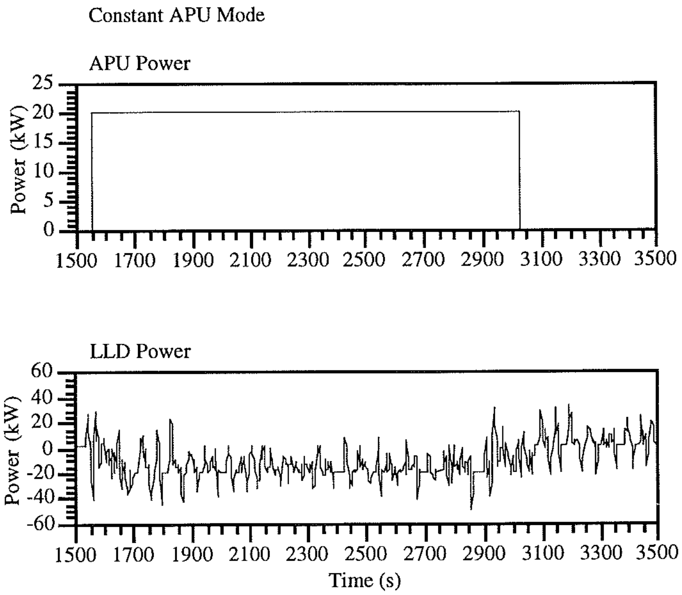

Figure 5: The APU and LLD power outputs that satisfy the wheel requirements using a constant APU thermostat strategy.

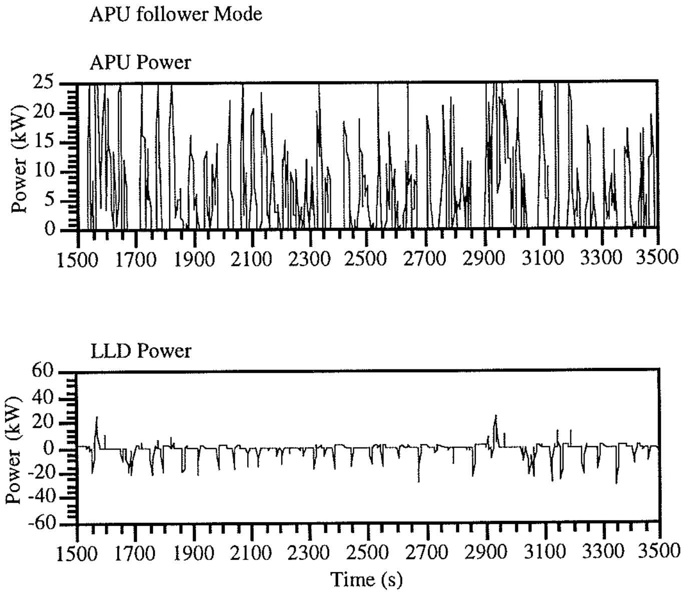

Figure 6: The distribution of power for a load following APU.

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 electric vehicles (particularly for a power assist hybrid where the APU is of considerable size). To maintain the same performance, therefore, the power density must be greater. In addition, the state of charge of the battery can be significantly affected during a short acceleration or deceleration so that the small-scale charge/discharge period (or "microcycling") that the pack sees is a more significant percentage of its capacity. Differing control strategies can place varying demands on the cycling of the battery. Using the thermostat APU strategy, the battery would be required to cycle at the frequency of the wheel power demand, while the follower APU strategy would only require the battery to cycle when the wheel power demand exceeds the APU power capability.

There are several characteristics of the battery that one must keep in mind when trying to quantify tradeoffs between the battery and the rest of the system: the charge/discharge efficiency, the total capacity of the pack, the transient capabilities, and, the hardest to determine, the life of the batteries.

Charge/Discharge Efficiencies - A battery is most efficient within a range of SOCs that minimizes its charge and discharge resistances. In figure 7, one can see the general shape of a Pb-Acid battery's internal resistance versus state of charge curves for charging and discharging the battery. A balance point must be chosen on these curves to minimize resistive losses, yet still leave room for power peaks (both motoring and regenerative braking) at the wheels. This tends to push the strategy design to keep the SOC within the 50-70% region for minimum losses in both charge and discharge. This leaves enough capacity to handle an extended period of battery discharge (such as during a long hill climb) and enough "headroom" to absorb a long period of charging such as that which occurs during a long downhill. If the SOC is not maintained within the 50-70% region, the performance may be compromised. This diminished performance may take the form of lost regenerative energy or limited power output during accelerations.

Capacity - The capacity of the pack is comparatively easy to measure, and the effects of the change of capacity on the strategy are fairly intuitive. (It should be noted that the capacity at one rate of discharge is different from the capacity at another rate, and therefore the definition of "capacity" is subject to discussion.) In general, the larger the battery pack capacity, the more the vehicle can be run like an pure electric vehicle with the APU providing supplemental power. With a large capacity, it is easier to achieve the power required for standard driving, and the pack does not have to be so rigidly constrained to a small window of states of charge. A small pack, however, must be used almost exclusively as a short-term energy buffer without significant energy storage.

Transient Capabilities - A battery can change power levels almost instantaneously, unlike the APU which is limited by its mechanical inertia. When the APU cannot respond quickly enough to fluctuations in power demand, the battery must make up the difference. The battery must be able to sustain output at a peak power during these transients until the APUs power output reaches the commanded power.

Life - Unfortunately, most available data on battery life is of limited applicability to hybrid systems. The complexities of the reactions within batteries make it almost impossible to predict battery life except as a questionable extrapolation of empirical data. Although few quantitative predictions of battery life are available, some qualitative statements can be made:

1. A lead acid battery will degrade more (per a throughput kWh) if cycled deeply (cycled through a wide range of SOCs) than shallowly. The long term effects of microcycling (cycling over a small range of SOCs) are not fully known.
2. A battery will last longer if it has lower energy throughput.
3. Hard cycling (high power cycling), even hard microcycling, will shorten the life.

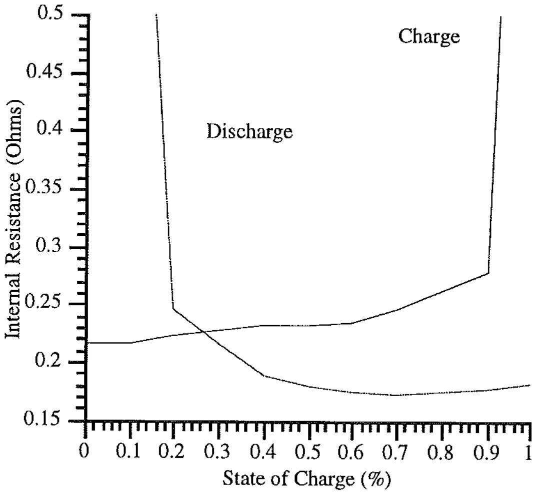

Figure 7: The charge and discharge internal resistances versus the state of charge of a battery.

Figure 8 shows the difference between the SOCs of the thermostat and follower extremes discussed above (see figures 3-5) over multiple repetitions of the federal urban driving cycle. In the thermostat mode, the APU power output is greater than the average power for the cycle causing the state of charge to continue to increase until it reaches a defined maximum state of charge (in this case 80%) requiring the APU to turn off. The follower mode, on the other hand, provides only a slight constant increase in SOC due to the battery's absorption of regenerative energy during the cycle.
The deep cycled battery might only last half as long as the one kept within a tight SOC window. However, the costs of replacing the battery versus the cost of building an APU capable of fast transient response(that can protect the battery) must be weighed.

APUs - Because the APU is decoupled from the drivetrain, there is greater flexibility in its design. The design need not be performance driven as in conventional IC engines, but can be focused on other characteristics, such as emissions, that may be more important for the specific vehicle being designed. Most importantly, however, the APU characteristics must be chosen to complement the LLD requirements; thus, the need for a working strategy throughout the design process. Characteristics crucial to the design include maximum power output, transient capabilities, fuel efficiency, emissions characteristics, engine noise vibration harshness (NVH), and service life.

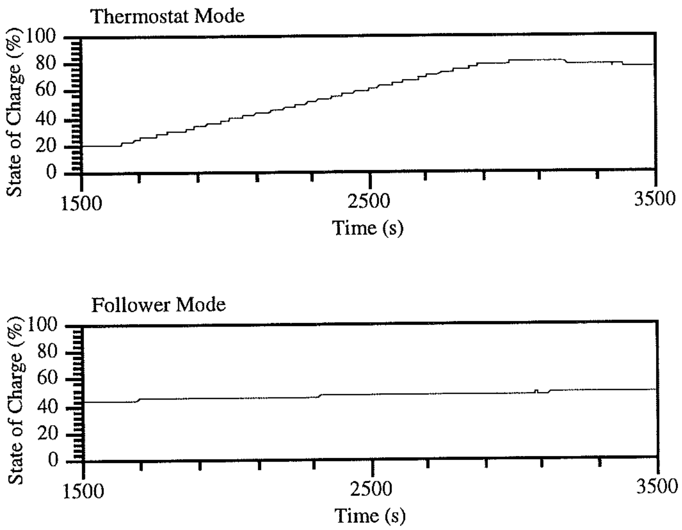

Figure 8: The state of charge during repetitions of the federal urban driving cycle with a constant APU at 20 kW in the thermostat mode (see figures 2,3) and in the follower mode(see figure 4).

Maximum Power Output - The maximum power output of the APU will affect strategy design choices in a similar manner to the capacity of the battery. With a high power capability, one may design the strategy to operate more or less like a conventional car engine in a power following mode, whereas a low power capability will force the strategy to run the engine at its highest power level so that it can keep up with current demands and store extra energy for periods of high demand.

APU Transient Capabilities - Mechanically, the transient capabilities of an engine are limited by the inertia involved in increasing or decreasing the engine speed. Although slower transients are desirable for reducing emissions, slow transients can curtail the life of the battery or potentially harm the engine. For example, slow transients can be a serious problem during a transition from a hard acceleration to a hard braking. If the APU has been commanded by the control strategy to supply a high power during an acceleration, and suddenly full regenerative braking is required, the LLD may not be able to accept the total power coming to it, unless the APU can reduce its power quickly. This limitation will cause a loss of much of the regenerative energy available. In an extreme case, the APU may be unloaded by an over-voltage condition, leading to potential overspeed. The APU control strategy must be robust, such that no combination of driver actions will result in damage to any drivetrain component.

Fuel Efficiency - The fuel efficiency of an APU generally varies as a function of the power level. The specific fuel consumption (SFC) of an engine is typically best at middle power levels and worst at the low and high power extremes. The APU operating strategy that will maximize fuel efficiency is one that runs the APU primarily in the range of powers over which the SFC is best (often termed the engine's "sweet spot"). The ratio of the highest power level to the lowest power level used in the strategy is called the turn down ratio. The narrower this sweet spot is, and, thus, the smaller the most efficient turn down ratio is, the more the fuel efficiency requirements constrain the strategy toward a thermostat mode (see figure 9, a series of SFC graphs showing varying sweet spots.). Increasing the range of high efficiency and thus the turn down ratio and the ability of the strategy to follow drive power more closely (therefore relieving some stress on the battery) can increase the complexity and cost of the engine or lower the peak fuel efficiency. Tradeoffs must be made between engine complexity, cost, fuel efficiency, and battery lifetime. For example, if a long battery lifetime is the most important aspect of the system, then a large sweet spot is desired, possibly sacrificing engine simplicity, efficiency, or low engine emissions. In a situation where the average power is fairly constant a smaller sweet spot may be the most efficient solution.

Emissions - Frequently, one of the principle aims of a hybrid vehicle is to reduce vehicle emissions to ULEV (Ultra Low Emission Vehicle) levels. Consequently, APU emissions are very important for system success. In general, emissions are minimized when a stoichiometric air to fuel ratio is maintained by a closed loop feedback system (using an oxygen sensor for feedback). In some operating regimes, such as engine starts and transients, the stoichiometric ratio is very difficult to maintain resulting in an increase in emissions.

During a cold-start, the engine must run rich to achieve sufficient vaporization of the fuel. Rich running results in high hydrocarbons (HC) and carbon monoxide (CO) emissions, but low nitrogen oxides (NOx) emissions. A hot-start has many of the same problems as a cold start, but the time duration before the engine and catalytic converter warm up is much shorter. A hybrid strategy which minimizes engine cycling will minimize start-related emissions, but that may require that the engine have a higher turn-down ratio.

Transients present an emissions problem that is largely related to the speed of the transient. The closed loop feedback system that maintains the stoichiometric air fuel ratio is sufficient during quasi-steady state modes, however, it can only react as fast as the O_2 levels can be sensed. If the transient is too fast, the engine may run rich, increasing CO and HC emissions, or lean, increasing NOx emissions. Some of this effect can be reduced using a hybrid strategy that only allows slow transients, but this places greater strain on the LLD.

As a series hybrid vehicle decouples both the speed and the power of the APU from the speed and power requirement at the wheels, this extra degree of freedom can also be used to reduce emissions. For a given required power output, there are many combinations of speed and torque that could be used to provide that power. If the engine is run in a low speed, high load state, the fuel efficiency, noise, and hydrocarbon emissions are all improved. At high loads, however, the NOx emissions are high and traditional NOx reducing measures such as Exhaust Gas Recirculation (EGR) are more difficult. Choosing this optimum engine operating point as a function of power is an important design consideration but it is not necessarily part of the hybrid strategy design.

Noise Vibration Harshness (NVH) - Engine noise is not much of an issue as far as the performance of a drivetrain is concerned, but to avoid customer distress, it must be considered as an influencing factor on a hybrid strategy. For example, a strategy that has the engine on at full power while the vehicle is at a complete stop could be extremely disconcerting for the driver. Fortunately, the periods of low ambient (masking) noise are mostly concurrent with low power demands, so throttling back an engine at low vehicle speeds is not too much of a compromise in performance.

Life - The life of an APU can generally be extended by running it at low, constant power levels. Constant running at a sweet spot (for emissions and fuel economy) during low power demand driving, however, may cause the battery SOC to rise and the engine to be shut off. Depending on the control strategy this on/off cycling can be quite frequent. Numerous hot starts may shorten the life of an engine unless it is designed for multiple starts per trip.

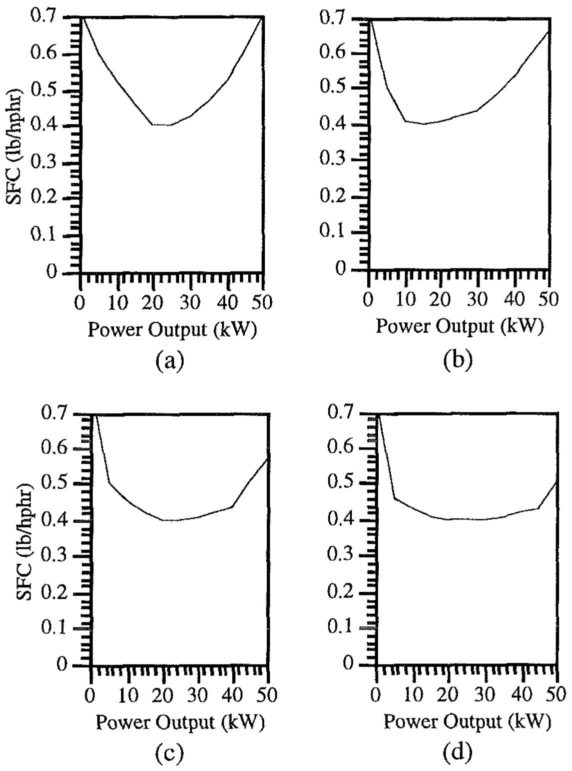

Figure 9: Four examples of engine efficiency curves. Specific Fuel Consumption versus Power Output. The "sweet spot" is smallest in (a) and largest in (d).

BRAKING CONTROL SYSTEMS - The only other system component whose specific characteristics are crucial to the optimization of the powertrain is the braking system. The added feature of regenerative braking ("regen") can improve fuel economy greatly. Unfortunately, because a typical vehicle must use all four wheels for braking to maximize control, a front wheel drive vehicle with balanced braking will not be able to capture all available regen energy. A scheme must be devised to maximize the amount of regen captured without destablizing the car's decelerations. An optimum division of braking power between the front and the rear is a function of the degree of deceleration and the desired handling of the car. For example, a braking strategy may use regen for all declarations up to 0.25 g, then feather in the rear brakes to prevent skidding and instability during hard decelerations.

The amount of energy available from regenerative braking influences the fuel economy greatly, especially in heavy stop and go traffic. The efficiency of the regenerative braking depends on the resistance of the battery to charging and, therefore, on the state of charge of the battery. This, once again, creates conflicting optimization factors, for the APU cannot be run at its most efficient point if it is desired that the battery stay within a certain range of SOCs. The APU must be run within its limited high efficiency range and the battery must be maintained around a state of charge that has minimum charge and discharge resistances.

COST - Inasmuch as hybrid powertrains must compete against conventional powertrains for cost and performance, the overall success of the powertrain is extremely dependent on cost. More expensive components may increase the capabilities and the life, but if that makes the system unsaleable, the improvements are useless. In the end, every tradeoff that is made in the powertrain system must be done with cost in mind.

DEVELOPMENT OF A WORKING STRATEGY

The design of hybrid systems must begin with the overall system constraints. Depending on the type of vehicle (for example, a large passenger car or a delivery truck), there are weight and volume limits. These limits include both the general physical dimensions of the car as well as the physical characteristics of the powertrain. These limits and the power requirements of the system provide an initial basis for choosing the relative sizes of the APU and the LLD. System power electronics are more efficient if constrained to within a fairly narrow bus voltage range. This additional limiting factor must also be considered in the component design. These constraints, along with the control strategy provide the system wide link between components.

All of the design factors discussed above influence the characteristics of the final vehicle; therefore, it is crucial to know the general specifications of the system as a whole. The characteristics to be optimized in the design must be prioritized to provide a path to guide the designers. A design focused on minimizing emissions will result in a very different vehicle than one focused on extending battery lifetime.

For example, a generic strategy may begin with a focus on fuel economy. A basic strategy would drive the APU at a constant peak efficiency power level (based on the first APU efficiency estimates), similar to the thermostat APU scheme discussed previously. Bringing in aspects of battery life would push the turn down ratio up (using an approximation of the engine sweet spot) until a suitable balance point between life and fuel efficiency appears, incorporating their relative importance. Emissions characteristics may then be included by slowing down the engine transient response time. The balance between the first two factors (fuel efficiency and battery life) must then be re-adjusted, resulting in a three way balance that enforces the order of priority of characteristics. This process will continue until all optimization characteristics are included, in order of their importance.

The second half of the design process focuses on interactive optimization of all the components of the system. A series of sensitivity studies will show the effects of variations in each characteristic on the whole system, including parameters contained within the strategy. Questions must be asked of the system such as: If the battery's charge resistance can be decreased by 5%, by how much will the fuel efficiency be increased? When the battery is maintained within a smaller SOC window, how much will the fuel efficiency change, and how much longer can the battery be expected to last? What happens if the relative importance of the fuel efficiency to the peak power performance is increased? As each of these questions are answered the designers can get a better understanding for which improvements in the system will provide the most benefit, economically and physically.

RECOMMENDATIONS

Compared to the design of a conventional automobile, the design of a hybrid vehicle has an extra degree of freedom. This degree of freedom requires an added component to bring the system together: the hybrid control strategy. The adaptability of a hybrid powertrain can reduce many of the component design constraints found in a traditional vehicle.

In order to take full advantage of the system flexibility, the hybrid control strategy must be incorporated into the design from the beginning of the process. Sensitivity studies should be performed throughout the design iterations so that the hybrid control strategy can guide the vehicle design towards optimization, while satisfying the initial design criteria. As was discussed previously, many characteristics of the APU and LLD are interdependent, and often create conflicting situations during optimization. The effects of these conflicting characteristics must be weighed through the sensitivity studies and engineers must judge the relative importance of each optimization characteristic.

Although hybrid vehicle development programs are aimed at developing vehicles with high fuel economy and low emissions, care must also be taken to retain vehicle acceleration performance and maintain reasonable powertrain cost. It is recommended that a systems approach to the powertrain design be taken to maximize the benefits of a hybrid system.