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HYBRID VEHICLE DESIGN OPTIMIZATION

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ABSTRACT

This paper describes the optimization of hybrid vehicles for maximum fuel efficiency and minimum emissions with performance constraints. The energy management subsystem, called the control strategy, is optimized. This work required coupling the commercial optimization system, VisualDOC, with the hybrid vehicle drive train simulation, ADVISOR.

INTRODUCTION

High-efficiency hybrid electric vehicles (HEV) offer a number of technical design challenges that are different from conventional vehicles. Design optimization is one approach for meeting and understanding these technical challenges. This paper discusses the coupling of design optimization and the National Renewable Energy Laboratory's (NREL) ADvanced VehIcle SimulatOR (ADVISOR) to explore some of these challenges from an optimization standpoint.

This paper begins by offering a brief explanation of what HEVs are and why they are important to the future of transportation. Next some of the technical challenges and the motivations for this work are discussed. Then an overview of the ADVISOR simulation program is provided. Finally, VisualDOC is reviewed as an optimization tool.

The last several sections outline the current design tasks that ADVISOR and VisualDOC solve and examples of these design tasks. This paper ends with a set of conclusions and a discussion of some future work that we plan on investigating.

What are HEVs

A Hybrid Electric Vehicle (HEV) is basically a vehicle that uses two power-generating devices to provide propulsion energy. A hybrid vehicle typically will combine a chemical energy conversion device (i.e. fuel cell, gas turbine, and internal combustion engine) with an energy storage device (i.e. flywheel, ultra-capacitor, and battery). The energy management system of the hybrid vehicle will intelligently decide when and how to use each of these devices operate to provide clean and efficiency operation.

The hybrid vehicle is the result of government actions intended to jumpstart the development of more efficient and cleaner vehicles. The need for clean and efficient vehicles is evident in California where Los Angeles has five times worse air-quality than the nearest US rival. Federal standards for emissions (EPA Tier II) and fuel economy (CAFE) provide automakers with the motivation to explore alternative vehicle designs.

The ultimate clean, efficient car is an Electric Vehicle (EV), especially if the power plant generating mix is heavily weighted toward hydroelectric and natural gas or other renewable energy sources such as solar and wind. But there are questions about the mid-term viability of EVs. This is due to unresolved technical issues of on-board energy storage capacity, high vehicle cost, and infrastructure limitations (e.g., lack of public charging stations, repair/replacement facilities, battery-recycling centers).

HEVs may not be as clean as EVs but they offer significant fuel and emissions benefits over conventional vehicles without sacrificing vehicle performance.. More important, such technology appears to be available in the mid-term future (e.g., 2001), and therefore represents a practical, technically achievable alternative approach.

An HEV design can typically be classified as one of two types, a parallel configuration or a series configuration. An HEV with a parallel configuration (Figure 1) has a direct mechanical connection between the hybrid power unit and the wheels as in a conventional vehicle, but it also has an electric motor and energy storage system connected to the drive-line in parallel to the hybrid power unit. This configuration allows for both the hybrid power unit and the motor/energy storage system to provide power to the wheels at the same time. A parallel vehicle could use the power generated by an internal combustion engine for normal driving and the power from the electric motor for hard accelerations and regenerative braking.

An HEV with a series configuration (Figure 2) uses the hybrid power unit (IC engine and generator or fuel cell) to supply electricity for the energy storage system and electric motor. Series HEVs have no mechanical connection between the hybrid power unit and the wheels; therefore, all power is transferred electrically to an electric motor that drives the wheels.

There are several tradeoffs that designers must consider when evaluating the relative benefits of these vehicle configurations. The following list describes some of the tradeoffs between parallel and series configurations.

- The engine never idles, which reduces vehicle emissions and fuel use.
- Engine accessory loads (i.e. Air conditioning, water pump, cooling fans) can be converted to more efficient electrically driven devices.
- Opportunity for increased range.
- Possibly better performance.

The benefits of a series configuration over a parallel configuration are:

- The engine operates at or near its optimal point at all times.
- Allows a variety of options when mounting the engine and vehicle components.

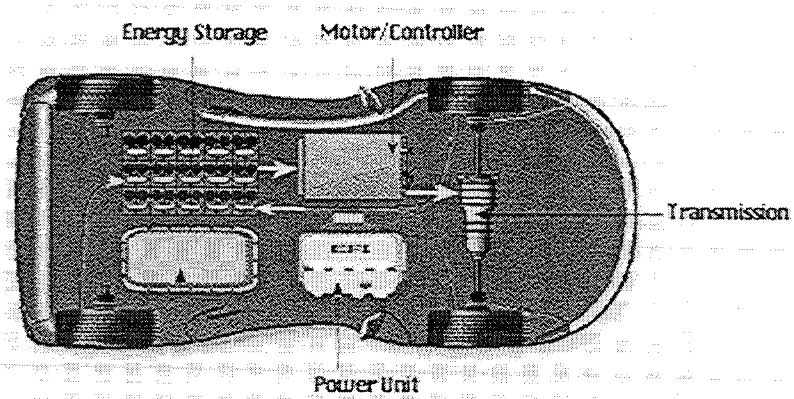

Figure 1: Parallel Configuration

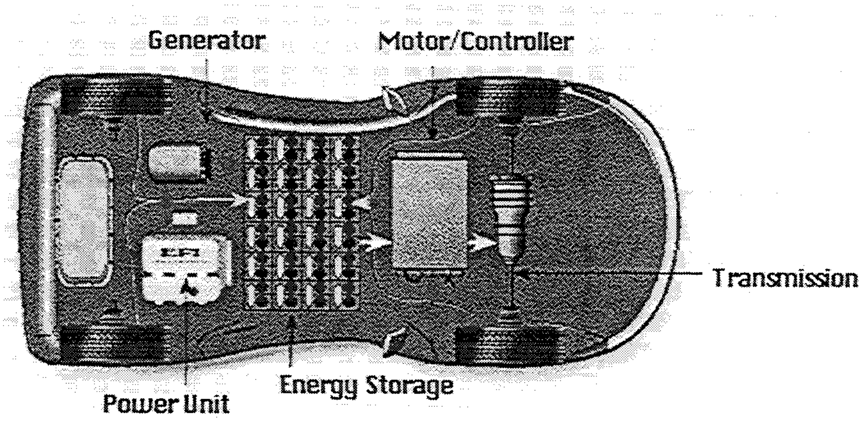

Figure 2: Series Configuration

The benefits of a hybrid configuration over a conventional vehicle

- Some series hybrids do not need a transmission.

The benefits of a parallel configuration versus a series configuration are:

- The engine and motor size can be reduced since neither must satisfy the entire vehicle load at any one time.
- Most parallel vehicles do not need a generator. The hybrid power unit is directly coupled to the road, thus, eliminating the losses due to the conversion of mechanical energy to electrical energy and back to mechanical energy.

Motivation for HEV Optimization

Any vehicle design is a complex endeavor that involves multiple disciplines and multifaceted interacting systems (drive train, structures, aerodynamics, and auxiliary systems). HEVs offer additional technical challenges because they combine multiple power sources within a single drive train. In most complex systems, it is difficult to qualify and quantify how the variables in these systems interact. Parametric studies can offer a great deal of insight; however, as the number of design variables increase, the interactions become less tractable. Design optimization offers a powerful set of tools that help engineers understand and improve different design options.

In the area of HEV design, the federal government has set fuel economy and emissions goals with through the Partnership for New Generation Vehicles (PNGV) and EPA Tier II standards. How best to achieve these standards without compromising vehicle performance is a technical challenge that confronts HEV designers today.

ADVISOR is a tool to help automotive engineers evaluate the performance of HEVs and other vehicles. It is described in the next section.

ADVISOR

ADVISOR is NREL's ADvanced VehIcle SimulatOR[1]. It is designed for quick analysis of the performance and fuel economy of conventional, electric, and hybrid electric vehicles. ADVISOR also provides a backbone for the detailed simulation and analysis of user-defined drive train components. ADVISOR has been developed in the MATLAB/Simulink environment.

ADVISOR models components using mostly empirical data, relying on drive train component input/output relationships measured in the laboratory, and quasi-static analysis, using data collected in steady state (for example, constant torque and speed) tests and correcting them for transient effects such as the rotational inertia of drive train components. ADVISOR uses simple physics and measured component performance to model existing or virtual vehicles. Its real power lies in the prediction of the performance of vehicles that have not yet been built. It can answer the question "what if we build a car with certain characteristics?" ADVISOR can predict fuel use, tailpipe emissions, acceleration performance, and gradeability.

ADVISOR users take two steps to analyze a vehicle.

1 Define a vehicle using measured or estimated component and overall vehicle data.

2 Prescribe a speed versus time trace and road grade that the vehicle must follow.

ADVISOR then puts the vehicle through its paces, making sure it meets the cycle to the best of its ability and measuring (or offering the opportunity to measure) just about every torque, speed, voltage, current, and power passed from one component to another.

VISUALDOC

VisualDOC is Vanderplaats Research and Development's (VR&D) general-purpose optimization package[2]. It contains a number of optimization algorithms and tools that make using optimization easy and robust. VR&D's VisualDOC program is designed to be coupled to almost any analysis or multidisciplinary design optimization problem[3].

VisualDOC consists of several programs, which include a graphical user interface (GUI), optimization algorithms module, and a MATLAB interface module. The GUI allows users to define almost any optimization problem before sending it to one of the included optimizers. Alternatively, users can define an optimization problem using a simple ASCII formatted file. The optimization algorithm modules allow users to solve continuous, discrete, or mixed variable problems. The problems may be constrained or unconstrained, and users can use either gradient based optimization or response surface approximations. There is also a Design of Experiments (DOE) module that users can employ when constructing response surface approximations or as a standalone tool.

DESIGN TASK

Previous work has coupled optimization to ADVISOR with success[4]. The work described here extends the scope of the optimization problems and uses a commercially available optimization tool. Furthermore, we demonstrate the effective use of DOE in the design optimization process.

Two optimization problems were identified as trial problems. It was determined that based on the outcome of these investigations, we would be better able to plan future work. The first of these problems is the generation of the optimal component sizes. It is described in the next subsection. The second of these problems is the design of the energy management or control strategy. Its description is in the second subsection.

Autosize

Autosize is automatic component size optimization. The purpose of autosize is to help the user generate a vehicle that will meet certain performance criteria with the optimal set of components. It accomplishes this by adjusting component sizes and reevaluating the performance criteria until all of the specifications have been met.

The possible objectives include any combination of the following: minimize component sizes, minimize vehicle mass, and maximize combined city/highway fuel economy.

ADVISOR users also have flexibility in setting their own design constraints. The constraints can include performance on a constant grade, maximum effort acceleration criteria, and maximum vehicle speed. For the gradeabilty constraint, the user defines the speed that the vehicle will be expected to maintain indefinitely on the specified grade. The acceleration constraints define the acceleration times the vehicle will be expected to meet. The maximum vehicle speed is used to ensure that appropriate gear ratios are used in the vehicle. The default grade and acceleration constraints are based on the PNGV performance criteria.

For hybrid vehicles, the user can select the size of the fuel converter, the energy storage system, and the motor controller as design variables. For a series vehicle and fuel cell vehicles (since they are modeled as series hybrid vehicles), the grade constraint drives the required fuel converter size (and possibly the motor size) while the acceleration constraint drives the energy storage system size (and possibly the motor size). If the motor controller has been specified as a design variable it will be minimized. Otherwise, it will be sized such that it will never limit the performance of the fuel converter or the energy storage system.

ADVISOR is also able to analyze conventional and electric vehicles. For conventional vehicles, the only design variable is the fuel converter size. For electric vehicles, the energy storage system and optionally the motor controller are the design variables. If the user chooses not to include the motor controller as a design variable, then it is sized such that it will never limit the performance of the energy storage system.

Control Strategy Optimization

The control strategy of a hybrid vehicle determines how the components of the vehicle will work together as a system to meet the vehicle demands. This includes controlling the operating point(s) of the IC engine and the electrical system Usually such a strategy is designed to minimize fuel use or emissions or maximize ESS pack life. ADVISOR currently provides models for series thermostat, series power follower, and parallel electric power assist control strategies. Each strategy has multiple parameters that allow the user to tune the strategy to their desires. VisualDOC works with ADVISOR to provide an optimal set of control strategy parameters for a given set of design constraints and objectives. The fuel use and each of the four emissions (CO, HC, NOx, PM) performance parameters can be included as either constraints or objectives.

Series Control Strategy

The series control strategy uses the generator and fuel converter to generate electrical energy for use by the vehicle. The series thermostat control strategy uses the fuel converter to maintain charge in the energy storage system. The fuel converter turns on when the battery pack's state of charge (SOC) reaches the low limit and fuel converter turns off when the SOC reaches the high limit. The fuel converter should operate at the most efficient speed and torque level whenever it is on. The series power-follower control strategy uses the same engine on/off criteria as the thermostat strategy but allows the engine to follow the power request of the vehicle within a set of limits whenever it is on. These limits include a min and maximum power range and a maximum power rise and fall rate of change. The limits allow the engine to provide the majority of the vehicle demands while operating near its optimal point. Both strategies use the same set of parameters but differ by the parameter settings.

Table 1: Series Control Strategy Design Variables

Description	Units
Battery Pack's High SOC	Percentage
Battery Pack's Low SOC	Percentage
Charge Power (SOC stabilizing adjustment made to the bus power requirement)	Watts
Maximum Power (commanded of the fuel converter)	Watts
Minimum Power (commanded of the fuel converter)	Watts
Maximum Power Fall Rate (the fastest the fuel converter power command can decrease)	Watts/second
Maximum Power Rise Rate (the fastest the fuel converter power command can increase)	Watts/second
Minimum Off Time (the shortest allowed fuel converter off time before the fuel converter can restart)	Seconds

Table 1 lists the design variables considered for series control strategy optimization.

Parallel Control Strategy

The parallel electric power assist control strategy uses the engine as the primary power source and the motor for additional power when needed by the vehicle and to maintain charge in the batteries. This parallel hybrid strategy can use the electric motor in of the following ways.

1. The motor can be used for all driving torque below a certain minimum vehicle speed.
2. The motor is used for torque assist if the required torque is greater than the maximum producible by the engine at the engine's operating speed.
3. The motor charges the batteries by regenerative braking.
4. When the engine would run inefficiently at the required engine torque at a given speed, the engine will shut off and the motor will produce the required torque.
5. When the battery SOC is low, the engine will provide excess torque that will be used by the motor to charge the batteries.

Table 2 lists the design variables for parallel control strategy optimization:

For either the parallel or the series control strategy, the users can enforce the gradeability and acceleration performance constraints while including fuel economy and emissions (nitrous oxide, hydrocarbons, particle matter, and carbon monoxide) as either constraints or objectives.

COUPLING ADVISOR AND VISUALDOC

ADVISOR includes a GUI that is specifically designed to specify all parameters required to simulate and analyze drive train components. ADVISOR is also setup to run without the GUI. For both the autosize and the control strategy optimization problems, ADVISOR has a GUI to prompt the user to define the optimization problem. This data is then transferred between ADVISOR and VisualDOC using ASCII files. Once this data has been transferred to VisualDOC, VisualDOC takes control and uses the ADVISOR simulation engine as a response generator. When VisualDOC is satisfied with the solution control along

Table 2: Parallel Control Strategy Design Variables

Description	Units
Battery Pack's High SOC	Percentage
Battery Pack's Low SOC	Percentage
Electric Launch Speed (vehicle speed below which vehicle operates as a Zero Emissions Vehicle)	m/s
Charge Torque (torque loading on the engine to recharge the battery pack whenever the engine is on)	Nm
Off Torque Fraction (fraction of the torque capability of the engine for a given speed at which the engine may shut off)	--
Minimum Torque Fraction (fraction of the torque capability of the engine for a given speed at which the motor may act as a generator)	--

with the optimal solution is passed back to ADVISOR.

Since ADVISOR uses empirical data for much of its analysis capabilities, it is difficult to obtain good gradient results for gradient-based optimization. For that reason, all optimization problems use VisualDOC's response surface approximations, which provide up to a second order approximation for each response.

EXAMPLES

Two examples are discussed here that demonstrate the capabilities of VisualDOC and ADVISOR. It is important to note that ADVISOR uses a great deal of empirical data for the analysis.

Autosize

Autosize optimization for hybrid vehicles is a mixed variable problem since the number of battery modules in the battery pack must result in an integer value. VisualDOC solves this problem by first finding the continuous optimum, which defines the lower bound on the discrete solution. It then uses branch and bound to find the discrete solution.

VisualDOC constructs the initial set of response surfaces using an initial set of design points supplied by ADVISOR. ADVISOR chooses these points based on the initial vehicle parameters set by the user. During the optimization, VisualDOC improves the approximations using exact response data at intermediate optimums until it converges at the continuous optimum.

Using the approximations at the continuous optimum, VisualDOC begins the branch and bound process. During this process, it improves the approximations around candidate discrete optimums in a similar fashion as during the continuous solution until VisualDOC converges.

For this example, a series vehicle will be autosized using ADVISOR and VisualDOC. The initial fuel converter is a 1991 Geo Metro 1.0-liter SI engine (41 kW). The initial generator is a 95% efficient generic generator. The motor controller is a Westinghouse 75 kW AC induction motor (75 kW). The batteries are Hawker Genesis 12 volt sealed lead-acid batteries. Conventional exhaust aftertreatment for a gasoline-powered vehicle is used. The gearbox is a one-speed gearbox. The vehicle is a hypothetical small car, roughly based on a 1994 Saturn SL1. Standard power train control parameters for a series vehicle are specified in ADVISOR and a constant 700 W auxiliary systems load is also included.

The design variables are the number of battery modules, the peak power of the fuel converter, and the peak power of the motor/controller. The peak power of the fuel converter and the motor are adjusted in the model by adjusting a scale factor. This scale factor will linearly adjust the torque capability and the mass of the component while maintaining the relative efficiency of the component. The constraints are the acceleration and gradeability performance. The time from 0 to 60-mph must be less than 12 seconds. The time from 0 to 85-mph must be less than 23.4 seconds, and the time from 40 to 60-mph must be less than 5.3 seconds. The vehicle must be able to maintain 55 mph on a 6% grade. The objectives are to minimize the sizes of the fuel converter and motor control and minimize the number of battery modules. Thus, the design variables are also the design objectives.

VisualDOC required 40 analyses to find the discrete optimum. The multiple objective function history is shown in Figure 3. The initial and final values of the design variables (and objectives) are in Table 4.

Table 3: Autosize Results

Description	Initial	Final
Fuel Converter Size (kW)	41	40
Motor Controller Size (kW)	75	65
Number of Battery Modules	25	23

Initially the grade and 0 to 85-mph acceleration constraints were active. At the discrete optimum, the grade, 0 to 85-mph, and 40 to 60-mph acceleration constraints are active. VisualDOC used the SQP algorithm to generate this solution.

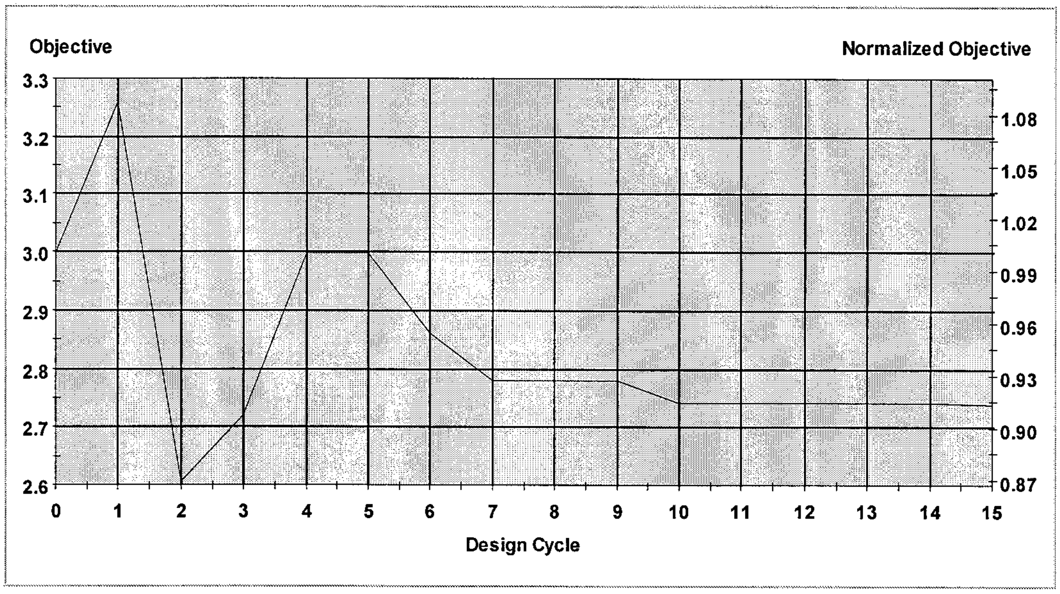

Figure 3: Multiple Objective Function History

Control Strategy

In this example, VisualDOC and ADVISOR will design the parallel control strategy for a hybrid vehicle. The vehicle is a "typical" mid-size 4-door car. The required vehicle performance is a gradeability of 6.5% @ 55mph, 0 to 60-mph in less than 12 seconds, 40 to 60-mph in less than 5.3 seconds, and 0 to 85-mph in less than 23.4 seconds. The fuel economy is evaluated on the US EPA city/highway test cycle and the emissions are evaluated on the US EPA city test cycle (FTP 75). The base engine is the 1.9-Liter VW Turbo-diesel. The battery packs are advanced lead-acid batteries.

The design variables are shown in Table 2. The optimization proceeded as a two-stage process. First, a Koshal DOE was performed to generate 28 design points. Then a response surface approximate optimization was performed using the Koshal points to construct an initial set of approximations. VisualDOC then uses the responses surface approximations method. When it finds an approximate optimum, VisualDOC has ADVISOR evaluate the actual responses at that point. If the responses are within tolerances, then VisualDOC assumes that this point is a good optimum and stops. If VisualDOC does not converge, then it adds this point to the basis and regenerates the approximations and continues the optimization process. This cycle continues until VisualDOC finds an optimum or until it feels it cannot make more progress.

The multi-variable objective function for this problem includes minimizing the hydrocarbons and nitrous oxide emissions while maximizing the fuel economy. The weighting of the fuel economy is equal to the combined weight of the two emissions responses, as in the following equation.

$$objective = max(FE) + min(0.5HC + 0.5NO)$$

The solution required a total of 57 ADVISOR analyses. This includes 28 analyses for the Koshal design. The optimum objective values and design variable values are shown in Table 4.

Table 4: Parallel Control Strategy Optimization Results

Description	Initial Value	Optimum Value	% Change
Fuel Economy	53.74 mpg	57.205 mpg	+6.45
Hydrocarbons	0.15667 ppm	0.15102	-3.61%
Nitrous Oxide	0.898 ppm	0.79462	-11.51%
High SOC	0.7	0.58898	
Low SOC	0.6	0.48898	
Electric Launch Speed	8.94	5.2868	
Off Torque Fraction	0.4	0.1	
Min. Torque Fraction	0.4	0.3707	
Charge Torque	500	494.36	

FURTHER WORK

We are continuing to extend the optimization problems that ADVISOR and VisualDOC solve. NREL VR&D engineers will be combining the autosizing and control strategy optimization problems into a single optimization problem to take advantage of the added level of flexibility in the design with increased number of design variables. Results from these studies will be provided in future publications.

CONCLUSIONS

Using ADVISOR and VisualDOC, automotive designers can gain a great deal of insight into the problems and technical challenges of hybrid electric vehicle design. VisualDOC allows designers to consider the complex interactions between design variables and responses in a mathematical, systematic way that they do not have by performing traditional parametric studies.

It is important to note that in the control strategy optimization neither the nitrous oxide emissions or fuel economy objectives meet CAFE and EPA Tier II standards; however, using VisualDOC and ADVISOR, designers can easily evaluate different vehicles. As more test data becomes available for existing components, these can be easily added to the ADVISOR database of empirical data. Furthermore, ADVISOR is able to accommodate new components, as they become available.

NREL and VR&D engineers realize that we are only considering a small part of the vehicle design. Further gains in fuel economy and emissions are possible if we consider other vehicle design factors, such as exhaust after treatment, vehicle aerodynamics and mass, and more efficient auxiliary systems, to name a few.

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