A Control Analysis of High-Performance Hybrid Electric Vehicles

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***Abstract*—This paper presents a control analysis of hybrid electric vehicles (HEVs) designed for high-performance applications. Comparisons are made between performance-oriented HEVs and those primarily concerned with fuel economy and efficiency. In order to examine the key differences between these two classes of vehicles, a case study is carried out using a hybrid-electric racer designed and built at Illinois Institute of Technology. Different control strategies are discussed with an accompanying model, as well as simulation and experimental results to support the discussion.**

I. Introduction

During the first five years that hybrid electric vehicles (HEVs) were available in the United States, sales grew 80% year-to-year [1]. In recent years, with an 18% yearly decrease in auto sales in 2008, and another 21% in 2009, HEV sales growth has been understandably stunted. However, despite this setback, HEVs' share of overall sales continues to increase. Accordingly, in 2009 nearly 300,000 hybrid electric vehicles were sold in the United States, representing close to 3% of the auto-sales for that year [2], making HEVs a significant emerging player in today's automotive market. The importance of HEVs in the automotive industry has been further validated as nearly every major car manufacturer has already, or has plans to introduce hybrid models into its line-up.

Though this paper focuses on HEVs, electric vehicles (EVs) are discussed as well because they share commonalities in their electric drives. Furthermore, the case for using electric drives in high-performance vehicles is supported by their inherent advantages of higher energy efficiency, high torque output across a wide speed range, zero vehicle emissions, and ability to harvest otherwise-lost energy through regenerative braking. Nonetheless, there typically exists a tradeoff between operating a vehicle at high-performance versus operating it at high-efficiency, particularly with internal combustion engines [3]; therefore, an appropriate balance between the two needs to be attained. For the purpose of comparison in this discussion, a distinction must be made between performance-focused vehicles, where the primary goal is maximizing performance, and efficiency-focused vehicles, which center on achieving the highest energy efficiency.

The case study in this paper will examine a formula-style hybrid race car designed and built by students at Illinois Institute of Technology (IIT). By analyzing different control strategies, attention will be drawn to important details of control in high-performance HEVs that must be handled differently than with efficiency-focused hybrids.

II. High-Performance HEVs

A. Purpose and Potential

Though sales numbers of high-performance vehicles is not readily available for sports cars, luxury, and other high-powered luxury vehicles, the continued development of these vehicles by manufacturers and the public attention they tend to attract indicate their importance in the automotive industry. Furthermore, the advancement of EV and HEV technology has allowed multiple start-up companies, including media superstars such as Tesla Motors and Fisker Automotive, the opportunity to bring high-performance vehicles with electric drives to market.

However, the fact remains that vast majority of HEV options currently available to consumers are sold based on their ability to improve gas mileage: ultimately saving owners money in the long-run, as well as appealing to the environmentally-conscious by reducing harmful emissions at the tailpipe. On the other hand, the price tag of conventional performance vehicles is typically found to be higher than that of vehicles in most lower-powered classes. Moreover, vehicles with electric drive components suffer an even higher incremental cost per unit horsepower than their gasoline or diesel equivalents. Though a higher initial cost of ownership decreases the likelihood that the owner will recover the cost of ownership due to savings in gas mileage, the added benefits of decreased emissions and the desirable characteristics of electric drives remain as attractive selling points for many prospective buyers. Indeed, early high-performance EV and plug-in HEV (PHEV) offerings seem to be very promising, as Tesla has produced more than 1,000 of its electric *Roadster* and Fisker Automotive garnering much attention with its promise to deliver its *Karma* PHEV during the second half of 2010.

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TABLE I. CURRENT AND FUTURE HIGH-PERFORMANCE EVS AND PHEVS

Name / Manufacturer *	**EV Range (mi)**	**MSRP**	**Rated Power (as listed)**	**Battery (kWh)**	**ICE**	**Topology**	**Notes**
Tesla	245	$101,500	248-hp	53 kWh	None	EV	Z60 in 3.9 seconds
Roadster 2010				Li-ion			Top speed: 125 mph
Fisker Automotive	50	$87,000	400-hp	22 kWh	N/A	Series PHEV	Z-60 < 6 seconds
Karma				Li-ion			Release: 2nd-half 2010
Tesla	160	$49,900	N/A	N/A	None	EV	Z60 < 6 seconds
Model S				Ni-MH			2011 production plan
Venturi	155	$400,000	241-hp	N/A	None	EV	Z60 < 5 seconds
Fetish				Li-ion			25 units produced/year

* all prices and specifications have been either taken from manufacturer websites, or in the case of unreleased vehicles, are best-known estimates

B. Current High-Performance EVs and PHEVs

Table I lists various high-performance vehicles that are either currently in production or have plans for future production. These are a few examples of vehicles for which a majority of the technical specifications have been announced at the time of this writing.

C. Areas for Consideration

The two parts of a HEV that have the largest direct influence on performance are its powertrain and controller designs. At their respective cores, the vehicle's powertrain design determines the performance and efficiency constraints of the vehicle, while its controller decides how to function within those constraints. It should be noted that other aspects of vehicle design may have significant impact on performance characteristics, but none as directly as powertrain and controller design [3]. This paper will focus on the controller under the assumption that the powertrain has been appropriately designed to be capable of high-performance output.

Four controllers have been developed and simulated under various drive conditions that exemplify the control challenges faced in high-performance HEVs based on work done in [4-8]. Primarily, two rule-based controllers have been developed separately: one that focuses solely on maximizing performance and the other on efficiency. A third rule-based controller has been developed to attempt to maximize performance and efficiency at the same time making as few compromises and trade-offs as possible. Lastly, an artificial neural network is used as an optimization technique to combine the behavior of the performance-targeted and efficiency-targeted controllers into a single controller that also attempts to maximize both.

III. CASE-STUDY: IIT'S FORMULA HYBRID RACER

A. Application

The Formula Hybrid competition is an international engineering design challenge for undergraduate and graduate students. Student teams must design, build, and complete with open-wheel, single-seat race cars that conform to set of rules, or formula. This formula, derived from the well-established Formula SAE competition, emphasizes powertrain innovation and fuel-efficiency for a high-performance application [9].

Three specific dynamic events are used in order to illustrate the need to devise an appropriately diverse control strategy. The first is an acceleration run that tests the time it takes the vehicle to cover a distance of 75-meters from a stand-still. The second is a single timed-lap autocross: evaluating the vehicle's ability to break and accelerate very rapidly into and out of sharp turns. The third is an endurance run, which challenges the extended-range capability of the vehicle by asking it to travel a certain distance with a fixed allotment of energy (electrical and gasoline-equivalent), and to do so in the least amount of time possible. The event is designed to push the vehicles to operate at a high-level of efficiency (as opposed to the first two events, where energy use is not a factor) in order to conserve enough energy to finish; however, the vehicle must also perform well in order to complete the distance in the fastest amount of time. It should be noted that energy remaining at the end of each event does not provide any benefit for teams; therefore, it is advantageous to save weight by only carrying as much fuel as is needed for propulsion during an event [10].

B. Vehicle Design

The vehicle under study is a series-HEV with independent front- and rear-wheel drive and is pictured in Fig. 1. There are three on-board propulsion motors: one connected through a planetary gearbox to each of the front wheels, and the third powering the rear wheels through a differential. The rear and front electric drive systems are coupled through-the-road for a total of 50 hp-continuous and 70 hp-peak electric traction power. There is also an internal combustion engine connected to an electric generator, capable of generating 12 hp-continuous and 18 hp-peak. The energy storage system (ESS) consists of a hybrid battery and ultra-capacitor [5-6] with a 3 kWh capacity. Finally, the total vehicle weight is 750 lbs.

Figure 1. IIT’s hybrid racer.

The design of the vehicle is such that the maximum power output at the wheels can only be delivered when the engine-generator unit is supplementing the power output of the ESS. It is this characteristic that will be used in the simulations to exemplify key points in the difference between performance- and efficiency-optimized control.

As part of the Formula Hybrid competition’s requirements for a fixed on-board energy allotment, a formula is used to determine a common unit of energy between the ESS and the gas tank, namely the Joule. Essentially, the amount of energy available in the ESS is subtracted from the total energy allowance and the remainder is provided as gasoline or diesel fuel. This amount is determined as the equivalent energy per unit volume of fuel accounting after a reduction due to loss in engine inefficiency.

It is particularly important for the vehicle’s controller to maintain a precise balance between efficiency and performance: even more so because there is no benefit to having fuel left over at the end of the endurance event. In fact, the ideal case would be if the controller managed to use all of the allotted energy during the endurance event. Finally, since the energy allotment changes each year as the competition rules evolve, this paper assumes an allotment of 0.25 gallons for the endurance simulation.

IV. Modeling and Simulation

It is particularly important for the vehicle’s controller to maintain a balance between efficiency and performance because there is no benefit to having fuel left over at the end of the endurance event. In fact, the ideal case would be if the controller managed to use all of the allotted energy during the endurance event. Since the energy allotment changes each year as the competition rules evolve, this paper assumes an allotment of 0.25 gallons for the endurance simulation.

The vehicle model has been constructed and simulated in PSAT using drive cycles representing the three dynamic events from the Formula Hybrid competition: acceleration, autocross, and endurance. Fig. 2 shows two of the three drive cycles used to simulate the acceleration and endurance events. The cycles are defined as desired vehicle linear speed versus time. The goal is to test for efficiency in the endurance cycle and performance in the autocross and acceleration cycles. Additionally, four distinct control strategies will be studied: one that prefers performance over efficiency, one that prefers efficiency over performance, a third that is a rule-based blend of the two former strategies, and a fourth is composed of an artificial neural network that is trained using the first two controllers.

The strategy that gives preference to performance over efficiency, named Highest Performance, blindly attempts to satisfy driver’s demand under all circumstances: regardless of ESS state-of-charge (SOC), fuel remaining, or operating efficiency of the engine. In short, any power demand from driver that cannot be supplied by the energy storage system results in a command to engine to supplement the ESS by providing the extra power needed at the wheels. The controller is very willing to run the engine near its peak power point resulting in less efficient operation. The controller also maintains a relatively high target SOC range of 70 to 80% in order to maintain its output power capability.

Conversely, the Highest Efficiency strategy makes all efforts to maximize operating efficiency at all times during driving, effectively limiting performance demanded by the driver in favor of efficient use of energy. The vehicle operates in charge-discharging [4] mode until the battery SOC is below a threshold value of about 30%. At which point, the engine is started and only allowed to operate at its peak efficiency point at all times in order to maximize the efficiency of the energy conversion from gasoline to electrical energy. For example, during times when the driver demands more power than can be delivered by the ESS and the engine is unable to supplement the ESS in an efficient manner, the driver’s demand for torque is not fully met by the controller.

The third strategy is called the Efficiency-Performance Blend (EPB) controller. It operates by combining the characteristics of the first two strategies and taking into

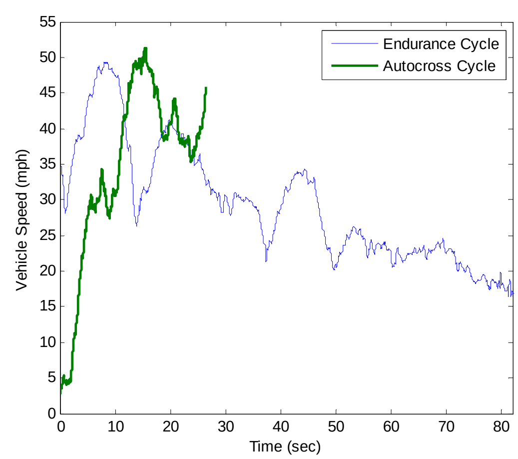

Figure 2. Acceleration cycle and a single lap of the endurance cycle used in simulations.

consideration the state of each of the vehicle's key subsystems, while simultaneously respecting the driver's demand for high-performance. The goal of this controller is to determine in real-time when to operate the engine at a constant high-efficiency point, when to supplement extra power needed by the energy system, and when to turn off the engine entirely. This is based on the controllers estimation of the driver's intentions, based on pedal input.

Finally, a fourth strategy, named Neural Network Blend (NNB), uses an artificial neural network trained using simulation behavior of the High Efficiency and High Performance controllers. Typically, artificial neural networks are used to replicate or learn the behavior of non-linear systems [7]. Accordingly, a trained neural network is fitted inside a controller as its "brain" to combine the behavior of two different controllers. More precisely, it learns to mimic the high-performance behavior of the High Performance controller during aggressive driving. At the same time, it is trained to reproduce the efficient-operation of the High Efficiency controller during normal driving. It may seem like an easy task at first glance to just combine these two rule-based strategies into a third rule-based strategy; however, the real challenge lies in identifying what will be classified as aggressive and what as passive. This along with optimizing the balance between performance and efficiency during a combination of passive and aggressive driving becomes a very time consuming task. In this respect, a neural network has the capacity to reduce the design complexity of a controller with multiple degrees of freedom and more than one output to optimize.

V. Results

A. Overall Analysis

Tables II and III show the results of various simulations comparing the performance and efficiency of each control strategy simulated with each drive cycle. As anticipated, the High Performance and the High Efficiency controllers generally yielded the highest performance and efficiency, respectively. The one exception having occurred during the endurance cycle will be examined in this section. Also examined will be the ability of the two blended controllers (EPB and NNB) to find an appropriate balance between performance and efficiency during the simulations.

During the autocross cycle, the two blended strategies yielded times just slightly slower than the High Performance strategy; however, a noticeable difference was seen during the acceleration cycle, as the NNB controller finished the cycle in a full tenth of a second faster than it's rule-based counterpart. This indicates that the NNB controller was able to detect the driver's desire for maximum acceleration better than the EPB based on its lower acceleration time. However, unlike the High Performance controller, the response of the NNB controller still did not provide maximum acceleration under full pedal command indicating that the neural network

TABLE II. ENGINE EFFICIENCY AND ADJUSTED TIME DURING SIMULATIONS

Controller	Drive Cycle		
	Acceleration	***Autocross***	***Endurance***
High Performance	4.25 sec 23.2 %	29.07 sec 30.1%	2,635.76 sec 26.47%
High Efficiency	4.61 sec 27.8 %	34.59 sec 33.4 %	2,673.32 sec 27.4 %
EPB (blended, rule-based)	4.40 sec 26.1 %	29.12 sec 31.0 %	2,617.82 sec 26.3 %
NNB (blended, neural net.)	4.30 sec 25.0 %	29.14 sec 31.0 %	2,610.87 sec 24.9 %

did not perfectly match the performance behavior demanded by the driver. Nevertheless, the fact that the two blended controllers achieved similar times to the High Performance controller indicates that both controllers exhibit a satisfactory amount of performance characteristics.

Understandably, the High Performance controller consumed the most energy and achieved the least engine efficiency during the endurance cycle. This is simply due to the fact that it is designed to blindly meet driver's demand without any regard for efficiency. Interestingly, the energy consumption for High Performance controller was 31% greater than that of the High Efficiency controller, but with only a 1% reduction in completion time. Furthermore, the High Performance controller required more gasoline than the 0.25 gallons allotted; although the vehicle was able to complete the course on the charge remaining in the ESS, its electric drive was underpowered without the peak current assistance of the engine during demanding parts of the cycle. This explains why the High Performance controller did not yield the best time during the endurance cycle. It further stresses the importance of finding a proper balance between

TABLE III. EFFICIENCY DURING THE ENDURANCE CYCLE

Controller	Drive Cycle		
	Fuel Economy	***Fuel Consumed***	***Total Energy Consumed***
High Performance	50.3 mpg	0.29 gal	10,004 Wh
High Efficiency	78.2 mpg	0.20 gal	6,856 Wh
EPB (blended, rule-based)	72.7 mpg	0.18 gal	7,383 Wh
NNB (blended, neural network)	68.4 mpg	0.21 gal	7,869 Wh

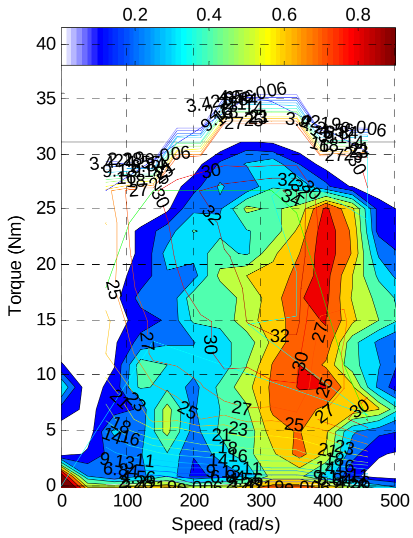

Figure 4. Engine operating points as a function of time for the High Efficiency controller.

the performance and efficiency blend.

B. Engine Operating Points

Figs. 3-6 show a breakdown of engine operating points for each controller during the endurance simulation. By looking at Fig. 4, one can see that, in the High Performance controller, the engine spends most of its time at its near-maximum power output, which is a range of relatively low efficiency between 22% and 24%. It also spends a great deal of time at a point of high speed and low torque, where efficiency is rock-bottom at 10%. On the other hand, Fig. 3 shows that the High Efficiency controller tends to favor the regions of higher efficiency in the range of 27% to 34%,

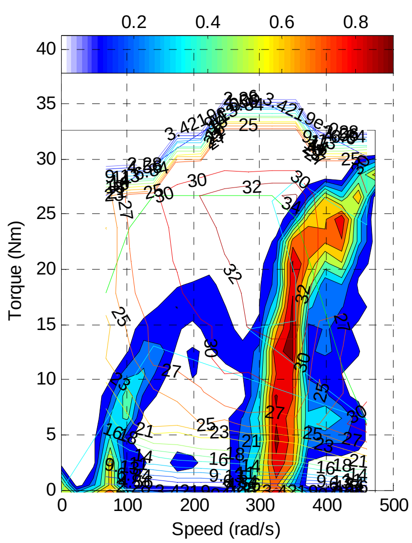

Figure 3. Engine operating points as a function of time for the EPB controller.

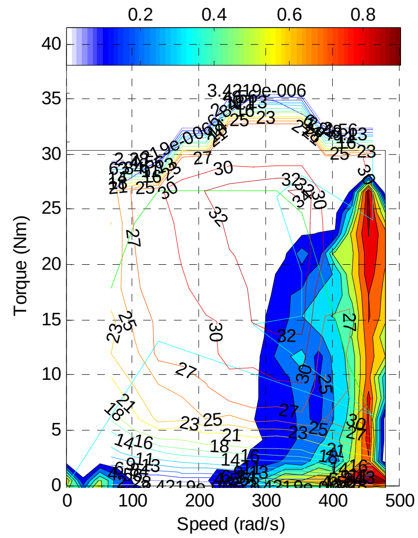

Figure 6. Engine operating points as a function of time for the High Performance controller.

spending very little time in the areas of lower efficiency, simultaneously avoiding the point of highest power output. In Fig. 5, one may observe that the EPB controller operates the vehicle's engine operation is characteristic of both the High Efficiency and the High Performance controllers. Essentially, the engine operates in both a higher power range than that of the efficiency-centric controller, and better efficiency than its performance-only counterpart. The engine operation under the NNB controller, shown in Fig. 6, clearly favors high speed points that are in the range of about 27% efficient, similar to the High Performance controller. It is also evident from the plot that some characteristics have been drawn from the High Efficiency controller in its lower speed

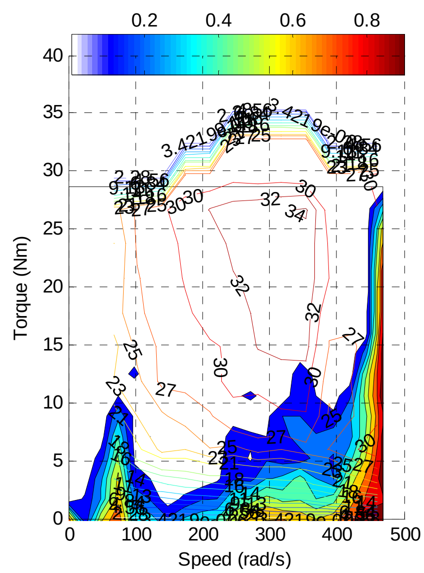

Figure 5. Engine operating points as a function of time for the NNB.

operation.

C. *Limitations*

It must be noted that the use of PSAT has certain limitations when used as a simulation tool for measuring performance. The main reason lies in the nature of its drive cycles, which are comprised of vehicle speed versus time datasets. In order to measure performance, it would be better if PSAT instead used a vehicle position map as a drive cycle, wherein a vehicle is required to travel from one point in space to another along a specific path. Naturally, this would increase the complexity of the simulation software and also the controllers, but it would allow for more accurate timing of cycle completion and other performance-based measurements.

The simulations in this paper were, however, performed under the current method of defining drive cycles. Therefore, the times in Table II are in fact calculated based on the cycle distance and actual distance traversed by the vehicle. This ratio is then used to determine an adjusted time value as a ratio of the time it would take to complete the drive cycle, if its speed curve were matched perfectly.

VI. CONCLUSION

The simulations performed in the case study of IIT's Formula Hybrid vehicle demonstrate some of the issues that make balancing efficiency and performance in high-performance control applications important. In this study, efficiency became important to the control strategy as the result of a fixed energy allotment. However, the bottom line of a high-performance vehicle is self-contained in that very classification: performance. What has been demonstrated in this paper is the ability of the vehicle's controller to be intelligent enough to sacrifice performance at times in order to conserve energy to last the entire drive cycle; yet meet the driver's demands for quick acceleration and aggressive driving when desired at the same time.

This study has also drawn attention to the difficulties in creating a controller that effectively balanced performance and efficiency. The comparison of the two blended controllers: rule-based and that using a neural network showed that neither are able to fully escape the inherent tradeoffs that exist between targeting performance and efficiency and, rightly so, given the nature of efficient and high power points falling at different engine operating regions. However, it has been shown that artificial neural networks are viable candidates for optimizing and attaining a balance.

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