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Development of a Willans Line Rule-Based Hybrid Energy Management Strategy

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Abstract

The pre-prototype development of a simulated rule-based hybrid energy management strategy for a 2019 Chevrolet Blazer RS converted parallel P4 full hybrid is presented. A vehicle simulation model is developed using component bench data and validated using EPA-reported dynamometer fuel economy test data. A combined Willans line model is proposed for the engine and transmission, with hybrid control rules based on efficiency-derived engine power thresholds. Algorithms are proposed for battery state of charge (SOC) management including engine loading and one pedal strategies, with battery SOC maintained within 20% to 80% safe limits and charge balanced behavior achieved. The simulated rule-based hybrid control strategy for the hybrid vehicle has an energy consumption reduction of 20% for the Hot 505, 3.6% for the HwFET, and 12% for the US06 compared to the stock vehicle.

Introduction

The looming threat of global climate change has pushed mankind to develop cleaner methods for manufacturing, energy production, and transportation. In addition to regulating existing industry, a focus has been placed on educating the next generation of engineers in advanced technology to usher in the new eco-friendly era.

In a collaboration between the public and private automotive sectors, the EcoCAR Mobility Challenge is a university engineering design competition with the goal of designing, building, and tuning a hybrid vehicle based on the 2019 Chevrolet Blazer RS platform. As a part of this challenge, the Hybrid Electric Vehicle Team (HEVT) at Virginia Tech has spent the first three years of the four-year competition cycle designing and constructing the hybrid Blazer, providing dozens of undergraduate engineering students hands-on design experience with industry-standard tools and methods.

This paper outlines the development process for the hybrid Blazer propulsion supervisory controller, focusing on the derivation and simulation of the energy management strategy. Due to project delays and testing restrictions as a result of COVID-19, on-vehicle test data is limited, so a validation and evaluation process is proposed within a simulation environment to prepare the control strategy for in-vehicle use without the ability to test on actual hardware. Viability of the control strategy on the vehicle is of key importance, so validation criteria along with applied battery energy management methods are explored.

Hybrid Architecture

A hybrid vehicle is defined by the use of more than one source of energy to propel the vehicle. While hybrid vehicles of many types have been marketed and sold, the most common consumer hybrid vehicles use gasoline and electric power, with or without the ability to charge the electric battery pack from external grid power [1, 2]. Typically, the primary goal of powertrain hybridization is energy efficiency improvements, usually realized through engine downsizing or engine downspeeding, allowing the engine to operate within regions of higher efficiency [3]. In addition to aiming for reduced energy consumption [4-6], there are many possible areas of improvement for vehicles when adding an additional source of tractive power such as optimizing performance [4] and increasing the lifespan of powertrain components [7].

The hybrid powertrain architecture for the HEVT Blazer was developed during the first year of the competition to balance expected fuel economy gains with ease of development, integration, and control of the new powertrain components [8]. The chosen architecture utilizes a downsized 2.5 L inline-four engine on the front axle along with an 80 kW integrated traction motor on the rear axle in a P4 configuration as shown in Figure 1. The two powertrains are not mechanically linked but are still considered coupled through the road, with most hybrid operating strategies feasible.

Methods of Energy Management

Within the field of hybrid vehicle propulsion control research, there are three primary categories of control system implementation and analysis: offline optimization, online optimization, and rule-based control.

FIGURE 26 Engine lower efficiency sensitivity analysis power output.

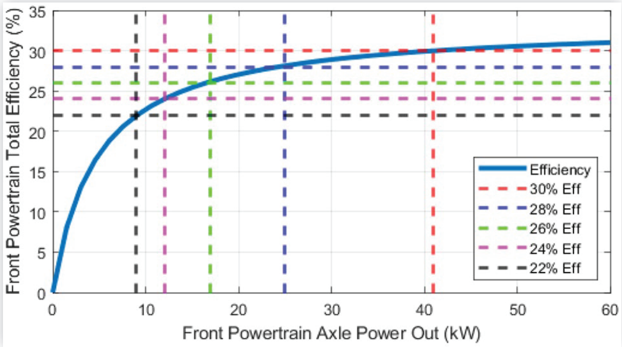

TABLE 10 Sensitivity analysis for engine lower efficiency boundary with the chosen design parameter highlighted.

		US06	Hot 505	HwFET
η = 22%	*mpg*	24.7	29.6	35.9
	CS	+0.15%	−0.55%	−0.31%
η = 24%	*mpg*	24.8	30.9	36.1
	CS	−0.62%	+0.50%	+0.05%
η = 26%	*mpg*	24.9	32.4	36.7
	CS	−0.21%	−0.07%	−0.22%
η = 28%	*mpg*	25.2	33.3	37.9
	CS	+0.38%	−0.59%	−0.49%
η = 30%	*mpg*	26.2	31.7	36.7
	CS	−0.62%	+0.52%	+0.60%

TABLE 11 Sensitivity analysis for Engine Only operation speed with the chosen design parameter highlighted.

		US06	Hot 505	HwFET
v_{eng}= 40 mph	*mpg*	25.1	33.3	37.7
	CS	−0.18%	+0.18%	+0.31%
v_{eng}= 45 mph	*mpg*	25.2	33.3	37.9
	CS	+0.38%	−0.59%	−0.49%
v_{eng}= 50 mph	*mpg*	25.2	33.3	37.2
	CS	−0.22%	+0.18%	−0.37%
v_{eng}= 55 mph	*mpg*	25.2	33.0	36.1
	CS	−0.24%	−0.40%	+0.60%
No Limit	*mpg*	26.0	33.8	34.7
	CS	−0.11%	−0.89%	−0.52%

cutoff speed can be seen in the MIL simulation results plots in Figure 25, specifically noting the operating points near the zero-torque x-axis.

Comparing the "45 mph" to "No limit" cases, the Hot 505 has a negligible difference, the HwFET gains around 3 mpg, and the US06 loses around 1 mpg. The HwFET, being a relatively mild drive cycle, benefits from the 9-speed transmission and engine DFCO, maintaining top gear through the majority of the cycle. On the other hand, US06 has a higher fuel economy when there is no limit on electric motor operation, as the aggressive drive cycle benefits from the available motor torque assist near zero torque.

Conclusion

As a part of the EcoCAR Mobility Challenge engineering design competition, HEVT is tasked with converting a stock 3.6 L Chevrolet Blazer RS into a hybrid electric vehicle. The engine is downsized to a 2.5 L engine, and a high-voltage battery electric powertrain is integrated using the best available combination given the selection criteria.

A model for the conventional driveline including a 2.5 L engine and 9-speed transmission is developed. A model validation procedure for a control development process without access to a functional prototype vehicle is proposed using EPA test car list data including analysis of the driver model and engine model including accessory load. The US06, Hot 505, and HwFET drive cycles are simulated, and the energy consumption data have 5% error or less for each analyzed validation case.

A Willans line model for the front powertrain is developed including the engine, transmission, and 12 V accessory load. A rule-based control strategy is proposed, with a region of optimal engine operation derived based on the combined Willans line model. Two algorithms for battery SOC management are proposed within the framework of the rule-based strategy, and a one pedal regenerative braking strategy is developed.

The proposed hybrid energy management strategy has a 12% energy consumption reduction for the US06, 20% for the Hot 505, 3.6% for the HwFET over the baseline 3.6 L Blazer, with charge-sustaining hybrid behavior remaining within the allowable 20% to 80% SOC limits for each EPA drive cycle. The result of the control system development process is a relatively simple and time-invariant rule-based hybrid propulsion energy management strategy suitable for deployment in an online vehicle controller.

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Definitions/Abbreviations

APP - accelerator pedal position
AWD - all-wheel drive
ADAS - advanced driver assistance systems
BPP - brake pedal position
CAV - connected and automated vehicles
CS - charge sustaining metric
DOF - degree of freedom
DP - dynamic programming
ECMS - energy consumption minimization strategy
EPA - U.S. Environmental Protection Agency
FWD - front-wheel drive
ETW - equivalent test weight
HEVT - Hybrid Electric Vehicle Team at Virginia Tech
HwFET - Highway Fuel Economy Test
ICE - internal combustion engine
NA - naturally aspirated
P4 - hybrid motor position on separate axle as ICE
SOC - battery state of charge