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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

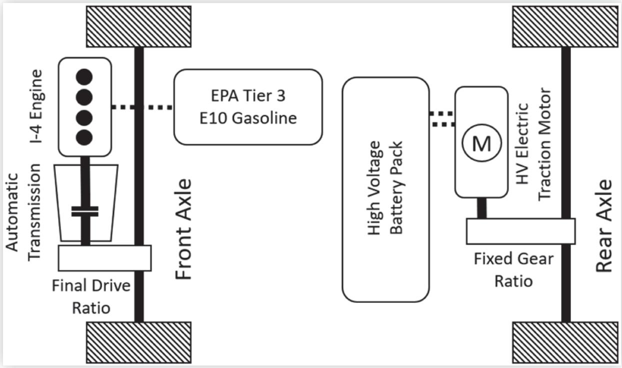
A hybrid vehicle is defined by the use of more than one source of energy to propel the vehicle. While hybrid vehicles of many types have been marketed and sold, the most common consumer hybrid vehicles use gasoline and electric power, with or without the ability to charge the electric battery pack from 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 1 Hybrid Blazer powertrain architecture.



Offline Optimization

The first category, offline optimization, involves the simulation and optimization of a particular vehicle powertrain in a particular software suite. The term "offline" refers to testing within simulation, whereas "online" refers to the control code running on real-time hardware.

The most common form of offline optimization utilizes dynamic programming (DP), a Markovian solving method for finding the global optimal solution for any given system [9]. Although DP is a powerful tool with many applications, the solution complexity increases exponentially with the size of the state vector, and as a result, cannot be efficiently applied to complex systems without simplifying assumptions.

Especially in academic circles, DP is commonly applied to hybrid vehicles with energy consumption as the chosen objective function [10, 11]. The application of DP methods is used to predict the optimal route of each state variable to minimize fuel consumption over a given speed trace. Although DP cannot be used in an online controller, the result from a DP simulation is an invaluable tool for development of online strategies, as the DP results offer the globally optimal path through a given scenario [12, 13].

The Hamiltonian system optimized under DP is defined as the following, where λ is the gradient of the cost-to-go function (otherwise known as the costate), x is the state vector, and u is the control vector [14].

$$H(x,u,t) = f(x,u,t) + \lambda^T g(x,y,t) \tag{1}$$

For a hybrid vehicle, the primary control inputs are the torque requests to the powerplants on the vehicle and the friction braking force. For a vehicle with two sources of tractive power, such as the parallel hybrid architecture under analysis, the torque production of the two powertrains, gasoline-powered and electric, must sum to be equal to the torque demand of the driver. With the driver torque demand being an input to the system, the control input can be simplified to the torque demand of one powertrain (which implies the torque demand of the other by subtraction). To keep the complexity of the DP model down, the control vector, which could include variables such as clutch control or transmission gear, are typically neglected for computational efficiency [14].

Online Optimization

The hottest area of energy management research in the past decade has been the development of methods of adapting optimization techniques from Markovian methods like dynamic programming to real-time online methods. The most commonly used method is the optimal control energy consumption minimization strategy (ECMS), which involves discretizing the Pontryagin's Minimum Principle (PMP) control formulation to run on an online controller [15].

Research has been performed in multiple applications of the ECMS algorithm, including as a control strategy for the HEVT hybridized Blazer [8, 16]. Studies have included adapting ECMS to a series hybrid city bus [17], accounting for transient thermal properties of powertrain components [18], maximizing the torque output from a power-split hybrid [4], and additional cost functions to influence the behavior of optimal algorithms, such as gear shift and engine start penalty functions [19].

One of the major design difficulties for the ECMS controller is the optimization horizon, which can be as short as a few controller cycles. Additionally, because the source of control inputs is a human driver, the unpredictability makes it challenging to maintain optimal operation. As a result, the ECMS algorithm alone is generally not adequately equipped to run on a vehicle, as the torque requests are instantaneous solutions of the system, which can result in large power variations between time steps, causing the system to rapidly switch between high and low torque requests. The result can be high jerk on the vehicle due to the lack of accounting for component response time, resulting in worse than expected fuel efficiency due to higher engine transient fuel consumption.

Solutions to these issues can be implemented, typically in the form of augmenting cost functions or correction factors, such as penalizing large engine power differentials between time steps or frequent engine starts/stops [15]. However, adding additional cost functions is analogous to adding rules, and thus moves the control implementation away from an "optimal" solution.

Additionally, the DP costate factor, reformulated to the equivalency factor in ECMS, is extremely dependent on the specific drive cycle for charge sustaining behavior. As a result, the equivalency factor is often formulated to a dynamic function of SOC, often requiring tuning depending on the specific vehicle configuration and drive cycle test.

Researchers have attempted to address the problem of ECMS on vehicle-specific tuning and rules. Recent studies [20] have focused on reducing the dependence of online real-time optimization-based methods on specific drive cycle, with the goal of maintaining a relatively balanced battery state of charge while reducing fuel consumption. Other studies [21] have embraced rules by attempting to merge rule-based and optimal control strategies by utilizing a rule-based strategy to control the engine operating points, then balancing efficiency against battery SOC using an ECMS strategy. Generally, the online optimization strategies implemented in research require significant modification from the original offline optimization problem, meaning that no solution provides a universally optimal result.

Rule-Based Control

The most traditional method for hybrid vehicle control involves defining a set of rules which control engine and motor behavior depending on the current vehicle state. A rule-based control strategy is typically computationally simple and is well-suited for online implementation in hybrid vehicles. The rules in the control strategy are typically derived from experience and tuned through simulation to optimize fuel economy and emissions performance for a given vehicle [22]. As a result, rule-based control strategies are typically highly dependent on the specific vehicle architecture for which they are designed.

Rather than solving for the optimal control sequence, rule-based strategies use analysis of component efficiency at various operating points to inform a control strategy. Typically, such control strategies include E-Launch, where the vehicle uses only the electric motor at low speeds, as well as an Engine-Only region, where the vehicle uses the engine in regions of higher efficiency.

Research has been performed on how to optimize the rule-based control strategy development process by reducing the dependence of rule formulation on human intuition, typically by using the unstructured DP model results to inform operating behavior of the hybrid vehicle; examples of such research include methods for utilizing results of DP models to calculate optimal operating parameters within the defined rules [5, 10, 11], using offline simulation adapted to operating maps for optimal engine performance [23], developing rules based on total powertrain efficiency [6], and specific optimization such as rule modification for cabin air temperature [18]. The hybrid energy management strategy developed in this paper partially falls into this category of control strategy, with a focus on rule development for battery SOC management.

System Modeling

To develop the rule-based hybrid control strategy for use in the HEVT hybrid Blazer, a simulation model of sufficient fidelity is required. The development and validation of the vehicle model is presented, including the glider model and conventional and high-voltage powertrains.

Glider Physics

For a simulation model developed for energy consumption analysis, a 1-DOF (degree of freedom) longitudinal lumped-mass vehicle glider model is sufficient. The physics of the vehicle can be broken down into a few constituent equations for resistive forces, and a simple force balance provides a method to model dynamic behavior. Specifically, the resistive forces are broken down into F_{aero}, F_{rr}, and F_{grade}, the aerodynamic drag, rolling resistance, and grade forces, respectively, with the positive tractive effort labeled $F_{tractive}$, inertial force labeled F_{inert}, and the road angle labeled α, shown Figure 2.

The force summation can be written as shown in Equation 2.

$$F_{inert} = F_{tractive} - F_{aero} - F_{rr} - F_{grade} \tag{2}$$

FIGURE 2 Free-body diagram of a vehicle with primary forces labeled.

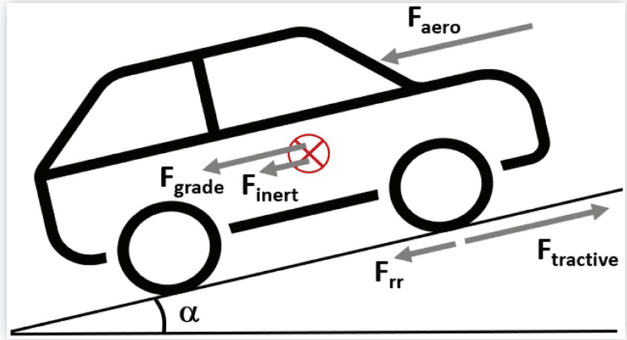


TABLE 1 EPA dynamometer parameters for the 2019 Chevrolet Blazer RS AWD along with the mass-scaled hybrid Blazer glider model parameters.

Parameter	EPA Stock Blazer [26]	Mass-Scaled Hybrid
ETW	4500 lb_m	2270 kg (5000 lb_m)
A	30.64 lb_f	156 N
B	0.4421 $\frac{lb_f}{mi/hr}$	1.82 $\frac{N}{m/s}$
C	0.02399 $\frac{lb_f}{mi/hr^2}$	0.589 $\frac{N}{m/s^2}$

The force components for the vehicle glider model can be determined in a variety of ways, including experimentally on a vehicle. One such method is used by the U.S. Environmental Protection Agency (EPA) for the measurement of emissions performance and fuel economy of vehicles sold in the United States, where testing is carried out on dynamometers using mathematically modeled vehicle forces. In this EPA fuel economy testing, the road is assumed to be flat, with no headwind forces, no precipitation, and a reference ambient temperature of 20 °C [24]. The EPA dynamometer parameters are experimentally determined by coast-down testing and quadratic fitting to road load data from 70 to 10 MPH based on the SAE J2263 standard [25]. The reported road load forces for any tested vehicle can be used to model the glider forces, as shown in Equation 3 and 4.

$$F_{inert} = F_{tractive} - \left(A + Bv + Cv^2\right) \tag{3}$$

$$F_{rr} + F_{aero} = A + Bv + Cv^2 \tag{4}$$

The A, B, and C parameters along with the vehicle equivalent test weight (ETW), which are freely available online, are listed in Table 1 for the stock 3.6 L Blazer. The glider parameters accurately represent the total vehicle drag, including aerodynamics, tire rolling resistance, and driveline mechanical drag.

In addition, the inertial force is defined as the following, where the 1.03 scaling factor is an adjustment for the effect of the inertia of rotating components on vehicle acceleration, as defined by the SAE J2263 standard [25]:

$$F_{inert} = 1.03 \cdot \mathrm{ETW} \cdot a \tag{5}$$

FIGURE 26 Engine lower efficiency sensitivity analysis power output.

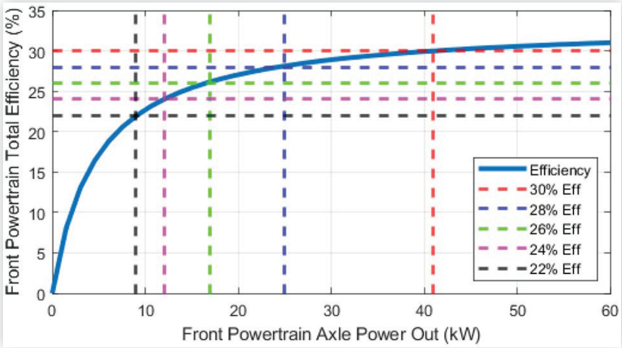


TABLE 10 Sensitivity analysis for engine lower efficiency boundary with the chosen design parameter highlighted.

		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

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