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Development and Testing of a Hybrid Vehicle Energy Management Strategy

Justin Quach Wu and Douglas Nelson Virginia Tech

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Abstract

An energy management strategy for a prototype P4 parallel hybrid Chevrolet Blazer is developed for the EcoCAR Mobility Challenge. The objective of the energy management strategy is to reduce energy consumption while maintaining the drive quality targets of a conventional vehicle. A comprehensive model of the hybrid powertrain and vehicle physics is constructed to aid in the development of the control strategy. To improve fuel efficiency, a Willans line model is developed for the conventional powertrain and used to develop a rule-based torque split strategy. The strategy maximizes high efficiency engine operation while reducing round trip losses. Calibratable parameters for the torque split operating regions allow for battery state of charge management. Torque request and filtering algorithms are also developed to ensure the hybrid powertrain can smoothly and reliably meet driver demand. Vehicle testing validates that the hybrid powertrain meets acceleration response targets while delivering an enjoyable driving experience. Simulation testing shows that the energy management strategy improved fuel economy in most drive cycles with improvements of 8.8% for US06, 9.8% for HWFET, and 0.1% for the EcoCAR Mobility Challenge Cycle. Battery state of charge management behavior is robust across a variety of drive cycles using inputs from both simulated and test drivers. The resulting energy management strategy delivers an efficient, responsive, and reliable hybrid electric vehicle.

Introduction

As a part of the EcoCAR Mobility Challenge, an energy management strategy is developed for a prototype Chevrolet Blazer integrated with a hybrid powertrain. The goal of the energy management strategy is to reduce energy consumption by efficiently using the conventional and electric powertrains while managing battery state of charge. Drive quality is also a critical goal with hybrid powertrain operation needing to be smooth and responsive to driver input.

The objective of this paper is to discuss the development of a parallel hybrid energy management strategy with consideration for battery SOC management and drive quality in addition to the simulation and in-vehicle testing performed to validate that its performance. To facilitate the development of the energy management strategy, a comprehensive model of the vehicle longitudinal dynamics, conventional & electric powertrain physics, and powertrain controllers is developed. A Willans line model is used to develop a rule-based torque split strategy with flexible operating regions for battery state of charge management. Strategies for improving drive quality by smoothly blending conventional and electric powertrain torques are also developed and validated with in-vehicle testing. Simulation and vehicle testing results also show that the overall energy management strategy reduces energy consumption while meeting drive quality targets.

As this energy management strategy is part of the overall control strategy for a functional prototype hybrid electric vehicle, it interacts with many other software features that are out of the scope of this paper. Torque request strategies are only discussed for human drivers, with adaptive cruise control and connected vehicle interactions considered out of scope. The development of the torque split algorithm is thoroughly discussed explored but the details of interfacing with powertrain controllers is omitted. While system safety, thermal management, power moding, and human machine interfaces are all closely tied to the energy management strategy, they are also not discussed here.

The contributions of this paper include discussion on the development of an energy consumption focused hybrid vehicle model, definition of a rule-based torque split strategy, robust battery state of charge management techniques and drive quality features validated with extensive in-vehicle testing.

EcoCAR Mobility Challenge

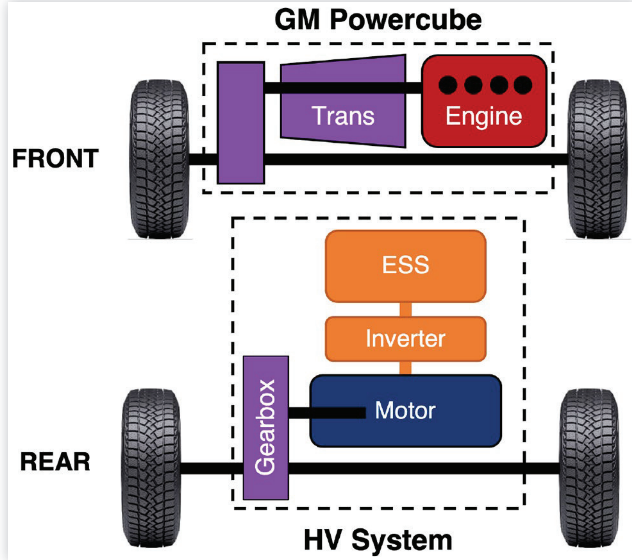
The EcoCAR Mobility Challenge is a four-year engineering design competition that is aimed at developing confident and skilled engineers through hands-on real-world experiences. The competition is headline sponsored by General Motors (GM), the U.S. Department of Energy and MathWorks. The overall goal of the competition is to incorporate advanced propulsion systems and connected and automated vehicle technology into a 2019 Chevrolet Blazer that will improve the energy efficiency, safety, and the consumer appeal of the vehicle of the growing SUV market. As one of the eleven teams participating in the EcoCAR Mobility Challenge, the Hybrid Electric Vehicle Team (HEVT) at Virginia Tech has spent the past four years developing and integrating a hybrid electric powertrain, energy management strategy, and advanced driver assist systems into our Chevrolet Blazer, as shown in Figure 1.

Powertrain & Architecture Selection Each of the EcoCAR Mobility Challenge teams is provided with a 2019 Chevrolet Blazer RS donor vehicle equipped with a 3.6L V6 engine and tasked to downsize the engine and integrate an electric powertrain. When selecting a potential architecture, integration feasibility is an equal priority to technical potential as competition scoring favors functionality and reliability as highly as absolute performance. Competition rules also strongly encourage a P0 or P4 hybrid architecture, or a combination of the two.

At the end of Year 1, HEVT selected a P4 through-the-road parallel hybrid powertrain architecture for the Blazer, as shown in Figure 2. For the conventional powertrain, the team chose a GM 2.5L I4 engine for its high marginal efficiency and ease of integration, as it was an existing option on the Chevrolet Blazer. For the electric powertrain, HEVT selected a 90 kW 5.0 kWh (2.0 kWh usable) battery pack paired with an 80 kW, 250 Nm traction motor. This pairing offered significant capability that would offer more opportunity for EV-only operation, while still being feasible to integrate into our donor vehicle.

FIGURE 1 HEVT Blazer conducting drive quality testing at Motor Mile Dragway

FIGURE 2 Hybrid Blazer P4 through the road parallel powertrain layout



However, due to challenges arising from the COVID-19 pandemic, HEVT switched to a smaller 50 kW, 150 Nm traction motor. The decision was driven almost entirely by integration feasibility and component availability, with minimal consideration for performance. As such, the traction motor is a significant bottleneck for vehicle performance and the energy management strategy as the vehicle could not take advantage of the full power capability of the battery. A summary of the powertrain components is provided in Table 1.

Limitations Relative to Production Vehicles Due to the nature of the EcoCAR Mobility Challenge, there are inherent limitations to the prototype vehicles the teams develop relative to production hybrid electric vehicles (HEVs). Many limitations arise from the fact that the Chevrolet Blazer donor vehicle is designed by General Motors to be a conventional vehicle, without a hybrid variant. Additionally, teams are limited by competition organizers to a small selection of both conventional and electric powertrain components. This restricts the possible powertrain configurations and the ability to intelligently develop a hybrid powertrain by considering the system holistically like vehicle OEMs would be able to.

For example, the conventional powertrain options are limited to a set of three General Motors engine and transmission pairings. While most HEVs utilize an Atkinson cycle engine for their higher efficiency [1], all three engines

TABLE 1 Summary of HEVT Blazer P4 powertrain components

Component	Details	Peak Capability
Engine	2.5L NA I4	150 kW, 250 Nm
Transmission	9AT	
Traction Motor	PM	50 kW, 150 Nm
HV Battery	96s8p	90 kW, 5.4 kWh

operate using the more common Otto cycle. Additionally, all of the provided engine options are relatively large for a hybrid vehicle, eliminating the opportunity to seek greater engine efficiency by downsizing the engine [2]. Engine torque control is also limited to the axle level, meaning that engine crank torque control and transmission shifting behavior is not easily accessible. While axle torque control simplifies the controls interface significantly and adds robustness to the control strategy, nuanced engine crank torque and speed control is required to extract optimal fuel efficiency.

Since these engines are not designed for implementation in a hybrid vehicle, engine start-stop capability is limited to the stock capability of the Chevrolet Blazer. An engine autostop can only be performed when the vehicle is at a complete stop and an autostart automatically occurs when the driver begins to release the brake pedal. Due to limitations in the engine controller, a flying start where the engine is started at a non-zero vehicle speed was not possible. Similarly, decel fuel cutoff (DFCO) where the engine is unfueled during deceleration events was also extremely limited. As such, true EV-only operation is not possible as the engine is almost always fueled when the vehicle is on.

The braking system on the Chevrolet Blazer also limits the potential for regenerative braking, as the brake pedal is tied hydraulically to the brakes themselves. As such, the EMS does not have the capability to determine how much of the driver demanded braking torque would be fulfilled by regenerative braking as any brake pedal travel will engage the friction brakes. This is essentially wasting energy to heat that could otherwise be recaptured as battery energy.

While the P4 hybrid architecture allows for relative ease of hybridization, it does limit the flexibility of the EMS relative to the more common P2 or power split configurations [3]. Since the electric motor is on a separate axle than the engine, the vehicle must be in motion for the battery to be charged, which eliminates the possibility for idle charging [4]. Additionally, the motor is unable to leverage the multi-speed transmission commonly found on P2 hybrids or the eCVT on power split hybrids for improved operating capability.

Finally, the student-developed nature of this prototype HEV results in the vehicle weighing significantly more than a similarly configured production vehicle. While this is unsurprising, it does make it more challenging for the vehicle to achieve fuel efficiency improvements as additional power is now required to accelerate the vehicle. Anecdotally, this is a significant reason why most EcoCAR student vehicles do not see fuel efficiency improvements over the stock donor vehicle, even with a downsized powertrain.

Competition Events & Milestones Success in the Energy Consumption and Drive Quality competition events at the end of Year 4 is a critical requirements for the EMS. The objective of the Energy Consumption event is to evaluate the charge-corrected fuel consumption of all the team vehicles relative to each other. The event is split into two sections with a human driver running a competition-developed trapezoidal drive cycle in one section and the adaptive cruise control (ACC) system following a human-driven lead vehicle driving the UDDS and HWFET drive cycle in the other section. The Drive Quality event evaluates the ability for team vehicles to achieve acceleration and transient acceleration response targets in addition to broader drive quality characteristics assessed by industry-standard software.

The Vehicle Development Process (VDP) goals set forth by the competition organizers also guide the development of the EMS. Most relevant are the mileage targets throughout the year and the end-of-year mileage accumulation goal of 1,200 mi. These targets reinforced the need for reliable powertrain operation before moving onto to the refinement necessary for competitive performance at the events mentioned above.

Vehicle Model

A vehicle model is created in Simulink to aid in the development, testing, refinement, and calibration of the EMS. Simulating the control strategy in a MIL environment allows for rapid improvements to the EMS by allowing a wide variety of scenarios to be tested from any computer in faster than real time. Eliminating the need for the physical vehicle and a testing location also greatly expands the opportunities and scenarios available for testing.

Glider Model

A lumped-mass longitudinal glider model is used to characterize the vehicle physics and model dynamic behavior. A simple force balance yields Equation 1 where F_{tr} is the tractive force at the wheels, $F_{interia}$ is the inertial force required to accelerate the vehicle, F_{aero} is the aerodynamic drag, F_{rr} is the rolling resistance of the tires, and F_{grade} is the gravitational force vector acting parallel to the direction of motion.

$$F_{tr} = F_{inertia} + F_{aero} + F_{rr} + F_{grade} \quad (1)$$

The aerodynamic drag and rolling resistance terms are also commonly referred to as road load and are often represented by coefficients that can be obtained by coast-down testing. Equation 2 shows the road load equation with the addition of mass-adjusted terms to account for increased mass from hybridization. The mass correction factor is only applied to the A and B terms as the C term represents aerodynamic drag which is not a function of vehicle mass.

$$F_{rl} = F_{aero} + F_{rr} = \left(A + Bv\right)\cdot\frac{ETW_{target}}{ETW_{ref}} + Cv^2 \quad (2)$$

FIGURE 3 Glider model force balance free body diagram

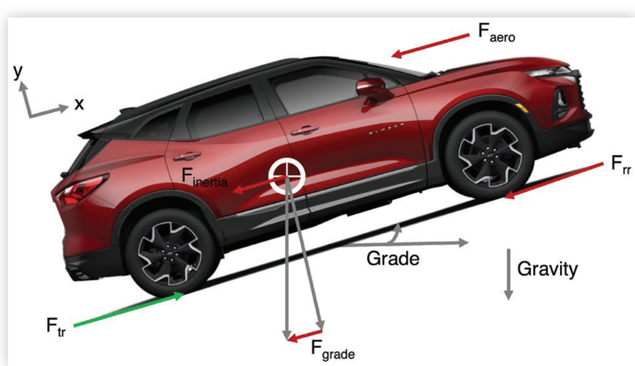
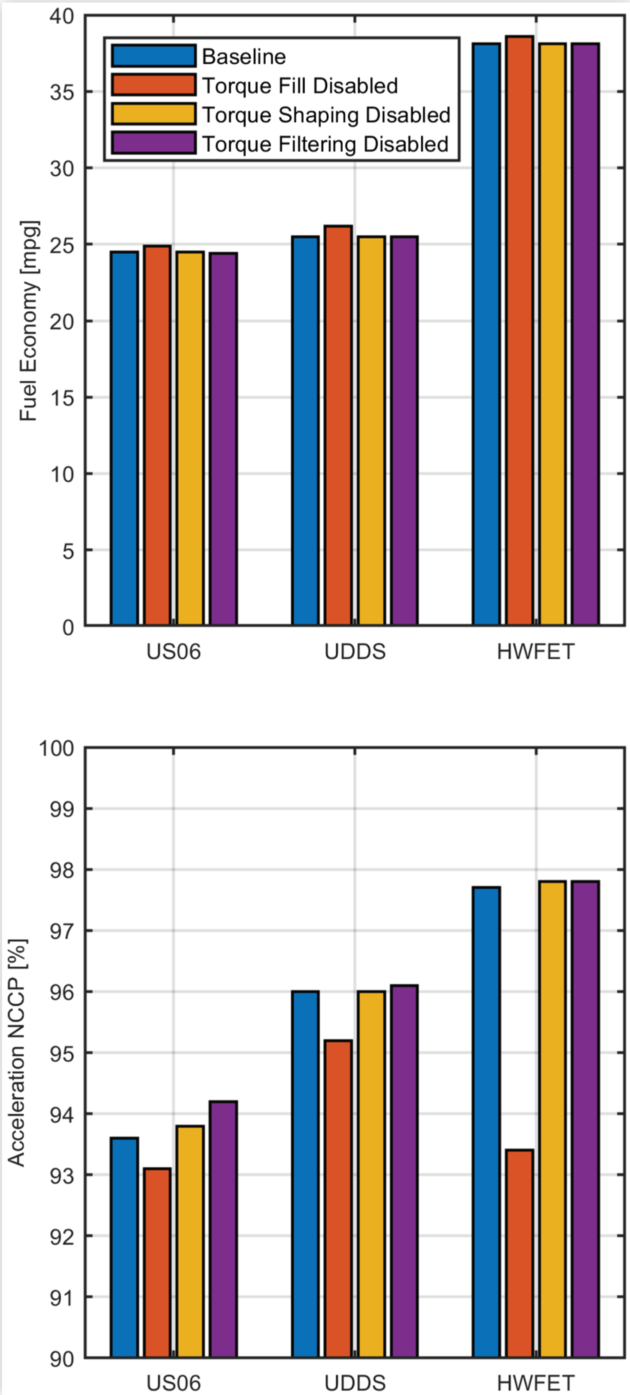


FIGURE 36 Sensitivity of fuel economy and acceleration NCCP to DQ features



acceleration correlation due to significant Engine Loading operation, which relies heavily on the torque fill strategy as shown in Figure 22.

The torque shaping and torque filtering features show no impact on fuel economy or acceleration correlation. This is expected as those features are primarily focused on motor lash control which is not included in the motor physics model. However, since both features are designed to leverage the fast response of motor torque for very short periods of time, effects on fuel economy can be expected to be completely negligible. Additionally, real-world driver feedback has also shown that these features are critical for consumer acceptability.

Conclusions

HEVT developed a prototype Chevrolet Blazer with a hybrid powertrain to compete in the EcoCAR Mobility Challenge. An energy management strategy is developed to meet the competition goals of reduced energy consumption while maintaining drive quality. Mileage accumulation goals and end-of-year energy consumption and drive quality competition events drove vehicle development and strategy requirements.

To validate control strategy developments in a simulation environment, a comprehensive hybrid powertrain and vehicle model are developed. This includes a glider physics model with mass-adjusted road-load coefficients and comprehensive powertrain physics models based on manufacturer-supplied proprietary data. The vehicle model is later validated and shown to have a high correlation of 88% for fuel consumption, which is the most critical signal for an energy consumption focused model.

Leveraging the vehicle model, a rule-based energy management strategy is developed using insights from a Willans line model of the conventional powertrain. Torque split operating modes are developed to maximize high-efficiency engine operation while minimizing round-trip losses. Four parameters for battery state of charge management are included in the torque split strategy and calibrated with a combination of simulation results and in-vehicle testing. A novel method of parameter calibration is introduced for simple yet effective parameter tuning for rapid iteration during testing sessions.

Several drive quality features are also developed to smoothly blend torque from both the conventional and electric powertrains while ensuring that driver demand is met. These strategies allow the hybrid powertrain to consistently meet acceleration response targets in real-world vehicle testing while smoothly delivering power. Vehicle deceleration is tuned to maximize energy recapture without compromising consumer acceptability. Noise, vibration, harshness are also minimized through motor lash control and mode transition hysteresis.

Simulation testing shows that the energy management strategy improved fuel economy in most drive cycles with improvements of 8.8% for US06, 9.8% for HWFET, and 0.1% for the EcoCAR Mobility Challenge Cycle. The charge sustaining strategy is proven to be robust across a wide variety of driving scenarios using both simulated and human driver inputs. Simulation testing also validates that the implemented drive quality features do improve how smoothly the vehicle could follow a drive cycle and that they are worth the minimal reduction in fuel efficiency.

At the EcoCAR Mobility Challenge Year 4 Competition, the energy management strategy achieved a second-place finish in the Energy Consumption event and contributed towards a fourth-place overall finish and a second place in dynamic testing events. Competition organizers, General

Motors test drivers, and event judges were all impressed with the robustness and performance of the energy management strategy and how smoothly the hybrid powertrain delivered torque and transitioned between operating modes. The prototype hybrid powertrain also accumulated over 3,500 miles without a single breakdown, a truly remarkable feat that serves as a testament to the quality of the control strategy and vehicle powertrain. The energy management strategy succeeds in its objectives of reducing energy consumption and meeting drive quality targets while proving to be exceptionally robust and providing an excellent driving experience.

References

1. Chandra M., Dan P.K., Bhattacharjee D., Mandol S., et al., "Devising Product Design Architecture Strategies: Case of HEV Powertrain," in *Smart Innovation*, Systems and Technologies, 134, 229-239, 2019.
2. Cardoso, D.S., Fael, P.O., and Espírito-Santo, A., "A Review of Micro and Mild Hybrid Systems," *Energy Reports* 6, no. 2 (2020): 385-390.
3. Wu, J., Ruan, J., Zhang, N., and Walker, P.D., "An Optimized Real-Time Energy Management Strategy for the Power-Split Hybrid Electric Vehicles," *IEEE Transactions on Control Systems Technology* 27, no. 5 (2019): 1194-1202.
4. Won, H.W., "Development of a Hybrid Electric Vehicle Simulation Tool with a Rule-Based Topology," *Applied Sciences* 11, no. 11 (2021): 11319.
5. Meng, Y., Jennings, M., Tsou, P., Brigham, D. et al., "Test Correlation Framework for Hybrid Electric Vehicle System Model," *SAE International Journal of Engines* 4, no. 4 (2011): 2011-2001.
6. Jeoung, H., Lee, K., and Kim, N., "Methodology for Finding Maximum Performance and Improvement Possibility of Rule-Based Control for Parallel Type-2 Hybrid Electric Vehicles," *Energies* 12, no. 5 (2019): 1924.
7. Xu, N., Kong, Y., Chu, L., Ju, H. et al., "Towards a Smarter Energy Management System for Hybrid Vehicles: A Comprehensive Review of Control Strategies," *Applied Sciences* 9, no. 5 (2019): 2026.
8. Zhu, D., Pritchard, E., Dadam, S., Kumar, V. et al., "Optimization of Rule-Based Energy Management Strategies for Hybrid Vehicles Using Dynamic Programming," *Combustion Engines* 184, no. 1 (2021).
9. Li, X. and Evangelou, S.A., "Torque-Leveling Threshold-Changing Rule-Based Control for Parallel Hybrid Electric Vehicles," *IEEE Transactions on Vehicular Technology* 68, no. 7 (2019): 6509-6523.
10. Shabbir, W. and Evangelou, S.A., "Threshold-Changing Control Strategy for Series Hybrid Electric Vehicles," *Applied Energy* 235, no. 2 (2019): 761-775.
11. Legg, T. and Nelson, D., "Development of a Willans Line Rule-Based Hybrid Energy Management Strategy," SAE Technical Paper 2022-01-0735, 2022, https://doi.org/10.4271/2022-01-0735.
12. Pachernegg, S.J., "A Closer Look at the Willans-Line," SAE Technical Paper 690182, 1969, https://doi.org/10.4271/690182.
13. Theodossiades, S., Gnanakumarr, M., Rahnejat, H., and Kelly, P., "Effect of a Dual-Mass Flywheel on the Impact-Induced Noise in Vehicular Powertrain Systems," *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering* 220, no. 6 (2006): 747-761.

Contact Information

Justin Wu
justinwu@vt.edu

Dr. Doug Nelson
nelsondj@vt.edu

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