Development and Testing of a Hybrid Vehicle Energy Management Strategy

Justin Quach Wu

Thesis submitted to the Faculty of the
Virginia Polytechnic Institute and State University
in partial fulfillment of the requirements for the degree of

Master of Science
in
Mechanical Engineering

Douglas J. Nelson, Chair
Steve C. Southward
Scott T. Huxtable

August 12, 2022
Blacksburg, Virginia

Keywords: hybrid vehicle, energy management, rule-based, vehicle testing, EcoCAR

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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.
A control strategy for a hybrid vehicle is developed to improve fuel efficiency without sacrificing vehicle responsiveness. Efficiency improvements are achieved by the strategy intelligently selecting to use the engine, motor, or a combination of the two to minimize fuel consumption. The strategy also handles the important tasks of maintaining the battery pack charge and smoothly transitioning between the engine and motor power. All together, this results in a hybrid vehicle with both improved fuel economy and an enjoyable driving experience.
Acknowledgments

I would like to thank all the team members of the Hybrid Electric Vehicle Team that I had the honor of working with. As my mentors, teammates, and students, their contributions to the team were critical to our success in the final year of the EcoCAR Mobility Challenge. I am also grateful for the guidance and technical expertise of the competition organizers and sponsors at General Motors, Mathworks, Ford Motor Company, and Argonne National Labs.

I would also like to thank Candy Li for her steadfast support as a teammate, fellow graduate student, and as a friend. I am grateful for all that you have done for me and I am glad that we have made it through together.

Finally, I would like give a special thank you to Dr. Nelson, who has been a great faculty advisor, mentor, and teacher that has shaped me into the engineer that I am today. Your wisdom and experience have been an invaluable to the team and the competition as a whole. I am honored to have been your student and I know you will be sorely missed in retirement.

This work was partially funded by support from the U.S. Department of Energy EcoCAR Mobility Challenge.
Contents

List of Figures ix

List of Tables xiii

1 Introduction 1

2 EcoCAR Mobility Challenge 3

2.1 Vehicle Development Process 3

2.2 Powertrain & Architecture Selection 4

2.3 Limitations Relative to Production Vehicles 7

2.4 Competition Events & Milestones 9

3 Energy Management Strategies 10

3.1 Thermostat Control Strategy 11

3.2 Exclusive Operating Strategy 11

3.3 Power Follower Control Strategy 12

3.4 Torque-leveling Threshold-changing Strategy 12

3.5 Optimal Primary Source Strategy 13

3.6 Blazer Energy Management Strategy 13
4 Vehicle Model

4.1 Glider Model ................................................................. 15

4.2 Conventional Driveline Model ........................................ 17

4.3 Electric Driveline Model .................................................. 18

4.4 Model Correlation .......................................................... 19

4.5 Simulink Model .............................................................. 24

5 Energy Consumption ......................................................... 25

5.1 Willans Line Estimation ................................................... 25

5.2 Rule Definitions ............................................................. 27

5.2.1 Motor Only ............................................................... 29

5.2.2 Engine Only ............................................................. 29

5.2.3 Engine Loading .......................................................... 30

5.2.4 Motor Assist ............................................................. 30

5.2.5 Engine Assist ............................................................ 31

5.2.6 Regenerative Braking .................................................. 31

5.3 Torque Split Strategy ....................................................... 31

5.4 Battery SOC Management ............................................... 33

5.4.1 Engine Only Power .................................................... 34

5.4.2 Engine Loading Power ................................................ 34
5.4.3 Engine Loading Speed ........................................ 38
5.4.4 Motor Torque Limits ........................................ 38
5.4.5 In-Vehicle Calibration ....................................... 39
5.5 Engine Dominant Strategy ................................... 40

6 Drive Quality .................................................... 44
6.1 Torque Request Determination ................................. 44
6.2 Engine Torque Fill ............................................. 46
6.3 Torque Request Filtering ...................................... 48
6.4 Motor Torque Shaping ......................................... 51
6.5 Deceleration Strategy ........................................... 52
6.6 Mode Transition Hysteresis .................................. 54
6.7 In-Vehicle Calibration .......................................... 56

7 Simulation Results ................................................ 57
7.1 Energy Management Strategy Comparison ................. 57
7.2 Drive Cycle Simulation ......................................... 59
7.2.1 US06 Combined Cycle ..................................... 60
7.2.2 UDDS Cycle .................................................. 62
7.2.3 HWFET Cycle ................................................ 64
7.2.4 EcoCAR Mobility Challenge (EMC) Cycle .............. 66
List of Figures

2.1 HEVT Blazer conducting drive quality testing at Motor Mile Dragway ........ 5
2.2 Hybrid Blazer P4 through the road parallel powertrain layout ............... 6
4.1 Glider model force balance free body diagram .......................... 16
4.2 Simplified diagram of conventional driveline model ....................... 19
4.3 Simplified diagram of electric driveline model ............................ 20
4.4 Model correlation of in-vehicle data collected during energy consumption testing 22
4.5 Differences in simulation model results and vehicle test data .............. 23
4.6 Vehicle model and control code shown in top level of Simulink model .... 24
5.1 Willans lines for engine, transmission, and the combined conventional powertrain .................................................. 27
5.2 Torque split operating regions with torque and power limits .............. 28
5.3 Torque split operating regions at SOC = 35% .............................. 35
5.4 Torque split operating regions at SOC = 65% .............................. 36
5.5 Engine only power limit vs battery SOC .................................... 37
5.6 Engine loading power limit vs battery SOC .................................. 37
5.7 Engine loading speed limit vs battery SOC .................................. 38
5.8 Motor torque limit vs battery SOC ........................................... 39
7.10 Battery SOC over various drive cycles with initial SOC at 30%, 50%, and 70% 69

7.11 Sensitivity of fuel economy and acceleration correlation to drive quality features 71

A.1 Torque split operating regions at SOC = 25% 79

A.2 Torque split operating regions at SOC = 30% 80

A.3 Torque split operating regions at SOC = 35% 81

A.4 Torque split operating regions at SOC = 40% 82

A.5 Torque split operating regions at SOC = 45% 83

A.6 Torque split operating regions at SOC = 50% 84

A.7 Torque split operating regions at SOC = 55% 85

A.8 Torque split operating regions at SOC = 65% 86

A.9 Torque split operating regions at SOC = 70% 87

A.10 Torque split operating regions at SOC = 75% 88

B.1 US06 cycle engine operating points 89

B.2 UDDS cycle engine operating points 90

B.3 HWFET cycle engine operating points 90

B.4 EMC cycle engine operating points 91

C.1 US06 cycle motor operating points 92

C.2 UDDS cycle motor operating points 93

C.3 HWFET cycle motor operating points 93
List of Tables

2.1 Summary of HEVT Blazer P4 powertrain components ................................... 6

5.1 Definition of regions for torque split operating regions ............................... 32

6.1 Transition hysteresis times for torque split operating mode transitions .......... 55

7.1 Comparison of simulated fuel economy for stock and hybrid Blazer ............. 58

7.2 Sensitivity of fuel economy and acceleration correlation to drive quality features 70
Chapter 1

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.
Chapter 2

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.

2.1 Vehicle Development Process

Year 1 of the EcoCAR Mobility Challenge focused on developing a set of vehicle technical specifications as well as selecting propulsion system components and architectures based on Model-in-Loop (MIL) simulation results. In Year 2, the team began integrating the hybrid powertrain proposed in Year 1 of the competition. Activities included benchmarking the stock Chevrolet Blazer as well as the integration of the powertrain components and vehicle controllers. Year 3 focused on the development of a functional energy management strategy
(EMS) and advanced driver assistance system (ADAS). However, the COVID-19 pandemic posed significant challenges including restricted garage access, limited testing availability and reduced manpower. Similar challenges in industry left the team without the ability to properly interface with either the high-voltage (HV) battery or traction motor at the end of Year 3.

The goal for the fourth and final year of the EcoCAR Mobility Challenge is to refine the EMS and ADAS to near-production quality. However, in the beginning of Year 4, the team learned that the existing traction motor integrated into the Blazer was no longer feasible due to a withdrawal of support from the manufacturer. The team was fortunate and able to quickly secure the donation of a new motor drive system, but this change still dictated a significant redesign of the powertrain integration and EMS.

HEVT pushed hard to redesign the vehicle component packaging to support the new motor, inverter, and required HV electrical routing. Tremendous work was done to overhaul the EMS and develop new motor interfacing algorithms. In the remaining three months before competition, HEVT also conducted hybrid powertrain testing to refine the reliability, efficiency, and drive quality of the vehicle, as shown in Figure 2.1. The team also met and exceeded competition mileage accumulation targets, accruing miles over 6x faster than competition guidelines. The hard work and dedication were rewarded with a fourth-place overall finish as well as second place finishes in both the Energy Consumption event and overall dynamic testing events.

2.2 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
2.2. Powertrain & Architecture Selection

Figure 2.1: HEVT Blazer conducting drive quality testing at Motor Mile Dragway

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 2.2. 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.

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 2.1.

Table 2.1: Summary of HEVT Blazer P4 powertrain components

<table>
<thead>
<tr>
<th>Component</th>
<th>Details</th>
<th>Peak Capability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engine</td>
<td>2.5L NA I4</td>
<td>150 kW, 250 Nm</td>
</tr>
<tr>
<td>Transmission</td>
<td>9AT</td>
<td></td>
</tr>
<tr>
<td>Traction Motor</td>
<td>PM</td>
<td>50 kW, 150 Nm</td>
</tr>
<tr>
<td>HV Battery</td>
<td>96s8p</td>
<td>90 kW, 5 kWh</td>
</tr>
</tbody>
</table>
2.3 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 [2], all three engines 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 [1]. 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 [11]. 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 [10]. 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.
2.4 Competition Events & Milestones

Success in the Energy Consumption and Drive Quality competition events at the end of Year 4 is a critical requirement 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 the refinement necessary for competitive performance at the events mentioned above.
Chapter 3

Energy Management Strategies

The EMS is critical to the success of a HEV, with fuel economies for HEVs varying significantly due to the performance of the EMS [3]. The objective of an EMS is to coordinate the hybrid powertrain to reduce fuel consumption and balance battery SOC. It may be intuitive to simply chase the highest component efficiencies but that often results unnecessary increases in energy consumption as well. Instead, the key objective is to distribute driver demand such that the engine can operating in a high-efficiency zone as much as possible [12].

There are several strategies that have been discussed in literature, with most being categorized broadly into rule-based or optimization based strategies [12]. While rule-based strategies cannot obtain globally optimal solutions, they are effective and robust while being easily implementable in real-time [5]. As such, real-world hybrid vehicles, like the one discussed in this paper, use heuristic rule-based controls to perform the split between conventional and electric powertrains [3]. These strategies are based on several predetermined thresholds to encourage high efficiency component operation while considering battery SOC management. Threshold selection is generally based on engineering experience and the efficiency characteristics of the powertrain, and require considerable time for refinement and validation. Mode switching is done to minimize fuel consumption while still meeting driver demand and keeping the battery within a reasonable range during the drive cycle [12].

Rule-based EMS in literature vary widely in implementation, and some notable strategies include the Thermostat Control Strategy (TCS), Power Follower Control Strategy (PFCS),
Exclusive Operating Strategy (XOS), Torque-leveling Threshold-changing Strategy (TTS) and Optimal Primary Source Strategy (OPSS) [8, 10].

3.1 Thermostat Control Strategy

TCS is one of the most common strategies, known for simplicity and robustness. The principle of the strategy is operating the engine at a constant high efficiency power such that fuel efficiency is maximized. The electric motor is used to fill in the difference to driver demand, whether that requires positive or negative power. This continues until an upper SOC limit is reached, which is when operation switches to motor only until a lower SOC limit is reached. The strategy then switches back to engine operation at its optimal power, and repeats the cycle [8]. While the simplistic nature of this strategy would be greatly beneficial for a student-developed prototype HEV, the relatively small electric motor in the powertrain limits the capability for the engine to operate at a single power level. However, as discussed in 5.3, a larger power range of high efficiency power can still yield fuel economy improvements while providing the flexibility required by the limited capability of the motor.

3.2 Exclusive Operating Strategy

XOS is a strategy in which the hybrid powertrain operates solely in motor only or engine only mode unless the driver demand exceeds the capability of the engine. To maintain battery SOC within an acceptable window, the power threshold between motor only and engine only operation is adjusted as a function of SOC [8]. The strategy relies heavily on regenerative braking for battery SOC management as the battery is never charged during engine on operation. Additionally, there is no consideration for engine efficiency at high power, which
is addressed in 5.2.4. This strategy is ill suited for implementation in the Blazer due to the limited regenerative braking and the low efficiency of the Blazer engine at high loads.

### 3.3 Power Follower Control Strategy

PFCS is strategy popular in series HEVs in which the engine generally follows the driver demand. However, for low power operation, the electric motor is used to avoid operating the engine at low efficiencies. Above this power threshold, the engine is the primary source of power with the motor only used to maintain an acceptable battery SOC window [8]. This is done so that battery energy expended during motor only operation can be recaptured, or so that battery energy stored during regenerative braking can be used up. This strategy has many similarities to the one implemented in the Blazer, but it lacks the well-defined boundaries for motor assist or generation during engine on operation. Controlling battery charging or depletion as just a function of $\Delta$SOC from the target SOC could result in significant round-trip losses, which are especially relevant for a through-the-road parallel hybrid.

### 3.4 Torque-leveling Threshold-changing Strategy

TTS is based on the idea that engine efficiency varies primarily with engine crank torque, so engine torque is held constant regardless of engine speed [5]. This strategy is similar to TCS, but the engine produces constant crank torque as opposed to constant power. However, low power operation is still handled entirely by the motor and the motor is still used to meet driver demand if it differs from the engine operating point during engine on operation. Unfortunately, the lack of direct engine crank torque control eliminates this strategy for
3.5 Optimal Primary Source Strategy

OPSS combines several elements from TCS, PFCS, and TTS in the attempt to create a novel and improved EMS. At low load, OPSS uses the motor exclusively to meet driver demand like in PFCS. However, during engine on operation, the engine operates at a constant power selected for high component efficiency like in TCS. During engine on operation, the motor is still used to supplement the difference to driver demand like in TCS and TTS. This resulting operation is similar to that of an optimal equivalent consumption minimization strategy [8], while maintaining the relative simplicity and robustness of rule-based control. Of the strategies discussed here, this strategy is the most similar to the one implemented in the Blazer. The primary difference is that a Willans line model shows that efficient engine operation can be achieved over a power range as opposed to a specific engine power as implemented in OPSS. This expands the engine on operating strategy into the engine only, engine loading, and motor assist regions discussed in 5.2.2 - 5.2.4. This larger region of engine only operation also helps avoid the frequent switching on/off of the engine during higher demand drivecycles, which would cause real-world fuel economy to suffer in addition to significant noise, vibration, and harshness (NVH).

3.6 Blazer Energy Management Strategy

The Blazer EMS is developed from a Willans line modeling approach built upon research detailed in [4] and performed by a former HEVT graduate lead. A power region of high
engine efficiency is identified and motor operation is used to maximize engine operation in this efficient region while ensuring charge sustaining behavior. This has many similarities to the parallel hybrid operating modes discussed in [10], primarily in the characteristics of the operating modes. However, this strategy is based on engine efficiency regions as a function of engine crank torque and speed, and thus impossible to implement in the Blazer given limitations in engine torque control. Additionally, transmission shifting causing changes in operating mode would be detrimental, especially for a vehicle with close-ratio transmission gearing. Using a Willans line based approach simplifies the strategy and results in good robustness and reliability with minimal expense to absolute efficiency, making it the best EMS for implementation into the prototype hybrid Blazer.
Chapter 4

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.

4.1 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 4.1 where $F_{tr}$ is the tractive force at the wheels, $F_{inertia}$ 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.

$$F_{tr} = F_{inertia} + F_{aero} + F_{rr} + F_{grade}$$  \hspace{1cm} (4.1)

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 4.2 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.

$$F_{rt} = F_{aero} + F_{rr} = (A + Bv) \cdot \frac{ETW_{\text{target}}}{ETW_{\text{ref}}} + Cv^2 \quad (4.2)$$

The $F_{\text{inertia}}$ term is defined by Equation 4.3 with the 4% inertial mass factor (IMF) used to account for the rotating inertia of wheels and tires. This is increased slightly from the 3% defined by the SAE J2263 standard to account for modern vehicles with larger wheels, like the 21” wheels on the Chevrolet Blazer.

$$F_{\text{inertia}} = 1.04 \cdot ma \quad (4.3)$$
Combining Equations 4.1, 4.2, 4.3 and substituting \( F_{\text{grade}} = mg \sin(\theta) \) yields Equation 4.4, which forms the foundation on which the vehicle model is built.

\[
F_{tr} = 1.04 \cdot ma + (A + Bv) \cdot \frac{ETW_{\text{target}}}{ETW_{\text{ref}}} + C \nu^2 + mg \sin(\theta) \quad (4.4)
\]

To prevent undesirable and unrealistic behavior of resistive or braking forces causing negative acceleration at zero speed, the sum of all forces is restricted to non-negative values at zero speed.

### 4.2 Conventional Driveline Model

The objective of the conventional driveline model is to model the fuel burned by the engine given an engine axle torque request. As shown in Figure 4.2, the model needs to accurately calculate the torque losses through the final drive, transmission, torque converter, alternator, and engine to calculate an accurate engine crank torque request and fuel flow rate as the engine control module (ECM) would. The fidelity of this model is critical to the accuracy of energy consumption and vehicle dynamic response simulation results. Fortunately, GM provided proprietary documentation and technical specifications that allowed for a much higher fidelity model than would otherwise be possible.

At the core of the engine physics model is a Mapped Spark Ignition engine block which uses dynamometer data provided by GM and Mathworks to calculate crank torque achieved, fuel flow rate, exhaust gas temperature, and emissions given a crank torque request and engine speed. The provided dynamometer data is obtained by smoothing experimentally measured fuel flow rates at steady state engine torques and speeds. A low fidelity model of the accessory load on the alternator is also developed, with electrical loads estimated at 1600
W due to the multitude of team-integrated controllers that have been retrofitted. Using the sum of engine crank torque request and alternator load, the engine model can calculate fuel flow rate accurately throughout the operating range of the engine. While real-world results will diverge for transient engine operation and cold starts, these situations are minimally relevant for typical energy consumption testing.

The torque converter model calculates engine speed and the torque multiplication ratio of the torque converter using proprietary data for torque ratio, K-factor, and torque converter clutch control provided by GM. The transmission model calculates transmission gear, gear ratio and losses using shift map and efficiency data provided by GM. The total transmission torque multiplication, and torque loss data is used by the ECM model to calculate an appropriate engine crank torque request to achieve an engine axle torque request. DFCO behavior is also modeled using technical documentation provided by GM to better predict fuel burn. However, the engine start-stop logic is too complex to model with any reasonable level of fidelity. As such, it is left out with the intention that the model would be more conservative with fuel flow estimates.

4.3 Electric Driveline Model

Similar to the conventional driveline model, the goal of the electric driveline model is to accurately model power draw from the HV battery and track its state of charge (SOC). As the EMS is dependent on battery SOC, robust electric driveline modeling is also important for accurate simulation of the torque split strategy.

As shown in Figure 4.3, the electric driveline model is comparatively simple and made up of just a battery, motor, and inverter model. The battery model uses battery cell capacity, open circuit voltage, and internal resistance data provided from the battery manufacturer to
4.4 Model Correlation

To benchmark the accuracy of the vehicle model, specifically for fuel consumption results, simulation data is compared with vehicle data recorded during the Energy Consumption competition event. Data from this event is well-suited for model correlation as the event calculate pack voltage and SOC. The battery model also includes battery current limits that are a function of temperature and SOC. The motor model uses maximum torque and power loss information provided by the motor manufacturer to calculate motor torque achieved and current draw. Current protection limits and torque slew rate limits are also included in inverter model.
operation procedures are developed from industry best-practices for fuel economy testing. Additionally, the vehicle was driven by well-trained GM test drivers on the test track they use to conduct energy consumption testing themselves.

To eliminate the influence of the simulated driver model, accelerator pedal position (APP) and brake pedal position (BPP) inputs recorded from the vehicle testing event are fed directly into the vehicle model. This differs from the common approach of having a simulated driver follow either the same drive cycle or the actual achieved speeds of the test vehicle. As the only inputs into the EMS are APP, vehicle speed, and battery SOC, feeding the recorded APP signal directly into the vehicle model eliminates any divergence in behavior due to the driver model. Additionally, the initial battery SOC for the simulation is also updated to match the vehicle testing data.
4.4. Model Correlation

To measure the similarity between simulation model outputs and vehicle test data, a normalized cross-correlation power (NCCP) from [6] is used, as defined in Equation 4.5.

\[
\text{NCCP} = \frac{\max[R_{xy}(t)]}{\max[R_{xx}(t), R_{yy}(t)]}
\]  

(4.5)

As shown in Figure 4.4, the NCCP between the simulated and actual vehicle speed is very high, at 95.3%. This supports the conclusion that the glider physics and axle torque determinations in the powertrain physics models are accurate. Some of the divergences in vehicle speed can be attributed to the slight non-zero grade on some parts of the test track, while the vehicle model assumes zero grade. Grade data was recorded from vehicle sensors during the testing event, but the data is noisy and influenced by vehicle pitch and dive during acceleration. Initial attempts to filter the data using moving averages and compensate during vehicle acceleration proved unsuccessful.

Fuel flow rate also has high correlation at 87.5%, indicating that the engine crank torque request and torque loss calculations are of sufficient fidelity. Some of the divergence here is likely due to incorrectly modeled DFCO behavior and the divergence of vehicle speed also influences the transmission shift schedule and engine speed. However, Figure 4.5 shows lower average fuel flow rate in the simulation model along with higher average vehicle speed. This may indicate that there are additional losses in the driveline that are not accounted for in the model.

HV battery current had a much lower correlation at 52.8%, likely as a result from differences in engine torque responsiveness. As discussed in 6.2, the torque split strategy relies heavily on the motor to fill torque holes caused by changes in operating mode or from driver demand. As such, HV current draw is very sensitive to a multitude of factors including engine torque response, transmission shifting, and vehicle speed. However, the near-zero average difference
Figure 4.4: Model correlation of in-vehicle data collected during energy consumption testing
Figure 4.5: Differences in simulation model results and vehicle test data
in HV current and the fleeting nature of the divergences has very minimal effect on charge-corrected fuel economy calculations.

Although the electric driveline could benefit from improvements in model fidelity, the vehicle model overall has sufficient fidelity to realistically model fuel economy results. Additionally, since the Energy Consumption event is relatively scored, absolute accuracy is not paramount if relative changes in fuel consumption due to refinements of the EMS are reflected in simulation results.

4.5 Simulink Model

The vehicle glider physics and powertrain models discussed above make up the Vehicle Model block shown in Figure 4.6. The Control Code block contains the EMS as well as algorithms for powertrain controller interfacing, ADAS features, driver HMI, power moding, and system safety. The interface between the Control Code and Vehicle Model is designed to match that of the actual vehicle so the Control Code block used in MIL simulation is the same one running in real-time on the on-board hybrid vehicle supervisory controller. The Calibration block houses all of the calibratable parameters and overrides and the Visualization block organizes signals for ease of access during MIL simulation.

Figure 4.6: Vehicle model and control code shown in top level of Simulink model
Chapter 5

Energy Consumption

Reducing energy consumption is one of the overarching goals for the EcoCAR Mobility Challenge and is greatly influenced by the hybrid powertrain EMS. To accomplish this, the EMS seeks to keep the conventional powertrain in a region of efficient operation and use the electric powertrain strategically to either provide additional torque, eliminate the need for engine power, or capture power in excess of driver demand.

5.1 Willans Line Estimation

To form a simplified model of powertrain efficiency suitable for robust control strategy development, the Willans Line estimation method is used to characterize the conventional powertrain. Willans line models follow the relationship in Equation 5.1 where \( \eta \) is the marginal efficiency and \( b_w \) is the offset or constant loss [7].

\[
P_{in} = \frac{1}{\eta} P_{out} + b_w \tag{5.1}
\]

Using the GM provided engine data for engine power output between 0 and 60 kW, the linear Willans line estimation shown in Equation 5.2 is fit with an \( R^2 \) of 0.976 [4]. While the data begins to diverges from the model for engine power outputs in excess of 60 kW, the roughly linear nature of the data remains. The model suggests that when output power is near zero
at idle, the power into the engine in the form of fuel is approximately 8.95 kW. Additionally, for every 1 kW of additional fuel flow, the engine will produce an additional 0.372 kW of power at the crank.

\[
P_{\text{in,eng}} = \frac{1}{0.372} P_{\text{out,eng}} + 8.95
\]  

(5.2)

The same Willans line model is applied to transmission data provided by GM and the Willans line estimation yields Equation 5.3. Idle losses are estimated to be approximately 620 W with a marginal efficiency of about 90% [4].

\[
P_{\text{in,trans}} = \frac{1}{0.901} P_{\text{out,trans}} + 0.65
\]  

(5.3)

Combining these equations to form a comprehensive Willans line model of the conventional powertrain yields Equation 5.4 [4]. While higher axle power output yields higher efficiencies, there are diminishing returns, as shown in Figure 5.1. Setting a lower efficiency target of 28% yields a minimum axle power limit of approximately 23 kW. This limit is well within the 50 kW power rating of the electric traction motor, which will allow EV-only operation below this minimum engine power limit to avoid operating the engine in a low efficiency region. While a higher minimum power limit may theoretically yield higher conventional powertrain efficiency, the limitations imposed by battery capacity and motor thermal limits would present challenges in real-world operation.

\[
P_{\text{fuel}} = \frac{1}{0.334} P_{\text{axle}} + 14.12;
\]  

(5.4)
5.2 Rule Definitions

With guidance from the Willans line model of the conventional powertrain, operating modes and regions for a torque split strategy can be defined. The objective of the torque split strategy is to most efficiently meet a driver demanded axle torque request at any given vehicle speed. Figure 5.2 shows the operating regions along with peak torque and power capabilities for the motor, engine, and total powertrain. While the motor maximum torque limit is well-defined, the engine maximum torque limit is dependent on various factors including torque converter clutch control, engine temperature and altitude. As such, the engine maximum torque limit is primarily for illustrative purposes and is not used in the control strategy.
Figure 5.2: Torque split operating regions with torque and power limits
5.2.1 Motor Only

The boundaries for the motor only mode are the lower power limit for Engine Only operation $P_{\text{eng,low}}$, the upper Motor Only speed $v_{\text{gen}}$, and 80% of the maximum torque capability of the motor $T_{\text{mot,max}}$. Operating in Motor Only mode below the Engine Only power limit avoids the inefficient operation of the engine by meeting driver demand entirely with motor power. Motor Only operation is also limited to below the motor only speed to allow for engine loading, as discussed below in 5.2.3. However, there are limits to the motor torque capability, so this region is also capped at 80% of the motor torque capability. The remaining 20% is left as torque margin to fill any torque holes that may arise during mode transition, as discussed in 6.2.

Unfortunately, due to limitations with the GM-provided engine controller, the engine is unable to be shut off or started while the vehicle is in motion. Similarly, DFCO is rarely possible if the driver is pressing on the accelerator pedal, even if engine torque is not requested. As such, this mode is not true EV-only operation in practice since the engine is always idling, which results in some loss in overall efficiency. A modified strategy developed in response to this limitation is presented in 5.5.

5.2.2 Engine Only

This region is defined by the Engine Only lower $P_{\text{eng,low}}$ and upper power limits $P_{\text{eng,up}}$, which are more restrictive than the actual engine power capability. At nominal battery SOC, the limits are derived from the Willans line model, but both are flexible to allow for battery SOC management, which will be discussed in 5.4. Additionally, the lower Engine Only power limit is eliminated at highway speeds to reduce operating mode transition during steady-state highway cruising. Since engine efficiency is high during highway driving, there
is minimal sacrifice to absolute efficiency.

### 5.2.3 Engine Loading

The objective of this region is to opportunistically charge the battery when driver demand is below the minimum Engine Loading power limit $P_{\text{eng,load}}$. In this operating mode, the engine axle torque request is set at the Engine Only power limit, which is above the driver demanded power. The motor is used as a generator to capture the excess power produced by the engine and ensure that the power produced at the wheels does not exceed driver demand. The lower and upper vehicle speed limits of $v_{\text{gen}}$ and $v_{\text{eng}}$ imposed on this operating mode are intended to encourage operation during city cruising. Since this operating mode requires relatively high engine torque, it is not ideal at lower vehicle speeds where the instantaneous torque of the motor affords the driver with more agility. Similarly, at highway cruising speeds, the diminishing efficiency returns are not worth the NVH experienced by the driver due to persistently high engine load.

### 5.2.4 Motor Assist

For driver power demands above the upper Engine Only power limit $P_{\text{eng,up}}$, the engine axle torque request will be held at the upper Engine Only power limit and the difference to driver demanded torque will be supplied by the motor. This is designed to slightly improve fuel economy by avoiding fuel enrichment with the additional benefit of improving powertrain responsiveness.
5.3. Torque Split Strategy

5.2.5 Engine Assist

This region is defined as either above the Motor Assist upper limit or below the lower Engine Only power limit $P_{eng,low}$ in addition to being above the Motor Only torque limit $T_{mot,max}$. Efficiency is not a consideration in this region as the motor torque capability is saturated and the engine is outside of its efficient operating region. Due to the reduced torque capability of the new motor, Engine Assist mode is often seen during launch to accelerate the vehicle from a stop.

5.2.6 Regenerative Braking

When the driver is not pressing on the accelerator pedal, the motor is used as a generator to recapture the kinetic energy of the vehicle. A low-speed cutoff between 5 and 10 mph blends out regenerative braking torque at low speeds where the motor is not efficient. The region is also limited to the maximum regenerative torque capability of the motor. Calibrating regenerative braking torque demands for consumer acceptability is also an important consideration in this region. As competition rules forbid modification to the hydraulic braking system, all regenerative braking torque commanded by the brake pedal must be in addition to the existing friction brake torque.

5.3 Torque Split Strategy

Using these operating modes, regions of powertrain operation for each of the torque split rule modes are defined in Table 5.1. While these region definitions are in terms of axle torque, the boundaries are more directly related to power due to the relationship between efficiency and power as defined by the Willans line model. As such, $T_{eng,low}$, $T_{eng,up}$ and $T_{eng,load}$ are
derived from $P_{\text{eng,low}}$, $P_{\text{eng,up}}$ and $P_{\text{eng,load}}$, respectively.

<table>
<thead>
<tr>
<th>Table 5.1: Definition of regions for torque split operating regions</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Motor Only</strong></td>
</tr>
<tr>
<td><strong>Engine Only</strong></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td><strong>Engine Loading</strong></td>
</tr>
<tr>
<td><strong>Motor Assist</strong></td>
</tr>
<tr>
<td><strong>Engine Assist</strong></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td><strong>Regen Braking</strong></td>
</tr>
</tbody>
</table>

Axle torque requests for the engine and motor in each operating mode are shown in Equations 5.5 and 5.6, respectively. While efficiency is the primary objective of the EMS, the torque split always seeks to meet driver demand. As such, the sum of $T_{\text{eng}}$ and $T_{\text{mot}}$ is always equal to the driver torque demand $T_{\text{axle}}$. To consistently meet driver demand during mode transitions, the motor is used to fill torque holes, or gaps between the driver demanded torque and the total axle achieved torque. The values for $T_{\text{mot}}$ shown in Equation 5.6 are for steady-state engine operation, but during transient events, the torque split has the authority to command motor torque to fulfill driver demand. This strategy is critical for drive quality and is discussed further in 6.2.
5.4 Battery SOC Management

Managing the SOC of the battery is another important role of the EMS. Given that the Blazer is a full hybrid without grid or idle charging capability, reliable charge sustaining behavior is crucial. Engine loading is the primary means by which the EMS will recharge the battery as regenerative braking cannot be depended on for long-term battery SOC management.

To maintain battery SOC in the safe window of 25% and 75%, the EMS will adjust the relative size of the operating regions as a function of SOC. This is accomplished by modifying the $P_{eng,low}$, $P_{eng,up}$, and $P_{eng,load}$ power limits as well as the Engine Loading speeds $v_{gen}$ and
As SOC decreases, the size of the Motor Only and Motor Assist region will shrink while the Engine Loading and Engine Only regions expand. This discourages the use of motor torque depleting the battery and encourages engine loading for battery charging. Figures 5.3 and 5.4 illustrate the differences in operating regions at either end of the SOC spectrum, with additional plots for the full 25% to 75% range shown in Appendix A. Discussion on the calibration of the battery SOC management parameters can be found in 5.4.5.

### 5.4.1 Engine Only Power

The engine only power limits $P_{\text{eng,low}}$ and $P_{\text{eng,up}}$ represent the boundaries between Engine Only operation and Motor Only below and Motor Assist above, as shown in Figure 5.3. As SOC decreases, $P_{\text{eng,low}}$ approaches zero while $P_{\text{eng,up}}$ approaches the approximate maximum power output of the engine, as shown in Figure 5.5. This greatly expands the Engine Only region and reduces the operating region where propulsive motor torque is requested. However, as SOC increases, both $P_{\text{eng,low}}$ and $P_{\text{eng,up}}$ approach values slightly offset from the motor peak power limit, as shown in Figure 5.4. This encourages motor propulsive torque at high SOC while still using the engine when it is most efficient to do so.

### 5.4.2 Engine Loading Power

Increasing the Engine Loading region is the most reliable way to recharge the battery. To accomplish this, $P_{\text{eng,load}}$ increases as SOC decreases to expand the Engine Loading region, as shown in 5.6. On the other end of the spectrum, $P_{\text{eng,load}}$ collapses to zero as SOC increases with the region replaced by Motor Only operation to avoid overcharging the battery pack. Since the Willans line model shows that increases in engine power output yield increases in efficiency, $P_{\text{eng,load}}$ could theoretically be increased even further for slight gains in effi-
5.4. Battery SOC Management

Figure 5.3: Torque split operating regions at SOC = 35%
Figure 5.4: Torque split operating regions at SOC = 65%
5.4. Battery SOC Management

Since the engine commanded power is always higher than driver demanded power in the Engine Loading mode, this should always be more efficient than engine only operation. However, NVH issues arise when setting $P_{eng,load}$ too high as sustained high power engine operation is noisy with exhaust drone that is unpleasant. Additionally, a sustained regenerative torque request will place significant thermal stress on the motor cooling system.
5.4.3 Engine Loading Speed

The size of the Engine Loading region can also be increased by expanding the speed range of \([v_{\text{gen}}, v_{\text{eng}}]\) in which the mode can operate. As shown in Figure 5.7, the lower Engine Only speed limit \(v_{\text{gen}}\) falls quickly as SOC decreases. Near the 30% minimum SOC, this expands the Engine Loading operating region to essentially all non-highway driving. As SOC increases to past 63%, the Engine Loading speed limits intersect which eliminates the Engine Loading mode to protect the battery from overcharging.

![Figure 5.7: Engine loading speed limit vs battery SOC](image)

5.4.4 Motor Torque Limits

To further protect the health of the battery while the EMS was in active development, lower-level motor torque limits are imposed to prevent the battery SOC from being pushed outside of the safe window. Shown in 5.8, the torque split is restricted from commanding propulsive motor torque below 25% SOC and from commanding regenerative torque above 80% SOC. Between the intended operating range of 35% to 70% SOC, the torque split has no limits on motor torque commands. This adds another layer of protection against unexpected EMS
behavior or miscalibration of battery SOC management parameters.

![Motor Torque Limit vs Battery SOC](image)

Figure 5.8: Motor torque limit vs battery SOC

### 5.4.5 In-Vehicle Calibration

To aid in the calibration of the battery SOC management parameters across the SOC range, all the calibratable parameters are designed to be calibrated with just two pairs of calibratable input/output values. Equation 5.7 is developed to take advantage of the “S”-shaped curve of the tanh function with \( u_1, y_1 \) and \( u_2, y_2 \) being the two calibratable pairs. Equation 5.8 simply ensure that \( y \) is limited to the range \([y_1 : y_2]\).

\[
\beta = (y_1 - y_2) \cdot \tanh \left( \frac{\arctanh(0.95) \cdot (u - u_2)}{u_1 - u_2} \right) + u_1 \quad (5.7)
\]

\[
y = \min(\max(\beta, \min(y_1, y_2)), \max(y_1, y_2)) \quad (5.8)
\]

The calibratable pairs define the desired output limits as a function of a control input. The function uses these calibratable values to transform the hyperbolic tangent functions to meet
the specified requirement. The $u_1, y_1$ pair are associated with the sharp corner, making them suitable for absolute component protection. The $u_2, y_2$ pair has a gentle curve which avoids rapid output limit changes as the control input approaches the derating region.

For example, in Figure 5.8, the propulsive motor torque limit uses the parameters $u_1 = 30, y_1 = 100$ and $u_2 = 25, y_1 = 0$. The rationale is that at 25% SOC, the motor must be limited to 0% of the motor propulsive torque capability to avoid further depleting the battery pack. As SOC rises towards 30%, the allowable propulsive motor torque approaches 100% with a gentle curve to avoid rapid changes unless the SOC is approaching the limit.

### 5.5 Engine Dominant Strategy

Due to the lack of engine start-stop control discussed in 2.3, the propulsive efficiency during Motor Only mode is greatly reduced. Equation 5.9 is used to holistically assess the cost of using the motor while the engine is still idling by calculating the round trip efficiency of fuel to propulsive motor power efficiency and the associated losses. $\eta_{\text{mot, propel}}$ is calculated using manufacturer-supplied motor loss data with a 14.12 kW constant engine idle loss from Equation 5.4. The marginal efficiency of the conventional powertrain, $\eta_{\text{conv, marginal}}$, is 33.4% and also from the same Willans line equation. $\eta_{\text{mot, regen}}$ is assumed at a constant 90% as motor regenerative efficiency is relatively constant in the Engine Loading operation region. Figure 5.9 shows that within the motor torque capability, motor operation results in fuel to propulsive power losses of 30 to 65 kW more than engine operation. As such, motor operation is about 8% less efficient in most of the motor operating envelope.

$$\eta_{\text{mot, round trip}} = \eta_{\text{conv, marginal}} \cdot \eta_{\text{mot, regen}} \cdot \eta_{\text{mot, propel}}$$ (5.9)
Figure 5.9: Difference in losses and efficiencies during motor and engine operation
With this insight, an alternative engine dominant strategy is developed to improve fuel economy by reducing round trip losses. As shown in Figure 5.10, the Motor Only mode is restricted to only regenerative torque and the low power Engine Assist region is completely eliminated. The Engine Loading region is greatly reduced to maintain charge sustaining behavior with the removal of low power motor operation. The Engine Only lower boundary is moved downwards to reduce the likelihood of fuel enrichment at high driver demands. This is all accomplished by using the battery SOC management parameters discussed in 5.4 with $P_{\text{eng,low}} = 0 \text{ kW}$, $P_{\text{eng,up}} = 60 \text{ kW}$, and $v_{\text{gen}} = 45 \text{ mph}$.

This strategy is not implemented or tested in-vehicle as the spirit of the EcoCAR Mobility Challenge is to develop and integrate technologies that could be used in production vehicles. While the inability for the engine to shutoff during Motor Only operation does hurt real-world fuel economy, the standard EMS is representative of the intent of the powertrain control strategy. However, in the interest of more optimal EMS performance, this engine dominant strategy is developed to minimize the shortcomings of the limited powertrain. Simulation testing of this strategy does show improvements in fuel economy over the standard strategy, as discussed in 7.1.
Figure 5.10: Torque split operating regions for engine dominant strategy
Chapter 6

Drive Quality

Efficient operation of hybrid powertrain requires the vehicle to switch between combinations of engine and motor torque as the vehicle operating point changes with driver demand. Ensuring the smooth transitions between these operating modes is of critical importance for drive quality and overall consumer acceptability. Three drive quality focused features are employed in the EMS with the goal of reliably meeting driver demand while minimizing vehicle jerk and driveline lash.

6.1 Torque Request Determination

Driver inputs via the accelerator pedal are converted to axle torque requests via a pedal map that feeds into the torque split strategy. The pedal map implemented is developed based on a competition-provided acceleration response map (ARM) which details the expected acceleration achieved as a function of vehicle speed and APP. Figure 6.1 shows the ARM data used during development with the axes unlabeled to protect the proprietary nature of the information.

Axle torques are calculated by summing the road load at a given speed and the inertial force to achieve a desired acceleration, as shown in Equation 6.1. Axle torques for APP values less than 10% or greater than 50% are extrapolated from stock GM pedal maps and tuned for the hybrid powertrain via extensive in-vehicle calibration. In-vehicle testing also led to
refinement in the glider physics parameters that improved how consistently the vehicle could follow the acceleration response map, as shown in Figure 6.2.

\[
\tau = R_e \left( 1.04 \cdot ma + (A + Bv) \cdot \frac{ETW_{target}}{ETW_{ref}} + Cv^2 \right) \tag{6.1}
\]

The in-vehicle testing data in Figure 6.3 shows vehicle acceleration as function of vehicle speed for APP pedal blocks ranging from 10% to 50%. All values fall within the marginally acceptable range with the vast majority falling within the ideal limits. Fluctuations in vehicle acceleration due to gear shifting, such as those seen in the 50% pedal block, are exempted from the ARM requirements. This data shows that the torque request determination strategy works successfully in real-world use and yields a responsive driving experience.
6.2 Engine Torque Fill

The torque fill strategy uses the fast response rate of the motor to fill in torque holes during mode transitions and during Engine Only operation. Fundamentally, the motor axle torque request is the difference between the driver demanded axle torque and the engine achieved axle torque. Since the motor torque response is nearly instantaneous, the driver demanded axle torque is always met unless the motor torque capability is saturated. The exception to this is during Engine Only mode where the motor will only fill torque holes in excess of 150 Nm to avoid excessive motor operation for torque holes that are insignificantly small.

In real-world operation, the strategy operates very smoothly, with drivers commenting that the only indication of a mode transition is a change in pitch from the engine and motor.

The torque fill strategy is most active during mode transitions such as a transition from Motor
Figure 6.3: In-vehicle data from vehicle acceleration response testing
Only to Engine Only, as shown in the vehicle test data in Figure 6.4. In this transition, driver demanded axle torque is approximately constant, but an increase in vehicle speed causes the torque split to transition. Without the torque fill strategy, there would be a significant torque hole on mode transition at $t = 0$ as the motor can reach zero torque much faster than the engine can take over and meet the driver demanded torque. As such, the torque fill strategy uses the motor to fill in the torque hole until about $t = 0.8$ when the engine is meeting driver demand.

This strategy is also critical in the transition out of Engine Loading mode as the sudden removal of negative motor torque can cause unintended acceleration. This scenario is illustrated using vehicle test data shown in Figure 6.5 where driver demanded torque is held approximately constant but the torque split transitions from Engine Loading to Motor Only mode. The torque fill strategy is needed so that the motor continues to produce negative torque while the engine achieved torque falls. Without the strategy, the vehicle would jerk forward on the mode transition which would be incredibly alarming to the driver.

Implementing this strategy such the motor axle torque request always seeks to fill the gap to the driver demanded axle torque also eliminates the need to calculate a maximum engine axle torque. This simplifies the control strategy and guarantees that both the engine and motor torque capabilities are saturated during wide open throttle events.

### 6.3 Torque Request Filtering

Vehicle testing led to the development of a torque request filtering strategy that would smoothly transition to and from the coasting mode. While the five main torque split modes (Motor Only, Engine Only, Engine Loading, Motor Assist, and Engine Assist) require accelerator pedal input and Regenerative Braking requires brake pedal input, coasting mode
Figure 6.4: In-vehicle data of torque fill strategy during Motor Only to Engine Only
Figure 6.5: In-vehicle data of torque fill strategy during Engine Loading to Motor Only
occurs when there is no accelerator pedal or brake pedal input. For a conventional vehicle, rapidly tipping out of the accelerator pedal results in the engine smoothly reducing torque achieved despite the rapid drop in torque demand. However, in the Motor Only or Engine Assist modes where the motor is providing most or all the axle torque, tipping out rapidly would result in an instantaneous drop in axle torque. To avoid this, driver axle torque requests are filtered on the transition to the coasting mode using a first-order low pass filter with a time constant $\tau = 0.1$ seconds.

6.4 Motor Torque Shaping

While torque capability of the motor is essential for the torque fill strategy and significantly improves vehicle responsiveness, the rapid surge is torque can be a double-edged sword. Changing torque too quickly can be uncomfortable and cause an audible clonk in the driveline [1], especially when crossing between positive and negative torque. The torque shaping strategy limits the slew rate of the motor, with positive slew rate limits being a function of APP and negative slew rate limits being a function of BPP.

Additionally, the strategy also limits slew rates when a lash crossing is detected. Whenever the sign of the motor torque request differs from the sign of the motor achieved torque, a more restrictive torque slew rate limit is applied for 0.2 seconds. This slew rate limit is a function of motor achieved torque, with the limit falling as the absolute value of torque achieved approaches zero. Figure 6.6 shows the torque shaping strategy reducing motor lash during a zero-torque crossing event by more slowly transitioning through the lash region. As the motor achieved torque approaches zero from the negative direction, the slew rate limits decrease so that the zero cross happens slowly. Once the crossing is complete, the slew rate limits increase again so that the motor can reach the requested value.
6.5 Deceleration Strategy

Recapturing vehicle kinetic energy using regenerative braking is a key component of the fuel economy improvements that HEVs are capable of. The EMS utilizes regenerative motor torque during the Coasting and Regenerative Braking modes. Limited control of the hydraulic brakes and engine fueling limit the potential for energy recapture, so consumer acceptability is the primary focus.

During the Coasting mode when the driver is not pressing the accelerator or brake pedal, the energy management requests a small amount of regenerative torque from the motor, as shown in Figure 6.7. Since engine fueling control is not available, any regenerative motor torque would be in addition to negative torque produced by the engine during DFCO. As such, the motor torque curve is calibrated for driver comfort with vehicle deceleration just slightly more aggressive than a conventional vehicle.

While a one-pedal driving strategy could be possible, it would be difficult to implement as the friction brakes are tied directly to the brake pedal. Additionally, the ARM requirements
begin at 10% APP so any one-pedal driving strategy would be constrained below that value. Finally, one-pedal driving is not usually available in full HEVs, so consumer acceptability of the feature is less likely.

For the Regenerative Braking mode, the objective is also to increase energy recapture while maintaining consumer acceptability. Figure 6.8 shows the motor regenerative braking curve as well as a fitted model of friction brake torque data collected during braking stability testing. At low BPP where most drivers operate, the motor regenerative torque makes up most of the braking torque. The braking fraction decreases to around 25% as more brake pedal input is applied, which saturates the motor torque capability. While overall braking torque is increased, by maintaining similar characteristics between the stock friction braking curve and the total braking curve, drivers are accepting of the change. The increase
in braking torque is also masked in part by the additional weight of hybrid powertrain components added to the vehicle.

![Braking torque and regenerative braking fraction vs BPP](image)

Figure 6.8: Braking torque and regenerative braking fraction vs BPP

### 6.6 Mode Transition Hysteresis

To avoid rapid transitions between torque split operating modes, a mode transition time hysteresis is implemented, as shown in Table 6.1. For robustness, each torque split operating mode is designed to meet driver demand even if the operating point is outside the intended region of operation. While this may result in some sacrifices in efficiency, avoiding oscillatory behavior in operating modes and powertrain component torque demands reduces NVH and may reduce energy consumption by limiting transients. The torque fill strategy discussed in
6.6. Mode Transition Hysteresis

6.2 also ensures that driver demand is still being met by slowly blending motor torque as the engine achieves its torque request.

Table 6.1: Transition hysteresis times for torque split operating mode transitions

<table>
<thead>
<tr>
<th>From</th>
<th>Motor Only</th>
<th>Engine Only</th>
<th>Engine Loading</th>
<th>Motor Assist</th>
<th>Engine Assist</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motor Only</td>
<td>⊘</td>
<td>1 s</td>
<td>1 s</td>
<td>1 s</td>
<td>1 s</td>
</tr>
<tr>
<td>Engine Only</td>
<td>0</td>
<td>⊘</td>
<td>0</td>
<td>1 s</td>
<td>1 s</td>
</tr>
<tr>
<td>Engine Loading</td>
<td>1 s</td>
<td>1 s</td>
<td>⊘</td>
<td>⊘</td>
<td>⊘</td>
</tr>
<tr>
<td>Motor Assist</td>
<td>0</td>
<td>0</td>
<td>⊘</td>
<td>⊘</td>
<td>1 s</td>
</tr>
<tr>
<td>Engine Assist</td>
<td>0</td>
<td>0.3 s</td>
<td>⊘</td>
<td>1 s</td>
<td>⊘</td>
</tr>
</tbody>
</table>

The transition from the Motor Only mode to Engine Only, Motor Assist, and Engine Assist are instantaneous to maximize efficiency. However, the transitions from Motor Only to Engine Loading requires 1 second of hysteresis as it would require significant time for the engine to reach its torque request, which is in excess of driver demand for the Engine Loading mode.

Transitions out of Engine Only mode have some time hysteresis as the engine can meet all reasonable driver torque demands while the motor is very much undersized to be the sole source of propulsion for a vehicle. Since engine efficiency around the Engine Only region is still high, there is only a minimal sacrifice in overall efficiency.

Transitioning from Engine Loading to Engine Only is instantaneous as the engine torque request would be lower and NVH would decrease. However, the transition to Motor Only requires 1 second as the motor must cross through the lash region from negative to positive
torque as the engine achieved torque falls.

Transitions from the Motor Assist and Engine Assist modes also require 1 second of hysteresis as the expectation is that the driver needs the performance capability of the powertrain. Remaining in these modes improves vehicle responsiveness with minimal sacrifices in efficiency due to the transient nature of these operating modes.

### 6.7 In-Vehicle Calibration

Drive quality pain points are difficult to discover in simulation, not due to lack of model fidelity, but because of the fleeting and contextual nature of the issues. For example, a motor lash transition only lasts a few tenths of a second [9] and is difficult to spot in a drive cycle simulation lasting thousands of seconds. Rather than sifting through simulation results, drive quality issues are identified in vehicle, where the driver or accompanying calibrators could review relevant vehicle data at the moment of the disturbance. To support this effort, calibratable parameters are built into the drive quality features with the expectation that they would be tuned during in-vehicle testing. For issues that required more in-depth control strategy refinement, the in-vehicle identification of pain points would allow team members look for similar scenarios in simulation results to evaluate the performance of their new changes. This allows for accurate identification of drive quality improvements using in-vehicle testing while still leveraging the benefits of the MIL simulation model.
Chapter 7

Simulation Results

MIL simulation of the vehicle model discussed in 4 along with the EMS discussed in 5 allows for energy consumption testing to be done across a wide variety of drive cycles and powertrain configurations. The US06, UDDS, and HWFET cycles are selected as they are commonly used in standardized fuel economy testing in the United States. The addition of the EcoCAR Mobility Challenge (EMC) cycle represents the EMS responding to real-world driver inputs.

7.1 Energy Management Strategy Comparison

Fuel economy simulations are run for four model variants of the Blazer. The primary model is of the hybrid Blazer which uses the measured vehicle mass and the corresponding mass-adjusted glider model parameters. To isolate the fuel economy improvements from the EMS, another hybrid Blazer is simulated operating in Engine Only mode with the EMS deactivated. Simulations are also run for a stock Blazer using the same 2.5L engine as the hybrid Blazer without the additional weight of the hybrid powertrain. Finally, the alternative engine dominant strategy discussed in 5.5 designed to decrease round trip losses is also simulated. These results in Table 7.1 and Figure 7.1 show that the EMS produces meaningful gains in fuel economy relative to the vehicle running with the EMS deactivated. Improvements across most of drive cycles shows that the EMS to can extract additional efficiency across many
driving scenarios. However, the fuel economy of the hybrid Blazer also shows no significant difference from that of the stock Blazer, yielding the conclusion that the improvements in fuel economy are offset by the additional weight in hybrid powertrain components. This shortcoming can likely be attributed to the prototype nature of the vehicle and the limitations in the flexibility of powertrain selection and controls strategy, as discussed in 2.3. However, the hybrid powertrain does increase peak power for improved performance, and achieving the same performance in a conventionally powered vehicle would likely come with a drop in fuel economy.

The engine dominant strategy shows slight improvements in fuel economy over the standard strategy. By avoiding the use of motor torque when the engine would otherwise be idling, overall fuel economy improves by avoiding round trip losses. The most significant gain is made in the UDDS cycle where the frequent motor usage in the standard operating strategy likely reduced fuel economy. Improvements in fuel economy can also be contributed to reduced losses associated with circulating energy between the engine, battery, and motor. The engine torque fill strategy is still enabled so there is no penalty for vehicle responsiveness relative to the standard strategy.

Detailed comparisons of battery power use between the standard and engine dominant strategies are shown in Appendix D.

<table>
<thead>
<tr>
<th>Test Mass [kg]</th>
<th>EMS</th>
<th>Fuel Economy [mpg]</th>
<th>US06</th>
<th>UDDS</th>
<th>HWFET</th>
<th>EMC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stock</td>
<td>1930</td>
<td>Off</td>
<td>24.6</td>
<td>28.2</td>
<td>37.0</td>
<td>29.8</td>
</tr>
<tr>
<td>ICE Only</td>
<td>2250</td>
<td>Off</td>
<td>22.4</td>
<td>26.2</td>
<td>34.9</td>
<td>28.8</td>
</tr>
<tr>
<td>Hybrid</td>
<td>2250</td>
<td>Standard</td>
<td>24.5</td>
<td>25.5</td>
<td>38.2</td>
<td>28.8</td>
</tr>
<tr>
<td>Engine Dominant</td>
<td>2250</td>
<td>Alternate</td>
<td>24.5</td>
<td>30.0</td>
<td>37.4</td>
<td>29.0</td>
</tr>
</tbody>
</table>


7.2 Drive Cycle Simulation

To better understand and evaluate the torque split and battery SOC management strategies, the simulated operating points of the hybrid Blazer are overlaid with the torque split regions discussed in 5.2. The colored dots correspond to the operating mode of the same color, with dots outside of their corresponding region being due to either the mode transition hysteresis discussed in 6.6 or shifts in operating regions from the battery SOC management strategy discussed in 5.4.

The operating points shown in the rest of this chapter are for total axle torque requests representative of driver demanded torque for the standard EMS. Engine and motor operating points from these simulations are shown in Appendix B and C respectively.

Figure 7.1: Comparison of simulated fuel economy for stock and hybrid Blazer
7.2.1 US06 Combined Cycle

The US06 drive cycle is by far the most demanding of the drive cycles under study, with both aggressive accelerations and high-speed driving. This results in large axle torque requests during launch, pushing the torque split into the low power Engine Assist region, as seen in Figure 7.2. This figure also illustrates the hysteresis between mode transitions, as the operating points indicating Engine Assist extend into the Engine Only region. Engine Loading operation rarely occurs during this drive cycle as the city operation is very transient and the only cruising scenario occurs at speeds significantly higher than the engine loading maximum speed. As shown in Figure 7.3, battery SOC stays nearly constant with most of the time being spent in Engine Only mode. Most of the motor activity occurs during the hills at the end of the cycle, where the motor torque improves vehicle responsiveness with engine torque fill while reducing engine fuel consumption.

Figure 7.2: US06 cycle operating points
Figure 7.3: US06 cycle simulation results
7.2.2 UDDS Cycle

The low power city driving characteristics represented by the UDDS cycle results in the most mode transitions commanded by the EMS to extract overall vehicle efficiency. The UDDS operating points are all relatively low power, with most falling within the capability of just the electric motor, as shown in Figure 7.4. As such, most of the powertrain operation is in either the Motor Only or Engine Loading operating modes. The motor is very active during this drive cycle with motor torque often reaching the limits in both propulsion and regeneration, as you shown in Figure 7.5.

Figure 7.4: UDDS cycle operating points
Figure 7.5: UDDS cycle simulation results
7.2.3 HWFET Cycle

The highway cruising that the HWFET drive cycle represents lends itself well to Engine Only and Engine Loading operation, which can be seen in Figure 7.6. Motor propulsive torque is only used to bring the vehicle up to speed except for some engine torque fill in the middle of the cycle. Otherwise, the motor is regenerating during Engine Loading as well as the Regenerative Braking event at the end of the cycle. This storage of battery energy increases the charge-corrected fuel economy, giving the hybrid an edge over the stock vehicle even though the drive cycle is dominated by Engine Only operation.

Figure 7.6: HWFET cycle operating points
Figure 7.7: HWFET cycle simulation results
7.2.4 EcoCAR Mobility Challenge (EMC) Cycle

The presented data from the EMC cycle is unique in that it uses driver input data recorded during in-vehicle testing as opposed to relying on a simulated driver model. The speed trace is relatively simple, which is reflected in the repeating transitions from Motor Only to Engine Assist to Engine Only, as seen in Figure 7.8. The data shown in Figure 7.9 is also like that of the other drive cycles, lending confidence to the assertion that the EMS performs as intended regardless of if driver inputs are real or simulated. This cycle was run during the EcoCAR Mobility Challenge Year 4 Competition where the HEVT Blazer achieved the second highest fuel efficiency out of eleven total Blazers developed by other university teams.

Figure 7.8: EMC cycle operating points
Figure 7.9: EMC cycle simulation results
7.3 SOC Management Robustness

Drive cycle simulations are also run with varying initial battery SOC values of 30%, 50%, and 70% to evaluate the robustness of the battery SOC management strategy. As shown in Figure 7.10, the battery SOC always stays within the safe bounds of 25% to 75% with battery SOC converging during most drive cycles.

The US06 cycle sees the least change in battery SOC due to the high vehicle speeds encouraging Engine Only operation combined with the relatively short duration of the cycle. Despite this, battery SOC always trends towards the safe range with the SOC never dropping below 30% or above 70% SOC. The HWFET cycle is slightly longer and has much more opportunity for Engine Loading, as reflected by the rapid SOC rise in the scenario with an initial SOC of 30%. The HWFET scenario starting at 70% SOC sees less change due to motor propulsive torque being mostly limited to the first acceleration. The lack of high-power driver demand that would require Motor Assist operation also limits battery discharge. The UDDS and EMC cycles are both longer and show clear convergence of battery SOC as the drive cycle progresses due to the varied driving scenarios. This demonstrates that the battery SOC management parameters are well calibrated and robust charge sustaining behavior regardless of initial conditions.

7.4 Energy Consumption Impact of Drive Quality

The trade-off between drive quality and energy consumption is a delicate balance that the EcoCAR competition organizers explicitly challenge teams to find. To assess the fuel economy impact that the drive quality features have, simulations are run with each feature disabled. The simulation configuration is the same as for the energy consumption simulations
Figure 7.10: Battery SOC over various drive cycles with initial SOC at 30%, 50%, and 70%
above but only the standard EPA cycles are used here.

To assess drive quality, the NCCP between the simulated vehicle acceleration and the drive cycle acceleration is calculated using Equation 4.5. These values are compared to the baseline configuration with all features enabled. Simulated vehicle acceleration is calculated from the glider physics model while drive cycle reference acceleration is generated by the Simulink drive cycle block using Savitzky-Golay differentiation. A higher NCCP means that the vehicle acceleration more closely follows the drive cycle acceleration, with minimal deviation (jerk) in either the positive or negative directions. Sensitivity of fuel economy and acceleration correlation to drive quality features is shown in Table 7.2 and Figure 7.11.

Table 7.2: Sensitivity of fuel economy and acceleration correlation to drive quality features

<table>
<thead>
<tr>
<th></th>
<th>Fuel Economy [mpg]</th>
<th>Acceleration NCCP [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>US06</td>
<td>UDDS</td>
</tr>
<tr>
<td>Baseline</td>
<td>24.5</td>
<td>25.5</td>
</tr>
<tr>
<td>Torque Fill Disabled</td>
<td>24.9</td>
<td>26.2</td>
</tr>
<tr>
<td>Torque Shaping Disabled</td>
<td>24.5</td>
<td>25.5</td>
</tr>
<tr>
<td>Torque Filtering Disabled</td>
<td>24.4</td>
<td>25.5</td>
</tr>
</tbody>
</table>

Of the three drive quality features, only torque fill has any significant impact of fuel economy with improvements over the baseline averaging 2.1%. This can likely be attributed to the elimination of motor propel torque during torque split mode transitions and during engine only mode. However, this reduction in energy consumption comes at the expense of drive quality, with acceleration correlations falling by an average of 1.8% relative to baseline. While the percentage gains in fuel economy are approximately equal to the sacrifices in drive quality, the removal of the torque fill features comes with significant compromises for consumer acceptability. The HWFET drive cycle shows a significant reduction in acceleration correlation due to significant Engine Loading operation, which relies heavily on the torque fill strategy as shown in Figure 6.5.
Figure 7.11: Sensitivity of fuel economy and acceleration correlation to drive quality features
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.
Chapter 8

Conclusion

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.
Bibliography


Appendices
Appendix A

Torque Split Operating Regions

To encourage charge sustaining operation, the operating regions of the torque split vary with battery SOC. The following figures show how the operating regions shift from 25% to 75% SOC.
Figure A.1: Torque split operating regions at SOC = 25%
Figure A.2: Torque split operating regions at SOC = 30%
Figure A.3: Torque split operating regions at SOC = 35%
Figure A.4: Torque split operating regions at SOC = 40%
Figure A.5: Torque split operating regions at SOC = 45%
Figure A.6: Torque split operating regions at SOC = 50%
Figure A.7: Torque split operating regions at SOC = 55%
Figure A.8: Torque split operating regions at SOC = 65%
Figure A.9: Torque split operating regions at SOC = 70%
Figure A.10: Torque split operating regions at SOC = 75%
Appendix B

Engine Operating Points

The objective of the EMS is to operate the engine in a region of high efficiency as often as possible. This is represented by the blue Engine Only operating region in which most of the operating points fall into.

Figure B.1: US06 cycle engine operating points
Figure B.2: UDDS cycle engine operating points

Figure B.3: HWFET cycle engine operating points
Figure B.4: EMC cycle engine operating points
Appendix C

Motor Operating Points

The following figures illustrate that the EMS uses the full capability of the motor to achieve improved engine efficiency. The motor capability is often saturated at lower speeds which indicates that the strategy may benefit from higher peak torque capability.

Figure C.1: US06 cycle motor operating points
Figure C.2: UDDS cycle motor operating points

Figure C.3: HWFET cycle motor operating points
Figure C.4: EMC cycle motor operating points
Appendix D

Battery Power Use by Operating Mode

Battery power use in each torque split operating mode for both the standard and engine dominant EMS are shown. Battery power use for the propulsive operating modes are much smaller for the engine dominant strategy to eliminate low power motor operation.
Figure D.1: Battery power use comparison between standard and engine dominant strategies for US06 cycle.
Figure D.2: Battery power use comparison between standard and engine dominant strategies for UDDS cycle
Figure D.3: Battery power use comparison between standard and engine dominant strategies for HWFET cycle.
Figure D.4: Battery power use comparison between standard and engine dominant strategies for EMC cycle