Modeling and Control of an Automated Manual Transmission for EcoCAR 3 Vehicle

THESIS

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By

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Abstract

EcoCAR 3 is a part of the Advanced Vehicle Technology Competition series hosted by the Department of Energy, and it challenges 16 North American university teams to re-engineer a 2016 Chevrolet Camaro and turn it into a hybrid electric vehicle, thus improving the environmental impact of the car while retaining its performance aspects.

The Ohio State University’s EcoCAR 3 vehicle has a plug-in hybrid architecture, with operation in series and parallel power flows. The architecture features a 5-speed manual transmission that was automated by the team to retain the efficiency of a manual transmission while providing the convenience of an automatic transmission. The team-developed controllers manage the clutch and shift actuators to provide supervisory control of the automated manual transmission.

The simplicity and efficiency of a manual transmission combined with the advantages provided by the hybrid architecture make it a good candidate for an HEV. This thesis provides an overview of the modeling, component testing, and controls development for the AMT system. The controls development includes high level control for vehicle launch, gearshift process, and strategies used in different hybrid vehicle operation modes.
To my family for their ceaseless support and encouragement throughout my education.

ज्ञानं परमं बलम्
Acknowledgments

This thesis is meaningless if I do not thank the entities responsible for making it happen. OSU’s Center for Automotive Research hosts many talented people who helped with the work done in this thesis. I thank Prof. Shawn Midlam-Mohler, a phenomenal advisor, for his guidance and immensely practical advice over the last two years, and Prof. Giorgio Rizzoni, for his support and insights during my tenure at CAR.

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Finally, I am thankful to the competition and the sponsors for giving many others like me the opportunity to work with advanced automotive powertrains.
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Publications


Fields of Study

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Chapter 1: Introduction

1.1 Background

Increasingly strict government regulations pertaining to automotive fuel economy and emissions, increasing awareness and willingness to curb pollution among consumers, and the advancements in hybrid vehicle technology have all contributed to the increase in the number of hybrid vehicles on the road [1]. While maintaining their efforts towards increasing the efficiencies of conventional powertrains, most automotive manufacturers are also pushing for increasing electrification of the automobile.

There are different types of hybrid vehicles, depending on their degree of hybridization and powertrain architecture – ranging from mild hybrids (engine start-stop and regenerative braking) to Extended Range Electric Vehicles (EREV). Hybrid vehicle technology has penetrated the entire spectrum of automotive applications, from small cars to construction equipment to Formula 1 cars.

To aid this effort and help develop the next generation of automotive engineers through hands-on experience and exposure to hybrid vehicle technologies, the U.S. Department of Energy (DOE) has sponsored Advanced Vehicle Technology Competitions (AVTC) for almost 30 years starting from Methanol Marathon in 1988 to the ongoing EcoCAR 3. AVTCs partner with automotive OEMs and are sponsored by automotive
suppliers, and thus provide opportunities for students by introducing them to advanced propulsion and alternative fuel technologies.

1.2 EcoCAR 3

EcoCAR 3 is a 4-year competition sponsored by DOE and General Motors (GM), and organized by Argonne National Laboratories (ANL), with 16 North American universities transforming a stock conventional 2016 Camaro to a hybrid vehicle. The goal is to re-engineer the Camaro to reduce its environmental impact while still retaining the ‘feel’ of a performance vehicle. The competition is structured to mimic an automotive product cycle, with participants judged not only on the technical capabilities of the product, but also their market research and consumer acceptability.

![Figure 1: EcoCAR 3 vehicle development process](image)

In Year 1, teams apply modeling tools to select a powertrain architecture that they feel best supports their Vehicle Technical Specifications (VTS) and choose the powertrain components from the choices available to them. Year 2 sees the maturation of their vehicle
simulation models with the chosen architecture, and the mechanical integration of the vehicle, aiming at basic safe operation of the vehicle by the year end competition. Year 3 aims to have the vehicle operational in all modes, albeit not with the most sophisticated feel, ready to complete all dynamic events at the year end competition, the most important one being the Emissions and Energy Consumption (E&EC) event. Year 4, the final year of the competition, aims at a marketable product, with the focus being on controls optimization and consumer acceptability.

The Ohio State University (OSU) EcoCAR team’s vehicle has a Plug-In Hybrid Electric Vehicle (PHEV) architecture, with the vehicle capable of operating in an Electric Only (EV) mode, Engine Only mode, and series and parallel hybrid modes. It features an economy mode tailored towards better energy consumption, and a performance mode, making the vehicle more fun to drive. The vehicle architecture is shown in Figure 2, and Table 1 lists the powertrain components and their specifications.

![OSU EcoCAR 3 vehicle architecture](image)

**Figure 2: OSU EcoCAR 3 vehicle architecture**
Table 1: OSU EcoCAR 3 vehicle powertrain component specifications

<table>
<thead>
<tr>
<th>Component</th>
<th>Manufacturer / Model</th>
<th>Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>BAS Motor</td>
<td>Denso Integrated Permanent Magnet Motor</td>
<td>32 kW, liquid cooled</td>
</tr>
<tr>
<td>BAS Inverter</td>
<td>Rinehart PM100DX</td>
<td>100 kW, liquid cooled</td>
</tr>
<tr>
<td>Engine</td>
<td>2.0 L 4 Cyl DI E85</td>
<td>119 kW @ 6500 RPM</td>
</tr>
<tr>
<td>REM Motor</td>
<td>Parker Hannifin IPM</td>
<td>112 kW, liquid cooled</td>
</tr>
<tr>
<td>REM Inverter</td>
<td>Rinehart PM150DXR</td>
<td>150 kW, liquid cooled</td>
</tr>
<tr>
<td>Transmission</td>
<td>TREMEC T5</td>
<td>5 - speed manual transmission</td>
</tr>
<tr>
<td>Shifting Control Unit</td>
<td>ASaP - Mastershift</td>
<td>Electromechanical shifting</td>
</tr>
<tr>
<td>Clutch</td>
<td>RAM Performance</td>
<td>Single plate dry clutch</td>
</tr>
<tr>
<td>Clutch Control Unit</td>
<td>FTE CP1</td>
<td>Electrohydraulic actuator</td>
</tr>
<tr>
<td>Energy Storage System</td>
<td>A123 Systems</td>
<td>18.9 kWh, air cooled</td>
</tr>
<tr>
<td>HV Charger</td>
<td>Brusa NLG 513</td>
<td>3.3 kW, air cooled</td>
</tr>
<tr>
<td>DC-DC Converter</td>
<td>GM</td>
<td>2.2 kW, air cooled</td>
</tr>
<tr>
<td>Power Transfer Unit</td>
<td>Team Developed</td>
<td>2.77 gear ratio</td>
</tr>
<tr>
<td>Rear Differential</td>
<td>GM</td>
<td>2.77 gear ratio</td>
</tr>
</tbody>
</table>

The Internal Combustion Engine (ICE), and the Belted Alternator Starter (BAS) constitute the front powertrain, and they are connected to the wheels through the clutch and transmission, with the P3 Rear Electric Machine (REM) connected post transmission through the Power Transfer Unit (PTU).

In Year 3 of the competition, the team developed the controls to make the vehicle operate in all of its intended modes, and conducted validation of the controls software.
through Model In the Loop (MIL), Hardware In the Loop (HIL) and Vehicle In the Loop (VIL) testing. The controls focus in Year 3 was to have reliability over sophistication.

1.3 Thesis Objective

Ohio State’s EcoCAR vehicle has an Automated Manual Transmission (AMT) that was developed by the team by automating a stock manual transmission. Year 3 involved extensive work on the AMT system, from controls development to component testing and in-vehicle validation. The thesis describes the modeling, testing, and controls development of the AMT system during Year 3, and its operation during different hybrid vehicle operation modes.

1.4 Thesis Organization

The subsequent portion of the thesis is organized as follows:

- Chapter 2 provides a brief overview on AMTs, their advantages in a hybrid powertrain, and the research that has been done on AMT control.
- Chapter 3 provides an overview on the components of the AMT system in the EcoCAR 3 vehicle and their operation.
- Chapter 4 describes the modeling approach for the individual subsystems.
- Chapter 5 details the component level testing done on the clutch and the transmission subsystems to characterize their behaviour.
- Chapter 6 elaborates on the controls development process, deep dives into a few key areas of the shifting logic, and shows in-vehicle results.
- Chapter 7 is the concluding portion highlighting the accomplishments and challenges in key areas and the way forward for Year 4 of the competition.
Chapter 2: Literature Review

2.1 Introduction

This chapter provides an overview of the background for the material presented in this thesis. The different types of transmissions used in vehicles (conventional and hybrid), and their advantages and disadvantages are discussed. Automated manual transmissions are looked at in detail, focusing on their types, control approaches, drive quality perceived by the consumer, and their applications in a hybrid vehicle architecture. The background was important in the vehicle architecture selection as well as the controls development process.

2.2 Transmissions Overview

A transmission forms an important power transfer point between the propulsion systems and the wheels of an automobile. This enables the propulsive units to be paired with the wheels through different gearing ratios based on the torque required, component speed ranges, etc. In the case of an engine, it allows the engine to spin with the vehicle at standstill to prevent stalling. Following are the prevalent transmission types-

2.2.1 Manual Transmission

Manual Transmissions (MT) have two parallel gear shafts – the main shaft and the layshaft, connected with different gear ratios. The gears on the layshaft are rigidly attached to it, while the ones on the mainshaft are ‘floating’. The gears on the mainshaft are coupled
to it using a shift fork, which is operated by the driver through the gear shifter. The transmission is coupled to the engine through the clutch, which is operated by the driver through a foot pedal. Most contemporary manual transmissions for road cars have 4 to 6 continuous synchromesh forward ratios and 1 reverse. Manual transmissions are relatively simple, lighter, exclusively controlled by the driver, and more efficient than other types of transmissions [2]. Table 2 shows some representative efficiencies.

Figure 3: Internal structure of a manual transmission [3]

Table 2: Typical gear efficiencies for a manual transmission [2]

<table>
<thead>
<tr>
<th></th>
<th>Time in Gear</th>
<th>Representative Efficiency</th>
<th>Current Production Efficiency Variation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gear 1</td>
<td>8%</td>
<td>93.5%</td>
<td>92-96%</td>
</tr>
<tr>
<td>Gear 2</td>
<td>10%</td>
<td>92.0%</td>
<td>92-97%</td>
</tr>
<tr>
<td>Gear 3</td>
<td>21%</td>
<td>94.0%</td>
<td>93-97%</td>
</tr>
<tr>
<td>Gear 4</td>
<td>20%</td>
<td>97.4%</td>
<td>93-99%</td>
</tr>
<tr>
<td>Gear 5</td>
<td>41%</td>
<td>93.8%</td>
<td>92-97%</td>
</tr>
</tbody>
</table>
The manual transmission has the highest efficiency of all the transmission types, and the driver is always in control of the gearshifts. This makes the driver feel more ‘connected’ with the vehicle, but also relies on driver skill for smoothness during gearshifting and vehicle launches.

### 2.2.2 Automatic Transmission

Automatic Transmissions (AT) consist of a pump, turbine, and a planetary gearset. The driver does not have a separate clutch pedal and the driver cannot select a gear by manipulating a stick. The vehicle’s Transmission Control Unit (TCU) selects a gear by manipulating a system of clutches and brakes in the transmission to lock components of the planetary gearset. There is no interruption of torque during the shifting process [4]. This type of transmission is very complex in structure which makes it heavy compared to manual transmissions. Their efficiency is low compared to a manual transmission [2]. The drive quality during shifting is better than that of a manual transmission and no driver effort is required during launching and shifting.

**Table 3: Typical gear efficiencies for an automatic transmission [2]**

<table>
<thead>
<tr>
<th>Gear</th>
<th>Time in Gear</th>
<th>Representative Efficiency</th>
<th>Current Production Efficiency Variation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gear 1</td>
<td>9%</td>
<td>70.3%</td>
<td>60-85%</td>
</tr>
<tr>
<td>Gear 2</td>
<td>4%</td>
<td>78.1%</td>
<td>60-90%</td>
</tr>
<tr>
<td>Gear 3</td>
<td>5%</td>
<td>86.0%</td>
<td>85-95%</td>
</tr>
<tr>
<td>Gear 4</td>
<td>32%</td>
<td>86.2%</td>
<td>85-95%</td>
</tr>
<tr>
<td>Gear 5</td>
<td>40%</td>
<td>88.7%</td>
<td>83-94%</td>
</tr>
</tbody>
</table>

New technologies like torque converter lock-up, increased gear ratios and optimization of components have increased efficiencies of automatic transmissions [4].
2.2.3 **Dual Clutch Transmission**

The Dual Clutch Transmission (DCT) is structured like a manual transmission with two layshafts, with the gears split between them. This transmission has two clutches, one attached to each layshaft. Both layshafts are geared to the output shaft, and the layshaft currently engaged to its clutch is the one transferring torque. The next gear ratio is already selected on the other layshaft, and an upshift involves disengaging the first clutch and engaging the second. The DCT control logic preselects the next gear anticipating an upshift or a downshift, which makes sequential shifts very fast, but block shifts are comparatively slower.

![Figure 4: Schematic of DCT, ZF 6 speed AT [4]](image)

2.2.4 **Continuously Variable Transmission**

There are two types of Continuously Variable Transmissions (CVT) – belt type and toroidal type. Belt type CVTs have two discs connected by a belt, and a variator that changes the distance between a pair of pulleys, changing the belt radius and thus offering theoretically infinite transmission ratios. A toroidal CVT has two discs with inner surfaces
resembling a toroid, and a friction disc that transmits torque between the two discs. Changing the angle of the disc causes it to contact different parts of the torus on each disc leading to variable gear ratios. Belt type CVTs have overall efficiencies around 84.6% [2], which are lower than an MT but allows the engine to be kept in its most efficient operating zone. Toroidal CVTs have efficiencies around 91%. Belt driven CVTs have limited torque transfer capability, and toroidal CVTs are heavy and require more manufacturing precision than their AT counterparts [4].

2.2.5 Automated Manual Transmission

Automated manual transmissions are manual transmissions with the clutch operation and gear shifting controlled by the TCU. The driver does not have a physical clutch pedal and the gear shift lever is similar to an AT. Clutch and shift actuation can be electromechanical or electrohydraulic, depending on the manufacturer/supplier. The transmission itself may be a modified manual transmission or it may use a stock unit. The transmission efficiency is the same as a manual transmission, but the TCU selects the most efficient gear ratio for an operating condition. Also, since vehicle launch and shifting are electronically controlled, consistency is maintained and drive quality is not subject to driver skill.

Compared to ATs, however, gear shifts see interruption of torque during shifting, and vehicle launch quality depends on clutch control calibration since manual transmissions do not have the ‘creep’ functionality inherent to ATs. Shift quality of AMTs is usually rated poorer in comparison to ATs [5].
AMT designs may be custom, where the internal structure of a manual transmission is modified with automation as the goal. These modifications could include additional clutches, engine brakes, synchronizer changes or torque assist motors [6]. These types of transmissions are usually sold as complete units to OEMs. They usually represent the more mature AMTs, but at the same time increase costs. The other design is ‘retrofit’ transmissions, where add-on units are added to existing manual transmissions, often without modifications to the transmission internals. The shifting is slower compared to custom AMTs, but they are more business-viable for small urban cars [6].

![Figure 5: Classification of AMTs [6]](image)

### 2.3 AMT Control

Taking into account the pros and cons of different transmission types, OSU EcoCAR team decided to use an AMT in its vehicle architecture. The AMT was selected for the following reasons:

i) To retain the high efficiency and low weight of an MT
ii) To allow the supervisory controller to select the optimum gear depending on operating conditions

iii) To leverage the hybrid architecture to improve drive quality compared to conventional AMTs

During Year 1 of the competition, the team evaluated 4 different architectures for performance and economy metrics [7] and selected an architecture with a 2.0 L engine and a 5-speed manual transmission to be automated by the team. The team also leveraged its previous experience in automating a manual transmission in EcoCAR 2. The important aspects of a controller for the AMT are described below.

2.3.1 Vehicle Launch

In a conventional MT vehicle, the driver controls both the accelerator and clutch pedal during a vehicle launch. In an AMT, control of the clutch is either electromechanical or electrohydraulic. The aim of the clutch control is to achieve a clutch position in order to follow a position trajectory commanded by the supervisory controller to achieve the vehicle launch. The higher-level controller commands a suitable clutch engagement trajectory to achieve a smooth launch, as is illustrated by an example shown in Figure 6. On receiving a position command from the higher-level controller, the lower-level controller actuates the motor to move the master piston to the desired position.
This trajectory usually involves a quick release to the bite point, followed by a slower release until the wheels get up to speed, and a quick release until full engagement [8]. The clutch engagement trajectory also determines the gentleness of the engagement, with a fast engagement needed for an aggressive launch. The TCU determines the quickness of the clutch engagement based on the Accelerator Pedal Position (APP) [8]. Typical goals of vehicle launch are to minimize engagement time while providing a smooth launch, avoiding engine stall and redlining during launch, and having minimum rollback during a hill start [6].

Identification of the clutch bite point is an important step in the clutch engagement trajectory. [9] describes a method for a clutch bite point estimation when pressure is the control variable. [10] shows the nonlinear relation between the clutch diaphragm spring displacement and stiffness, while [11] shows a similar relationship between throwout bearing load and travel, as seen in Figure 7.

Figure 6: Typical clutch engagement trajectory, actual launch at 30% APP [8]
[12] illustrates how clutch torque changes with clutch wear, and [13] shows its dependency on slip. These clutch characteristics were of great use when setting up the torque transmissibility test rig.

### 2.3.2 Gearshift Sequence

The process of a gearshift (upshift or downshift) can be broadly sequenced as releasing the throttle, disengaging the clutch, changing gears, engaging clutch, and increasing throttle [14]. [12] further splits the process into the following phases:

- **i)** Engaged – Clutch is completely engaged.
- **ii)** Slipping opening – Clutch is slipping towards disengagement.
- **iii)** Synchronization – Layshaft speed equals speed of next gear ratio.
- **iv)** Go-to slipping – Engine speed starts to match layshaft speed.
- **v)** Slipping closing – Clutch is slipping towards engagement.

Different controllers are used for each of these phases as they have different objectives and variable states. The actual gearshifting phase, where the selector fork is
engaged with the desired gear, consists of getting a fork ‘out’ of gear, pushing the selector fork until the synchronizer makes contact with the next gear, and completely engaging it when speed match occurs. [6] makes use of position control until the synchronizer makes contact, and switches over to force based control during speed match and dog engagement. [15] makes use of sliding mode control and has the same phases for a gearshift. The control relies on identification of the balk position along with the gear positions in the H shift pattern, as shown in Figure 8.

![Figure 8: Gearshift positions and control phases [15]](image)

Position feedback is an important part of gearshift process. Controllers discussed in [15] and [6] use analogue sensors to determine current position. Most approaches make use of a selector position and shifter position to define the H pattern on an X-Y co-ordinate system.

With increasing vehicle electrification, gearshift phases get modified to improve drive quality, avoid shift shock and circumvent the torque interruption during shifting. In
general, hybrid vehicles with P1 motors can attain accurate speed matching on the engine side since speed control can be better achieved with an electric motor than by manipulating engine throttle. [16] describes a clutch-less shifting method for a hybrid vehicle architecture with a P2 motor and a centrifugal clutch. The method performs a clutch-less shift by shifting to neutral, uses the motor to match the engine speed to the expected transmission input shaft speed of the next gear, and then shifts into the next gear.

To avoid complete torque interruption during shifting, [17] uses an actuated wet clutch between the input shaft and layshaft as a torque assist mechanism. Hybrid vehicles with a P3 motor can also use this motor as torque assist during gearshifts. The Zeroshift AT has a modified shifter fork mechanism that eliminates torque interruption by shifting in zero time [18].

2.3.3 Shift Scheduling and Drive Quality

Automating the manual transmission allows the TCU to be in control of selecting the gear, and gear shift maps can be designed for economy and performance based on vehicle speed and driver torque request, as is done for AT vehicles [5]. With hybrid vehicles, the supervisory controller can request more torque from the motor and avoid a downshift to keep the engine in its efficient zone [19].

Drive quality being an important part of consumer acceptability, smoothness of clutch engagement and gearshifting should be paid attention to during controller development and vehicle calibration. [5] and [20] performed a quantitative study of AMTs by evaluating AMTs in different vehicle and comparing them with ATs. Different tests such as creep, launch, hill starts and gearshifts were evaluated and on the whole, it was
found that consumers perceive AMTs to be worse than ATs in these aspects. Both papers suggest that drivers tend to be more critical of AMTs than an MT due to the ‘lack of involvement’ in the shifting process and vehicle jerks, which are perceived as normal when driving an MT, are not tolerated when ‘someone else’ takes control. The main reasons are the gearshifts taking the driver by surprise, the torque interruption during a gearshift and longer gearshift time than an AT. Both studies found that in contrast with drivers, the passengers viewed the AMT to be similar or better than the manual transmission.

Using an AMT in a hybrid vehicle architecture has the potential to overcome these negative aspects by avoiding torque interruption during gear shifts and using speed matching to minimize the shift shock.
Chapter 3: Component Description

3.1 Introduction

This chapter describes the setup and operation of the components used in OSU EcoCAR’s AMT system. The AMT system forms the junction between the front powertrain and the rear powertrain, and can be used to couple or decouple them while providing different torque transmission ratios. The AMT system can be split into the clutching and shifting subsystems. Figure 9 shows the components, controllers, and interfaces of the AMT system while Figure 10 shows their location in the vehicle.

![Figure 9: Components in the AMT system](image-url)

<table>
<thead>
<tr>
<th>Component Interfaces</th>
<th>SC – Slave Cylinder</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CCU – Clutch Control Unit</td>
</tr>
<tr>
<td></td>
<td>SCU – Shift Control Unit</td>
</tr>
<tr>
<td></td>
<td>GCM – General Control Module</td>
</tr>
<tr>
<td></td>
<td>HSC – Hybrid Supervisory Controller</td>
</tr>
</tbody>
</table>
Figure 10: Location of AMT system components in OSU EcoCAR 3 vehicle
The following are the two team-developed controllers that oversee the operation of the vehicle:

i) Hybrid Supervisory Controller (HSC) – This is the vehicle supervisory controller, and is referred to as ‘supervisory’ or ‘HSC’ throughout this thesis. This controller is responsible for the entire vehicle operation, and it monitors the operation of the individual component controllers. The HSC is responsible for the energy management, vehicle mode operation, and high-level fault detection and mitigation. The controller used is a dSPACE MicroAutoBox II (MABx II).

ii) General Control Module (GCM) – This controller is primarily responsible for the sensors and actuators on the vehicle since it has greater electrical ability and can interface with switching relays and PWM signals as it has a higher current capability than the HSC. The controller used is a Woodward SECM 112 control module.

3.2 Clutching Subsystem

The clutching subsystem consists of the Clutch Control Unit (CCU), Concentric Slave Cylinder (CSC), friction clutch, diaphragm springs and pressure plate. The CCU consists of the master cylinder, piston, brushless motor, and the controller housed in a single unit. The controller provides position control over the motor, thus controlling stroke on the master cylinder side.

The CSC is connected to the CCU via hydraulic lines. It rests on the transmission wall with the throwout bearing contacting diaphragm springs, and actuates the clutch just
like a standard hydraulic clutch, as seen in Figure 11. In the resting position, the motor position is ‘0’, and the clutch is completely engaged. As an increasing motor position is requested from the HSC, the CCU drives the motor to attain the position, pushing on the piston, which in turn, pushes on the CSC to disengage the clutch.

![Clutch actuation system](image)

*Figure 11: Clutch actuation system*

The supervisory level control for the clutch is based on the motor position and fluid pressure reported by the CCU. The CCU is present on one of the vehicle’s 4 Controller Area Networks (CAN) and sends out status messages and error messages, which the HSC uses for its mitigation strategies.

### 3.3 Shifting Subsystem

The shifting subsystem consists of the Shifting Control Unit (SCU), shifting cables, shifting adapter, and the 5-speed manual transmission. The SCU is an aftermarket unit for manual transmissions, to replace the stock shifter with paddle shifters. As an aftermarket unit, it is not CAN capable, and relies solely on electrical signals for operation.

The package includes a shifting adapter, which consists of a rod that replaces the stock shifter. The adapter is controlled by two cables, one controlling the rotational motion
of the rod (the side-to-side movement of the stock shifter) and the other cable controls the fore-aft motion of the rod (the front-back motion of the stock shifter). The cable controlling the rotation is referred to as the selector cable, and the fore-aft cable is referred to as the shifter cable throughout this thesis.

The cables are operated by two 12V motors controlled by the SCU. The motors are individually attached to potentiometers via linkages. These potentiometers read the position of the motors, and indirectly, the position of the shifter rod. The position read by the potentiometers is used by the SCU for feedback control when shifting, and is also used by the GCM to determine the current gear. The lever arrangement is shown in Figure 12.

Figure 12: SCU actuator lever arrangement

The links of the lever arrangement shown in Figure 12 are:

A – Motor shaft to cable, shaft to potentiometer linkage
B – Motor link to potentiometer arm link
C – Potentiometer arm
D – Push pull cable to shifting adapter
The same arrangement is in place for both the selector and shifter cables. The difference lies between the motor forces. The selector motor experiences lesser force than the shifter motor since the sideways motion (between 1-2, 3-4, etc) on a manual stick is easier compared to the act of pushing it into gear.

As mentioned previously, the selector motor controls the rotational motion of the shifting rod (sideways motion on a stick) while the shifter motor controls the fore-aft motion of the rod (front-back motion on a stick). When the SCU is commanded to shift from 2\textsuperscript{nd} to 3\textsuperscript{rd}, for example, the shifter motor first pulls the shifting rod from 2\textsuperscript{nd}, the selector motor then gets it from the 1-2 slot to 3-4 slot, and the shifter motor pushes it into 3\textsuperscript{rd}. This process is illustrated in Figure 13, with the H shift pattern as reference.

During initial programming of the SCU, the cables were first disconnected from the motor arms, the transmission was manually moved into gear, and the motors were
individually commanded into position until the cable disconnected could fit snugly in place. These positions were calibrated as row-column positions into the SCU through Electrically Erasable Programmable Read Only Memory (EEPROM), and the potentiometer readings were considered while setting the boundaries on the GCM to determine motor positions.

The EEPROM interface allowed the shift positions to be programmed, and shifts could be commanded individually through EEPROM. This was done for the initial sequential testing, to tweak the position values a bit to allow for the variance of the SCU control. The shifting package, being designed for aftermarket use, has optional protection features in it, that can be set through EEPROM. These are downshift protection (does not allow downshifts at higher engine speeds), reverse protection (does not shift into reverse unless speed is low), clutch safety (does not shift unless clutch pedal is pressed).

The gearshift commands are supposed to be received by the SCU through two steering column mounted shift paddles – one for upshifts and one for downshifts. In the EcoCAR vehicle, these two wires are switched by the GCM, emulating the paddle shift functionality. GCM Low Side Output (LSO) drivers are used that ground these wires, complete the circuit in the SCU, and request an upshift/ downshift.

The ‘Clutch Safety’ feature of the SCU is enabled in the vehicle. This feature causes the SCU to wait for a signal indicating that the clutch pedal is depressed. This signal is sent out by the GCM, after looking at the clutch status sent out by the HSC over CAN. While this feature in itself is not necessary, since the HSC and GCM both look at clutch status before requesting a shift, it allows block shifts to be performed. This is accomplished by
requesting multiple upshift/downshift blips, depending on the increments needed, and then
sending the clutch signal. The SCU counts the number of shifts before the clutch switch
signal, and shifts accordingly.

As mentioned before, the SCU uses the potentiometers to determine the position of
the selector and shifter arms, and detects the gear based on these positions. The SCU sends
out the indicated gear over a one-wire network, meant for a digital gear indicator in the
cockpit for aftermarket applications. This protocol, however, cannot be utilized by any
team developed controller, and as a result, probes had to be inserted into the rotary
potentiometers and sent as analogue inputs to the GCM. The GCM thus determines the
gear independent of the SCU.

The SCU has another parameter, ‘stall timeout’. This parameter is the time the SCU
keeps trying to power the motor for if the selector/shifter does not reach the desired
position, before retreating. This parameter is meant to stop trying to shift in case of a
blocked shift. The parameter had to be updated since it was found during testing that the
default timeout was less than the time it took for the synchronizers in the transmission to
spool up to make the shift possible. Using the default timeout worked in static testing, but
would ‘time out’ when shifting at speed. The stall timeout threshold was increased to allow
for synchronization time.
Chapter 4: Modeling

4.1 Introduction

This chapter introduces the full-vehicle model, the clutch and transmission subsystems modeled for full-vehicle and standalone simulations, and the softECU – plant structure followed by the various component models.

The team’s full-vehicle model is called EcoSIM 3, and is developed in the MATLAB/ Simulink environment. Its function is to model the different vehicle components and their controllers to provide a platform to test the vehicle supervisory controller logic. This supports the team’s core philosophy of Model Based Design (MBD), allowing supervisory logic testing before availability of the vehicle prototype. EcoSIM 3 is an energy based model that has a PI controller to act as the ‘driver’, generating accelerator pedal and brake pedal signals to provide torque request to the vehicle supervisory controller. The full-vehicle model helps in estimation of energy consumption of the vehicle and testing out different supervisory energy management strategies.

EcoSIM 3 is structured in a modular fashion, with the full-vehicle model being split up into three sections: Supervisory controller, GCM, and powertrain model, as shown in Figure 14. This structure allows for easy splitting when validating the controller through different in the loop (xIL) testing phases.
The powertrain section of EcoSIM 3 consists of the energy storage components, propulsive components and the vehicle road load model. The structure of the model is in sync with the actual torque flow, allowing for a more intuitive understanding of the model structure. Each component is further split into a softECU, which models the component controller, and the plant, which models the physical side. The softECU subsystem communicates with the supervisory controller and the plant sensors. This makes it possible to emulate the communication as it happens on vehicle. The component level structure is shown in Figure 15.
4.2 Modeling Approach

The OSU EcoCAR team has adopted a Model Based Design approach based on the Systems Engineering V-diagram, shown in Figure 16. This approach focuses on development of a model that allows controller testing to start much before a prototype is available.
The process begins with defining vehicle requirements. Requirements are defined based on component documentation, simulations, past experience, and are updated as new information is available. The vehicle model and the controller logic both go through the development process in parallel. Preliminary models are developed based on requirements and component documentation. Preliminary testing and controls development can be started at this stage since the model developed from component documentation is sufficient to give an estimate of the energy consumption and general vehicle behaviour. The controls logic then goes through the different ‘In-the-loop’ xIL phases, undergoing refinement in each stage.

Component level testing is one of the most beneficial test phases, since it helps realize the interface between the supervisory controller and the component controller. Component handshakes, signal behaviour, component behaviour can be observed and implemented into the softECU and plant models. Actual component behaviour and response times also help to update the requirements to make them more realistic.

The controller and the model jump back and forth between the two arms of the V process, and this results in continuous model updates. The modular structure of EcoSIM goes a long way in easing the xIL transition and thus streamlines the process of regression testing.

The models have the following goals to support controls testing:

i) Suitable I/O fidelity to support requirements testing

ii) Suitable I/O nature to match test environment
iii) Implementation of softECU features and signals needed to test fault detection and mitigation strategies

The component model development process is summarized in Figure 17.

![Figure 17: Component model development summary](image)

Selection of the softECU I/Os to be modeled is an important part of the softECU development process. A component controller transmits a variety of signals on the CAN bus, from heartbeats and physical values to Diagnostic Trouble Codes (DTC) and error signals. It is important to identify the signals that will be used by the supervisory controller and correctly model them to mimic the real process. While all the signals can be modeled, it is not necessary and only adds to development time without helping in controls development. Table 4 shows an example of softECU I/O selection for the CCU softECU development.
The Clutch Control Unit sends out a wide range of signals over CAN, ranging from physical parameters like piston position, line pressure, motor torque, current, etc. to diagnostic signals. The supervisory controller makes use of only a part of these signals for component operation and fault detection. It is enough to model just these signals and model them accurately.

Table 4: CCU softECU I/O selection

<table>
<thead>
<tr>
<th>Total I/Os</th>
<th>Required</th>
<th>In Vehicle</th>
<th>Modeled</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Commands</td>
<td>11</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Heartbeat</td>
<td>2</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Physical Measurements</td>
<td>22</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Component Status/ Errors</td>
<td>11</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>Component version</td>
<td>5</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Reserved</td>
<td>9</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

4.3 Clutching Subsystem

The clutching subsystem used in the vehicle consists of the Clutch Control Unit, the Electrohydraulic Actuator, the hydraulic lines, the Concentric Slave Cylinder, and the disc friction clutch.

The CCU is CAN controlled and is present on the Front Powertrain CAN (FPTCAN), which is the CAN network consisting of the Front Powertrain component controllers, the GCM, and the supervisory controller. The CCU controls the electrohydraulic actuator, which is a brushless motor that drives a recirculating ball spindle that actuates a hydraulic piston to create pressure and displace fluid.
The CSC is used to apply pressure on the fingers to disengage the clutch, and is from a stock automotive application. The components used in the clutching subsystem are listed in Table 5.

Table 5: Clutching subsystem components

<table>
<thead>
<tr>
<th>Component</th>
<th>Interface</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clutch Control Unit</td>
<td>CAN, 500 kbaud</td>
</tr>
<tr>
<td>Electrohydraulic Actuator</td>
<td>Brushless motor</td>
</tr>
<tr>
<td>Slave Cylinder</td>
<td>Hydraulic</td>
</tr>
<tr>
<td>Friction Clutch</td>
<td>Mechanical</td>
</tr>
</tbody>
</table>

The softECU for the CCU is modeled to emulate the startup and shutdown procedure, along with normal component operation and component level fault detection. A well-modeled softECU has enough I/Os and the appropriate level of fidelity so that the supervisory controller interfaces with the CCU as it would on the vehicle, and the CCU interfaces with the plant sensors and actuators.

The softECU is modeled to represent CCU operation to achieve the desired functionality and ensure the appropriate level of component-level fault handling. The various states have been summarized in Figure 18, while the CCU functions during those states are detailed in Table 6. All the modes and their associated functionalities have been modeled in the softECU, with the exception of the ‘Remove Air Mode’. The team does not use the air removal mode provided by the CCU. Table 7 details the signals modeled in the softECU.
Table 6: CCU operation states

<table>
<thead>
<tr>
<th>CCU State</th>
<th>Transition</th>
<th>Action</th>
</tr>
</thead>
<tbody>
<tr>
<td>Secure Mode</td>
<td>On powerup</td>
<td>Clutch engaged</td>
</tr>
<tr>
<td>Operation Mode</td>
<td>Mode request</td>
<td>Obey position request</td>
</tr>
<tr>
<td>Fault</td>
<td>Component fault</td>
<td>Clutch engaged, error message sent on CAN</td>
</tr>
<tr>
<td>Shutdown</td>
<td>Sleep request</td>
<td>Proper shutdown</td>
</tr>
<tr>
<td>Remove Air Mode</td>
<td>Mode request</td>
<td>Pump piston to remove air</td>
</tr>
</tbody>
</table>

Table 7: CCU I/O signals

<table>
<thead>
<tr>
<th>Signal</th>
<th>Nature</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>Powerup</td>
<td>Electrical Input</td>
<td>Component power</td>
</tr>
<tr>
<td>Wake</td>
<td>Electrical Input</td>
<td>Controller wake</td>
</tr>
<tr>
<td>MU02_st_ModeReq</td>
<td>CAN Input</td>
<td>Mode request</td>
</tr>
<tr>
<td>MU02_pos_Des</td>
<td>CAN Input</td>
<td>Position request</td>
</tr>
<tr>
<td>MU01_SleepAckn</td>
<td>CAN Input</td>
<td>Shutdown request</td>
</tr>
<tr>
<td>CP01.Counter</td>
<td>CAN Output</td>
<td>Heartbeat</td>
</tr>
<tr>
<td>CP01_stMode</td>
<td>CAN Output</td>
<td>Current mode</td>
</tr>
<tr>
<td>CP01_pos_Curr</td>
<td>CAN Output</td>
<td>Current position</td>
</tr>
<tr>
<td>CP01_p_Curr</td>
<td>CAN Output</td>
<td>Current pressure</td>
</tr>
<tr>
<td>CP01_errX</td>
<td>CAN Output</td>
<td>Error</td>
</tr>
</tbody>
</table>
The signals are modeled as per their nature on the HIL simulator e.g. powerup and wake signals are physical electrical signals, while the CAN signals are sent over HIL CAN using component DataBase Container (DBC) files.

Emulating mode and fault functionality has the advantage of being able to simulate component level faults during MIL and HIL testing, allowing the supervisory controller to receive the signals it would receive on the vehicle, and thus perceive a fault in a realistic manner.

The clutch disc is modeled using SimDriveline Disk Friction Clutch block available in Simscape. This block has two inputs – one for the input torque and one for the normal pressure. The actual line pressure is modeled using a lookup table that outputs the line pressure based on the piston position. A standalone Simulink model was used to model the piston position – line pressure relationship. This model was made using SimHydraulics blocks in order to better capture fluid material properties. The standalone model is also capable of modeling air in the clutch lines.

Imperfect bleeding of the clutch lines during installation leads to trapped air in the lines. This leads to more piston stroke being required to generate the pressure to be able to push the pressure plates and disengage the clutch. More air in the system leads to the possibility of not being able to achieve clutch disengagement even with complete piston movement.

The model was used to generate position – pressure curves for varying amounts of air in the lines, and was compared to the curves obtained during bench testing with different bleeding procedures.
Figure 19: Motor position – line pressure behaviour with varying air amounts

The data trend from the model is the same as the trend observed during testing, with the line pressure rising slowly at first as air gets compressed. The standalone model was useful to design the ‘Clutch Initialization Procedure’, which will be dealt with in the later sections.

The standalone model was only used to model air in the system. It was not included in EcoSIM 3 since the fast pressure dynamics would necessitate a stiff solver with variable step time, greatly increasing simulation time, and making it unsuitable for HIL simulations. In EcoSIM 3, electrohydraulic actuator position – line pressure – transmissible torque behaviour observed during bench testing was implemented using lookup tables. The black box approach helped reduce simulation time while still maintaining the motor position –
clutch torque relationship. This approach does not, in any way, compromise the fault insertion capability of the model. The model structure is summarized in Figure 20.

![Figure 20: Clutch subsystem model summary](image)

### 4.4 Shifting Subsystem

The shifting subsystem consists of the Shifting Control Unit, actuator motors, shifting cables, and the 5-speed manual transmission. The SCU accepts shift requests from the GCM, and controls the shifter and selector motors in order to move the shift forks and select the desired gear.

The SCU does not have CAN capability, and functions completely on digital inputs, with upshift and downshift ‘blips’ being used to request the desired gear. Since it was meant
to be an aftermarket product to add ‘paddle shift’ functionality to a stock manual transmission, it has limited diagnostic capabilities. The SCU uses potentiometers attached to the motor arm to determine the shifter / selector position. The GCM is probed into these potentiometers and is thus able to detect shifter / selector arm positions. The potentiometer signals are the only feedback signals available from the SCU. The SCU I/O capabilities are listed in Table 8.

Table 8: SCU I/O signals

<table>
<thead>
<tr>
<th>Signal</th>
<th>Nature</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>Powerup</td>
<td>Electrical Input</td>
<td>Component power</td>
</tr>
<tr>
<td>Upshift_Sw</td>
<td>Electrical Input</td>
<td>Electrical blips to indicate gear increments</td>
</tr>
<tr>
<td>Downshift_Sw</td>
<td>Electrical Input</td>
<td>Electrical blips to indicate gear decreases</td>
</tr>
<tr>
<td>Clutch_Sw</td>
<td>Electrical Input</td>
<td>Electrical blip to indicate clutch status</td>
</tr>
<tr>
<td>ShifterPos</td>
<td>Electrical Output</td>
<td>Analogue signal indicating shifter pot position</td>
</tr>
<tr>
<td>SelectorPos</td>
<td>Electrical Output</td>
<td>Analogue signal indicating selector pot position</td>
</tr>
</tbody>
</table>

These signals are implemented as electrical signals on the HIL. Certain adaptations were made in the HIL wiring harness to implement the Switch signals. The GCM operates the switch signals through its LSO drivers. An LSO needs to have a pull-up resistor somewhere in the circuit. The SCU has an internal pull-up that can be selected through EEPROM. The schematic in Figure 21 shows the external pull-up resistors that had to be added to the HIL simulator wiring harness to have proper inputs going in to the SCU softECU.

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The internal operating states of the SCU are unknown since the component documentation does not mention operating states and no such diagnostic information is available through serial interface. This resulted in the softECU being modeled with just two basic operating states – ‘Off’ and ‘Normal Operation’, depending on the state of the SCU powerup. The states are summarized in Table 9.

Table 9: SCU operating states

<table>
<thead>
<tr>
<th>SCU State</th>
<th>Transition</th>
<th>Action</th>
</tr>
</thead>
<tbody>
<tr>
<td>Off</td>
<td>Initial / power off</td>
<td>Shifting not available, sensors powered off</td>
</tr>
<tr>
<td>Operation Mode</td>
<td>Power on</td>
<td>Obeys shift requests, sensors powered on</td>
</tr>
</tbody>
</table>

The softECU counts the gear increments / decrements requested using Simulink Counter block. The shift counting operation was implemented on the softECU to mimic the behaviour of the SCU. For example, if the current gear is 2\textsuperscript{nd} and 5 upshift blips are
sent, the SCU shifts into 5th gear. Similarly, if 4 downshift blips are requested, the SCU shifts into neutral. The SCU had its EEPROM parameters set so that it would include neutral in the counting sequence, and reverse gear functionality was disabled.

The clutch switch functionality was also implemented in the softECU to allow block shifts to happen. This is done by counting the upshift/ downshift blips until the Clutch_Sw signal is true, then shifting to the appropriate gear.

The SCU affords many protective functionalities, such as overspeed protection, where it does not allow a downshift when there is a risk of overspeeding the engine. These functionalities were disabled through EEPROM, since they are inherently taken care of by the supervisory controller. Consequently, they were not included in the softECU logic.

The transmission is modeled using ‘Double- Sided Synchronizer’ blocks available in SimDriveline. The block represents a double-sided synchronizer with two back-to-back dog clutches, two back-to-back cone clutches, and one translational detent. Translating the shift linkage in either direction causes it to engage with the cone clutch- dog clutch on that side, causing it to transmit torque input through the clutch pair. This mechanism simulates the behaviour of the actual synchromesh gearbox, with the shifting linkage translation being similar to moving a shift fork in the transmission. The translational detent represents the force required to overcome the speed difference of the cone clutches and engage the dog clutch. This also serves to model the physical force required to move the shift fork and ‘select’ a gear.

The double-sided synchronizer block can model one pair of gears on the same shift fork, and hence three double-sided synchronizers were used to model gear pairs 1-2, 3-4,
and 5-R, representing the arrangement on H pattern shifts. It must be mentioned that in an actual manual transmission, reverse gear does not have synchromesh, and is often selected by sliding the idler gear into place. Often, 5th and R are not present on the same shift fork. For the sake of simplicity, the model has 5 and R on the same double-sided synchronizers, and no idler gear is modeled. The arrangement is shown in Figure 22.

![Diagram of transmission model with double-sided synchronizers](image)

**Figure 22: Transmission model with double-sided synchronizers**

The gear ratios were set using Simscape ‘Simple Gear’ blocks added on the input to each double-sided synchronizer block. The constant efficiency setting was used and an efficiency of 90% was used for all gears.

The double-sided synchronizers do not model inertia. A lumped layshaft inertia was modeled on the transmission input. The lumped inertia assumption is valid since all gears
move along with the transmission shaft and countershaft, and the inertia remains constant. Thermal effects were not modeled for the transmission.

The shifting mechanism was modeled using a PI controlled actuator to apply force to cause movement on the shift linkage, as shown in Figure 23. The PI can have three target positions for each double-sided synchronizer as shown in Table 10.

Table 10: Shift linkage positions

<table>
<thead>
<tr>
<th>Shift Linkage Position</th>
<th>Torque connection</th>
</tr>
</thead>
<tbody>
<tr>
<td>Center</td>
<td>No torque transfer</td>
</tr>
<tr>
<td>Left</td>
<td>Torque transfer from left conical clutch i.e. gear ratio corresponding to left input HA</td>
</tr>
<tr>
<td>Right</td>
<td>Torque transfer from right conical clutch i.e. gear ratio corresponding to left input HB</td>
</tr>
</tbody>
</table>

Figure 23: Gear shift actuating mechanism
The double-sided synchronizer block outputs the translational position of the shift linkage as well, making feedback control possible, and allowing potentiometer sensor models to be based off these positions. The softECU actuates the proper shift linkages based on the gear shift desired through the PI controller. An upshift from 2\textsuperscript{nd} to 3\textsuperscript{rd} gear, for example, would require pushing the linkage on 1-2 synchro from ‘right’ to ‘center’ (out of 2\textsuperscript{nd} into neutral) and then pushing the 3-4 synchro shift linkage from ‘center’ to ‘left’ (from neutral to 3\textsuperscript{rd}). Simscape linkage positions are shown in Figure 24.

![Figure 24: Shift linkage positions for 2-3 upshift](image)
The PI parameters were tuned to obtain the same shift times as those taken by the shifting unit-transmission combination during bench testing. A comparison is shown for the 3\textsuperscript{rd} to 4\textsuperscript{th} upshift in Figure 25.

![Shifter Potentiometer Voltages 3-4 Upshift](image)

*Figure 25: Shift time comparison for 3-4 upshift*

The sensor models convert the shift linkage positions reported by the Simscape blocks into a selector potentiometer voltage and a shifter potentiometer voltage. The voltage values are selected based on the values observed from component testing. As in the actual case, the selector voltage is based on which double sided synchronizer is selected, and the shifter voltage is based on the shift linkage position. Figure 25 shows these voltages for the 3-4 upshift.

The sensor voltages are used by the GCM to determine the selector and shifter arm positions and thus recognize the current gear. These signals are implemented as analogue
electrical signals on the HIL simulator. A summary of the entire shifting process is shown in Figure 26.

Figure 26: Shifting subsystem model summary
Chapter 5: Component Level Testing

5.1 Introduction

This chapter describes the testing done at a component level for both the clutching and the shifting subsystems. The team has performed component level testing on the major powertrain components, to validate their operation and controls before integrating them on the vehicle. The purpose of the component level testing in the case of the clutch and the transmission was to get the controller handshakes down correctly and characterize component behaviour to increase the fidelity of the simulation models.

5.2 Controller I/O Testing

Component documentation usually describes the component controller operation in detail and is enough to give a basic understanding of the controller startup procedures and fault handling capabilities. Testing the controllers is essential to validate the controller handshakes and to make sure the signals being sent out by the team-developed controllers are in the manner the component controller expects to receive them. This process usually involves providing 12V power supply and wake signals to the ECUs and trying to communicate with them over a suitable communication channel (CAN), then sending out the handshake signals manually one at a time until the controller reaches its operational state. Testing out ECU I/Os before bench testing ensures the controller is ready for the bench testing.
The CCU was tested by connecting it to CANoe, powering it up, and recognizing the version of the CAN DBC file flashed on it, since the documentation provided by the supplier had three different dbc files. The CCU was then connected to the HIL simulator, and operation in different modes was verified. Piston movement at this stage was executed slowly since the CCU was standalone without any load on it.

The SCU was tested for I/O compatibility in a similar fashion, connecting the Upshift, Downshift, ClutchSwitch, and two potentiometer sensor wires to the GCM, and commanding shifts from the GCM. Sequential shifting and block shifting (without shifter cables attached) was tested to verify proper signal generation. The smallest time for which a blip could be sent out so that it could be detected by the SCU was also determined. It was necessary that the blip time be small enough since that added to the required shifting time. For example, to downshift from 5th to 2nd requires 3 downshift blips. Setting the blip ‘ON’ time to be 0.5 sec requires a blip generation time of 3 sec, adding a lot of time to the shifting process. Making the blip time too low, on the other hand, would confuse the SCU, making it wrongly count the blips and shift into the wrong gear. The smallest time for shift detection was found to be 0.07 sec, and it was set to be 0.1 sec in the logic for robustness.

After the SCU and CCU were individually tested and the I/O interface was established, both were connected to their respective controllers, and the entire shifting logic, elaborated in the next chapter, was executed to check their behaviour in real time, set the appropriate time thresholds to account for signal noise, delays, etc. This testing, while not representative of in-vehicle behaviour, involved actual controllers and resulted
in a first-cut validation of the handshakes and operation. Figure 27 shows the setup used in this I/O testing.

![Figure 27: SCU I/O testing setup](image)

### 5.3 Shifting Testing

The transmission was tested on a test rig consisting of the 5-speed transmission and an electric motor attached to the input shaft. The purpose of the motor was to provide motion to the input shaft to check shifting while providing rotation to the components to smoothen the shifts. The transmission was connected via the shifting cables to the SCU, which was, in turn, connected to the GCM, the controller responsible for the shifting operation. The purpose of this test rig was to conduct an accelerated shift testing to identify problematic shifts patterns, if any, and set the correct position and temporal limits for potentiometer-position based gear detection by the GCM.
The gear position co-ordinates were first mapped manually by commanding the SCU into different positions through the serial interface. These positions were found to be slightly different than the mapping done without the GCM in the loop, since the GCM connected to the potentiometers introduced external resistance in the circuit. Calibrating the gear position co-ordinates requires some iterations to get them ‘just right’ (make sure the variance on the motor position would still get the shifting rod into the correct slot for a successful shift).

Accelerated shift testing was done by feeding automated gear requests to the GCM and having it generate the corresponding blips as it would on the vehicle. The shifts were sent out both in sequential (N-1-2-3-4-5) and block (2-4, 5-2, etc.) patterns. The following issues were encountered and resolved during testing:

i) Motor Issues – During initial stages of testing, the shifter arm on the motor kept shearing off, resulting in a slotted arm being put in. After about 1500 shifts, the shifter motor itself broke, with the nylon teeth inside the motor being stripped off. This resulted in new motors with metal teeth and higher torque rating being used on the shifting unit.

ii) Slack in joints – The stock shifting package had the cables connect to the studs on the shifting unit and shifting adapters by quick disconnect versions of rod ends. This arrangement inherently has play at the ends. The joint play, coupled with the play in the shifting adapter, was enough to cause the unit to miss shifts occasionally. This slack was confirmed to be the cause since when the positions for the selector motor were noted after a failed shift, and they were the same positions programmed
into the SCU. This led to modifications being made in the linkages. New rod ends were installed and the play in the system was reduced. Along with the mechanical modifications, the ‘slack compensation’ feature of the SCU was used. This feature is used to adjust for cable slack and makes the motors overshoot their target position by a programmed amount. These two modifications made the shifting more robust and reduced the variance caused by slack.

iii) Potentiometer failures – It was noticed a few times that during component powerup, the selector potentiometer would read invalid values, both on the serial interface and the actual potentiometer voltage as measured by a multimeter. The failure manifested as a ‘pull-up to supply’, with the potentiometer reading its extreme position and the voltage reading the supply voltage. This voltage would remain pulled up even if the potentiometer arm was moved. The SCU does not look for sensor validity, and read the potentiometer as being at the extreme end of its travel. In such a condition, if the SCU is commanded to shift, it tries to actuate the motor to move the arm to the other end, but has no position feedback since the potentiometer reads a constant voltage. This results in the motor arm moving until it is physically blocked either by the transmission or the linkage constraints. This resulted in implementation of potentiometer validity detection on the GCM and HSC, with shifts not requested in case of invalid readings from the potentiometers. This issue was taken care of by re-soldering the potentiometer connections. This issue has not been observed on the vehicle at all.
The shift testing had around 4000 shifts being put on the test rig, validating the controller handshakes and multiple shifts through all gear combinations except reverse. While reverse gear was initially programmed through EEPROM, and tested on the rig, it was disabled on the SCU since vehicle travel in reverse was decided to be done through the REM alone. A sample plot of the selector-shifter potentiometer read values is shown in Figure 28. This plot was useful to observe the variance of the positions, both due to actual position variance, as well as the electrical noise.

![Selector Shifter positions](image)

*Figure 28: Potentiometer reported values on shifting test rig*

This position variance helped to set the limit threshold on gear position recognition to mark a successful shift by the SCU. The thresholds thus set were neither too restrictive nor too lenient, and avoided overlap between adjacent positions.
5.4 Clutch Testing

After testing the shifting subsystem, the transmission was used on a different test rig, this time with the clutch and Dual Mass Flywheel (DMF) attached to it. The aim of this testing was to have the cluthing subsystem installed as it would be on vehicle, validate clutch operation, and characterize the torque transmissibility of the clutch at different positions from complete engagement to complete disengagement. This behaviour was then used to fine tune the cluthing strategies and increase the fidelity of the plant models.

The transmission was supported by the test rig, and the dual mass flywheel was bolted to the test rig frame, as shown in Figure 29. This had the effect of locking the flywheel in place to serve as reference to observe clutch slip. The transmission was set in 4th gear, since it had a 1:1 gear ratio and input torque was thus same as the output torque. The output shaft of the transmission was free to rotate. This was attached to a yoke with a hexagonal bolt (the torque application point), and a torque wrench was used to apply torque at this point to record the torque at which the clutch began to slip. On the vehicle, the engine output shaft spins clockwise (seen from the front), and so does the transmission output shaft. The engine thus sees the road load torque acting in the opposite direction (clockwise seen from the back). The torque wrench was thus used to apply torque in the clockwise direction from the output shaft. The 1:1 direct ratio meant the torque recorded by the wrench was the slipping torque seen by the clutch.
The test rig was first used to observe the CCU piston position – line pressure behaviour, to set the overpressure protection limits and design the pressure based control that was employed for the Clutch Initialization Procedure (CIP). The CIP is dealt with in detail in the next chapter. The data obtained from these tests was also used to develop the models mentioned in the previous chapter. The pressure trends were obtained each time the installation and bleeding was carried out. At each motor position, the line pressure and displacement on the CSC were recorded. The pressure trends are shown in Figure 30.
The procedure followed for the torque transmissibility test was to command the motor to various positions in steps from completely disengaged (the output shaft could be spun freely by hand) to completely engaged (zero position on motor). Torque was applied on the wrench until it began to slip – this was recorded to be the peak torque, and further torque was applied to keep the clutch slipping steadily - this was recorded as the slipping torque. An average of 3 to 4 readings was taken to get both the peak torque and the slipping torque corresponding to the clutch position. The position-torque plot for the test rig is shown in Figure 31.

Figure 30: Motor position – line pressure plots on different setups

![Position Pressure plots with varying air](image)
In Figure 31 it is seen from the position – torque plot that as the clutch is released (going right to left on the x axis) there is no torque transmitted during the initial travel, then it increases almost linearly and plateaus to the maximum transmissible torque around 250 Nm. This behaviour is similar to what is experienced with a conventional clutch pedal. The bite point is usually around 60% to 80% disengagement. If the transmissible torque is plotted against percent engagement in Figure 32, a more intuitive idea is obtained.

The vehicle launch bite point shown in Figure 32 is the clutch position required for initial vehicle movement during an engine only launch. To move the EcoCAR 3 vehicle from standstill, a wheel torque of about 180 Nm is required. This translates to about 20 Nm of torque on the engine side (and roughly the same at the clutch side), which is attained at around 30% engagement (which corresponds to 70% disengagement).
Figure 32: Clutch transmissible torque plotted against percent engagement
Chapter 6: Control

6.1 Introduction

This chapter explains the control logic and strategies used to handle the gear shifting process. Owing to the different vehicle operating modes available due to the hybrid nature of the vehicle, strategies differ according to the operation mode of the vehicle. Depending on the operation mode and component speeds, different clutch engagement strategies are employed to suit differing scenarios from vehicle launch to a series-parallel mode transition.

6.2 Shifting Logic Overview

The overall shifting process is controlled by the supervisory controller, and the logic is situated in the ‘Propulsion Actuators’ section of the supervisory code structure. It is placed after the ‘Mode Operation’ logic and before the ‘Torque Security’ logic. This placement allows the shifting logic to access component status through CAN and accept gearshift commands and clutch engagement mode requests from the Mode operation section.

The ‘AMT Actuators’ section is further broken down into three main sections:

i) Overall Shifting Logic

ii) Clutch Initialization

iii) Clutch Engagement Control
The Shifting Logic section deals with the complete gear shifting procedure, from receiving a gear change request to handling component torques, performing clutch disengagements and requesting gear change from the GCM. The process is summarized in Figure 33.

![Figure 33: Overall shifting logic in HSC](image)

The important steps involved are:

1) Engine torque cutoff – Accelerator pedal signal to the Engine Control Module (ECM) is set to zero, cutting off torque coming into the clutch.
2) Clutch disengagement – After engine torque is cutoff, a disengagement request is sent to the later part of the logic, where it gets converted into a position request for the CCU.

3) Gear change – The HSC receives the clutch piston position over CAN. Once the clutch is confirmed to be in the disengaged state, the HSC sends out the gear request as well as the clutch status to the GCM over CAN. The GCM performs the gear shift, as explained in the later sections, and sends out the current gear and ‘Shift_Complete’ signal over CAN.

4) Speed match (optional) – Once the transmission is in the desired gear, the HSC estimates the transmission input shaft speed for the new gear ratio based on the REM speed. This speed is set as the target speed for the PI controller that requests torque from the BAS to change the engine speed so it matches the transmission input speed. The speed matching is done if the BAS is in the proper operational state and the engine speed is not high enough. This part of the logic has not been validated on the vehicle. The speed match is said to be complete when the engine speed and transmission input speed difference has been less than ~100 RPM for more than a certain time.

5) Re-engage clutch – In this phase, a clutch engagement request is sent to the ‘Clutch Engagement Control’ section of the algorithm. The section engages the clutch using an engagement strategy suitable for the vehicle speed and the speed difference between the engine and the transmission.
6) Allow engine torque – After clutch engagement is complete, driver torque request is again sent out to the engine, after being rate limited depending on the vehicle mode in operation.

The speed matching process using the BAS is currently not implemented on the vehicle, and the different phases of shifting process are shown for 3-4 upshift in Figure 34.

![Figure 34: Shifting process events for a 3-4 upshift in engine only mode](image)

6.3 GCM Shifting Logic

The GCM controls the actual shifting process through the SCU. It is connected electrically to the SCU and sends out the Upshift/ Downshift blips to the SCU through its LSO drivers. The HSC requests a gear shift to the GCM through CAN and the GCM sends the shifting status and SCU status to the HSC. Figure 35 shows the shifting logic.
Following are the important steps in the execution of a gearshift by the GCM:

1) Blip generation – The GCM compares the new gear request with the current gear, determines the incremental difference, and generates the corresponding number of blips. For example, a shift from 2\textsuperscript{nd} to 4\textsuperscript{th} will generate 2 upshift blips while a shift from 2\textsuperscript{nd} to 1\textsuperscript{st} will generate 1 downshift blip. The shortest blip time offering reliable shifting as observed during component testing was 0.07 sec. To account for larger transport delays and in-vehicle noise, this blip time was set to 0.1 sec. After gear shift blips are generated, the ‘Clutch\_Sw’ blip is generated. This is an indication to the SCU that the clutch is disengaged and it can start actuating the shift cables. An example of blip generation for an upshift and a downshift is shown in Figure 36.
2) Shift reporting – The GCM monitors the selector and shifter potentiometer voltages to determine the current gear. If the actual gear does not match the requested gear within a time threshold, the GCM tries to resolve the failed shift. A failed shift could either be a shift into an incorrect gear, or a mechanical blockage causing the shifter/selector to get stuck at an odd location.

3) Failed Shift Handling (FSH) – In case of a failed shift, the GCM asks for a shift to neutral, and then tries to shift into desired gear again. After three failed attempts, it flags a fault and declares a failed shift. Temporary shift blocks are resolved by this retry method, while something more serious warrants further investigation and the number of tries are limited to three. Another method of handling failed shifts was to shift into neutral, shift into 3\textsuperscript{rd} or 4\textsuperscript{th} to realign the dog clutch teeth and then try...
to shift again. Most of the failed shifts were found going into $1^{st}$ gear, as is often the case with manual transmissions.

6.4 Clutch Initialization Procedure

The CCU initialization handshake, position determination, and fault handling is handled in this section of the logic. CCU initialization handshake occurs during vehicle start up, and involves powering up the CCU, receiving status messages on CAN and requesting a transition to ‘Operation Mode’. In case of a fault reported by the CCU, the mode requested is ‘Secure Mode’, and CCU failure section of the supervisory failure detection and mitigation strategies is activated. During vehicle shutdown, the clutch is first engaged and sleep signal is sent to get the CCU into shutdown mode.

![Figure 37: CCU startup and shutdown handshakes](image)

The entire clutch engagement-disengagement strategy is developed in terms of normalized clutch position, where 0 represents fully engaged position and 100 represents
fully disengaged. Representing the logic in terms of normalized position has two advantages:

i) More intuitive understanding

ii) Adaptability

The electrohydraulic motor position at which the clutch is completely disengaged varies between installations, and greatly depends on how well the system was bled. In vehicle, for example, the motor position at complete disengagement is 1500°, while on the bench test rig it was around 3300°. The Clutch Initialization Procedure, or Post Service Procedure, is used to estimate the position of complete disengagement after servicing of the clutch subsystem, or after the vehicle has been in use for some time.

When the CIP is activated, the logic ramps up the position request to the CCU, and monitors the line pressure reported by the CCU. When a certain reference pressure is reached, the logic uses the motor position at that point to estimate the motor position at complete disengagement, and reports it as the ‘Max Disengaged Position’. The estimation procedure is based on the position-pressure behaviour observed during bench testing of the clutch.

It is seen from the position-pressure curves that depending on the air in the system, the rise in pressure with increasing motor position is slow initially, as the air gets compressed. After a certain pressure, the trend is linear and it becomes easier to estimate the motor position at complete disengagement. This pressure is considered to be the reference pressure. For the estimation algorithm, the reference pressure is taken to be 8 bar.
From the standalone model developed for the clutch system, simulations were done with differing air volumes in the lines. The curves generated were then fitted to a line from 8 bar to 18 bar of pressure, and data from bench testing was used to find the distance between the point at 18 bar pressure and the disengagement point. Using this relationship, a lookup table was created. This lookup table estimates the motor position at complete disengagement once the position at 8 bar pressure is known. Table 11 shows a comparison of actual disengagement positions and estimated disengagement position when the position at the reference pressure was known.

Table 11: Comparison of CIP estimated disengagement positions

<table>
<thead>
<tr>
<th>Comparison</th>
<th>Position at 8 bar</th>
<th>Estimated Disengagement</th>
<th>Actual Disengagement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test Rig 1</td>
<td>3900</td>
<td>5196</td>
<td>5200</td>
</tr>
<tr>
<td>Test Rig 2</td>
<td>2150</td>
<td>3309</td>
<td>3300</td>
</tr>
<tr>
<td>Vehicle</td>
<td>550</td>
<td>1555</td>
<td>1500</td>
</tr>
</tbody>
</table>

The disengagement position estimated by the algorithm very closely matches the actual disengagement for the test rigs, but is slightly higher for the vehicle. On the test rig, it was very easy to feel the resistance on the clutch by spinning the transmission output shaft. The exact point of disengagement could thus be recorded as the point where no resistance was offered by the clutch. On the vehicle, however, complete disengagement is taken to be the point where the wheels are able to spin freely on a lift with the transmission locked in gear. This state has the clutch slipping at a low friction state. When the clutch is completely disengaged, rattle is noticed as the clutch is ‘floating’. Even though the point of complete disengagement on the vehicle is close to 1550, the disengaged state is
considered to be at 1500, so as to load the clutch up a bit to eliminate the rattle at a disengaged state. The CIP was thus validated against three different setups with different air amounts.

The estimation algorithm is also useful in knowing if complete disengagement of the clutch is possible. With too much air in the system, a full stroke of the master piston will not achieve complete disengagement of the clutch and the proper bleeding of the system needs to be carried out. The CIP can also be carried out at certain intervals during normal running, to adapt to changes in line air volume over time.

**6.5 Bite Point Finding Procedure**

The bite point, as defined earlier, is the clutch engagement which is enough to cause vehicle movement by transmitting engine torque to the wheels (in 1st gear). A human driver operating a car with a manual transmission for a while knows the bite point of that particular vehicle and is able to release the clutch fast to that point during vehicle launch. The vehicle launch clutch engagement strategy used in EcoCAR 3 vehicle follows a similar approach, and it requires knowing the bite point of the clutch.

The procedure involves getting the vehicle on flat ground, and initializing the Bite Point Finding Procedure (BFP). The supervisory controller starts with a disengaged clutch, transmission in first gear, and the engine running, and starts a ramped release of the clutch. The clutch output speed is monitored and once movement is detected, the clutch is disengaged and the clutch position at which movement was detected is recorded as the bite point. The recorded bite point is then used as reference for clutch release during vehicle
launch. The procedure does not request torque from the engine, since the engine’s idle controller usually generates enough torque to start pulling the car away.

The bite point estimate is around 1100 degrees motor position. The full disengagement in-vehicle is at 1500 degrees, so the bite point is around 30% engagement, which matches the prediction in Figure 32 in 5.4. The BFP process during a test on the vehicle is plotted in Figure 38.

![Figure 38: Execution of BFP on vehicle](image)

### 6.6 Clutch Engagement Strategies

The hybrid architecture of the vehicle offers immense scope for use of the AMT. It allows the clutch operation to be executed differently from a conventional IC engine powertrain. The P1 motor in the EcoCAR vehicle, for example, makes it possible to better
control engine speeds during shift events, making speed matching possible and eliminating the shift shock during clutch engagement. The P3 motor makes possible motor assisted launches, thereby eliminating the need to slip the clutch to launch the vehicle. Certain modes on the EcoCAR 3 vehicle, however, like the ‘Engine Only’ mode, make use of the clutch the same way a conventional IC engine vehicle with a manual transmission does.

6.6.1 Clutch Engagement Types

Different types of clutch engagement options have been developed to suit the engagement need of the vehicle operation mode. The vehicle mode operation section of the supervisory control logic decides the engagement mode suitable for the vehicle mode, and the Clutch Engagement Control section of the logic engages the clutch according to this selection. Three clutch engagement options are available:

i) Direct engagement

ii) Counter based clutch engagement

iii) Assisted launch engagement

**Direct Engagement** - This is the simplest clutch engagement type and just involves completely engaging the clutch without considering at component speeds or vehicle speeds. This type is used during vehicle modes where the engine and transmission are not needed, and the clutch is free to be engaged with the transmission in neutral. The mode operation is responsible for ensuring that it is safe to engage the clutch, after verifying that the transmission is in neutral. Modes where this engagement type is used are Startup, EV Only, and Shutdown.
Counter Based Clutch Engagement – This is a comprehensive clutch engagement method and caters to unassisted vehicle launch, gear shifting, and clutching in during a series – parallel mode transition at speed. It is based on a counter to control clutch engagement. The counter speed is based on the clutch output (transmission input) speed, and in essence, involves a fast release of the clutch until the bite point, slow release through the bite region until clutch lockup, and then fast release until complete engagement. The counter is used during vehicle launch. This strategy also considers speed difference between the engine speed and transmission input speed to provide for a gradual engagement.

Assisted Launch Engagement – Since the engine is not the only component producing propulsive torque, the P3 REM can be used to get the vehicle moving, and the clutch is then engaged when the transmission input shaft speed matches the engine speed.

6.6.2 Vehicle Launch

This section deals with the clutch engagement strategy employed during an ‘Engine Only’ launch, where the IC engine is the only source of propulsive power and the launch is similar to a conventional manual transmission vehicle. Different approaches were considered to execute the launch. These approaches involved different control strategies to modulate engine torque and regulate clutch position.

The ‘Counter Based Clutch Engagement’ uses the method that was introduced in the previous section. The rationale behind developing this launch method was to make the supervisory controller launch the vehicle the same way a human would.

This method controls release of the clutch based on the clutch output speed. When the driver presses the accelerator pedal, the clutch release is started. The initial clutch
release is fast, and continues until bite point (set through BFP) is crossed. The logic then switches over to the clutch speed based release table, which slows down the clutch release, to make the clutch dwell near its bite point and engage gradually. Once the clutch output speed is near engine idle speed, clutch release is again quickened and once clutch output speed is close to engine output speed, the clutch is completely engaged fast, so that the launch process is complete. The controller structure is shown in Figure 39. The counter starts on receiving the enable signal, and is primarily controlled by the position and speed based rates. The engine speed based compensator starts disengaging the clutch if the engine speed drops below idle speed, and the speed difference based compensator slows down the engagement if the speed difference between the engine and the clutch is high.

Figure 39: Counter based launch algorithm structure

The vehicle starts with the transmission in 1st gear, the engine idling, and the clutch handshake completed, with the vehicle in a ready state. The inputs required by this logic are listed in Table 12.
Table 12: Important signals used by counter based launch method

<table>
<thead>
<tr>
<th>Input</th>
<th>Origin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clutch Engagement Request</td>
<td>Mode Operation</td>
</tr>
<tr>
<td>Engine Speed</td>
<td>FPTCAN</td>
</tr>
<tr>
<td>Clutch Output Speed</td>
<td>Input Conditioning</td>
</tr>
</tbody>
</table>

The counter is implemented as a resettable integrator, with the reset being the Clutch Engagement Request, and the value to be integrated is the ‘rate’ that is provided by a lookup table. The clutch output speed is estimated in the ‘Input Conditioning’ section of the supervisory logic. This estimation makes used of the REM speed sent over CAN by the REM inverter, and then uses the current gear to determine the transmission shaft input speed. While the transmission does have a Transmission Output Shaft Speed (TOSS) sensor, the REM speed is more reliable since it is a processed and filtered signal sent out by the REM inverter, and is thus used to determine the clutch speed. The clutch output speed is then used by the lookup table to determine the clutch engagement rate. An example of this lookup table is shown in Figure 40.
The engagement logic also modulates the engine torque so that excessive accelerator input does not cause high engine speeds during launch. The current strategy is tailored for non-aggressive launches and limits the accelerator pedal input to the engine so the engine speed stays below a set limit. The strategy does not exclusively control engine torque, as some of the other approaches, but allows the driver to remain in control. The clutch engagement strategy also considers engine speed, and overrides the counter to disengage the clutch a bit if the engine speed starts falling below idle speeds, to avoid the possibility of stalling the engine during the launch. An example of this strategy is shown in Figure 41, with data for an ‘Engine Only’ launch on the vehicle.
The clutch engagement trajectory is plotted from 100% (completely disengaged) to 0% (completely engaged). Vehicle movement is seen after clutch position crosses the bite point. The clutch position trace exhibits the rapid release until bite point, dwell until lock up, and rapid release until complete engagement. The clutch takes around 8 seconds to completely engage.

This is a very slow vehicle launch, but the reason for the slow launch lies in the very tall gearing ratio from engine to wheel even in 1st gear. A comparison of gear ratios of the stock Camaro and OSU EcoCAR vehicle are shown in Table 13.
Table 13: Comparison of gear ratios for OSU EcoCAR and stock Camaro

<table>
<thead>
<tr>
<th>Vehicle</th>
<th>Gear Ratio</th>
<th>Differential Ratio</th>
<th>Overall Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>EcoCAR 3</td>
<td>2.95</td>
<td>2.77</td>
<td>8.17</td>
</tr>
<tr>
<td>2016 Camaro 1st Gear</td>
<td>4.40</td>
<td>3.27</td>
<td>14.39</td>
</tr>
<tr>
<td>2016 Camaro 2nd Gear</td>
<td>2.59</td>
<td>3.27</td>
<td>8.47</td>
</tr>
</tbody>
</table>

The overall ratio for the stock Camaro is 14.39 while that of the EcoCAR vehicle is 8.17. This is taller even than the ratio of stock Camaro in 2nd gear. Launching the EcoCAR vehicle in 1st gear is equivalent to launching the stock Camaro in 2nd gear. The extremely tall gear ratio results in the slow vehicle launch.

To compare the controller based launch against a human driver launch, a third pedal was added to the driver footwell as seen in Figure 42 and connected to the supervisory controller. This third pedal was the same as the stock accelerator pedal, but the mounting was done a bit differently to provide the feel of a clutch pedal. The pedal input was then mapped inside the logic, with a 100% pedal press corresponding to 100% disengagement in the clutch position request to the CCU. A switch was added inside the logic to be able to switch between the driver clutch pedal and the logic requests.

The idea behind installing the temporary drive-by-wire clutch was to see how fast a human launch was compared to the controller launch, compare the human clutch release profile to that of the controller, and, if possible, use that trajectory as feedforward for vehicle launch with a wraparound PI controller.
The clutch release profile for a human controlled launch are shown in Figure 43. Similar vehicle launch times were seen when the driver was in complete control of both the accelerator and clutch pedals, and the drivers perceived the launches to be difficult and slow, and an aggressive launch usually resulted in the engine stalling.

The drivers first took a couple of dry runs to get used to the clutch pedal position and feel. The initial launches were either very harsh or ended up stalling the engine. Once the drivers got an idea of the bite point and the expected vehicle response, a clutch release trajectory similar to the one produced by the controller was obtained. It is to be noted that the clutch position trajectories are quite similar to the controller directed launch, with the three distinctly defined regions.

The controller was also tested on the vehicle model in EcoSIM 3, and similar results were obtained from the simulation, as seen in Figure 44.
Figure 43: Clutch release for human controlled launch

Figure 44: Vehicle launch in simulation
The results are the same as seen on vehicle, with the clutch taking around 8 seconds to engage completely. The simulation was repeated for the stock Camaro ratios of 4.40 and 3.27 to obtain the results shown in Figure 45.

![Clutch Position Diagram](image)

*Figure 45: Simulation results for vehicle launch with stock Camaro gear ratios*

With the stock Camaro ratios, the lockup phase is faster and clutch engagement takes 5 seconds. If a more aggressive clutching strategy is used with the stock ratios, it is possible to get a faster launch, as seen in Figure 46. The deeper ratios make it possible to have a faster launch owing to higher wheel torque and faster engagement of the clutch. When the aggressive strategy is simulated with the EcoCAR gear ratios, the engine stalls in spite of the clutch starting to disengage. This is seen in Figure 47.
Figure 46: Simulation launch for stock ratios with aggressive controller

Figure 47: Simulated vehicle launch with EcoCAR gear ratios
6.6.3 Performance Launch

The vehicle has a ‘Performance Mode’ tailored for acceleration, and to retain the feel of a performance vehicle. Launching the vehicle in performance mode uses the REM, the engine, and the BAS to provide maximum wheel torque. The clutch engagement strategy used during a performance launch is kept aggressive to get the engine torque to the wheels as soon as possible.

The strategy uses the APP to determine the aggressiveness of the launch required. Depending on how aggressive the driver wants the launch to be, the supervisory requests varying torques from the REM, the engine, and the BAS, and also determines when to engage the clutch. Below is the supervisory logic described for a WOT launch, which would be the case when doing an acceleration test or a 0-60 mph run.

The supervisory logic demands maximum torque from all propulsive components. At the start, just the REM provides full torque to get the car rolling, the clutch starts to engage, and then the BAS and the engine are requested to provide full torque. An aggressive clutch engagement strategy is possible during performance launch since the combination of BAS torque and engine torque does not let the engine stall out during the quick clutch engagement.

The clutch engagement during a performance launch can be seen in Figure 48.
Clutch engagement during a performance launch depends on the accelerator pedal position and vehicle speed. Since component torque requests are linked directly to accelerator pedal position, quickly releasing the clutch at lower APPs can result in stalling the engine.

At lower APP, the launch is similar to an REM assisted launch, where the REM provides torque at the start, and the clutch engages at a speed above engine idle speeds, with the engine and BAS belting out torque post clutch engagement. BAS torque is requested only above 60% APP.
With the accelerator pedal floored, it indicates an actual performance launch request. In this condition, the REM provides full torque at the start, the engine gets 10% of the driver APP as its torque request as long as the clutch is disengaged. This allows the engine to rev up a bit to avoid a stallout. At a speed of above 1 mph, the clutch is quickly engaged, and the engine and BAS get full torque request when the clutch is more than 90% engaged. The resultant clutch engagement is seen in Figure 48 and the engagement process for a high APP and a low APP are shown in Figure 49.

**Figure 49: Clutch engagement logic in performance mode**

Clutch engagement for two extreme values of APP in performance mode are shown in Figure 49, but the actual logic gradually transitions between these two extremes based on APP. The clutch engagement speeds are defined based on the APP, and component torques are requested based on the APP as well. A summary of the entire logic is given in the next section.
In Figure 48 during a full performance launch, it is seen that the engine speed continues to be greater than the clutch speed i.e. the clutch continues to slip for about a second even after the clutch is completely engaged. This is due to the fact that the combined torque produced by the BAS and the engine is greater than the maximum transmissible torque of the clutch at complete engagement. As was observed during torque transmissibility test of the clutch, the clutch can transmit around 250 Nm of torque at maximum engagement. While this is enough to handle the maximum torque produced by the engine alone, the BAS at peak torque of 60 Nm causes an addition of an extra 160 Nm of torque, leading to a maximum crankshaft output torque of ~ 320 Nm.

6.7 Vehicle Mode Based AMT management

![Mode Operation and Actuator Commands Diagram]

Figure 50: Breakdown of AMT control tasks

The AMT logic is split into two sections in the code – the operational parameters and high level requests are made in the ‘Mode Operation’ section that deals with vehicle mode, and the actual operation is governed based on these requests in the ‘Actuators’
section of the supervisory logic. A breakdown of the actual tasks handled by each section is shown in Figure 50.

The AMT management strategies, involving clutching, shifting, and component torque management are described below for the major vehicle operation modes.

6.7.1 Vehicle Startup

The supervisory controller logic first goes into this mode when the vehicle is started, either for the first time, or after a shutdown. This mode involves closing the right relays, component startup handshakes, and transition into subsequent modes on successful startup. The gear request is neutral and the clutch is commanded to engage after verifying the transmission is in neutral. The direct engagement option is used to engage the clutch since the vehicle is stationary.

6.7.2 EV Only Mode

EV only mode involves operating the vehicle using the REM alone. The engine and BAS are woken up and enabled but not operational, and do not provide any torque. This mode has the transmission in neutral and the clutch engaged.

6.7.3 Charge Sustaining Mode

The Charge Sustaining mode uses all torque producing components on the vehicle and the torque is split to maintain the State Of Charge (SOC) of the battery pack. The vehicle may operate either in series or parallel mode, depending on the torque request and the SOC. In series mode, the clutch is disengaged to decouple the front powertrain from the wheels, and the REM alone propels the wheels. The engine charges the battery pack through the BAS, which acts like a generator. In parallel mode, the clutch is engaged and
the engine and REM both power the wheels, with the REM providing either propulsive torque or performing regeneration, based on the SOC and torque request. The torque flows during these two operations is shown in Figure 51.

![Torque Pathways](image)

*Figure 51: Torque pathways in series and parallel operation*

Gear selection in this mode depends on driver torque request. The most economic gear is chosen based on vehicle speed and torque request. The counter based clutch engagement type is chosen, and a gentler engagement table is selected. The counter based engagement strategy is chosen since it also considers speed difference between the engine and the clutch during engagement. This is essential since there might be a considerable difference between these speeds when transitioning from series to parallel mode. The counter does not have to be used for a vehicle launching, since this strategy allows a series
to parallel transition only when the clutch speed is above engine idle speed, and switches to series mode if it falls below this speed. The clutch engagement in this mode is less aggressive to minimize jerks, since the REM can provide wheel torque while the front powertrain is decoupled.

6.7.4 Performance Mode

Performance mode has been implemented as a vehicle operation mode to retain the feel of a performance vehicle. In this mode, all torque producing components are allowed to supply peak torques to the wheels. This is a permanent parallel mode, with the front drivetrain connected to the wheels at all times except launch and gearshifts. The engagement strategy for the clutch has been dealt with in the previous section, and this section looks at the high-level logic clutch engagements, gear changes, and torque requests.

Gear selection is based on a performance shift map, and a fast clutch release table is used for quick clutch engagements. Transition to this mode can occur only at a standstill, similar to getting the stock Camaro into a launch control mode. Transition into this mode involves starting up the engine, disengaging the clutch and shifting the transmission into 1st gear.

Clutch engagement and disengagement requests are made based on accelerator pedal position, Brake Pedal Position (BPP), and vehicle (clutch output) speed. The following requirements were considered to determine the engagement / disengagement speed thresholds:

i) Early engagement at high APP for faster launch

ii) Late engagement at low APP to avoid stalling
iii) Early disengagement to avoid stalling under hard braking

iv) Disengagement speed should be lower than engagement speed.

Separate tables were made for engagement and disengagement speed thresholds, to cater to the requirements listed above. Starting with the lowest speed that would allow the clutch to engage without stalling the engine at 100% APP, the engagement threshold curve was made for APP position. Starting with a disengagement speed that would not stall the engine, the disengagement speed threshold curve was made for the APP position. The curves were then slightly adjusted to maintain some gap between them to add hysteresis and eliminate hunting. The resultant curves are shown in Figure 52.

![APP Based Clutch Speed Thresholds](image)

*Figure 52: APP based clutch speed thresholds*
At 100% APP, it was found that the clutch could be engaged at a clutch speed of 100 rpm. While this speed is very low compared to the engine idle speed, the engine and BAS both produce propulsive torque at high APP, and the engine does not stall owing to the combination of engine/BAS torque at the front and REM torque at the wheels, which quickly raises clutch speed while the clutch engages.

At low APPs, the clutch disengagement speed threshold is set around 1000 -1200 RPM, which is slightly higher than the engine idle speed. The steepest threshold changes occur above an APP of 80%, which is where the most aggressive launches are requested. At APP below 60%, no BAS torque is requested, and hence the thresholds are near the engine idle speed.

Different disengagement speed thresholds are required based on brake pedal position. The disengagement thresholds have to be higher to allow for time to disengage the clutch under heavy braking forces. If the same thresholds as Figure 52 are maintained, there exists the possibility of the engine stalling out if the rapid deceleration does not allow enough time for the clutch to disengage. Figure 53 shows the disengagement threshold depending on the BPP.

The logic is set up so that in the event the BPP based table requests a disengagement and the APP table requests an engagement (an unlikely occurrence, will occur only if the accelerator pedal and the brake pedal are simultaneously pressed at particular values), the logic will favour a disengagement. The fault detection part of the supervisory logic code also sets the conditioned APP to zero if both pedals are pressed simultaneously.
Braking below a BPP of 20% is subjectively considered to be light braking for the EcoCAR 3 vehicle, and braking above 30% BPP is considered moderate to heavy. The BPP based disengagement threshold speeds were set to ensure adequate time for declutching the engine under very hard braking.

While there exist separate thresholds for APP and BPP, the maximum value requested by each is taken into consideration when engaging or disengaging the clutch.

6.7.5 Series Mode

This mode operates the vehicle completely in series mode, and was designed to be the limp home mode in case of a failure in the AMT system. This mode requests both
neutral gear and a disengaged clutch, to allow for the possibility of failure in either the clutch or transmission subsystem.

### 6.7.6 Engine Only Mode

In this mode, the engine is the only source of propulsion, and this mode was designed to be the limp home mode in case of failure in the HV torque producing components. This mode operates in lower gears (1st/2nd/3rd) since the engine alone cannot generate enough wheel torque at higher gears owing to the tall gearing ratios. The counter based clutch engagement type is used and a gentler clutch engagement table is used. The vehicle launch is done solely by the engine and the process mentioned in 2.3.1 is followed in this mode. Clutch based speed thresholds similar to those in Figure 52 are used to request clutch engagement / disengagement. The thresholds are again decided based on APP and BPP, but the threshold tables differ from those shown in Figure 52 and Figure 53, since the engine is the only torque producing component now and a conventional vehicle launch is required by slipping the clutch.

There is no threshold table based on APP, since the brake is the only deciding factor now that the engine is the only propulsive source. The clutching logic and the speed thresholds are shown in Figure 54. The counter based clutch engagement strategy is used for this mode since the engine is the only propulsive source, and the vehicle is now equivalent to a conventional IC Engine vehicle. After vehicle launch, subsequent gearshifts are handled by the counter based strategy as well, since it has a compensator to slowly engage the clutch in case of a speed difference between the engine and the clutch.
The BPP based speed thresholds are mentioned in terms of absolute vehicle speeds since complete disengagement of the clutch is required when bringing the vehicle to a halt, and the transmission is in 1st gear at these speeds. When the vehicle is at rest initially, the clutch is disengaged and the transmission is in 1st gear. As the driver presses the accelerator pedal, engagement is requested and the vehicle launch clutch engagement logic is triggered. If the accelerator pedal is released while the vehicle is below the engagement threshold, clutch disengagement is requested and the launch is aborted. If, however, the vehicle is above the thresholds and the accelerator pedal is released, the clutch is still kept engaged, as would be the case in a conventional manual transmission vehicle. If the accelerator pedal is released and the speed falls below the disengagement threshold (naturally or through application of brakes), the clutch is disengaged and the vehicle can be stopped without stalling the engine.

Figure 54: Clutching logic and speed thresholds for engine only mode
6.7.7 Vehicle Shutdown

This mode involves the shutdown handshakes for all components and the power-down procedure for the vehicle. The gear requested is neutral and clutch engagement is requested after the transmission is confirmed to be in neutral. The clutch is engaged at shutdown since that is the natural power-off state for the clutch. The transmission being in neutral and the clutch being engaged are some of the required conditions for the ‘Shutdown Complete’ signal being sent to mark a successful shutdown.

6.7.8 Parked Charging Mode

This mode is used for engine charging where the engine charges the ESS through the BAS while the vehicle is in Park. In this mode, the transmission is kept in neutral and the clutch is disengaged.

6.7.9 Miscellaneous Modes

Modes that do not involve any propulsive components, such as ‘Accessories Mode’ and ‘Charging mode’ have the transmission in neutral and the clutch engaged. In charging mode, it does not matter since the vehicle relay is not closed and hence the SCU and CCU do not have power.
Chapter 7: Conclusions and Future Work

7.1 Accomplishments and Challenges

The team accomplished the task of automating the shifting process and the shifting logic for its EcoCAR vehicle, which was one of the most important system level goals for Year 3. The developed logic was robust and worked reliably throughout vehicle testing and the Year 3 competition at General Motors’ Milford Proving Grounds in Milford, Michigan. The extensive testing done by the team, both at a component level and the vehicle level, ensured safe and reliable operation of the vehicle in Year 3 competition.

The team won the Year 3 competition held at Milford and Washington D.C., and the work done for this thesis contributed to the following awards for individual events:

- dSPACE Embedded Success Award – 1st place
- Mathworks Modeling Award – 2nd place

One of the main challenges faced during the development of the AMT system controls was the lack of inbuilt fault diagnosis on the SCU. The SCU is not capable of telling the supervisory controller its status at a given time, and any faults it might have encountered. This results in the supervisory controller having no control over the shift itself; it can just command shifts. Another drawback is the lack of adaptability on the SCU-it relies on good calibration by the user for mapping the gear positions, and does not go through an initialization process. Moreover, since the supervisory controller cannot
command the SCU to move the motor to a certain position, it cannot execute a position calibration procedure itself. This resulted in extra steps being added to the shifting logic for safety and fault detection.

7.2 Future Work

The AMT system controller needs to be refined for drive quality and faster overall shifting times. The team plans to use the BAS to perform speed matching during a gear shift so that the clutch can be released fast while eliminating the shift shock and improving the drive feel. The team also plans to change the gear ratios of the transmission and the differential, making them deeper to have better launches, both in engine only and performance mode. The Year 3 controls strategy uses a basic shift scheduling strategy, but to maximize economy and performance, a better shift scheduling strategy needs to be developed and optimized to reduce gear hunting and keep the engine at a point of high efficiency. This requires validating the existing engine fuel map on the engine dynamometer and recalibrating it, if necessary. To increase the fault detection capabilities of the SCU, the team plans to develop an SCU of its own, incorporating sensors at different locations and setting up the controller to be on CAN. These hardware and software upgrades will ensure better utilization of the AMT system, a powerful tool in a hybrid vehicle, while improving the drive quality and energy consumption of the vehicle.
Bibliography


