Control and Drive Quality Refinement of a Parallel-Series Plug-in Hybrid Electric Vehicle

A Thesis

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By

Matthew Alexander Yard, B.S.

Graduate Program in Mechanical Engineering

The Ohio State University

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Master’s Examination Committee:

Dr. Shawn Midlam-Mohler, Advisor

Dr. Giorgio Rizzoni, Advisor
Abstract

Increasingly stringent government regulations and the rising price of oil are causing automotive manufactures to develop vehicles capable of obtaining higher fuel economies and lower emissions. To achieve these goals, automotive manufactures have been developing hybrid-electric vehicles (HEV) and plug-in hybrid-electric vehicles (PHEV) that use both electricity and petroleum based fuels as their power sources. While hybridizing the vehicle powertrain improves the fuel efficiency of the vehicle, the addition of multiple power sources and modes creates many unique issues with vehicle driveability that are difficult and time-consuming to calibrate.

The drive quality (also referred to as driveability) of a vehicle refers to the vehicle’s responsiveness to driver inputs and overall smoothness of the vehicle in operation. A vehicle with good drive quality results in a comfortable ride for both the driver and passengers. Drive quality is a subjective measure of the driver’s perception of the dynamic responses of the vehicle. It is typically measured using highly trained test drivers that analyze the vehicle’s behavior under specific driving conditions such as take-off, acceleration, pedal tip-in/tip-out, gear shifts, and braking. Assessing and improving vehicle drive quality in this way can be time consuming and is subject to human error. Recently, major automobile manufacturers have begun to move towards the use of specially-designed software packages to evaluate drive quality objectively.
This thesis discusses the development of control strategies for The Ohio State University’s EcoCAR 2 competition vehicle with an in-depth analysis of the effects of the control strategies on the objectively-measured drive quality of the vehicle. The OSU EcoCAR 2 vehicle had serious issues tip-in drive quality due to the high amount of gear backlash present in the powertrain. A feedforward control was implemented to smooth the driver’s torque request to minimize the negative effect of gear backlash on the tip-in drive quality. The control system developed to accomplish this contains easily calibratable parameters that can be quickly adapted to be used in future EcoCAR vehicles and is mostly independent of the powertrain architecture.

A control system for implementing regenerative braking in the OSU EcoCAR 2 vehicle was developed and calibrated to provide smooth torque delivery and positive drive quality characteristics. This included both creep torque at low vehicle speed as well as coastdown torque at higher vehicle speeds in order to mimic the behavior of a conventional vehicle with a traditional internal combustion engine and automatic vehicle.

Finally, a robust and reliable control system is presented for shifting the automated manual transmission in the OSU EcoCAR 2 by speed matching the input and output shaft speeds using an electric machine. This control system includes a gear shifting handshaking process that was implemented between the supervisory and transmission controllers to facilitate the complex gear shifting process. The effects of this unique gear shifting process on the drive quality of the vehicle is also discussed.
This thesis is dedicated to my parents, Dennis and Mary Jo, and my girlfriend, Katherine, for all their patience, love and support.
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Vita

June 2008 ................................. Tuscarora High School

June 2012 .............................. B.S. Electrical & Computer Engineering,
                                   The Ohio State University

August 2012 to Present ................. Graduate Research Associate,
                                      Department of Mechanical Engineering,
                                      The Ohio State University

Publications


Fields of Study

Major Field: Mechanical Engineering
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Chapter 1: Introduction

1.1 Motivation

Government regulations are requiring automotive manufacturers to develop vehicles that are capable of achieving lower emissions and higher fuel economies than ever before. Additionally, as oil prices increase, fuel efficiency is becoming a major factor in the vehicles that consumers purchase. These trends are forcing automotive manufactures to develop advanced technologies to increase the fuel efficiency of their vehicles. These technologies range from increasing the efficiency of the internal combustion engines through technologies such as direct injection to the hybridization of the vehicle’s powertrain.

While hybridizing the vehicle powertrain improves the fuel efficiency of the vehicle, the addition of multiple power sources and modes creates many unique issues with vehicle driveability that are difficult and time-consuming to calibrate. Additionally, hybrid electric vehicles often employ complex control strategies to further increase the fuel economy, but these often further exacerbate drive quality issues that already exist in the powertrain.
1.2 Objective

The objective of this thesis is to:

- Measure the drive quality of the Ohio State EcoCAR 2 vehicle using objective drive quality measurement tools
- Improve the drive quality by developing control strategies that reduce the impact of driveability issues present in the vehicle’s powertrain
- To develop these control strategies to be easily implementable and calibratable in future EcoCAR competition vehicles.

1.3 EcoCAR 2: Plugging into the Future Competition

EcoCAR 2: Plugging into the Future is an Advanced Vehicle Technology Competition (AVTC) headline-sponsored by the United States Department of Energy and General Motors. The three-year competition challenges student teams to re-engineer a 2013 Chevrolet Malibu for increased fuel economy and decreased emissions, while maintaining the vehicle’s original performance and consumer acceptability. Each team is tasked to design, build, and optimize a hybrid powertrain for their vehicle, resulting in a fully functioning prototype vehicle by the end of the third year. The prototype vehicles created by each team are evaluated over a wide range of metrics that include consumer acceptability, fuel economy, emissions, driveability, acceleration and braking.
1.4 Vehicle Architecture

The OSU vehicle architecture is a Parallel-Series PHEV [6], [7], [8]. The architecture can be seen in Figure 1.1. The front axle is powered by a 1.8L Honda engine clutched directly to a 6-speed automated manual transmission that drives the front wheels. An 80 kW peak electric machine is connected by a belt to the input to the transmission input shaft. The rear axle is powered by another 80 kW peak electric machine. This is connected to a single speed gearbox which drives the rear wheels. This architecture has great versatility in its operation due to the front and rear drives, as well as the transmission’s ability to be used as an additional clutch when set to neutral or one of the six gear ratios. This allows the vehicle to operate in charge-depleting, charge-sustaining series, and charge-sustaining parallel modes.

The different operating modes of the vehicle and the transitions between operating modes are shown in Figure 1.2. At high battery state of charge (SOC), the vehicle
initially operates in charge depleting mode, which is shown in Figure 1.2A. In charge depleting mode, the vehicle is all-wheel drive as both the front and rear electric machines are powering the vehicle at the same time. The vehicle then transitions from charge depleting to charge sustaining mode by shifting the transmission to neutral and engaging the engine clutch when the battery SOC drops below 18%. While in charge sustaining mode, the vehicle operates in either series or parallel mode depending on vehicle speed. When vehicle speed drops below 48 kph the vehicle operates in series mode, as shown in Fig. 1.2B. When the vehicle speed increases above 56 kph, the vehicle operates in parallel mode, as shown in Figures 1.2C. The 8 kph hysteresis between the series-to-parallel and parallel-to-series transition is to prevent the vehicle from oscillating between series and parallel modes when driving at around 48-56 kph. The vehicle transitions between the series and parallel modes by shifting into and out of 6th gear.

1.5 Vehicle Control Architecture

The Ohio State team has developed a modular and hierarchical control system approach widely used in the automotive industry. Figure 1.3 shows a diagram of the control system architecture. The controllers highlighted in red were programmed and calibrated by the Ohio State team. These controllers include the supervisory controller, the engine control unit, and the general control module, which includes the automated manual transmission controls. The rest of the control system consists of many stock and commercial low-level control modules that manage individual vehicle subsystems. All low level controllers report to the supervisory controller which manages the overall operation of the vehicle. Benefits of this approach include the
Figure 1.2: OSU EcoCAR 2 Vehicle Operating Modes
ability to develop low-level controllers on a per-system basis as well as facilitating a flexible hardware configuration to accommodate modifications. Extensive use of Controller Area Networks (CAN) facilitates this modular and hierarchical approach as well as integration with the vehicle’s existing GMLAN network.

The supervisory controller is responsible for making high-level decisions that affect the general state of the powertrain (e.g., engine on/off) and the operating mode of the vehicle (e.g., engine start, charge sustaining, charge depleting, etc.). The engine controller manages all low level control and emissions performance of the engine. The automated manual transmission and all auxiliary controls, such as coolant pump controls, are performed by vehicle’s General Control Module (GCM). Additional low level stock controllers are used to manage the vehicle DC-DC converter, brakes, body control module, electric power steering and assembly line diagnostic link sub-systems. The front and rear electric machines, clutch and battery management systems all use their original commercial controllers. Additional detail on the control strategies within these three main control modules is given in the following sections.
Supervisory Controller

The supervisory controller is responsible for determining what mode of operation the vehicle is in and how to split the driver’s torque request to the different torque producing components in the vehicle. For parallel operation of the vehicle, the Equivalent Consumption Minimization Strategy (ECMS) is used [9]. The primary objective of ECMS is to find a local minimum for an equivalent fuel metric while also satisfying a number of equality and inequality constraints. These constraints are imposed by the driver’s power demand, the actuator torque limitations, and the high voltage battery SOC power availability and energy capacity limitations. To reduce complexity, in series mode, a simple conversion to determine the driver’s power request is used to request the highest efficiency operating points of the front electric machine and engine while the rear electric machine drives the vehicle. The charge depleting mode strategy has a gear selection algorithm that selects the current gear in the transmission based on the power consumption of the two electric machines and the speed limitations of the mechanical components connecting the front electric machine to the transmission. The torque split between the front and rear electric machine in charge depleting mode is pre-determined based on an offline optimization. The supervisory control strategy also manages mode transitions, charging, start-up, and shutdown sequencing.

Engine Controller

The engine is used in the charge sustaining series and parallel operating modes to extend the range of the vehicle. The engine was converted from CNG to E85, which required the development of a new engine control unit. This was accomplished by programming and calibrating a rapid prototyping controller using a model based
calibration approach [10], [11], [12]. The overall structure of engine controller is shown in Figure 1.4. Each of the control systems in the engine controller was developed, tested, programmed and calibrated on an engine dynamometer test setup.

**General Control Module**

The transmission control software is part of the team’s General Control Module. The transmission software is responsible for coordinating the movements of the two linear actuators used to control the X and Y coordinates of the transmissions shift lever in order to shift the transmission into the correct gear. The transmission controller is also in constant communication with the supervisory controller during a gear shift to ensure the shift is executed successfully. More detail on the transmission gear shifting strategy incorporated in this controller is given in Chapter 6.

1.6 Thesis Overview

This thesis discusses the development of control strategies for The Ohio State University’s EcoCAR 2 competition vehicle with an in-depth analysis of the effects of the control strategies on the objectively-measured drive quality of the vehicle. An overview of the chapters contained in this thesis is provided below.
• Chapter 2 - Literature Review

  – Chapter 2 summarizes three topics:

    1. Various hybrid vehicle architectures
    2. Drive quality metrics
    3. Control techniques for improving drive quality

• Chapter 3 - Tools and Methods

  – Chapter 3 discusses tools used to objectively measure drive quality of the vehicle powertrain and the drive quality metrics it measures, as well a vehicle simulator used to help develop the control strategies implemented in this thesis.

• Chapter 4 - Accelerator Pedal Tip-in Control

  – Chapter 4 details the problems present in the OSU EcoCAR 2 vehicle’s tip-in drive quality performance and a control strategy to drastically improve the tip-in drive quality. Additionally, this control strategy is further refined and compared back to the baseline performance.

• Chapter 5 - Regenerative Braking Control

  – Chapter 5 details the control strategy for implementing a regenerative braking system in the OSU EcoCAR 2 vehicle. This includes creep and coastdown torque control as well as additional regenerative braking done when the brake pedal is pressed. Additionally, the effect of this control strategy on the vehicle’s deceleration drive quality performance is explored.
• Chapter 6 - Transmission Shifting Control
  
  – Chapter 5 details the control strategy and gear shifting handshake process developed to shift gears in the vehicle’s automated manual transmission. Additional refinements made to the control strategy are discussed as well as a brief assessment of drive quality is performed and presented.

• Chapter 7 - Conclusions and Future Work
  
  – Chapter 7 summarizes the work completed and future applications or additions.
Chapter 2: Literature Review

2.1 Introduction

The following chapter provides background information for hybrid vehicle architectures, vehicle drive quality metrics, and control strategies for improving vehicle driveability.

2.2 Hybrid Vehicle Architectures

The introduction of electric machines and high voltage batteries into automotive applications has allowed for the emergence of electric vehicles (EV), hybrid electric vehicles (HEV), and plug-in hybrid electric vehicles (PHEV) into the consumer automotive marketplace. Each of these types of electrified powertrains have a variety of architectures and their own advantages and disadvantages.

2.2.1 Electric Vehicles

An electric vehicle powertrain consists of one or more electric machines, a high voltage battery pack, and does not contain an internal combustion engine. As a result of eliminating the need for an internal combustion engine, electric vehicles use no liquid fuel and have no tailpipe emissions. Electric vehicles also benefit from the
high efficiency of electric machines at converting electrical energy from the battery pack to mechanical tractive power. Electric vehicles are also capable of recapturing a portion of the mechanical energy that is normally lost during braking and converting it into electrical energy that is stored in the high voltage battery. This operation mode is called regenerative braking and increases the range and efficiency of the electric vehicle. Despite all the advantages associated with electric vehicles, there are major drawbacks that prevent them from being widely adopted by the general public. A major disadvantage of electric vehicles is the low energy density of the current battery technology when compared to fossil fuels in a conventional vehicle with an internal combustion engine. Because of this, the overall range of a typical electric vehicle is less than 100 miles. Also, due to the high cost of the high voltage batteries, electric vehicles have a high initial purchase price. Additionally, the scarcity of electric vehicle charging stations and long amount of time it takes to charge the battery pack can make electric vehicles less convenient than a conventional vehicle for the average consumer [1], [13].

2.2.2 Hybrid Electric Vehicles

Hybrid electric vehicles use both electricity and some type of liquid fuel (i.e. gasoline, diesel, ethanol, etc.) to propel the vehicle. This requires hybrid vehicle powertrains to have an internal combustion engine in conjunction with a high voltage battery and one or more electric machines. Both the engine and electric machines are used to meet the torque demand of the driver, therefore the engine can be downsized to improve overall vehicle fuel economy while still maintaining the performance of a conventional vehicle. HEVs operate in a charge sustaining mode, therefore they
do not consume any external electric power to charge the battery system. Instead, the battery is recharged by the electric machine operating in a generating mode. This occurs either during regenerative braking or when the driver torque demand is below that of the engine maximum torque (i.e. during cruise or at standstill). Since the battery charge is maintained, HEVs do not suffer from the low range of electric vehicles. Although HEVs have advantages that make them more appealing to the average consumer, they do still have some disadvantages. HEVs lack the all-electric driving capability of electric vehicles. Additionally, due to the addition of a high voltage battery pack and one or more electric motors, HEVs are typically substantially more expensive than their conventional counterparts [1], [13].

2.2.3 Plug-in Hybrid Electric Vehicles

A plug-in hybrid electric vehicle is essentially the same as hybrid electric vehicle with a larger capacity high voltage battery that is plugged-in to the electrical grid to be recharged. This allows a PHEV to be operated in a charge depleting mode. This can be done either by operating as a fully electric vehicle until the battery is depleted and the internal combustion engine is turned on to extend the range of the vehicle or by operating like an HEV with a heavier emphasis on using electricity than the internal combustion engine to meet the driver torque demand. This is typically determined by the size of the electric machines in the vehicle and whether they are capable of meeting the entire torque demand. A PHEV combines both the benefits of the highly efficient, all-electric operation of an EV and the benefits of a long range and high fuel economy of a HEV. However, due to the additional battery capacity,
PHEVs are even more expensive than HEVs, which prevents them from being a more viable option for the general consumer [14].

2.2.4 Configurations of HEVs and PHEVs

Hybrid electric vehicle and plug-in hybrid electric vehicle powertrains can be implemented in three main configurations: series, parallel, and multi-mode configurations. These architectures are described in the following section.

Series

In a series architecture, there is an internal combustion engine and generator combination whose sole purpose is to provide electricity to the battery and tractive system in order to maintain the battery state of charge. The tractive system is made up of one or more electric machines that are capable of solely propelling the vehicle. A series architecture is shown conceptually in Figure 2.1.

Series architectures have the distinct advantage of being very simple to design, control and integrate into a vehicle. Additionally, because the engine is completely decoupled from the driven wheels, the engine speed is independent of vehicle speed and therefore can operate in its most efficient operating regions at all times. The primary disadvantage of series architectures is that power has to be converted from mechanical (internal combustion engine) to electrical (generator) to mechanical again (traction motor), losing efficiency in each conversion. These efficiency losses at highway speeds can begin to outweigh the gains from operating at optimal efficiency zones in the engine and electric machines. Another potential disadvantage is that series architectures require at least two electric machines, whereas parallel architectures can require as little as one electric machine, which can add to the cost of the vehicle [1].
Parallel

In a parallel architecture, the internal combustion engine and electric machine(s) can directly supply torque to the driven wheels through a mechanical coupling. This mechanical coupling can be a gearbox, a belt, a chain, or even directly to the driven axle. A conceptual illustration of a parallel architecture can be seen in Figure 2.2.

Major advantages of the parallel architecture include efficiency and compactness. Since both the engine and the electric machine can directly supply torque to the driven wheels, there is no energy conversion process such as the one seen in the series architecture. Additionally, since there is no need for a generator and the electric machine does not need to be sized to meet the full torque demand of the driver, the design can be very compact and fit in many small vehicles. A major disadvantage of the parallel architecture is that the internal combustion engine is coupled to the
Figure 2.2: Conceptual Illustration of a Parallel Hybrid Configuration [1]
wheels and therefore cannot operate in an optimal operating region for efficiency at all times like it can in the series architecture. Another disadvantage is that parallel hybrid require complex control strategies to operate efficiently [1].

**Multi-Mode**

A multi-mode hybrid architecture combines the advantages of both the series and parallel architectures. It uses a planetary gearset to decouple the engine speed from the wheel speed, allowing the engine to operate in more efficient regions. A typical multi-mode configuration is shown in Figure 2.3.

The generator/motor electric machine can be used in this configuration to change the engine speed for a given vehicle speed. When the generator/motor machine speed is negative (opposite direction of the torque, the machine is in generating mode. In this mode, the engine power is split between the drivetrain and the generator. When the generator/motor speed is positive, the machine is in motoring mode, adding power to the driven wheels. The traction motor is always adding additional power to the drivetrain, power that either comes from the generator (in generating mode) and/or from the battery (in motoring mode). The multi-mode architecture combines the advantages of series and parallel architectures, but requires an additional electric machine as well as the planetary gearset, which adds additional cost and weight to the vehicle. Additionally, it adds even greater complexity to the controls of the powertrain than either series or parallel architectures [1].

**2.3 Improving Drive Quality**

The drive quality (also referred to as driveability) of a vehicle refers to the vehicle’s responsiveness to driver inputs and overall smoothness of the vehicle in operation. A
Figure 2.3: Illustration of a Multi-Mode Hybrid Configuration [1]
vehicle with good drive quality results in a comfortable ride for both the driver and passengers. This section describes common issues associated with drive quality and reviews some of the control techniques used to overcome driveability problems in conventional and hybrid electric vehicles.

Drive quality is a subjective measure of the driver’s perception of the dynamic responses of the vehicle. It is typically measured using highly trained test drivers that analyze the vehicle’s behavior under specific driving conditions such as take-off, acceleration, pedal tip-in/tip-out, gear shifts, and braking. Assessing and improving vehicle drive quality in this way can be time consuming and is subject to human error. Recently, major automobile manufacturers have begun to move towards the use of specially-designed software packages to evaluate drive quality objectively [15]. This software, called AVL DRIVE, utilizes learning methods (such as neural networks) to process acceleration data obtained from specific driving conditions. AVL DRIVE is discussed in more detail in Chapter 3.

2.3.1 Critical Driving Conditions to Drive Quality

In this section, issues that commonly arise in both conventional and hybrid vehicles due to torque interruptions, inherent driveline characteristics (gear backlash), sluggish response (delay, time lag, etc.), and mode transitions (engine start/stop, etc.) are discussed.

Gear Shifting

The most commonly studied problem affecting drive quality in both conventional and hybrid-electric vehicles is gear shifting. During a gear shift, torque to the driven wheels is temporarily interrupted and if that transition is not carefully controlled,
it can cause very serious driveability problems. In [16], recent drive quality work done in the control of automatic, automated manual, and continuously-variable and electrically-variable transmissions is presented. Each type of transmission requires unique control approaches to manage the driveability characteristics of the vehicle.

In automatic transmissions, the traditional control system is through clutch-to-clutch shifts between the on-coming and off-going clutches.

2.3.2 Symptoms of Poor Drive Quality

The following terms describe symptoms of poor vehicle drive quality [17], [2]:

- **Hesitation or delay**: momentary lack of response from the vehicle to driver inputs
- **Sluggish**: powertrain does not produce as much torque as expected resulting in less vehicle acceleration than expected at a given accelerator or brake pedal position
- **Hard start**: engine either fails to start or shuts down unexpectedly
- **Surge**: torque produced by powertrain varies under steady accelerator pedal position causing variations in vehicle acceleration
- **Noise and oscillations**: noise or vibrations in the powertrain especially during hard acceleration or deceleration, engine start/stop, gear shifts, and braking

An example of poor drive quality during an accelerator pedal tip-in event is shown in Figure 2.4. Figure 2.4 shows that following an increase in throttle position, the vehicle’s acceleration experiences a delay and sag before rising and overshooting the
desired acceleration. The overshoot is also coupled with large oscillations in longitudinal acceleration before finally settling down. All of these things can be felt by the driver and result in poor vehicle driveability [2].

2.3.3 Objective Measures of Vehicle Driveability

Many studies have been performed on how to improve the drive quality of a vehicle during specific vehicle operation events. These events include gear shifts, pedal tip-in/tip-out, smoothness of vehicle operation and hybrid vehicle electric launch. The majority of these studies were performed by collecting data, analyzing it offline with an objective measure and then changing the control parameters that affect the desired event to try to improve the driveability of the vehicle. The objective measures used in these studies include dynamic response characteristics, longitudinal jerk, amount of
time delay, peak-to-peak longitudinal acceleration, number of engine start and gear shift events, energy spectral density plots, and vibration dose voltage. Each of these objective measures are described in more detail in the following sections.

**Dynamic Response Characteristics**

Dynamic response characteristics include system behaviors such as overshoot, rise time, rise rate, oscillation frequency, etc. In [18], longitudinal vehicle acceleration was measured during full throttle accelerator pedal tip-in events. The resulting acceleration traces filtered using an FFT technique and were then characterized as 2nd order responses in terms of overshoot, natural frequency, damping ratio, rise rate, and rise time.

**Longitudinal Jerk**

Another objective measure of vehicle driveability used is jerk, the differential of acceleration. Jerk can be used to measure harshness of gear shifts and engine start events, as well as accelerator tip-in/tip-out. In [19], shift quality of kick-down gear shift events for automatic transmission vehicles was studied. Mechanical properties, such as jerk and acceleration profile, were measured and correlated with subjective evaluations performed by participants.

**Time Delay**

Time delay is an objective measure of how long the delay is between the driver accelerator or brake pedal input and the resulting acceleration of the vehicle. In [3], the amount of time delay is used as a measure of driveability in the model of an engine combustion system. Too small of a time delay can cause large longitudinal acceleration overshoot and oscillations that the driver can perceive and are undesirable. Too
Figure 2.5: Example of Time Delay during a Tip-In Event [3]

large of a time delay between driver pedal input and the resulting acceleration can leave the vehicle feeling sluggish and slow. Figure 2.5 shows an undesirable response from an abrupt change in acceleration coupled with large shock in red. It also shows a slow response from too large of a time delay in blue, which is also undesirable. The optimum response shown is both responsive and shock-free but is very difficult to achieve and often requires extensive testing to narrow down the root cause and identify potential solutions [3].

Peak-to-peak Longitudinal Acceleration

Peak-to-peak longitudinal acceleration is used as an objective measure of gear shift quality, as well as tip-in/tip-out response. It gives a quantitative number of how much acceleration was felt by the driver. Ideally, a gear shift event would cause no longitudinal acceleration and be perceived as completely smooth by the driver.
In an automatic transmission, this is impossible to achieve and therefore allows for peak-to-peak acceleration to be a good indicator of the quality of gear shift event. In [20], peak-to-peak longitudinal acceleration was measured and quantified in order to describe the feel of a gear shift event. In [3], peak-to-peak acceleration was used to characterize the response of the vehicle to an accelerator pedal tip-in event.

**Engine Start and Gear Shift Event Frequency**

The number and frequency of gear shifts and engine starts (in hybrid vehicles) can be a good indicator of overall vehicle drive quality. A vehicle that excessively shifts gears or starts and stops the engine exposes the driver to the accelerations and jerks associated with those events and can lead to poor overall vehicle driveability. In [21], the number of gear shifts and engine start/stop events were considered as driveability criteria in the development of an optimal controller for a hybrid electric vehicle.

**Energy Spectral Density**

Energy spectral density (ESD) is used to determine the magnitude of each vibration frequency involved during a gear shift event and can be used as a metric for gear shift quality. The ESD’s are the narrowband spectra of various shift events and can be useful for evaluating shift quality. The ESD plots can then be compared to other vehicles in the vehicle’s class under the same operating conditions to give insight into the vehicle’s shift quality [22].

**Vibration Dose Voltage**

Vibration dose voltage (VDV) is a concept that describes the total amount of vibration felt by being in contact with a vibrating surface over a single period of time. The VDV accounts for the vibrations direction, frequency characteristics and
The VDV is defined as the fourth root of the time integral of the fourth power of the acceleration and is shown in Equation 2.1.

\[
VDV = \sqrt[4]{\int_{t_a}^{t_f} a^4(t)dt}
\]  

(2.1)

The VDV is typically performed on the frequency range from 1-32 Hz as it is the critical range for human perception of vibration [22]. A higher VDV value corresponds to more noticeable vibration. The VDV metric has a strong correlation to the drive quality during a gear shift, but does not have as strong of correlation to the drive quality of other vehicle behaviors such as tip-in/tip-out [23].

**2.3.4 Control Techniques for Improving Drive Quality**

Drive quality rarely has a specific control function or algorithm devoted to achieving it. Driveability is typically achieved through careful design, calibration, and modification of control rules. Therefore, outstanding drive quality is achieved in a very different manner than optimizing efficiency.

Control techniques employed to improve drive quality includes a variety of algorithm modifications and additions. In one case, a filter might be applied to smooth oscillations in signals going into or out of the control strategy. In another case, introducing a hysteresis may reduce oscillations in mode switching. Many controls that can improve drive quality can also harm it, such as filters or rate limits that add too much delay or lag to a system response.

Electric and hybrid-electric vehicles have very different drive quality characteristics than conventional vehicles. Oftentimes, implementing control systems that reproduce normal conventional vehicle driving behavior such as creep torque at low vehicle
speed or coastdown torque at high vehicle speed is often desired. However, simulated
creep torque robs energy when the vehicle is stopped and should be blended in and
out. Additionally, braking at various speeds requires different amounts of braking
torque, so the regenerative braking torque should vary based on speed in order to
allow the vehicle to smoothly come to a stop. [24]
Chapter 3: Tools and Methods

3.1 Drive Quality Measurement

3.1.1 Introduction

Drive quality (also often referred to as driveability) is the collective response of a vehicle to the driver’s inputs. Typical inputs include accelerator pedal tip-in and tip-out, gear shifts, decelerations, idle, etc. Drive quality is how these inputs create acceleration or deceleration that drivers perceive as good or bad. Therefore, drive quality is highly subjective and difficult to objectively measure.

Traditionally, drive quality refinement is calibrated using subjective methods by professional drivers and executives at automotive manufacturers. This process is very time and cost intensive, limited in repeatability, and subject to human error. The resulting product is that these subjective assessments are difficult to correlate to customer requirements. Because of this, objective drive quality assessment tools such as AVL DRIVE were developed.

3.1.2 AVL DRIVE

AVL DRIVE is a commercial objective drive quality assessment tool. The software tool is shown in Figure 3.1. AVL DRIVE requires knowledge of the vehicle that
is being assessed in order to trigger different events that affect drive quality such as tip-ins, tip-outs, gear shifts, etc. This is done by parameterizing a vehicle configuration in the configuration section of the software, shown in Figure 3.2. In particular, AVL DRIVE needs to know what kind of transmission is being used, the gear ratios of the transmission, the peak torque and power ratings of the engine and electric machines, among other powertrain specifics.

Longitudinal acceleration measurements, among other important vehicle signals such as vehicle speed, engine speed and torque, electric machine speeds and torques, current gear, accelerator and brake pedal position, are recorded during prescribed tests. AVL DRIVE can then be fed these signals and can automatically trigger and score each event that affects drive quality on various criteria that are discussed in Section 3.1.3. The scoring rubric is a relative scoring system, with scores between 1-10 and is defined in Table 3.1. The overall score for each event is then calculated as a weighted average of the scores, with higher weights being assigned to lower scores. Typically, anything below a score of 7 is deemed unacceptable for most automakers that use the AVL DRIVE software.

<table>
<thead>
<tr>
<th>Score</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>9-10</td>
<td>Excellent</td>
</tr>
<tr>
<td>8-9</td>
<td>Good</td>
</tr>
<tr>
<td>7-8</td>
<td>Satisfactory</td>
</tr>
<tr>
<td>6-7</td>
<td>Acceptable</td>
</tr>
<tr>
<td>5-6</td>
<td>Poor</td>
</tr>
<tr>
<td>4-5</td>
<td>Unacceptable</td>
</tr>
<tr>
<td>3-4</td>
<td>Defective</td>
</tr>
<tr>
<td>2-3</td>
<td>Unsafe operation</td>
</tr>
<tr>
<td>1-2</td>
<td>No operation</td>
</tr>
</tbody>
</table>

Table 3.1: AVL DRIVE 1-10 Scoring Rubric
To assess repeatability of AVL DRIVE’s scoring system, data was collected on the same event and run through the AVL DRIVE software. The resulting percent deviation of each score from the mean drive quality score is shown in Figure 3.3. From this, it can be seen that all drive quality scores were within 20% of the mean score, while almost all of the drive quality scores were within 10% of the mean score. This shows that AVL DRIVE has very consistent scoring within each event and test, and does not require a large number of the same tests to be performed for each event that is desired to be scored.
Figure 3.2: Screenshot of AVL DRIVE Software Configuration
Figure 3.3: Percent Error from Mean Driveability Score
3.1.3 Drive Quality Metrics

In this section, the different drive quality metrics that are scored for tip-in are presented. All of the drive quality metrics use the 10 Hz low-pass filtered longitudinal acceleration of the vehicle to calculate them. This is because the human body acts as a passive filter and can only detect frequencies lower than 10 Hz. Each plot in this section shows the filtered acceleration signal (bold red) as well as the unfiltered signal (unbolded red). Many of these metrics are also used for scoring other drive quality events, but the focus here is on tip-in scoring because that is what is primarily scored later in this document.

Figure 3.4 shows the measurement of response delay in a tip-in event. Response delay is measured as the delay between applying the accelerator pedal and a significant acceleration increase (greater than 0.5 m/s$^2$ increase).

Figure 3.5 shows the measurement of the initial bump in a tip-in event. The initial bump is defined as the maximum acceleration gradient that occurs on the initial acceleration after the accelerator pedal position is increased.

Figure 3.6 shows the measurement of the kick in a tip-in event. The kick is the magnitude of the first acceleration amplitude after applying the accelerator pedal.

Figure 3.7 shows the measurement of the jerks in a tip-in event. The jerks are the amplitudes of the five negative accelerations after applying the accelerator pedal.

Figure 3.8 shows the measurement of the torque build-up during a tip-in event. Torque build-up is defined as the correlation between driver demanded torque and delivered torque and is shaded in red in the figure.
Figure 3.9 shows the measurement of the torque smoothness during a tip-in event. The torque smoothness is defined as the smoothness of the electric machines’ and/or engine’s torque shape after the kick during the acceleration.

3.2 EcoSIM

Once the parallel-series plug-in hybrid electric vehicle architecture was selected by the Ohio State EcoCAR team, a unique hybrid vehicle model was developed to estimate the vehicle’s fuel economy and performance. The vehicle model is called EcoSIM and it is an energy-based model that runs in the Matlab/SIMULINK environment [25]. The general structure of the model is based on previous iterations of hybrid vehicle models developed by the Ohio State team in the FutureTruck, ChallengeX and EcoCAR competitions [26], [27], [28]. Figure 3.10 shows a top-level overview of the simulator. For the purposes of this research, EcoSIM was used primarily as a software-in-the-loop (SIL) test bed for the control strategies before implementing...
Figure 3.5: Initial Bump

Figure 3.6: Kick
Figure 3.7: Jerks

Figure 3.8: Torque Build-up
them on the vehicle. Each control strategy being developed was tested first on in SIL to ensure the desired functionality was achieved and it did not affect any of the safety-critical control systems in the vehicle control strategy or have unintended consequences (unintended accelerations, oscillations in torques, rapid mode switching, etc.).
Figure 3.10: Overview of EcoSIM
Chapter 4: Accelerator Pedal Tip-in Control

4.1 Introduction

One of the most significant factors that effect drive quality is accelerator pedal tip-in quality. The OSU EcoCAR 2 vehicle had serious issues tip-in drive quality due to the hybrid powertrain architecture. Both the front and rear powertrains lack a viscous torque coupler such as the torque converter found in a conventional automatic transmission. Due to this, there is very little damping of driveline disturbances in the powertrain. In this chapter, a baseline tip-in test is conducted and analyzed. Next, an initial control design is proposed and tested. Finally, the design is refined, tested, and the improvement to the baseline and initial control is assessed.

4.2 Baseline Assessment

To begin, it is necessary to establish the baseline tip-in response performance of the vehicle without modification to the control strategy. For this, two separate tests were conducted: a tip-in from zero to 50% accelerator pedal at a vehicle speed of 20 mph and a tip-in from zero to 75% accelerator pedal the same speed. Figures 4.1 and 4.2 show the results of the 0-50% and 0-75% tip-in tests, respectively. From both plots, it can be seen there is a large amount of kick at the beginning of the
acceleration with many jerks and oscillations in acceleration following, before finally settling down to the requested level of acceleration. This is very apparent in the baseline drive quality scores from AVL DRIVE, shown in Table 4.1. Both the kick and the jerks are the lowest scoring metrics for the tip-in. Additionally, the initial bump also scored poorly. It is notable, however, that the response delay and torque build-up scored very well. This can be attributed to the instantaneous response of the electric machines to the torque request. These high scores, however, do not make up for the extremely poor scores on the initial bump, kick, and jerks, as evidenced by the overall scores for the two tests.

4.3 Tip-in Control Development

4.3.1 Problem

Based on results from the baseline tip-in tests shown in Section 4.2, it was determined that the tip-in drive quality was extremely poor. It was theorized to be caused by gear backlash present predominantly in the rear powertrain of the vehicle. Gear
backlash is defined as the unavoidable spacing in the gear teeth in any gearbox or other mechanical coupling (such as axle CV joints) that causes play in the system. This is illustrated in Figure 4.3. An example of a dynamic powertrain model with gear backlash incorporated into it is shown in Figure 4.4. The total backlash in the OSU EcoCAR 2 vehicle’s rear powertrain was measured to be about 18.5°, which is very large for a vehicle powertrain.

4.3.2 Control Methods

There were two main control methods that were studied to reduce the effect of gear backlash on the vehicle’s tip-in drive quality performance: feedforward-based and feedback-based control. Feedforward control involves shaping the torque through the backlash region to reduce the initial impact of the gear engagement. Feedback control is more sophisticated and allows for active control and damping of the oscillations caused by the gear engagement, however this requires knowledge of the location in the gear backlash region. This is very difficult to estimate in practice and either
Figure 4.3: Gear Backlash [4]

Figure 4.4: Example of a Dynamic Powertrain Model with Gear Backslash [5]
Table 4.1: Baseline Tip-in Response Drive Quality Scores

<table>
<thead>
<tr>
<th>Criteria</th>
<th>50% Tip-in Mean Score</th>
<th>75% Tip-in Mean Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Response Delay</td>
<td>9.6</td>
<td>9.7</td>
</tr>
<tr>
<td>Initial Bump</td>
<td>5.1</td>
<td>5.5</td>
</tr>
<tr>
<td>Kick</td>
<td>3.4</td>
<td>3.5</td>
</tr>
<tr>
<td>Jerks</td>
<td>4.6</td>
<td>5.0</td>
</tr>
<tr>
<td>Flare</td>
<td>6.7</td>
<td>6.3</td>
</tr>
<tr>
<td>Stumble</td>
<td>10.0</td>
<td>10.0</td>
</tr>
<tr>
<td>Torque Build-up</td>
<td>9.5</td>
<td>9.3</td>
</tr>
<tr>
<td>Torque Smoothness</td>
<td>7.5</td>
<td>7.7</td>
</tr>
<tr>
<td>Absolute Torque</td>
<td>8.0</td>
<td>9.5</td>
</tr>
<tr>
<td>Overall Score</td>
<td>4.2</td>
<td>4.4</td>
</tr>
</tbody>
</table>

requires additional precision sensors to be installed in the powertrain or requires sophisticated control techniques such as Kalman filtering to estimate [5]. Therefore, it was determined that feedback control was out of the scope of this research and a feedforward control method was developed.

4.3.3 Initial Torque Smoothing Control Design

To control the torque through the backlash region, a feedforward function was used to modify the driver torque request before it is sent to the mode operation controls and split between the electric machines and/or engine. The initial design was to use a hyperbolic tangent function that smooths the torque request when the torque request changes direction. This function is shown in Equation 4.1. The \( \delta t \) term is the time in seconds since the driver torque request crossed zero. The resulting smoothed torque request (when the driver input is a step input) is shown in Figure 4.5.
The 0-75% tip-in test was repeated using the $tanh$ feedforward control and the result is shown in Figure 4.6. Comparing this back to the baseline performance in Figure 4.2, it is easy to see a large improvement in the acceleration trace. The drive quality scores from AVL DRIVE, shown in Table 4.2, reflect large improvements in the initial bump, kick, and jerks during the tip-in. Almost all of the metrics meet the ”Satisfactory” requirement, including the overall score. The radar plot shown in Figure 4.7 more clearly illustrates the main differences in the drive quality scores. It can be seen that the initial bump, kick, jerks and flare all improve significantly,

$$T_{req_{modified}} = \delta t \times \frac{1 + tanh(-5:5)}{2} T_{req}$$  \hspace{1cm} (4.1)
while the torque build-up and response delay only decreased slightly. This decrease is mainly due to the delay that is caused by smoothing the torque request.

### 4.3.4 Torque Smoothing Control Refinement

Overall, the \textit{tanh} feedforward control succeeded in smoothing the torque request and improving the tip-in drive quality scores. However, it was found that the \textit{tanh} function was difficult to calibrate to further improve the scores or to be adapted to other vehicles. Therefore, a more calibratable and adaptable function was sought that could perform the same torque smoothing as the \textit{tanh} function. The Wiebe function, shown in Equation 4.2, performs the same function while containing three main calibratable parameters that affect its shape, duration, and the offset from zero at which the feedforward function is enabled. The \( n \) term affects the shape of the function and the \( \Delta t \) term modifies the duration of the smoothing effect. The resulting torque smoothing is shown in 4.8. The ability to change the offset from zero at which the feedforward control is triggered is extremely important because the
Figure 4.7: \textit{tanh} Tip-in Response Drive Quality Improvement Radar Plot
<table>
<thead>
<tr>
<th>Criteria</th>
<th>Baseline</th>
<th>tanh Feedforward</th>
</tr>
</thead>
<tbody>
<tr>
<td>Response Delay</td>
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</tr>
<tr>
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<td>6.7</td>
</tr>
<tr>
<td>Kick</td>
<td>3.5</td>
<td>7.4</td>
</tr>
<tr>
<td>Jerks</td>
<td>5.0</td>
<td>7.1</td>
</tr>
<tr>
<td>Flare</td>
<td>6.3</td>
<td>9.5</td>
</tr>
<tr>
<td>Stumble</td>
<td>10.0</td>
<td>10.0</td>
</tr>
<tr>
<td>Torque Build-up</td>
<td>9.3</td>
<td>8.3</td>
</tr>
<tr>
<td>Torque Smoothness</td>
<td>7.7</td>
<td>8.2</td>
</tr>
<tr>
<td>Absolute Torque</td>
<td>9.5</td>
<td>9.0</td>
</tr>
<tr>
<td>Overall Score</td>
<td><strong>4.4</strong></td>
<td><strong>7.3</strong></td>
</tr>
</tbody>
</table>

Table 4.2: tanh Tip-in Response Drive Quality Improvement at 75% Accelerator Pedal

function modifies the torque request, not the actual torque in the gearbox and axle CV joints where the backlash occurs. By tuning the offset to occur where the "neutral torque" request occurs, it allows the torque request to change slowly while in the backlash zone, eliminating the kick caused by the gear engagement. This is shown more closely in Figure 4.9.

Wiebe Torque Smoothing Function

\[ T_{req, modified} = \left[ 1 - \exp\left[ -a \left( \frac{t - t_0}{\Delta t} \right)^n \right] \right] T_{req} \quad (4.2) \]

Once again, the 0-75% tip-in test is performed to test the improvement of the Wiebe feedforward control over the tanh function and the baseline. The resulting tip-in response is shown in 4.10. When comparing back to the tanh controlled response shown previously in Figure 4.6, it can be seen that the initial kick is almost completely negated, improving the overall acceleration trace. The drive quality scores from AVL DRIVE are shown in Table 4.3 and as expected, the scores improved even further.
Figure 4.8: Torque Request Smoothing using Wiebe Function
Figure 4.9: Effect of Offsetting Wiebe Function
with the Wiebe feedforward control. The lowest score was the initial bump, receiving a 7.6 ("Satisfactory"), while all other scores were above 8 ("Good") including the overall score. The radar plot, shown in Figure 4.11, illustrates the improvement more clearly.

Overall, by smoothing the torque request, particularly through the gear backlash region, the tip-in drive quality of the OSU EcoCAR 2 vehicle was able to be improved immensely. Additionally, by using an easily calibratable control function, the feedforward control developed here can be quickly adapted to be incorporated in other vehicles with different powertrains to improve tip-in drive quality.
Figure 4.11: Wiebe Tip-in Response Drive Quality Improvement Radar Plot
<table>
<thead>
<tr>
<th>Criteria</th>
<th>Baseline</th>
<th>$tanh$ Feedforward</th>
<th>Wiebe Feedforward</th>
</tr>
</thead>
<tbody>
<tr>
<td>Response Delay</td>
<td>9.7</td>
<td>8.3</td>
<td>8.2</td>
</tr>
<tr>
<td>Initial Bump</td>
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<td>6.7</td>
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<tr>
<td>Kick</td>
<td>3.5</td>
<td>7.4</td>
<td>8.6</td>
</tr>
<tr>
<td>Jerks</td>
<td>5.0</td>
<td>7.1</td>
<td>8.3</td>
</tr>
<tr>
<td>Flare</td>
<td>6.3</td>
<td>9.5</td>
<td>10.0</td>
</tr>
<tr>
<td>Stumble</td>
<td>10.0</td>
<td>10.0</td>
<td>10.0</td>
</tr>
<tr>
<td>Torque Build-up</td>
<td>9.3</td>
<td>8.3</td>
<td>8.1</td>
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<tr>
<td>Torque Smoothness</td>
<td>7.7</td>
<td>8.2</td>
<td>8.1</td>
</tr>
<tr>
<td>Absolute Torque</td>
<td>9.5</td>
<td>9.0</td>
<td>8.9</td>
</tr>
<tr>
<td><strong>Overall Score</strong></td>
<td><strong>4.4</strong></td>
<td><strong>7.3</strong></td>
<td><strong>8.2</strong></td>
</tr>
</tbody>
</table>

Table 4.3: Wiebe Tip-in Response Drive Quality Improvement at 75% Accelerator Pedal
Chapter 5: Regenerative Braking Control

5.1 Introduction

In electric vehicles and hybrid electric vehicles, regenerative braking is essential to extending the vehicle’s electric range and meeting fuel economy targets. The more energy that is able to be recaptured through regenerative braking, the more electrical energy that is available to be used for propelling the vehicle. Therefore, from a fuel economy standpoint, the goal is to recapture as much energy as possible. However, aggressive regenerative braking, especially as low vehicles speeds, can cause poor driveability and even startle the driver. The following chapter details the regenerative braking control strategy that was designed and implemented in the OSU EcoCAR 2 vehicle, as well as a brief drive quality assessment of the braking performance of the vehicle.

5.2 Regenerative Braking Control Design

There are two integral parts to the regenerative braking strategy in the OSU EcoCAR 2 vehicle. First, there is a creep/coastdown torque that is used to simulate the feel of 0% accelerator and brake pedal position of an automatic transmission and internal combustion engine in a conventional vehicle. The calculation of this
creep/coastdown torque is discussed in Section 5.2.1. Section 5.2.2 details the additional regenerative braking that is blended into the torque request when the driver presses the brake pedal. Both of these torque request calculations are incorporated into the overall driver torque request calculation as depicted in Figure 5.1.

5.2.1 Creep/Coastdown Torque

A conventional vehicle with an automatic transmission and internal combustion engine has a certain amount of "creep" torque that is applied when the vehicle is moving at low speed. In order to simulate this, a creep torque curve was created and is shown in red in Figure 5.2. At zero vehicle speed, the torque request starts out high in order to get the vehicle moving. It quickly drops off as the vehicle speed increases and drops all the way to zero when the vehicle reaches 10 mph. This creep torque not only simulates an automatic transmission’s behavior, but also acts as a hill-hold function and prevents the vehicle from rolling back when the brake is released.
Figure 5.2: Creep/Coastdown Torque Curve
A conventional internal combustion engine also exerts a negative drag torque when the accelerator pedal is at zero and the vehicle is at higher speeds. This drag torque is referred to as coastdown torque. To replicate this, a negative torque is requested when the accelerator pedal is at 0% and the vehicle is moving at speeds above 10 mph. This torque curve is shown in blue in Figure 5.2. Instead of keeping this coastdown torque constant, however, the negative torque request is increased with increasing vehicle speed. This not only allows for more energy recapture through regenerative braking, but also improves pedal feel (linearity of the accelerator pedal) by keeping the negative acceleration of the vehicle constant at varying vehicle speeds. Additionally, this coastdown torque allows for deceleration of the vehicle without the use of the friction brakes.

Both the creep and coastdown torque requests are combined into one curve in order to allow for smooth transition between the two operations. Additionally, it can be seen in the curve shown in Figure 5.2 that the slope of the curves around zero torque request (10 mph) is much lower than the rest of the curve. This keeps the control from oscillating between positive and negative torque requests around 10 mph, which would lead to poor driveability.

5.2.2 Additional Regenerative Braking

To add additional regenerative braking capability, the brake pedal modifies the creep/coastdown torque curve discussed in 5.2.1. Increasing the brake pedal position shifts the curve downward, increasing the negative torque being requested from the electric machines. This is shown Figure 5.3. Modifying the creep/coastdown torque curve in this manner allows for a very linear and predictable response as the brake
pedal position is increased, which is desired for good driveability. Note that the electric machines are controlled to not go below zero speed, so as to not have a negative torque request at zero speed cause the vehicle to accelerate backwards. Additionally, due to restrictions on modifications to the stock vehicle’s friction brake system imposed by the EcoCAR 2 competition, regenerative braking controlled by the brake pedal position could only be additive to the friction brakes. This means that the regenerative braking is blended in with the friction brakes.
5.3 Drive Quality Assessment

To briefly assess the drive quality implications of the regenerative braking in the vehicle, deceleration from 30 kph to 15 kph was performed with the brake pedal depressed 25% with the regenerative braking off and the regenerative braking on. These two tests can be seen in Figure 5.4 and Figure 5.5 respectively. The 10 Hz low-pass filtered acceleration is shown in bold red on top of the original acceleration signal. Comparing the two tests, it can be seen that the while the negative acceleration of the vehicle is much greater with regenerative braking on, as expected, the overall smoothness of the acceleration trace is about the same between the two tests. Therefore, it is not surprising that the AVL DRIVE drive quality scores for the two decelerations are not significantly different, as seen in Table 5.1. The braking performance does increase, however, in that the deceleration was completed in 3 seconds with the regenerative braking on versus 10 seconds without regenerative braking.
Figure 5.5: 30-15 kph Braking at 25% Brake Pedal With Regen

Table 5.1: 30-15 kph Braking at 25% Brake Pedal Drive Quality Scores

<table>
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<tr>
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<td>8.1</td>
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<tr>
<td>Acceleration Steps</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Overall</td>
<td>8.5</td>
<td>8.4</td>
</tr>
</tbody>
</table>
Chapter 6: Transmission Shifting Control

6.1 Introduction

Due to the unique design of the OSU EcoCAR 2 vehicle, a complex algorithm was needed to coordinate the gear shifting process. To facilitate this, a complex handshaking process was developed and refined for robustness and reliability, as well as drive quality.

6.2 Transmission Shifting Control Design

6.2.1 Controller Handshake

To complete a gear shift in the OSU EcoCAR 2 vehicle, it requires a coordinated effort between the supervisory controller and the general control module (also referred to as the transmission controller). To facilitate this, a controller "handshaking" process was implemented between the supervisory and transmission controllers to keep them on the same page during a gear shift. This handshake process is outlined in Figure 6.1. First, the supervisory controller strategic controls determines when a gear shift is necessary. It then shifts the total driver torque request to the rear electric machine. Once that is complete, the transmission controller shifts the transmission into neutral and notifies the supervisory controller. The supervisory controller then
Figure 6.1: Shifting Handshake Between Supervisory Controller and General Control Module

uses speed control in the front electric machine to speed match the transmission input shaft to the transmission output shaft speed (through the oncoming gear ratio). The transmission controller then shifts the transmission into gear and tells the supervisory controller that the gear shift is complete. Finally, the supervisory controller redistributes the driver torque demand across both powertrains.

An example of a gear shift is shown in Figure 6.2. The top plot shows the Shift Status and Shift Request messages from the handshaking process, as well as what gear the transmission is in and the front electric motor speed. The bottom plot shows the front and rear electric machine torques to better illustrated the shifting process. Due to the complex nature of the gear shift and the communication required, the overall process takes about 2.5 seconds to complete a gear shift. During that time, the rear electric machine provides torque to minimize the torque hole felt by the driver. The
amount of torque the rear electric machine is able to supply during that time has a profound effect on the drive quality of the shift, which is discussed in more detail in Section 6.3.

6.2.2 Control Refinement

The majority of the effort spent on refinement of the gear shifting control strategy revolved around improving robustness and reliability of the shifting algorithm. To
make the algorithm more tolerant of a wider variety of driving conditions, timeouts were added to prevent the gear shifting process from getting stuck in one state. Additional criteria to enter and exit states within the gear shifting process were also added to help manage the speed matching, shifting into neutral and shifting into gear stages. As an example, a miscommunication between the supervisory controller and transmission controller occurred in Figure 6.3. When the gear shift process started, the gear requested was 6th gear. However, by the time the gear shift process completed, the supervisory control strategy requested 3rd gear and assumed it was in 3rd gear based on the gear shift complete message. This caused the transmission to get stuck in 6th gear, even though it was supposed to be in 3rd gear. To fix this, an additional condition was added to allow the handshake to remember the original gear request and if that request changes, to go back in the process to shift into the new gear. Figure 6.4 shows a successful gear shift in a similar situation.

6.3 Drive Quality Assessment

To highlight some of the issues in the drive quality of gear shifts in the OSU EcoCAR 2 vehicle, two tests were performed: an upshift from 3rd to 5th gear at 50% accelerator pedal and at 75% accelerator pedal. The results are shown in Figures 6.5 and 6.6, respectively. The brown line shows the gear request (3rd or 5th) and the black line shows the current gear of the transmission (the sharp dips in the signal are numerical anomalies). At 50% accelerator pedal, the gear shift is extremely smooth and hardly noticeable by the driver or passengers. This is because the rear electric motor is capable to provide enough torque to satisfy the entire torque request while the front electric machine is disconnected during the gear shift. At 75% accelerator
Figure 6.3: Miscommunication Example - Transmission is Stuck in 6th Gear
Figure 6.4: Successful Shift into 3rd Gear
Figure 6.5: Gear Shift from 3rd to 5th Gear at 50% Accelerator Pedal

pedal, the rear electric machine is not capable of providing enough torque to satisfy the entire torque request, leading a torque hole and larger disturbances in the driveline. In both plots, it can be seen that when the front electric machine ramps down and ramps up torque, disturbances (kick and jerks) in the acceleration trace are present. This is one area of the gear shift drive quality that could be improved upon in the future. Additionally, transferring the torque request to the rear powertrain during a gear shift can have an effect on the lateral handling of the vehicle, especially in slippery road conditions such as rain or ice. This warrants further study, however it is out of the scope of this research.
Figure 6.6: Gear Shift from 3rd to 5th Gear at 75% Accelerator Pedal
Chapter 7: Conclusions and Future Work

7.1 Conclusions

Drive quality is an essential part of designing and calibrating any production vehicle. Electric and hybrid-electric vehicles present unique challenges and opportunities to improve drive quality because of the rapid response and extremely quick torque delivery of the electric machines. However, due to the complex architectures and sophisticated control systems present in hybrid-electric vehicles, it can be very difficult to eliminate serious drive quality issues and improve the overall driveability of the vehicle.

The Ohio State EcoCAR 2 vehicle had serious issues tip-in drive quality due to the high amount of gear backlash present in the powertrain. It was found that smoothing the driver's torque request had a profound effect minimizing the negative effects of gear backlash on the tip-in drive quality. The control system developed to accomplish this contains easily calibratable parameters that can be quickly adapted to be used in future EcoCAR vehicles and is mostly independent of the powertrain architecture.

A control system for implementing regenerative braking in the OSU EcoCAR 2 vehicle was developed and calibrated to provide smooth torque delivery and positive drive quality characteristics. This included both creep torque at low vehicle speed as
well as coastdown torque at higher vehicle speeds in order to mimic the behavior of a conventional vehicle with a traditional internal combustion engine and automatic vehicle. The drive quality of the deceleration of the vehicle with and without regenerative braking was studied and determined to be on par or better with the control active.

Finally, a robust and reliable control system was developed for shifting the automated manual transmission in the OSU EcoCAR 2 by speed matching the input and output shaft speeds using an electric machine. This control system includes a gear shifting handshaking process that was implemented between the supervisory and transmission controllers to facilitate the complex gear shifting process. The effects of this unique gear shifting process on the drive quality of the vehicle was also discussed.

7.2 Future Work

The control strategies developed have many improvements that can be made to them. The Wiebe feedforward function developed for smoothing the driver’s torque request through the gear backlash region can be better calibrated to improve the drive quality of the tip-in and tip-out further. A design of experiments can be run to determine the optimal calibration of the parameters that determine the offset, shape and duration of the Wiebe feedforward function. Additionally, gear backlash estimation techniques, such as the Kalman filtering presented in [5], can be used to provide feedback control. This feedback would allow for active damping of the gear backlash disturbances. Finally, the shifting control strategy presented can be further refined to improve the gear engagement and to shorten the time it takes to complete a gear shift. Also, smoothing the front electric machine torque ramping out and back
in during the gear shifting process could vastly improve the overall drive quality of the gear shifts.
Bibliography


