Drive Quality Improvement and Calibration of a Post-Transmission Parallel Hybrid Electric Vehicle

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Abstract

The Hybrid Electric Vehicle Team (HEVT) of Virginia Tech is one of 16 university teams participating in EcoCAR 3, the latest competition in the Advanced Vehicle Technology Competitions (AVTC) organized by Argonne National Labs. EcoCAR 3 tasks teams with converting a 2016 Chevrolet Camaro into a hybrid electric vehicle with 5 main goals: reducing petroleum energy use and greenhouse gas emissions while maintaining safety, performance, and consumer acceptability. Over the last 4 years, HEVT has designed and built a plugin parallel hybrid electric vehicle with a unique powertrain architecture. This work deals with utilizing the unique powertrain layout of the HEVT Camaro to improve drive quality, a key component in consumer acceptability. Although there are many ways to approach drive quality, most aspects can be analyzed in the smoothness of the vehicle longitudinal acceleration response.

This research is focused on improving the drive quality of the vehicle developed for EcoCAR 3. Multiple algorithms are developed to address specific aspects of drive quality that can only be done with the powertrain developed. This begins by researching the control strategies used in modern automatic transmissions, and moves into the modeling strategy used to begin algorithm development. Two main strategies are developed and calibrated in the vehicle. The first being a strategy for reducing jerk in pure electric mode by limiting motor torque response. The second strategy aims to improve transmission shift quality by using the electric motor to reduce torque fluctuations at the driveshaft. The energy consumption impact of both of these strategies is also analyzed to ensure that drive quality does not come at the large expense of energy consumption.

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General Audience Abstract

The Hybrid electric vehicle team (HEVT) of Virginia Tech is one of 16 university teams participating in EcoCAR 3, the latest competition in the Advanced Vehicle Technology Competitions (AVTC) organized by Argonne National Labs. EcoCAR 3 tasks teams with converting a 2016 Chevrolet Camaro into a hybrid electric vehicle with 5 main goals: reducing petroleum energy use and greenhouse gas emissions while maintaining safety, performance, and consumer acceptability. Over the last 4 years, HEVT has designed and built a plugin parallel hybrid electric vehicle with a unique powertrain architecture. This work deals with utilizing the unique powertrain layout of the HEVT Camaro to improve drive quality, a key component in consumer acceptability. Multiple strategies were examined and implemented for different driving conditions, and ultimately an improvement was made. However, new challenges are introduced by having some components remain stock that limit the success of smoothing gear shifts.

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I'd also like to thank every coffee shop in and around campus: without them this paper wouldn't be possible.

And finally I'd like to thank Dr. Doug Nelson, who has not only been a great faculty advisor but also my greatest mentor and teacher over the 5 years I have worked on the team. Without his help, I doubt I could be where I am today as an engineer.

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1 Introduction

1.1 EcoCAR 3 and Powertrain

The Hybrid electric vehicle team (HEVT) of Virginia Tech is one of 16 university teams participating in EcoCAR 3, the latest competition in the Advanced Vehicle Technology Competitions (AVTC) organized by Argonne National Labs. EcoCAR 3 tasks teams with converting a 2016 Chevrolet Camaro into a hybrid electric vehicle with 5 main goals: reducing petroleum energy use and greenhouse gas emissions while maintaining safety, performance, and consumer acceptability. To determine the powertrain for development, HEVT conducted extensive market research and determined that to the customers of the New River Valley, performance was the primary attraction of performance cars such as the Camaro. As such, the selected powertrain needed to improve or match the performance of the unmodified vehicle while offering improved fuel economy. The powertrain was selected using the top-down approach shown in Figure 1-1.

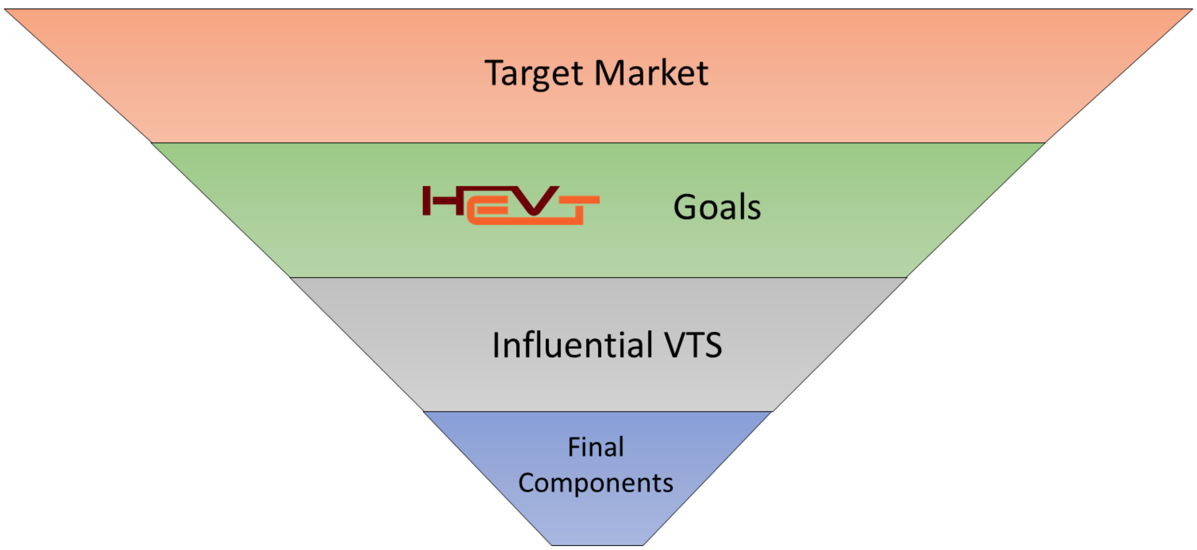

Figure 1-1: Focused approach to component selection.

The resulting powertrain architecture is a parallel layout, plug-in hybrid vehicle, shown in the figure below. The engine is a 5.3L L83 V8 engine from a 2014 Chevrolet Silverado, coupled to a GM 8L90 automatic transmission. The motor shaft replaces a section of the conventional driveshaft to maintain 100% rear wheel drive through the rear differential. The motor is a custom designed, post transmission (P3) unit that produces 100 kW and 500 Nm or torque. The high voltage pack is built by team members, and is rated for 118 kW at 340 V nominal with a storage capacity of 12.6 kWh.

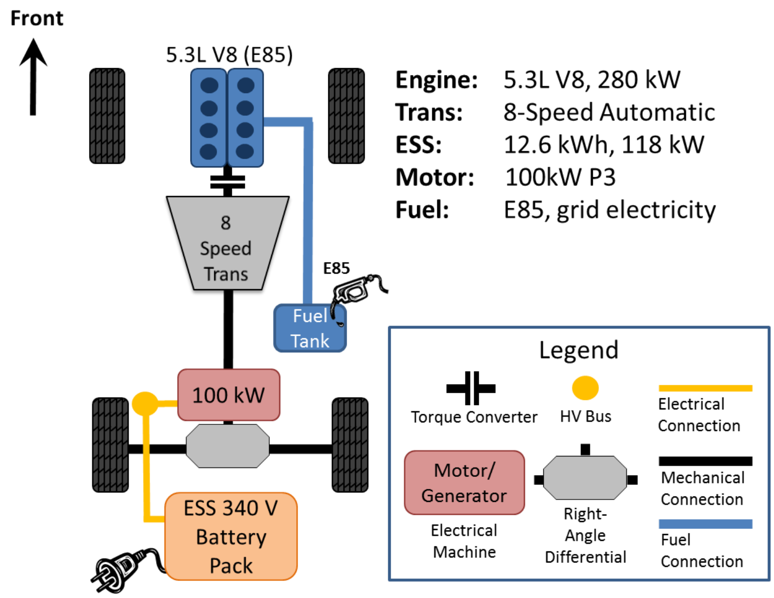

Figure 1-2: HEVT P3 parallel hybrid architecture

1.2 Vehicle development process

As a primarily undergraduate project, HEVT and EcoCAR 3 place an emphasis on teaching students the processes used in industry for vehicle development. As a four-year long undertaking it is key that the process be well defined for year-to-year communication with new team members. The EcoCAR 3 vehicle development process (VDP) is shown in Figure 1-3, and includes 4 phases of development: design, integration, refinement, and market engagement. As the final year of competition, Year 4 is focused on optimization of the control system and overall vehicle, along with outreach to target markets to gauge the success of the vehicle. The overall goal of the VDP is to reduce the time and cost of developing a vehicle platform, however the shortened timeframe of EcoCAR 3 further constrains the work done, as it does not focus on some aspects that would be presented in industry. These include, but are not limited to: supply chain, purchasing, manufacturing, and individual component costs.

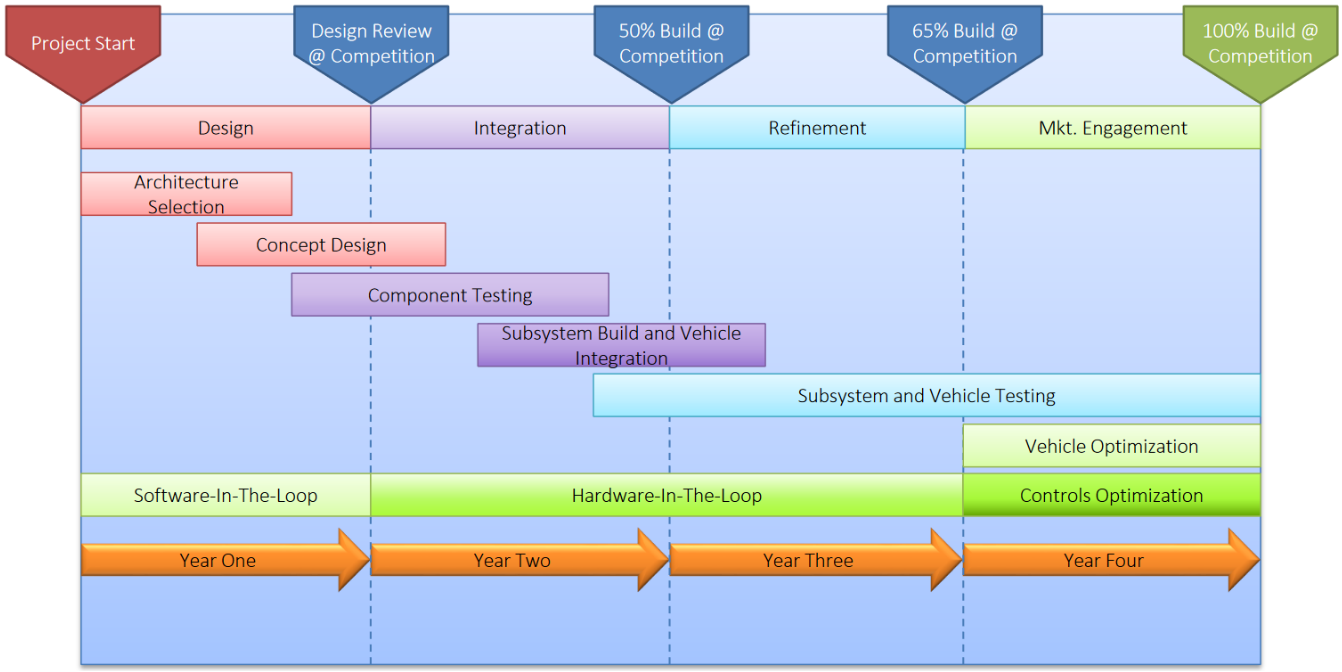

Figure 1-3: EcoCAR 3 Vehicle development process. [1]

To achieve the specific goals in the controls development of the VDP, the V-diagram for controls development is shown in Figure 1-4. The V-diagram aims to build code based on a hierarchy of requirements to ensure properly functional code is developed at all stages of the VDP. By following the requirements down the left side of the V diagram, controls development can trace functionality and testing back to requirements, and revisit them if needed.

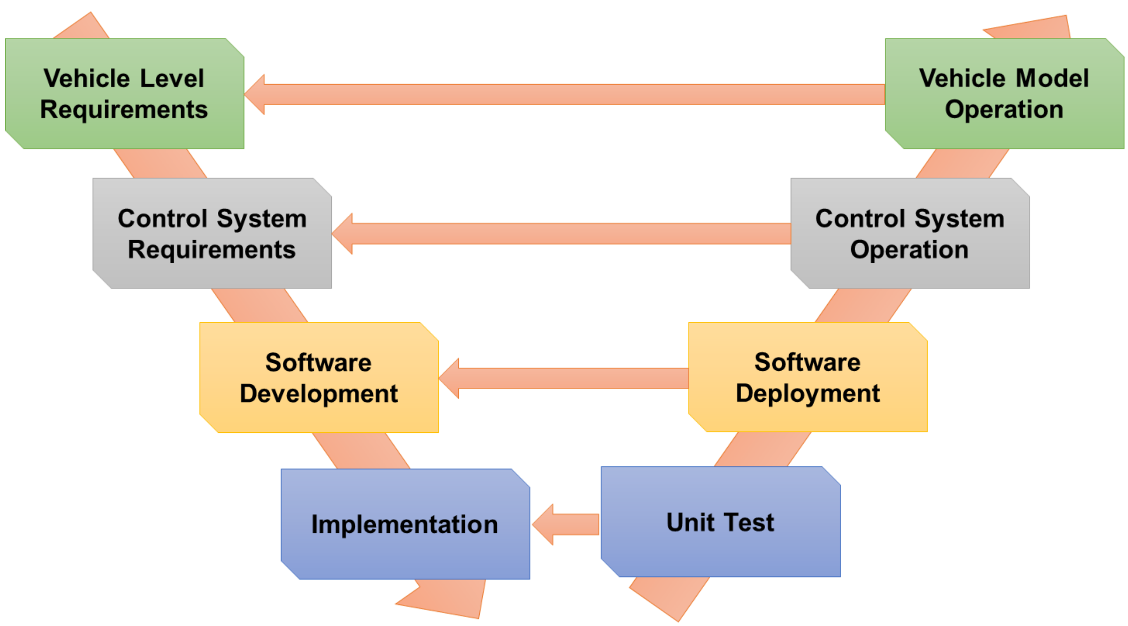

Figure 1-4:Vehicle Software development process V-diagram.

1.3 SIL and HIL development environments

In order to rapidly develop control code for EcoCAR 3, a series of testing methods are employed for testing requirements and changes. Similar to the VDP and V-diagram, these methods are aimed at replicating the methods employed in industry to develop vehicle control systems. Starting on the bottom of the V-diagram in Figure 1-4, any individual feature is tested on its own, against its own requirement cases, to ensure functionality. When features and subsections of code are fully tested, they code is fully assembled with all features and sections for full software testing.

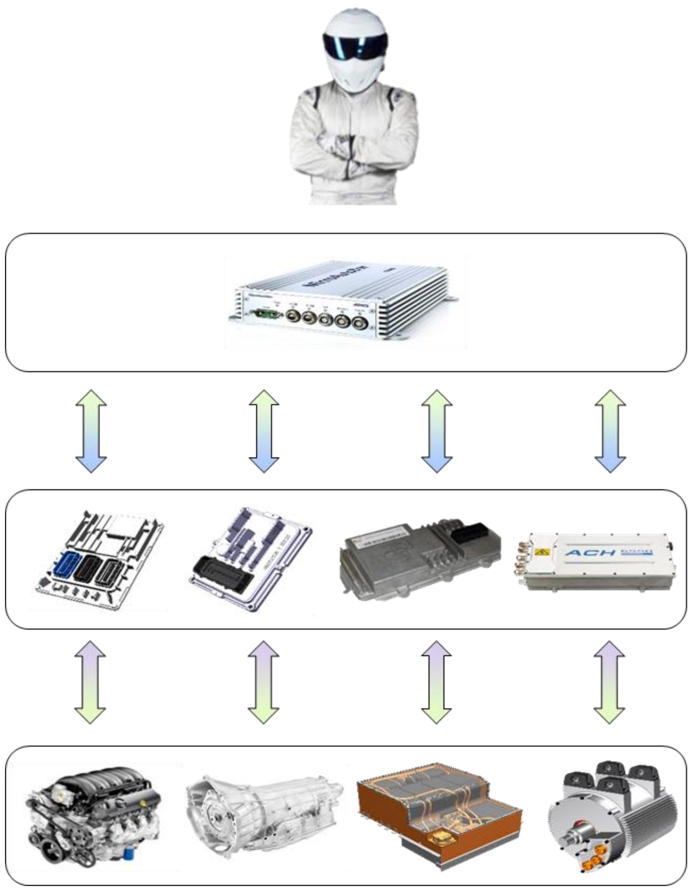

Figure 1-5: Communication between driver, supervisory controller, and component controllers to control components.

The control software is tested against a model of the vehicle and external controllers. HEVT focuses control of the vehicle as an overarching, supervisory controller, allowing off the shelf controllers to manage individual components. This relationship is illustrated in Figure 1-5. This full vehicle model includes software representations of the component controllers (softECUs) as well as equation based estimations of the component physics and interactions. Each of these softECUs and component models are based on the components used in the vehicle, using publicly available data or data collected on the components during bench tests.

To conduct tests at the software deployment phase of the V-diagram, the control code and the full vehicle model are used for software in the loop (SIL) testing. In SIL tests, the Simulink representations of the control code and vehicle model are combined to form a single model that can be run in various test cases. This modeling layout is shown in Figure 1-6. Because the control code and vehicle model are contained in a single file, simulations can be run on a single computer. SIL models can also be used to estimate the vehicle's fuel economy based on standardized fuel economy test cycles.

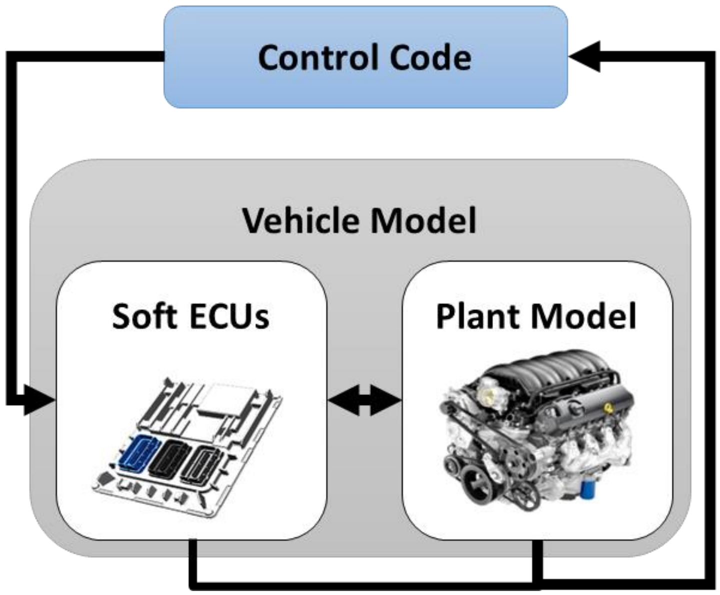

Figure 1-6: SIL model layout of code and models.

SIL tests are extremely useful for rapid development of new code and features. Without the need for real-time hardware in this phase of testing, any tests cases and drive cycles can be tested significantly faster than real time. Any changes made, or wide ranges of test cases, can be conducted in extremely short amounts of time. The limitation of SIL arises from the same lack of real time hardware that makes it so rapid. In order to test code performance on the controllers, SIL testing transitions into controller hardware in the loop testing (HIL). HIL testing compiles the control code tested in SIL and deploys it to the controller used in the vehicle to test full control system operation. Rather than testing this in-vehicle, HIL also requires the vehicle model to be compiled and deployed to a simulator that generates all of the hardware inputs/outputs used in the vehicle. This includes real analog and digital voltages for sensor and actuator simulation, physical CAN networks, and graphical user feedback for testing. Additionally, all HIL testing is run at a fixed time step, as it is run on real-time hardware, and any CAN networks used introduce real response delays and signal latencies that they experience in the vehicle. HIL testing aims to simulate vehicle behavior close enough that to the supervisory controller there is no difference between operating on a HIL bench and operating in the vehicle.

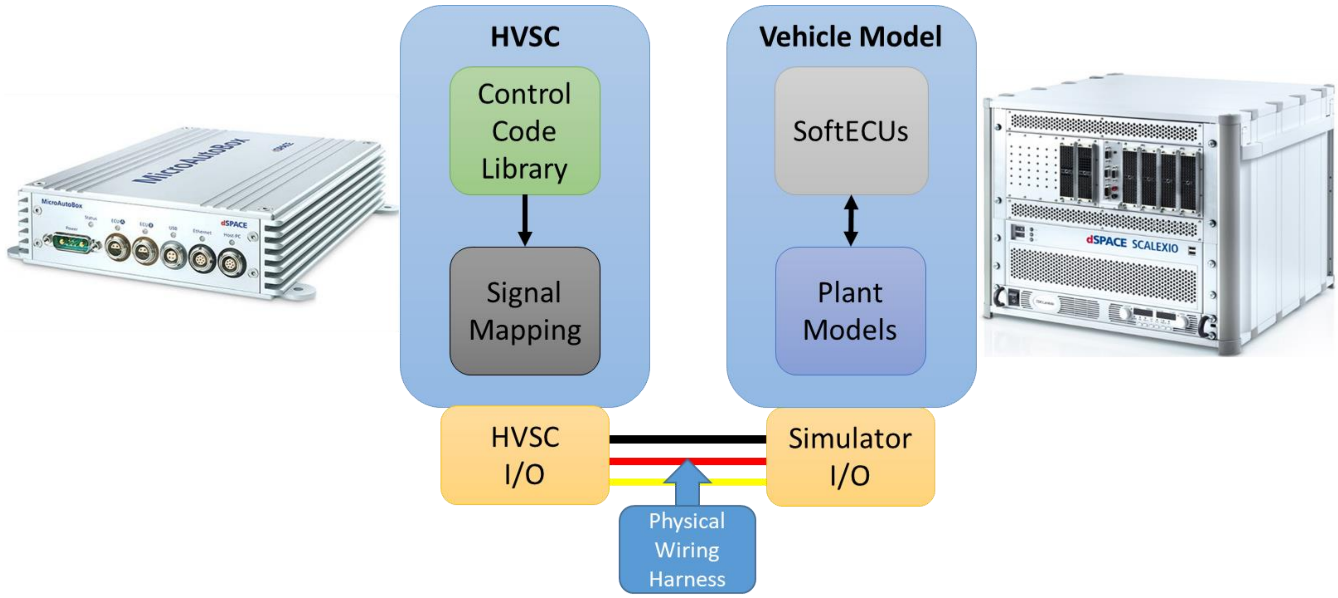

Figure 1-7: HIL testing diagram showing what code is compiled to what device.

1.4 Hybridization and drive quality

As the level of technology in modern production vehicles increases, so too does the level of refinement expected by consumers. Demand for quieter, smoother vehicles has driven the constant development of countless innovations in the automotive world, including the development of more advanced automatic transmissions. While these improvements have continued to increase the complexity of developing a user experience, the more recent trend of hybridization has added another layer of complexity to this process.

In conventional vehicles, regardless of engine type, transmission type, or driven wheels, there is a single path from torque development to delivery at the wheels. With hybrid electric vehicles, there are multiple sources of complexity added. First, there is the introduction of multiple torque sources, and the need to manage production from both sources depending on driving conditions. Second is the introduction and development of transmission systems that utilize these torque sources. The final challenge for drive quality development in hybrid architectures is the sheer number of vehicle specific powertrain layouts. Even among a single manufacturer, there often exist multiple hybrid configurations. These configurations require completely different approaches to drive quality depending on motor placement and transmission type.

2 Literature review

2.1 Measurement and Modeling of Perceived gear shift quality for Automatic Transmission Vehicles

The paper written by Jeon & Kim [2] discusses an investigation of perceived shift quality, specifically the way that drivers describe shifts and how it relates to physical, measurable qualities of the shift. Jeon begins with a description of why using trained drivers or engineers is not always the best way to gauge consumer acceptability. A trained driver's experience and sensitivities cannot be extrapolated to customer experiences. Additionally, existing subjective testing methods and metrics are hard to tie back to calibration parameters or design changes. The metrics proposed in this paper aim to establish a testing method and subjective metrics for drivers that can be tied back to mechanical variables that can be measured in the vehicle. These metrics also mention the use of tools such as AVL DRIVE. DRIVE is a program that rates vehicle drive quality objectively, based on in vehicle accelerometer data, and rates the vehicle against competitive set vehicles [3].

First, to determine driver perception of shift quality, a list of 28 semantic pairs to describe shifts was generated. This list was used in an initial survey of drivers to describe their own vehicles shift quality. From this list of semantic pairs, and survey responses, the subjective terms were grouped into four overall descriptor terms: Responsiveness, Smoothness, Strength, and Unperceivable. These descriptor terms were used for experimental analysis of shift quality among drivers.

To gauge the metric, an experiment involving vehicles from multiple manufacturers as well as different calibrations on the transmission controllers is conducted. In addition to the qualitative analysis, the vehicles are equipped with data collection systems measuring various transmission parameters and vehicle acceleration. The mechanical measurements from the vehicle are paired with qualitative responses to find the correlation between certain descriptors and the physical actions of the vehicle. The study found that the strength factor had the biggest impact on perceived drive quality, closely followed by responsiveness. Smoothness, then Unperceivable had smaller impacts on shift quality.

While mechanical factors such as shift time and average acceleration have an impact on the perceived shift quality, the initial, final, and maximum jerk during a shift have a significant correlation to the responsiveness and strength scores given by drivers. Thus, the jerk experienced during a shift has a large impact on perceived shift quality, and should be avoided when designing and calibrating transmission response.

This analysis of perceived shift quality metrics and their relation to mechanical variables is valuable when assessing how to improve shift quality in the hybrid powertrain designed by HEVT. It outlines physical variables that must be controlled during shifts to improve perceived quality. During the development of the shift fill algorithm, the information presented by Jeon & Kim was used to gauge the effectiveness of new strategies.

2.2 Clutch-to-Clutch Transmission Control Strategy

The technical paper by Marano et al. [4] is a detailed report on the development of the previous generation General Motors 6-speed transmissions. This 6-speed transmission family is the predecessor of the 8-speed used in the HEVT powertrain, and builds upon the control strategy presented by Marano. The paper first discusses the applications of the new transmission family, as well as the benefits to fuel economy, drive quality, and controls calibration. Marano then covers the component level design of the clutch-to-clutch system in the transmission family.

The first topic is the development of new strategies for detecting if the oncoming clutch is full, which must happen before the offcoming clutch can begin releasing pressure. Then, Manaro covers the importance of including the clutch compliance in control of the oncoming clutch.

Without accounting for the clutch compliance, the oncoming clutch is not fully controlled, and causes torque disturbances at the transmission output. These disturbances are eliminated when the designed clutch compliance is included in the clutch control algorithm. Finally, a new 'learning' strategy is introduced that allows the transmission control to adapt clutch pressure parameters based on tests performed in the vehicle after vehicle assembly. By including these learn algorithms, Marano states that there is a significant gain in control accuracy for individual transmission/controller pairs. It also has the added benefit of allowing detection of faulty hardware sooner than previous transmissions during this learn procedure.

Finally, the paper covers the streamlined calibration of the transmission control strategy, by allowing simplified calibration using desired shift times, torque phase times, and a desired output torque profile. By making these calibrations more intuitive to calibrators, and handling more of the calculations on the controller itself, the shift quality and characteristics are much easier to calibrate from vehicle to vehicle.

The detailed paper by Marano is incredibly useful in understanding what parameters the GM transmission systems consider when coordinating transmission shifts with engine torque. While this paper is specifically about the last generation 6-speed transmissions, the 8-speed shares many designs and control components, and the controls system builds on that of the 6-speed.

2.3 Smooth Gear Shifting Control Technology for Clutch-to-Clutch Shifting

Minowa et al. [5] describes the ideal control of clutches in an automatic transmission, and presents a method of control for smooth shifting. The goal, as described by Minowa, of coordinating the on-coming clutch and off-coming clutch is to prevent torque fluctuations at the output of the transmission. The specific technology presented deals with accurate clutch timing and precise clutch pressure control.

Minowa presents several useful figures that shown the behavior of clutches during upshifts and downshifts plotted with output torque and vehicle acceleration. For both shifts, the torque phase and inertial phase are identified, along with the necessary clutch control during these shifts. A key measure presented here is that fluctuations of torque at the transmission output will produce undesirable fluctuations in vehicle acceleration during the shift. The paper then covers the designed controller for clutch actuation, as well as the dynamometer test setup used to collect data.

The main value from Minowa's paper is the description of clutch behavior during a shift and the various figures used to aid this discussion. Additionally, the description of why torque fluctuations must be avoided was directly similar to the goal of the shift fill algorithm presented in this study. Although the presence of an electric motor changes how the powertrain is controlled, the same shift dynamics apply, and the same goal to avoid torque fluctuations is held.

2.4 A Study on Evaluation Method and Improvement of Shift Quality of Automatic Transmission

Similar to Jeon [2], the paper by Naruse et al. [6] is focused on developing an evaluation method for gauging human reaction to shift quality based on numerical evaluations. Naruse begins by reviewing human sensitivity to frequency in vehicle. This sensitivity is different in the vertical and fore/aft directions, with vertical sensitivity being largest from 8-10 Hz and fore/aft sensitivity greatest at 1-2 Hz, however Naruse notes that 1-2 Hz is not prominent in the measurements taken previously in-vehicle. Naruse shows that fore/aft acceleration is inversely proportional to the subjective rating given to a shift, and therefore the lower the fore/aft acceleration the better the shift. Naruse explains that for measurement purposes, the acceleration measurement uses a bandpass filter from 2.8 to 28 Hz.

Based on the data presented, Naruse points out that the acceptable level of fore/aft acceleration is also dependent on the type of shift. Specifically, Naruse found that power-on downshifts can have significantly more, often double or more, fore/aft acceleration as power-on upshifts. Additionally, for small driveshaft torque fluctuations, Naruse concludes that any vertical acceleration has a more significant impact.

When investigating the relationship between torque fluctuation and acceleration, Naruse finds that 90% of the vibrations occurred in the 0-7 Hz range, which is directly caused by torque disturbances in the driveline affecting vehicle acceleration. The remaining 10% is primarily in the 7-10hz range, and is attributed to both the torque fluctuations and to the drivetrain mounts. Specifically, any offset between the engine roll center and the roll center of the engine/transmission mounting system.

To determine the shifts that were most important to increasing consumer acceptability, Naruse found that there are four major shifting events that were most common in the Japanese market vehicles operation. The first were partial throttle, power-on upshifts, followed by off-pedal downshifts during deceleration. The third item identified by Naruse appears to be an odd choice: garage shifts out of neutral into drive or reverse. The frequency of these garage shifts is not stated. The fourth shift identified is the 4 to 3 downshift, which for the vehicles used in the study is a downshift from top gear.

Naruse then discusses possible solutions that were tested to successfully reduce the shock in power-on upshifts, which involved a learning algorithm on correct clutch pressure when initiating the shift. A similar learn procedure was also incorporated into the electronic control of the clutches during garage shifts. Finally, to address mounting concerns, Naruse introduces a hydraulic mount for the powertrain to significantly reduce the force transmitted to the frame.

Naruse’s study proves invaluable when deciding on the frequency range to target with shift fill and other drive quality improvements. The overview of both human response as well as source of the vibrations is important for understanding how to improve driver comfort.

3 Planetary gear transmission shifting dynamics

Fully automatic transmissions represent the vast majority of vehicle sales in the US and several other regions of the world. They are preferred for both the ease of use they provide, and for the comfort that comes from not requiring the driver to change gears. Since their introduction nearly 80 years ago, automatic transmissions have progressed from having 2 speeds to having 8, 9, or 10 speeds in modern transmissions. Despite the increase in gears, modern automatics also strive to provide a smoother drive than manual transmissions.

To achieve automatic gear changes, modern automatics employ a hydraulic system that actuates a series of clutches. These are connected to a series of planetary gear sets to allow for multiple output gear ratios without the need for individual gear sets for each output ratio. By fixing a piece of each planetary gearset to the case of the transmission (to keep if from moving) or to another part of a gearset, the transmission can move between different ratios.

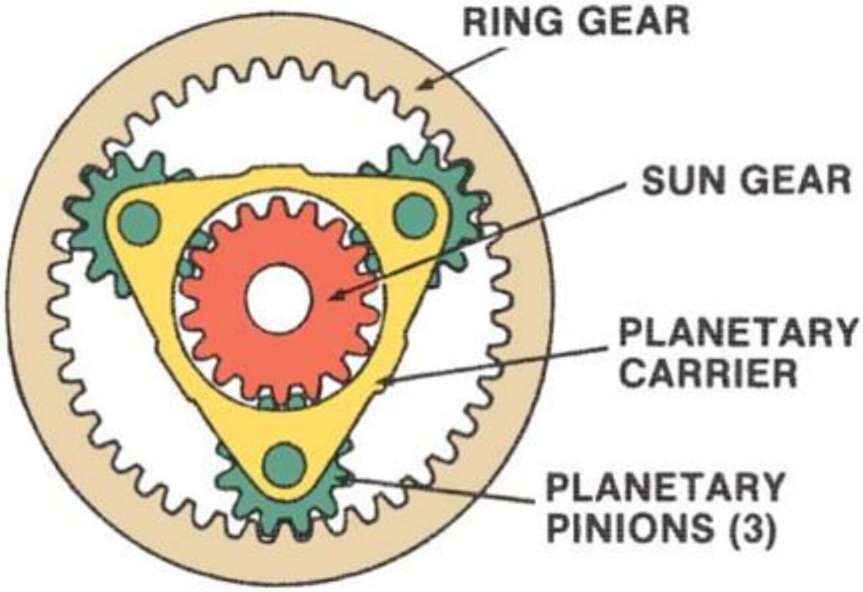

Figure 3-1: Planetary gearset layout [6]

To prevent the transmission from binding gears in place, the engine must stop providing torque to the transmission while it shifts gears. Ordinarily, this would mean that the vehicle would start to decelerate whenever a gear shift was initiated. During this shift, the driver would experience a harsh deceleration before the gear shift ended. To prevent this, most vehicles will increase engine torque output as a shift begins in order to accelerate the vehicle just before the gear shift. As the gear shift continues, engine torque is decreased to allow the gear change before returning to normal levels.

3.1 Transmission Shift Schedule plots

To simplify displaying shift schedules, the shift points can be summarized by relating them to accelerator pedal position (APP) and vehicle speed. The upshift and downshift points are then plotted for each gear change to form lines. When APP and speed are plotted over time, a transmission shift is planned based on when the shift lines are crossed.

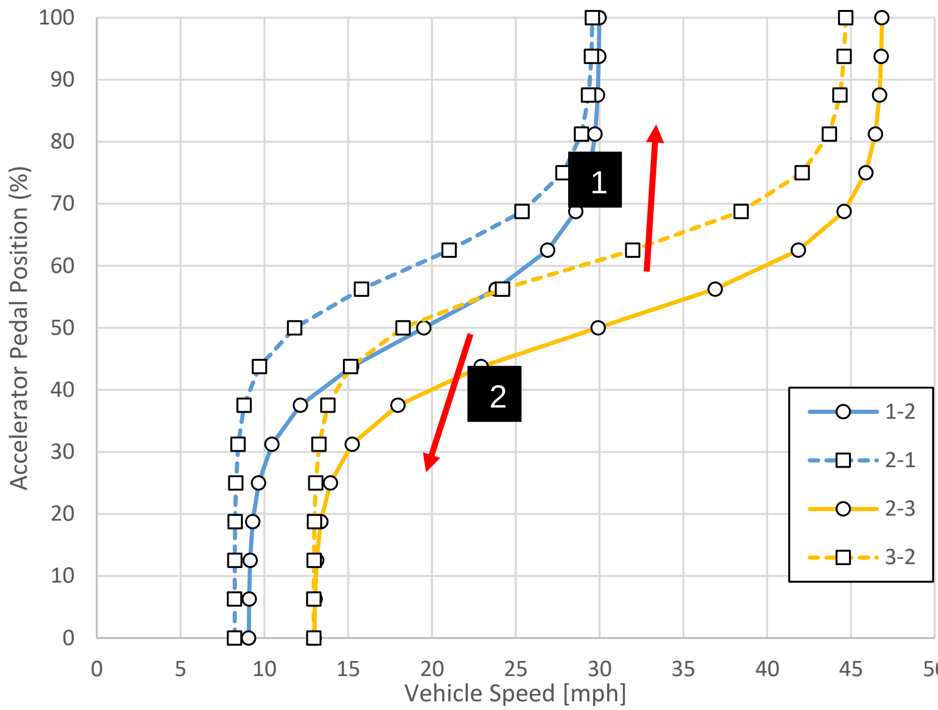

Figure 3-2: Example Synthesized shift map

In Figure 3-2 is an example of a synthesized shift map. In the red line labeled 1, the driver presses down on the accelerator pedal and the vehicle starts to accelerate. As the driver continues to press the pedal down further, the red line crosses the 3-2 downshift line (marked as a dotted yellow). When pedal position and vehicle speed cross this line, the transmission gear is commanded to change from 3 to 2.

The red line labeled 2 shows a driver letting off the pedal as the vehicle slows down. When the pedal continues to decrease, the red line crosses the 2-3 upshift line, and an upshift is commanded.

3.2 **Overall shift terminology**

Depending on the company or organization, specific shifts are often described with different words even when they would be discussing the same shift event. Therefore, the terminology used in shift events for the remainder of this paper are described in this section.

3.2.1 Garage Shifts

Garage shifts are typically the main interaction between the driver and the transmission shift. Garage shifts refer only to transmission ratio changes involved with a change in shift lever (or similar mechanism) position. Thus the most typical example is shifting from park to reverse or drive, or from drive to reverse. As their name suggests, garage shifts are most common when pulling out of or maneuvering in a garage.

3.2.2 On-power upshifts

On-power upshifts occur when the transmission changes from a lower gear to a higher gear while the vehicle is accelerating. For example, if a vehicle is merging onto the highway and the driver holds a constant pedal. As the vehicle speed increases, the transmission will upshift to a higher gear while accelerating. An example of such a shift is shown as the green arrow labeled 1 in Figure 3-3. On-power upshifts often have a large impact on drivability, as excessive accelerations during a shift are uncomfortable for the driver.

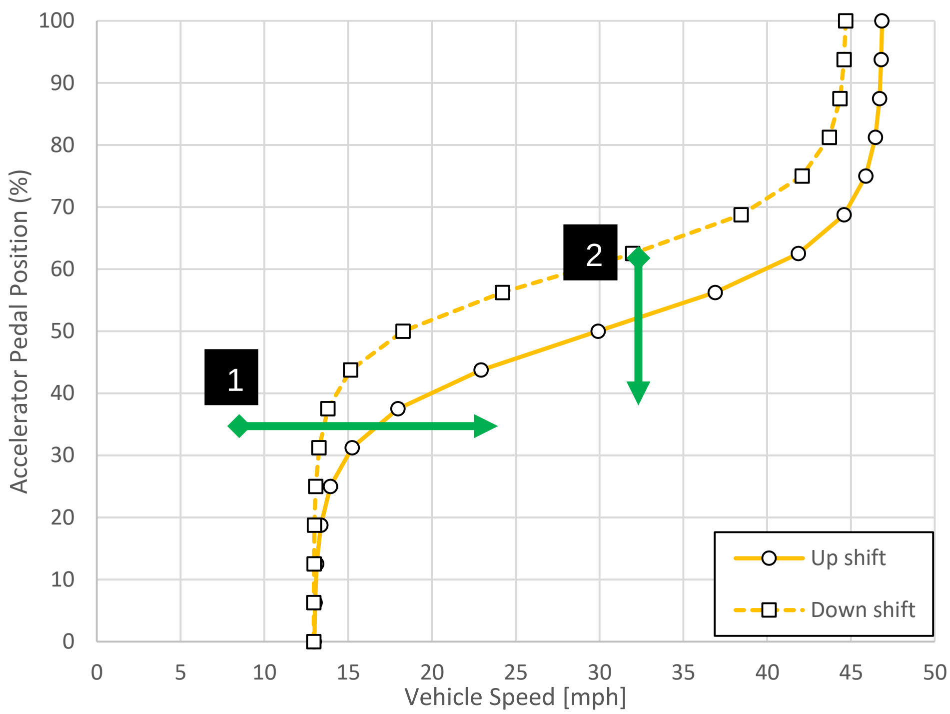

Figure 3-3: Upshifts displayed on shift schedule map

3.2.3 Off-power upshifts

Off-power upshifts generally occur when the driver has tipped out of the accelerator pedal after an acceleration, to either a low or zero pedal position. When the driver tips out and acceleration is no longer required, the transmission will downshift to place the engine in a better operating torque-speed region. An example of this, labeled 2 in Figure 3-3, is best visualized on a shift map plot. Off-power upshifts do not impact drivability as much as on-power upshifts, as the desired acceleration is very low allowing for longer, smoother shifts.

3.2.4 On-power downshifts

When a driver tips in aggressively on the accelerator pedal, an on-power downshift will be performed to allow the vehicle to accelerate. A prime example is highway overtaking maneuvers. Starting at a constant pedal, the driver tips in to high pedal position to pass a slow moving vehicle in their lane. The desired acceleration is high, so the transmission will drop from a higher gear to a lower gear for higher torque multiplication. An example of such a passing maneuver is shown as the orange arrow labeled 1 in Figure 3-4. On-power downshifts need to be smooth to maintain driver comfort during a shift event, but depending on the aggressiveness of the acceleration, shift quality may be sacrificed to meet driver torque demand.

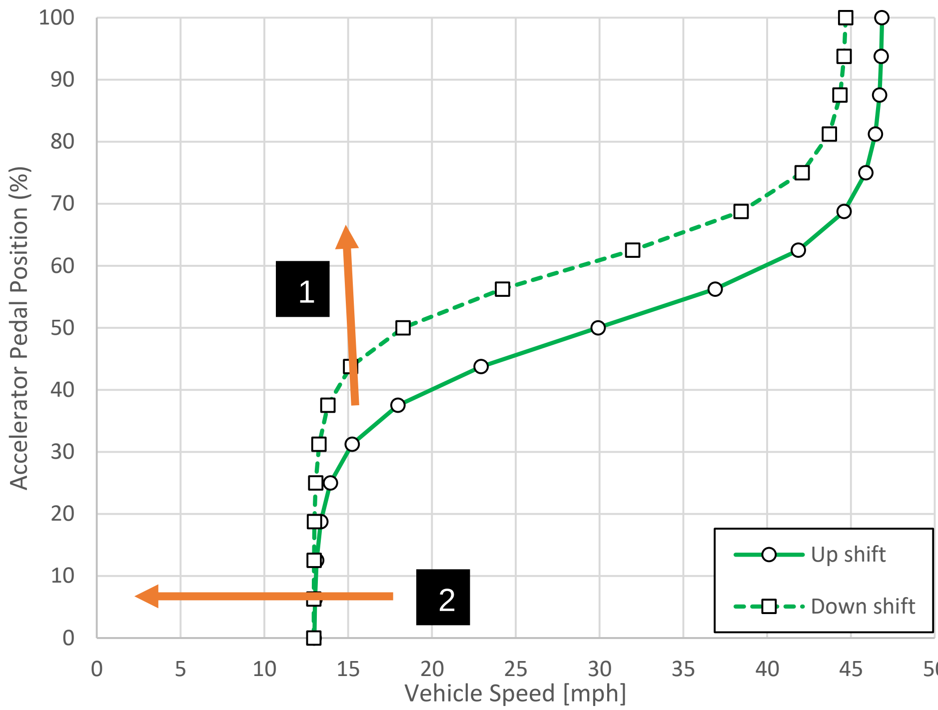

Figure 3-4: On-power and off-power downshift examples on shift map

3.2.5 Closed-Throttle or Off-power downshifts

Historically, off-power downshifts occurred primarily when the engine throttle was closed, and are often referred to as "closed throttle" downshifts. Off-power downshifts can occur without a truly closed throttle, so that is the preferred, broader term. Off-power downshifts occur when the vehicle is decelerating. In order to keep the engine from stalling, the transmission shifts from a higher gear to a lower gear to raise the engine speed. An example of a low-pedal, off-pedal downshift is shown labeled as 2 in Figure 3-4. This situation would occur as the driver lets off the pedal, slowing down for a stop off a highway exit.

3.2.6 Shifting phases

All shifts conducted while moving have two phases involved: the torque phase and the inertia phase. The torque phase occurs at the beginning of the shift, when the off-coming clutch begins to lose pressure and the oncoming clutch begins to fill with fluid. During the torque phase, the transmission has not yet changed ratios, and an increase in engine torque demand is often used to maintain vehicle acceleration through the torque phase. The inertia phase occurs when the clutches trade positions, with the on-coming clutch achieving higher pressure than the off-coming clutch. It is dubbed the inertia phase because the inertia of the internal mechanisms is used to allow the ratio change to occur. To facilitate this the engine will also lower torque production to allow for the smoothest ratio change. When the inertia phase is concluded, the shift has ended and the engine returns to normal torque production.

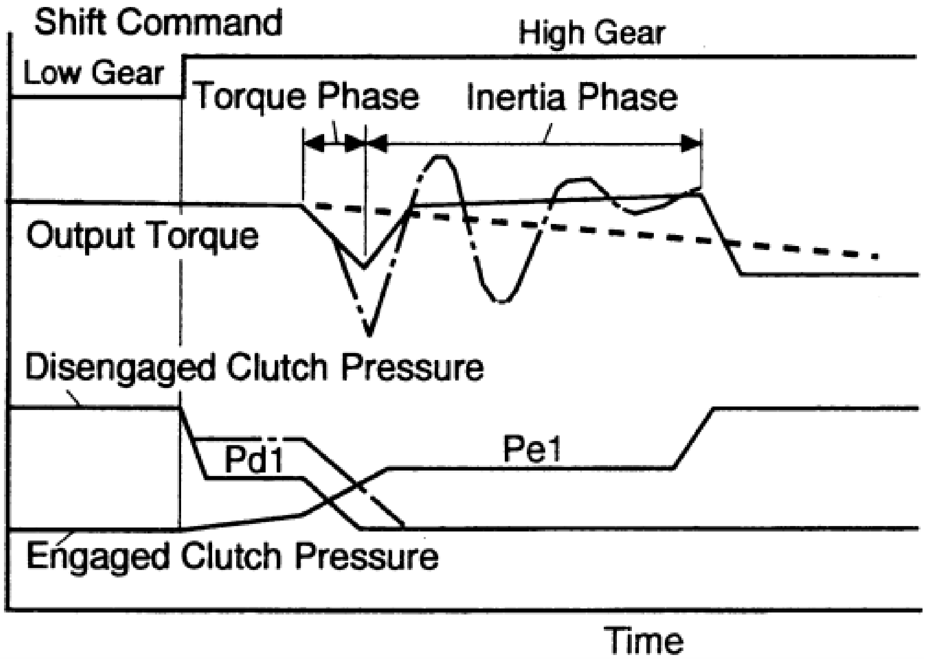

Figure 3-5: Ideal upshift clutch control for smooth clutch-to-clutch shifting from Minowa et al. [5].

4 Drive Quality measurement

4.1 Background

Historically, the drive quality of a vehicle was based almost entirely on subjective measurements. Test drivers from automotive manufacturers, with a wealth of experience driving a wide range of vehicles, rated vehicles based on feel. These ratings were based on past experience and the perception of the driver. Recently, manufacturers have moved towards objective benchmarking of drive quality. One tool used by many manufacturers to assess vehicle drive quality is AVL-DRIVE™ [3]. DRIVE aims to remove subjective ratings by basing ratings on specific drive events with on board data collection. This scoring is primarily based on the chassis longitudinal acceleration, with data on engine/transmission parameters and driver inputs being used to determine the type of event. While the equations used to calculate an event scored are considered proprietary, the factors that impact each events score are provided by AVL to allow calibrators to improve vehicle scores. When vehicles are scored, they are compared against a database of other vehicles in their class, based on vehicle size, powertrain components and layout, and market. In this way, economy vehicles can be scored separately from upscale vehicles with different market expectations.

Operational modes are further broken down into sub-operation modes. Tip-in, for example, is classified further by the acceleration of the vehicle prior to the tip-in. Closed pedal, constant speed, and during an acceleration are three separate sub-operation modes for tip-in events. All sub-operation modes in the same operational mode are rated based on the same criteria. The number of criteria varies based on operational mode, but all are factored into an operational mode score. All operational mode scores are weighted to produce an overall vehicle drivability score. The specific weightings and details of the scoring criteria are AVL proprietary.

In order to benchmark drivability scores for the hybrid Camaro powertrain, initial measurements of the stock donor vehicles are made. The engine donor, a 2014 Chevrolet Silverado with the L83 V8 and a 6-speed transmission, is tested to examine the drivability rating of the engine in the original vehicle. Similarly, the donor chassis, a stock 2016 Camaro equipped with a V6 and an 8-speed automatic, is evaluated to set a baseline for the vehicle before modification.

4.2 Drive Quality Metrics

For each of the five drive quality metrics used in the EcoCAR 3 drive quality event, there are individual criteria that determine the scoring produced by DRIVE. While some criteria are shared between events, the individual events are broken down into criteria to better understand what causes a vehicle to score poorly. Each drive quality metric also classifies individual events into sub-metrics to provide a more detailed analysis of vehicle behavior. All events that belong to a specific metric, however, are scored on the same criteria regardless of sub-category for the event. Table 4-1 summarizes the operation modes and criteria used in EcoCAR 3.

Table 4-1: Drivability operational modes and criteria

Operational Mode	Criteria
Drive Away	Response Delay
	Stumble
	Acceleration peak
Acceleration	Surge
	Acceleration Step
Deceleration	Surge
	Acceleration Step
Tip-in	Response delay
	Stumble
	Kick
	Jerks
	Torque buildup
Tip-out	Response Delay
	Kick
	Jerks

4.2.1 Drive away Events

Drive away events occur anytime that a vehicle is stopped and moves forward away from a speed of zero. Drive away events can occur in the form of creep, where the accelerator pedal is not applied but the brake pedal is released, or can occur with pedal application. The three main criteria used in DRIVE for drive away events are Response delay, Stumble, and Acceleration peak. Response delay is used to assess how quickly the vehicle powertrain responds to an application of accelerator pedal during a drive away. The criteria sets forth targets for very low delay, less than 400 ms, for both an initial response and a response in excess of 1 m/s^2. The lower the delay, the better the score. Stumble is defined in DRIVE as a decrease in acceleration during a drive away event prior to peak acceleration. A vehicle that scores well will have little to no stumble during drive away events, with any stumble negatively effecting the drive away score. Finally, acceleration peaks are scored based on large negative jerks directly after maximum acceleration. The target for acceleration peaks is to avoid peaks in acceleration, and to have the acceleration response during drive away events to be as smooth as possible.

4.2.2 Acceleration Events

Acceleration events can begin in a variety of ways, but the DRIVE score for acceleration is used to quantify the characteristics of any form of acceleration event. Acceleration events exclude only one kind of acceleration, which are instead classified as tip in events. Therefore, normal acceleration events do not include step inputs to accelerator pedal. Regardless of how an acceleration begins, the main criteria used in acceleration events for EcoCAR 3competition are surge and “Acceleration Steps”. Surge is classified as high frequency disturbances in acceleration above a specified threshold, with a target of zero surge events in an acceleration. While all acceleration events will have some high frequency component to acceleration, minimizing the amplitude of these components is key to a high score in DRIVE. Acceleration Steps are low frequency changes to acceleration amplitude. These steps can occur during gearshifts or for other reasons, but minimizing the amplitude of acceleration steps leads to better scores from DRIVE. An example of surge and acceleration steps is shown in Figure 4-1. This acceleration behavior for surge and stepping is the same as observed in deceleration events.

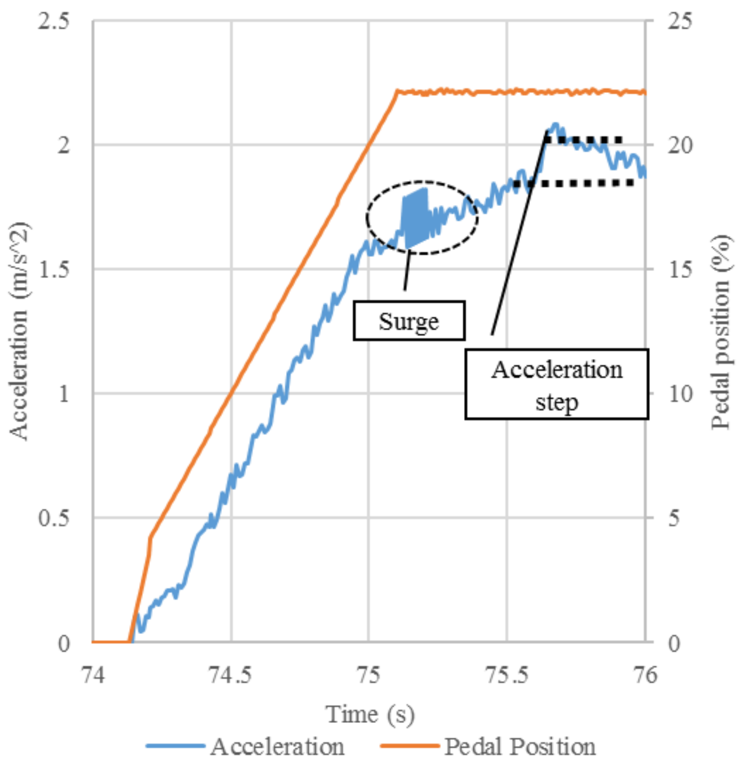

Figure 4-1: Deceleration event example

4.2.3 Deceleration Events

Deceleration events are identified primarily by a zero accelerator pedal position. Additionally, deceleration events must last at least 2 seconds and maintain a constant transmission gear throughout the deceleration. Decelerations are rated during braking and coasting separately, but both are used to generate a deceleration score.

4.2.4 Tip-in and Tip-out events

Tip-in events are characterized by a positive step change in accelerator pedal position, although real tip-ins generally are not true step changes. Tip-in for EcoCAR 3 focuses on response delay and stumble, which are described in acceleration events, as well as kick, jerk, and torque build up. Kick is measured as the first oscillation of acceleration after peak acceleration, as shown in Figure 4-2 as item number 3. Similarly, the first 5 oscillations are measured as the jerk criteria, which are grouped as item 4 in Figure 4-2. Both the amplitude of the five jerks and the rate at which they decay are used to score the jerk criteria of tip-in. Minimizing or eliminating initial kick and following jerks leads to better scores for Tip-in. Torque build up is shown as the shaded region labeled 2 in Figure 4-2, and is the discrepancy between a normalized plot of pedal position and a normalized plot of acceleration. To reduce poor scores from torque build up, the vehicle powertrain must aim to build torque rapidly after a tip-in pedal is applied.

Tip-out events are analyzed similarly to tip-in events, focusing on response delay, initial kick, and following jerks. To be classified as a tip-out event, the accelerator pedal must have a negative step change, but does not have to return to zero. Tip-out events do not include gear changes.

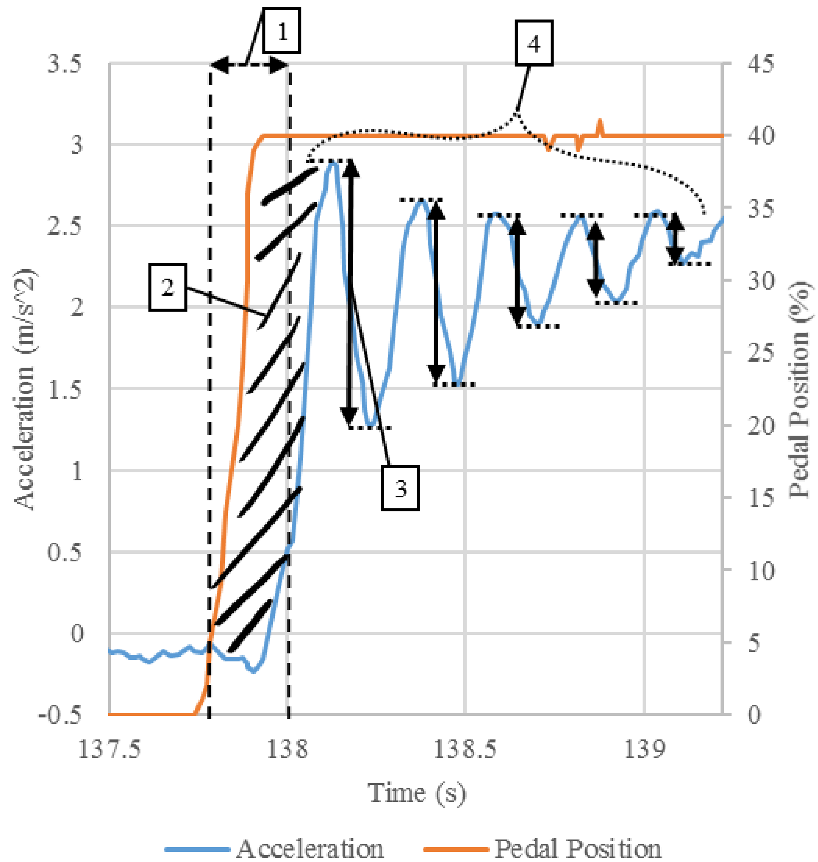

Figure 4-2: Tip-in event example data taken from stock 2014 Silverado.

4.3 Testing Methods and Data Collection

The data required for AVL DRIVE processing is all recorded from a vehicle main controller area network (CAN) bus. To collect CAN traffic, a Vector CANcase is connected to the on board diagnostics (OBD) port located underneath the dashboard of the vehicle. The CANcase is connected to a laptop that records CAN traffic using Vector CANoe, which is saved in full for later processing. A description of all CAN data required for analysis in AVL DRIVE is shown in Table 4-2.

Table 4-2: CAN data required for AVL DRIVE analysis

CAN signal recorded	Units or Values
Engine Speed	rpm
Vehicle Speed	kph
Chassis Longitudinal Acceleration	m/s^2
Brake Apply	On/Off
Gear	Gear # (dependent on transmission)
Selector Lever Position	P/R/N/D
Torque Converter Turbine Speed	rpm
Wheel Speed Front Left	kph
Wheel Speed Front Right	kph
Wheel Speed Rear Left	kph
Wheel Speed Rear Right	kph

The chassis longitudinal acceleration recorded in the test vehicles is reported by the vehicle internal accelerometers. Some drive quality metrics in AVL Drive require an independent accelerometer, however to ease testing requirements EcoCAR 3 does not measure these metrics.

The laptop and all logging is handled by the passenger of the vehicle to allow the driver to maintain focus on the road. The driver of the test vehicle only uses the laptop to observe real time pedal position during tip-in testing. In Figure 4-3Figure 4-3: Data collection setup for AVL DRIVE, the full data recording setup is shown. The laptop, labeled 1, records CAN data received from the Vector CANcase, labeled 2, which is reading CAN off of the OBD port under the dashboard, which is labeled as 3.

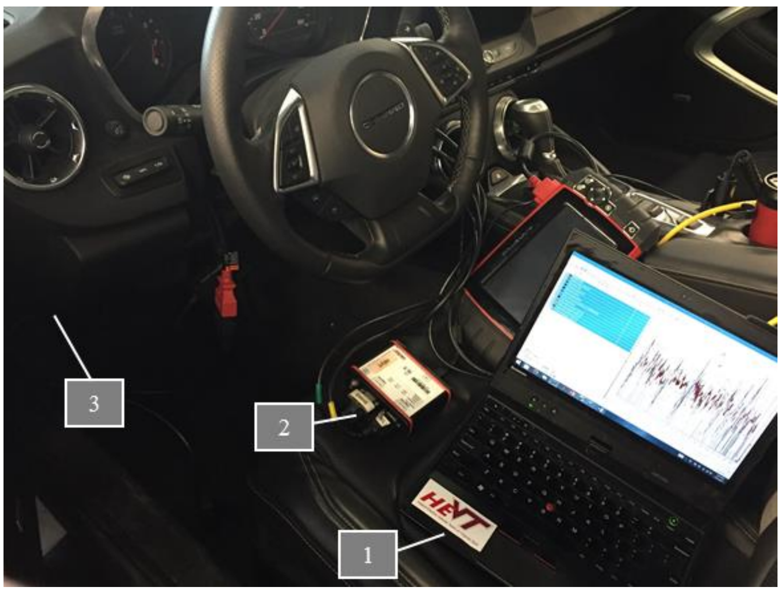

Figure 4-3: Data collection setup for AVL DRIVE

To build a set of data for repeated drive away, acceleration, and deceleration events, the stock vehicles are driven in a normal fashion at low and high speeds to gather a range of data useful for processing. This includes repeated stops, stop and go traffic, and passing maneuvers at highway speeds. While the vehicles are driven in similar conditions, with events repeated in similar fashions, events do not need to be identical to one another, and it is in fact key to have subtle differences between most events used in AVL DRIVE. The data processing performed during analysis in DRIVE corrects for the differences in data and uses the variety to better assess the overall drive quality. DRIVE performs these corrections based on factors that may be affecting performance, and weights events with undesired complications (steep grade, less smooth driver inputs, excessive steering motion). While no single event can completely alter a score, minimal poor scores are important to achieve high scores from the program.

To collect data for tip-in and tip-out events, the driver of each vehicle repeats a series of pedal positions to get a range of responses from the vehicle. A general tip-in tip-out pair will start with the vehicle at a constant speed, then include a tip-in to a specific pedal position which will be held for 3 to 5 seconds to allow the vehicle to respond, before tipping out to 0% pedal. Once the vehicle drops down to the original speed, the driver will tip-in to the same position again for 3-5 seconds and tip-out to 0% pedal.

4.4 Benchmark Results

To correctly compare the vehicle performance in relation to vehicles of the same type, the Silverado and Camaro are analyzed using different settings in DRIVE. The Camaro is classified as a "sportive" vehicle to be compared to other sports cars, while the Silverado is classified as a "large" vehicle given its large physical size and mass.

The numeric scores from DRIVE are shown in Table 4-3. The scores for each vehicle are recorded for each of the specified drive quality metrics, and are a score out of ten. While DRIVE generates an overall vehicle score, a lack of data for all drive quality metrics makes these scores very low. Per the help documentation in DRIVE, most vehicles will score around 7 out of ten in their vehicle category, with anything below a 6 being considered to be a poor performing vehicle in its class.

Table 4-3: Drive quality metric scores for Tested vehicles

Drive Quality Metric	Silverado	Camaro
Drive away	7.7	7.5
Acceleration	6.8	7.0
Deceleration	6.9	6.4
Tip-in	7.3	7.2
Tip-out	8.0	7.6

Figure 4-5 shows an example of an acceleration event from the Silverado, which scored at 7.1. The relatively low scores in acceleration and deceleration events for the Silverado are mainly caused by poor scores for surge in both operation modes. The average score for surge in both modes was 6.8, while torque build up and response scored very highly with an average of 8.3. Examples of each operational mode from the Silverado data are shown in Figures 4-4 through 4-9. Figure 4-4 shows a drive away event with of median score for the Silverado, which shows no stumble before peak acceleration, and about 0.5 s of response delay. The acceleration peak is smooth, which contributes to the high score.

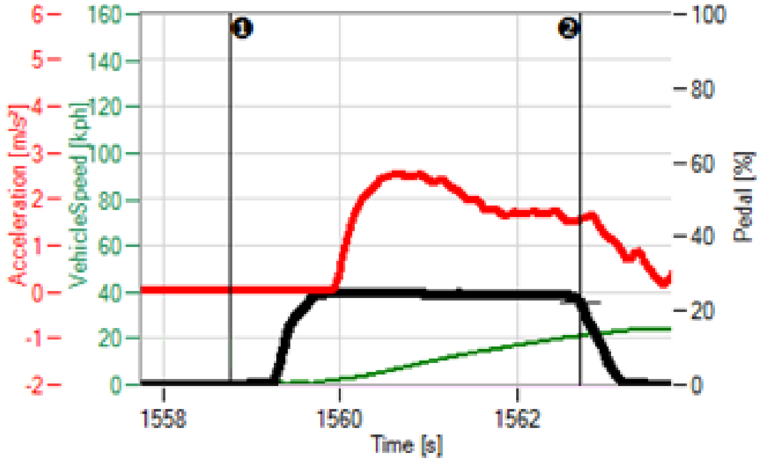

Figure 4-4: Drive away event example from Silverado

Figure 4-5 shows an Acceleration event recorded from the Silverado. This event shows some surge behavior in the oscillations of acceleration in red, but no major acceleration steps without proportional changes in accelerator pedal.

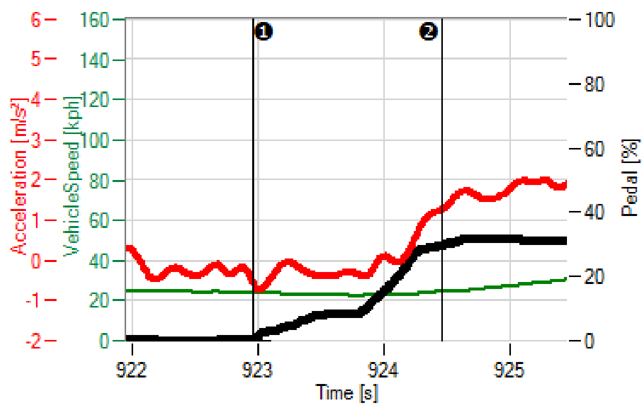

Figure 4-5: Example of Silverado Acceleration event scored at a 7.1

Figure 4-6 shows a deceleration event from the Silverado. Again there are no major acceleration steps but a noticeable amount of surge in the acceleration plot.

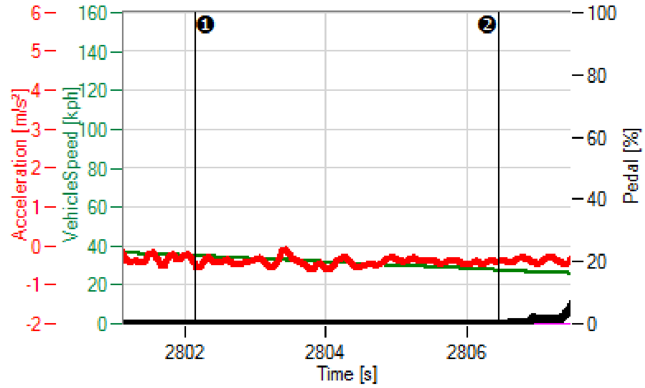

Figure 4-6: Example of a silverado Deceleration event scored at a 7.4

Figure 4-7 shows a tip-in event from the Silverado. There are no major kicks or jerks after peak acceleration, but the is a delay between the tip-in pedal and the acceleration response, which negatively effects torque build up and response delay scores.

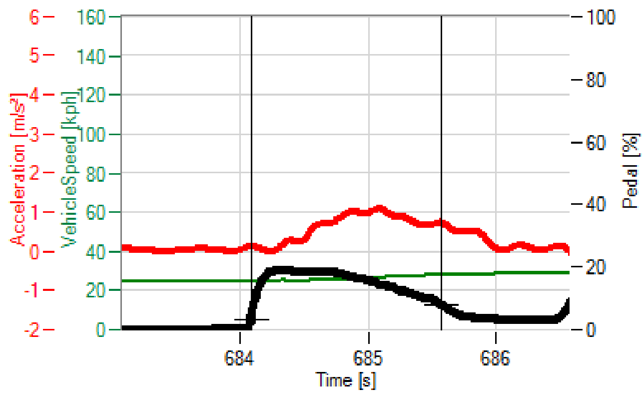

Figure 4-7: Example of a Silverado tip-in event, scored at a 7.1

Figure 4-8 shows a tip-out event recorded in the Silverado. Directly following the tip-out there is a steep slope to the first kick, as well as the several following jerks in acceleration afterwards. The magnitude of the kicks is relatively small, thus the high 7.9 score.

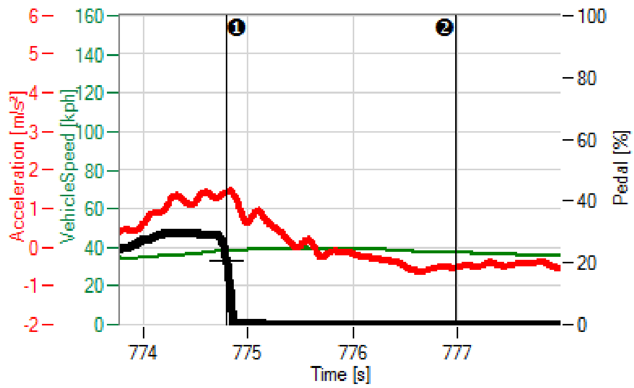

Figure 4-8: Example of a Silverado tip-out event scored at a 7.9

In almost all of the Silverado operational modes, a series of outliers significantly less dense than the main grouping of events appear. The full data set for acceleration events are shown in Figure 4-9 separated by sub-operational mode.

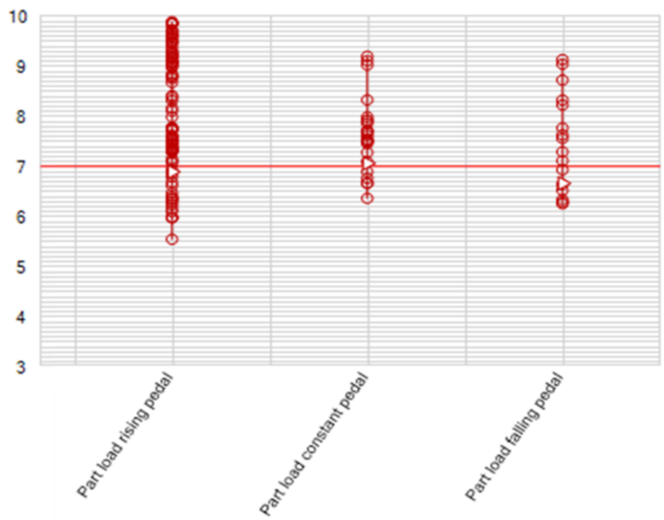

Figure 4-9: Silverado acceleration events shown by sub-operation mode, with a significant number of outliers

The Camaro is only scored higher than the Silverado in the acceleration operational mode. The major criteria that affected the Camaro scores for tip-in and tip-out events were kick and jerk, which on average scored 6.8 and 6.9 respectively. These lower scores affect the overall tip-in and tip-out scores for the Camaro. Additionally, the Camaro received poor scores for surge in many of the deceleration events, with over half of the scores for surge scoring at or below 6.0. Examples of common event scores for the Camaro are shown in Figures 4-10 through 4-15. Figure 4-10 shows an example drive away event for the Camaro, which is smooth without any stumble in acceleration following initial vehicle movement.

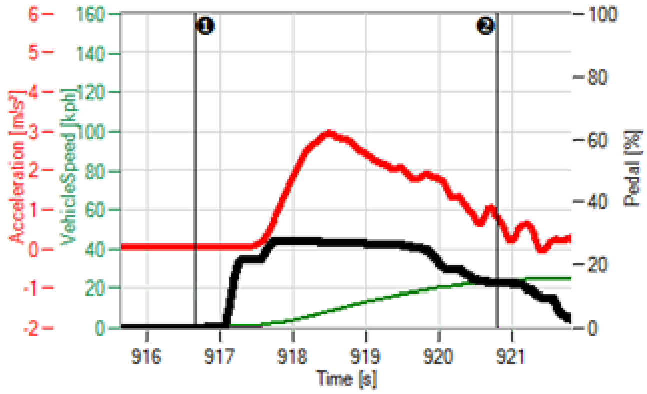

Figure 4-10: Example of a Camaro drive away event, scored at 7.6

Figure 4-11 shows an example acceleration event for the Camaro. The oscillations in acceleration at 3052 s show the surge measured in the Camaro, as well as an acceleration step down at the same time, before stepping back up.

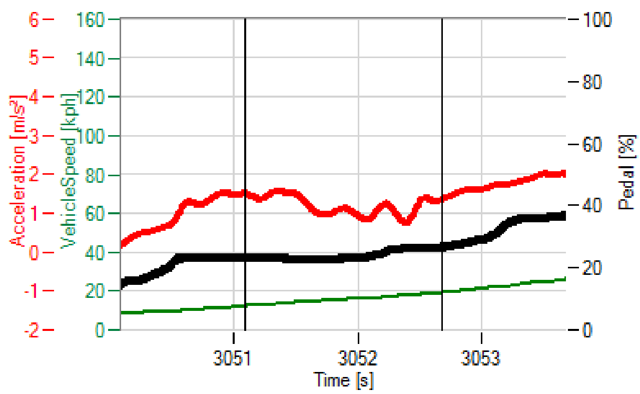

Figure 4-11: Example of Camaro acceleration event scored at 7.1.

Figure 4-12 shows a deceleration event from the Camaro. The acceleration plot, in red, shows significant surge during deceleration that lowers the Camaro's score.

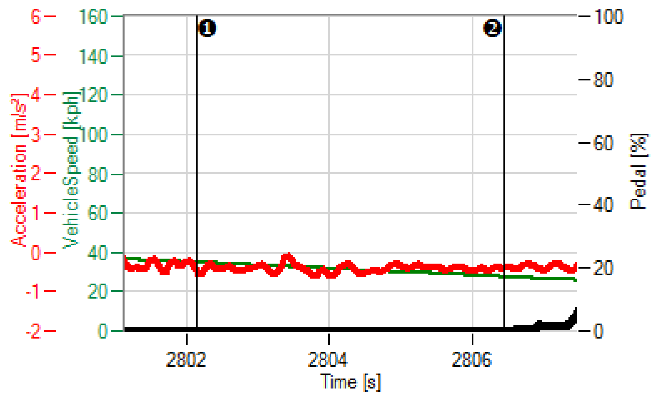

Figure 4-12: Example of Camaro deceleration event scored at 7.4.

Figure 4-13 shows a tip-in event from the Camaro. The response delay is low, with acceleration response occurring within about a quarter of a second. The initial kick after peak acceleration is relatively shallow, with low amplitude jerks following.

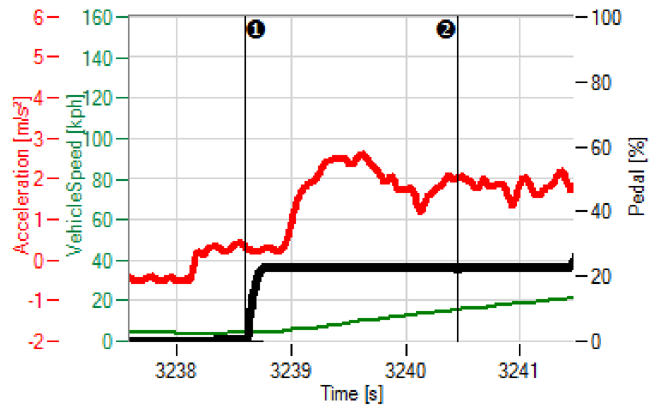

Figure 4-13: Tip-in event scored at 7.9 by AVL for the Camaro Test vehicle.

Figure 4-14 Shows an example of tip-out from the Camaro testing. Response delay after tip-out is rapid, less than a quarter of a second, and initial kick and following jerks are low amplitude.

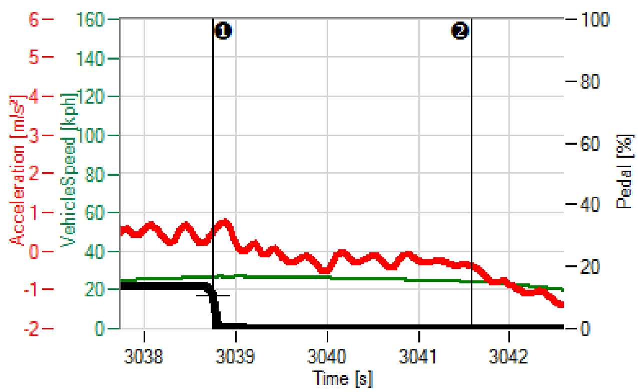

Figure 4-14: Example of Camaro tip-out event scored at 7.9.

The overall spread of most events for a particular metric is evenly spread out, with few outlier events. The spread of the Camaro acceleration event data is shown in Figure 4-15, broken down into sub-operation modes.

A full size chart containing all data collected for both vehicles is located in the appendix.

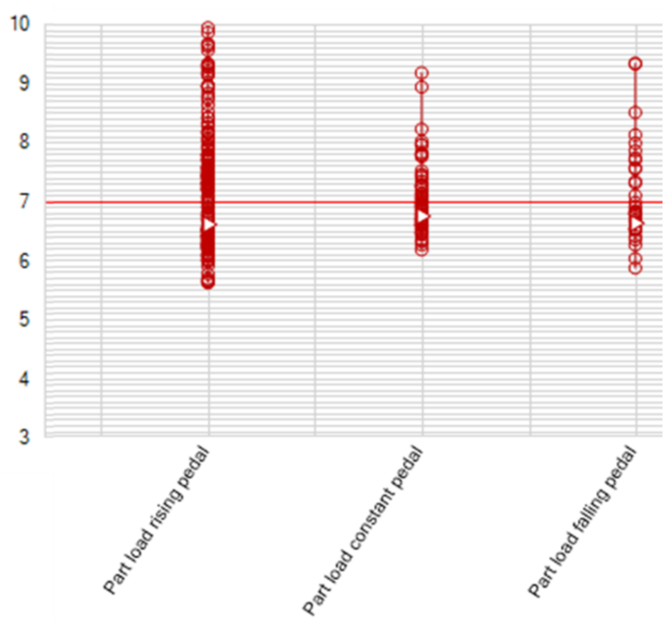

Figure 4-15: Camaro Acceleration scores broken down by sub operation modes.

5 Development of a cost effective accelerometer data logger.

To collect acceleration data in-vehicle across many different makes and models, a small, easily constructed and cost effective solution for collection, data logging, and potentially data processing was needed. To achieve this, a small collection setup is built using a Raspberry Pi with a “sense Hat” attachment. The low cost of the entire setup, well under $90 for all components, allowed for multiple devices to be built for data collection. The Raspberry Pi with the sense HAT attachment is shown inside of a case in Figure 5-1.

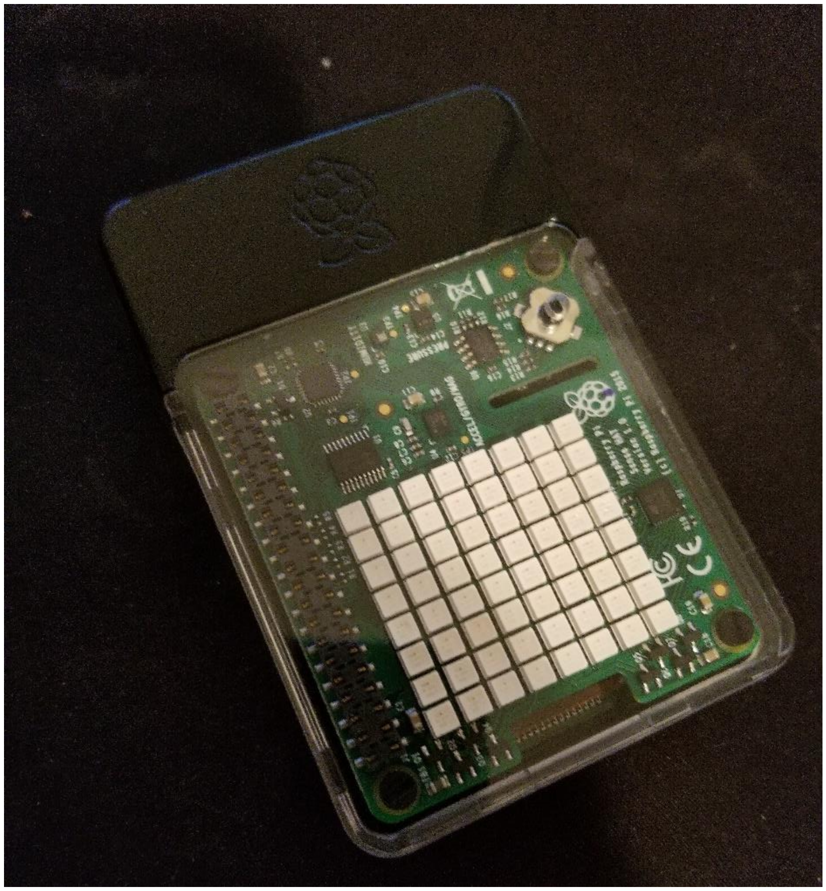

Figure 5-1: The Raspberry Pi data collection setup, inside of a small case.

The Raspberry Pi was chosen because it is low-cost, and can easily be programmed using MATLAB using the Raspberry Pi hardware support package (which is free to anyone with a MATLAB license). The support package includes Simulink blocks for reading data from the various sensors on the sense HAT, which allows for rapid addition of filters or other processing. Additionally, the flexible nature of Simulink's hardware support allows for both connected and remote operation. Connected operation allows the user to view live data over ethernet directly in the Simulink window, and monitor any processing that is occurring. In remote mode, the pi can collect data without any user input and log it to the on-board SD card.

The sense HAT includes a 3-axis accelerometer, gyroscope, and mangnometer with a pressure, temperature, and humidity sensory as well. The 3-axis components can be sampled up to 952 Hz, and can be set from a range of ±2 g to ±16 g and is reported as a 16-bit output for each direction. For in-vehicle data collection, a sample rate of 100 Hz and a range of ± 2 g is used.

6 Shift Tracking and identification

As described in the review of the paper by Naruse [6], torque disturbances during shifts are a major contributor to poor drive quality. With the unique post-transmission position of the motor in HEVTs powertrain, the control system can vary torque at both the input and output of the transmission during a shift. This gives the potential to alter shift behavior from conventional vehicles, as the motor can be used to smooth the torque disturbances caused by clutch-to-clutch shifting.

In order to provide a smooth shift, the engine and transmission controllers in the vehicle communicate specific information during a shift. When the transmission shift map determines that a gear shift is needed, the transmission takes control of engine torque production to move through the torque phase and inertia phase. Doing so, the transmission controller is able to control input torque to best smooth shifts when needed. This behavior is not limited to the transmission used in the HEVT Camaro, and is common throughout the industry for planetary gear set transmission.

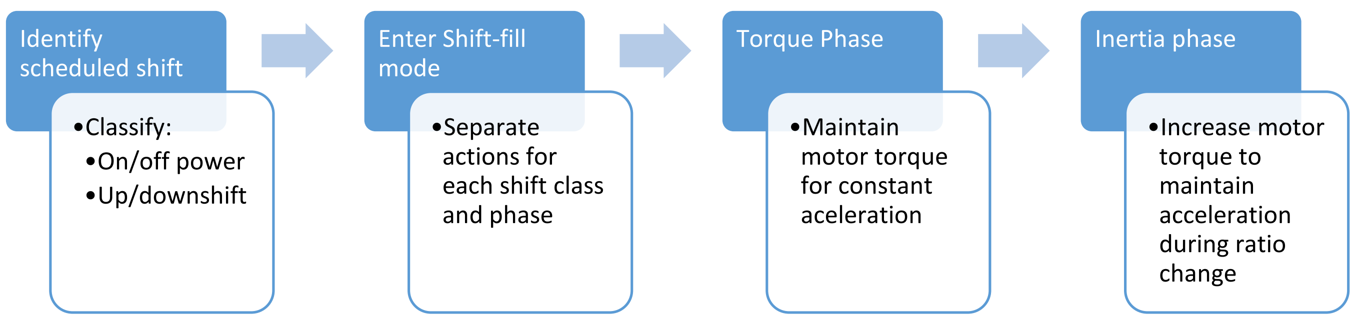

Figure 6-1:Overall shift fill strategy process for all shifts

Although each of the 4 shift classes discussed in section 3.2 have slight differences between them, the control strategy for shift smoothing follows the same guidelines presented in Figure 6-1:Overall shift fill strategy process for all shiftsFigure 6-1. The first diagnostic acts to identify shifts as they occur, primarily by comparing the desired and current gears. The shift is then identified as a power on/off shift based on current accelerator pedal position and vehicle speed. A shift occurring at high pedal, for example, is easily classified as on-power.

Once the shift has been classified, the control strategy monitors TCM to ECM interactions to determine if the vehicle will decelerate during the shift. To avoid excessive longitudinal jerk, the positive jerk during torque phases is canceled by the motor. The successive negative jerk is mitigated by applying positive tractive torque with the motor during the inertia phase. The torque commands and control strategies for filling each class of shift are described in the following sections.

6.1 **On-power upshift**

Figure 6-2 shows this interaction during an on-power upshift. When the commanded gear changes from 2 to 3, the shift begins. The transmission requests a slight increase in engine torque, shown in purple in the torque plot. As this increase in torque begins the torque phase, the off-coming clutch begins to release pressure to allow for a change of ratios. This increase in torque aims to maintain vehicle acceleration, as the transmission output torque will drop during the inertia phase.

As the off-coming clutch disengages, the transmission commands a decrease in torque, shown as the yellow torque line. While engine torque is lowered, the transmission allows the off coming clutch to begin fully releasing pressure, and the on-coming clutch to increase in pressure. As the clutches trade off the bulk of the input torque, the ratio of input speed to output speed drops rapidly from 2nd gear to 3rd gear's ratio. Once the off-coming clutch is fully disengaged and the oncoming clutch has fully engaged, the transmission indicates the shift has ended by releasing torque commands to the engine and changing indicated gear to match the commanded gear, shown in the gear ratio section of Figure 6-2.

The torque phase and inertia phase are indentified based on transmission torque command. While the transmission is requesting an increase in engine torque (the purple line), the clutches begin to slip in the torque phase. When the yellow torque command line shows a large reduction in engine torque, the inertia phase has begun. As there are two clear phases in power-on upshifts, there are two different motor torque responses that can be used based on the shift phase.

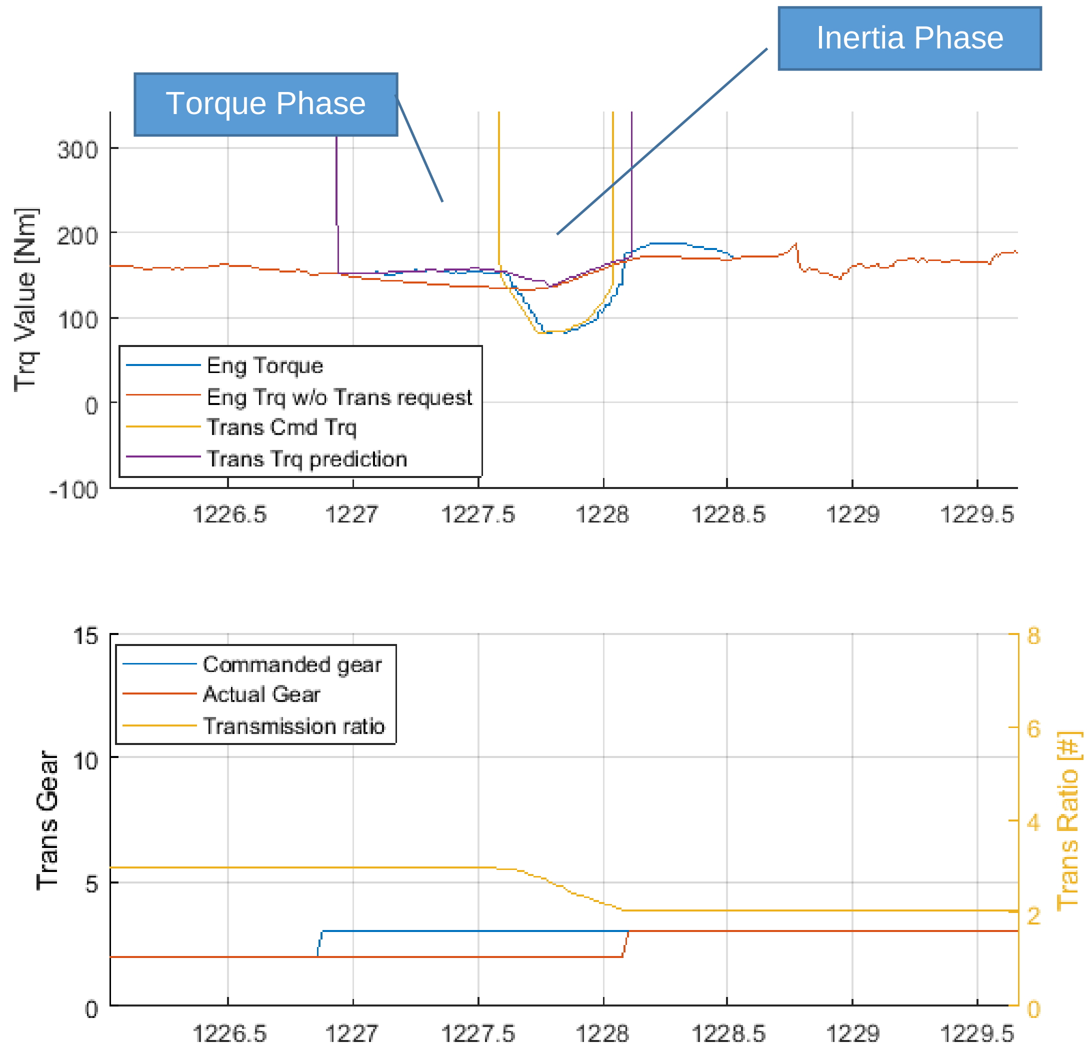

Figure 6-2: On-power upshift torque commands during shift, measured on HEVT Camaro.

6.2 On-power downshift torque profile

When executing an on-power downshift, excessive torque input to the transmission could cause unwanted jerk as well as damage the transmission if unmanaged. To prevent excess torque, hard downshifts for on-power events have been observed to include a torque request from the transmission that limits engine torque during the inertia phase. The torque limit in inertia phase is similar to power on upshifts, and is likely needed to allow proper clutch-to-clutch movement during the inertia phase. Figure 6-3 shows an example of the transmission attempting to limit torque on a downshift while the driver tips into the pedal.

As there is no clear torque phase during most on-power downshifts, there is only one motor torque response phase. This torque request is similar to that used in on-power upshifts, and uses a similar response strategy.

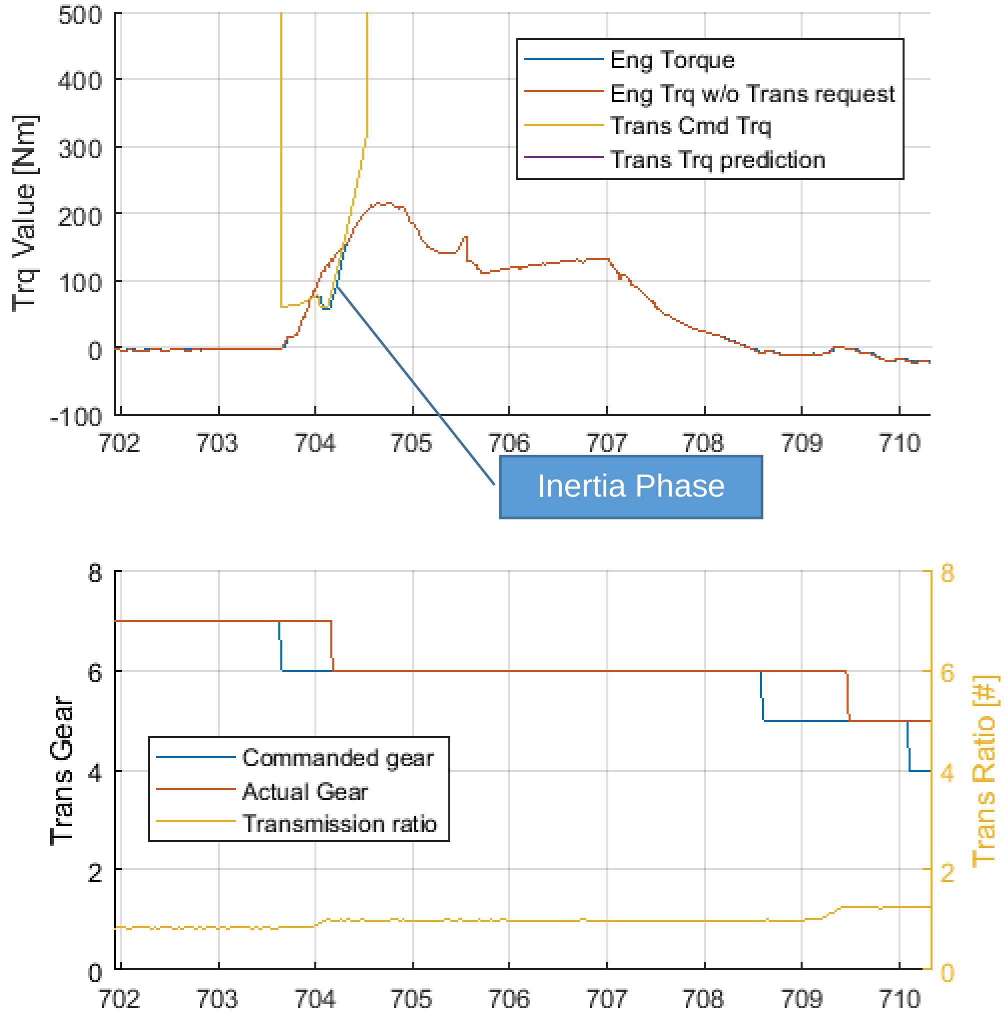

Figure 6-3: On-power downshift torque profile during a tip-in

6.3 **Off-power downshift**

During off-power downshifts, no torque coordination occurs between the engine and transmission. Particularly in completely off-pedal downshifts, driver expected vehicle behavior is a relatively mild deceleration. Proper clutch control and very low, near idle engine torques are sufficient to smoothly transition between the oncoming and off coming clutches. A series of off-power, zero APP downshifts are shown in Figure 6-4. No transmission commanded torques occur, as the engine is in decal fuel cut, allowing the compression of the pistons to provide negative torque.

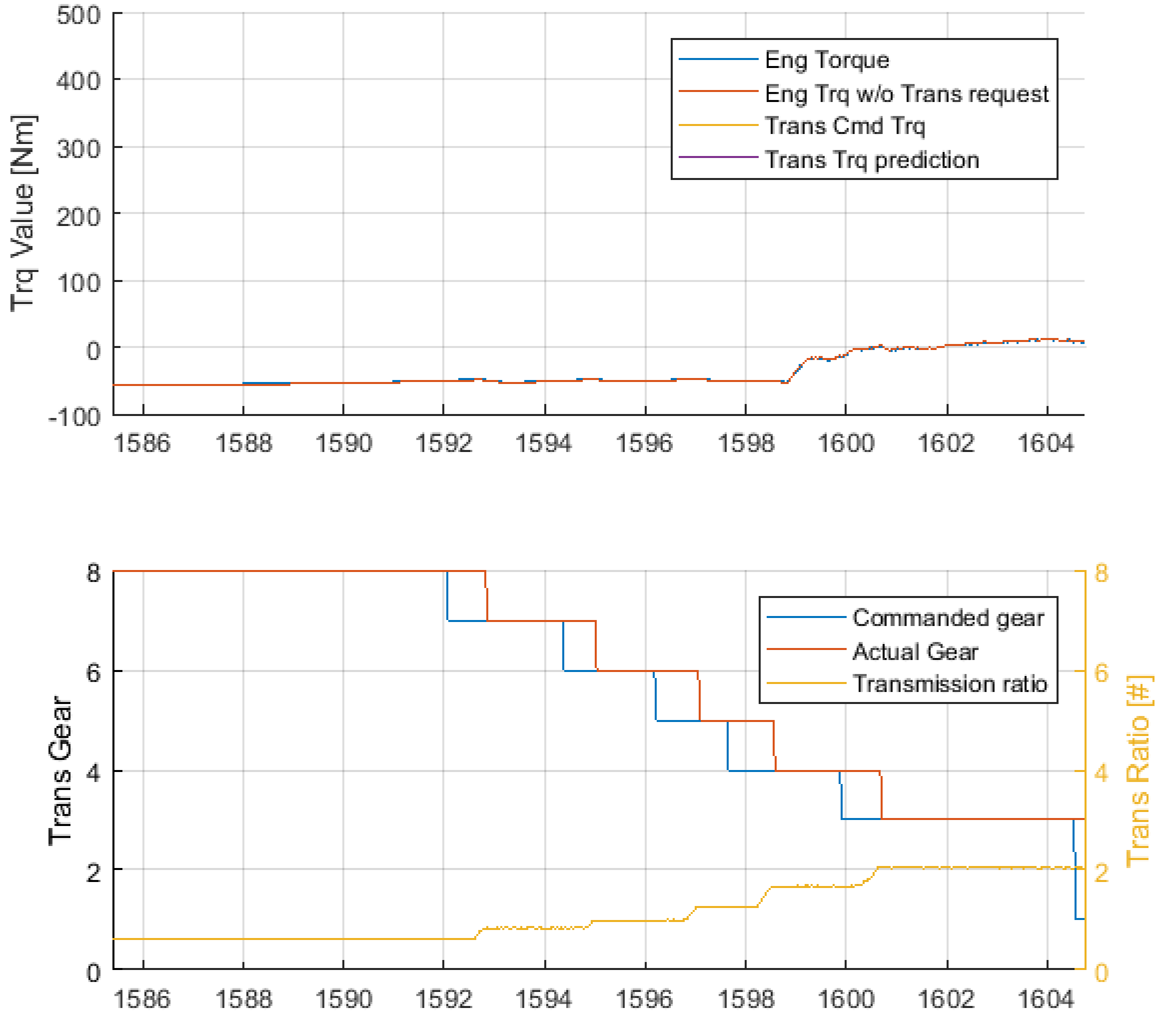

Figure 6-4: A series of off-power downshifts occurring as the vehicle slows down

6.4 **Off-power upshift**

Similar to off-power downshifts, there is no torque request from the transmission during off-power upshifts. These shifts primarily occur at highway speeds immediately following a tip-out from the driver. As a result, there is little engine torque through the shift and the transmission can change clutches without the need to change engine behavior. Figure 6-5 shows a direct comparison of an on-power upshift (from 6th to 7th gear) and an off-power upshift (from 7th to 8th) after a tip-out. While the first shift has a transmission torque request through the shift, the second upshift has no commands from the transmission. Due to the lack of torque commands, off-power upshifts do not require motor intervention to prevent torque fluctuations.

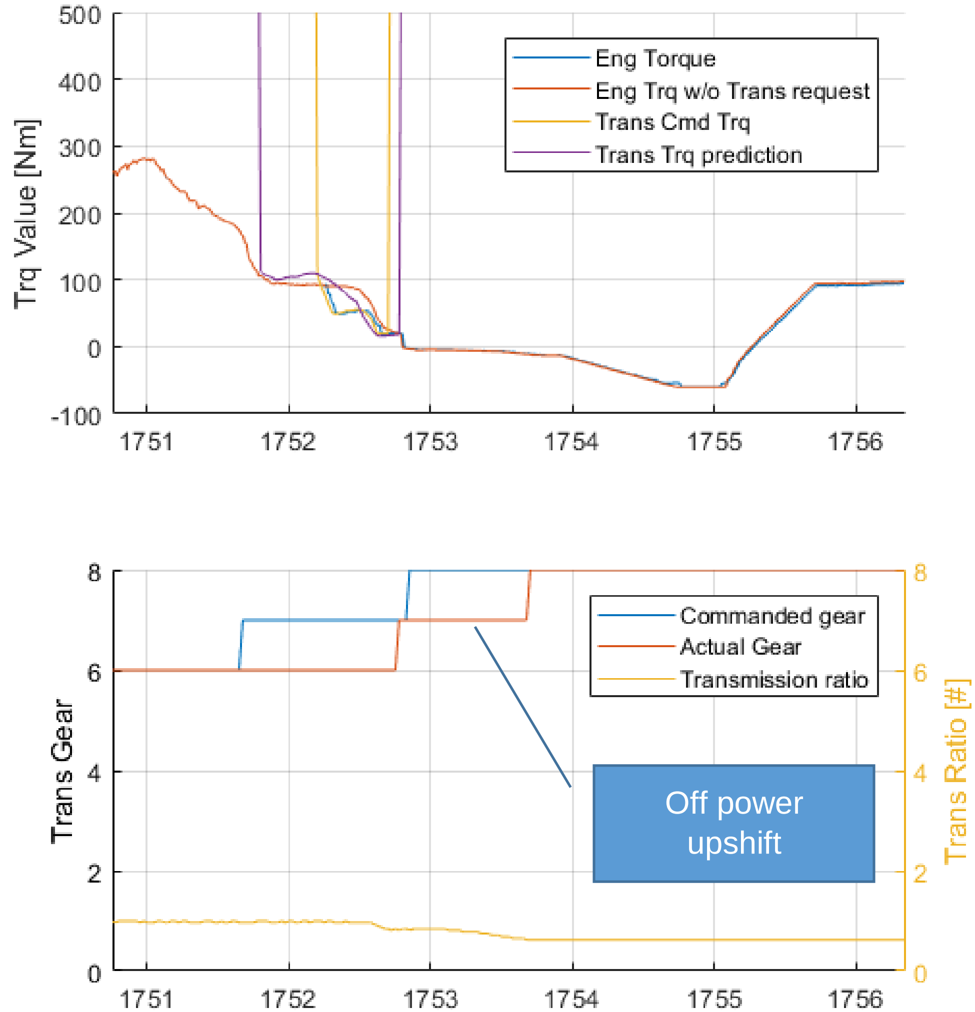

Figure 6-5: An off-power 7-8 upshift torque interaction.

7 Shift Fill Powertrain Model development

In order to examine the impact of the P3 motor on shifting dynamics, a Simulink model is developed using the Simscape blockset. The Simscape blockset allows the modeling of physical systems by connecting components as they exist in real connections. A torque converter, for example, is placed with the input shaft connected to the crankshaft of the engine model, and its output shaft is connected to the input shaft of the transmission model. This allows more complicated systems, such as the transmissions internal gear structure, to be modeled without developing the equations specific to the system interactions.

The Simscape model allows for rapid testing of algorithms that aim to improve shift quality, without the need to drive the vehicle on the road. Once an algorithm has been developed with the model, it can be tested in vehicle to verify results.

7.1 Model Layout

Overall, the model layout follows the topology of the physical powertrain. However, alternative component models are used to verify functionality and compare directly to in-vehicle data.

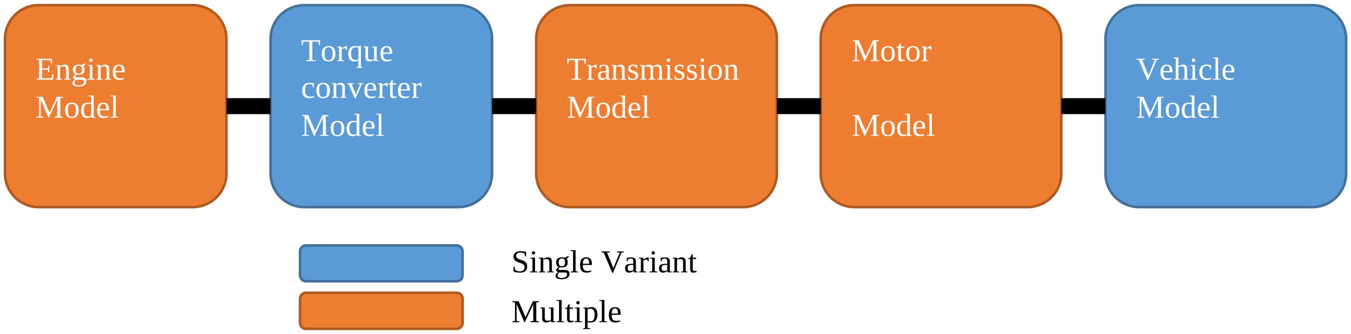

Figure 7-1: Powertrain model components including variant options.

The powertrain model aims to simulate the true vehicle powertrain with an acceptable degree of accuracy. To do so, the powertrain layout is the same as the parallel PHEV shown in Figure 1-2. Components shown in orange in Figure 7-1 have multiple variants developed for them to aid in testing. Having these variants allows for swapping one component model for another quickly when testing code.

7.2 Engine and motor models

The engine and motor models each contain two variants that are switched depending on test conditions. For general behavior testing, a true Simscape Engine and Motor model are used, to better predict behavior. These models are predefined blocks meant to model a generic combustion engine and electric motor using equation based physics. The engine model includes an option for redline and idle speed control, to better predict vehicle behavior. These variants are used to check overall model functionality, and run approximately four times faster than the real-data variants.

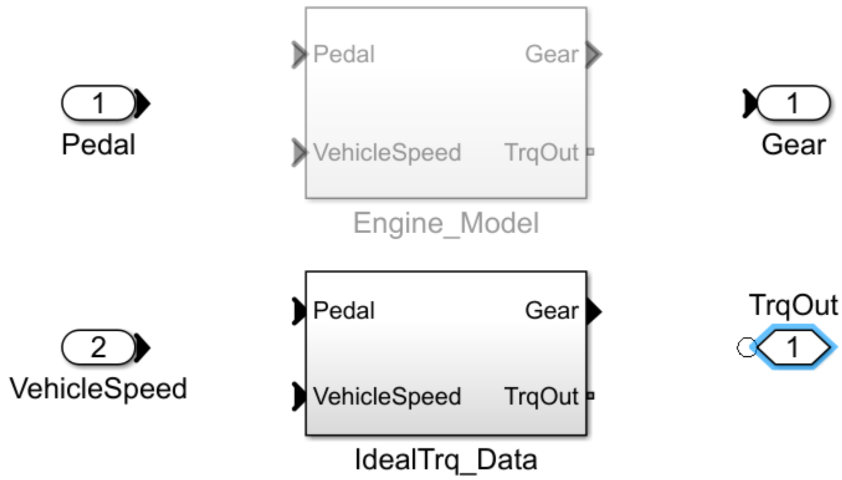

Figure 7-2: Variant setup for engine modeling.

When using in-vehicle data to validate model parameters, the engine model is replaced with an ideal torque and speed source, which allows for reproduction of in-vehicle test cases. The motor model is also replaced with an ideal torque source to remove any inaccuracies in model parameters for the motor while testing other subsystems. These variants aid in validating model parameters, as well as potential shift improvements using real shift data.

7.3 Transmission model

The transmission model is maintained as a stock model provided in the Mathworks Simdriveline blockset. As this model is devealoped to predict 8L90 behavior, it is designed to replicate the same mechanisms that exist in the production transmission. The stick diagram for the model, as well as the production transmission, is shown in Figure 7-3.

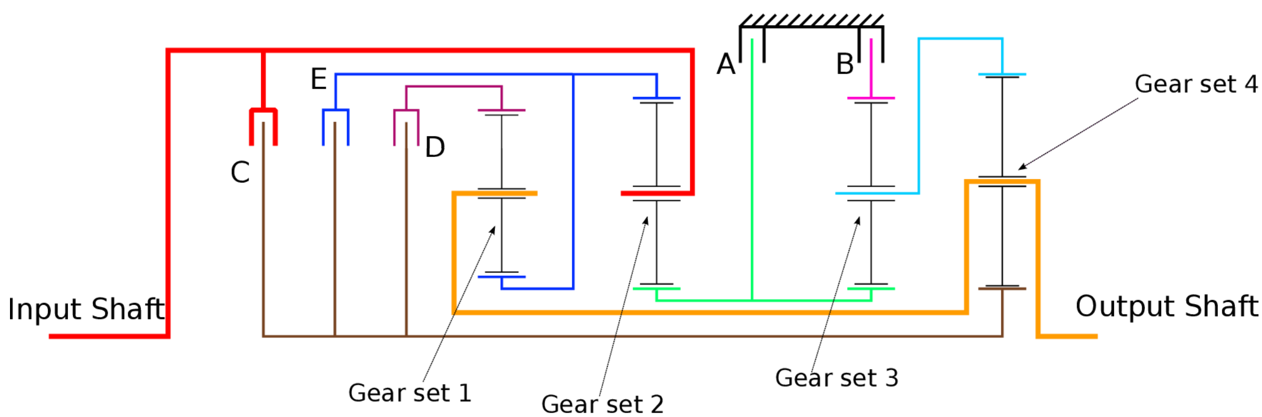

Figure 7-3: Stick diagram of a GM 8L90 transmission [8]

The GM 8L90 consists of 4 planetary gear sets that are linked and controlled with 3 clutches and 2 brakes, labeled A through E in the diagram. The planetary gears sets are represented with three connection points: the ring gear connection is made at the top, the planetary carrier connection is made at the center, and the sun gear connection is made at the bottom. The physical constraints are shown below, as well as the results of clutch/brake actuation.

Table 7-1: 8L90 gear set physical constraints

Constraints	
1	Input shaft is always linked to the planetary carrier of gear set 2
2	The planetary carriers of gear sets 1 and 4 are coupled to each other and to the output shaft
3	The sun gear of gear set 1 is coupled to the ring gear of gear set 2
4	The sun gears of gear sets 2 and 3 are connected
5	The planetary carrier of gear set 3 is connected to the ring gear of gear set 4

Table 7-2: 8L90 Actuator resulting effects

Actuator	Action
Brake A	Grounds the sun gears of gear sets 2 and 3 to the transmission casing
Brake B	Grounds the ring gear of gear set 3 to the transmission casing
Clutch C	Connects the input shaft (and carrier 2) to the sun gear of gear set 4
Clutch D	Connects the ring gear of gear set 1 to the sun gear of gear set 4
Clutch E	Connects the sun gear of gear set 4 to the constrained connection of sun gear 1 and ring gear 2

The Simscape model approach quickly replicates the physical layout of the transmission, without the need to develop equations of motion directly. Connections in the model are made just as they are in the real transmission. The Simscape model layout is shown in Figure 7-4. It includes all five clutches and all four planetary gearsets. The modifications made primarily focus on clutch actuation. The transfer function for actuating clutches, as well as the clutch pressure, did not accurately represent what was occurring in the vehicle itself. While the clutch pressure remains inaccurate to the true clutch actuation, the results are comparable enough for reasonable estimations.

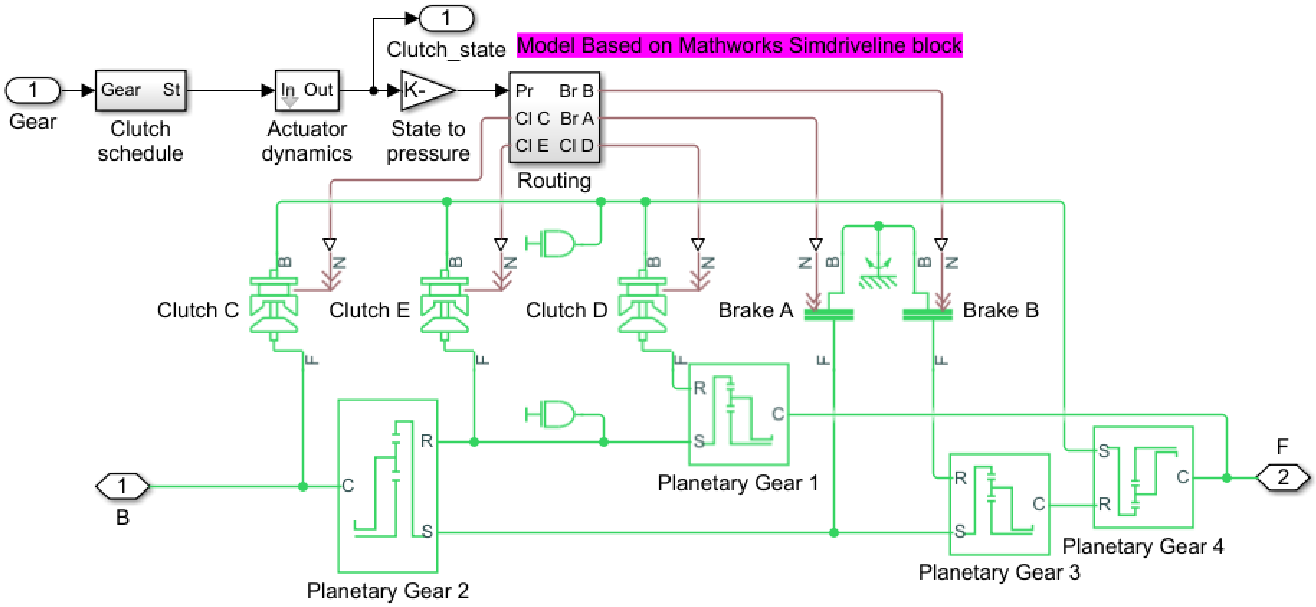

Figure 7-4: 8L90 transmission model based on stock Mathworks 8-speed model.

7.4 **Model Validation**

In order to validate the model, a set of test data using ideal torque source variant subsystem is used to run through multiple low speed shifts. The engine torque data was used to ensure that the transmission model and shift timing models accurately represented the real vehicle behavior. This data set is collected with the electric motor disabled to cancel any effects the normal torque split might have on the baseline data set.

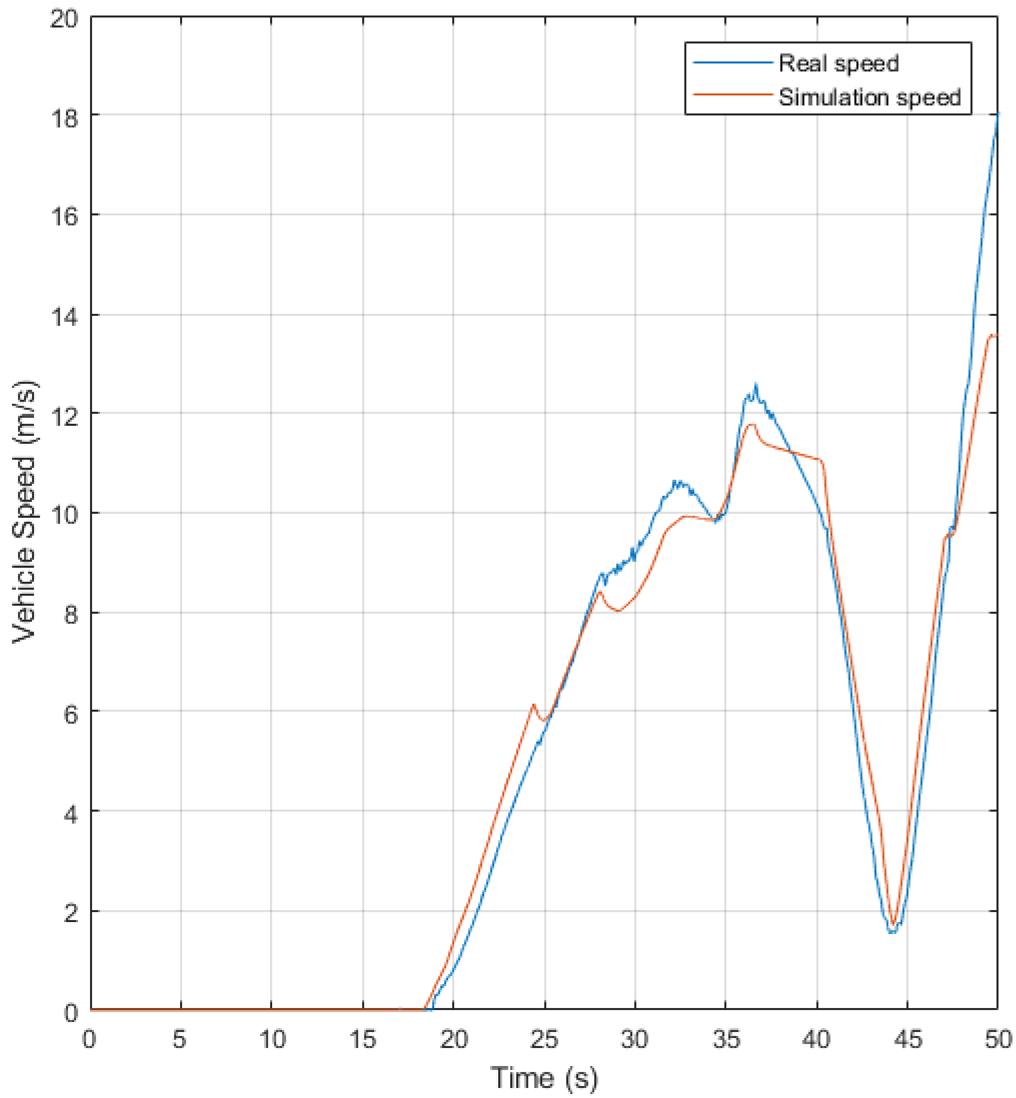

Figure 7-5: Simulation validation of vehicle speed characteristics

Although they do not match perfectly, Figure 7-5 shows the speed traces of the real-world data from the vehicle versus the simulation. The speed in simulation is relatively close, but is off in multiple places due to the grade the real world data was taken on. The model does not account for dynamic grade, so the same amount of torque in the model produces slightly different accelerations in some cases. Additionally, the large spikes in simulation velocity are due to limitations of modeling clutch pressure. As the clutch pressure is not broadcasted over CAN, the transfer function and maximum pressures used in the model are calibrated to match the real world data as well as possible. Ideally, these clutch control pressures would be simulated using the clutch pressures used in the vehicle itself, but limitation on the access to transmission software do not allow tracking of these pressures.

Thus these results, while not perfectly matching real world data, emulate vehicle performance accurately enough for algorithm development. Simulation results provide important insight for comparing simulation data to other sets of simulation data, and improvement in this model simulation is considered accurate enough for development to be valid.

8 Motor Torque smoothing

In addition to the shift fill algorithm, a second feature needed to be implemented in the vehicle to ensure high drive quality. The addition of the post transmission motor created issues with the gear lash management of the stock transmission controls. The presence of a fast actuator directly coupled to the differential caused a severe clunk noise when loading or unloading the driveshaft, and a large, uncomfortable jerk when changing from propel to braking. To counteract excessive jerk, a filter was designed to limit the motor torque rate of change through 0 acceleration to smooth the transition and reduce the overall jerk through this region. As discussed by Naruse [6], significant jerk during driving events is often the cause of driver discomfort, and should be avoided. The motor torque smoothing filter aims to decrease the jerk experienced by the driver during accel/decel transitions to improve driver comfort. While these events appear mainly in pure electric driving, they can occur in any mode and at any speed. Therefore the torque smoothing filter can increase driver comfort in a variety of driving scenarios.

Initially, a limit on motor torque rate of change was imposed only when the net driveline torque crossed through zero. However, this proved to not enhance driver comfort significantly. The second method employed a ramped decrease in allowable rate of change down to zero motor torque, then allowed the rate of change to increase as it moved away. The third, and ultimately selected, method combined the previous two into a single filter. A region of limited rate of change is centered around zero net torque, with a ramp out outside of that region. All three of these options are shown Figure 8-1 for comparison.

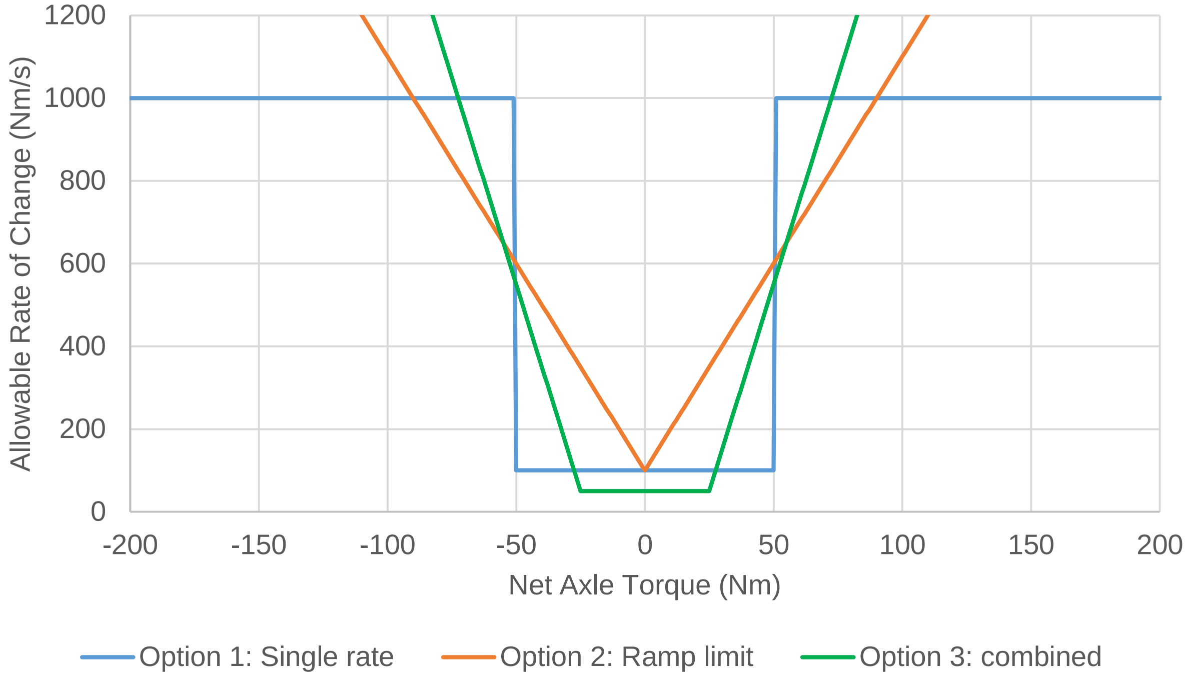

Figure 8-1: Example limiting curves for the three options for motor torque smoothing considered.

Ultimately, Option 3 proved to be the most versatile and provided the largest decrease in jerk across the most events. Option 3 can be calibrated to change the ramp rate outside of the lash region, the limit in the lash region, and the size of the lash region.

Rather than motor torque, this algorithm in Figure 8-1 is based on the net axle torque. This net torque takes into account previously measured driveline losses as well as estimated vehicle road load parameters to ensure that the lash prevention occurs at the correct transition from accel to decel. Thus, as speed increases, the motor torque at which zero net torque occurs is higher. When the engine and the transmission are engaged, the transmission output torque is also included in the net torque calculation to ensure that torque smoothing does not limit motor performance when switching between assisting and loading the engine.

These filters produce 3 similar, but distinct, curves of motor torque during worst-case scenarios. Here, the worst case scenario is going from high acceleration to maximum regen (without friction brakes). These time based signals are shown in Figure 8-2. Options 2 and 3 are very similar, but the versatility of option 3's calibrations makes it superior for in-vehicle use.

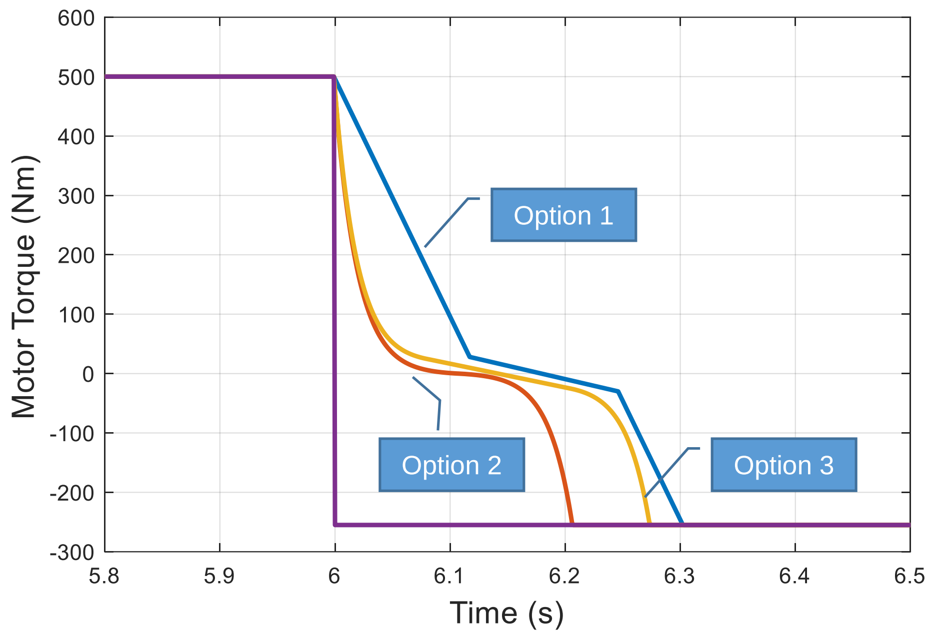

Figure 8-2: Torque vs time of the three filers presented.

Ultimately, option 3 is used in all in-vehicle development. After tuning the calibration using a full vehicle model in SIL and HIL, calibrations are further refined in the vehicle itself. The final calibrations succeeded in reducing worst-case scenario jerk by 50% and providing a smoother qualitative event for the driver. The difference between a smoothed and a non-smoothed event are shown in Figure 8-3. Both potential lash events go from 1.5 m/s^2 to -1.5 m/s^2, crossing through zero acceleration. Without torque smoothing active, the vehicle acceleration drops as quickly as possible, and experiences a jerk of about -6.5 m/s^3. With torque smoothing active, this drops to -3.0 m/s^3 on the same tipout event. The shape of the acceleration curve also matches the shape generated in Figure 8-2.

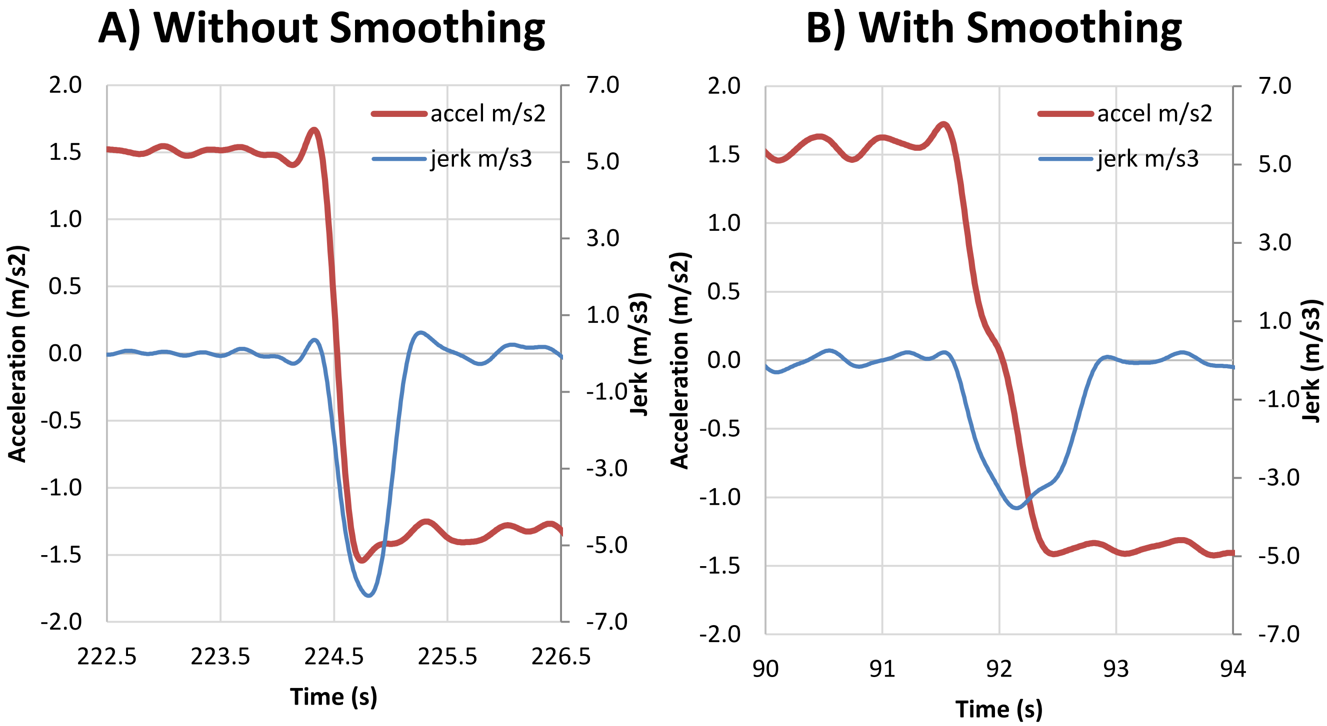

Figure 8-3: Acceleration and estimated jerk measured in-vehicle without(A) and with(B) torque smoothing.

9 Final Shift Fill Algorithm and Calibration

9.1 Final Implementation and Calibration parameters

The final algorithm developed based on section 8 targets only on-power shifts. Due to the lack of torque intervention in off-power shifts, there is no reactive strategy possible with the powertrain configuration. The final motor intervention strategy focuses on the inertia phase of on-power shifts only. These phases represent the best opportunity to improve shift quality as they are the primary cause of torque disturbances in the driveline.

Ultimately, the main calculation of the algorithm operates using the calculation shown in Equation 1 below.

$$T_{motorFill} = \frac{T_{EngNTrns} - T_{actual}}{R_{trans}} + T_{motorSplit} \qquad \textit{Equation 1}$$

Where $T_{motorFill}$ is the motor command for shift fill, $T_{EngNTrns}$ is the non-transmission regulated engine torque, T_{actual} is the actual engine torque, R_{trans} is the transmission ratio, and $T_{motorSplit}$ is the motor torque command based on the main hybrid torque split (ie without shift fill active). The engine and transmission signals are read over the CAN bus and have an average cycle time of 10 ms. $T_{motorSplit}$ is calculated in the control code, and is calculated on the same cycle as Equation 1. The control code runs mixed cycle rates, with the torque split running a cycle time of 5 ms. The Motor torque command message the $T_{motorfFill}$ is used for is sent with an average cycle time of 10ms. Thus, the maximum possible delay in the torque command for shift fill is approximately

25 ms. However, the response time of the motor torque command is significantly faster than the engine torque command, which enables the reactive strategy to operate well in-vehicle.

The final calibration parameters internal to the shift fill algorithm allow for adjustment in the behavior, and are shown below in Figure 9-1 as green lines. The first calibration parameter is the torque phase gain, which sets the degree to which the motor will respond to torque disturbances in the torque phase. In this example the gain is set to zero to observe the effects of the inertia phase fill on its own. The second calibration parameter sets the gain on inertia phase torque commands. This example shows a gain of 1 on the inertia phase. The third parameter allows for a delayed start or overall delay to be added to the torque response if desired.

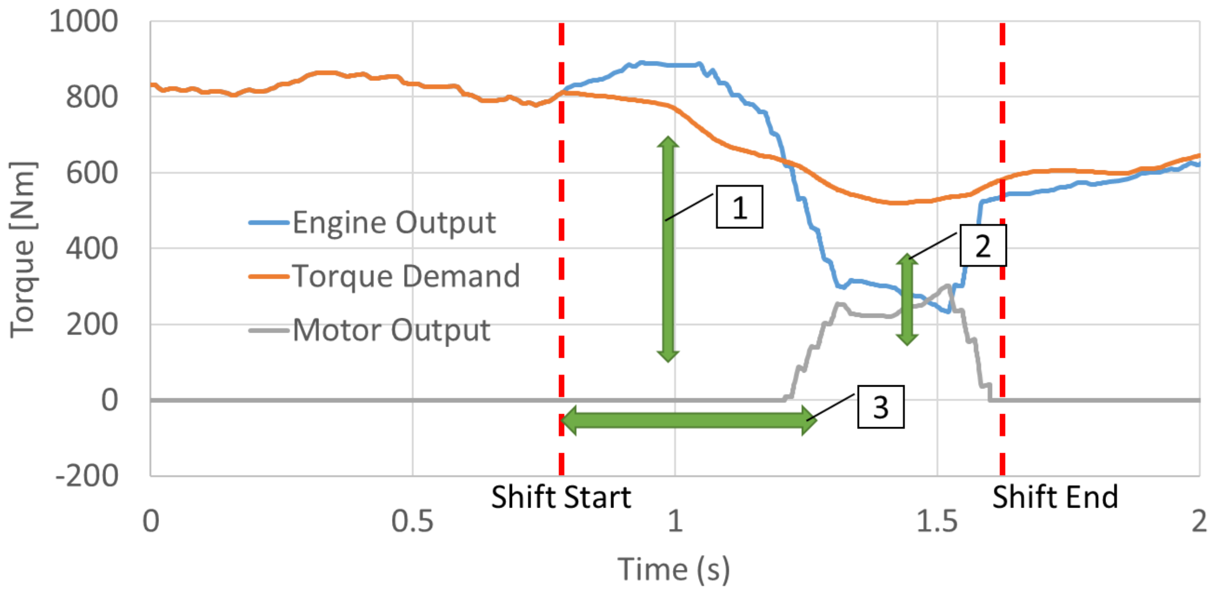

Figure 9-1: Calibration parameters for shift fill shown graphically.

The algorithm is effected by other factors in the overall control code. Thermal limitations, battery current limitations, and reduced power modes can lower response limits or completely disable shift fill if needed. Additionally, the calibration of the motor torque smoothing system can effect on-power downshifts when switching from deceleration to acceleration.

9.2 In-vehicle data and calibration

To test the algorithm in-vehicle, a controlled test of varying acceleration was conducted on a closed course. Starting from 0 speed, a constant pedal position was applied, first with shift fill turned off, then repeated with shift fill active. The pedal was held constant by using a software limit on the allowable pedal position. Additionally, when the brake is depressed, no tractive effort is applied to the wheels. This method allows the driver to tip in to 100% pedal on every launch while still on the brakes, and remove any driver error from the launch. The pedal was limited in steps of 10% from 20% to 70%. Above 70%, the tires began to slip on some launches. High pedal positions also begin to exceed the maximum motor torque to fill the shifts, and performance becomes more important than comfort. A comparison of the vehicle speed and acceleration data for each of the tests is shown in the figures below.

Due to EcoCAR 3 licensing limitations, the license for AVL drive expired before testing could be concluded. As a result, there is no AVL Drive rating for the vehicle with shift fill active.

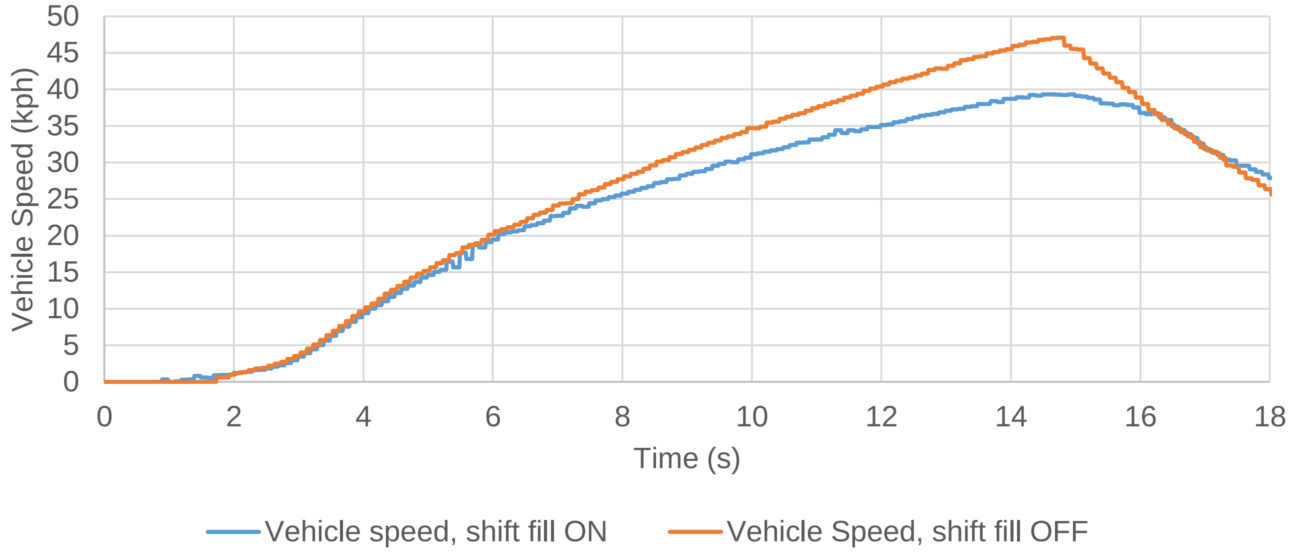

Figure 9-2: vehicle speed comparison for 20% pedal with shift fill on and off.

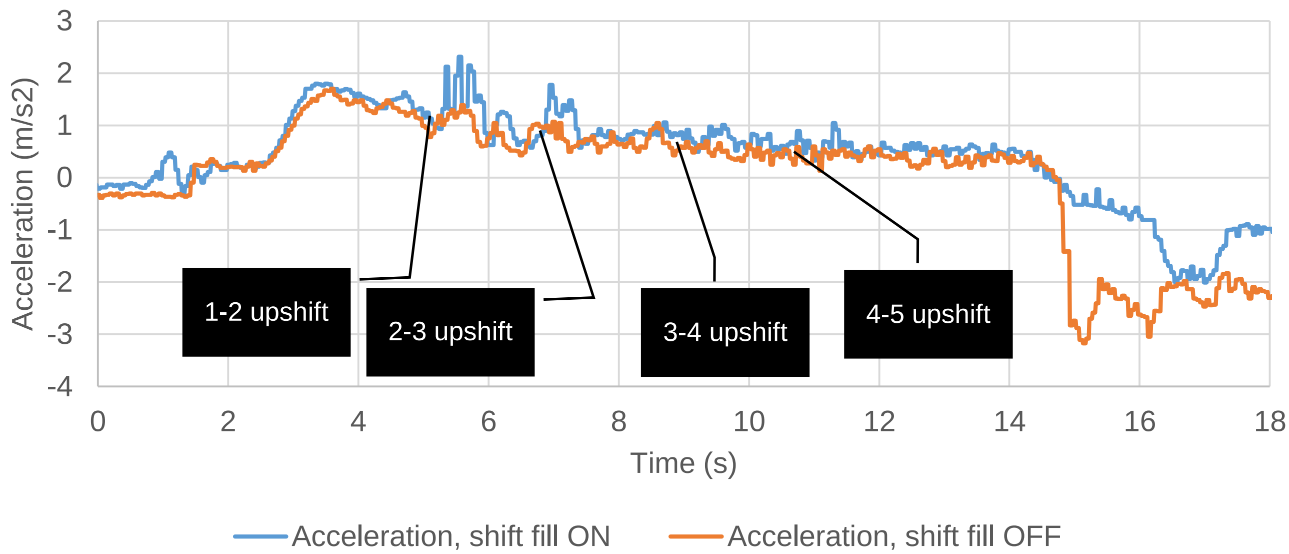

Figure 9-3: Acceleration comparison for 20% pedal with shift fill on and off.

In this low torque case, the vehicle has a sudden surge of acceleration during the shift from the motor. Although this has succeeded in reducing the torque hole, it has instead caused an excess in torque. This issue is primarily noticeable in Figure 9-3 on the 1-2 and 2-3 upshifts. Subsequent upshifts do not have this surge issue at low load.

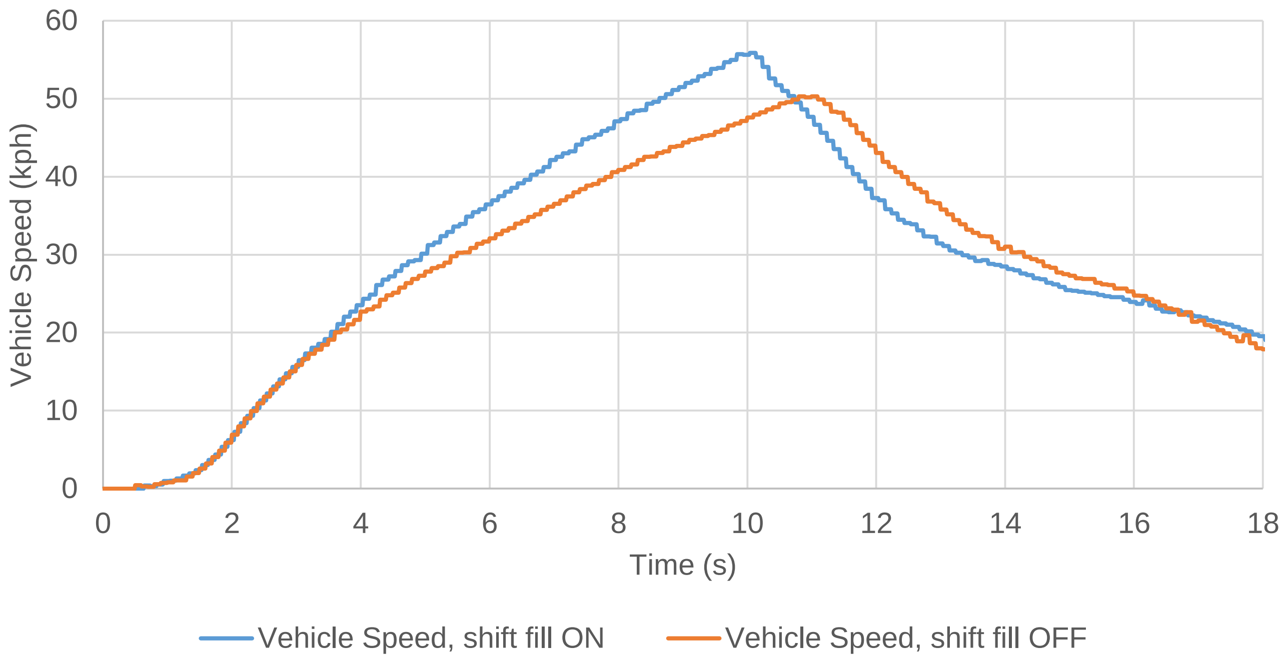

Figure 9-4: Vehicle speed comparison for 30% pedal shift fill test.

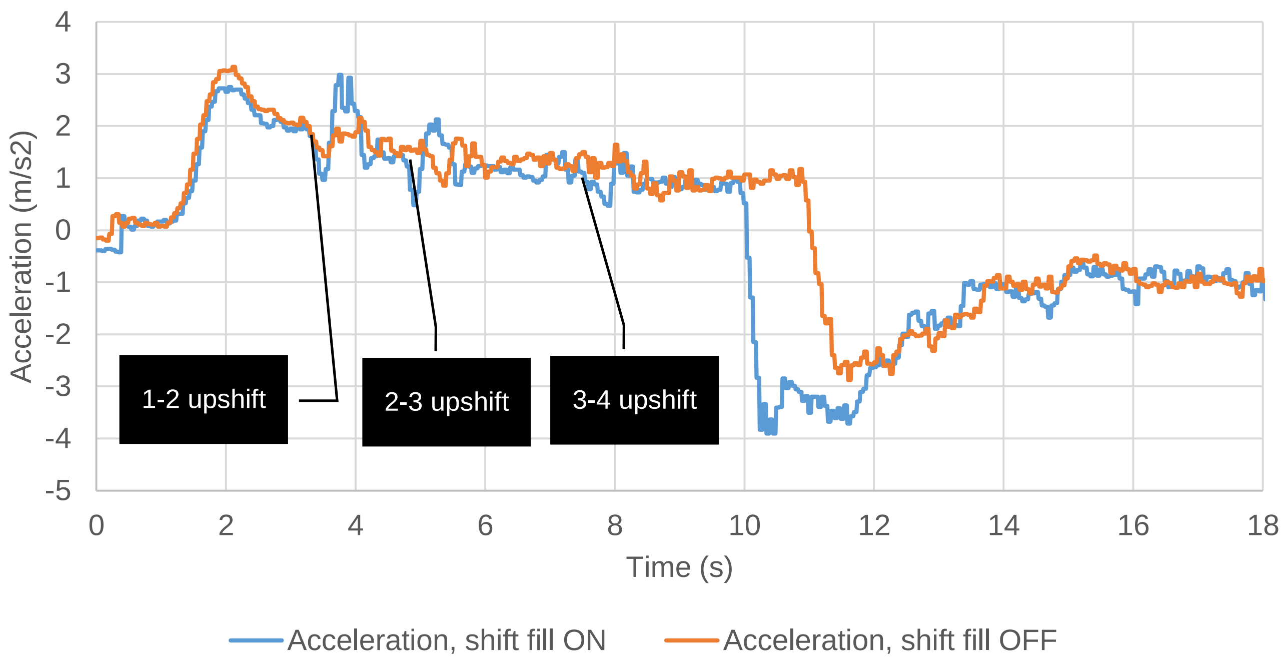

Figure 9-5: Acceleration comparison for shift fill testing at 30% pedal.

As with the 20% pedal case, the 1-2 and 2-3 upshifts in Figure 9-5 have significant surge issues while higher gear shifts do not. During calibration, reducing the inertia phase gain reduced this surge, but made shift fill ineffective for higher gear shifts.

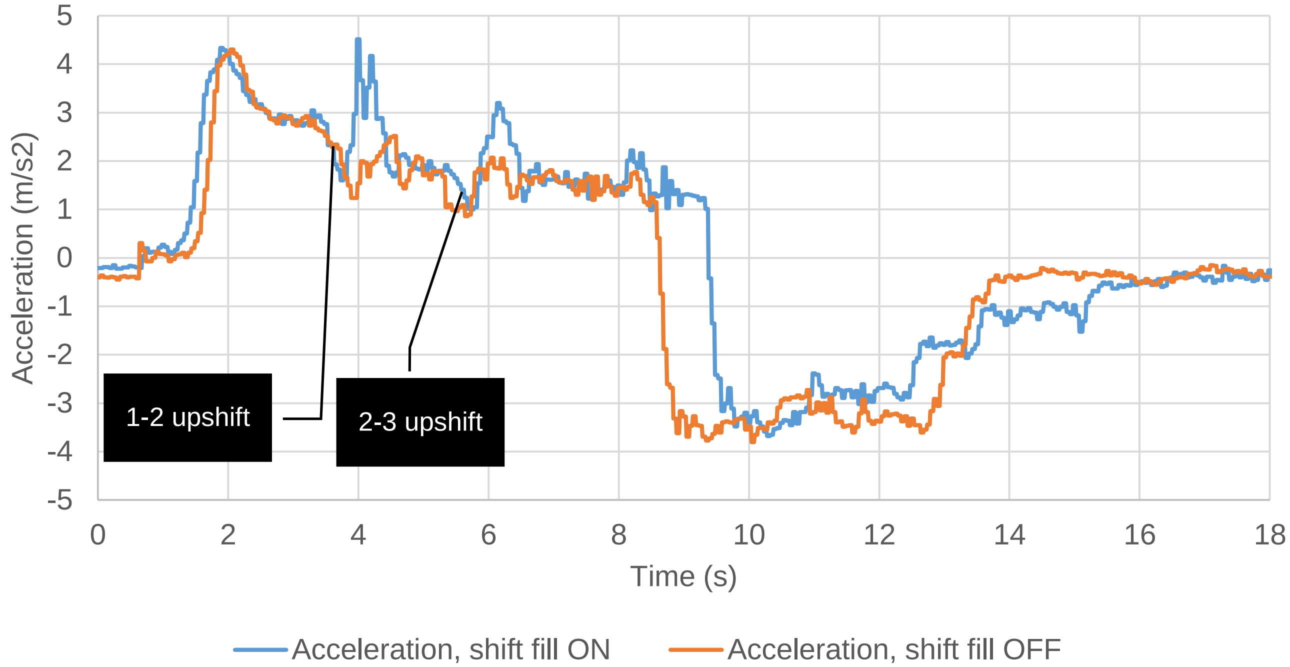

Figure 9-6: Acceleration comparison for shift fill testing at 40% pedal.

For 40% pedal and above, gear shifts above the 2-3 upshift could not be tested, as space limitations constrained the maximum speed that could be reached. At these higher loads, the surge becomes more pronounced in the 1-2 upshift due to the large inertia change in the transmission. In the 50-70% tests, the surge continued to prove an issue. The initial surge at the beginning of the inertia phase was not unpleasant to drivers, but at the end of the inertia phase most found the drop out of shift fill to be uncomfortable.

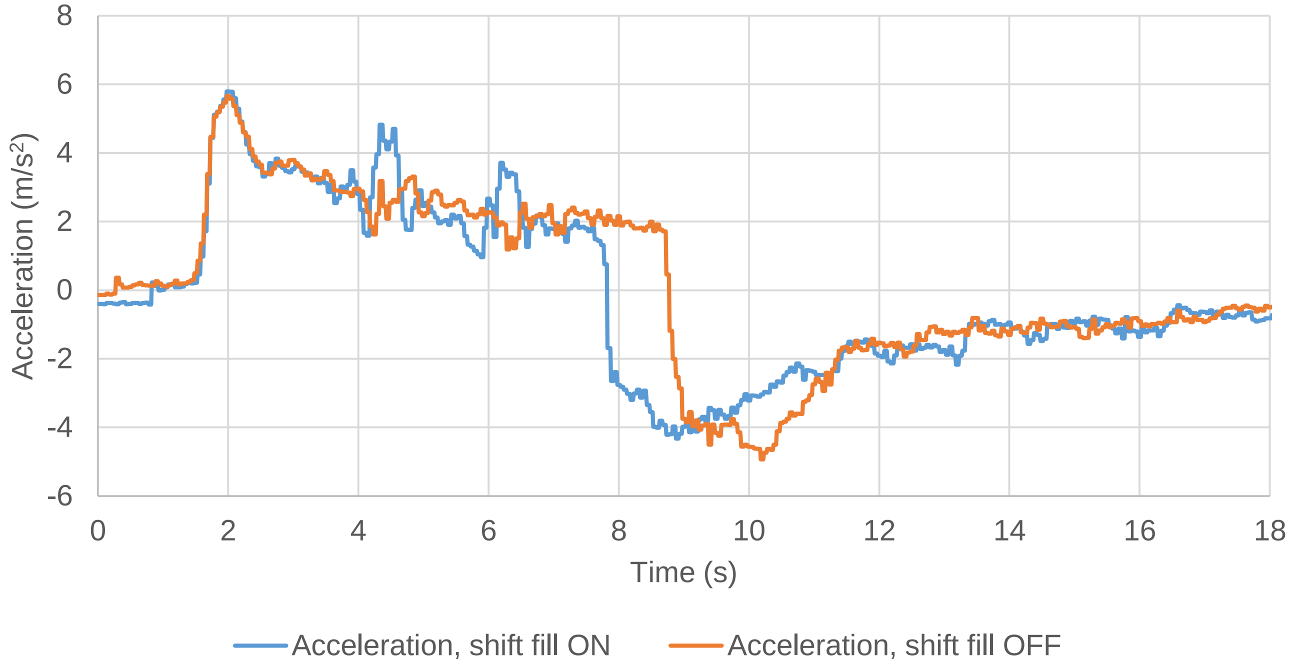

Figure 9-7: Acceleration comparison for shift fill testing at 50% pedal.

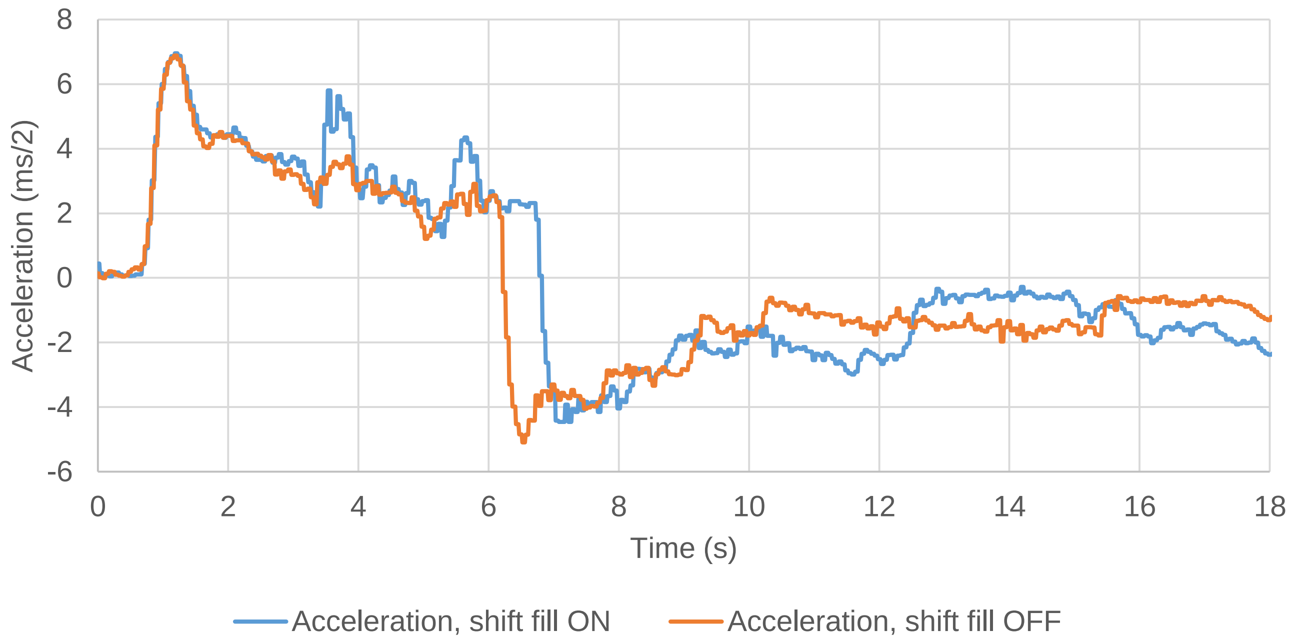

Figure 9-8: Acceleration Data for shift fill testing at 60% pedal.

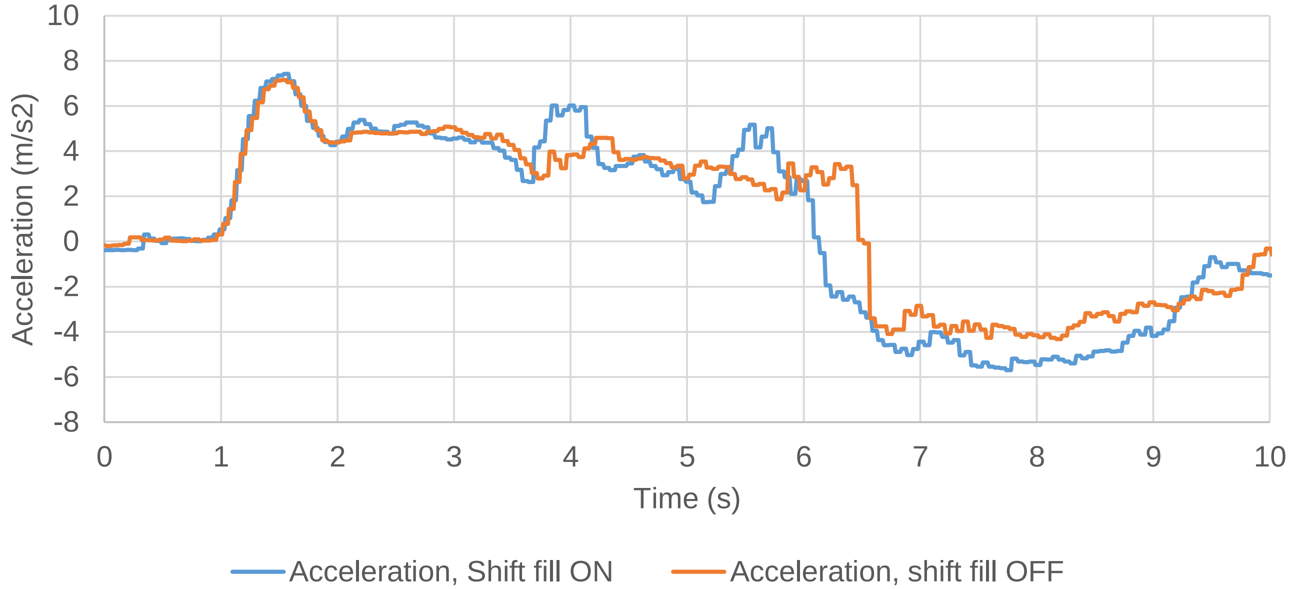

Figure 9-9: Acceleration comparison for shift fill testing at 70% pedal.

While this algorithm has proven that the motor has significant torque authority, there are clear improvements to be made. The first is a calibration map to vary inertia phase gain with overall driver torque demand. At higher loads, such as the 50% and 60% tests, the inertia phase gain be significantly reduced, while the low load inertia phase gain should be higher. Second, the phase gain must also vary with particular shifts. The 1-2 and 2-3 shifts require lower gains, while the higher gears can make use of high gains during shifts.

Testing showed that adding any delay to the shift fill response proved incredibly uncomfortable and caused significantly higher surges. Thus, no final calibrations were set for the inertia phase delay.

After in-vehicle calibration, the limitations of a reactive strategy that relies on monitoring the transmission commands to the engine are clear. Ideally, the transmission controller (or other powertrain controller) would coordinate engine torque, motor torque, and clutch pressure together to produce a smooth shift. While the algorithm presented here had success in some shifts, many shifts had significant surges or jerks during the shift due to the transmission controller being unaware of what was occurring at the transmission output. In order to get the most benefit from the post transmission motor, it must be included in the design of the overall transmission controls. As a custom powertrain, clutch control and transmission controller were not able to be modified for competition.

10 Energy consumption impact of torque smoothing and shift fill

Although torque smoothing is important to driver comfort, the tradeoff between comfort and energy consumption is the biggest challenge of any drive quality calibration. The torque smoothing algorithm improves drive quality by reducing excessive jerk, but as a result it also decreases the amount of regenerative braking captured during a smoothed event by a small amount. This impact is shown in Figure 10-1 during similar lash events. The gray line shows the battery current in an unsmoothed event, which achieves peak current sooner than the blue line from a smoothed event. Although this difference is small, the smoothed event is regenerating nearly zero energy during the time that the non-smoothed line is at its peak value. The result is a decrease in energy recovery of 3 Wh. While this is a relatively small amount per event, across a standard UDDS drive this increases overall energy consumption by 5 Wh/mi. In terms of overall energy consumption, this is a small price to pay to reduce the jerk experienced in the lash region. This low penalty for increased comfort is the best case scenario for changes made to improve drive quality.

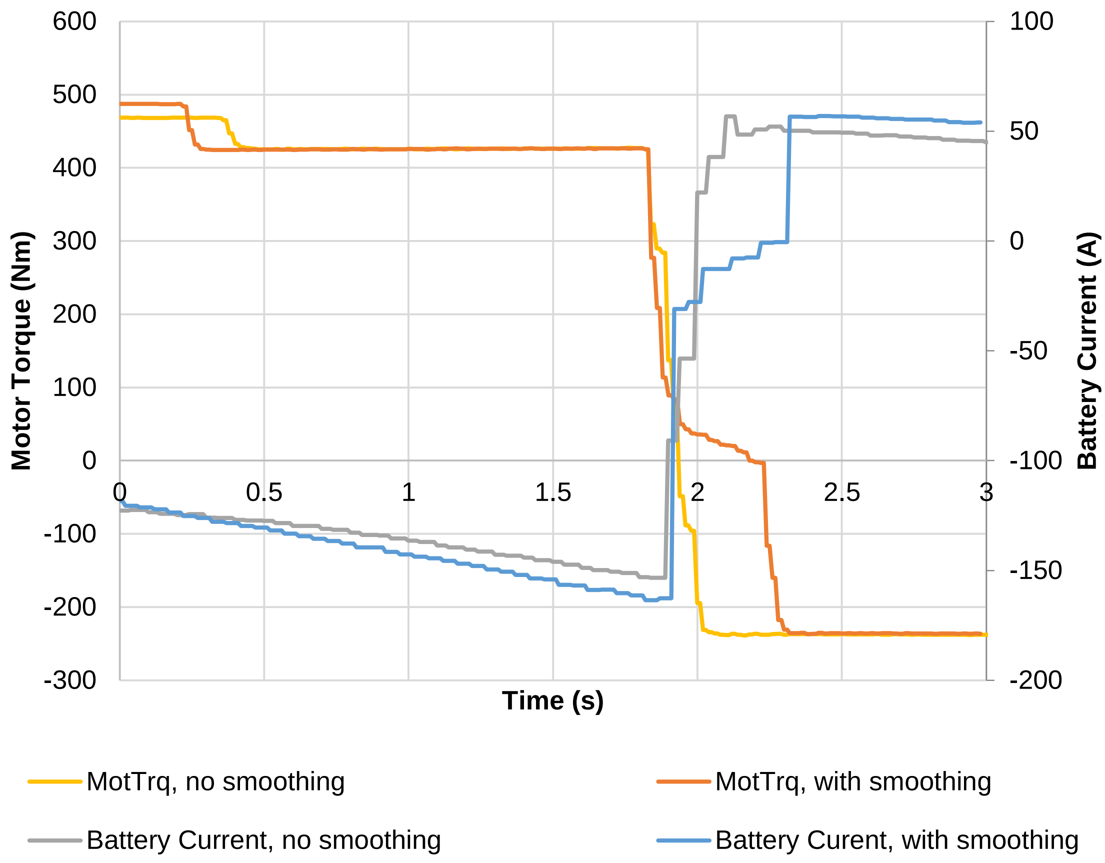

Figure 10-1: Battery current and motor torque during events that torque smoothing impacts.

Shift fill also adds a penalty to energy consumption, as it is adding more energy to the driveline during a shift. For shifts below 4th gear, an average of 5 Wh of additional energy is consumed at the battery terminals over normal shifts. On standard drive cycles, this increases energy consumption by 30-40 Wh/mi depending on the drive cycle.

11 Conclusion

This study presents the development, implementation, and calibration of multiple drive quality improvement strategies for a unique hybrid electric powertrain. The overall goal for drive quality improvement, and the methods by which it can be achieved are discussed.

The basis of the shift fill algorithm requires the discussion of the underlying principles and mechanics involved in a transmission shift. The mechanics of a clutch to clutch shift in modern automatics are based on precise control of transmission output torque, which can be directly controlled with the post transmission motor. Then, the five major types of transmission shifts are introduced. Garage shifts typically do not involve vehicle movement, so they are not included in the developed shift fill algorithm. Next, an industry standard method for drive quality measurement, AVL DRIVE, is used to benchmark the donor vehicles for the hybrid Camaro powertrain. The specific strengths and weaknesses of these vehicles drive quality scores are discussed as potential impacts on the drive quality of the hybrid Camaro. The method for tracking shifts and determining the appropriate shift fill level is described, using the transmission engine torque commands to calculate the expected torque hole. Using this method, and the literature reviewed on shift control, power-on upshifts prove to be the greatest opportunity to improve drive quality. Some power-on downshifts and off-power upshifts can also be corrected, but most of these shifts do not require shift fill based on transmission torque demand.

The process of building and validating a simscape model of the powertrain is documented, and the model is used to predict powertrain response to the implementation of shift fill. With successful improvements to shifts in the model, testing moved from SIL to HIL, and eventually into in-vehicle development and calibration. In order to make acceleration measurements in-vehicle, a cost effective accelerometer that can have processing and data logging built in is presented. This accelerometer is used to measure data in vehicle for torque smoothing and shift fill. A method for smoothing jerk through the lash region is presented, along with the potential calibration levels. The result of this algorithm is presented to successfully cut jerk in half in worst case scenarios. The final calibration results for shift fill are shown to eliminate the torque hole during shifts. However, on the 1-2 and 2-3 upshifts this is replaced by a large torque surge through the shift. This is the result of the transmission controller not having knowledge of what is going on after the transmission output. Without the proper adjustments to clutch control, the transmission clutch behavior becomes unpredictable from CAN data. The ideal control setup would allow the transmission controller to monitor motor torque and alter clutch control as a result, but this would require access to the transmission control code which is a locked controller.

Finally, the energy consumption impact of these drive quality improvements are shown to cause only a small increase in energy consumption: 5 Wh/mi for torque smoothing and 30 Wh/mi for shift fill. These increases are deemed acceptable sacrifices for the improvement in drive quality they provide.

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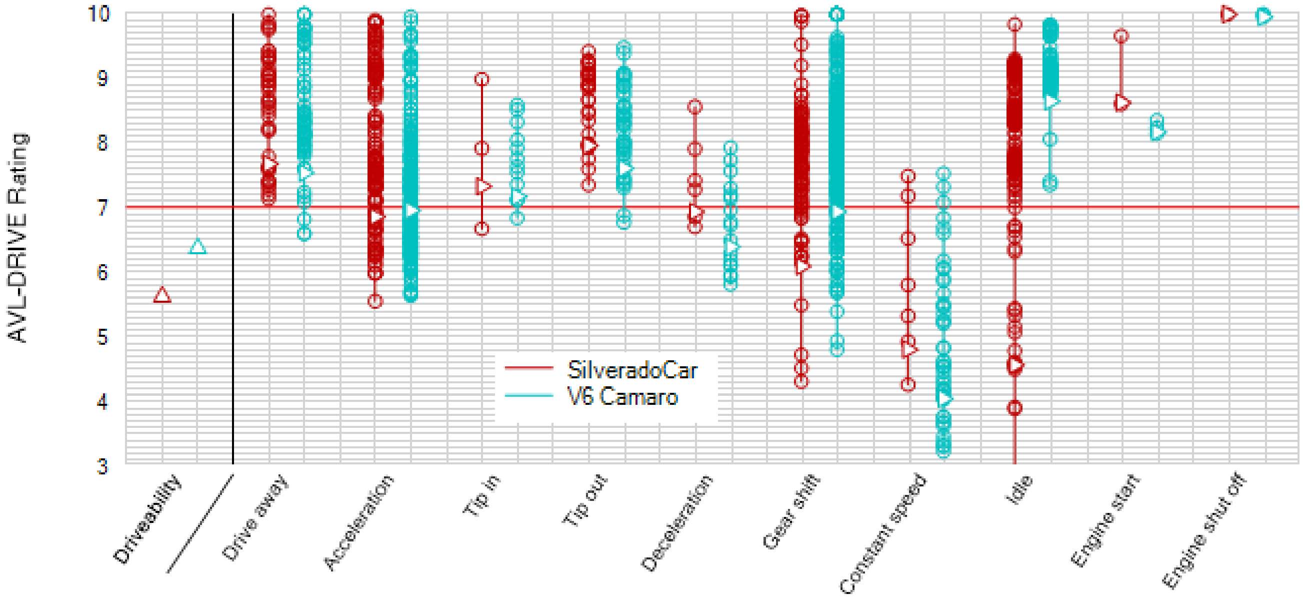
Appendix A

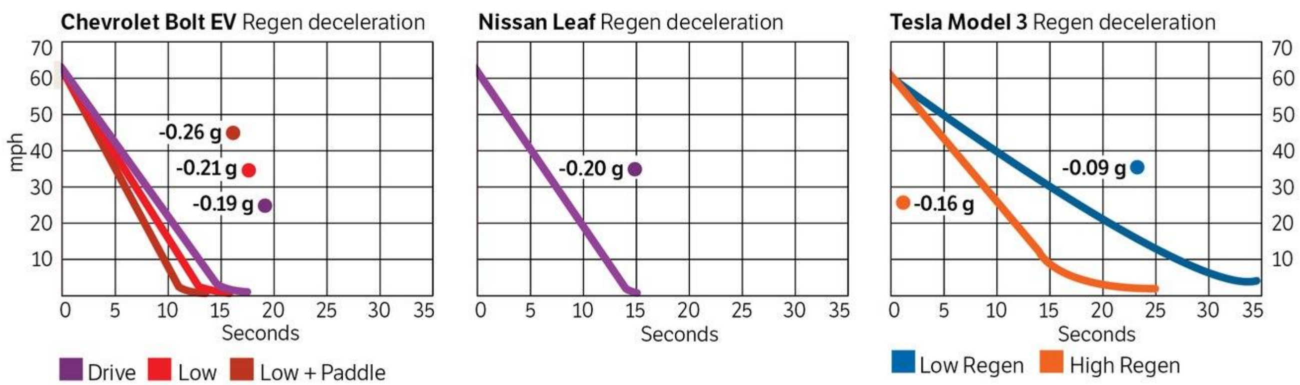
A.1 Full data set for AVL DRIVE benchmarking



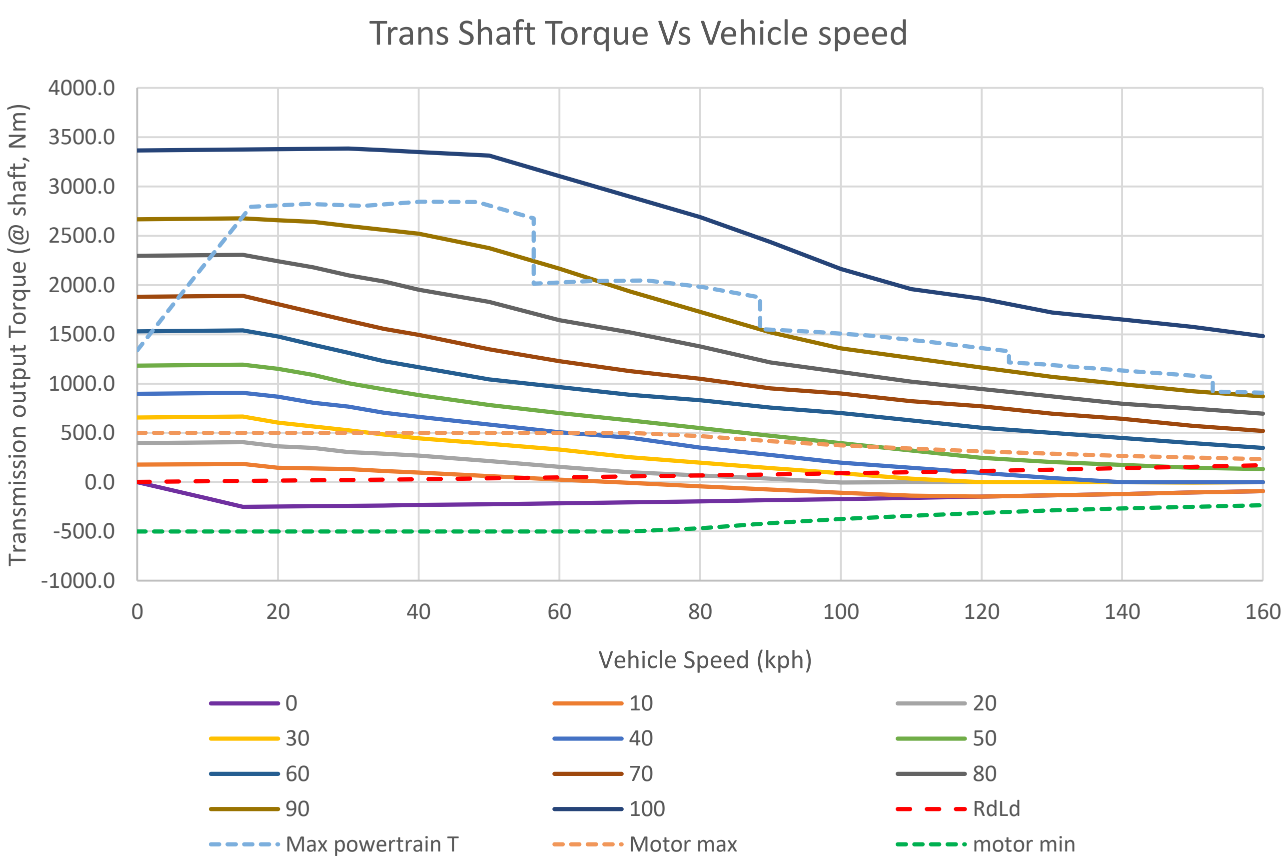
A.2 One-pedal mode for Hybrid Camaro

A common feature on modern Hybrids and electric vehicles is the use of a one pedal mode. These one-pedal modes allow the driver to slow down by simply lifting off of the accelerator pedal, rather than pressing the brakes. This requires the control of braking through either regenerative braking, or in more modern cars, electronic control of the brakes. Single pedal driving is a relatively natural extension of off-pedal deceleration experienced in conventional vehicles due to compression braking of the engine. In hybrid vehicles, the deceleration level can be decoupled from engine compression and set to more aggressive levels using the electric motors. The inclusion of a single pedal driving mode gives the driver more precise control over the use of regenerative braking over friction braking, which can in turn improve energy consumption.

Motor trend magazine tested multiple new electric vehicles for this braking factor. In conventional vehicles, lift off decal is limited to around 0.04 g to 0.06 g as it relies on engine compression braking. Motor trend found the Chevy Bolt to have 3 distinct levels of one pedal, the 2018 Nissan Leaf to have a single mode, and the Tesla model 3 to have two.



To achieve a similar effect in the HEVT Camaro, a pedal map was generated that sets desired vehicle acceleration. This desired acceleration is then factored into a road load and static driveline loss equation to determine the need powertrain output torque to achieve the target acceleration. The resulting torque map is shown below.



Initially one pedal mode was calibrated for 1.5 m/s^2 of decal at 0% pedal, but after repeated motor overheat occurrences, this was dropped to 1.2 m/s^2. The 1.5 target is on the edge of maximum motor power at speed, so the reduction helped keep motor temperature low.

Over standardized drive cycles, this mode does not change energy consumption as the acceleration and deceleration rates are fixed, and the simulation of the driver does not make use of one pedal. However, as a feature on an electrified vehicle, this mode is beneficial to consumer acceptability.