THESIS

IMPLEMENTATION AND EVALUATION OF BACKWARD FACING FUEL CONSUMPTION SIMULATION AND TESTING METHODS

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ABSTRACT

IMPLEMENTATION AND EVALUATION OF BACKWARD FACING FUEL CONSUMPTION SIMULATION AND TESTING METHODS

The Colorado State University Vehicle Innovations Team (VIT) participates in numerous Advanced Vehicle Technology Competitions (AVTC's) as well as several hybrid-electric vehicle projects with outside sponsors. This study seeks to develop and quantify the accuracy of simulation and testing methods that will be used in the VIT's predictive optimal energy management strategy research that is to be used in these projects. First, a backward facing vehicle simulation model is built and populated with real-world OBD-II drive data collected from a 2019 Toyota Tacoma. This includes the creation of both an engine speed vs accelerator position vs engine load map as well as an engine speed vs engine load vs engine fuel rate map. Acceleration events (AE's) are performed with a baseline shift schedule and vehicle performance is recorded. The backward facing vehicle simulation model is used to predict how a modified shift schedule will affect the vehicle's fuel consumption. Further AE's are performed with the modified shift schedule and the performance data is compared to the vehicle simulation. The backward facing simulation model was capable of predicting average engine speed within 0.3 RPM, average engine load within 5.2%, and average total fuel consumption within 0.2 grams of the actual testing data. This study concludes that the vehicle simulation methods are capable of predicting fuel consumption changes within 1.4% of what is actual measured during real-world testing with a 95% confidence.

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1. Introduction

It has been determined and widely acknowledged that climate change and its results are likely to have a significant negative effect on our society [1]. The usage of petroleum products as a fuel source in the transportation industry has shown to be one of the largest contributors to the changes in air quality an increases of greenhouse gasses in our atmosphere that have been observed [2]. Of the large amounts of $CO2$ that are emitted each year, 23% has been attributed to the transportation industry [1]. Furthermore, 60% of the transportation industry's emissions can be attributed to light duty vehicles [2].

The CSU Vehicle Innovations Team (VIT) aims to reduce the impact that light duty vehicles have on our environment by reducing their fuel consumption and emissions output with the application of innovative automotive technologies along with novel vehicle control strategies. The CSU VIT has taken part in numerous advanced vehicle technology competitions (AVTC's) that focus on the improvement of vehicle efficiency as well as various projects with vehicle manufacturers to produce hybrid-electric vehicle and battery-electric vehicle technologies. These programs regularly require the modeling and simulation of vehicle systems with the purpose of substantiating fuel economy benefits as well as informing engineering design decisions. In-vehicle testing is used to both collect data that is used for the improvement of vehicle system models as well as the verification and validation of such models and simulations.

This study explores the simulation, modeling, and testing methods that will be used in the design and development of CSU VIT's hybrid-electric Toyota Tacoma test platform. This project's focus is the design and testing of a hybrid-electric vehicle platform that is controlled with predictive optimal energy management strategy algorithms (POEMS) with the purpose of decreasing fuel consumption during acceleration events. The intention of this study is to evaluate the procedures and methods that will be used to simulate and measure fuel economy in this prototype vehicle and to determine if these methods are viable.

1.1 Background and Literature Review

The purpose of the following sections are to explore and describe fuel consumption modeling, simulation, data collection, and testing techniques that have been used in previous work.

1.1.1 Contributing Factors of Fuel Consumption in Hybrid-Electric Vehicles

A large number of vehicle parameters and operational factors have an impact upon fuel consumption in hybrid-electric vehicles. Simple vehicle parameters such as tire characteristics, vehicle mass, and aerodynamic efficiency all have an effect on fuel consumption regardless of vehicle type [3]. These phenomena are widely understood and accepted. Operational factors such as acceleration rates, usage of brakes, and gear selection have also been shown to have a significant influence on fuel consumption, in both conventional and hybrid-electric vehicles. Fuel consumption in hybrid-electric vehicles is uniquely affected by the state of charge (SOC) of their energy storage system (ESS), high-voltage system efficiencies hybrid drivetrain control strategies [4].

One area of research that is in process is the effect of acceleration rates on the effectiveness of optimal energy management (OEM) strategies in hybrid-electric vehicles. Previous work has shown that acceleration events (AEs) are of particular importance in these strategies as this is when fuel consumption rates are high and engine efficiencies are low. The prediction and classification of these AEs can be used to optimize hybrid-electric control strategies for reduced fuel consumption when POEMS are implemented [4].

1.1.2 Fuel Consumption Measurement

A number of techniques are used to measure fuel consumption in both research vehicles as well as on-highway consumer vehicles. The direct measurement of before-and-after fuel levels in the fuel tank is a common method as it does not require specialized measurement equipment to be utilized [5]. The downfalls of this method are that it requires the removal of the fuel tank both before and after a fuel consumption test is conducted and that amounts of fuel located throughout the rest of the vehicle's fuel system remain unaccounted for. Fuel consumption can also be determined through the installation of aftermarket fuel flow sensors within the vehicle's fuel system [6]. The addition of fuel flow sensor(s) can provide detailed real-time fuel data but are difficult to implement within modern vehicles due to tight packaging constraints of modern fuel systems and can be expensive. The most common form of fuel consumption measurement is the use of fuel flow estimations based upon intake air flow data that is provided by the vehicle's MAF sensor [7]. This data is provided to the user through the on-board diagnostic (OBD-II) data port that is equipped on all consumer vehicles that were produced post 1995 [8]. While this real-time data is easily accessible, it can be inaccurate at times as the data is not sourced from a direct measurement of fuel flow. As fuel usage is directly correlated to the emissions output of a vehicle, a portable emissions measurement system (PEMS) can also be used to determine fuel consumption [9]. These systems are attached to a vehicle's exhaust outlet and measure the constituents that make up the exhaust gasses. Using a PEMS unit to measure real-time fuel consumption is not ideal as there is a delay between the moment that fuel is consumed and the moment the PEMS unit can measure the resulting exhaust gasses. This delay and data accuracy is dependent upon exhaust system size, layout and the use of any emission reduction devices.

1.1.3 Fuel Consumption Predictive Simulation

Fuel consumption simulation models that are used in the automotive industry are classified in a number of forms, primarily the White-Grey-Black Box method. This ideology classifies a simulation model based upon both the fundamental knowledge and the data that was utilized to construct said model. This classification system is illustrated in Figure 1 below:

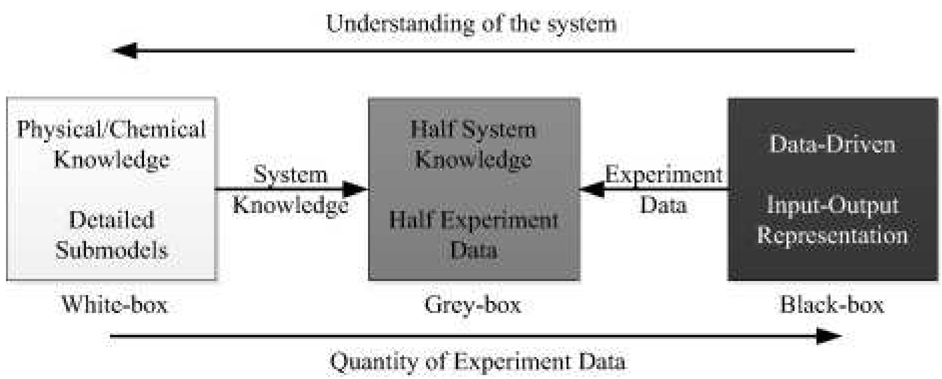

Figure 1: White-Grey-Black Box Modeling

White-box fuel consumption models are constructed with detailed chemical and physical knowledge of an engine and vehicle. This can take the form of the carbon-balance method or the mean value phenomenological method. Black-box fuel consumption models are constructed using data that is directly measured from a vehicle during on-road or chassis dynamometer testing. Black-box models can take the form of an engine-based model or a vehicle-based model and often have inputs and outputs in the form of vehicle speed, engine load, engine speed, engine load, and fuel rate. Grey-box models are a mix of both White-box and Black-box models which requires both detailed knowledge of how the vehicle is constructed as well as having vehicle performance data [10].

Fuel consumption models can also be classified as with forward facing or backward facing. Forward facing simulation models have external inputs such as throttle/brake pedal positions (also known as a driver model), road grade, and environmental conditions and output vehicle parameters including fuel consumption, engine speed, engine load and engine power. Forward facing models are often complex and require considerable technical knowledge of the vehicle but are highly adaptable and can predict a wide range of vehicle behavior [11]. In contrast to forward facing models, backward facing models backtrace vehicle parameters based upon a predetermined and tested speed trace [11]. For example, instantaneous engine torque can be determined by the calculation of engine speed based upon the angular velocity of the driven wheels and the gear ratio changes through various driveline components along with vehicle acceleration rates. This modeling technique relies on vehicle data maps that are created through in-vehicle dynamic testing. Backward facing models have a limited ability to predict vehicle dynamics that are out of the range of the data that was collected in the creation of the model but require a significantly smaller amount of technical knowledge of the vehicle being modeled. Forward-facing and backward-facing models are illustrated in Figures 2 and 3 below:

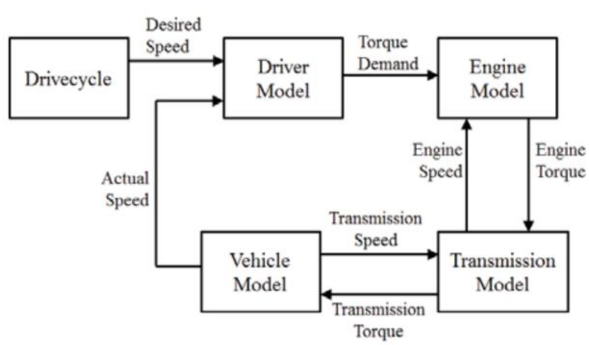

Figure 2: Forward Facing Vehicle Modeling

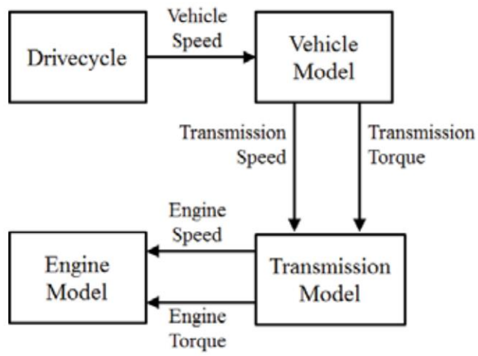

Figure 3: Backward Facing Vehicle Modeling

1.2 Research Questions

The CSU VIT regularly conducts fuel consumption studies for research projects and AVTCs but the accuracy and precision of the methods used in these studies has not be greatly explored. As any results or conclusions that are made from these studies are of importance, the following questions have been raised with the goal of generating understanding of, and confidence in, the methods used by the CSU VIT:

1. Are the testing methods of the CSU Vehicle Innovations Team adequate to consistently measure fuel economy and any subsequent fluctuations during on-road vehicle testing?
2. Are the simulation capabilities of the CSU Vehicle Innovations Team adequate to create a vehicle model that can accurately predict vehicle fuel consumption during acceleration events?
3. Is data collected from the OBD-II data port adequate for vehicle fuel economy modeling, simulation, and measurement in studies conducted by the CSU Vehicle Innovations Team?

1.3 Novel aspects of research

This study produces a vehicle model and predictive simulation without the use of any external sensors beyond what is installed on the vehicle from the factory or any technical data that is not provided by the vehicle manufacturer. This simulation model is then be used to predict how changing vehicle parameters effects fuel consumption during acceleration events.

Through this study, it is intended to understand the capability of CSU's VIT to collect vehicle performance data, create vehicle models, and perform predictive fuel consumption simulations on a vehicle without the use of external sensors or outside technical information. This study is also intended to inform upon and quantify the capability of CSU's VIT to accurately measure fuel consumption through on-road dynamic testing. This information is then to be used to improve upon the results and conclusions of any fuel economy study that is performed by the CSU VIT.

1.4 Thesis Outline

The structure of this thesis is outlined in this section. Section 2 discusses the creation of a vehicle simulation model through the use of real-world testing and data collection via OBD-II. This includes the creation and surface fitting of fuel flow and engine loading maps. Section 3 describes the testing methodology that is used to collect data for modeling and testing purposes. This section also characterizes various shift schedules that are used for testing and how these are implemented during testing. The comparison of simulation and in-vehicle testing acceleration event data is performed in Section 4 and conclusions and future work recommendations are made in Section 5.

2. Toyota Tacoma Simulation Model

2.1 Simulation Methodology

2.1.1 Forward Facing vs Backward Facing Modeling

Forward facing vehicle simulations are powerful tools in the simulation of vehicle systems. These simulations can predict a large number of vehicle parameters in a wide variety of simulated situations. For example, forward facing simulations have the capability of using simple a simple torque command to provide insight into every component of the powertrain system including engine speed, engine torque, fuel rates, transmission input/output speeds and torques, wheel torque, tire dynamics, and overall vehicle system performance [11]. While these simulations are a powerful engineering tool they require a tremendous amount of technical knowledge about the vehicle system, which is often confidential and not available to the public. This information includes detailed engine and transmission efficiencies, engine and transmission control strategies, as well as individual component masses and inertias. Due to the limited technical information that is provided for the 2019 Toyota Tacoma a forward facing simulation model is not feasible.

In contrast a backward facing simulation model utilizes a vehicle velocity trace as an input to the system rather than a driver model. Using this velocity trace the state of the powertrain can be calculated. For instance, the wheel speed and torque can be directly determined from the acceleration and velocity of the vehicle, then the engine speed and torque can be estimated if the transmission state is known. Backward facing simulations suffer in terms of the scope of scenarios that can be accurately simulated and in flexibility of changes that can be made to the vehicle model. These simulations do, however, benefit from the small quantity of technical knowledge that is required to build the model. Backward facing vehicle models are often constructed using data that is collected from real-world system testing rather than individual component specifications, drastically simplifying the vehicle modeling process. A backward facing simulation model was employed for the purpose of this study for this reason.

2.1.2 Simulating Fuel Flow

To evaluate CSU VIT's simulation capability of simulating vehicle fuel consumption a vehicle model was constructed that meet the following requirements: the model must use vehicle speed, throttle position and gear selection as inputs while outputting fuel consumption, the model must constructed using real-world drive data and public technical specifications only, and the model must be able to simulate the effect that changes in shift scheduling have on fuel consumption. An outline of the vehicle simulation model is shown in Figure 4 below.

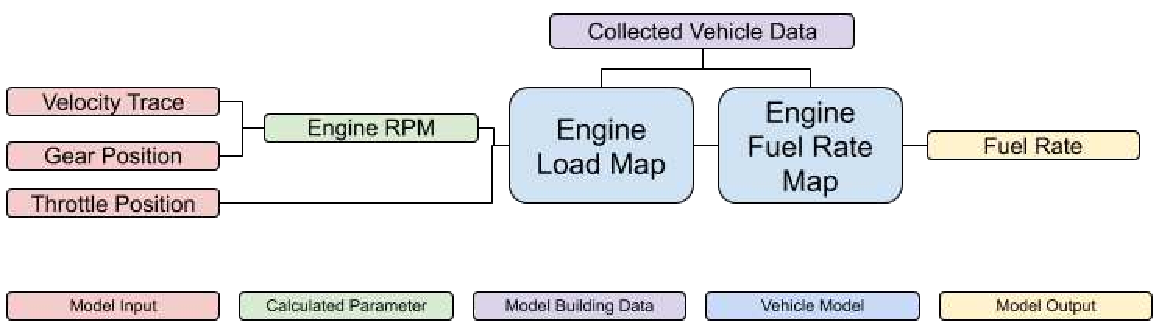

Figure 4: Vehicle Model Layout and Overview

The model has the following inputs: a velocity trace of the acceleration event that is to be simulated, the throttle position trace that was used to create the velocity trace, and a desired transmission shift schedule that is to be simulated. Both the velocity trace and throttle position inputs are directly collected from the OBD-II data port on the 2019 Toyota Tacoma while performing a real-world acceleration event. The model then uses published tire size and gear ratios as well as measured torque converter dynamics to calculate the angular velocity of the engine. The details of this process are discussed in Section 2.3.1. Engine load is calculated with the inputs of throttle position and engine RPM using an engine load map that is detailed in Section 2.3.2. The engine's fuel consumption rate is calculated with inputs of engine load and engine RPM with a engine fuel rate map that is detailed in Section 2.3.3. Both the Engine Load Map and the Engine Fuel Rate Map are constructed using real-world drive data that is detailed in Section 2.2.2.

2.2 Data Collection via. OBD-II

2.2.1 OBD-II Data Collection and Limitations

The vehicle data that is provided via the OBD-II port is intended for vehicle troubleshooting, diagnostics and emissions verification. Due to this purpose, the data provided via the OBD-II port often has a low temporal resolution and does not provide information about many vehicle components in comparison to the data that is provided by the vehicles main CAN bus system. Unfortunately, the data on the CAN system is difficult to access without confidential knowledge about the system. Depending on the date of manufacture and make of the vehicle the temporal resolution of the OBD-II data may vary from 1 Hz up to 10 Hz [8]. As the temporal resolution of the data increases as does feasibility of using such data for accurate data collection and model building, especially in respect to fuel consumption modeling. The refresh rate of the 2019 Toyota Tacoma's OBD-II bus is 2 Hz.

The types of vehicle parameters that are provided over the OBD-II bus are standardized across all vehicles with a few exceptions in the cases that manufactures require extra vehicle parameters for diagnostics. As the data on this bus is provided for emissions purposes it is limited to powertrain information including: engine load, engine speed, throttle position, MAF air flow rate, intake temperature, oxygen sensors, actual and commanded air fuel ratio, and calculated engine fuel rate among others.

Of particular interest is the engine fuel rate parameter. This parameter is not a direct measurement of fuel usage through the engine's fuel injection system, rather it is a calculation based upon the measured intake airflow mass at the MAF and the engine's measured air fuel ratio. Other vehicle parameters including engine load are based upon calculations from other parameters rather than direct measurement and it is understood that this potentially introduces error into the calculated parameters, though this error is impossible to quantify without highly detailed data.

2.2.2 Vehicle Data Collection

Vehicle data is collected via the Tacoma's OBD-II port through the use of a ELM327 OBD-II Scanner. This dongle is a Wifi enabled OBD-II data collection unit that is capable of reading data at a rate of up to 10 Hz and transmitting data to a smartphone for display and storage. The smartphone utilizes the Torque App which is capable of displaying and logging any vehicle parameters that are provided via the OBD-II port. The data is saved into a .csv file and imported into MATLAB for analysis. The vehicle parameters used in this study are shown in Table 1 below:

Table 1: Vehicle Parameters Collected from OBD-II

Vehicle Parameter	Unit
Engine Load	% of peak torque at current RPM
Engine Speed	RPM
Vehicle Speed	MPH
Accelerator Pedal Position	%
Fuel Flow Rate	Gal/hour
Current Time	Month/Day/Year Hr:Min:Sec

In order to create an accurate vehicle simulation model a dataset of vehicle performance characteristics in standard driving conditions must be collected. To accomplish this a series of in-vehicle driving tests were performed. These tests can be seen in Figure 5 below:

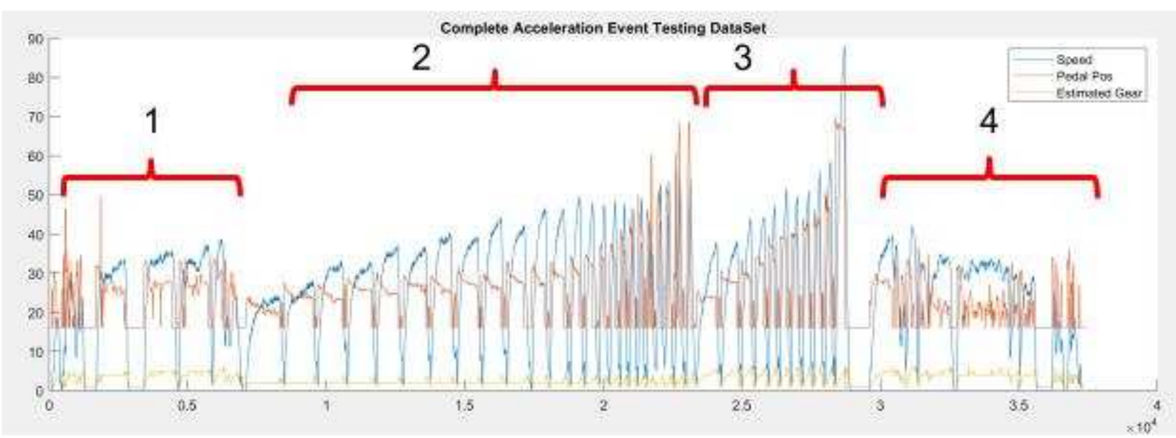

Figure 5: Model Building Vehicle Data

The 1st and 4th sections of the above test data are of on-road driving in standard urban traffic conditions. These sections of data were collected with the goal of understanding on-road driving habits, real-world acceleration events, and throttle control habits. Section 2 of the above data involved accelerating the vehicle at various constant throttle inputs while holding the vehicle in 2nd gear. The purpose of this section of vehicle data is to collect engine load and engine fuel rates at all engine speeds and loads. Section 3 of the above data involved accelerating the vehicle at various throttle positions. The purpose of this section of data collection was to quantify vehicle parameters at various acceleration rates as well as to quantify the relationship between pedal position and acceleration rate.

2.3 Vehicle Modeling

2.3.1 Gear Selection and Torque Converter Dynamics

As the data collected from the Tacoma's OBD-II port does not included selected gear information, this data must be calculated from other vehicle parameters. This is done by comparing the rotational speed of the engine's output shaft to the calculated speed of the output shaft of the transmission. Equation 1 shows this calculation below:

$$\omega_{Trans\ Output} = \frac{Vehicle\ Speed}{(Circumference_{Tire} * Final\ Drive\ Ratio)}$$

Equation 1: Transmission Output Speed

The ratio of the engine's output speed to the transmission's output speed is calculated and is called the Effective Gear Ratio. The Effective Gear Ratio is compared to the Toyota Tacoma's published gear ratios and is binned into a gear ratio if it is close to the published gear ratios. Table 2 below shows the Tacoma's gear ratios and the Effective Gear Ratio bins. The binning process is necessary as the calculated Effective Gear Ratio is not always equivalent to the expected gear ratios.

Table 2: Toyota Tacoma Gear Ratios and Vehicle Model Gear Ratio Bins

Gear Number	Tacoma Gear Ratio	Effective Gear Ratio Bins
1st	3.60:1	>3.50:1
2nd	2.09:1	2.00:1 to 3.50:1
3rd	1.49:1	1.40:1 to 2.00:1
4th	1.00:1	0.95:1 to 1.40:1
5th	0.69:1	0.68:1 to 0.95:1
6th	0.58:1	0.50:1 to 0.68:1

Torque converter (TC) slip is another parameter that is not provided in the data collected via the OBD-II port and is required for vehicle modeling and simulation. With the vehicle's gear state determined it is now possible to estimate the torque converter slip ratio. This is accomplished by calculating the expected engine RPM at a given vehicle speed assuming the torque converter is completely locked i.e. a torque converter ratio of 1. Equation 2 below describes the expected engine RPM with a torque converter ratio of 1.

$$\omega_{Engine,Locked\ TC} = \frac{Vehicle\ Speed}{(Circumference_{Tire} * Final\ Drive\ Ratio * Transmission\ Ratio)}$$

Equation 2: Engine Speed Assuming Locked Torque Converter

The expected engine RPM is compared to the actual engine RPM to calculate the torque converter ratio. A TC Ratio > 1 means that the torque converter is slipping and the engine speed is higher than expected if the torque converter is locked. Equation 3 shows the equation for torque converter ratio.

$$TC_{Ratio} = \frac{\omega_{Engine,Actual}}{\omega_{Engine,Locked\ TC}}$$

Equation 3: Torque Converter Ratio

With the torque converter ratio estimated it is possible to examine the dynamics of torque converter slip with respect to vehicle speed. Figure 6 shows the torque converter slip ratio compared to vehicle speed.

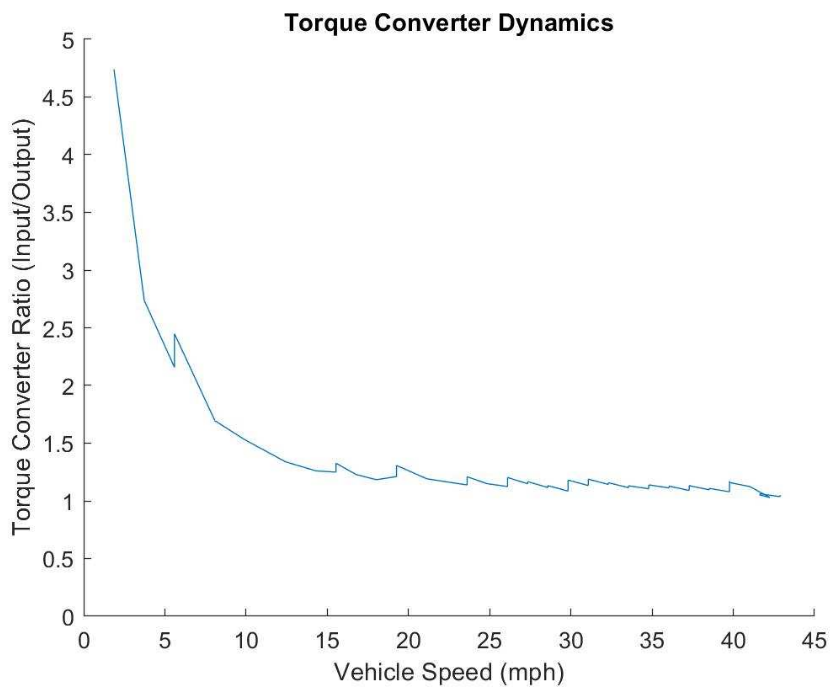

Figure 6: Torque Converter Dynamics Estimation

It can be seen that the torque converter ratio falls to 1 (locked) as the vehicle increases in speed. It is assumed that the rate that the torque converter locks up is a function of the vehicle's acceleration rate therefore it is unchanged if the acceleration rate of the vehicle remains constant.

2.3.2 Engine Load Mapping

Engine load is an important vehicle parameter as it is directly correlated with the fuel rate of the engine. In modern vehicles the accelerator pedal is connected to the engine's throttle body through the use of a digital signal. With this digital connection Toyota engineers have created a non-linear lookup table to optimize the engine's torque production for smoothness and responsiveness. Reverse engineering this lookup table is necessary for vehicle modeling to predict engine load given a throttle input and engine RPM. Engine load is expressed in a percentage of maximum torque at the current engine speed. Using the drive data collected in Section 2.2.2 a map was created that determines engine load given the accelerator pedal position and the current engine speed. This can be seen below in Figure 7.

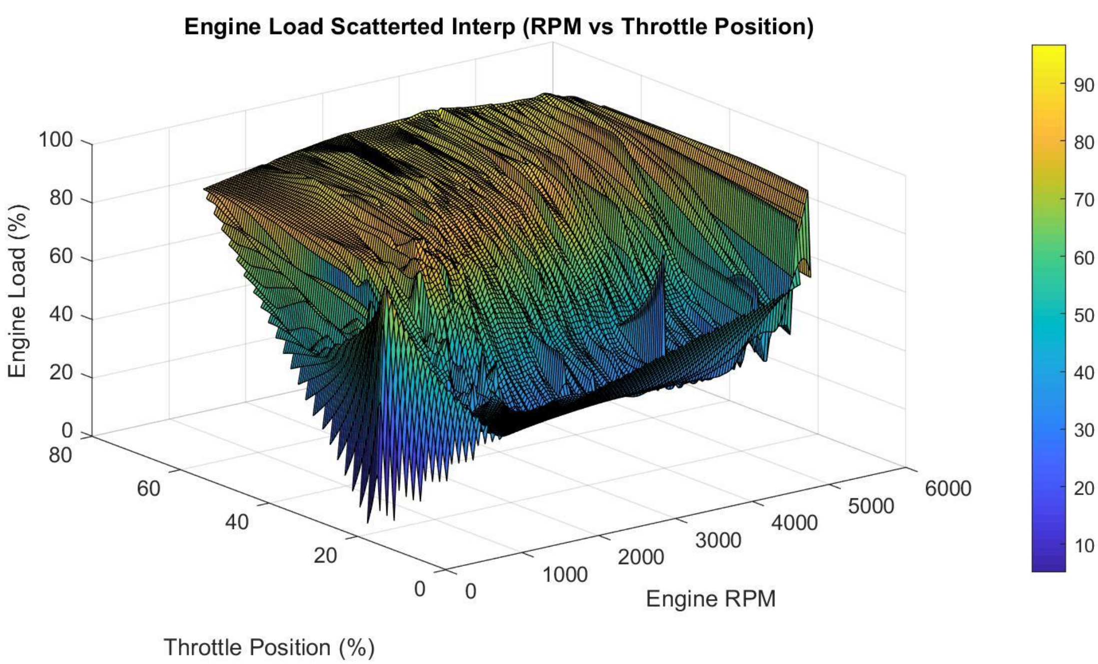

Figure 7: Linearly Interpolated Engine Load Map Based on Throttle Position and Engine Speed

The map above was created using a scattered linear interpolation of the collected drive data. It can be seen that above 2000 RPM the response of engine load to the accelerator pedal position remains fairly constant. Due to the low sampling rate of the OBD-II bus the map has a number of minor artifacts at low throttle positions and high engine speeds that may skew the resulting engine load output.

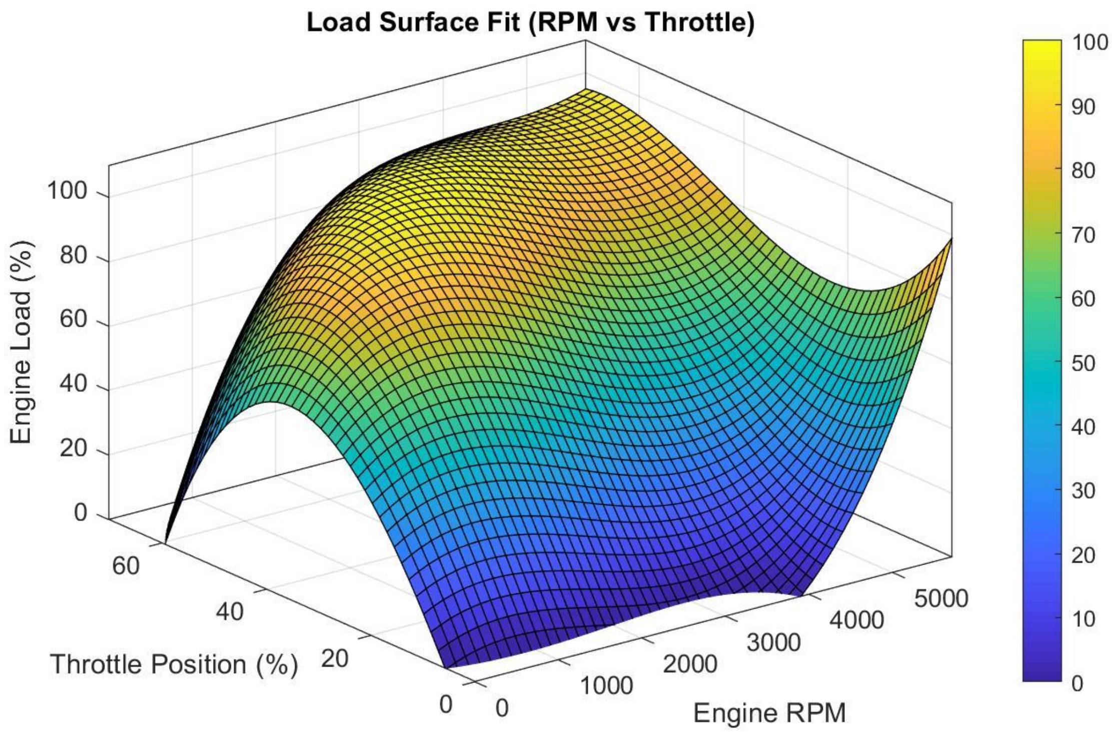

Figure 8: Surface Fit Engine Load Map Based on Throttle Position and Engine Speed

To combat the roughness of the data that is exhibited by the interpolated engine load map the response surface in Figure 8 was created. This response surface was created using MATLAB's Poly33 surface fitting tool with engine speed in RPM on the x-axis, throttle pedal position in % on the y-axis and engine load on the z-axis. While the response surface shows a significantly smoother output, there are anomalies below 800 RPM and below 10% throttle positions where the engine load is negative. This has little effect on the viability of using the response surface in the vehicle model as the engine cannot operate within these conditions as the idle speed of the engine is approximately 800 RPM and the minimum throttle position is roughly 15%.

2.3.3 Fuel Flow Mapping

Engine fuel flow is a function of engine load and engine speed. Using the engine load, engine speed and calculated fuel flow rate collected in the drive data detailed in Section 2.2.2 a fuel flow map was constructed. This map can be seen below in Figure 9.

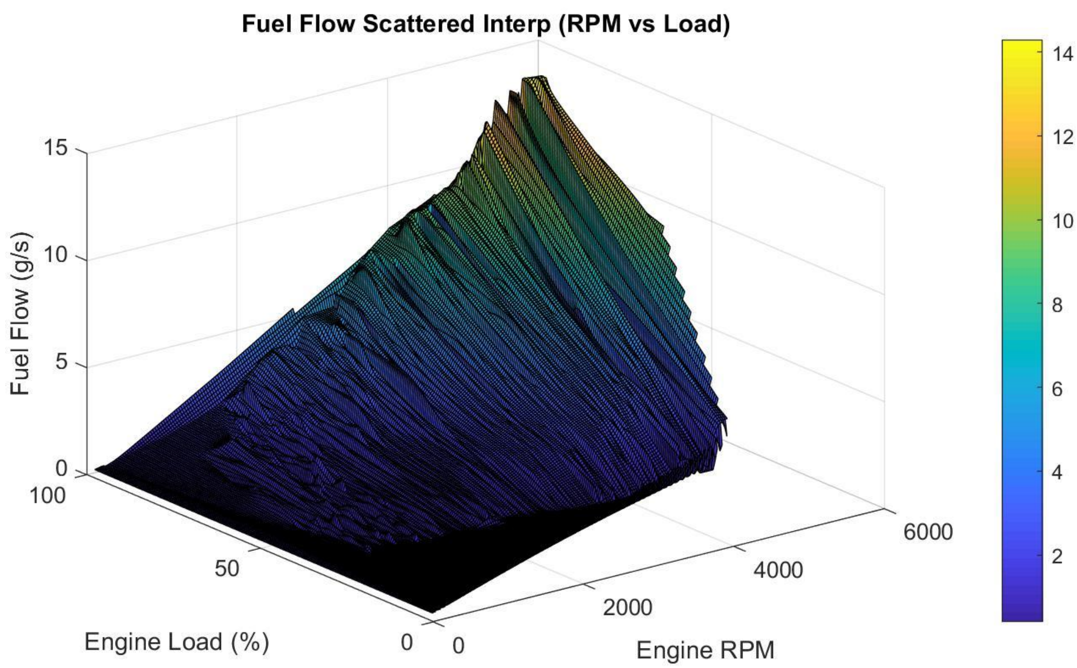

Figure 9: Linearly Interpolated Fuel Flow Map Based on Engine Load and Engine Speed

The map was constructed with a scattered linear interpolation of the collected drive data with engine speed in RPM on the x-axis, engine load on the y-axis and fuel flow in grams/sec on the z-axis. The fuel flow increased roughly linearly with both increased engine speed and engine load. Like the engine load map, the engine fuel rate map has small artifacts due to the slow sampling rate of OBD-II data that may skew the resulting fuel flow rate output. To compensate for the artifacts caused by scattered interpolation a response surface was fit to the drive data and compared to the interpolated map. This response surface is shown in Figure 10 below.

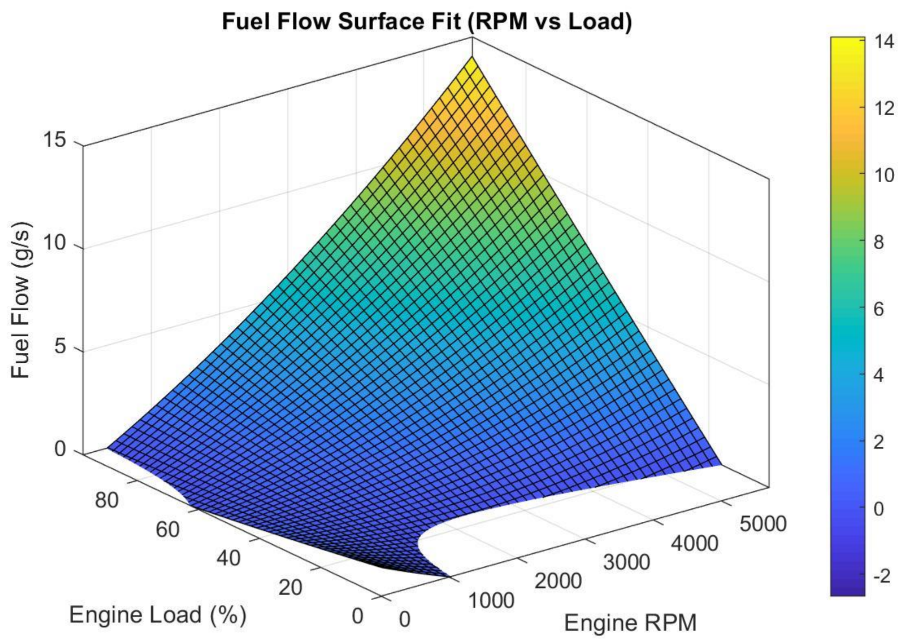

Figure 10: Surface Fit Fuel Flow Map Based on Engine Load and Engine Speed

The response surface was created using MATLAB's Poly22 surface fitting tool. While the response surface shows significantly fewer artifacts, there is an anomaly below 1000 RPM and 20% engine load where the fuel flow rate is negative. This has little effect on the feasibility of using the response surface in the vehicle model as the engine rarely operates within these conditions, especially during acceleration events.

2.3.4 Map Verification

In order to understand the accuracy of both the engine load map and the engine fuel rate map, a simple fuel usage verification test was conducted. An acceleration event was performed and the vehicle's engine speed, accelerator pedal position and fuel rate was recorded. The engine speed and throttle position were fed into both the interpolated and surface fit engine load maps, then the resulting engine loads were fed into the interpolated and surface fit fuel flow maps. This resulted the fuel flow rates shown below in Figure 11 and are compared to the actual fuel flow rate of the vehicle.

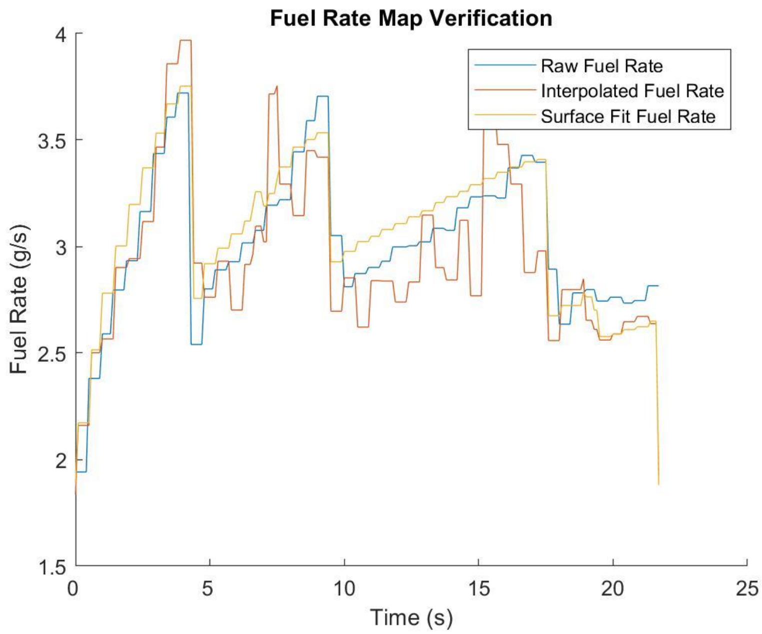

Figure 11: Fuel Rate and Engine Load Map Verification (Linear Interpolation vs Surface Fit)

The interpolated maps resulted in an error in fuel consumption of -2.13% and the surface fit maps resulted in an error of 1.73% when compared to the actual fuel usage during the acceleration event. Not only did the surface fit maps result in a more accurate fuel consumption estimation, the resulting fuel rate exhibited significantly less variation than the fuel rate that was estimated by the interpolated maps. As such, the surface fit engine load and fuel rate maps are used in the vehicle model.

3. Testing of Acceleration Event Fuel Consumption

The purpose of this section is to detail the methodologies that are used to evaluate the vehicle simulation model as well as the results of the simulation and testing phases of this study.

3.1 Acceleration Event Testing Methodology

The evaluation and simulation of the Toyota Tacoma performance of acceleration events is partitioned into 3 sections. These are detailed in Table 3 below.

Table 3: Acceleration Event Testing Methods and Purpose

	Baseline (Real-World)	**Modified Shift Schedule (Simulated)**	**Modified Shift Schedule (Real-World)**
Purpose	- To collect fuel consumption data using a baseline shift schedule - To collect a baseline velocity trace and pedal position trace	- To predict fuel consumption changes when the modified shift schedule is applied	- To validate the modified shift schedule simulation
Shift Schedule	1st to 2nd: 20 MPH 2nd to 3rd: 30 MPH 3rd to 4th: 40 MPH	1st to 2nd: 23 MPH 2nd to 3rd: 35 MPH 3rd to 4th: 55 MPH	1st to 2nd: 23 MPH 2nd to 3rd: 35 MPH 3rd to 4th: 55 MPH
Inputs	- Baseline throttle trace - Baseline shift schedule	- Baseline velocity trace - Modified shift schedule - Baseline throttle trace	- Baseline velocity trace - Modified shift schedule - Baseline throttle trace
Outputs	- Actual fuel consumption with baseline shift schedule - Baseline velocity trace	- Predicted fuel flow rate trace with modified shift schedule	- Actual fuel flow rate trace with modified shift schedule

The procedure begins with a real-world baseline test. As the vehicle simulation is backward-facing the velocity trace that is produced during the baseline test will be used by the simulation as an input. Furthermore, the velocity trace produced by the modified shift schedule will be compared to this baseline velocity trace to ensure that the vehicle acceleration rate is equivalent between the two tests. The details of the design of the baseline acceleration event is described in Section 3.1.1. The second phase is the simulation of the modified shift schedule. This phase inputs the baseline velocity trace, throttle position, and desired shift schedule into the vehicle model to calculate the expected change in fuel consumption. The final stage of the procedure is real-world testing of the modified shift schedule. The vehicle is driven with the baseline pedal position trace and the modified shift schedule. The measured fuel consumption is compared to the estimated fuel consumption from the simulation and the velocity trace is compared to the baseline velocity trace to ensure equivalent acceleration rates. Each of these phases are completed 4 times in order to produce useful statistical data.

3.1.1 Acceleration Event Design

Acceleration event tests were designed to emulate real-world driving scenarios in urban areas. Many urban roadways have a speed limit of 35-45 mph with intersections controlled by stop lights and stop signs. This leads to a high number of 0-40 mph acceleration events in many urban real-world driving scenarios. On-road driving data shown in Figure 12 below depicts the velocity trace of the Toyota Tacoma accelerating from a stop sign on a roadway with a speed limit if 40 MPH.

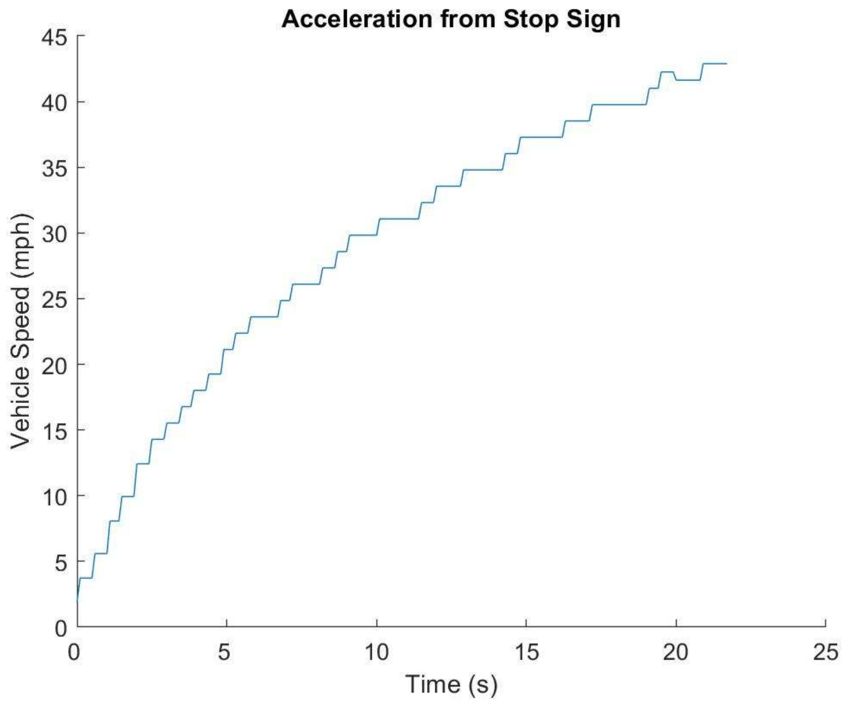

Figure 12: Toyota Tacoma Accelerating from a Stop Sign to 40 mph

Acceleration rates from a stop vary depending upon both the individual driver, vehicle type and traffic conditions so using a measured real-world acceleration rate is preferable to using historical data. As such, the above stop sign acceleration event is used as the baseline for testing and simulation. It was found that independent of acceleration rate, most acceleration events are performed at a near-constant throttle position up until the speed limit of the roadway is reached. Therefore, all acceleration events, both real-world and simulated, are performed at constant throttle. This also assists in repeatability between acceleration event tests.

All dynamic vehicle testing was completed at Christman Airfield located at CSU's foothills campus. This location was selected as it is a closed course that is void of traffic and pedestrians. Christman Airfield is ideal for fuel consumption testing as it has little elevation change along its length, especially over the southern 2/3rds with a elevation variation of 3m. Due to this, all acceleration event testing is conducted going north starting on the south end of the runway to keep run-to-run data consistent. Figure 13 below shows the layout and elevations of Chrisman Airfield.

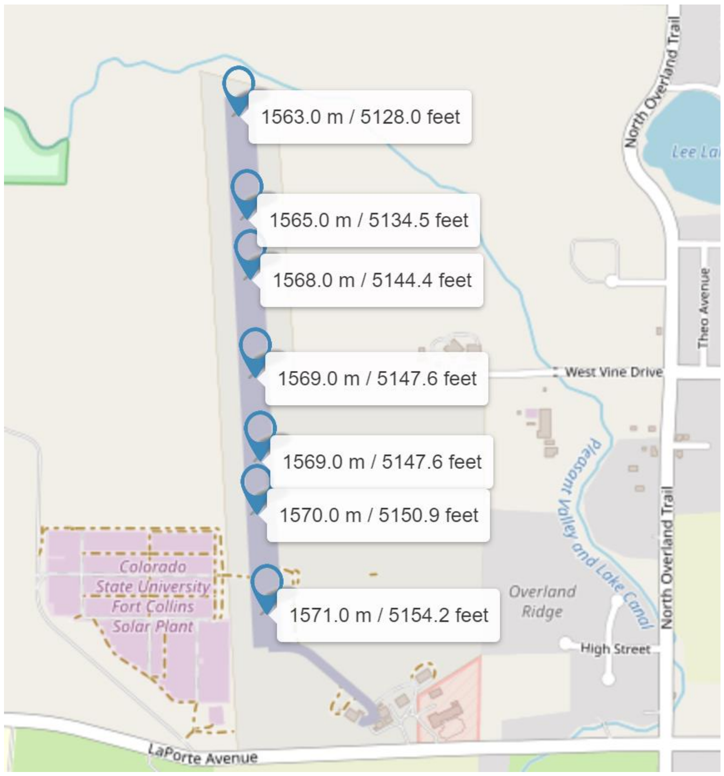

Figure 13: Layout and Elevations of Chrisman Airfield

3.1.2 Throttle Pedal Control

It is necessary to have the capability of holding the throttle pedal in a constant position to both accurately emulate real-world acceleration events as well as to achieve consistency between acceleration event tests. Constant throttle control was accomplished by the installation of a custom pedal block that is capable of holding the accelerator pedal in a constant position and is adjustable to achieve different accelerator pedal positions. The installed pedal block is shown in Figure 14 below:

Figure 14: Installed Pedal Block on Toyota Tacoma

The pedal block is attached to the backside of the accelerator pedal and ensures that the pedal position is held constant by controlling the distance between the pedal and the floor. The pedal block can be adjusted higher on the pedal for a lower throttle input and lower on the throttle to produce a higher throttle input.

3.1.3 Gear Selection Control

Gear selection control is achieved by using the 2019 Toyota Tacoma's sport shifting mode. This allows the driver to select the highest gear ratio that the transmission can have selected, effectively giving the driver control of the current gear ratio selection. During an acceleration event, the driver starts the vehicle in S-1, forcing 1st gear. As the vehicle accelerates the driver increases the shift mode (S-2, S-3, etc.) at specified vehicle speeds to match the desired shift schedule. The speed readout from the Torque App is used as a speed reference as it outputs a digital readout rather than the analog speedometer that is installed in the

Tacoma. The performance of this method is shown in Section 4.2.1. The procedures listed in Table 4 below were used to conduct all acceleration event tests.

Table 4: Testing Procedures

Setup of Data Acquisition System

- With the vehicle turned off, connect WiFi enabled OBD-II dongle to the OBD-II port
- On a compatible smartphone connect to the OBD-II dongle's WiFi network and open the Torque App on compatible smartphone
- Check that connectivity with the OBD-II dongle is operational
- Go to Settings > OBD2 Adapter Settings and enable Faster Communication
- Go to Settings > Data Logging and Upload > Select what to log and select the following PID's
    - Accelerator PedalPosition D
    - Engine Load
    - Engine RPM
    - Fuel Flow Rate/Hour
    - Speed OBD
- Turn on vehicle and check to ensure that all relevant data channels are reading as expected in the Realtime Data feature
    - It is best to show the pedal position, fuel flow, and vehicle speed on this display for use in testing

Pre-testing Procedures

- It is recommended that in-vehicle tests should be conducted with a starting amount of fuel between ½ tank an a full tank a fuel
- Before testing is to be conducted the vehicle must be warmed to operational temperature. This can be done by either:
    - 10 minutes of driving in urban environment (15-20 for low ambient temps)
    - 20 minutes of idling (25-30 for low ambient temps)
- During the warm-up, it is best to check that data logging is operational
    - On the Realtime Data screen select Settings > Start Logging
    - After a few minutes, select Settings > Stop Logging
    - Check the results in the .csv file that is saved in the smartphone's Torque folder
- Install pedal block onto the accelerator pedal and check its placement by reading the pedal position in the Torque App
- Set the smartphone on the dash/windshield by using any type of phone mount so that the screen is visible by the driver
- Ensure that the A/C system is disabled

In-Vehicle Acceleration Event Testing Procedures

- Position the vehicle on the white lines on the southern end of Chrisman Airfield facing north.
- With the vehicle on and the DAQ system operational, go to RealTime Data > Settings > Start Logging
- Wait a couple seconds to let the data logging begin
- Move the transmission stalk to S and pull backwards until S1 is selected
- Quickly apply the accelerator pedal until the pedal block reaches the floor
- Using the Torque App speed display as reference, push forward on the transmission stalk to shift into S2, S3, etc. at the desired shift points.
- When the acceleration event test is completed select Settings > Stop Logging
- Repeat the above steps until testing is completed

3.2 Acceleration Event Simulation and Testing

3.2.1 Baseline Shift Schedule Testing

The real-world baseline tests were conducted per the methodology described in Section 3.1. The vehicle velocity, accelerator pedal position, gear selection, engine load, engine speed and fuel rate of the 4 baseline tests are shown in Figure 15 below:

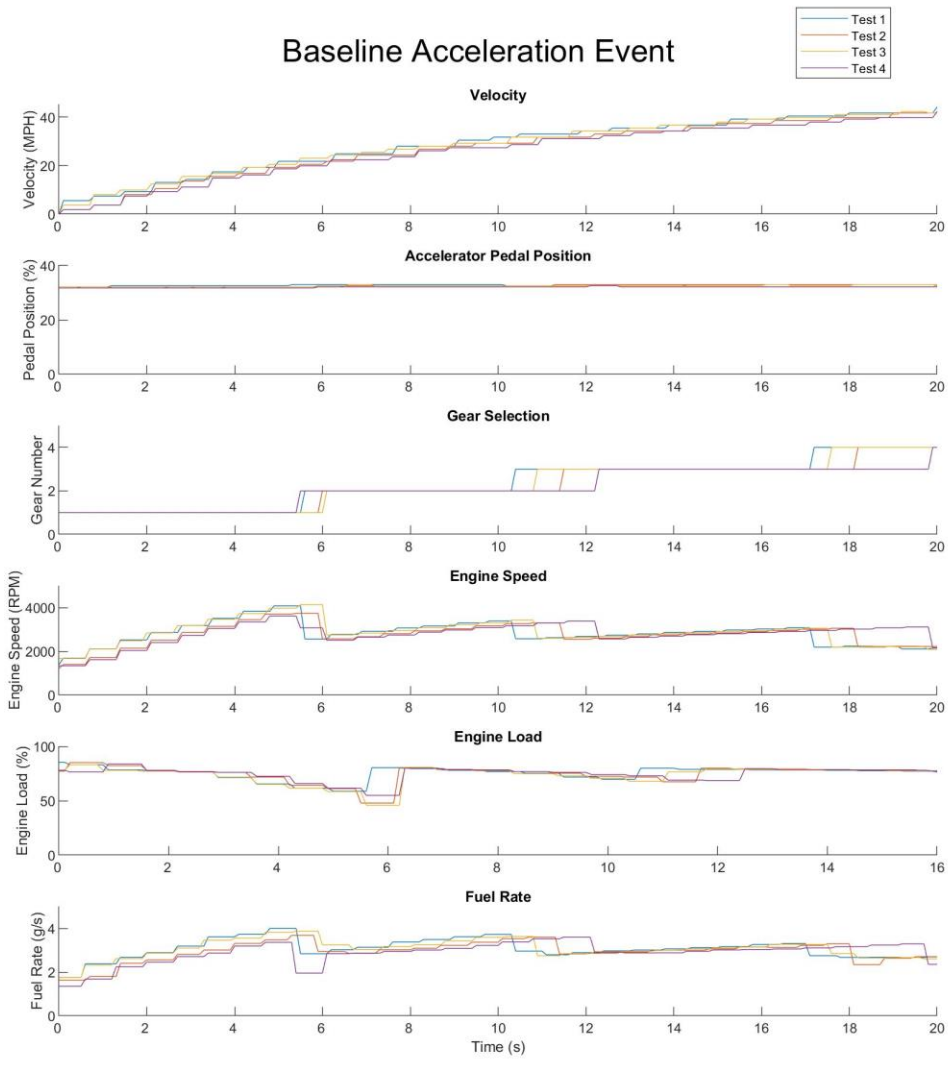

Figure 15: Baseline Acceleration Event Test Data

3.2.2 Modified Shift Schedule Simulation

The velocity and pedal position traces from the baseline test were input into the vehicle model per the methodology described in Section 2. The vehicle velocity, accelerator pedal position, gear selection, engine load, engine speed and fuel rate of the four simulated modified acceleration events are shown in Figure 16 below.

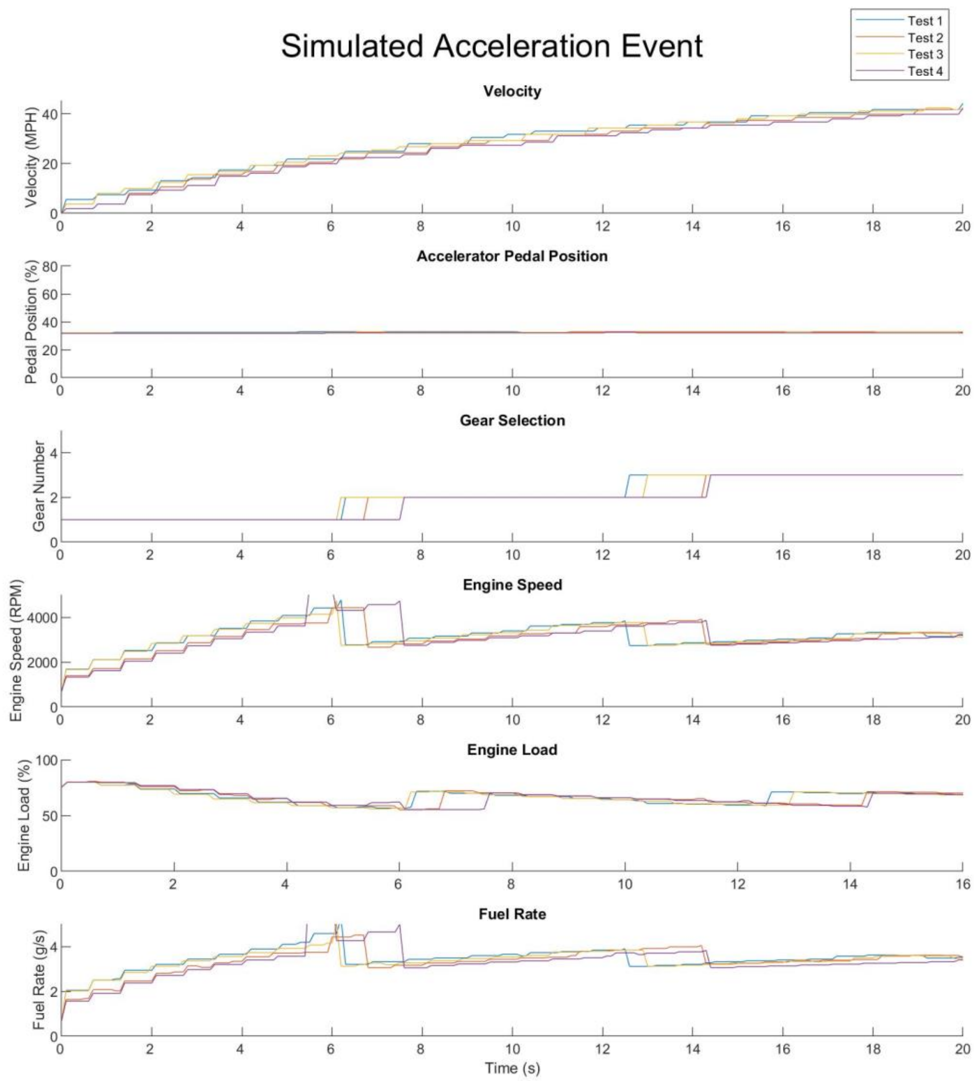

Figure 16: Modified Shift Schedule Simulation Data

3.2.3 Modified Shift Schedule Testing

The real-world modified shift schedule test was conducted per the methodology described in Section 3.1. The vehicle velocity, accelerator pedal position, gear selection, engine load, engine speed and fuel rate of the four modified shift schedule tests are shown in Figure 17 below.

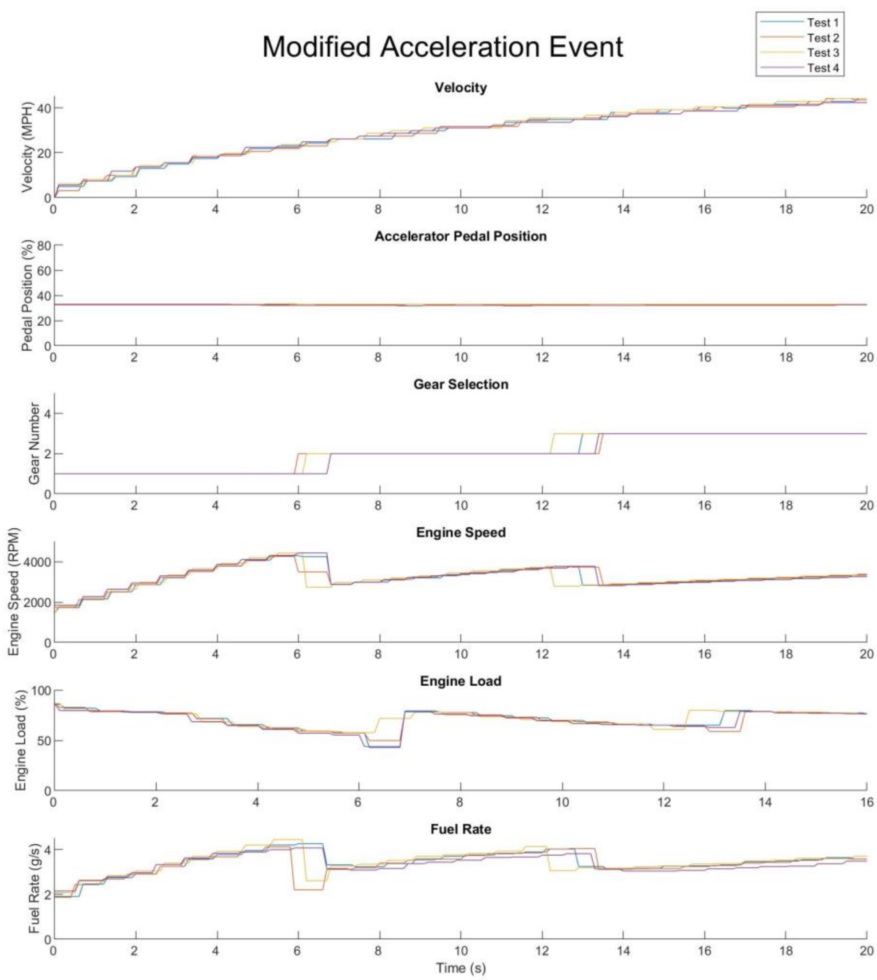

Figure 17: Modified Shift Schedule Test Data

4. Overall Results and Discussion

The purpose of this section is to compare the results of the three phases of simulation and testing and to discuss the implications of the results.

4.1 Testing and Simulation Methodology Verification

Due to the nature of the backward facing vehicle model it is necessary to ensure that the acceleration rate of the modified shift schedule test is equivalent to the acceleration rate of the baseline shift schedule test. If this assumption is not held true then the use of a backward facing model is no longer valid. The velocity traces of one of the baseline shift schedule tests and one of the modified shift schedule tests are shown in Figure 18 below.

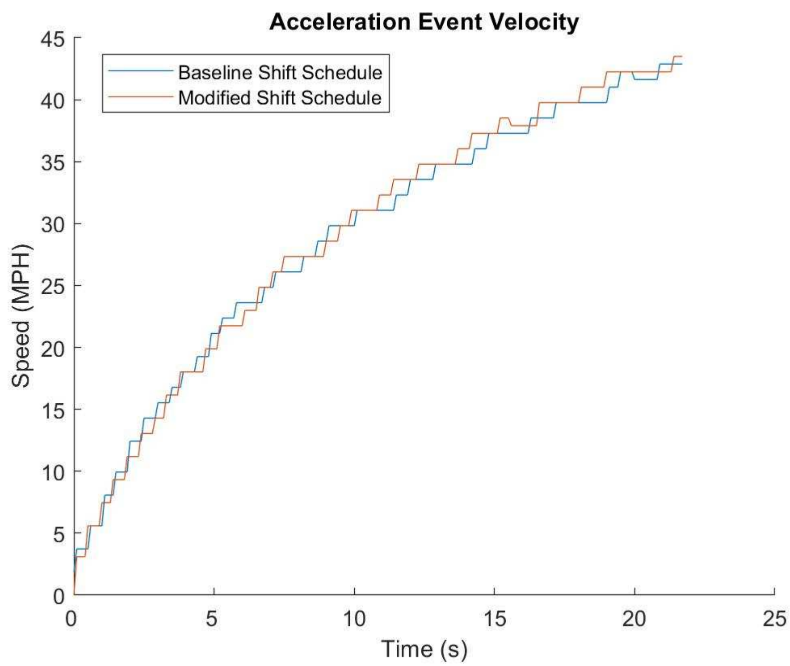

Figure 18: Comparison of Velocity Traces of Baseline and Modified Shift Schedule Tests

It can be seen that the acceleration rate of the vehicle did not change with the application of the modified shift schedule, validating the use of a backward facing vehicle simulation.

Since the modified shift schedule simulation is performed using the accelerator pedal trace that was collected during the baseline shift schedule test it is important to verify that the modified shift schedule test is performed at the same accelerator pedal position. Figure 19 below shows the accelerator pedal traces for both the baseline shift schedule and modified shift schedule tests.

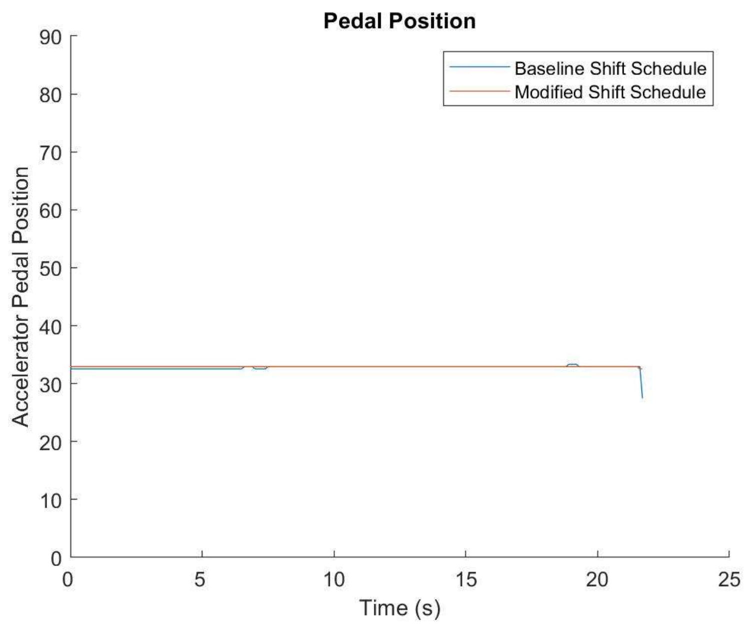

Figure 19:Comparison of Accelerator Pedal Traces of Baseline and Modified Shift Schedule Tests

Disregarding a small number of slight variations, the accelerator pedal position between the two tests the pedal positions are considered equivalent. The small variations in pedal position are likely due to the Toyota Tacoma's soft floor not being capable of holding the pedal block completely rigid.

4.2 Testing and Simulation Results Comparison and Evaluation

Sections 4.2.1 through 4.2.4 evaluate the effectiveness of the testing and simulation methods for each of the following parameters: gear selection, engine speed, engine load, and fuel consumption. These sections detail a single acceleration event while section 4.2.5 details the statistical variation between a number of separate baseline tests, modified shift schedule simulations and modified schedule tests.

4.2.1 Gear Selection

Table 4 below describes the desired shift schedule, the actual shift schedule and the error between the two for the baseline schedule, the simulated modified schedule, and the tested modified schedule.

Table 5: Analysis of Shifting Methodology

	Baseline (Real-World)	**Modified Shift Schedule (Simulated)**	**Modified Shift Schedule (Real-World)**
Desired Shift Schedule	1st to 2nd: 20 MPH 2nd to 3rd: 30 MPH 3rd to 4th: 40 MPH	1st to 2nd: 23 MPH 2nd to 3rd: 35 MPH 3rd to 4th: 55 MPH	1st to 2nd: 23 MPH 2nd to 3rd: 35 MPH 3rd to 4th: 55 MPH
Actual Shift Points	1st to 2nd: 19.3 MPH 2nd to 3rd: 29.8 MPH 3rd to 4th: 39.7 MPH	1st to 2nd: 23.6 MPH 2nd to 3rd: 34.8 MPH 3rd to 4th: N/A	1st to 2nd: 21.7 MPH 2nd to 3rd: 34.8 MPH 3rd to 4th: N/A
Error	1st to 2nd: 0.7 MPH 2nd to 3rd: 0.2 MPH 3rd to 4th: 0.3 MPH	1st to 2nd: 0.6 MPH 2nd to 3rd: 0.2 MPH 3rd to 4th: N/A	1st to 2nd: 1.3 MPH 2nd to 3rd: 0.2 MPH 3rd to 4th: N/A

The gear selection methodology presented in Section 2.3.1 was capable of matching the desired shift schedule within +/- 1 MPH in all gear selection operations except the 1st to 2nd shift in the modified shift schedule test. This error is likely caused by operator error combined with slow data readouts from the digital speedometer on the Torque App. Also, the accuracy of the above shift timings may be slightly suspect as the low temporal resolution of the collected data may mask either smaller or larger shift timing errors. It is of note that the vehicle did not complete the 3rd to 4th gear shift in the modified schedule simulation or test as the vehicle did not reach the speed required for the shift.

Figure 20 below shows the gear selection trace over the course of the baseline schedule test, the modified schedule simulation and the modified schedule test.

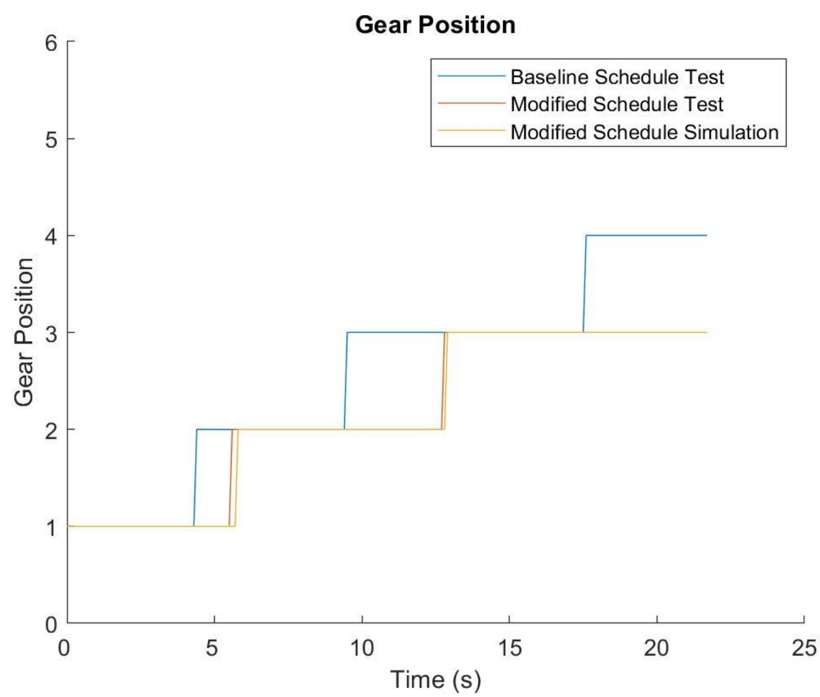

Figure 20: Comparison of Shift Timing During Baseline Testing and Modified Schedule Simulation and Testing

The gear selection methodology was capable of matching desired shift schedules adequately but required a significant amount of focus and practice on the part of the driver. While these methods are suitable it would be recommended to automate this process where possible in future VIT tests.

4.2.2 Engine Speed

Figure 21 below shows the engine speed during the baseline schedule test, the modified schedule simulation and the modified schedule test.

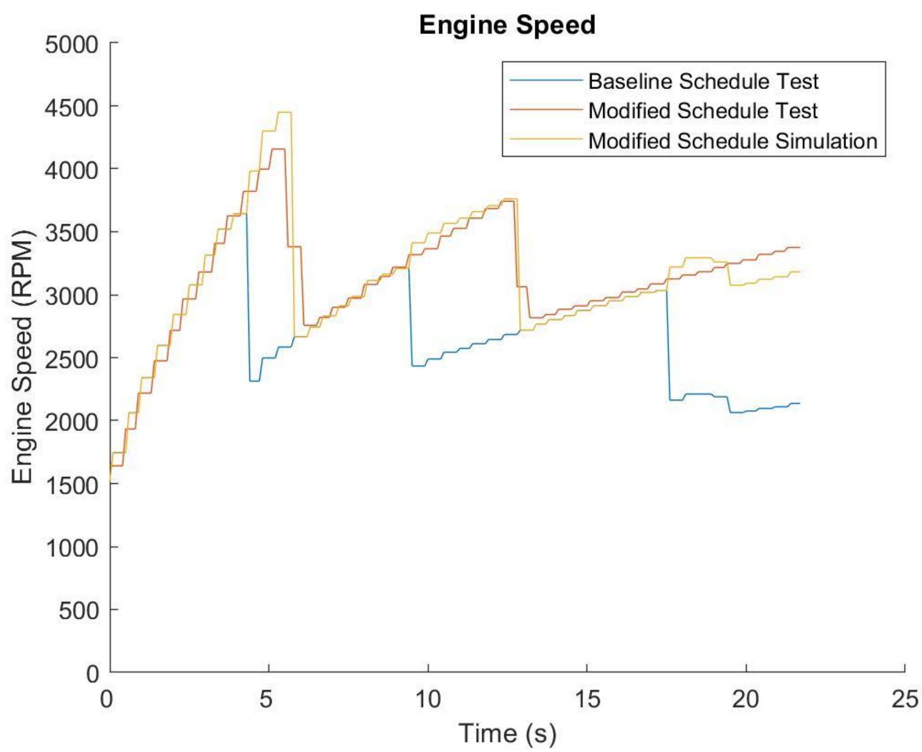

Figure 21: Comparison of Engine Speed During Baseline Testing and Modified Schedule Simulation and Testing

Figure 22 below depicts the error between the simulated engine speed trace and the actual speed trace of an acceleration event performed with the modified shift schedule.

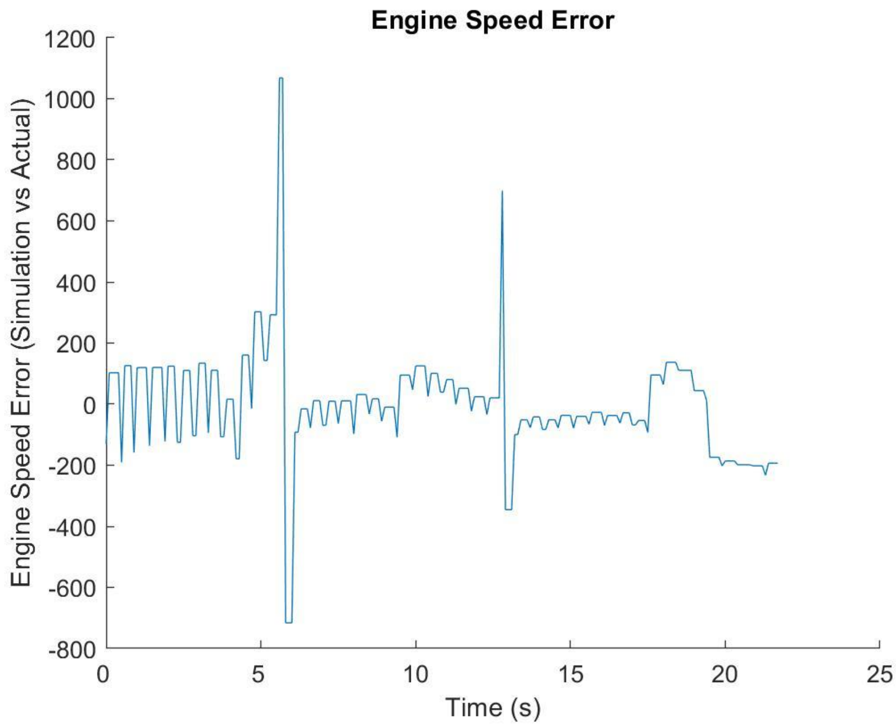

Figure 22: Engine Speed Error Between Modified Shift Schedule Simulation and Testing

The engine speed trace predicted by the vehicle simulation was on average 0.30 RPM lower than what was measured during the modified schedule test with a standard deviation of 184 RPM. The simulated engine speed displayed its highest error of 1050 RPM during the 1st to 2nd shift and another error spike during the 2nd to 3rd shift. These high error spikes are an artifact created by the slight mistiming of the shift schedules shown in Section 4.2.1 as well as the lack of understanding of torque converter dynamics during gear changes. The low average error results in a conclusion that the methodology used to simulate engine speed is more than adequate for CSU VIT testing and modeling.

4.2.3 Engine Load

Figure 23 below shows the engine load during the baseline schedule test, the modified schedule simulation and the modified schedule test.

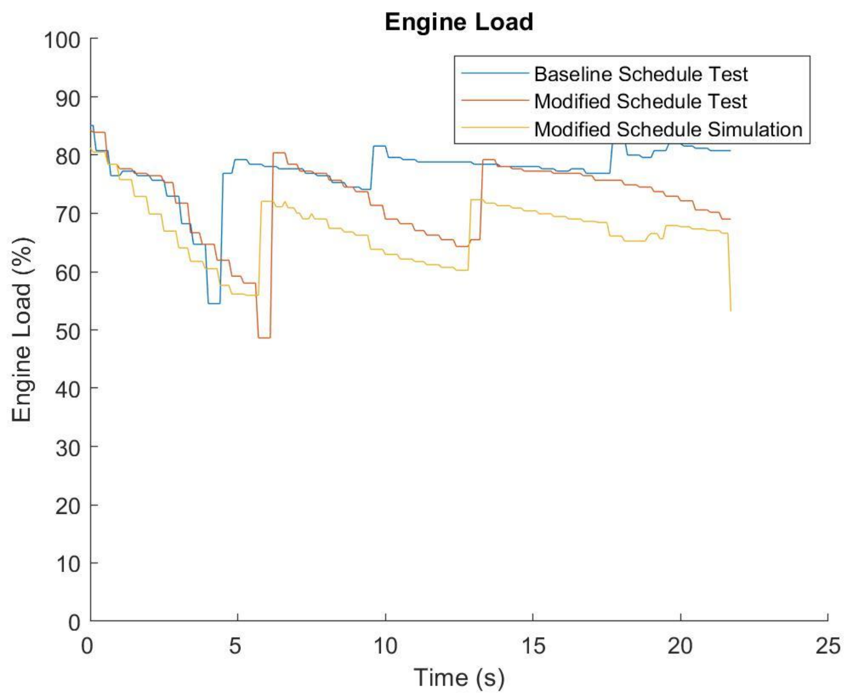

Figure 23: Comparison of Engine Loading During Baseline Testing and Modified Schedule Simulation and Testing

Figure 24 below depicts the error between the simulated engine load trace and the actual engine load trace of an acceleration event performed with the modified shift schedule.

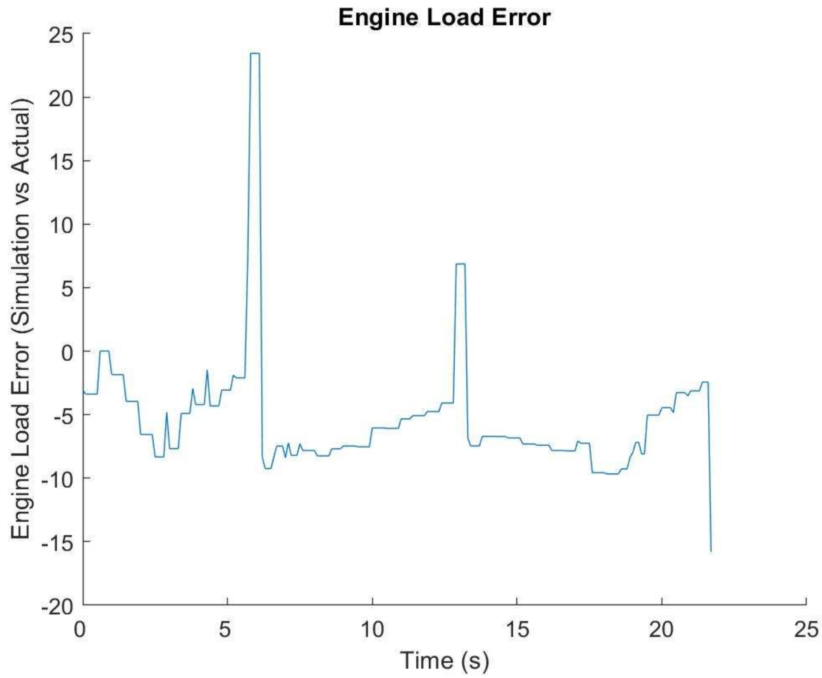

Figure 24: Engine Load Error Between Modified Shift Schedule Simulation and Testing

The simulation calculated the engine load 5.2% lower on average than what was measured during the modified schedule test with a standard deviation of 4.69%. The simulated load displayed its highest error of 24% during the 1st to 2nd shift and another error spike during the 2nd to 3rd shift. The significantly large average error appears to be a result of poor engine load mapping and modeling. The high spikes in error during shifts are likely caused by inadequate torque converter modeling and the lack of understanding of engine load during shifts. The quality of the testing and simulation of engine load is adequate, as seen in section 4.2.4, but should be re-evaluated for use in future CSU VIT projects.

4.2.4 Fuel Consumption Rate

Figure 25 below shows the engine fuel rate during the baseline schedule test, the modified schedule simulation and the modified schedule test.

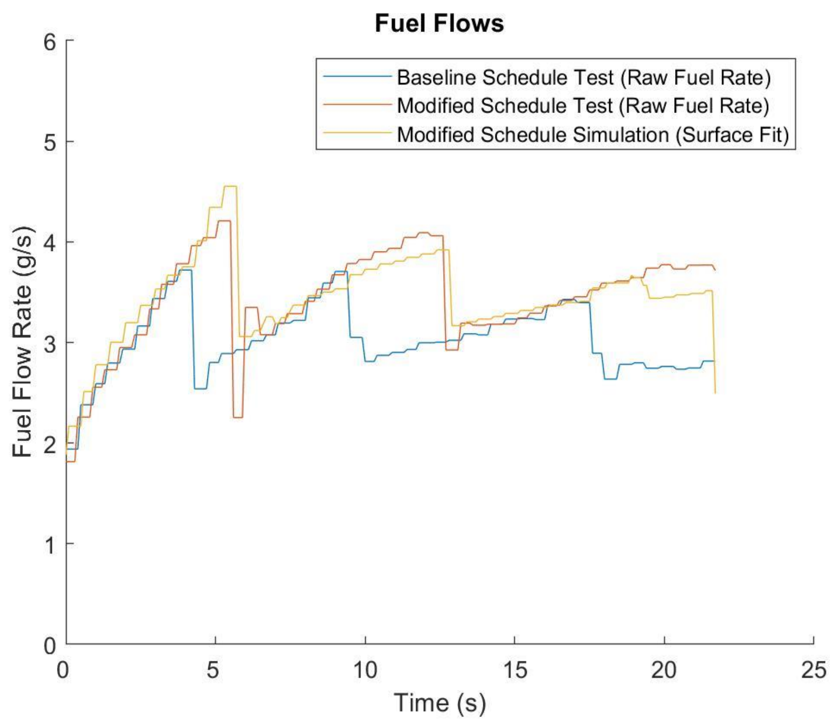

Figure 25: Comparison of Fuel Flow During Baseline Testing and Modified Schedule Simulation and Testing

Figure 26 below depicts the error between the simulated engine fuel rate trace and the actual engine fuel rate trace of the acceleration event performed with the modified shift schedule.

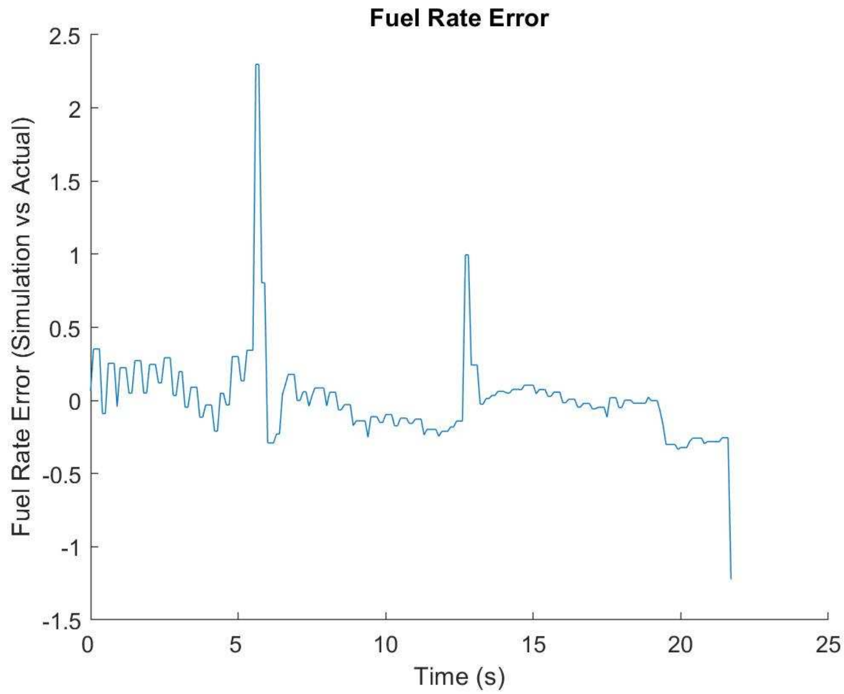

Figure 26: Fuel Rate Error Between Modified Shift Schedule Simulation and Testing

The simulation estimated that the fuel flow rate is 0.015 grams/sec higher on average than what was measured during the modified schedule test with a standard deviation of 0.314 grams/sec. The simulated fuel rate exhibited its highest error of 2.3 grams/sec during the 1st to 2nd shift and another error spike to 1 gram/sec during the 2nd to 3rd shift. A large dip in fuel flow rate was simulated at the end of the acceleration event that did not occur during the modified schedule test. This is a result of a small drop in throttle position at the end of the baseline throttle position trace that was not replicated in the modified shift schedule test.

4.2.5 Total Fuel Consumption and Statistical Analysis

The fuel consumption was measured for each of the baseline tests using the data collected from the OBD-II port. This data is shown below in Figure 27.

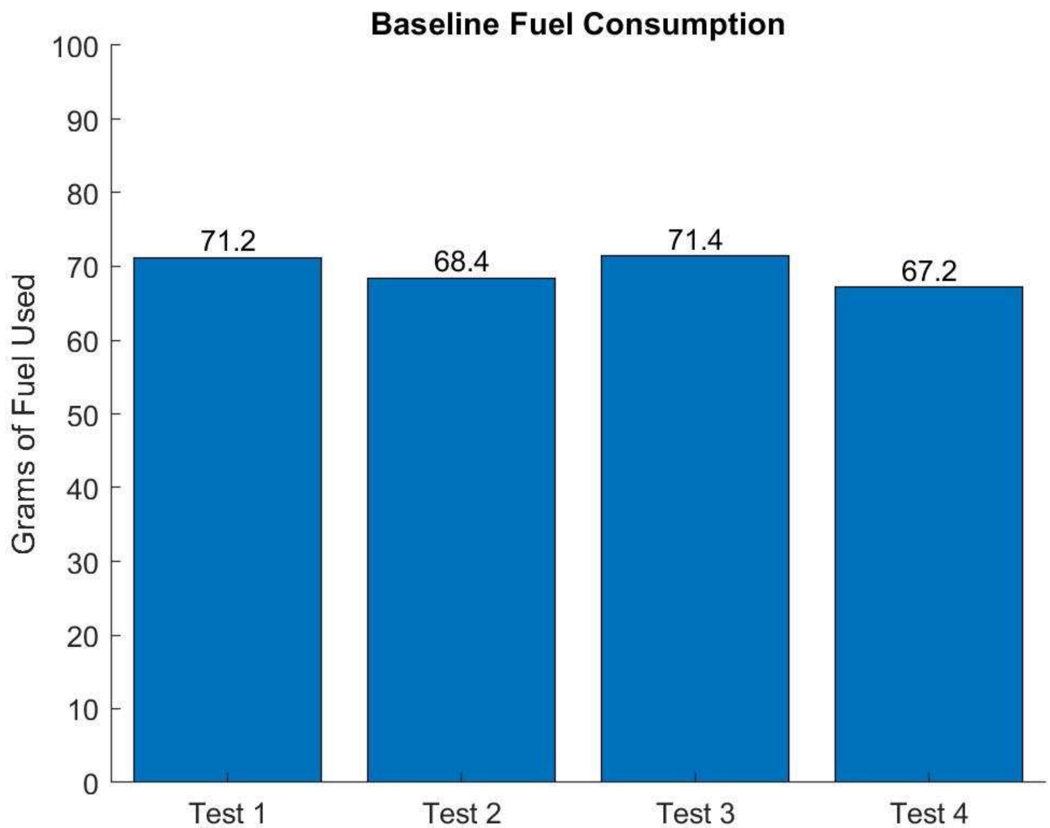

Figure 27: Fuel Consumption During Baseline Shift Schedule Testing

The average fuel consumption of the baseline tests was 69.5 grams with a standard deviation of 2.1 grams. 4 simulation tests were performed using the velocity and pedal position traces from the above baseline tests as inputs to the vehicle model. The fuel consumption of each of these tests are shown in Figure 28 below.

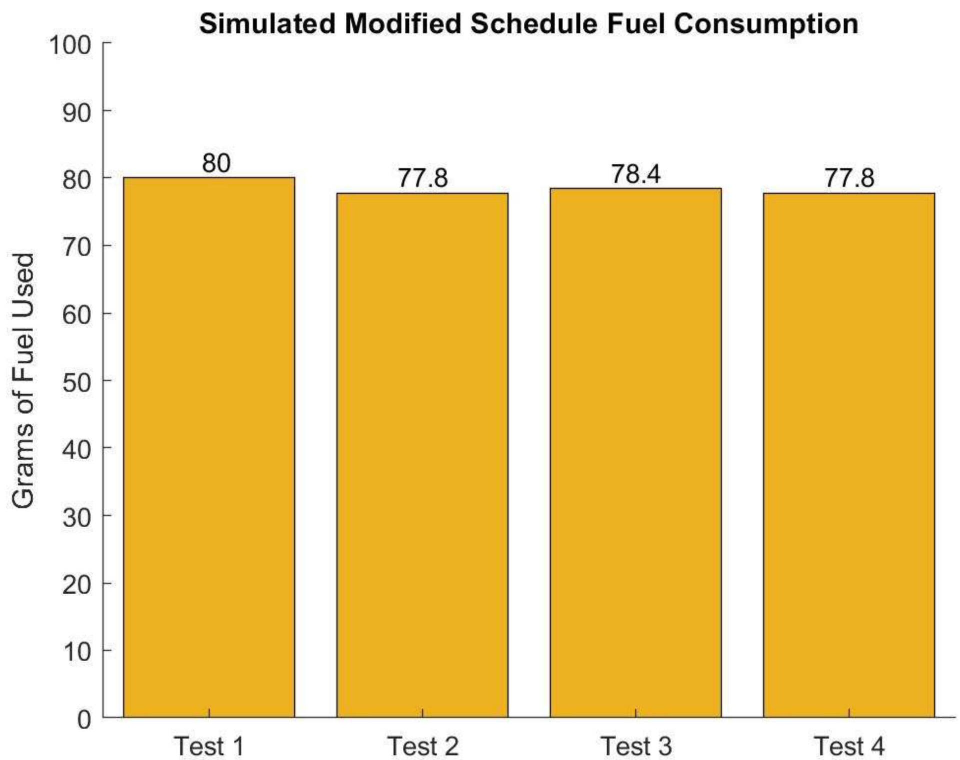

Figure 28: : Fuel Consumption During Modified Shift Schedule Simulation

The predicted fuel consumption of the modified shift schedule tests was 78.5 grams with a standard deviation of 1.0 grams. Tests were performed to verify these predictions and the fuel consumption of these tests are shown below in Figure 29.

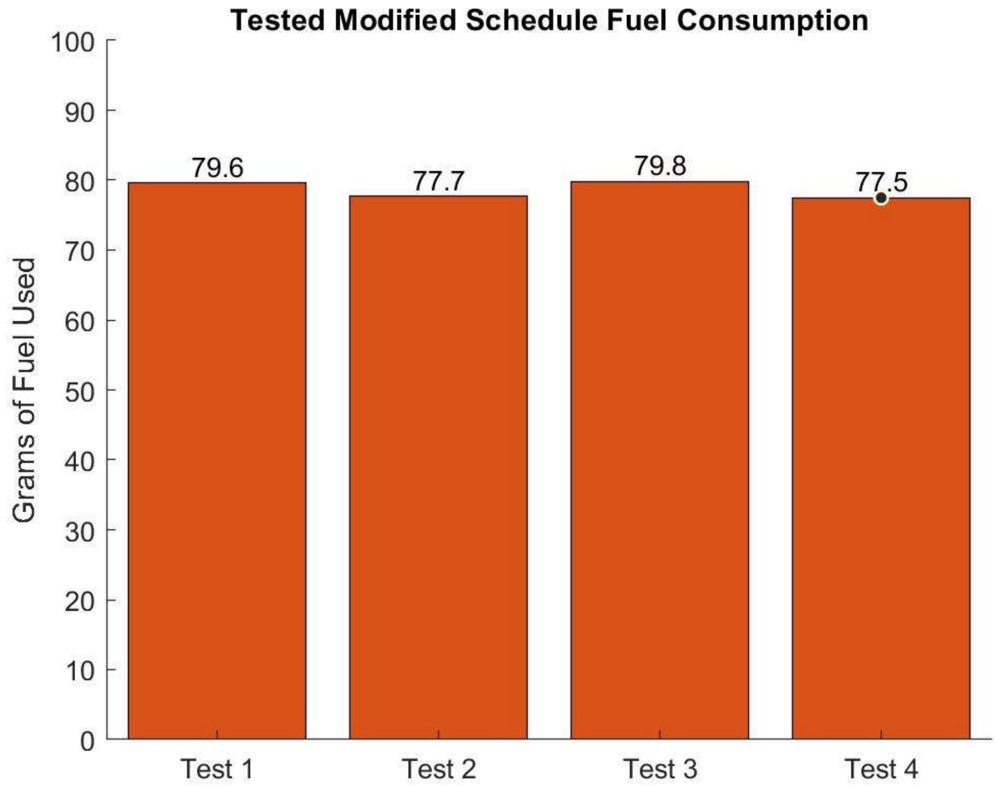

Figure 29:: Fuel Consumption During Modified Shift Schedule Testing

The measured fuel consumption during the modified shift schedules tests was 78.7 grams with a standard deviation of 1.2 grams.

Figure 30 below displays the average total fuel used during the baseline shift schedule tests , the modified shift schedule simulations, and the tested modified shift schedule tests.

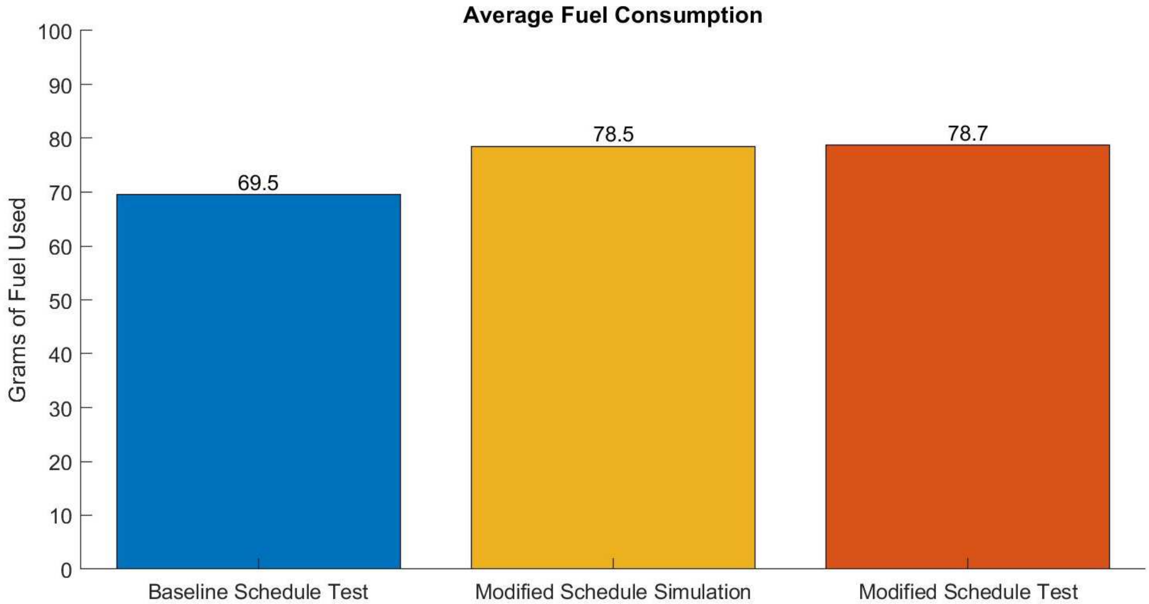

Figure 30: Average Fuel Consumption During Baseline Shift Schedule Testing and Modified Shift Schedule Simulation and Testing

Despite the significant error in engine load simulation, the vehicle simulation model was able to predict an average fuel consumption of 78.5 grams over the acceleration events with the modified shift schedule, within 0.25% of the actual fuel consumption that was measured during the modified schedule tests with a standard deviation of 1.1%. This means that by using the methods discussed in this paper, one is able to predict the fuel consumption of a vehicle during an acceleration event within 1.4% with 95% confidence. The high accuracy of the fuel consumption prediction exhibited by the testing and simulation methodologies used in this study lead to the result that, overall, these methodologies are more than adequate for testing and modeling vehicles with the purpose of fuel economy prediction.

4.3 Limitations of Testing and Simulation Methodology

While the results of the modeling and simulation study produced positive results, the methodologies used, and the resulting vehicle model are, at the time of writing, limited in flexibility and capability.

4.3.1 Throttle and Gear Control During Testing

The methods used to control the longitudinal motion of the vehicle are basic and limiting. Since the driver is responsible for requesting gear changes using the transmission stalk in the vehicle the length and complexity of any desired shift schedule is limited. The driver would be incapable of making accurate shifts in transient driving conditions and would not be able to remember shift schedules for a long drive cycle. Also, the driver is not capable of performing accurate throttle control in transient conditions. Currently, all acceleration event tests must be conducted at a constant throttle with a simple gear shift schedule.

4.3.2 Data Collection and Simulation Limitations

Beyond the inherent limitations of backward facing vehicle models, the current model is quite limited in the types of vehicle modifications that can be simulated. In its current state, the model is only capable of simulating changes in shift schedule. Changes in other parameters such as vehicle mass, engine characteristics, tire type and size, and hybridization are not possible.

Furthermore, the data collection methods are limited, specifically in temporal resolution. The current data refresh rate of 2 Hz is not sufficient to collect accurate data on transient operations such as gear shifts or high acceleration events.

5. Conclusions

5.1 Practical Applications of Research and CSU VIT Projects

The vehicle modeling, simulation and testing methodologies discussed in this paper will be used in the simulation and testing of a hybrid-electric powertrain and subsequent control strategies that are in development by the CSU VIT for the 2019 Toyota Tacoma. The understanding of the limitations of these methodologies will aid in shaping further improvements of the VIT's data collection procedures, vehicle modeling workflow, and vehicle testing instrumentation.

This study has provided a quantitative analysis on the repeatability of acceleration event testing that is conducted with the methods described in section 3. Based upon the testing results shown in Figure 27 it can be determined that the testing methods used are capable of being repeatable within +/- 3.0% (95% CI) in terms of fuel consumption between tests. This means that fuel consumption changes less than 3.0% measured during testing cannot be considered as conclusive results as this change may be due to test-to-test variation rather than changes in vehicle performance. This confidence interval may be improved with the implementation of automated longitudinal control that is discussed in section 5.2.

Furthermore, this paper has provided evidence that data with low temporal resolution that is collected from a vehicle's OBD-II data port is capable of being used for vehicle modeling. With a better understanding of the drawbacks of using data with low temporal resolution the CSU VIT can continue forward using the data provided by OBD-II with improved awareness of its capabilities.

The methods introduced in this paper may also be expanded upon in both breadth and accuracy to produce an alternative to expensive data collection and vehicle modeling methods. As many other vehicle modeling and simulation methods require the installation of expensive sensors onto vehicle platforms and the use of chassis dynamometers for data collection, less expensive and more accessible methods would be of value to many automotive engineering groups.

5.2 Future Work

Further development on the vehicle modeling methods discussed in this paper would be beneficial to future CSU VIT work. Specifically, if the limitations stated in Section 4.3 can be eliminated or reduced, the power of the power of the vehicle simulation model can be increased significantly.

The addition of the ability to accurately estimate the power produced by the engine of the vehicle and the power lost by the drivetrain would be the first step to increase the capability of the model. This would involve generating an understanding of the vehicle weight, rotating component inertias, engine power at all RPM's and loads as well as how all of these factors affect vehicle acceleration. With the vehicle's power requirements modeled, one could simulate the effect of differently sized engines as well as the effect of hybridization or electrification. An increase in the data rate collected from the vehicle may be necessary to achieve this as a higher temporal resolution in the velocity trace would provide for more accurate acceleration rate calculations, and as a result, more accurate power calculations.

The automation of the longitudinal control systems of the Toyota Tacoma would also provide a benefit to the capabilities of the vehicle model. The addition of the ability to emulate the throttle position signal with a microcontroller would allow for a near infinite set of drive cycles to be performed, especially in hybridization applications. Along with this, autonomous control over the transmission shift schedule would provide for further flexibility in testable drive cycles.

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List of Abbreviations

AE - Acceleration Event

AVTC - Advanced Vehicle Technology Competition

CAN - Controller Area Network

VIT - Vehicle Innovations Team

ESS - Energy Storage System

POEMS - Predictive Optimal Energy Management Strategies

MAF - Mass Air Flow

OBD - On-board Diagnostics

OEMS - Optimal Energy Management Strategy

PEMS - Portable Emissions Measurement System

RPM - Rotations Per Minute

SOC - State of Charge

TC - Torque Converter