Modeling Diesel Bus Fuel Consumption and Dynamically Optimizing Bus Scheduling Efficiency

William Andrew Edwardes

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

Master of Science
in
Civil Engineering

Hesham A. Rakha, Chair
Ihab E. El-Shawarby
Douglas J. Nelson

June 27th, 2014
Blacksburg, VA

Keywords: Transit Bus Fuel Consumption; Dynamic Bus Scheduling; Transit Bus; Fuel Consumption Modeling; VT-CPFM

Modeling Diesel Bus Fuel Consumption and Dynamically Optimizing Bus Scheduling Efficiency

William Andrew Edwardes

Abstract

There are currently very few models that estimate diesel and hybrid bus fuel consumption levels. Those that are available either require significant dynamometer data gathering to calibrate the model parameters and also produce a bang-bang control system (optimum control entails maximum throttle and braking input). This thesis extends the Virginia Tech Comprehensive Power-Based Fuel Consumption Model (VT-CPFM) to model diesel buses and develops an application for it. A procedure is developed to calibrate the bus parameters using publicly available data from the Altoona Bus Research and Testing Center. In addition, calibration is also made using in-field bus fuel consumption data. The research presented in this thesis calibrates model parameters for a total of 10 standard diesel buses and 3 hybrid buses from Altoona and 10 buses from Blacksburg Transit. In the case of the Altoona data, the VT-CPFM estimated fuel consumption levels on the Orange County bus cycle dynamometer test produce an average error of 4.7%. The estimation error is less than 6% for all but two buses with a maximum error of 10.66% for one hybrid bus. The VT-CPFM is also validated using on-road fuel consumption measurements that are derived by creating drive cycles from acceleration information producing an average estimation error of 22%. These higher errors are attributed to the errors associated with constructing the in-field drive cycles given that they are not available. In the case of the Blacksburg Transit buses, the calibrated parameters produce a low sum of mean squared error, less than 0.002, and a coefficient of determination greater than 0.93. Finally an application of the VT-CPFM is presented in the form of a dynamic bus scheduling algorithm.

Acknowledgements

To my adviser, Dr. Hesham Rakha, thank you for providing me the opportunity to work on a fascinating project while pursing my two graduate degrees. You have been a great mentor helping me to develop my research skills as well helping me start my career.

To my committee member, Dr. Doug Nelson and Dr. Ihab El-Shawarby thank you for providing oversight on this project as a member of my committee.

To Blacksburg Transit, and specifically Tim Witten, Aneil Samuel and Ignacio Guerrero, thank you; Tim for spear heading this somewhat out there project, Aneil for being a reliable technical contact at Blacksburg Transit, and Ignacio for completing the bus calibration data collection.

I'd also like to thank Tran*LIVE* University Transportation Center for partily funding this research, Altoona Bus Research and Testing Center for providing the bus data and Dr. Ahmed Kamal Ali for summarizing the data.

Table of Contents

List of Figures

List of Tables

Chapter 1 Introduction

Public transportation has many potential benefits including fuel saving, reduction of carbon dioxide (CO_2) emissions and congestion reduction. Each household could potentially reduce its carbon footprint by 30% by eliminating one car and taking public transportation [1-1]. However, due to inefficiencies and public perception transit does not always provide these benefits. These inefficiencies include poor reliability, scheduling, stop placement, and bus assignment. This resulted in an average of 9.2 people per bus in 2009, making it the second least energy efficient mode of transportation [1-2].

These issues have not been dealt with partly due to transit agencies having limited and stretched budgets. There has also been limited research on bus fuel consumption modeling and developing tools to enhance the system efficiency, specifically in real-time. To help address these inefficiencies Blacksburg Transit (BT) received a Transit Investment in Greenhouse Gas and Energy Reduction (TIGGER) grant to help improve some of these inefficiencies. BT is the local transit agency in Blacksburg, VA. It started in 1983 with 6 30 ft. buses and now has a fleet of 46 buses ranging from 35 ft. to 60 ft. BT serves over 3.5 million riders per year. It consists of 11 fixed routes and para-transit to assess locations off route. Of its riders 90% are Virginia Tech (VT) students, 5% are VT staff and 5% are Blacksburg citizens. BT is also 97% reliable [1-3].

1.1 Thesis Objectives

The objectives of this thesis are: (1) develop diesel bus fuel consumption models; (2) develop a procedure to calibrate these diesel bus fuel consumption models using publically available data; (3) develop an in-field procedure for calibrating diesel bus fuel consumption models; and (4) outline a potential application of the diesel bus fuel consumption model. In developing the diesel bus fuel consumption model, the Virginia Tech Comprehensive Power Based Fuel Consumption Model (VT-CPFM) was enhanced to reflect diesel bus fuel consumption data. The model was first calibrated using publically available data from the Altoona Bus Research and Testing center. The required changes included altering the mass factor, lowering the lower bound of the second-order power parameter, and using different dynamometer test cycles when using publically available data. Subsequently, the VT-CPFM model was enhanced to reflect diesel bus fuel consumption behavior. This enhancement entailed developing a piecewise function to account for the plateau in fuel consumption levels at higher power demands. Finally, a calibration procedure was developed to calibrate the VT-CPFM to in-field data.

The application of the fuel model developed is intended to enhance transit fleet efficiency by developing a dynamic dispatch decision support solution (3DSS). The 3DSS will alter bus schedules based on real-time demand assessment data from riders with the goal of improving reliability and reducing fuel consumption levels.

1.2 Thesis Layout

This thesis is organized into five chapters, beginning with this introduction as the first chapter. The second chapter is a paper that was accepted for publication in the Transportation Research Record entitled, "Virginia Tech Comprehensive Power-Based Fuel Consumption Model: Modeling Diesel and Hybrid Buses". This paper covers the extension of the VT-CPFM to model diesel buses using publically available data from Altoona. The third chapter is a paper that is currently being drafted and is entitled, "Calibration of the VT-CPFM using Real World Data". This paper enhances the VT-CPFM model and develops a calibration procedure for buses using in-field fuel consumption measurements. The fourth chapter is an outline of a purposed application of the VT-CPFM called the dynamic dispatch support solution (3DSS). The fifth chapter summarizes the conclusions of the thesis and directions for future research.

1.3 References

[1-1] A. P. T. Assoc. (2008). Public Transportation Reduces Greenhouse Gases and Conserves Energy [Online]. Available: http://www.apta.com/resources/reportsandpublications/Documents/greenhouse_brochure.pdf.

[1-2] S. Davis et al., "Transportation Energy Data Book ", Oak Ridge, TN, 2013, vol. 32.

[1-3] Blackburg Transit History and Background [Online]. Available: http://www.blacksburg.gov/Index.aspx?page=1071.

Chapter 2 Virginia Tech Comprehensive Power-Based Fuel Consumption Model: Modeling Diesel and Hybrid Buses

Based on W. Edwardes and H. Rakha, "Virginia Tech Comprehensive Power-Based Fuel Consumption Model: Modeling Diesel and Hybrid Buses," Transportation Research Record: Journal of the Transportation Research Board, 2014

2.1 Abstract

There are currently very few models for estimating diesel and hybrid bus fuel consumption and CO2 emission levels. Those that are available either require significant dynamometer data gathering to calibrate the model parameters and also produce a bang-bang control system (optimum control entails maximum throttle and braking input). This paper extends the Virginia Tech Comprehensive Power-Based Fuel Consumption Model (VT-CPFM) to model diesel and hybrid buses. The calibration of the bus parameters is made using publicly available data from the Altoona Bus Research and Testing Center. The research presented in this paper analyzes a total of 10 standard diesel buses and 3 hybrid buses. The VT-CPFM estimated fuel consumption levels on the Orange County bus cycle dynamometer test with an average error 4.7%. The estimation error was less than 6% for all but two buses with a maximum error of 10.66% for one hybrid bus. The VT-CPFM was also validated using on-road fuel consumption measurements that were derived by creating drive cycles from acceleration information producing an average estimation error of 22%. These higher errors are attributed to the errors associated with constructing the in-field drive cycles given that they were not available.

2.2 Introduction

Public transportation has many potential benefits including fuel saving, reduction of CO_2 emissions, and congestion reduction. Ridership has increased 30% since 1995 [2-1] and bus ridership accounted for over 50% of total public transit ridership in 2012 [2-2]. However, despite the benefits of buses they have some negatives, specifically increased NO_x and $PM_{2.5}$ emissions. Heavy-duty diesel vehicles (HDDV) only account for 7% of vehicle miles traveled (VMT), but they contribute 45% of the total NO_x and 75% of the total $PM_{2.5}$ emissions [2-3]. Despite these facts, very little work has been done in developing fuel consumption models for HDDVs [2-4].

The objective of this study is to extend the Virginia Tech Comprehensive Power-Based Fuel Consumption Model (VT-CPFM) to include diesel buses using data from the Altoona Bus Research and Testing Center. This paper outlines the changes made to the VT-CPFM model to accurately estimate bus fuel consumption. Even though this paper only looks at fuel consumption (FC), it has been shown that greenhouse gases (CO_2, CO, HC, NO_x, $PM_{2.5}$) and FC are correlated to vehicle specific power (VSP) [2-5]. Currently the work only considers CO_2 greenhouse gases given that this data was only available at the time the study was conducted.

2.3 Literature Review

There are currently very few models addressing HDDV fuel consumption and even fewer that can specifically model buses, despite the increased importance of public transportation. The majority of vehicle fuel consumption models are microscopic models based on VSP [2-6]. The models currently capable of modeling HDDV fuel consumption are:

1. The Comprehensive Modal Emissions Model (CMEM)
2. Physical Emission Rate Estimator (PERE)

Since this paper focuses on fuel consumption, and not emissions, only the fuel consumption components of the previous models are covered (although both have an emissions component based on fuel consumption). Also, there are many more models for estimating HDDV emissions; however, many require fuel consumption as an input but have no way to estimate it if the fuel consumption data is unavailable.

2.3.1 The Comprehensive Modal Emissions Model

The Comprehensive Modal Emissions Model (CMEM) consists of three components to derive fuel consumption: power demand, engine speed estimation, and fuel rate model. The model first calculates the power demand and engine speed. These are used to calculate the fuel rate. This model requires a large amount of data that needs to be collected from lab or field testing, such as engine friction and drivetrain and engine efficiency. It also needs the shift schedule and torque curve, which can be obtained from manufacturers (but not always from their website) [2-4]. The CMEM model suffers from two critical problems, namely: (1) the model cannot be calibrated using publically available data but instead requires testing of transit vehicle on a chassis or engine dynamometer, and (2) the model can produce a bang-bang control system. A bang-bang control system is when the optimal suggested control strategy is to accelerate at full throttle or at the maximum acceleration rate to cruise speed and then decelerate using full braking, this has been shown to not fuel-optimal [2-7]. A bang-bang control system occurs when the partial derivative of fuel consumption rate with respect to engine torque, is not a function of torque [2-6].

2.3.2 Physical Emission Rate Estimator

The EPA model MOVES (Motor Vehicle Emissions Simulator) replaced MOBILE6 in 2010 as the U.S.'s emissions estimator. In order to compensate for the lack of HDDV data, the Physical Emission Rate Estimator (PERE) was developed to support MOVES. PERE uses VSP to calculate fuel consumption. However, the power function has been simplified to $VSP = A + Bv + Cv^2$ where A, B and C are coefficients that can be calculated using dynamometer data or estimated based on the vehicle mass and road-load parameters [2-8].

To calculate engine friction and efficiency, a Willans line methodology is used. This requires field testing to collect second-by-second data including engine speed, fuel flow and engine load. This is then used to calculate the fuel rate. Fuel rate (FR) is calculated using $FR = \left(\frac{kNV_d}{2000} + \frac{P}{\eta_i}\right) * \frac{1}{LHV}$ where k is engine friction, N is engine speed, V_d is engine displacement, η_i is engine indicated efficiency and LHV is fuel lower heating value [2-8]. However, estimating fuel consumption using this model results in a bang-bang control system, similar to the CMEM.

VT-CPFM fills a gap in the modeling of fuel consumption by producing a non-bang-bang control system, which does not require extensive testing in the lab or field for calibration purposes [2-6]. This research developed procedures to extend and calibrate this model to diesel and hybrid transit vehicles.

2.4 Virginia Tech Comprehensive Power-Based Fuel Consumption Model

VT-CPFM is a microscopic fuel consumption model based on instantaneous power, the detailed VT-CPFM model can be seen in the original paper by Rakha et al. and a Matlab script is also available [2-6]. The advantage of VT-CPFM compared to other models is other models either require calibration of specific parameters from laboratory or field testing or produce a bang-bang control. However, data collection is not always feasible. Therefore, VT-CPFM uses only publicly available data. It avoids a bang-bang control system since the function for fuel consumption is a second degree polynomial with respect to VSP, therefore the partial derivative with respect to torque is a function of torque [2-6].

For light-duty vehicles (LDV), all required data for a specific vehicle can be found on the manufacturer websites, including the EPA estimated fuel economy. Power is calculated using Equation (2-1).

$$P(t) = \left(\frac{R(t)+1.04ma(t)}{3600\eta_d}\right) * v(t) \tag{2-1}$$

where, $P(t)$ is the power (kW), m is vehicle mass (kg), $a(t)$ is the vehicle acceleration $(\mathrm{m/s^2})$, $v(t)$ is the vehicle speed (km/h), η_d is driveline efficiency, and $R(t)$ is the resistance force (N). The resistance force is calculated using Equation (2-2).

$$R(t) = \frac{\rho}{25.92} C_d C_h A_f v(t)^2 + 9.8066m \frac{C_r}{1000}(c_1 v(t) + c_2) + 9.8066mG(t) \tag{2-2}$$

where ρ is the density of air ($1.2256\ \mathrm{kg/m^3}$ at sea level and 15^{o} C), C_d is the vehicle drag coefficient (unitless), C_h is a correction factor for elevation (which equals $1-0.085H$ where H is elevation (km)), $A_f$is the vehicle frontal area (m^2), $G(t)$ is roadway grade, and $C_r, c_1,$and c_2 are rolling resistance parameters (unitless) [2-6].

Then fuel consumption (FC) (l/s) is calculated using Equations (2-3) through (2-6). The α are parameters whose values are calculated using time, power and fuel consumed from the EPA city and highway test cycles.

$$\mathrm{FC(t)} = \begin{cases} \alpha_0 + \alpha_1 \mathrm{P(t)} + \alpha_2 \mathrm{P(t)}^2 & \forall \mathrm{P(t)} \geq 0 \\ \alpha_0 & \forall \mathrm{P(t)} < 0 \end{cases} \tag{2-3}$$

$$\alpha_0 = \max\left(\frac{P_{mfo}\omega_{idle}d}{22164QN}, \frac{\left(F_{city} - F_{hwy}\frac{P_{city}}{P_{hwy}}\right) - \varepsilon\left(P_{city}^2 - P_{hwy}^2\frac{P_{city}}{P_{hwy}}\right)}{T_{city} - T_{hwy}\frac{P_{city}}{P_{hwy}}}\right) \tag{2-4}$$

$$\alpha_2 = \frac{\left(F_{city} - F_{hwy}\frac{P_{city}}{P_{hwy}}\right) - \left(T_{city} - T_{hwy}\frac{P_{city}}{P_{hwy}}\right)\alpha_0}{P_{city}^2 - P_{hwy}^2\frac{P_{city}}{P_{hwy}}} \geq \varepsilon \tag{2-5}$$

$$\alpha_1 = \frac{F_{hwy} - T_{hwy}\alpha_0 - P_{hwy}^2\alpha_2}{P_{hwy}} \tag{2-6}$$

Here P_{mfo} is the idling fuel mean pressure (Pa), ω_{idle} is the idling engine speed (rpm), d is the engine displacement (liters), Q is the fuel lower heating value (J/kg), N is the number of strokes (2 or 4), F_{city} and F_{hwy} are the fuel consumed for EPA city and highway cycles respectively (liters), P_{city} and P_{hwy} are the sum of the power used for each cycle calculated using

Equation (2-1), P_{city}^2 and P_{hwy}^2 are the sum of the power squares and T_{city} and T_{hwy} are the duration of the cycle (seconds). The ε term is used to ensure that $\alpha_2 > 0$, for LDV a value of 1E-06 is used [2-6]. A detailed list of required variables and potential sources for the VT-CPFM can be found in Table 2-1 (Note, other sources may exist for finding parameters and listed sources are for buses).

Unfortunately, at the moment, the EPA does not measure fuel consumption for HDDV. As a result the current VT-CPFM needed to be modified to use data collected by Altoona. The remainder of this paper covers the data used, the adjustments made to the model, and validation.

2.5 Altoona Data

Altoona Bus Research and Testing Center is located in Altoona, PA. Their mission "is to provide the transit community with research, testing, and education resources to enhance the quality, safety, and efficiency of transit vehicles, operations, and components." [2-9]. Altoona began testing in 1990 following the Surface Transportation and Uniform Relocation Assistance Act (STURAA) of 1987, which mandated any bus purchased with federal funds be tested by an appropriate testing center. As of the writing of this paper Altoona has tested 404 buses and identified over 8,000 malfunctions [2-9].

Bus tests at Altoona consist of a bus check-in and nine tests: safety, structural integrity and durability, reliability, performance, maintainability, noise, fuel economy, brake and emissions. However, emissions tests were not added until 2010. For the purpose of this study, only the bus check-in, performance, fuel economy and emissions tests were used. The bus check-in includes measurements as well, noting the specifications of the bus, such as the engine, transmissions, tires, etc. For this research effort bus weight, number of seats, width, height, engine and any other unique items (such as hybrid components) were used [2-9].

Table 2-1: Required Parameters for VT-CPFM

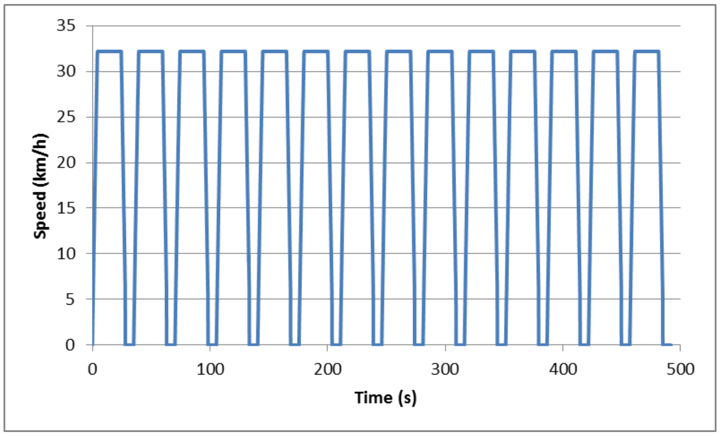
Parameter	Description	Potential Source
m	Vehicle mass	Vehicle manufacture's website
η_d	Driveline efficiency	EPA 2012 [2-13]
ρ	Air density	Calculated
C_d	Vehicle drag coefficient	[2-8, 2-13, 2-14]
C_h	Elevation correction factor	Calculated
H	Elevation	Google
A_f	Vehicle frontal area	Vehicle manufacture's website
C_r	Surface rolling resistance	Rakha [2-14]
c_1	Tire rolling resistance	Rakha [2-14]
c_2		
d	Engine displacement	Engine manufacture's website
Q	Fuel lower heating value	Rakha [2-6]
N	Number of strokes	Engine manufacture's website
P_{mfo}	Idling mean pressure	Rakha [2-6]
ω_{idle}	Idling engine speed	Altoona [2-9]
F_{cycle}	Fuel consumed during dynamometer cycle	Altoona [2-9]
P_{cycle}	Power used during dynamometer cycle	SAE [2-11]
P^2_{cycle}	Sum of $P(t)^2$ during dynamometer cycle	SAE [2-11]
T_{cycle}	Time of dynamometer cycle	SAE [2-11]
ε	Constraining term	Rakha [2-6] and this paper

2.5.1 Performance Test

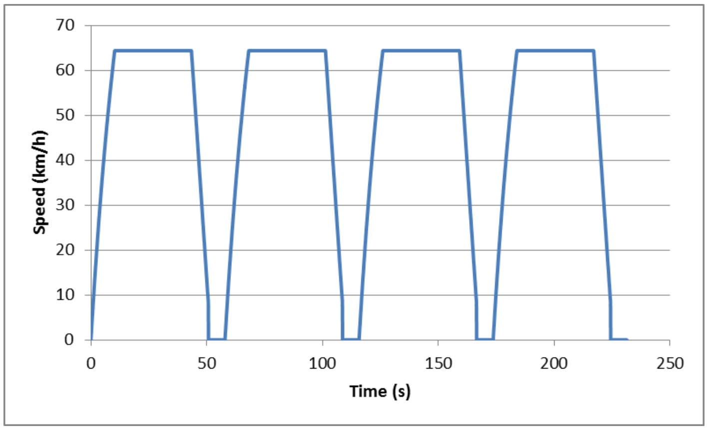
The performance test is designed to assess gradeability and brake performance. During the gradeability portion, acceleration and top speed are assessed. Buses are accelerated at full throttle to 50 mph or maximum velocity, on a smooth level test track. This is done at seated load weight. A non-contacting speed sensor is used to measure speed, and time intervals are recorded every 10 mph [2-9].

2.5.2 Fuel Economy Test

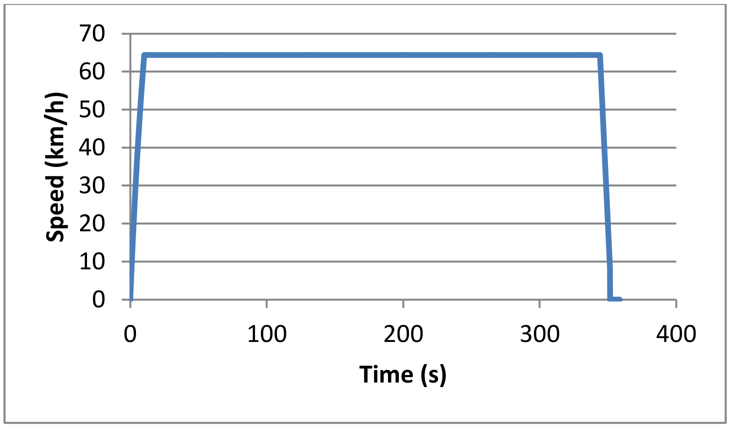
The fuel economy test is conducted on Altoona's outdoor test track using a procedure based on SAE 1376 July 82 with some slight modifications. A warm-up for one hour is done prior to testing. Buses are tested with the air conditioning off, evaporator or ventilation fan on, seated load weight, lights on, heater pump motor off, defroster off, windows and doors closed. One Transit Coach Operating Duty Cycle (ADB) consists of 3 central business district (CBD) phases, 2 arterial phases, and 1 commuter phase. The test order is CBD, arterial, CBD, arterial, CBD, then commuter and an idle fuel consumption measurement at the beginning and end. Time vs. speed plots for each phase can be seen in Figure 2-1. The test is complete after a minimum of two ABD tests in each direction (4 total), or until the fuel consumed is within ±4% of the mean. Acceleration is done at full throttle to improve repeatability. The fuel consumption in MPG is calculated from miles traveled, pounds of fuel consumed, standard density of water at 60^{o}F, standard volumetric heating value of standard fuel at 60^{o}F, and specific gravity of test fuel [2-9].



(a) CBD cycle



(b) Arterial Cycle



(c) Commuter Cycle

Figure 2-1: Road Based Fuel Consumption test cycles

2.5.3 Emissions Test

The emissions test is done in accordance with EPA's CFR40, Part 1065 and SAE J2711. The testing facility consists of a Schenk Pegasus 300 HP large-roll chassis dynamometer, a Horiba CVS dilution tunnel, a Horiba Mexa 7400 gas analyzer, and a Horiba HF47. PM is measured gravimetrically using a 47mm Teflon filter. The test includes three different cycles: Manhattan (Man) cycle (Figure 2-2), the EPA heavy-duty Urban Dynamometer Driving Cycle (UDDS) (Figure 2-3), and Orange County bus (OC) cycle (Figure 2-4). Each cycle is run twice and the results averaged. Prior to testing, a coast-down test is done in accordance with SAE J1263 to calculate road-load parameters. Before testing a 20-minute warm-up is complete. During the test runs buses have air conditioning off, evaporator or ventilation fan on, half seated load weight, lights on, heater pump motor off, defroster off, and windows and doors closed [2-9].

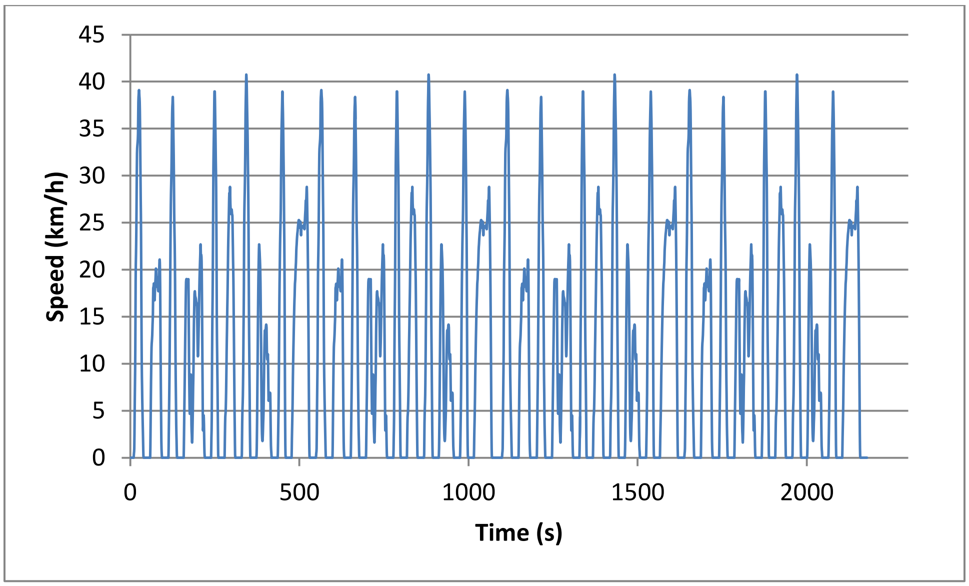


Figure 2-2: Manhattan Dynamometer Drive cycle

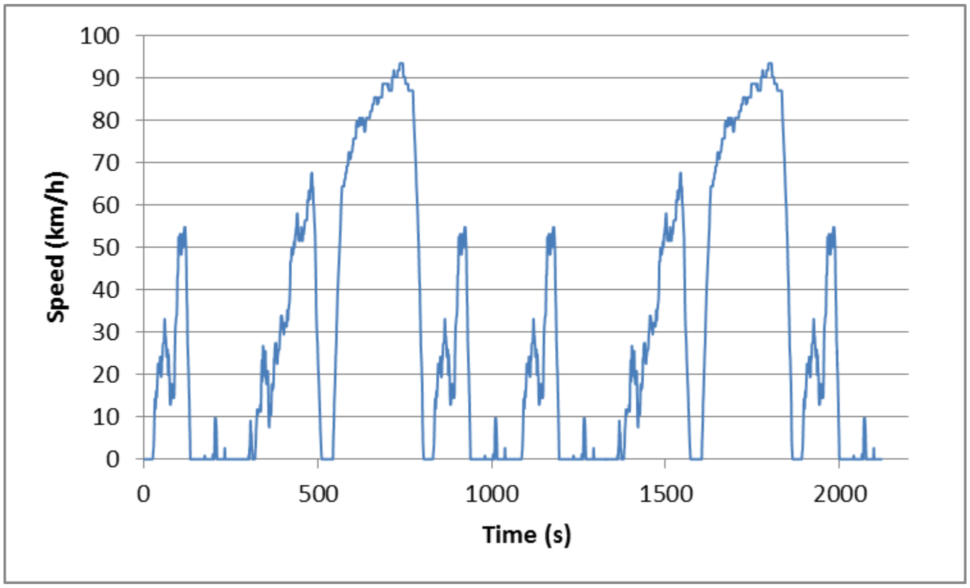


Figure 2-3: HD-UDDS Dynamometer Drive cycle

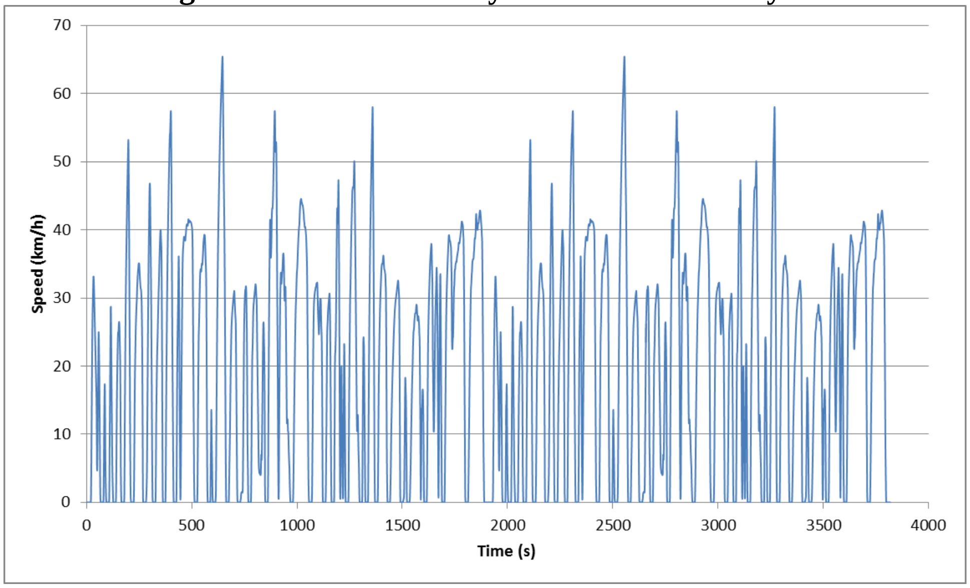


Figure 2-4: Orange County Bus Dynamometer Drive cycle

2.6 Enhancements to VT-CPFM

The basic structure shown in Section 2.3 is used for buses with a few changes. In Equation (2-1), the 1.04 is frequently written as $1 + \lambda$ where the λ term is a mass factor accounting for rotational masses, 0.04 is used for LDVs, since HDDV are larger and have more rotational mass, a value of 0.1 is used for HDV [2-10].

In Equations (2-4) and (2-5), ε is changed to 1E-08 from 1E-06, since 1E-06 was used to ensure that LDV have an optimum fuel economy cruising speed between 60 and 80 km/h [2-6].

The value was decreased to 1E-08 to account for the lower optimum fuel economy cruising speed of buses.

Due to the lack of EPA data for buses, dynamometer testing from Altoona was used. The UDDS test cycle was used for the EPA highway cycle and the Manhattan test cycle was used for the city cycle. The final OC cycle was used for validation purposes. Details for each cycle can be seen in Table 2-2.

Table 2-2: Details of dynamometer bus testing cycles (Manhatten, UDDS, Orange County). Surface Vehicle Recommended Practice, SAE J2711 Sept. 2002, Used under fair use 2014

	Avg. Speed (km/h)	Max Speed (km/h)	Max Accel. (m/s^2)	Max Decel. (m/s^2)	Total Time (s)	Idle Time (s)	Total Dist. (km)	No. of Idle Periods
Manhattan	10.99	40.71	1.78	-2.56	1089	393	3.32	20
UDDS	30.31	93.32	1.87	-2.02	1060	353	8.93	13
Orange County	19.84	65.37	1.81	-2.29	1909	406	10.52	30

Since idle fuel consumption is measured during the fuel consumption test at Altoona, the results from the test are used in place of $\frac{P_{mfo}\omega_{idle}d}{22164QN}$, unless unavailable, in which case the $\frac{P_{mfo}\omega_{idle}d}{22164QN}$ is used. The idle engine speed can be found in the Altoona noise test.

2.7 Methodology

2.7.1 Test Data

Altoona has tested a total of 19 buses since they started including the emissions test in March 2010. Of these buses, six buses (1010, 1012, 1104, 1108, 1116, and 1211) were removed from analysis for the following reasons:

- Buses 1012 and 1010 did not have acceleration profiles.
- Bus 1104 was removed because “a large concretion of solidified urea (about the size of a baseball) was discovered in the diesel exhaust fluid dosing valve section of the decomposition reactor, located just upstream from the SCR catalyst.” [2-12].
- Buses 1108 and 1211 were removed because their max speed was less than 50 mph (80.5 km/h) and thus they would not be able to drive the drive cycles.
- Bus 1116 did not have an emissions test.

This resulted in 13 buses with adequate data, as summarized in Table 2-3. Table 2-3 contains the make, model, type (Minibus, City, Trolley, School), if it contains hybrid components, C_d, curb weight (CW), seated load weight (SLW), A_f, and length (m) [2-9].

Table 2-3: Specifications of buses used for calibration from Altoona

Manufactor	Model	Type	Hybrid	C_d	CW (kg)	SLW (kg)	A_f (m^2)	Length (m)
Goshen Coach Inc. A Thor Company	Ford F550	Mini	No	0.60	6100.92	7393.68	6.13	10.26
Supreme Corp. (Startrans Bus)	President/Trolley	Trolley	No	0.80	8505.00	10886.40	7.59	10.68
Daimler Buses North America, LTD	Orion VII EPA10	City	Yes	0.80	13485.53	16411.25	7.38	12.55
North American Bus Industries, Inc.	416.15	City	No	0.80	13263.26	16188.98	6.90	12.45
New Flyer of America	XDE40	City	Yes	0.80	12641.83	15499.51	6.99	12.48
Independent Protection Company Inc.	Odyssey XL	Mini	No	0.60	6146.28	7915.32	6.71	9.87
Glaval Bus, A Div of Forest River, Inc.	Legacy	Mini	No	0.60	7629.55	10691.35	6.77	12.07
Elkhart Coach, A Div of Forest River Inc.	ECG Series	Mini	No	0.60	4554.14	5710.82	5.88	7.92
IC Bus/Champion Bus, Inc./ General Coach America, Inc.	AC Series/Challenger/ Defender/American Coach	Mini	No	0.60	6831.22	8804.38	6.23	10.25
Daimler Buses North America, LTD	Orion VII EPA10 Diesel	City	No	0.80	13295.02	16220.74	7.10	12.55
Gillig, LLC	40' Low Board BAE Hybrid	City	Yes	0.80	13793.98	16515.58	7.44	12.74
Blue Bird Body Co.	All American RE	School	No	0.60	9221.69	11330.93	6.36	10.95
Blue Bird Body Co.	All American FE	School	No	0.60	8563.97	10809.29	6.34	11.08

2.7.2 Variables

C_d values in the Table 2-3 were selected on the basis of values presented in the literature. For city buses and trolley, a value of 0.8 was used, and for minibuses and school buses a value of 0.6 was used [1-3]. Table 2-4 contains a list of other variables and values used in computing α_0, α_1, and α_2.

Table 2-4: Dynamometer test parameters for all buses.

Variable	Value	Source
η_d	0.95	EPA 2012 [2-15]
C_r	1.25	Rakha [2-16]
c_1	0.0328	Rakha [2-16]
c_2	4.575	Rakha [2-16]
H	0.38 km	Google

These values were selected on the basis of values presented in the literature. The value of C_r was chosen for good asphalt because the SAE coastdown procedure are used to calibrate the road loads for the dynamometer, and coastdown testing are to be performed on a dry, clean, smooth road where the road is concrete or rolled asphalt in good condition [2-17]. *H* is the elevation at Altoona, PA according to Google.

2.7.3 Validation

In order to validate the model, two approaches were used. First, the model was used to predict the overall fuel consumption of the unused dynamometer cycle, OC. Second, the outdoor fuel consumption tests conducted at Altoona were recreated. This was done using the acceleration profile to estimate vehicle acceleration to the maximum speed for the cycle. Then the vehicle remained at the maximum velocity until it reached the deceleration distance. Deceleration distance is defined as $\frac{\text{MaxV}^2}{2*a_d}$ where MaxV is the maximum velocity (km/h) and a_d is the deceleration rate (-2.13 m/s^2). Then, the vehicle would idle for 7 seconds before accelerating again. This sequence was repeated until the required number of stops was complete. The overall duration of the simulation was compared with the average actual duration to confirm that the estimated drive cycle was reasonable. Clearly by having to re-construct the drive cycles errors are introduced into the analysis and thus the results for the field testing should be analyzed with caution.

2.8 Results

Table 2-5 summarizes the results of the study described conducted in the paper.

Table 2-5: Calibration Results and Error of Model Compared with OC, CBD, Arterial and Commuter Cycle

BusNo	α_0	α_1	α_2	Fuel-Optimal Speed at SLW (km/h)	OC Error	CBD Error	Arterial Error	Commuter Error
1004	9.50E-04	9.34E-05	1.00E-08	43	-6.46%	-8.66%	-9.81%	6.81%
1006	1.33E-03	6.33E-05	1.00E-08	47	-6.24%	-20.42%	-17.72%	-7.03%
1007	8.31E-04	1.90E-05	5.34E-07	38	-2.34%	-0.44%	25.25%	-20.53%
1011	1.68E-03	5.49E-05	1.00E-08	53	-4.43%	-8.17%	-11.73%	-7.85%
1015	7.28E-04	5.52E-05	1.00E-08	39	1.13%	-4.87%	-8.21%	-21.92%
1102	8.40E-04	4.96E-05	1.00E-08	50	-3.54%	-49.43%	-58.02%	-46.23%
1110	1.18E-03	4.20E-05	1.00E-08	58	-9.80%	-47.13%	-51.92%	-27.44%
1111	7.21E-04	6.05E-05	1.00E-08	47	-4.17%	-11.22%	-14.65%	-8.27%
1113	8.00E-04	6.81E-05	1.00E-08	44	-0.56%	-42.86%	-38.37%	-17.22%
1202	1.16E-03	5.02E-05	7.52E-08	46	-5.06%	-21.89%	-14.26%	-18.12%
1206	9.04E-04	3.88E-05	1.79E-07	42	-10.66%	-11.35%	-19.64%	-57.43%
1217	1.21E-03	6.57E-05	1.00E-08	51	1.47%	-22.70%	-20.51%	-3.56%
1218	1.14E-03	5.42E-05	1.00E-08	54	-5.49%	-30.95%	-36.55%	-26.43%
Absolute Average	1.04E-03	5.50E-05	6.84E-08	47	4.7%	21.5%	25.1%	20.7%

2.8.1 Orange County Fuel Consumption

The results for the Orange County cycle are promising, with an average error of 4.7% and all errors being less than 10% except for bus 1206, which produced an error of 10.66%. Bus 1206 is a parallel drive hybrid vehicle with a BAE HybriDrive propulsion system. VT-CPFM is not specifically designed for hybrid vehicles, so this error appears to be acceptable. The parameters used for the Orange County calibration are the same as in Table 2-5, since it was done on the dynamometer the same way as UDDS and Manhattan.

2.8.2 Altoona Test Track Fuel Consumption

The error for the Altoona test tracks is much higher than the average estimated error of the Orange County cycle test with an average estimation error of 22%; however this is to be expected, since not only is the fuel consumption being estimated but also the second-by-second drive cycle is being created using course acceleration information. Some differences between this validation and the dynamometer are a value of 1.75 was used for C_r to represent fair asphalt [2-16] and the test was conducted at SLW instead of half SLW.

The results show that even though VT-CPFM produced high estimation errors it does a good job at estimating the trend of fuel consumption across the three cycles. Specifically, the VT-CPFM in general appears to overestimate the fuel consumption. A graph comparing the estimated vs. actual can be seen in Figure 2-5.

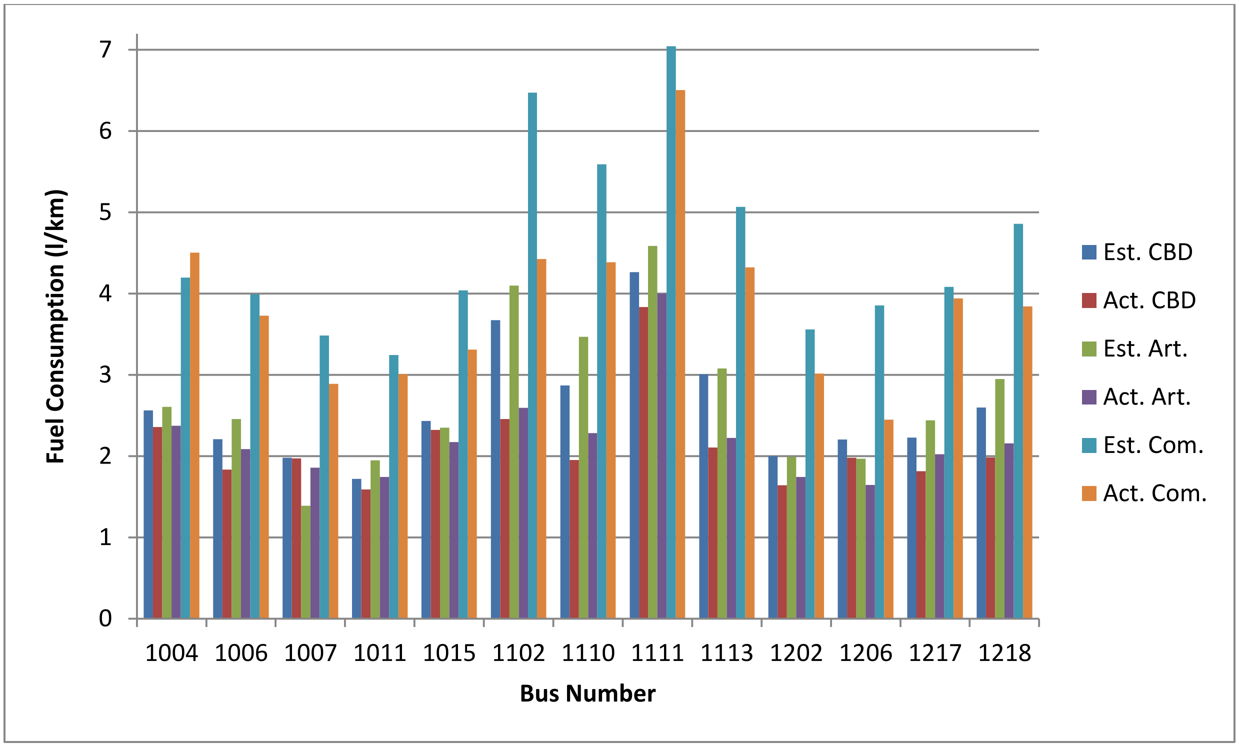


Figure 2-5: Actual (Act.) fuel consumption compared to estimated (Est.) fuel consumption for outdoor track.

2.8.3 Optimum Speed

The optimum speeds were also calculated at SLW; they range from 38 km/h to 58 km/h (23.75 mph to 36.25 mph). Figure 2-6 presents an example illustration of the cruising fuel consumption curve as a function of the distance traveled for bus 1111; all buses produce a similar convex shape.

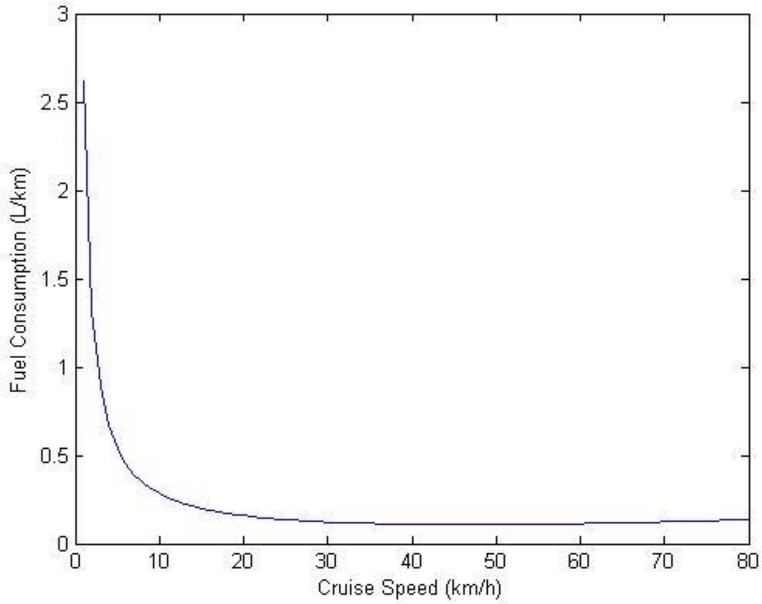


Figure 2-6: Fuel consumption (L/km) compared to cruising speed (km/h) for bus 1111.

2.9 Conclusion

The research presented in this paper extends the Virginia Tech Power-Based Comprehensive Fuel consumption Model (VT-CPFM) to model diesel and hybrid buses. The model does not produce a bang-bang control system and can be calibrated using publicly available data from the Altoona Bus Research and Testing Center. The model has been shown to be consistent with dynamometer and on-road testing with an average error of 4.7% for the dynamometer testing and 22% for the on-road testing.

2.10 References

[2-1] A.P.T. Assoc. (2008). Public Transportation Reduces Greenhouse Gases and Conserves Energy [Online]. Available: http://www.apta.com/resources/reportsandpublications/Documents/greenhouse_brochure.pdf.

[2-2] A. P. T. Assoc. Ridership Report [Online]. Available: http://www.apta.com/resources/statistics/Pages/ridershipreport.aspx, 2012.

[2-3] S. Yoon, "A new heavy-duty vehicle visual classification and activity estimation method for regional mobile source emissions modeling," Ph.D. dissertation, Dept. Civil and Environmental Eng., Georgia Institute of Technology, Atlanta, GA, 2005.

[2-4] M. Barth et al., "Modal emissions model for heavy-duty diesel vehicles" Transportation Research Record, vol. 1880, 10-20, 2004.

[2-5] A. Wang et al., "On-road pollutant emission and fuel consumption characteristics of buses in Beijing" Journal of Environmental Sciences, vol. 23, 419-426, 2011.

[2-6] H.Rakha et al., "Virginia Tech Comprehensive Power-Based Fuel Consumption Model: Model development and testing" Transportation Research Part D: Transport and Environment, vol. 16, 492-503, 2011.

[2-7] B. Saerens et al., "Assessment of Alternative Polynomial Fuel Consumption Models for Use in Intelligent Transportation Systems Applications" Journal of Intelligent Transportation Systems, 2012.

[2-8] R. Giannelli et al., "Heavy-duty diesel vehicle fuel consumption modeling based on road load and power train parameters," in SAE Technical Papers: Commercial Vehicle Engineering Congress and Exhibition, 2005.

[2-9] The Altoona Bus Research and Testing Center [Online]. Available: http://www.altoonabustest.org.

[2-10] C. Feng et al., "Transit bus load-based modal emission rate model development," U.S. E.P. A., Washington DC., Rep. EPA/600/R-07/106 July 2007.

[2-11] Surface Vehicle Recommended Practice, SAE J2711 Sept. 2002.

[2-12] STURAA Test 10 Year 350,000 Mile Bus from Supreme Model Startrans PS2 President [Online]. Available: http://146.186.225.57/home2011.

[2-13] C. Bell, "An Investigation of Road Load Effects on Fuel Economy and NOx Emissions of Hybrid and Conventional Transit Buses," M.S. thesis, Mechanical and Aerospace Eng., West Virginia University, Morgantown, WV, 2011.

[2-14] M. Thomas et al., "Aerodynamic Effects of Different Ventilation Methods on Buses" in Fourth International Symposium on Computational Wind Energy, 2006.

[2-15] U.S.E.P.A. "Development of Emission Rates for Heavy-Duty Vehicles in the Motor Vehicle Emissions Simulator" 2012.

[2-16] H. Rakha et al., "Vehicle Dynamics Model for Predicting Maximum Truck Acceleration Levels," Journal of Transportation Engineering, vol. 127, 418-425, 2001.

[2-17] Road Load Measurement and Dynamometer Simulation Using Coastdown Techniques SAE J1263 2009.

Chapter 3 Calibration and Enhancement of the VT-CPFM using Real World Data

Based on W. Edwardes and H. Rakha, "Virginia Tech Comprehensive Power-Based Fuel Consumption Model: Calibrating and Modeling Diesel Buses" Submitted to the Transportation Research Board Annual Meeting, 2015.

3.1 Abstract

There are currently very few models for estimating diesel and hybrid bus fuel consumption and CO_2 emission levels. Those that are available either require significant dynamometer data to calibrate the model parameters and also produce a bang-bang control system (optimum control entails maximum throttle and braking input). The only diesel fuel consumption model that does not suffer from these deficiencies is the Virginia Tech Comprehensive Power-Based Fuel Consumption Model (VT-CPFM). The model can be calibrated using publicly available data from the Altoona Bus Research and Testing Center. However, since each bus is built and tuned for the specific transit agency each bus is slightly different. Consequently, the research presented in this paper enhances the VT-CPFM model for the modeling of diesel buses and develops a basic procedure for calibrating bus fuel consumption models using in-field data. All models produce a good fit to the in-field data with a coefficient of determination (R^2) greater than or equal to 0.937 and the sum of mean squared error for each quarter of a second is very low, less than 0.002.

3.2 Introduction

Edwardes et al. showed that the VT-CPFM can be calibrated to specific buses using publically available data from Altoona [3-1], however, there are some advantages to calibrating the VT-CPFM to specific buses. One of the main advantages of calibrating is that unlike light duty vehicles (LDVs), buses are custom built for each agency. For example, Altoona tested the New Flyer D40LF multiple times and BT purchased a set of New Flyer D40LFs in 2007, Table 3-1 shows the similarities and differences between the curb weight, gross vehicle weight, tire manufacture and type, engine manufacturer and type, and transmission manufacturer and type. Although the differences in specifications may appear to be minor additional modifications to the engine control module (ECM) are also implemented. These changes can be made by the engine manufacture, bus manufacture or the transit agency.

Table 3-1: Comparison of Blacksburg Transit New Flyer D40LF and Altoona Tested D40LF

Specification	Blacksburg Transit	Altoona
Curb Weight	27640	27120
Gross Vehicle Weight	39230	37620
Tire Manufacture	Michelin	Goodyear Metro Miler
Type	XZU-2	B305
Engine Manufacture	Cummins	Cummins
Engine Model	ISL-07	ISL 280
Transmission Manufacture	Allison	Allison
Transmission Model	B400 R5	B400 R

3.3 Literature Review

There are currently very few models addressing HDDV fuel consumption levels and even fewer that can specifically model buses, despite the increased importance of public transportation. The majority of vehicle fuel consumption models are microscopic models based on Vehicle Specific Power (VSP) [3-2]. The models currently capable of modeling HDDV fuel consumption are:

1. The Comprehensive Modal Emissions Model (CMEM)
2. Physical Emission Rate Estimator (PERE)
3. VSP Binning by Frey, et al.
4. Virginia Tech Comprehensive Power-Based Fuel Consumption Model (VT-CPFM)

Since this research focuses on fuel consumption, and not emissions, only the fuel consumption components of the previous models are covered. Also, there are many more models for estimating HDDV emissions; however, many require fuel consumption as an input but have no way to estimate it if the fuel consumption data is unavailable.

3.3.1 The Comprehensive Modal Emissions Model

The Comprehensive Modal Emissions Model (CMEM) consists of three components to derive fuel consumption levels: power demand, engine speed estimation, and fuel rate model. The model first calculates the power demand and engine speed. These are used to calculate the fuel rate. This model requires a large amount of data that needs to be collected from lab or field testing, such as engine friction and drivetrain and engine efficiency. It also needs the shift schedule and torque curve, which can be obtained from manufacturers (but not always from their website) [3-3]. The CMEM model suffers from two critical problems, namely: (1) the model cannot be calibrated using publically available data but instead requires testing of transit vehicle on a chassis or engine dynamometer, and (2) the model can produce a bang-bang control system. A bang-bang control system is when the optimal control strategy is to accelerate at full throttle to cruise speed and then decelerate using full braking, this has been shown to not fuel-optimal [3-4]. A bang-bang control system occurs when the partial derivative of fuel consumption rate with respect to engine torque, is not a function of torque [3-2].

3.3.2 Physical Emission Rate Estimator

The EPA model MOVES (Motor Vehicle Emissions Simulator) replaced MOBILE6 in 2010 as the U.S.'s emissions estimator. In order to compensate for the lack of HDDV data, the Physical Emission Rate Estimator (PERE) was developed to support MOVES. PERE uses VSP to calculate fuel consumption. However, the power function has been simplified to $VSP = A + Bv + Cv^2$ where A, B and C are coefficients that can be calculated using dynamometer data or estimated based on the vehicle mass and road-load parameters [3-5].

To calculate engine friction and efficiency, a Willans line methodology, first developed by An and Ross [3-6], is used. This requires field testing to collect second-by-second data including engine speed, fuel flow and engine load. This is then used to calculate the fuel rate. Fuel rate (FR) is calculated using $FR = \left(\frac{kNV_d}{2000} + \frac{P}{\eta_i}\right) * \frac{1}{LHV}$ where k is engine friction, N is engine speed, V_d is engine displacement, η_i is the engine efficiency and LHV is fuel lower heating value [3-5]. However, estimating fuel consumption using this model results in a bang-bang control system, similar to the CMEM.

3.3.3 VSP Binning

Frey et al. developed an approach similar to PERE specifically for buses using data from Ann Arbor Transit Authority (AATA) and the city of Porto, Portugal. The model grouped VSPs into bins and a fuel rate was estimated for each bin based on the averages from real-world data. The model has an R^2 value of 0.70 for AATA data and of 0.90 for Porto data. However, the model is linear therefore it produces the same bang-bang control system as the CMEM and PERE models.

It is worth noting that Frey, et al. did notice that at a VSP around 120 kW the "*fuel consumption rate dampen considerably*" [3-7], however, they gave no attempt at explaining why.

3.3.4 Virginia Tech Power-based Fuel Consumption Model

VT-CPFM is a microscopic fuel consumption model based on instantaneous power, the detailed VT-CPFM model can be seen in the original paper by Rakha, et al. [3-2] and it was enhanced to include heavy duty diesel vehicles (HDDV) by Edwardes et al. [3-1]. The advantage of VT-CPFM compared to other models is that other models produce a bang-bang control. The VT-CPFM however, avoids a bang-bang control system since the function for fuel consumption is a second degree polynomial with respect to VSP, therefore the partial derivative with respect to torque is a function of torque [3-2].

All required data for a specific vehicle can be found on the Altoona Bus Research and Testing Center website. Power is calculated using Equation (3-1).

$$P(t) = \left(\frac{R(t)+1.1ma(t)}{3600\eta_d}\right) * v(t) \tag{3-1}$$

where, $P(t)$ is the power (kW), m is vehicle mass (kg), $a(t)$ is the vehicle acceleration $(\mathrm{m/s^2})$, $v(t)$ is the vehicle speed (km/h), η_d is driveline efficiency, and $R(t)$ is the resistance force (N). The resistance force is calculated using Equation (3-2).

$$R(t) = \frac{\rho}{25.92} C_d C_h A_f v(t)^2 + 9.8066m\frac{C_r}{1000}(c_1 v(t) + c_2) + 9.8066mG(t) \tag{3-2}$$

where ρ is the density of air (1.2256 $\mathrm{kg/m^3}$ at sea level and 15° C), C_d is the vehicle drag coefficient (unitless), C_h is a correction factor for elevation (which equals $1 - 0.085H$ where H is elevation (km)), A_f is the vehicle frontal area (m^2), $G(t)$ is roadway grade, and $C_r, c_1,$ and c_2 are rolling resistance parameters (unitless) [3-2].

Then fuel consumption (FC) (l/s) is calculated using Equations (3-3) through (3-6). The α are parameters whose values are calculated using time, power and fuel consumed from the EPA city and highway test cycles.

$$\mathrm{FC(t)} = \begin{cases} \alpha_0 + \alpha_1 \mathrm{P(t)} + \alpha_2 \mathrm{P(t)}^2 & \forall \mathrm{P(t)} \geq 0 \\ \alpha_0 & \forall \mathrm{P(t)} < 0 \end{cases} \tag{3-3}$$

$$\alpha_0 = \max\left(\frac{P_{mfo}\omega_{idle}d}{22164QN}, \frac{\left(F_{city} - F_{hwy}\frac{P_{city}}{P_{hwy}}\right) - \varepsilon\left(P_{city}^2 - P_{hwy}^2\frac{P_{city}}{P_{hwy}}\right)}{T_{city} - T_{hwy}\frac{P_{city}}{P_{hwy}}}\right) \tag{3-4}$$

$$\alpha_2 = \frac{\left(F_{city} - F_{hwy}\frac{P_{city}}{P_{hwy}}\right) - \left(T_{city} - T_{hwy}\frac{P_{city}}{P_{hwy}}\right)\alpha_0}{P_{city}^2 - P_{hwy}^2\frac{P_{city}}{P_{hwy}}} \geq \varepsilon \quad (3\text{-}5)$$

$$\alpha_1 = \frac{F_{hwy} - T_{hwy}\alpha_0 - P_{hwy}^2\alpha_2}{P_{hwy}} \quad (3\text{-}6)$$

where P_{mfo} is the idling fuel mean pressure (Pa), ω_{idle} is the idling engine speed (rpm), d is the engine displacement (liters), Q is the fuel lower heating value (J/kg), N is the number of strokes (2 or 4), F_{city} and F_{hwy} are the fuel consumed for Manhattan and HD-UDDS cycles respectively (liters), P_{city} and P_{hwy} are the sum of the power used for each cycle calculated using Equation (2-1), P_{city}^2 and P_{hwy}^2 are the sum of the squared power and T_{city} and T_{hwy} are the duration of the cycle (seconds). The ε term of 1E-08 is used to ensure that $\alpha_2 > 0$. A detailed list of required variables and potential sources for the VT-CPFM can be found in Table 3-2 (Note, other sources may exist for finding parameters and listed sources are for buses).

Table 3-2: Required Parameters for VT-CPFM

Parameter	Description	Potential Source
m	Vehicle mass	Vehicle manufacture's website
η_d	Driveline efficiency	EPA 2012 [3-8]
ρ	Air density	Calculated
C_d	Vehicle drag coefficient	[3-4, 3-5, 3-6]
C_h	Elevation correction factor	Calculated
H	Elevation	Google
A_f	Vehicle frontal area	Vehicle manufacture's website
C_r	Surface rolling resistance	Rakha [3-9]
c_1	Tire rolling resistance	Rakha [3-9]
c_2		
d	Engine displacement	Engine manufacture's website
Q	Fuel lower heating value	Rakha [3-2]
N	Number of strokes	Engine manufacture's website
P_{mfo}	Idling mean pressure	Rakha [3-2]
ω_{idle}	Idling engine speed	Transit Agency (BT)
F_{cycle}	Fuel consumed during dynamometer cycle	Transit Agency (BT)
P_{cycle}	Power used during dynamometer cycle	SAE [3-10]
P^2_{cycle}	Sum of $P(t)^2$ during dynamometer cycle	SAE [3-10]
T_{cycle}	Time of dynamometer cycle	SAE [3-10]
ε	Constraining term	Rakha [3-2] and Edwardes [3-1]

3.4 Calibration

This section describes the procedures that were developed for the calibration of the VT-CPFM model using in-field data.

3.4.1 Data Collection

In order to collect bus fuel consumption and engine data, a calibration procedure was developed using in-field driving. For the data collection a DashDAQ-XL was used to record data from the electronic control module (ECM) via the control area network (CAN) bus. The calibration was completed in Blacksburg, VA on days with dry roads and good weather (minimal wind). The calibration consisted of three components completed in sequential order.

1. Section A1: A flat section of road, Commerce Dr., was used. Drivers would accelerate at full throttle to 25 mph (40.2 km/h) then decelerate without braking, turn around a col-de-sac and accelerate to 25 mph again. At the beginning and end the driver would idle for one minute to collect idling data. This sequence was repeated three times.
2. Section B: A route around Blacksburg including Route 460, to capture high speeds (65 mph and 55 mph speed limit), and a signalized arterial street (Main Street) was driven. Main St. is a signalized roadway with a speed limit of 35 mph and 25 mph on some sections of the roadway.
3. Section A2: Same as Section A1.

Section A was used to create a repeatable test and focused on the speeds that buses typically travel on. The procedure was performed twice (at the beginning and end of the test) to warm up the bus, compare warmed up and cold start fuel consumption levels, and collect idling data. Figure 3-3 shows the typical drive profile during testing for Section A1 and A2. Section B was used to capture real world driving conditions, hills and stops, as well as high speeds (up to 105 km/h). Figure 3-4 shows a typical drive profile for Section B. The full test procedure is shown below and a map of the routes can be seen in Figure 3-1 and Figure 3-2.

Test Procedure

Section A: Commerce St.

<u>Lap 1:</u>

1) Drive down Commerce Street, turn right on partnership and **Stop** when bus is straight. This is point A in Figure 1. Perform the following
   - Put bus in **high idle** (put on parking brake, put transmission in neutral)
   - **Record time of arrival –** On Calibration Form in Start Time Run 1:
   - **Wait approximately 1 minute**

2) Accelerate at max throttle to **25 mph**, let off gas and decelerate using only the retarder.
3) Turn around at cul-de-sac, accelerate at max throttle to **25 mph**, decelerate using only the retarder. At the end of the cul-de-sac you should be able to coast through the turn at around 6mph, **do not stop**. Use the gas petal if needed to prevent stopping.
4) Stop where you started (facing the opposite direction). Perform the following:
   - **Wait approximately 1 minute.** (parking brake off, Transmission in Drive)
5) Proceed down Commerce St. and turn right onto trade street, right on State Strees and use cul-de-sac at the end to turn around.

<u>Lap 2:</u>

6) Return to point A again
   - Wait **approximately 1 minute.** (parking brake off, Transmission in Drive)
7) Accelerate at max throttle to **25 mph**, and then decelerate using only the retarder.
8) Turn around at circle and again accelerate at max throttle to **25 mph**, decelerate using only the retarder. At the end of the cul-de-sac you should be able to coast through the turn at around 6mph, **do not stop**. Use the gas petal if needed to prevent stopping.
9) Stop again at point A (facing opposite way)
   - Put bus in **high idle.** (Parking brake on, Transmission in neutral)
   - Wait **approximately 1 minute.**
10) Proceed down Commerce St. and turn right onto trade street and use cul-di-sac at the end to turn around.

<u>Lap 3:</u>

11) Return to point A again
   - Wait **approximately 1 minute.** (parking brake off, Transmission in Drive)
12) Accelerate at max throttle to **25 mph**, then decelerate using retarder.
13) Turn around at circle and again accelerate at max throttle to **25 mph**, and then decelerate using retarder. At the end of the cul-de-sac you should be able to coast through the turn at around 6mph, **do not stop**. Use the gas petal if needed to prevent stopping.
14) Stop again at point A (facing opposite way)
   - **Note end time** on “Calibration form: End Time Run 1”
   - **High idle for approximately 1 minute. (**Parking brake on, Transmission in neutral)
15) Proceed to Section B/Or return to Blacksburg Transit if second time doing Section A.

Section B: Rt 460

Drive as you normally would.

1. Proceed from point A to the **460 by-pass**.
2. Take 460 by-pass to **Tom's Creek exit**.
3. Exit onto Tom's Creek **toward Blacksburg**.
4. Take a **left onto Patrick Henry**.
5. Take a right on **Main St.**
6. Take Main St. **back to point A from Section A.**
7. **Repeat Part 1 then return to Blacksburg Transit**

Figure 3-1: Map of Calibration Testing Area for Section A

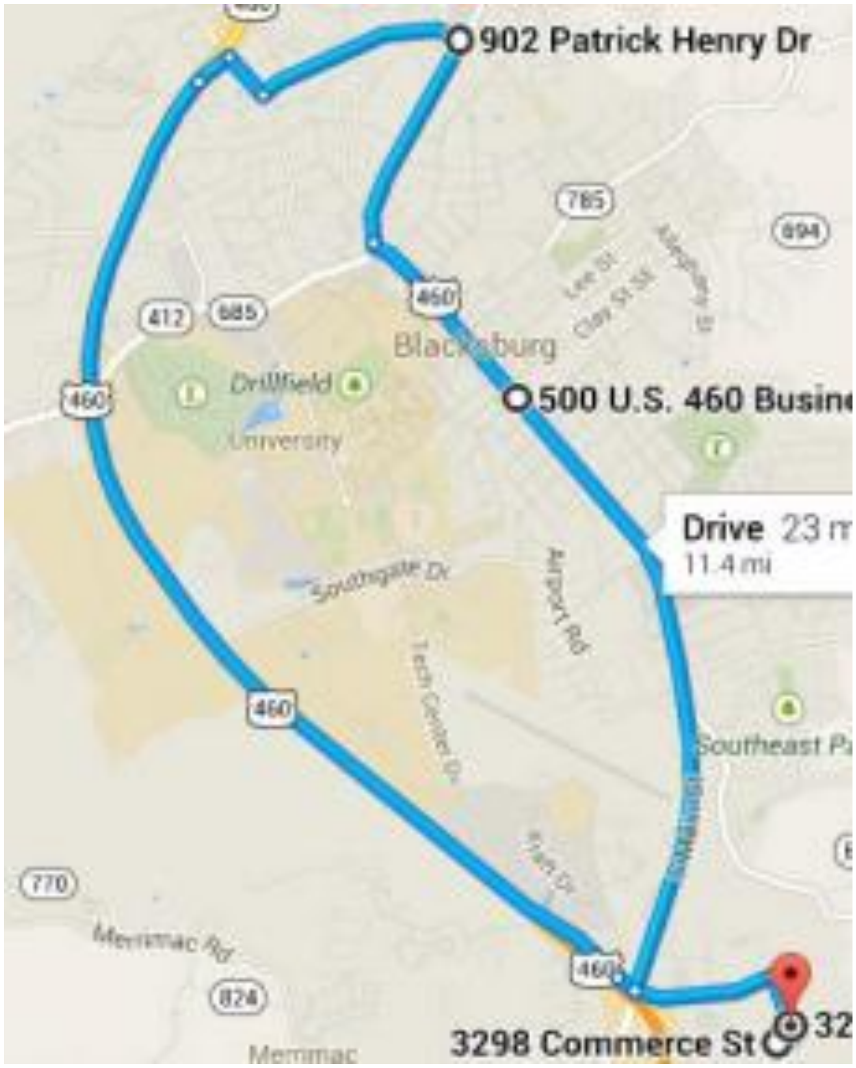


Figure 3-2: Map of Calibration Testing Area for Section B

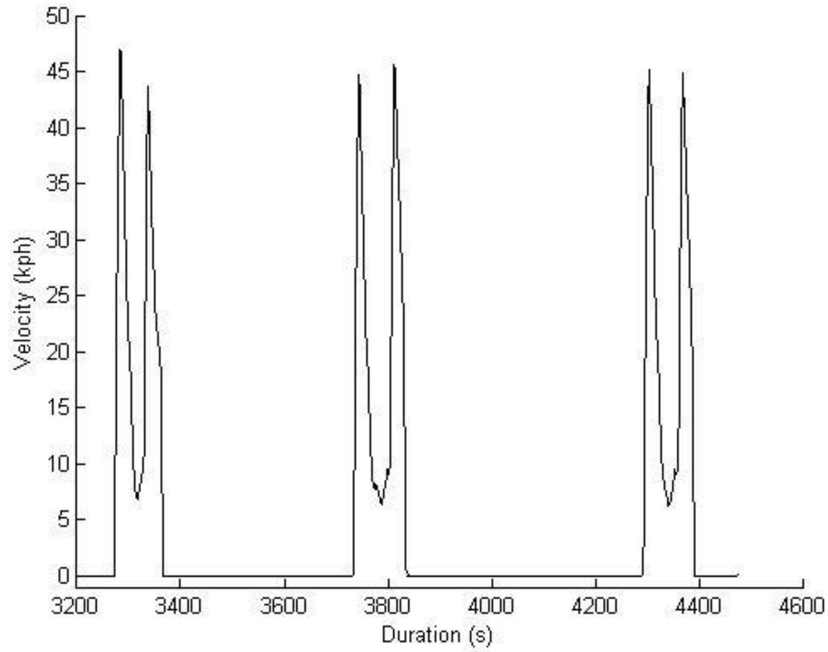


Figure 3-3: Typical drive profile (velocity vs. time) for section A1 and A2 (bus 1920)

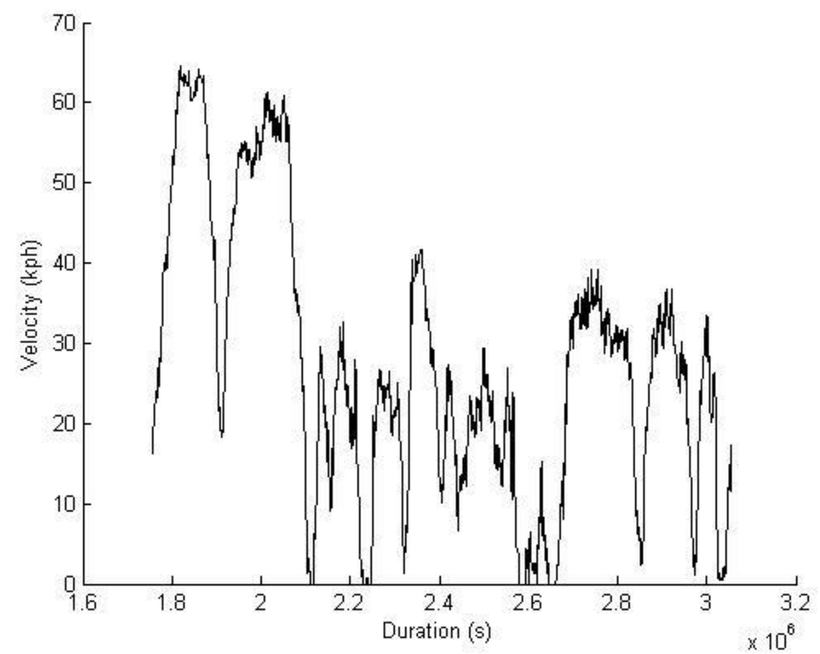


Figure 3-4: Typical drive profile (velocity vs. time) for section B (bus 1920)

Calibration was completed on two buses from the 6200, 6300 and 6320 series and four buses from the 1900 series. Extra buses from the 1900 series were tested because it makes up a third of the total BT fleet. A minimum of two buses per series was selected after observing that buses of the same series were statistically similar and statistically different from other series and due to time and resource constraints. A complete list of tested buses and there specifications can be seen in Appendix A.

3.4.2 Data Reduction

The DashDAQ collects data at a rate of 200 Hz, which is much faster than most signals outputted from the ECM. Consequently, the data were averaged to a frequency of 4 Hz. This was done to reduce the noise in the data because of the much faster than the signal output. A value of 4 Hz was selected in order to be consistent with the data collection rate BT will be using for its long-term data collection.

Next the velocities were smoothed using the Epanechnikov Kernel smoothing technique. Velocity for each time t (v_t) was smoothed using Equation (3-7) [3-11].

$$v_t = \frac{\left(.75v_t + .75^2(v_{t-1} + v_{t+1})\right)}{.75 + 2 * 75^2} \tag{3-7}$$

The data were then evaluated for any potential lag between the fuel signal and vehicle motion parameters. This was done because this lag was observed in Park et al. when testing the VT-Micro model at high speeds [3-12]. It was found that the fuel consumption did not have any lag, as illustrated in Figure 3-5, so no correction was required. Once the data were reduced it was separated into the three sections.

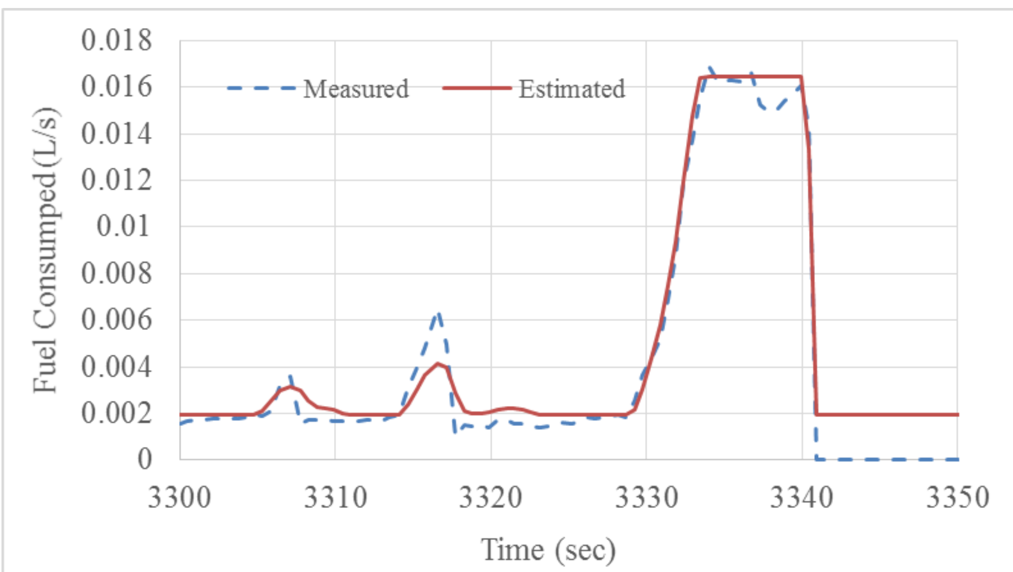


Figure 3-5: Comparison of actual and estimated fuel consumption for bus 1913

3.4.3 Model Development

The VSP versus FC data was expected to look similar to that of a LDV shown in Figure 3-6, this would have allowed the entire function to be modeled as a second degree polynomial using the VT-CPFM [3-1]. However, after analyzing the data a different trend was observed, similar to what Frey et al. found in the literature [3-7], and illustrated in Figure 3-7.

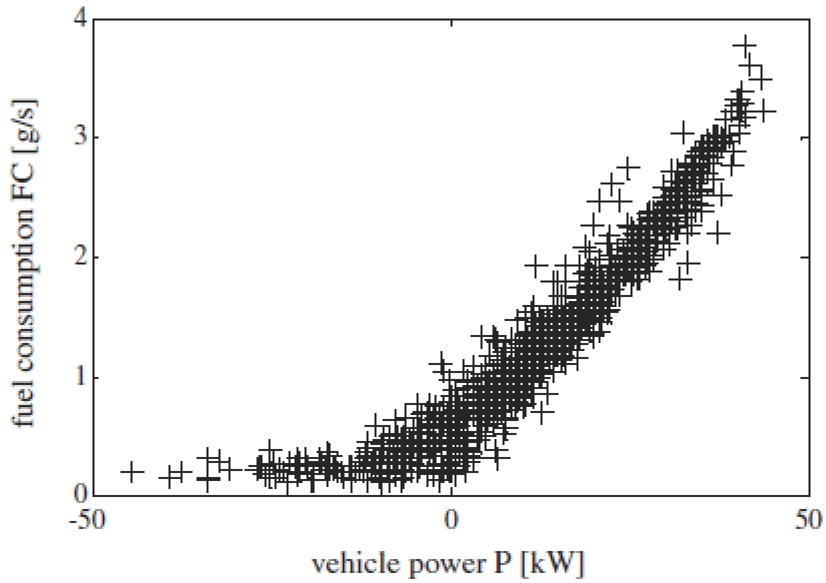


Figure 3-6: Typical relationship between power and fuel consumption for LDV. H. Rakha et al., "Virginia Tech Comprehensive Power-Based Fuel Consumption Model: Model development and testing" Transportation Research Part D: Transport and Environment, vol. 16, 492-503, 2011, Used with permission of Hesham Rakha, 2014.

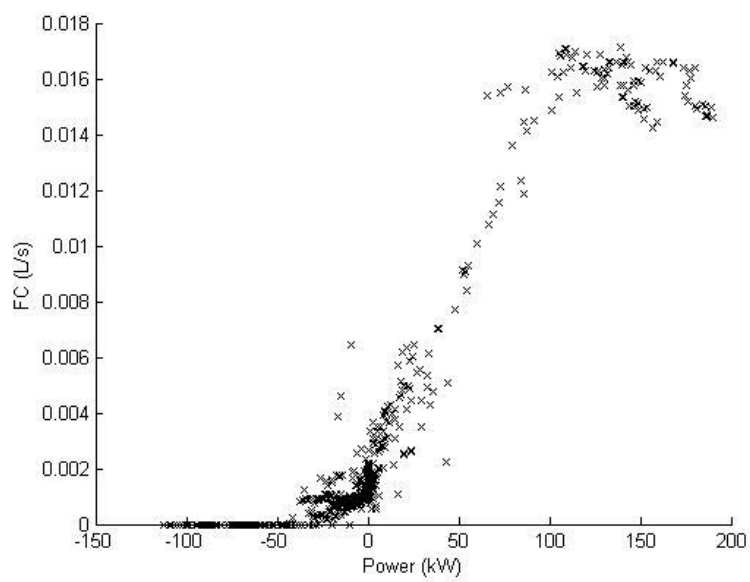


Figure 3-7: Typical relationship between power and fuel consumption for diesel bus

This unexpected difference resulted in a modification of the VT-CPFM. After reviewing the data it appeared that a two-regime model was required. The first regime uses the VT-CPFM polynomial model and the second regime is assumed to be constant. The resulting model is shown in Equation (3-8).

$$\mathrm{FC(t)} = \begin{cases} \beta & \forall \mathrm{P(t)} \geq \mathrm{P_r} \\ \alpha_0 + \alpha_1 \mathrm{P(t)} + \alpha_2 \mathrm{P(t)}^2 & \forall \mathrm{P_r} > \mathrm{P(t)} \geq 0 \\ \alpha_0 & \forall \mathrm{P(t)} < 0 \end{cases} \tag{3-8}$$

Where $P(t)$ is power at time *t* defined by equation (3-1), $\alpha_0, \alpha_1, \alpha_2$ are calibrated parameters, β is the maximum estimated fuel consumption rate (L/s) defined in equation (3-9), and P_r (kW) is the power when the regime shift occurs calculated using Equation (3-1).

$$\beta = \alpha_0 + \alpha_1 \mathrm{P_r} + \alpha_2 \mathrm{P_r^2} \tag{3-9}$$

3.4.4 Model Calibration

For calibration purposes only section A2 was used because the buses were warmed during these tests and because the repeatability of the test allowed for easy comparison of results. The first step in calibration was to find the idling fuel rate for low idling, since high idling only occurs when the parking break is on to decrease $PM_{2.5}$ emissions. Low idling was defined as idle at an engine speed less than 850 revolutions per minute (RPMs).

Next regime break threshold was estimated through visual inspection of the data. This study used velocity and acceleration to predict the regime break. For the 1900, 6300 and 6320 series if the velocity was below 18 km/h or the acceleration was below 0.6 m/s^2 the record was assigned to the first regime. For the 6200 series a velocity of 21 km/h was used as the threshold speed.

The model was then fit to Equation (3-8). The y-intercept (α_0) was fixed to the low idling fuel consumption rate and the quadratic term (α_2) was fixed to be greater than or equal to 1E-8 to prevent a bang-bang system from occurring as described by Edwardes et al. [3-1] and to ensure that the transit vehicle optimum speed was realistic (30 to 50 km/h). The calibrated parameters for individual buses are summarized in Table 3-4 as well as the model coefficient of determination (R^2) for the first regime and the entire model. The parameters used for calibration are shown in Table 3-3.

Table 3-3: Parameters for calculating power for VT-CPFM.

Variable	Value	Source
η_d	0.95	EPA 2010 *(13)*
C_r	1.25	Rakha (*14*)
c_1	0.0328	Rakha (*14*)
c_2	4.575	Rakha (*14*)
H	0.67 km	Google

Table 3-4: Calibration results (α values and R^2 values) for each bus.

Series	Bus Number	Idle rate (L/s)	α_0	α_1	α_2	R^2 of First Regime	β (L/s)	P_r (kW)	R^2 of Entire Model
1900	1911	1.896E-03	1.896E-03	1.230E-04	1.095E-07	0.771	1.647E-02	108	0.957
	1912	1.780E-03	1.780E-03	8.196E-05	6.494E-07	0.721	1.823E-02	108	0.962
	1913	1.922E-03	1.922E-03	1.331E-04	1.000E-08	0.883	1.572E-02	108	0.968
	1920	1.241E-03	1.241E-03	1.088E-04	2.228E-07	0.828	1.561E-02	108	0.978
6200	6201	1.083E-03	1.083E-03	1.003E-04	9.682E-08	0.891	1.446E-02	120	0.957
	6203	7.347E-04	7.347E-04	5.470E-05	4.255E-07	0.875	1.34E-02	120	0.948
6300	6305	5.875E-04	5.875E-04	1.165E-04	1.000E-08	0.947	1.260E-02	102	0.976
	6306	8.505E-04	8.505E-04	7.355E-05	3.693E-07	0.778	1.223E-02	102	0.910
6320	6323	6.162E-04	6.162E-04	9.051E-05	7.823E-08	0.892	1.612E-02	150	0.970
	6324	5.841E-04	5.841E-04	1.133E-04	1.000E-08	0.916	1.797E-02	150	0.976

The data for each series was then combined to develop parameters that could be used for the entire series. The results of the series calibrations are shown in Table 3-5.

Table 3-5: Calibration results (α values and R^2 values) for bus series

Series	Idle rate (L/s)	α_0	α_1	α_2	R^2 of First Regime	β (L/s)	P_r (kW)	R^2 of Entire Model
1900	1.779E-03	1.779E-03	1.201E-04	1.275E-07	0.753	1.625E-02	108	0.962
6200	1.007E-03	1.007E-03	8.159E-05	2.409E-07	0.867	1.421E-02	120	0.948
6300	7.060E-04	7.060E-04	8.368E-05	3.043E-07	0.834	1.244E-02	102	0.937
6320	5.997E-04	5.997E-04	1.051E-04	1.000E-08	0.902	1.675E-02	150	0.972

The resulting calibrated fuel consumption (FC) model together with the empirical in-field data vs. power for the 1900 series is illustrated in Figure 3-8. The figure clearly illustrates the need to model a dual regime.

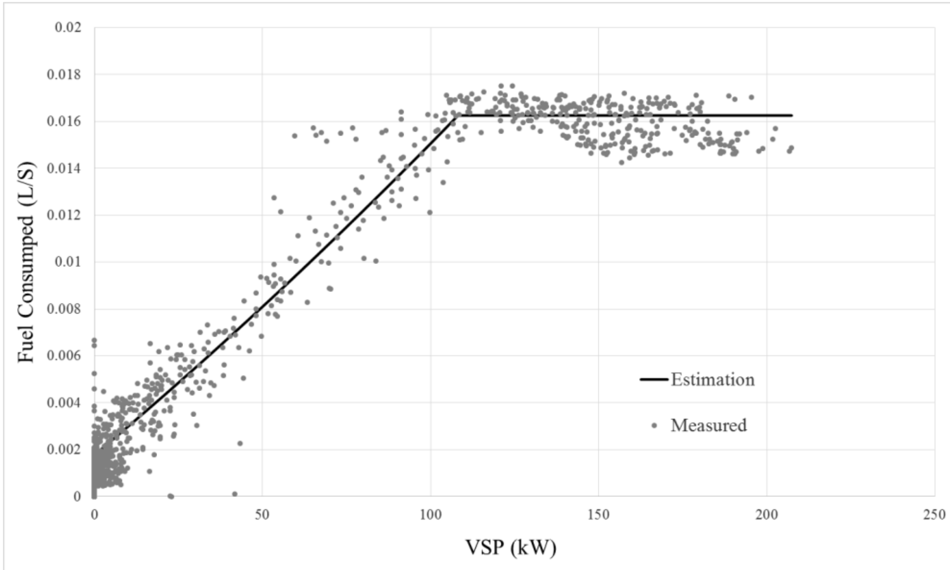


Figure 3-8: Estimated FC (L/s) and measured FC (L/s) vs. VSP (kW) for 1900 series

3.5 Data Analysis

After calibration was complete the results were used to determine the number of buses needed in each test series, the effect of AC on the model and to assess the two-regime VT-CPFM model.

3.5.1 Bus Differences

To justify collecting data from a minimum of two buses per series the p values were calculated for a variety of combination of buses using an ANOVA test considering an α value of 0.05. It was found that any two buses from the same series with the same AC state had a p value greater than 0.05 thus concluding that there was no statistical evidence for a difference in the buses. Also, all buses had a $p > 0.05$ when compared with the combined model for their series. When comparing different bus series all p were less than 0.03 and a $p < 0.01$ was observed when not comparing the XD series as they are the same bus, just purchased in different years. The results demonstrate that the buses of different series are statistically different. Consequently, buses of the same series with the same AC state were statistically similar, while buses from different series were not and thus were modeled separately.

3.5.2 AC Impact

To justify modeling buses with AC on and off with one model the p value was calculated between buses in the same series with AC on and off using the ANOVA test with an α value of

0.05. The results demonstrated that $0.05 > p > 0.01$ when comparing buses from the same series with the AC on versus AC off. This does show that they are likely statistically different, however when comparing the AC on and AC off to the series model separately $0.05 >$ I showing both are statistically similar to the final model for the series. A visual investigation of the data shows that having the AC on vs. off seems to have minimal impact on the model parameters (α_1, α_2, and β), but does have a significant impact on α_0.

Despite that fact that the AC on versus AC off does have some statistical difference one model for each series was developed for both AC on and off. This is due to that fact that modeling the AC on vs. off in real world conditions is very difficult since there is no way to know if the AC is actually engaged when it is determined by the temperature in the bus.

3.6 Results

The results from the calibration are promising, as demonstrated in Figure 3-9 and Figure 3-10. Specifically, the figures show the measured fuel consumption for bus 1911 and bus 1920, respectively, compared with the estimated fuel consumption using the model for the 1900 series. The sum of mean squared error (MSE) for each bus was very small, less than 0.002.

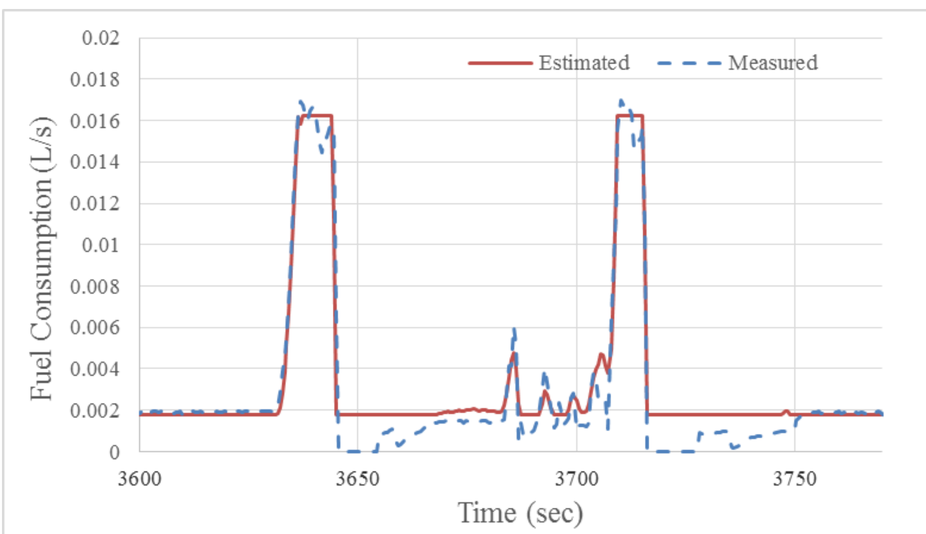


Figure 3-9: Estimated and Measure Fuel Consumption Rate for Bus 1911 (AC on)

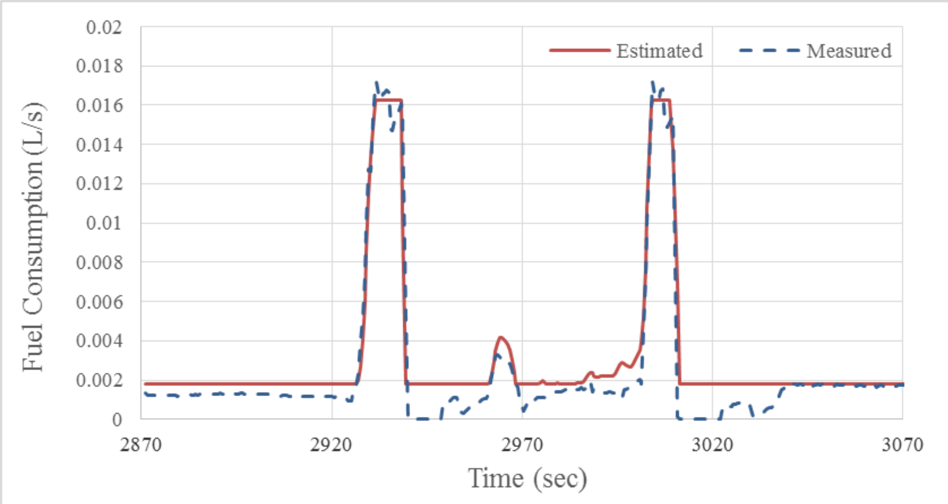


Figure 3-10: Estimated and Measure Fuel Consumption Rate for Bus 1920 (AC off)

3.7 Conclusions

The research presented in this paper creates a simple calibration procedure for the VT-CPFM to model diesel buses. It also develops a two-regime approach for dealing with diesel bus fuel consumption plateauing. The model does not produce a bang-bang control system and can be calibrated using the presented procedure or publicly available data from the Altoona Bus Research and Testing Center. The model has been shown to have a good fit to empirical data.

3.8 References

[3-1] W. Edwardes and H. Rakha, "Virginia Tech Comprehensive Power-Based Fuel Consumption Model: Modeling Diesel and Hybrid Buses" Transportation Research Record: Journal of the Transportation Research Board, 2014.

[3-2] H.Rakha et al., "Virginia Tech Comprehensive Power-Based Fuel Consumption Model: Model development and testing" Transportation Research Part D: Transport and Environment, vol. 16, 492-503, 2011.

[3-3] M. Barth et al., "Modal emissions model for heavy-duty diesel vehicles" Transportation Research Record, vol. 1880, 10-20, 2004.

[3-4] B. Saerens et al., "Assessment of Alternative Polynomial Fuel Consumption Models for Use in Intelligent Transportation Systems Applications" Journal of Intelligent Transportation Systems, 2012.

[3-5] R. Giannelli et al., "Heavy-duty diesel vehicle fuel consumption modeling based on road load and power train parameters," in SAE Technical Papers: Commercial Vehicle Engineering Congress and Exhibition, 2005.

[3-6] F. An. and M. Ross, "A Model of Fuel Economy and Driving Patterns," SAE 930328, 1993.

[3-7] C. Frey et al., "Comparing real-world fuel consumption for diesel- and hydrogen-fueled transit buses and implication for emissions," Transportation Research Part D: Transport and Environment, vol. 12, 281-291, 2007.

[3-8] C. Bell, "An Investigation of Road Load Effects on Fuel Economy and NOx Emissions of Hybrid and Conventional Transit Buses," M.S. thesis, Mechanical and Aerospace Eng., West Virginia University, Morgantown, WV, 2011.

[3-9] M. Thomas et al., "Aerodynamic Effects of Different Ventilation Methods on Buses" in Fourth International Symposium on Computational Wind Energy, 2006.

[3-10] Surface Vehicle Recommended Practice, SAE J2711 Sept. 2002.

[3-11] H. Rakha et al., "Field Evaluation of Energy and Emission Impacts of Traffic Flow Improvement Projects using GPS Data: Issues and Proposed Solutions," Transportation Research Record: Journal of the Transportation Research Board, vol. 1768, 210-223, 2001.

[3-12] S. Park et al., "Development of fuel and emission models for high speed heavy duty trucks, light duty trucks, and light duty vehicles," in 13th International IEEE Conference 2010.

Chapter 4 Dynamic Dispatch Decision Support Solution Outline

4.1 Abstract

Public transportation has many potential benefits including fuel saving, reduction of CO_2 emissions, and congestion reduction. However, due to inefficiencies and public perception transit is not always providing these benefits. These inefficiencies include poor reliability, scheduling, stop placement, and bus assignment. These issues have not been dealt with partly due to transit agencies having limited and stretched budgets. There is also limited research on ways to improve system efficiency, specifically in real time. To help address these inefficiencies Blacksburg Transit (BT) received a Transit Investment in Greenhouse Gas and Energy Reduction (TIGGER) grant to help improve some of these inefficiencies. This paper creates an outline for the dynamic dispatch decision support solution (3DSS) which will help dispatchers add, remove and switch buses in real time with the goal of reducing fuel consumption and maintaining or improving level of service. The algorithm will receive input from riders and buses and use it to assess current demand requirements.

4.2 Introduction

The goal of the dynamic dispatcher decision support solution (3DSS) is to use real time bus information and rider demand information to reduce total fuel consumed used while maintaining or improving the level of service (LOS) provided by the transit agency. To accomplish this this, ridership demand of the bus system is assessed in real time and buses are added if needed, removed if unneeded or swapped with a different size bus to either improve the LOS or reduce FC while still maintaining a defined minimum LOS. The study presented in this section is theoretical and subject to change following simulation and real world testing.

4.3 Literature Review

Due to a limited and stretched budget, transit agencies generally do not have the luxury of investing in new technologies or research to improve system efficiency. As a result it appears no one has done any work similar to what the 3DSS will do. However, there have been studies done on improving bus reliability, both static and in real time.

A key to improving bus reliability is to avoid bus bunching. The two main approaches for avoiding bunching are skipping stops and holding strategies [4-1]. Since leaving people stranded, a result of skipping stops, would decrease the LOS and BT currently uses a holding strategy, a holding strategy is used for this study. The majority of research on holding strategies use simulation so they are developed to be used in a static systems with the main goal of reducing passenger wait time [4-1]. Daganzo developed a strategy to improve reliability by dynamically maintaining bus headways, however this does not always result in the buses maintaining their schedule [4-2]. For this work a modified version of the optimal control strategy developed by Xuan et al. [4-1] is used because it the only dynamic strategy which allows buses to maintain schedules as well as headways and is executed using real time demand.

4.4 Demand Assessment

In order to collect real time demand information multiple technologies were explored and a mobile application for Android and iPhone (app) was selected for full system implementation. The goal of collecting real time demand assessment data is to allow transit agencies to be proactive as opposed to reactive. The hope is that individuals plan trips ahead of time using the app. The input will consist of their origin, destination and the time they wish to be at either their origin or destination, however they are not required to include all this information. The expectation is that a significant percent of riders will need to provide demand assessment data to BT for it to be useful; this is not expected to happen. Therefore, a forecasting algorithm is being developed. It will give real time ridership information via automated passenger counters (number of people that got on and off each bus at each stop) and forecasted rider demand to the 3DSS when app data is not available or minimal. IRB approval was received to use and analyze information collected from the app.

4.5 Methodology

4.5.1 Overview

The 3DSS algorithm will run in real time to assess if more, less or different buses are required on the routes. If the LOS is below a threshold defined by the agency the 3DSS well evaluate as many options as are available and select the best. The potential options are add an extra bus if available or replacing a bus with a larger bus if one is available. If multiple buses are available the one with the best score will be selected. If the LOS is above the given threshold removing a bus or replacing a bus with a smaller bus, if one is available, will be evaluated. The option with the best score will be selected. Lastly, the wait times of buses will be optimized to maximize LOS and FC. Since the 3DSS will be executed in real time it will have a maximum run time, which when reach the 3DSS will output the best solution it currently has.

4.5.2 Algorithm Outline

The 3DSS will take in real time and forecasted demand assessment data and current status of the buses (location and number of riders). Then:

1. Asses the $\mathrm{LOS_S}$
2. If $\mathrm{LOS_S} < \mathrm{LOS_{min}}$
    a. Find potential buses to be added to the system
    b. Select the stop with lowest LOS
    c. Select best bus to add to system (this may involve removing smaller bus)
    d. Add selected bus and remove smaller bus if necessary.
    e. Check if more buses need to be added.
3. Define base case incase maximum run time is exceeded.
4. Check each bus to see if it can be removed or replaced while keeping $\mathrm{LOS_S} \geq \mathrm{LOS_{min}}$ and decreasing FC. If this is possible
    a. Evaluate buses that can be removed or replaced.
    b. Select one with best score
    c. Remove or replace selected bus
    d. Check if more buses can be removed
5. Redefine the base case incase maximum run time is exceeded.
6. Optimize hold times at each stop to maximizeScore.

A flow chart of the general process can be seen in Figure 4-1.

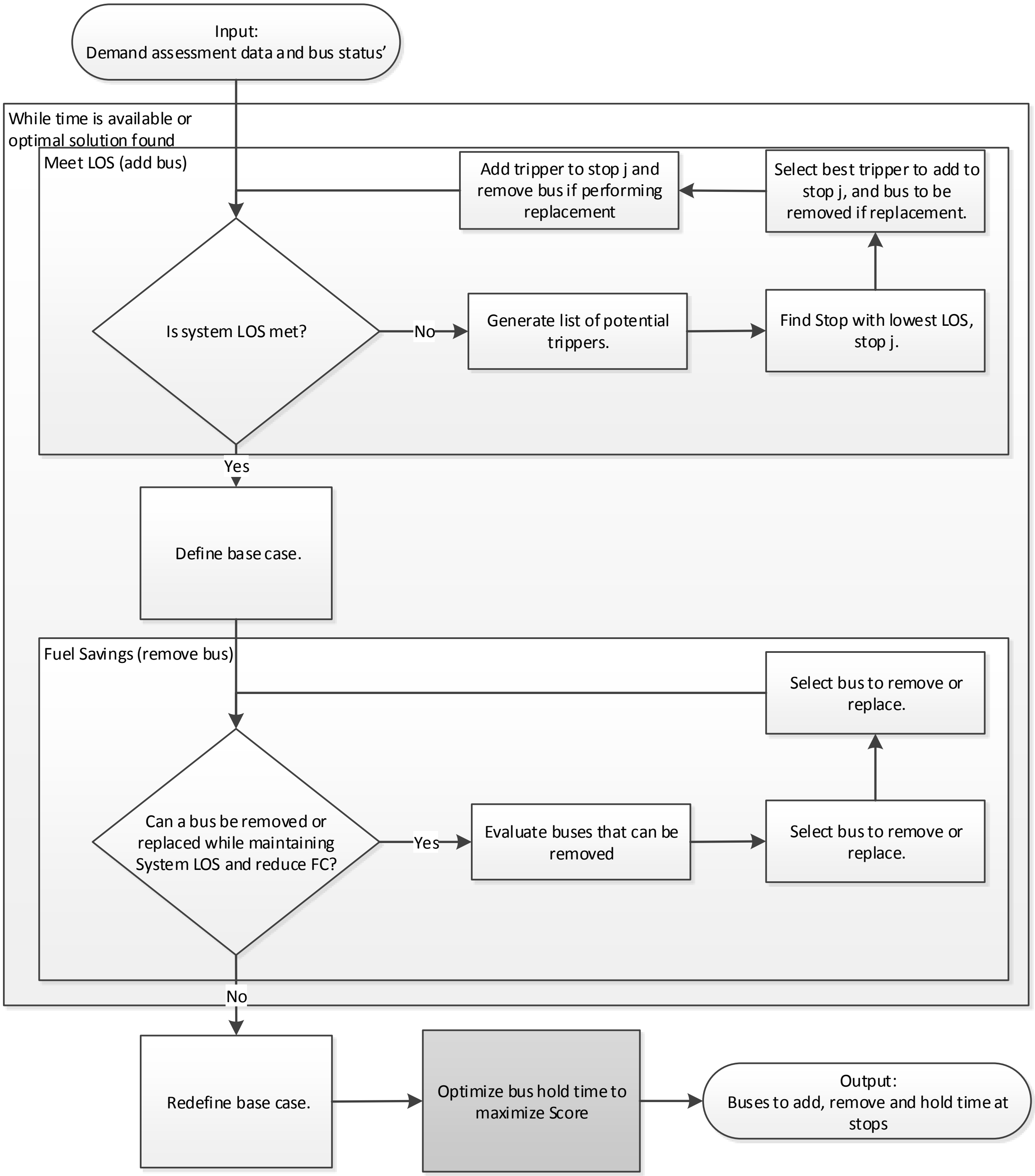


Figure 4-1: High Level Outline of 3DSS Algorithm

4.5.3 Level of Service

4.5.3.1 Traditional Transit Level of Service

Transit level of service is part of the system's overall quality of service. According to the third edition of the Transit Capacity and Quality of Service Manual (TCQSM), LOS captures all aspects of a user's experience from leaving their location till arriving at their destination. This includes walking to and from stops, waiting for the bus and the bus ride. Table 4-1 contains a list of factors from the TCQSM that are used to assess user experience [4-3].

Table 4-1: Transit Capacity and Quality of Service Manual LOS Factors

Factor	Experience Impacted
Frequency (Buses per hour)	Waiting at stop
Average excess wait time	Waiting at stop
Average load (crowdedness)	Ride
Average travel speed	Ride
Average passenger trip length	Ride
Percent of stops with shelter	Waiting at stop
Percent of stops with bench	Waiting at stop
Sidewalk Width	Travel to/from stop
Distance from sidewalk to street	Travel to/from stop
Barrier separating street and sidewalk	Travel to/from stop
Lane, shoulder and bicycle lane widths	Travel to/from stop
Number of lanes	Travel to/from stop
Vehicle flow rate	Travel to/from stop
Speed limit	Travel to/from stop

When calculating the LOS the first step is to determine the wait-ride score, which is a function of headway (frequency) and perceived travel time. Perceived travel time is a function of waiting at stop and ride factors. The second step is to determine the pedestrian environment score. This is a function of the factors impacting the experience of travel to and from stops. These two scores are combined to give a LOS. LOS defined by the TCQSM accounts for length of trips, frequency of buses, reliability, amenities and infrastructure.

4.5.3.2 Dynamic LOS

Since the 3DSS only impacts capacity and reliability of the system adaptations have been made to the TCQSM LOS to make it better fit the project's needs. One of the major alterations made to LOS is using real time or projected values in real time a opposed to using averages, since the

3DSS will calculate LOS in real time. The factors captured by LOS are also reduced for this study because the 3DSS cannot impact static elements. Therefore, only factors that can be altered by the 3DSS are included in LOS. A list of potential factors for the dynamic LOS is show in Table 4-2.

Table 4-2: Potential Factors for Dynamic LOS

Factor	Experience Impacted
Frequency (Buses per hour)	Waiting at stop
Average excess wait time	Waiting at stop
Average load	Ride
Average travel speed	Ride

However, due to low level of compliance from some drivers and safety concerns the ability to adjust average travel speed was removed. This left three factors that the 3DSS can adjust: frequency, excess wait time (reliability) and average load. Frequency and excess wait can both be captured by looking at the average wait time of passengers at a given stop for a given bus arrival. Therefore LOS for a given stop is defined by equation (4-1) where higher LOS is better.

$$\mathrm{LOS_i} = \frac{L_f}{a_W} \tag{4-1}$$

Where $\mathrm{LOS_i}$ is level of service of stop i, a_W is average wait defined by equation (4-2), load factor L_f is defined by equation (4-3) is used to assess the riders experience based on how crowded the bus is.

$$a_W = \frac{\sum_j^{J_i} w_{ji}}{J_i}, \tag{4-2}$$

Where w_{ji} is the wait time for passenger j at stop i and J_i is the total number of people at stop i,

$$L_f = \begin{cases} 0.7 & \text{if number of riders} \leq \text{number of seats} \\ 1 & \text{if number of seats} < \text{ number of riders} \leq \text{ .7} * \text{maximum capacity} \\ 1.3 & \text{if .7} * \text{maximum capacity} < \text{ number of riders} \end{cases} \tag{4-3}$$

The LOS of the system, $\mathrm{LOS_S}$, is defined by equation (4-4).

$$LOS_S = \sum_{i=1}^{N} \mathrm{LOS_i} \tag{4-4}$$

4.5.4 Fuel Consumption Estimation

The fuel consumption will be estimated using the VT-CPFM. The VT-CPFM is a microscopic fuel consumption model based on vehicle specific power. It was developed by Rakha, et al. [4-4] and enhanced to estimate diesel fuel usage of buses by Edwardes, et al. [4-5]. The VT-CPFM will be used on estimated drive profiles. The drive profiles will be generated in a similar way Edwardes, et al. generated drive profiles for Altoona testing [4-5]. These profiles will then be validated against real world data and stored for use by the algorithm.

4.5.5 Selection Criteria

When multiple option are available to add, remove or switch a bus the option with the lowest Score based on Equation (4-5) will be selected.

$$\text{Score} = \lambda_1 FC_s + \frac{\lambda_2}{LOS} \tag{4-5}$$

Where FC_S is the scaled fuel consumed of the system for that option, LOS is the level of service of the system, λ_1, λ_2 are weights the transit agency can define, where $\lambda_1 + \lambda_2 = 1$, depending on their focus. A higher λ_1 will put more emphasis on fuel usage and λ_2 will put more emphasis on LOS.

4.5.6 Hold Times

Currently BT uses two time checks per route to maintain reliability. A time check is a stop where if the bus arrives early it waits until a defined time before leaving and if it arrives late it leave immediately. Since this study will be making real time adjustments to the schedule. A dynamic bus holding strategy for schedule reliability developed by Xuan et al. was used. This method was selected because it allows buses to maintain regular headways and maintain schedules dynamically. Xuan et al. calculated hold time using equation (4-6) [4-1].

$$D_{n,s} = d_s - \left[\varepsilon_{n,s} + \mathrm{B}_s\left(\varepsilon_{n,s} - \varepsilon_{n-1,s}\right)\right] \tag{4-6}$$

Where $D_{n,s}$ is the holding time applied to bus n at stop s, d_s is the amount of slack (extra) time originally scheduled at stop s, $\varepsilon_{n,s}$ is the deviation from expected arrival time, B_s is a measure for demand rate, such that as headway increases the passenger loading time increases. Since, real time and future demand assessment is being used for this study the equation has been altered to equation (4-7).

$$D_{n,s} = d_s - \left[\varepsilon_{n,s} + \max\left(T_A * a_{n,s} + T_B * b_{n,s}\right)\right] \tag{4-7}$$

Where T_A, T_B are the time to alight (get off bus) and time to load per passenger and $a_{n,s}, b_{n,s}$ are the number of passengers alighting and boarding at stop s from or to bus n, respectively.

4.6 Conclusions

This research effort has outlined one application of the VT-CPFM to help optimize bus efficiency. It has laid out an outline for a procedure to improving fuel consumption and level of service by altering the schedule in dynamically using real time forecasted and demand assessment data. Further analysis of this algorithm will be completed via simulation and real world implementation on the Heathwood A and CRC route in Blacksburg, VA.

4.7 References

[4-1] H.Rakha et al., "Virginia Tech Comprehensive Power-Based Fuel Consumption Model: Model development and testing" Transportation Research Part D: Transport and Environment, vol. 16, 492-503, 2011.

[4-2] W. Edwardes and H. Rakha, "Virginia Tech Comprehensive Power-Based Fuel Consumption Model: Modeling Diesel and Hybrid Buses" Transportation Research Record: Journal of the Transportation Research Board, 2014.

[4-3] Y. Xuan et al., "Dynamic bus holding strategies for schedule reliability: Optimal linear control and performance analysis" Transportation Research Part B: Methodological, vol. 45, 1831-1845, 2011.

[4-4] C. Daganzo, "A headway-based approach to eliminate bus bunching: Systematic analysis and comparisons" Transportation Research Part B: Methodological, vol. 43, 913-921, 2009.

[4-5] P. Ryus et al., "Transit Capacity and Quality of Service Manual, Third Edition," Transportation Research Board, Washington DC., Rep. TCRP Report 165, 2013.

Chapter 5 Conclusions and Recommendations

5.1 Conclusions

The objectives of this thesis are: (1) develop diesel bus fuel consumption models; (2) develop a procedure to calibrate these diesel bus fuel consumption models using publically available data; (3) develop an in-field procedure for calibrating diesel bus fuel consumption models; and (4) outline a potential application of the diesel bus fuel consumption model. In developing the diesel bus fuel consumption model, the Virginia Tech Comprehensive Power Based Fuel Consumption Model (VT-CPFM) was enhanced to reflect diesel bus fuel consumption data. The model was first calibrated using publically available data from the Altoona Bus Research and Testing center. The required changes included altering the mass factor, lowering the lower bound of the second-order power parameter, and using different dynamometer test cycles when using publically available data. Subsequently, the VT-CPFM model was enhanced to reflect diesel bus fuel consumption behavior. This enhancement entailed developing a piecewise function to account for the plateau in fuel consumption levels at higher power demands. Finally, a calibration procedure was developed to calibrate the VT-CPFM to in-field data.

5.1.1 Develop a Model for Estimating Diesel Bus Fuel Consumption using Publically Available Data

Chapter 2 extends the Virginia Tech Power-Based Comprehensive Fuel consumption Model (VT-CPFM) to model diesel and hybrid buses. The model does not produce a bang-bang control system and can be calibrated using publicly available data from the Altoona Bus Research and Testing Center. The model has been shown to be consistent with dynamometer and on-road testing with an average error of 4.7% for the dynamometer testing and 22% for the on-road testing. The VT-CPFM will allow transit agencies to estimate fuel consumption for new route, new stops or any changes to the system with minimal resources since all data is publically available. It will also allow for them to develop various approaches to making there system more fuel efficient.

5.1.2 Develop a Procedure for Calibrating a Diesel Bus Fuel Consumption Model

In section 3.4 a procedure for calibrating buses and reducing the data was developed for use in Blacksburg, VA. This testing procedure should be exportable to other agencies as long as they are able to find a flat, level, low usage road or develop an alternative testing procedure. The data reduction is useful to anyone trying to analyze fuel consumption information collected via an on board diagnostic system such as the DashDAQ-XL.

5.1.3 Enhance the Diesel Bus Fuel Consumption Model based on Calibration Results

Section 3.5 and 3.6 use the results of the calibration to enhance the VT-CPFM and develop a two-regime model for estimating diesel bus fuel consumption levels. The model does not produce a bang-bang control system and can be calibrated using the presented procedure or publicly available data from the Altoona Bus Research and Testing Center. The model has been shown to have a good fit for the collected data by having a low MSE.

5.1.4 Outline a Potential Application of the Diesel Bus Fuel Consumption Model

Chapter 4 outlined one application of the VT-CPFM to help optimize bus efficiency. It has laid out an outline for a procedure to improving fuel consumption and level of service by altering the schedule in dynamically using real time forecasted and demand assessment data. Further analysis of this algorithm will be completed via simulation and real world implementation on the Heathwood A and CRC route in Blacksburg, VA.

5.2 Future Research Directions

This thesis has developed a model for estimating diesel bus fuel consumption using calibrated or publically available data. However, there is still a need to analyze the specific effect of grade and passenger loads on transit vehicle fuel consumption levels. There is also a need to develop a model for estimating diesel hybrid bus fuel consumption levels.

The development of this model opens up many research opportunities to improve bus efficiency both statically and dynamically, such as the 3DSS. Some potential algorithms to reduce fuel consumption that could be developed are bus to route assignment, stop placement, route design, and many others. It also allows for transit agencies to better evaluate what type of buses they may wish to purchase.

Appendix A: Tested Buses

Table A-1: Table of tested buses from Blacksburg Transit

Series	Bus Number	Length (ft)	Year	Make & Model	Engine Brand	Engine Model	Transmission Brand	Transmission Model	Curb Weight	AC
1900	1911	40	2009	New Flyer SR-1360 D40LFR	Cummins	ISL-07	Allison Transmission	B400R Gen 4	28300	On
	1912	40	2009	New Flyer SR-1360 D40LFR	Cummins	ISL-08	Allison Transmission	B400R Gen 4	28300	On
	1913	40	2009	New Flyer SR-1360 D40LFR	Cummins	ISL-09	Allison Transmission	B400R Gen 4	28300	On
	1920	40	2009	New Flyer SR-1360 D40LFR	Cummins	ISL-10	Allison Transmission	B400R Gen 4	28300	Off
6200	6201	35	2012	New Flyer SR-1614 XD35	Cummins	ISL-2010	Allison Transmission	B400 Gen 4	26750	On
	6203	35	2012	New Flyer SR-1614 XD35	Cummins	ISL-2010	Allison Transmission	B400 Gen 4	26750	Off
6300	6305	35	2013	New Flyer SR-1733 XD35	Cummins	ISL-2010	Allison Transmission	B400 Gen 4	26750	Off
	6306	35	2013	New Flyer SR-1733 XD36	Cummins	ISL-2011	Allison Transmission	B400 Gen 4	26750	On
6320	6323	60	2013	New Flyer SR-1734 XD60	Cummins	ISL-2012	Allison Transmission	B400 Gen 4	39675	On
	6324	60	2013	New Flyer SR-1734 XD60	Cummins	ISL-2013	Allison Transmission	B400 Gen 4	39675	On

*6201 was tested twice