CHARACTERIZATION OF POLLUTANT EMISSIONS AND FUEL USE FOR CNG TRANSIT BUSES

By

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CHARACTERIZATION OF POLLUTANT

EMISSIONS AND FUEL USE FOR CNG TRANSIT

BUSES

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Abstract:

Transit agencies have historically relied on diesel buses to move their passengers; however, many agencies have adopted alternative fuels such as compressed natural gas (CNG). New knowledge is needed to accurately assess the environmental impacts of CNG as a transportation fuel. The goal of this research is to characterize the air pollutant emissions and fuel use of CNG buses. This dissertation focuses on real-world data collection of emissions and fuel use rates and vehicle activity data for CNG buses. The case study fleet included five big capacity (32-seat) CNG buses and five small capacity (19-seat) CNG buses, and three (27-seat) diesel buses. The diesel bus data was used as a baseline to compare the environmental impacts of CNG buses. The central component of the field data collection process was a portable emissions measurement system (PEMS). Monitored pollutants included carbon dioxide (CO_2), hydrocarbons (HC), carbon monoxide (CO), and nitrogen oxides (NO_x). Vehicle activity data included, engine speed in revolutions per minute, intake air temperature, manifold absolute pressure, engine load and vehicle speed. The major outcome of the research is new knowledge that may lead to improved environmental and fleet management practices as well as improved decision making capacity for stakeholders.

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CHAPTER I

INTRODUCTION

1.1. Background

Transit agencies have heavily relied on diesel buses to move their passengers; however, this is changing considering energy and environmental issues. Many agencies are now moving away from diesel to adopt cleaner, cheaper and more efficient alternatives, such as biodiesel, methanol, chemically stored electricity, propane, liquefied natural gas (LNG), and compressed natural gas (CNG). CNG is the focus of this dissertation.

As an alternative fuel, CNG has several potential advantages: (1) CNG emits significantly lower quantities of some pollutants; (2) Compared with other hydrocarbon-fuel vehicles, Natural Gas Vehicles (NGVs) spend less on maintenance; and (3) NGVs cause fewer problems with spark plugs. Furthermore, the fuel economy, power and acceleration of NGVs are comparable with the conventional vehicles.

The benefits of CNG contribute to the worldwide distribution of NGVs. According to Natural Gas Vehicles Global (NGV Global, 2012), there are roughly 16,700,000 NGVs and 21,000 natural gas fueling stations around the world. Table 1.1shows the top ten countries with the largest NGVs fleets. According to Natural Gas Vehicle for America , natural gas powers about 142,000 vehicles on roads in the United States. Although these vehicles are less than 1% of worldwide NGVs, the use of NGVs in the United States is increasing, especially for transit buses. Use of natural gas (compressed, liquid, or blends) in transit bus fleets began increasing in the late 1990s, growing from 2.8% of buses in 1996 to 18% in 2009. American Public Transportation Association (APTA, 2010) indicates that natural gas-powered buses accounted for 26% of the new buses ordered by transit agencies in 2009. Currently, transit buses are the largest users of natural gas for vehicles in United States.

Table 1.1 Top Ten Countries with the Largest NGVs Fleets (NGV Global, 2012)

Country	NGV Population	Percentage of NGVs in World
Iran	3,000,000	18.8%
Pakistan	2,900,000	18.8%
Argentina	2,140,000	12.5%
Brazil	1,739,676	11.2%
China	1,577,000	6.6%
India	1,250,000	7.2%
Italy	746,470	5.1%
Ukraine	390,000	2.6%
Colombia	380,000	2.3%
Thailand	358,000	2.0%

1.2. Problem Statement

Previous studies about exhaust emissions of CNG transit buses are limited in number and scope. Many of these studies focused only on the fuel economy and fleet managements issues. The major goal of this study is to characterize the emissions and fuel use of CNG transit buses. CNG emissions and fuel use were compared to a baseline of diesel bus emissions and fuel use. The major output of this study is a case study comparing CNG versus diesel emissions and fuel use for transit buses. The major outcome of the case study is new knowledge that leads to improved environmental and fleet management practices as well as improved decision making capacity for stakeholders.

1.3. Scope

The foundation of this study was the transit bus fleet owned by Oklahoma State University (OSU), which serves the university and the surrounding Stillwater community. This bus fleet provides transit service from 6:20 a.m. to 10:30 p.m., Monday through Friday, throughout the academic year, with three on-campus routes and six off-campus routes. The stops vary depending upon demand (OSU, 2014).

The OSU fleet consists of 19 CNG transit buses, which include ten 2009 Ford E450 and nine 2010 El Dorado buses. There are seven diesel buses (2003 Blue Bird) that remain from the previous diesel fleet that were used prior to the switch-over to the current CNG fleet. These diesel buses are only used on “trail” routes to transport the overflow passengers or operate on routes when CNG buses are out of service for maintenance.

This study is unique in that it is based on real-world data instead of engine dynamometer data collected in a laboratory. The real-world emissions and fuel use data for each bus was collected by a portable emissions measurement system (PEMS) while the bus drove on its scheduled route. Emissions and fuel use measurements were taken on the diesel buses as well to establish an emissions and fuel use baseline for the original diesel fleet. Emissions and fuel use of the current CNG bus fleet and the previous diesel bus fleet were compared in order to assess the emissions and fuel use advantages (or disadvantages) of CNG versus diesel for transit bus fleet. There were four gas pollutant emissions measured and analyzed in this study, which are carbon dioxide (CO_2), hydrocarbons (HC), carbon monoxide (CO), and nitrogen oxides (NO_x).

1.4. Objectives

The major goal of this study is to characterize pollutant emissions and fuel use of a CNG transit bus fleet. In order to accomplish this goal, the following objectives were completed:

1. Collect real-world emissions, fuel use, and engine performance data for CNG and diesel buses;
2. Compare emissions and fuel use of CNG buses versus diesel buses;
3. Identify the relationships between emissions, fuel use, and engine performance data for CNG and diesel buses;
4. Develop emissions and fuel use predictive models for CNG and diesel buses; and
5. Develop emissions inventory for the CNG fleet and the old diesel fleet.

The specific outcomes of the study include:

1. A robust dataset of real-world emissions, fuel use, and engine performance data for CNG and diesel transit buses;
2. A comparison of the results and relationships between emissions, fuel use, and engine performance data for CNG and diesel buses;
3. A set of predictive models for emissions and fuel use for CNG and diesel buses; and
4. A emissions inventory for the CNG fleet and the old diesel fleet.

CHAPTER II

LITERATURE REVIEW

The body of literature related to CNG and diesel bus emissions and fuel use is limited in scope and nature; however, there are several studies related in a tangential manner. This section addresses previous work related to the objectives of this study, specifically data collection methods, emissions comparison approaches, and emissions predictive modeling techniques.

2.1. Data Collection Methods

Several methods have been utilized to measure mobile source pollutants. In this section, three testing methods related to this study are explained. These methods include engine dynamometer testing, remote sensing and portable emissions measurement system (PEMS).

2.1.1. Engine Dynamometer Testing

Engine dynamometer testing is widely used to estimate and quantify air pollutant emissions. In this type of test, only the engine, not the entire chassis, is set in a laboratory with test instruments. Emissions data and engine data are collected while the engine operates in several steady-state modes. The modes are usually classified by specified constant speed or engine loads (Abolhasani *et al*., 2008).

Dynamometer testing is a popular approach for transit bus research. For instance, Serrano *et al*. (2012) used dynamometer tests to study the impacts of biodiesel on buses engine. The test bench was equipped with a Schenk hydraulic dynamometer as shown in Figure 2.1. The test engine was also connected with an exhaust gas analyzer for emission data, as well as a fuel use measurement device for fuel use data. A control system was used to avoid the impacts of technician intervention. Emission rates of NO_x and engine performance parameters (RPM and Torque) were measured while the engine was fueled with seven different biodiesel fuels. The engine ran following the European Transient Cycle (ETC) during data collection. The results quantified the emissions and fuel use benefits of biodiesel blends on bus engines.

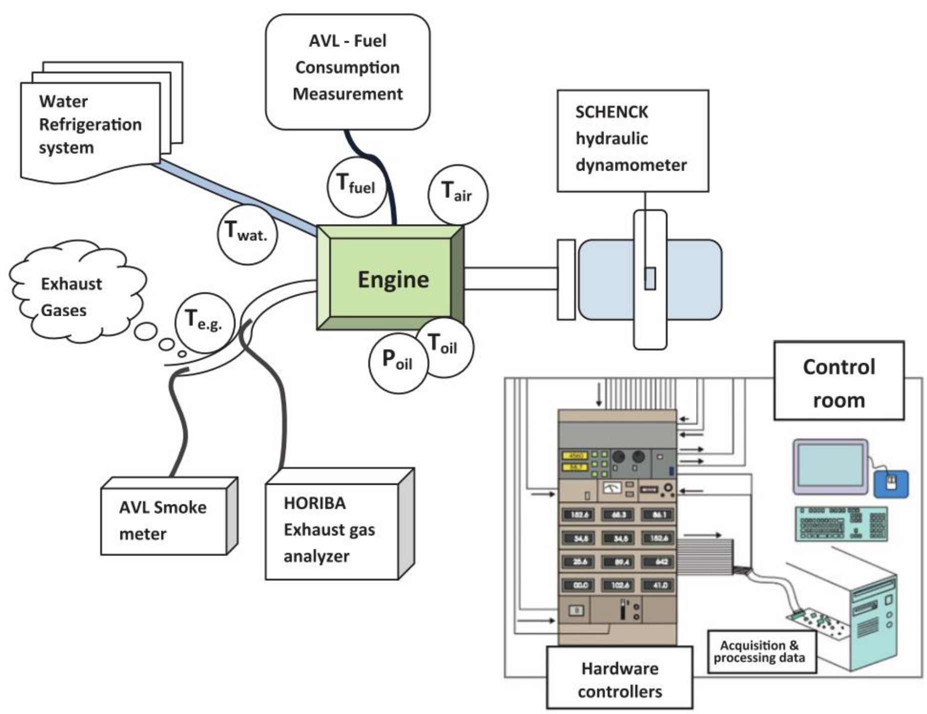


Figure 2.1 Diagram of Dynamometer Test Laboratory (Serrano *et al*., 2012)

Dynamometer tests also played an important role in the development of several emissions estimator models. For non-road equipment, the United States Environmental Protection Agency (EPA) developed the NONROAD model based on the data collected from eight-mode dynamometer tests. MOBILE was developed to predict the emissions of on-road mobile sources, such as cars, buses, trucks and motorcycles. Another model for on-road vehicles was Motor Vehicle Emission Simulator (MOVES), which was developed to replace MOBILE in 2004. As with NONROAD, both MOBILE and MOVES used the data collected from dynamometer tests as their primary resources.

Dynamometer tests do not always represent real-world situations since it is based only on engine data rather than whole vehicle activity. Moreover, some factors cannot be simulated in the laboratory, such as pavement and traffic conditions. Considering these shortcomings, other technologies have been developed in order to obtain emissions and fuel use data that mimics the real-world data. Nevertheless, dynamometer tests are still a common method for emissions research, especially when engine operations follow a fixed cycle.

2.1.2. Remote Sensing

Remote sensing technology is a viable option for collecting real-world emissions data from vehicles. The remote sensing devices measure gaseous pollutant concentrations in the exhaust plume of vehicles as they run in real-world conditions (SBRC, 1994). Hallquist *et al*. (2012) developed an experimental method to collect transit bus emissions data using this technology, which was called “Road”. A remote sensing device (AccuSan RSD 3000, Environmental System Products Inc.) was used for measurements of gas pollutants including CO, HC and NO_x . CO_2 was measured by a non-dispersive infrared gas analyzer (LI-840, LI-COR Inc. 1HZ). Engine Exhaust Particle Sizer Spectrometer (EEPS, Model 3090, TSI Inc.) was used to analyze particular matter (PM). Additionally, to minimize the impacts of ambient temperature on PM measurements, a thermo denuder (TD; Dekati) was used to heat the exhaust sample flow to 298K before the sample entered the EEPS. These four instruments were set up at one spot along the experimental bus route. Emissions data for pollutants were measured as transit buses passed the test location (Figure 2.2). The goal of this study was to characterize PM and gaseous emissions of a European transit bus fleet, which contained both CNG and diesel buses.

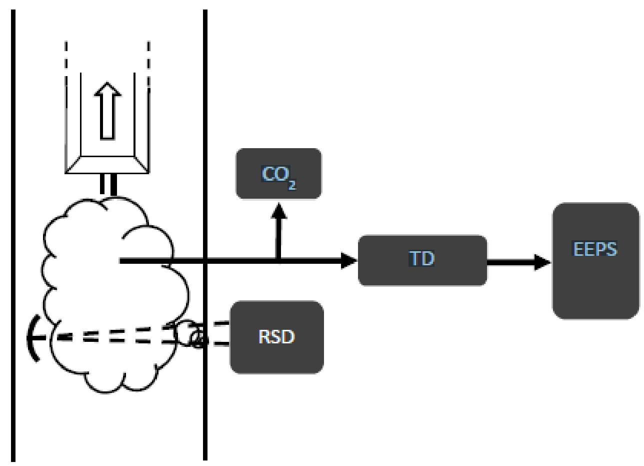


Figure 2.2 Schematic of the Experimental Set-up for Road Method (Hallquist, *et al*., 2012)

Compared with dynamometer testing, the emissions data collected by remote sensing instruments more closely resembles real-world data; however, there were still shortcomings for this method. For example, other traffic had a significant impact on the experiment. Since the instruments were set along the transit bus route, the emissions measurements were affected if other vehicles drove through the test location. In fact, in order to minimize the influence of other traffic, Hallquist *et al*.(2012) chose bus depots as the experiment locations, although bus depots did not represent the typical and real-world traffic conditions of transit buses. Another shortcoming of remote sensing was that limited data increased the level of variation in the results. Because all the instruments were deployed at one location along the route, the measurements only performed when the buses reached the location. Although each bus was tested three times, the quantity of data was not sufficient to build a database. In order to solve this problem, a chase car was used (Pirjola *et al*., 2004), in which an instrumented vehicle followed the test vehicle. Challenges with this approach included how to minimize the influence of emissions from the chase vehicle, and how to keep a constant distance between the chase vehicle and the test vehicle. Furthermore, mass emissions rates could not be determined, since the vehicle's exhaust flow rate was unknown and detailed vehicle activity was generally not known such as MAP, engine speed (RPM) and engine load, which dramatically affected emissions.

2.1.3. Portable Emissions Measurement System (PEMS)

Another advanced technology used for vehicle emissions studies is on-board portable emissions measurement system (PEMS). PEMS is usually contained in a carry-on luggage-size case. The PEMS is installed on the tested vehicle in advance, and then it collects emissions data on a second-by-second basis as the vehicle travels its real-world route. Simultaneously, engine activity data is measured and transmitted to the PEMS as well.

Several researchers have employed PEMS to study exhaust emissions from different types of vehicles, such as construction equipment, passenger cars, and transit buses. Frey (2010) and his North Carolina State University research team (Rasdorf *et al*., 2012; Lewis *et al*., 2009; and Aholhasani *et al*., 2008) conducted several research projects about emissions of construction equipment. For instance, Frey *et al*. (2010) developed a methodology for collecting and analyzing real-world in-use data from non-road construction equipment. Rasdorf *et al*. (2012) conducted a case study to identify construction activities that caused the most emissions and fuel use on a construction project. Lewis *et al*. (2009) developed a methodology for estimating weighted-average emission rates and fuel uses of construction equipment performing representative duty cycles. Abolhasani *et al*. (2008) characterized real-world emissions, fuel use, and engine activity for excavators. This research used the data collected by a PEMS, the Montana Universal System, which was manufactured by Clean Air Technology International (CATI). A schematic of this system is shown in Figure 2.3.

Besides Frey and his research team, Lee *et al*. (2012) conducted a study for the Texas A&M Transportation Institute (TTI) to compare vehicular emissions from real-world in-use PEMS test to the EPA emissions estimation model MOVES. Another recent PEMS system manufactured by CATI was the Axion. TTI used the Axion to collect real-world emissions data from a 1999 Dodge Grand Caravan. As seen in Figure 2.4, probes and hoses were installed on the test vehicle and connected to its tailpipe (left); the exhaust samples were sent to the Axion main unit (right), and during measurement, the emissions data displayed on the unit's screen on a second-by-second basis.

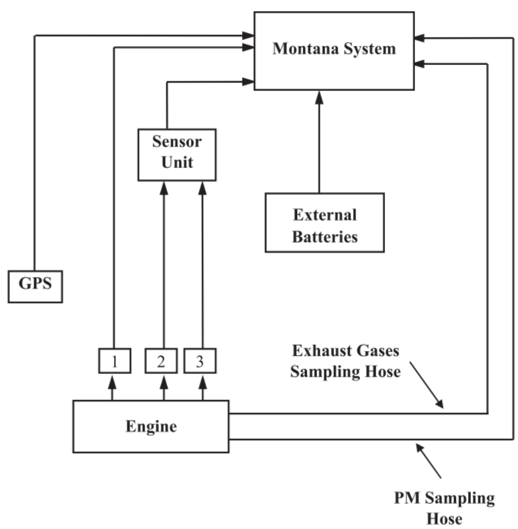


Figure 2.3 Schematic Diagram for Montana System (Abolhasani, *et al*., 2008)

Figure 2.4 Passenger Cars Installed with Axion (Lee *et al*., 2012)

Similarly, TTI used a PEMS for data collection on another research project related to the analysis of school bus emissions and activity data (TTI,2006). Five diesel school buses fueled with two types of diesel fuel, representing a sampling of the Texas fleet, were tested. Based on the collection and analysis of exhaust emissions and operating data, this project determined operating profile modification, fuel formulations and emissions control techniques of school bus fleets in Texas.

Compared with the previous methods, there are several advantages of PEMS, (1) capability of collecting real-world data; (2) second-by-second data collection during the experiment, which provides enough data for statistical analysis; (3) capability of collection of corresponding engine performance data on a second-by-second basis, and (4) easy set-up on test vehicles.

The three data collection methods were widely used on different mobile sources for different emissions research topics. Table 2.1 summarizes some previous emissions studies using these data collection methods including the references, year, test vehicle type, and research topics.

Table 2.1 Summary of Previous Emissions Study with Different Data Collection Methods

Reference	Year	Method	Vehicle type	Topic
Zhang *et al*.	1995	Remote Sensing	On-road vehicle	Worldwide on-road vehicle exhaust emissions study
Wang *et al*.	1997	Dynamometer	Alternative fuel and diesel transit bus	Emissions comparisons from alternative fuel buses and diesel buses
Clark *et al*.	1999	Dynamometer	Diesel and CNG transit bus	Diesel and CNG transit bus emissions characterization
TTI	2006	PEMS	Diesel school bus	Collection and analysis of school bus emissions and activity data
Abolhasani *et al*.	2008	PEMS	Heavy duty vehicle	Real-world in-use activity, fuel use, and emissions for non-road construction vehicle: a case study for excavators
Serrano *et al*.	2012	Dynamometer	Biodiesel transit bus	Performance study about biodiesel impact on buses engines
Fu *et al*.	2012	PEMS	Heavy duty vehicle	Characteristics of typical non-road machinery emissions in China
Lee *et al*.	2012	PEMS	Light duty vehicle	Comparisons between Vehicular Emissions From Real-world In-Use Testing and EPA Moves Estimation
Hallquist *et al*.	2013	Remote Sensing	Diesel and CNG transit bus	Particle and gaseous emissions from individual diesel and CNG buses
Fu *et al*.	2013	PEMS	Diesel transit bus	NO_x emissions from Euro IV busses with SCR systems associated with urban and suburban driving patterns

2.2. Emissions Comparison

Several technologies for emissions reductions have been developed and used on mobile sources, such as alternative fuels and after-treatment devices. In order to evaluate their benefits, emissions rates resulting from these reduction technologies are quantified and compared to the vehicles without reduction technologies. This section introduces common comparison approaches applied to transit bus studies.

Hallquist *et al*. (2012) tested particles and gaseous emissions from diesel and CNG buses. A remote sensing method was applied to collect data from a European fleet with 28 diesel and seven CNG buses. The instruments measured the gaseous pollutants and particle concentrations of the exhaust samples, and fuel use was estimated based on the CO_2 concentration. Based on concentrations, sample flow, and fuel use, the emission rates of each pollutant (PM, CO_2, CO, HC and NO_x) were calculated on mass per distance or fuel used basis and then compared with the road vehicle emission model HBEFA 3.1.

Fu *et al*. (2013) used PEMS collected NO_x emission data from Euro IV buses to determine the impacts of Selective Catalytic Reduction (SCR) systems on NO_x emission rates. The NO_x emission rate comparison was made between buses with and without SCR, on mass per distance basis. Since vehicle speed was highly correlated with SCR work efficiency and NO_x emission rate, the comparison was separated in different speed modes.

Jayaratne et al. (2009) monitored exhaust emissions from 13 CNG and nine diesel transit buses on a chassis dynamometer. PM_{10}, CO_2, and NO_x were measured under four identical conditions, which were 0% (idle), 25%, 50% and 100% of the maximum engine power. Emissions of idle mode were presented on mass per time basis, and emissions of other three modes were compared on mass per distance basis for each pollutant between CNG and diesel buses.

Zhang et al. (2014) characterized real-world fuel use and CO_2 emissions for a transit bus fleet, containing diesel, CNG, LNG and hybrid buses, based on the 30 min on-board data obtaining by PEMS for each bus. The fuel use rate and CO_2 emission rate of each type of bus were compared on mass per distance basis. Also, the traffic patterns were separated in 16 modes by speed distributions and road conditions. The fuel use rates and CO_2 emission rates of all the modes were compared on mass per distance basis for each type of bus.

Texas Transportation Institute (2006) tested five diesel school buses by a PEMS, which represented a sampling of the Texas fleet. Emissions data included CO, HC and NO_x . To quantify route impacts on emissions, the tested buses were required to drive along the rural and urban routes. Emissions of tested buses driving on these two routes were compared on mass per distance basis.

Different comparison approaches were applied in previous studies to achieve different goals: (1) quantify the benefits advanced emission reduction technologies, including alternative fuels (CNG and Bio-diesel) and exhaust gas after-treatment devices (SCR); (2) assess the impacts of engine performances on emission rates such as vehicle speeds and engine loads; (3) estimate the outside influences on emission rates such as road conditions. In these methods, the emission rates were commonly compared in three ways: (1) Mass per time; (2) Mass per distance; and (3) Mass per energy (fuel used). Some of the comparison methods discussed here will be developed and utilized for the dissertation research for the OSU bus fleet.

2.3. Emissions Predictive Models

Several factors have significant impacts on vehicle emissions, such as engine performance and vehicle kinematic variables. Some pollutant emissions even have strong relationships with each other. To quantify these influences, emission predictive models have been developed in previous studies. This section will highlight approaches applied to build these models, such as regression, weighted average and artificial neural network (ANN).

Kamarianakis *et al*. (2013) developed a predictive regression model for particle number (PN) emission rates of diesel buses. Data were obtained from two conventional diesel buses in a Connecticut Transit bus fleet. Several models were built based on engine performance variables, vehicle kinematic variables, vehicle specific power (VSP) and gaseous emissions. A combined model was developed as well, which included kinematic variables, VSP and gaseous emissions as the predictors. Least Absolute Value (LAV) and Ordinary Least Squares (OLS) regression were applied to develop the models. R^2 values for each model were presented to assess the precision and appropriateness of the models.

Zhai *et al*. (2008) applied a discrete modes approach to build emissions predictive models for diesel transit buses. The data were collected from a fleet consisting of 12 diesel buses. The VSP data were separated into eight modes, and the average emission rate of each pollutant in each mode was calculated. Similarly, speed data were divided into five modes to develop other emissions models. Seven buses with available GPS data were contained in this model but not the entire fleet. A comparison between these two models was made to test their predictive power of total trip emissions. The two models were used to predict the total trip emissions of seven buses selected from the fleet. The predicted emissions values were compared with the measured emissions values in order to get the prediction error.

Regression and weighted average models are appropriate when dependent variables (emission rates) show linear relationships with independent variables, such as VSP and Speed. However, sometimes these models do not capture the emissions spikes resulting in low R^2 values (Mudgal *et al*., 2011). ANN approach is often applied because it can handle nonlinearity and has no requirements of assumptions on input data as needed by statistical models.

Mudgal *et al*. (2011) employed ANN based emissions predictive models for biodiesel transit buses after finding the linear models had low R^2 values (maximum of 0.47). The inputs of these models were biodiesel percentage, speed, acceleration, RPM, VSP, passenger count, intake air temperature (IAT), and manifold air pressure (MAP). The outputs included emission rates of CO_2, CO, HC, NO_x and PM. The data were divided into three parts, 70% for training the models, 15% for validation and the remaining 15% for testing the predictive power of the models. Validation is an important part of ANN, which is used to check and control overfitting of the data. Compared with regression models in the previous example, ANN based models have higher R^2 values.

Compared with regression and weighted average, ANN can develop more powerful predictive models, especially for nonlinearity. However, the complicated ANN models lead to longer computation time. As a result, regression and weighted average, which have shorter computation time, are more appropriate when the variables have strong linear relationships. Table 2.2 summarizes the previous emissions modeling using these three approaches.

Table 2.2 Summary of Previous Emissions Modeling using Different Approaches

Ref	Year	Approaches	Input	Output
Atkinson *et al*.	1998	ANN	IAT, RPM, fuel rack position, engine coolant temperature, exhaust gas temperature, and fuel rail temperature and pressure	Instantaneous engine torque, fuel use, exhaust gas temperature and emissions (CO_2, CO, HC and NO_x)
Desantes *et al*.	2002	ANN	Engine speed, fuel mass, air mass, fuel injection pressure, start of injection, EGR[a] and nozzle diameter	Emissions (NO_x and PM)and BSFC [b]
Taylor *et al*.	2004	Weighted average	Emissions data from UDDS [c] (CO_2, NO_x and PM)	Emissions of other dissimilar driving cycles (CO_2, NO_x and PM)
Zhai *et al*.	2008	Weighted average	VSP, Speed	Emissions(CO_2, CO, HC and NO_x)
Ghobadian *et al*.	2008	ANN	Speed and bio-fuel blend	Torque, SFC [d] and exhaust emissions (HC and CO)
Mudgal *et al*.	2011	ANN	Biodiesel percentage, speed, acceleration, RPM, VSP, passenger count, IAT and MAP	Emissions (CO_2, CO, HC, NO_x and PM)
Lewis *et al*.	2012	Regression	Fuel use	Emissions (CO_2)
Kamarianakis *et al*.	2013	Regression	Engine performance, vehicle kinematic, VSP, and gaseous emissions	Emissions (PN)

[a] EGR means exhaust gas recirculation rate
[b] BSFC means brake specific fuel consumption
[c] UDDS means urban dynamometer driving schedule
[d] SFC means specific fuel consumption

CHAPTER III

METHODOLOGY

This chapter presents the methodology used to characterize and analyze the emissions and fuel use data of the OSU Bus Fleet. It includes four sections: (1) characterization of OSU bus fleet data, (2) Comparison of emissions and fuel use rates, (3) Emissions and fuel use predictive models, and (4) Emissions and fuel use inventory.

3.1. Characterization of OSU Bus Fleet Data

This section presents the process to create the database of transit bus emissions and fuel use. The experimental instrumentation of a typical PEMS unit is described as well.

3.1.1. Bus Fleet Information

The case study bus fleet belongs to the Oklahoma State University (OSU)-Stillwater Community Transit system. This system provides transit service from 6:20 a.m. to 10:30 p.m., Monday through Friday, throughout the academic year and reduced routes during non-academic months. Two routes are available on campus during the day, and one route is used during the evening and summer sessions. Off campus, there are five routes during the day and one in the evening. These routes provide service to downtown, dining, and entertainment establishments. The stops may vary depending upon demands. OSU recently transitioned its bus fleet from diesel to CNG. The current fleet consists of 26 buses, including 19 CNGs and seven diesels. The CNG buses include nine 2010 El Dorado (referred to as "Big CNG") and ten 2010 Ford E450 (referred to as "Small CNG"). The diesel buses were retained from the previous fleet and include seven 2003 Blue Bird (referred to as "Diesel"). The diesel buses are used on "trail" routes to transport overflow passengers and are placed on fixed routes only when a CNG bus is taken out of service for maintenance. The specifications of the three types of buses are shown in Table 3.1.

Table 3.1 Vehicle Information

Parameter	Big CNG	Small CNG	Diesel
Model Year	2010	2009	2003
Manufacturer	E1 Dorado	Ford	Blue Bird
Model Type	Axess	E-450	NA
Vehicle Weight(lbs)	42,760	14,500	36,200
Displacement (L)	8.9	6.8	8.3
Cylinders	6	10	6
Transmission	Automatic	Automatic	Automatic
HP @ RPM	320@2,000	305@4,250	300@2,000
Torque @ RPM	1,000@1,300	420@3,250	860@1,300

3.1.2. Instrumentation Description

An Axion RS+ PEMS unit was used for the data collection procedure, which contains several emission measurement instruments. Two non-dispersive infrared (NDIR) analyzers measure three gaseous pollutants concentrations, which are carbon dioxide (CO_2), hydrocarbons (HC) and carbon monoxide (CO). HC is non-methane hydrocarbons (NMHCs) since Axion Rs+ measures and reports HC as propane. Two electrochemical sensors (E-Chem) measure nitrogen oxides (NO_x). There is a zeroing instrument built into the Axion software so that while one analyzer (or sensor) is referencing ambient air, the other is still collecting data; this allows continuous and reliable data collection. For particle measurements, an advanced laser diode forward light scattering sensor can measure the concentration of particulate matter 10 (PM_{10}). However, particle emissions of both diesel and CNG buses are small size fine particles or ultrafine particles, which are too small to be measured by the laser scatter. Because of this limitation, particle emissions were not included in this study. Table 3.2 shows the specifications of those emission measurement instruments. To ensure data accuracy, the system was calibrated after every 10 hours operation, using Bar 97 low calibration gas (C_3H_8 203 ppm, CO 0.50%, CO_2 6.00%, NO 302ppm).

Table 3.2 Axion RS+ Pollutant Measurement Instruments Specifications

Gas	Measurement Range	Accuracy	Resolution	Type of Measurements
HC	0-4000 ppm	±8 ppm abs. or ±3% rel.	1 ppm	NDIR
CO	0.00-10.00%	±0.02% abs. or ±3% rel.	0.001 vol. %	NDIR
CO_2	0.00-16.00%	±0.3% abs. or ±3% rel.	0.01 vol. %	NDIR
NO_x	0-4000 ppm	±25 ppm abs. or ±4% rel.	1 ppm	E-Chem
PM_{10}	0.00-300 mg/m^3	NA	0.01 mg/m^3	Laser Scatter

Considering the scope limitation of the laser scatter, only one probe was inserted into the tailpipe of the tested buses to collect exhaust samples for gaseous pollutant emissions measurement (CO_2, HC, CO and NO_x). The probe sent the samples through a sample hose to the E-Chem sensors and NDIR analyzers, which were in a luggage-size case (main unit of PEMS). After processing by the PEMS, exhaust samples were removed through the exhaust instrument tubes. The emissions data were transmitted to a system computer, which was also contained in the main unit.

An OBD sensor was connected to the engine in order to measure engine performance data including Revolutions per Minute (RPM), Intake Air Temperature (IAT), Manifold Absolute Pressure (MAP), Engine Load (LOAD), Vehicle Speed (SPEED), air inflow and exhaust flow rate. The engine data were sent back to the system computer via a RS 232 cable. A global positioning system (GPS) was used to measure global positioning data. All the measured data were combined by the computer and displayed on its screen so that the whole process could be monitored.

3.1.3. Field Data Collection

The data collection procedure was divided into four steps, which were pre-installation, installation, data collection and decommissioning. At least one hour was needed to set up all of the PEMS instruments. Since transit buses always began service in the early morning, pre-installation was done during the previous evening before the data collection day, when the tested bus was out of service and back at the fueling station.

During the pre-installation step, other accessories were installed. A metal clamp was used to fix the probe to the tailpipe of tested bus. One port of the sample hose was connected to the probe, and the other port was put through the window at the end of the bus, where the main unit was placed. The exhaust tubes were directed out of the same window. The OBD sensor was connected to the engine and the RS 232 table, and the other port of RS 232 was set close to the main unit location.

During the installation phase, the main unit needed at least 30 minutes to warm up at the laboratory before collecting data. After that, the unit and other accessory equipment were brought on the bus. The main unit was connected with all the accessories placed in pre-installation stage, which were the sample hoses, exhaust tubes and RS 232 cable. The GPS was connected to the main unit as well. An independent battery (12-14DC) was also carried on the bus to supply power for the PEMS.

During the data collection procedure, the following data were collected and displayed on the system computer screen on a second-by-second basis while the bus drove along its route:

pollutant concentrations, engine performance data, and global positioning data. Emissions rates of all pollutants and fuel use rates were calculated by the computer and also displayed on a second-by-second basis. All the data were automatically saved in a txt file. One researcher was required to stay on the bus to monitor the operation of the PEMS during this procedure to ensure that the PEMS unit was functioning properly and also to protect the unit from damage. Figure 3.1 shows the work process of the PEMS during data collection.

After data collection, the researcher on the bus copied the .txt file to a flash drive, shut down the system computer, and disconnected all the accessories. Due to the schedule, the bus usually stopped for 10 to 15 minutes at the Multi-Modal Transportation Terminal. During that period, the researcher removed all equipment from the bus to finish the decommissioning phase.

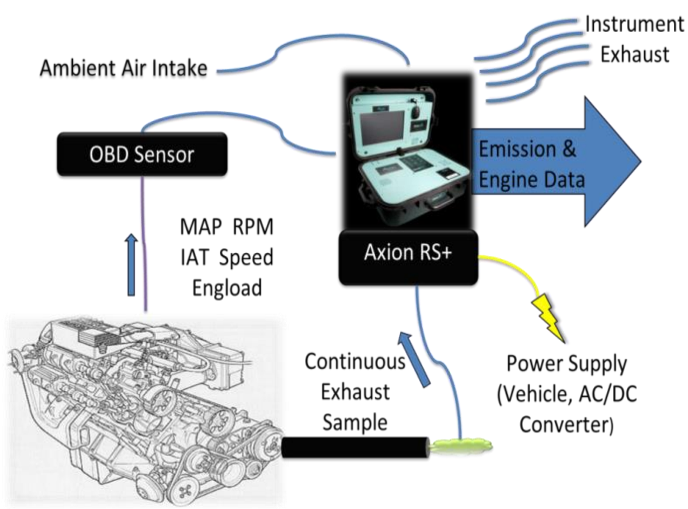


Figure 3.1 PEMS Work Process

3.1.4. Emissions Rates and Vehicle Activity Data

This section is to present the analytical methods used to estimate real-world emission rates and vehicle activity data of tested buses. The field data was collected from five Big CNG buses (32 seats) and five Small CNG buses (19 seats), and three Diesel buses (27 seats). Summary statistics including maximum (MAX), minimum (MIN), mean (AVG), standard deviation (SD), and coefficient of variation (CV) - which is the standard deviation divided by the mean, were computed for each pollutant, fuel use, and each engine performance parameter.

Summary statistics were computed for pollutant emissions rates of NO_x , HC, CO, and CO_2. Fuel consumption rates were also included in this analysis. Summary statistics were computed for common engine performance parameters as well, including revolutions per minute (RPM), manifold absolute pressure (MAP), intake air temperature (IAT), engine load (LOAD), and vehicle speed (SPEED). Summary statistics reveal the central tendencies and variation in the data and permit comparisons of different data categories. It is the first step of data processing, which presents the data characteristics.

3.2. Comparison of Emissions and Fuel Use Rates

Emissions and fuel use of vehicles are usually compared in order to quantify the benefits of advanced alternative fuels and emission reduction technologies, or estimate the influences of vehicle activity. This section briefly presents the comparison bases and approaches involved in this study. Emissions data of all gaseous pollutants (CO_2, CO, HC, and NO_x) and fuel use data were used for the comparisons.

3.2.1. Comparison Bases

Three common unit bases of emission rate comparisons were used: (1) mass per time; (2) mass per distance and (3) mass per fuel used. The basis of fuel use comparisons is presented as well.

1. Mass per time

The PEMS measures and reports data for emission rates on a gram per second basis (g/s). The average emission rate of each pollutant was compared among all the tested vehicles, and the preliminary findings from this comparison lead to more specific comparisons. This unit basis was also used to make the comparisons among different operational modes and engine modes.

Furthermore, emission rates on a gram per second basis were converted to gram per hour and kilogram per hour basis when they were used for mass per distance and mass per fuel used conversions.

2. Mass per distance

The mass per time emissions rates were converted to mass per distance rates based on the following equation:

$$E_D = \frac{E_T}{S} \qquad \text{Equation 1}$$

Where:
E_D=Emission rates (g/km)
E_T=Emission rates (g/hr)
S=Vehicle Speed (km/hr)

Considering the nature of this equation, S (km/hr) cannot be zero. Thus, it was not appropriate to use this equation when a tested bus was idling. Idling emission data need to be removed before the conversion. Furthermore, this equation would have a large value when the bus speed was low. Although the value was reasonable for that second, it could cause bias when calculating the average emission rates for a specific distance. To avoid this bias, average E_T (g/hr) and average S (km/hr) were calculated first, and then converted using Equation 1 to get unbiased average E_D (g/km) for a period or a route. Mass per distance is a common basis for emission data collected from dynamometer tests. In this study, this basis was used to characterize operation impacts on transit bus emission rates.

3. Mass per fuel used

In order to compare the average emission rates for CNG and diesel fuels, the emission rates were converted to mass per fuel used basis (grams per gallon) using Diesel Gallon Equivalents (DGE). DGE is the amount of alternative fuel it takes to equal the energy content of one liquid gallon of diesel.

A standard unit of measurement for CNG was developed by the National Conference of Weights & Measurements (NCWM). This unit is 1 diesel [US] gallon equivalent (DGE) per 6.31 pounds of natural gas. A CNG to DGE conversion index of 1.257(DGE/hr)/(g/s) was developed with this measurement value. It means that 1.257 DGE of fuel will be consumed per hour if the fuel use output from the PEMS is 1 gram per second. Similarly, based on the diesel density (3.2 kg/gallon), the diesel DGE conversion was developed, which is 1.125 (DGE/hr) / (g/s). Based on the DGE conversion index and fuel use, the emission rates were converted from mass per time to mass per DGE (Equation 2).

$$E_F = \frac{E_T}{FC \times A} \qquad \text{Equation 2}$$

Where:
E_F=Mass per fuel used emission rates (kg/DGE)
E_T=Mass per time emission rates (kg/hr)
FC=Fuel Consumption (g/s)
A=DGE conversion index; for CNG bus, it is 1.257(DGE/hr)/(g/s); for diesel bus, it is 1.125(DG/hr)/(g/s).

Similar to the mass per distance basis conversion equation, this equation gives large emission rate values when the fuel use is low, which leads to bias in average emission rates. As a result, average E_T (g/s) and average FC (g/s) were calculated first, and then converted using Equation 2 to get unbiased average E_F (kg/DGE) for a period or a route. In this study, this basis was used to characterize operation impacts on transit bus emission rates.

4. Fuel use comparison basis

This study also includes three bases of fuel use. The original fuel use data were reported by the PEMS on mass per time basis (gram per second). When presenting the fuel use of a bus in non-idling modes, the original data were converted to mass per distance basis (gram per kilometer) based on the speed data. When comparing the fuel use between different fuel types, according to the DGE conversion index, the fuel use data were converted to gallon per time basis (DGE per hour).

3.2.2. Comparison Approaches

The objective of the comparisons in this study is to: (1) quantify the emissions and fuel benefits of CNG compared with diesel; (2) assess the operational influences on emissions and fuel use rates of tested buses; and (3) estimate the engine activity impacts on emissions and fuel use rates of tested buses. This section presents the approaches used to achieve these goals.

Before the specific comparisons, a summary table was made for the bus fleet, which contains the average emissions and fuel use rate of each tested bus. This table reveals the variability of emissions and fuel use rates among the individual bus, which would be the base to make the specific comparisons.

3.2.2.1. CNG vs. Diesel Comparison

In order to compare the emissions rates between CNG and Diesel fuels, mass per time emissions rates were converted to mass per fuel used rates. A summary table was made containing the average mass per fuel used emissions rates of each tested bus in order to give an overview of the database. Mass per time fuel use rates were also converted to gallon per time rates, and the average gallon per time fuel use rates of all tested buses were added in the summary table. The average mass per DGE emissions rates and DGE per hour fuel use rates of each type of buses were calculated and displayed in the histograms.

3.2.2.2. Operational Modal Comparison

This section presents a method to evaluate the operational impacts on emissions and fuel use rates of all tested buses, with the following steps.

1. Determine operational modes

To assess the operational influence, the operational modes were categorized as idle, cruising, acceleration and deceleration (Frey et al., 2001; 2002). Idle was defined as zero speed and zero acceleration. To define the acceleration mode, several considerations were included. Firstly, the vehicle should be moving and increasing in speed; therefore, both speed and acceleration must be greater than zero. However, if vehicle speed varied slightly the mode was typically judged as cruising. As a result, in most instances, the acceleration mode needed a minimum acceleration of two mph/sec. Deceleration was defined in a similar manner, but the criteria for deceleration were based on negative acceleration rates. All other situations not classified were classified as cruising. The cruising mode was approximately steady-speed driving but some drifting of speed was allowed. All of the second-by-second data for each tested bus were categorized and separated into these four modes.

2. Quantify the amount of time spent on each operational mode

The amount of time spent on each operational mode for each tested bus was quantified. Based on that, the fraction of time spent on each mode was also calculated. Furthermore, in order to compare the time distribution among the three types of buses, the average percentage of time spent on each operational mode was calculated for each type of bus.

3. Categorize operational mode data for each tested bus

In order to assess the relative importance of each operational mode, the average emissions and fuel use rates (g/s) of the four modes were calculated for each tested bus. The average emissions rates were also converted from mass per time basis to mass per fuel used basis, and mass per distance basis. Similarly, the average fuel use rates were also converted from mass per time basis to gallon per time basis, and mass per distance basis. All of these values were summarized in the operational mode dataset table for each tested bus. The table also included the amount of time in each mode and the data collection information. All the operational mode analyses were based on these analysis tables.

4. **Analyze the relationship between operational modes and emissions and fuel use rates among bus type**

The average emissions and fuel use rates of each operational mode of each bus type were calculated and plotted in histograms, in order to identify if operational mode had similar impacts on emissions and fuel use rates for the different bus types. The same analysis was made on mass per distance and mass per fuel used rates as well.

5. **Assess the relative importance of each operational mode on emissions and fuel use rates**

The percent of time, emissions and fuel use of each operation mode were calculated and compared with each other for each type of buses. The modes with less percent of time but more emissions and fuel use were identified as the ones with more relative importance on emissions and fuel use. The results of all types of buses were also compared to find if each operational mode has the same relative importance for each type of buses.

3.2.2.3. Engine Modal Comparison

This section discusses the methodology used to quantify the engine performance impacts on emissions and fuel use rates of all tested buses. Several tasks are conducted to develop this method.

1. **Choose one engine parameter to identify the engine modes**

Based on the dataset, several engine parameters were checked to identity engine variables that were highly correlated with emissions and fuel use rates. These variables included RPM, MAP (or MAF) and LOAD. Among these three parameters, RPM had the highest correlation values and lowest coefficient of variation values for most test buses. Furthermore, RPM may be read directly from the vehicle dashboard, which facilitates data collection. Thus, in this study, RPM was chosen as the indicator of engine modes.

2. Categorize the RPM into 10 engine modes for each tested bus

The dataset shows tested buses have various ranges of RPM values, especially among different types of buses. In order to compare the buses on a consistent basis with RPM values, the measured RPM values were normalized by the following equation:

$$RPM_{nor} = \frac{RPM - RPM_{min}}{RPM_{max} - RPM_{min}} \qquad \text{Equation 3}$$

Where,
RPM_{nor} = Normalized RPM for a measured RPM for a specific item of equipment
RPM_{max} = Maximum RPM for a specific item of equipment
RPM_{min} = Minimum RPM for a specific item of equipment
RPM = Measured RPM for a specific item of equipment

Considering the character of this equation, the overall normalized RPM values range from zero to one (or 0% to 100%). The normalized RPM values from minimum to maximum were further categorized into 10 individual bins, ranging from 0 to 0.1, 0.1 to 0.2…0.9 to 1.0. These 10 bins represent the 10 engine modes. For example, 0.0 to 0.1 refers to engine mode 1; and 0.1 to 0.2 refers to engine mode 2. Engine mode 1 typically represents the minimum load imposed on the engine, and engine mode 10 represents the maximum engine load.

3. Quantify the amount of time spent on each engine mode

The amount of time spent on each engine mode for each tested bus was quantified. Based on that, the fraction of time spent on each engine mode was also calculated. Furthermore, in order to compare the time distribution among the three types of buses, the average percentage of time spent on each engine mode was calculated for each type of bus. Histograms were developed for time distribution among engine modes, which were used to demonstrate the relationships among the time spent on all engine modes of each type of buses.

4. Quantify the average emissions and fuel use rates for each engine mode

In order to demonstrate the relationships between the engine modes and emissions and fuel use rates, the average emissions and fuel use rates of all engine modes were calculated and histograms were plotted for all tested buses. These histograms were also compared with the time histogram in order to find the relationship between emissions and fuel use rates, and time distribution among the ten engine modes. The overall average emissions and fuel use rates of each engine mode for each type of bus were also calculated and plotted, which were then used to compare the results among the three types of buses.

5. Calculate weighted average emissions and fuel use rates for each engine mode

For each tested bus, the weighted average emissions and fuel use rates of each engine mode were calculated by multiplying the percent of time and the average emissions and fuel use rates of that particular engine mode. The total weighted average emissions and fuel use rates of each bus were also calculated by the following equation:

$$TW\ E_T = \sum_{i=1}^{10} T_i \times E_{Ti} \qquad \text{Equation 4}$$

$$TW\ F_T = \sum_{i=1}^{10} T_i \times F_{Ti} \qquad \text{Equation 5}$$

Where,
TW E_T= Total weighted average mass per time emission rates (g/s)
TW F_T= Total weighted average mass per time fuel use rates (g/s)
T_i=Percent of time for i^{th} engine mode, i=1, 2, 3…10
E_{Ti}=Mass per time emission rates for i^{th} engine mode, i=1, 2, 3…10
F_{Ti}=Mass per time fuel use rates for i^{th} engine mode, i=1, 2, 3…10

3.3. Emissions and Fuel Use Predictive Models

In order to estimate emissions and fuel use rates based on engine performance, predictive models were developed for each pollutant and fuel use using engine performance data. The engine performance data included RPM, IAT, MAP (or MAF), LOAD, and SPEED. Two-third of the data for each tested bus was used as the training set, and the one-third of data was used for validation of the models. Multiple Linear Regression (MLR) was used to develop the predictive models.

3.3.1. Correlation Matrix

Correlations were used to assess the dependent relationships between emissions, fuel use and engine performance variables. There are several correlation coefficients to measure the degree of correlations. In this research, the Pearson correlation coefficient was used, which is considered to be the most common and sensitive only to a linear relationship between two variables. The Pearson correlation coefficient's range is (-1 to +1). Positive one indicates a perfect increasing relationship and negative one indicates a perfect decreasing relationship. A correlation matrix is expressed by a table, which displays the coefficients of the columns and rows. In this study, emissions, fuel use and engine variables were included in the matrix in order to assess their relationship with each other.

3.3.2. Prediction Models using Multiple Linear Regression (MLR)

A Multiple Linear Regression model is a model that numerically describes the linear correlations between a single dependent variable and two or more independent variables. In this study, a model was developed for each of the four gaseous pollutants and fuel use, respectively based on the engine performance variables. The model is written in the form:

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \cdots + \beta_m X_m \qquad \text{Equation 6}$$

In this equation, Y is the dependent variable, which is the predictive value of each pollutant emission rate (or fuel use). The independent variables, X_i, i=1, 2…, m, are the engine performance variables, such as MAP, RPM and IAT. β_0 is the intercept, and β are the parameters for each independent variable. The $\beta_{i,}$ i=1, 2…, m, and β_0 were estimated based on the dependent and independent variables data. The model development process was conducted using the statistical software, SAS 9.3. The units of dependent and independent variables in the models was the original unit reported by PEMS, which are gram per second for CO_2 and FC; milligram per second for CO, HC and NO_x; revolution per minute for RPM; Celsius degree for IAT; kilo Pascal for MAP (or gram per second for MAF); percent (%) for LOAD, and kilometer per hour for SPEED.

The first step of model development was to examine if all the independent variables were necessary or a subset of them was adequate. In order to achieve this goal, the stepwise model selection method was applied which is a semi-automated procedure of building a model by adding or removing variables. This selection process started with no independent variables in the model, tested the addition of each variable, added the variable that improved the model the most, and repeated this process until none improved the model. If the variables that had been included in the beginning were no longer significant, those variables would be eliminated in the model. The p-value of each independent variable was checked to determine if this variable should be included in the model. If p-value of was less than 0.05, the variable was significant of the model; in other words, the variable should be included in the model. Conversely, if p-value was greater than 0.05, the variable should be excluded from the model.

After the stepwise model selection, an important statistics of the MLR model was checked for each independent variable, which is the Variance Inflation Factor (VIF). VIF was used to quantify the severity of multicollinearity in the MLR model. When multicollinearity occurs in the MLR model, it means two or more independent variables are highly correlated. Although it does not reduce the predictive power and accuracy of the model, it may make the model more complicated and cumbersome. A VIF of 5 or above indicates a multicollinearity problem. In this study, an independent variable that was bigger than VIF=5 would be excluded. The model would be adjusted until all the VIF values of independent variables were smaller than 5.

After model development, SAS 9.3 provided several statistics to assess the appropriateness of the model, such as root of mean square error (Root MSE) and R-square. Root MSE is the square root of the mean square error of the models, and lower Root MSE values indicate there are fewer errors in the models. R-square refers to coefficient of determination, which is a measurement of the effect of the independent variables in reducing the variation in dependent variable. It ranges from zero to positive one (or 0% to 100%). Zero (or 0%) indicates that the model explains none of the variability of the response data, and positive one (or 100%) indicates that the model explains all the variability of the response data. In this study, R-square was used to evaluate the appropriateness of the multiple linear regression models.

3.3.3. Model Validation

Model validation was used to determine how well the results from the predicted models fitted the actual data. After the predictive models were developed based on the two-third of total data for the tested bus, they were used to predict the emissions and fuel use rates of the remaining one-third data; then, simple linear regression analysis was conducted between the actual values and the predicted values of the remaining one-third data by Excel 2010. Simple linear regression is a method to describe the linear relationship between two variables. The software provided the equation in the following form. The R-square value of this equation was also estimated by Excel 2010.

$$Y = mX + b \qquad \text{Equation 7}$$

In equation 7, m was a parameter to assess the accuracy of the predictive model; the closer it was to 1, the accuracy was higher. The parameter b was used to assess the bias of the predictive model. A higher b value showed a greater bias. The R-square was used to assess the precision of the predictive model. Its range was from zero to positive one (0% or 100%). Positive one (or 100%) indicated 100% precision, and zero (or 0%) indicated 0% precision. Model validation was conducted for all MLR predictive models.

3.3.4. Variable Impact Analysis

A statistics method was developed to assess the impacts of each engine variable on MLR models of each type of buses. The stepwise selection has already made for each model of each tested bus in model development section. The order number of each variable of each model was filled in the variable impact table for Big CNG, Small CNG, and Diesel buses, respectively. There were several models excluding some engine variables because either the variables were not significant, or the variables led to multicollinearity problems. The order number of these excluding variables was six.

Then, the order numbers of each engine variable were summed for each type of buses. These summation values were the impact parameters, which stood for the impacts of the engine variables in each type of buses. The smaller values of impact parameters indicated that the engine variables had more influences on the models.

3.4. Emissions Inventory

An emissions inventory itemizes the quantities of air pollutants emitted for a specific area, period, and set of sources. This section introduces a methodology developing the emission inventory for the current OSU CNG bus fleet and the old diesel bus fleet. The goal of this research is to assess the environmental impacts of the CNG bus fleet. There are two primary components of the emissions inventory: (1) annual fuel use; and (2) estimated annual emissions.

3.4.1. Annual Fuel Use

The OSU fleet owner provided a fuel use database of the old diesel bus fleet, which contains the number of gallons of diesel fuel consumed by, and the operational hours of, each diesel bus during 2009 to 2010. Based on this database, the annual fuel use (DGE/yr) and the annual operation hour (hr/yr) of the diesel bus fleet were calculated.

The fuel use data of the current CNG bus fleet was not provided. Since the transit system did not change the routes when switching from the diesel fleet to the CNG fleet, it is appropriate to assume that the annual operation hour of the fleet kept same these years. Thus, the annual operation hour of the CNG fleet were roughly estimated as the diesel fleet's annual operation hour. Because there are nine Big CNG buses and 10 Small CNG buses, the annual operation hour of the Big CNG buses was estimated as the 9/19 of the total annual operation hour, and the annual operation hour of the Small CNG buses was estimated as the 10/19 of the total. Then, the annual fuel use (DGE/yr) of the Big CNG fleet and the Small CNG fleet were estimated as multiplying their annual operation hour (hr/yr) by their average fuel use rates (DGE/hr), respectively. The summation of the annual fuel use of the Big CNG fleet and the Small CNG fleet is the annual fuel use of the whole CNG fleet.

3.4.2. Estimated Annual Emissions

For the diesel fleet, the average emissions rates (g/DGE) of each bus were multiplied by its annual fuel use (DGE/yr), and then, the summation of the annual emissions of all diesel buses were the annual emissions of the diesel fleet. Since there were only three diesel buses were tested, the emissions rates of the other buses were estimated as the average emissions rates of the three tested buses.

For the CNG fleet, there were only estimated annual fuel uses of the Big CNG and Small CNG fleet. Thus, the annual emissions of the Big CNG fleet were roughly estimated as multiply the average emissions rates (g/DGE) of the tested Big CNG buses by its annual fuel use (DGE/yr). The annual emissions of the Small CNG fleet were estimated by the same procedure. The summation of these two CNG fleets was the annual emissions of the whole CNG fleet.

CHAPTER V

RESULTS

4.1. Characterization of OSU Bus Fleet Data

This section presents the characters of OSU bus fleet data, including field data collection, and emission rates and vehicle activity data.

4.1.1. Field Data Collection

Table 4.1 shows the summary of the field data collection effort. 11 of the field tests were completed in 2013 and three in 2014. The buses were tested on eight different routes including a variety of on- and off-campus routes. There were approximately 59,000 seconds (16 hours) of data collected for the Big CNG buses, approximately 39,000 seconds (11 hours) for the Small CNG buses, and approximately 32,000 seconds (9 hours) for the diesel buses; thus, the overall data collection effort yielded over 36 hours of usable data on a second-by-second basis. Although the information was not used for this research project, the research team recorded the ambient temperature and humidity at the time of the test. The bus number was used to represent tested buses in the result chapter. Big CNG 1568 bus was tested two times on two different routes. The two tests were numbered as Bus 1 and Bus 2, so that the data of both tests could be analyzed.

Table 4.1 Data Collection Summary

Bus Type	Bus No.	Bus ID	Date	Route	Data (s)	Ambient Conditions	
						T (℃)	H (%)
Big CNG	1	1568	03.19.2013	Gray	9831	3	61
	2	1568	09.11.2013	Orange	5926	30	43
	3	1572	09.19.2013	Gray	11855	22	78
	4	1566	09.20.2013	Scarlet	9560	18	77
	5	1567	09.27.2013	White	10047	28	54
	6	1569	11.08.2013	Orange	11544	7	76
Small CNG	7	1555	03.21.2013	Gray	10001	3	40
	8	1556	09.13.2013	Blue	8923	24	60
	9	1560	10.08.2013	Black	7315	6	92
	10	1561	12.20.2013	Purple	6582	5	56
	11	1558	06.12.2014	Blue	6319	20	82
Diesel	12	1530	03.20.2013	Gray	13256	-2	40
	13	1544	07.10.2014	Brown	9234	23	73
	14	1532	07.16.2014	Gray	9232	18	81

4.1.2. Emissions Rates and Vehicle Activity Data

Typical statistics values were calculated for each variable of engine performance data (RPM, IAT, MAP, LOAD and SPEED), emissions data (CO_2, CO, HC and NO_x), and fuel consumption data (FC). These statistics included maximum, minimum, mean, standard deviation, and coefficient of variation. Table 4.2, Table 4.3and Table 4.4 present the summary statistics for the Big CNG, Small CNG, and Diesel buses respectively. These tables include values for vehicle and engine activity data, emissions rates, and fuel consumption (FC) rates. Note that Table 4.2 and Table 4.4 provide MAP data and Table 4.3 provides mass air flow (MAF) data in lieu of MAP. MAP data was not available through the OBD system on the Small CNG buses but MAF data was available. Either MAP or MAF is required by the Axion RS+ to calculate the mass per time emissions rates based on pollutant concentrations in the exhaust flow from the tailpipe.

For the Big CNG buses shown in Table4.2, the average values for each engine activity parameter are quantitatively similar for all five buses (six tests). There tends to be more variability in LOAD and SPEED than the other parameters as indicated by their higher values of CV. With regard to emissions, the average mass per time emission rates of each pollutant and average fuel use rates are quantitatively similar for all six tests. The average CO emission rate of Bus 1, however, is approximately twice that of any of the other four Big CNG buses, even much higher than it tested on another route (Bus 2). In general, there tends to be more variability in the average emission rates of CO and NO_x than the other pollutants, as indicated by their higher values for CV.

For the Small CNG buses shown in Table 4.3, the average values for each engine activity parameter are quantitatively similar for all five buses. There tends to be more variability in MAF and SPEED than the other parameters as indicated by their higher values of CV; however, Bus 10 exhibited much higher variability in IAT than the other four Small CNG buses. With regard to emissions, the average mass per time emission rates of each pollutant and average fuel use rates are quantitatively similar for all five Small CNG buses. Bus 10, however, produced extremely high average emission rates of CO and NO_x compared to the other four Small CNG buses. Conversely, Bus 9 had a very low (nearly zero) average emission rate of CO. Similarly to the Big CNG buses, there tends to be more variability in the average emission rates of CO and NO_x than the other pollutants for the Small CNG buses based on their values of CV.

For the diesel buses shown in Table 4.4, the average values for each engine activity parameter are quantitatively similar for all three buses. There tends to be more variability in SPEED and LOAD than the other parameters as indicated by their higher values of CV. With regard to emissions, the average mass per time emission rates of each pollutant and average fuel use rates are quantitatively similar for all three diesel buses. However, Bus 13 produced extremely high average emission rates of CO compared with the other two diesel buses. Furthermore, there tends to be more variability in the average emission rates of CO than the other pollutants for the diesel buses, which are indicated by their CV values.

Table 4.2 Summary Statistics for Big CNG Buses

	RPM	IAT (℃)	MAP (kPa)	LOAD (%)	SPEED (km/hr)	CO_2 (g/s)	CO (mg/s)	HC (mg/s)	NO_x (mg/s)	FC (g/s)
					BUS 1					
MAX	2,200	44	250	100	82	50	6,600	200	53	19
MIN	630	11	97	0.0	0.0	0.0	0.0	0.0	0.0	0.0
AVG	1,200	27	120	34	25	12	160	10	1.3	4.6
SD	360	5.6	35	27	24	11	440	13	3.0	4.0
CV	0.30	0.21	0.29	0.79	0.96	0.92	2.8	1.3	2.3	0.87
					BUS 2					
MAX	2,200	57	240	99	51	45	3,400	210	67	17
MIN	630	33	97	0.0	0.0	0.0	0.0	0.0	0.0	0.0
AVG	1,100	51	100	33	12	10	55	5.4	1.7	3.7
SD	290	4.6	18	18	13	6.20	170	7.9	4.2	2.3
CV	0.26	0.09	0.18	0.55	1.1	0.62	3.1	1.5	2.5	0.62
					BUS 3					
MAX	2,200	58	260	100	98	35	4,200	190	100	13
MIN	610	29	97	0.0	0.0	0.0	0.0	0.0	0.0	0.0
AVG	1,200	46	120	40	24	8.5	88	8.2	1.5	3.2
SD	350	5.3	41	28	25	7.3	240	10	4.8	2.7
CV	0.29	0.13	0.23	0.68	0.86	0.80	2.9	0.89	1.9	0.79
					BUS 4					
MAX	2,100	45	210	99	74	45	5,300	210	54	17
MIN	590	21	98	0.0	0.0	0.0	0.0	0.0	0.0	0.0
AVG	1,200	34	110	40	22	11	76	18	1.6	4.2
SD	350	4.5	25	27	19	8.8	220	16	3.1	3.3
CV	0.29	0.13	0.23	0.68	0.86	0.80	2.9	0.89	1.9	0.79
					BUS 5					
MAX	2,200	55	240	100	56	46	3,100	170	52	17
MIN	580	35	97	0.0	0.0	0.0	0.0	0.0	0.0	0.0
AVG	1,100	47	110	37	15	10	81	7.2	1.3	3.7
SD	340	3.9	26	23	15	8.1	220	12	3.1	3.0
CV	0.31	0.08	0.24	0.62	1.0	0.81	2.7	1.7	2.4	0.81
					BUS 6					
MAX	2,200	42	240	100	61	32	1,800	200	140	12
MIN	590	12	98	0.0	0.0	0.0	0.0	0.0	0.0	0.0
AVG	1,100	29	110	33	12	6.1	29	3.0	1.7	2.2
SD	300	5.0	22	20	14	4.4	84	7.0	4.8	1.6
CV	0.27	0.17	0.20	0.61	1.2	0.72	2.9	2.3	2.8	0.73

Table 4.3 Summary Statistics for Small CNG Buses

	RPM	IAT (℃)	MAF (g/s)	LOAD (%)	SPEED (km/hr)	CO_2 (g/s)	CO (mg/s)	HC (mg/s)	NO_x (mg/s)	FC (g/s)
					BUS 7					
MAX	3,600	28	110	97	74	18	560	53	100	6.7
MIN	380	7.0	5.6	15	0.0	0.0	0.0	0.59	0.0	0.0
AVG	1,200	16	27	37	26	4.1	45	4.3	11	1.6
SD	640	4.2	25	18	23	3.9	72	3.4	15	1.5
CV	0.53	0.26	0.93	0.49	0.88	0.95	1.6	0.79	1.4	0.94
					BUS 8					
MAX	3,700	68	130	100	89	20	430	46	210	7.8
MIN	440	31	4.7	15	0.0	0.15	0.0	0.37	0.0	0.1
AVG	1,300	44	34	54	28	5.4	41	4.3	12	2.0
SD	760	9.4	30	19	25	4.6	60	3.0	15	1.8
CV	0.58	0.21	0.88	0.35	0.89	0.85	1.5	0.70	1.3	0.90
					BUS 9					
MAX	3,300	47	100	100	61	16	4.9	55	74	5.9
MIN	490	20	5.8	15	0.0	0.37	0.0	0.80	0.0	0.1
AVG	990	31	20	36	14	3.0	0.0	9.3	8.8	1.1
SD	510	5.8	19	14	14	2.9	0.13	7.0	13	1.1
CV	0.51	0.19	0.95	0.40	1.0	0.96	20	0.75	1.5	0.96
					BUS 10					
MAX	3,600	18	120	100	88	16	750	130	410	6.2
MIN	520	0.0	5.7	14	0.0	0.0	1.2	1.0	0.0	0.0
AVG	1,100	4.9	22.0	34	23	2.7	130	7.5	43	1.1
SD	560	5.6	22	15	26	2.7	130	6.7	66	1.1
CV	0.52	1.2	0.99	0.43	1.1	1.0	1.0	0.90	1.5	1.0
					BUS 11					
MAX	4,100	63	170	100	73	26	39	38	100	10
MIN	500	27	5.7	16	0.0	0.10	0.0	0.46	0.0	0.0
AVG	1,200	39	31	49	28	4.7	0.6	6.3	3.6	1.7
SD	640	10	29	20	24	4.4	1.9	5.8	11	1.6
CV	0.53	0.25	0.94	0.41	0.86	0.94	3.1	0.92	3.1	0.94

Table 4.4 Summary Statistics for Diesel Buses

	RPM	IAT (℃)	MAP (kPa)	LOAD (%)	SPEED (km/hr)	CO_2 (g/s)	CO (mg/s)	HC (mg/s)	NO_x (mg/s)	FC (g/s)
					BUS 12					
MAX	2300	31	220	100	85	38	210	20	180	12
MIN	770	12	64	0.0	0.0	0.01	0.0	0.89	0.13	0.01
AVG	1200	22	98	35	23	7.5	1.9	4.5	34	2.4
SD	450	3.2	46	34	25	10	7.7	3.7	35	3.1
CV	0.38	0.15	0.47	0.97	1.1	1.3	4.1	0.82	1.0	1.3
					BUS 13					
MAX	2500	57	270	100	94	65	8000	72	190	21
MIN	780	32	100	0.0	0.0	0.0	0.0	0.0	0.0	0.0
AVG	1400	45	140	13	26	10	85	8.9	41	3.3
SD	390	4.4	45	24	24	13	360	7.0	39	4.2
CV	0.28	0.10	0.32	1.8	0.92	1.3	4.2	0.79	0.95	1.3
					BUS 14					
MAX	2200	48	260	100	91	40	270	39	230	13
MIN	770	30	100	0.0	0.0	0.0	0.0	0.0	0.07	0.0
AVG	1300	37	130	28	25	7.9	20	6.0	46	2.5
SD	400	2.6	42	31	24	9.4	22	4.2	43	3.0
CV	0.31	0.07	0.32	1.1	0.96	1.2	1.1	0.70	0.93	1.2

Although the average emissions and fuel use rates are quantitatively similar for all individual buses in each bus type, the values are not equal. In order to assess the variability among the individual buses, A Tukey test was conducted for each pollutant emission rate and fuel use rate for each bus type. This test was used to classify which data are significantly different with others. Table 4.5 presents the test results of Big CNG buses. The values with parentheses mean there is no statistically significant difference between the two buses. For example, regarding to CO_2 emission rates, there is no significant difference between Bus 2 and Bus 5. The CO_2 rates of other buses are significantly different. Table 4.5 indicates that all pollutant emission rates and fuel use rates have variability among the individual Big CNG buses. Both Small CNG and Diesel buses show individual variability as well, which are indicated by their Tukey test matrices included in the Appendix.

Table 4.5 Tukey Test Results for Big CNG Buses

CO_2 (g/s)	Bus 1	Bus 2	Bus 3	Bus 4	Bus 5	Bus 6
Bus 1						
Bus 2	2.3					
Bus 3	3.8	1.5				
Bus 4	0.95	1.4	2.8			
Bus 5	2.2	**(0.09)**	1.5	1.3		
Bus 6	6.2	3.9	2.5	5.3	4.0	
CO (mg/s)	**Bus 1**	**Bus 2**	**Bus 3**	**Bus 4**	**Bus 5**	**Bus 6**
Bus 1						
Bus 2	100					
Bus 3	70	33				
Bus 4	81	21	11			
Bus 5	77	26	**(6.7)**	**(4.6)**		
Bus 6	130	26	59	47	52	
HC (mg/s)	**Bus 1**	**Bus 2**	**Bus 3**	**Bus 4**	**Bus 5**	**Bus 6**
Bus 1						
Bus 2	4.3					
Bus 3	1.5	2.8				
Bus 4	8.2	12.6	9.8			
Bus 5	2.5	1.8	0.95	11		
Bus 6	6.7	2.4	5.2	15.0	4.2	
NO_x (mg/s)	**Bus 1**	**Bus 2**	**Bus 3**	**Bus 4**	**Bus 5**	**Bus 6**
Bus 1						
Bus 2	0.34					
Bus 3	0.17	**(0.17)**				
Bus 4	0.27	**(0.065)**	**(0.11)**			
Bus 5	**(0.023)**	0.36	0.19	0.30		
Bus 6	0.37	**(0.033)**	0.20	**(0.098)**	0.39	
FC (g/s)	**Bus 1**	**Bus 2**	**Bus 3**	**Bus 4**	**Bus 5**	**Bus 6**
Bus 1						
Bus 2	0.91					
Bus 3	1.4	0.51				
Bus 4	0.38	0.53	1.0			
Bus 5	0.86	**(0.048)**	0.56	0.48		
Bus 6	2.4	1.4	0.93	2.0	1.5	

*values in parentheses indicate there is no statistically significant difference between the two buses

4.2. Comparison of Emissions and Fuel Use Rates

Table 4.6 presents the average emissions and fuel use rates of all tested buses on mass per time basis. The emissions and fuel use rates show variability among the different types of buses, and also among the individual buses of a particular type. In order to assess this variability, comparisons are made based on fuel types, operational modes, and engine modes.

Table 4.6 Mass per Time Emissions and Fuel Use Rates

Bus Type	Bus No.	Route	CO_2 (g/s)	CO (mg/s)	HC (mg/s)	NO_x (mg/s)	FC (g/s)
Big CNG	1	Gray	12	160	9.7	1.3	4.6
	2	Orange	10	55	5.4	1.7	3.7
	3	Gray	8.5	88	8.2	1.5	3.2
	4	Scarlet	11	76	18	1.6	4.2
	5	White	10	81	7.2	1.3	3.7
	6	Orange	6.1	29	3.0	1.7	2.2
	Average		*9.6*	*82*	*8.6*	*1.5*	*3.6*
Small CNG	7	Gray	4.1	45	4.3	11	1.6
	8	Blue	5.4	41	4.3	12	2.0
	9	Black	3.0	0.0	9.3	8.8	1.1
	10	Purple	2.7	130	7.5	43	1.1
	11	Blue	4.7	0.61	6.3	3.6	1.7
	Average		*4.0*	*43*	*6.3*	*16*	*1.5*
Diesel	12	Gray	7.5	1.9	4.5	34	2.4
	13	Brown	10	85	8.9	41	3.3
	14	Gray	7.9	20	6.0	46	2.5
	Average		*8.5*	*36*	*6.5*	*40*	*2.7*

4.2.1. CNG vs. Diesel Comparison

In order to evaluate the impacts of fuel type on emission rates, other factors' impacts should be minimized. To achieve this goal, the emissions rates were converted to mass per fuel used basis. The fuel use rates were converted to gallon per time basis. Table 4.7 summarized the average mass per fuel used emissions rates and gallon per time fuel use rates of all tested buses. As seen in Table 4.7, in each bus type, variability among individual buses was smaller for all emissions rates, especially for CO_2 emission rates; thus, the variability was reduced by the conversion.

The average emissions and fuel use rates of each type of bus were also calculated and plotted in histograms. As seen in Figure 4.1 , in general, both Big CNG and Small CNG have lower CO_2 and NO_x emissions rates but higher CO emission rates than Diesel. Big CNG has a lower HC emission rate than Diesel, but Small CNG has the highest HC emission rate compared with Big CNG and Diesel. For fuel use rates, Small CNG has a lower rate than Diesel, but Big CNG's rate is higher than Diesel.

Table 4.7 Mass per Fuel Used Emissions and Gallon per Time Fuel Use Rates

Bus Type	**Bus No.**	**CO_2 (kg/DGE)**	**CO (g/DGE)**	**HC (g/DGE)**	**NO_x (g/DGE)**	**FC (DGE/hr)**
Big CNG	1	7.7	99	6.1	0.83	5.8
	2	7.8	43	4.2	1.3	4.6
	3	7.7	79	7.4	1.3	4.0
	4	7.7	52	12	1.1	5.3
	5	7.7	62	5.6	1.0	4.7
	6	7.8	37	3.9	2.2	2.8
	Average	*7.7*	*62*	*6.6*	*1.3*	*4.5*
Small CNG	7	7.5	83	7.9	20	2.0
	8	7.6	57	6.0	16	2.6
	9	7.6	0.0	24	22	1.4
	10	7.1	350	20	120	1.3
	11	7.6	1.0	10	6.0	2.2
	Average	*7.5*	*97*	*14*	*36*	*1.9*
Diesel	12	10	2.5	6.1	46	2.7
	13	10	81	8.5	39	3.8
	14	10	26	7.7	58	2.8
	Average	*10*	*42*	*7.6*	*47*	*3.1*

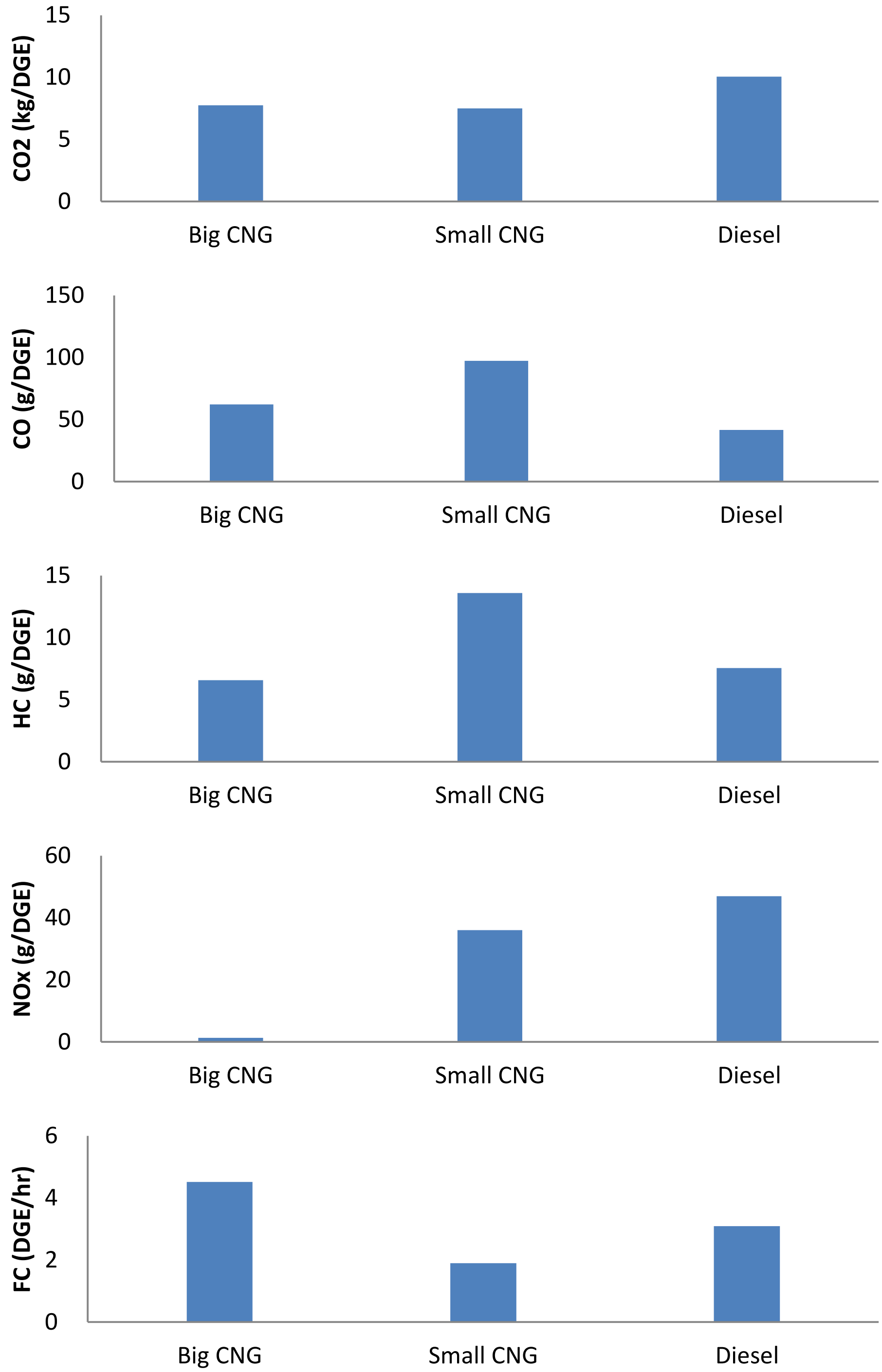


Figure 4.1 Comparison of Average Mass per Fuel Used Emissions Rates

(Big CNG n=6; Small CNG n=5; Diesel n=3)

4.2.2. Operational Modal Comparison

Second-by-second data of each tested bus were categorized into four operational modes based on speed and acceleration data. The percent of time spent on each mode of each tested bus were calculated and presented in Table 4.8. The average percentage of time spent on each mode of each type of bus was also calculated. As seen in Table 4.8, there are no big differences of time distribution on the operational modes among bus type. Generally, the tested buses spent about 30% time on idle, 35% time on cruising, 17% time on acceleration, and 18% time on deceleration. There are still some differences among individual tested buses, which may be caused by individual route impacts. However, that topic was not included in this study.

Table 4.8 Summary of Percentage of Time per Operational Mode

				Big CNG			
	Bus 1	**Bus 2**	**Bus 3**	**Bus 4**	**Bus 5**	**Bus 6**	***Average***
Idle	30%	38%	33%	20%	34%	36%	*32%*
Cruising	14%	45%	40%	51%	43%	7%	*33%*
Acc	28%	8%	14%	15%	13%	28%	*18%*
Dec	29%	8%	12%	15%	10%	29%	*17%*
				Small CNG			
	Bus 7	**Bus 8**	**Bus 9**	**Bus 10**	**Bus 11**		***Average***
Idle	19%	31%	29%	36%	41%		*31%*
Cruising	8%	48%	49%	40%	45%		*38%*
Acc	37%	10%	10%	11%	7%		*15%*
Dec	36%	11%	12%	12%	7%		*16%*
				Diesel			
	Bus 12	**Bus 13**	**Bus 14**				***Average***
Idle	33%	28%	26%				*29%*
Cruising	11%	43%	44%				*33%*
Acc	28%	15%	15%				*19%*
Dec	29%	14%	15%				*19%*

In order to assess the operational impacts on emissions and fuel use rates, the emissions and fuel use rates of each operational mode were calculated for each tested bus and also converted to mass per fuel used basis and mass per distance basis. Because fuel use rates cannot be converted to mass per fuel used basis, they were converted to gallon per time basis instead. Furthermore, because the original data of idle mode cannot be converted to mass per distance basis, these conversions were only made for the three non-idle modes. An operational mode dataset was made for each tested bus, which contained the percent of time, emissions and fuel use rates on the three unit bases of each operational mode. All the dataset tables are included in the Appendix.

Based on the dataset tables, the average emissions and fuel use rates on each operational mode of each type of buses were calculated and compared. Figure 4.2 presents the average mass per time emissions and fuel use rates per operational mode of the three bus types. As seen in Figure 4.2, all pollutant emissions rates and fuel use rates have a similar trend. The sequences of the four modes from the highest to the lowest emissions and fuel use rates are acceleration, cruising, idle and deceleration. The trend was also same among the three bus types.

The emissions and fuel use rates comparison was made among the three type buses on each operational mode as well. For CO_2 emission rates, besides the acceleration mode, on the other three modes, Small CNG has the lowest values, and Big CNG has the highest values which are slightly higher than Diesel; on the acceleration mode, Small CNG still has the lowest value, but Diesel's value is slightly higher than Big CNG. For CO emission rates, the values are comparable among the three bus types on the idle mode; on the cruising and deceleration mode, Big CNG's value is highest, Small CNG's is lower, and Diesel's is the lowest; on the acceleration mode, Big CNG still has the highest CO emission rate, but the CO emission rate of Diesel is higher than Small CNG. For HC emission rates, on all four operational modes, Big CNG has the higher values than Small CNG and Diesel, and Small CNG and Diesel have comparable values. For NO_x emission rates, Diesel has much higher values than both Big CNG and Small CNG on all four modes; Big CNG's values are even much lower than Small CNG on the three non-idling modes; the NO_x emission rates of Big CNG and Small CNG are comparable on the idle mode. For fuel use rates, Small CNG has the lowest values on all four modes; Big CNG and Diesel have comparable values on the three non-idling modes; on idle modes, Big CNG has higher fuel use rate than Diesel.

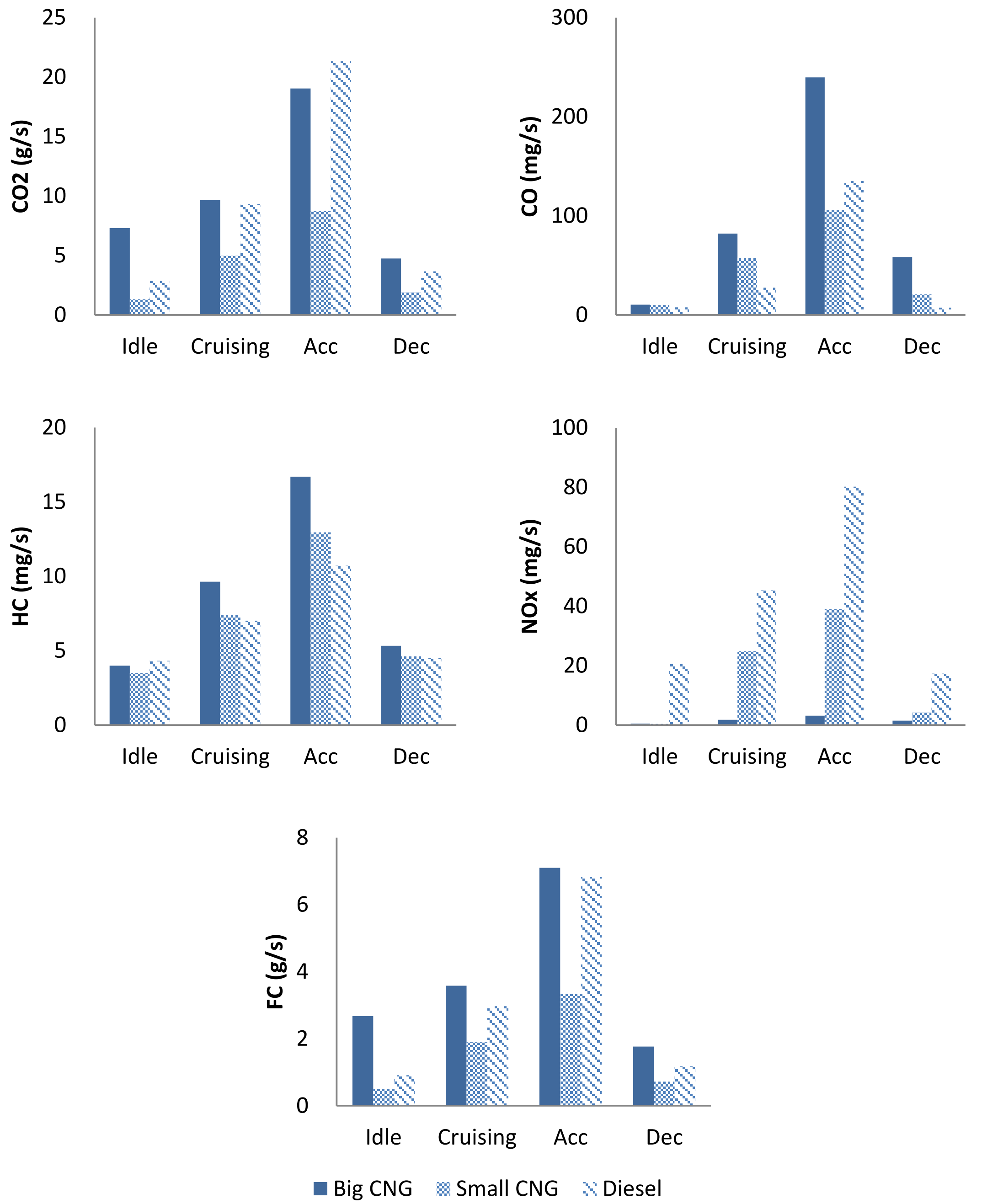


Figure 4.2 Average Mass per Time Emissions and Fuel Use Rates per Operational Mode (Big CNG n=6; Small CNG n=5; Diesel n=3)

In order to better understand operation impacts, the average emissions rates of the four operational modes of the three types of buses were converted to mass per fuel used basis and mass per distance basis. The average fuel use rates were converted to gallon per time basis and mass per distance basis. Figure 4.3 presents the average mass per fuel used emissions rates and average gallon per time fuel use rates per operational mode of the three bus types. As seen in Figure 4.3, the trends are different among the pollutants, and sometimes even among the bus types. So each pollutant emission rates should be analyzed individually. CO_2 emission rates are almost constant among the four modes of all three bus types; and on the four modes, Big CNG and Small CNG have almost same CO_2 emission rates, which are lower than Diesel. For CO emission rates, Big CNG show a similar trend with the mass per time basis, but Small CNG and Diesel show an increasing trend from idle to deceleration (idle<cruising<acceleration<deceleration); Small CNG has higher values than Diesel on the four modes, so does Big CNG except on idle and deceleration modes. For HC emission rates, Big CNG has almost constant values on the first three modes, and a significant increase on deceleration mode; Small CNG and Diesel have a sequence of deceleration, cruising, acceleration, and idle from the highest to lowest values. Compared with Diesel, Big CNG shows lower HC emission rates on all modes except acceleration mode but Small CNG shows higher values on all modes. For NO_x emission rates, Big CNG has a constant low values (almost 0) on the four modes. Small CNG has a sequence of cruising, acceleration, and deceleration from the highest to lowest values and the idle rate is significantly lower than the three non-idling modes. Diesel has similar values on idle and deceleration modes, and lower values on cruising and acceleration mode. Diesel has much higher values than Big CNG on all four modes and these values are also higher than Small CNG's values. Fuel use rates on gallon per time basis show a similar trend as the mass per time basis, which has a sequence of acceleration, cruising, idle and deceleration from the highest values to the lowest values. On all four modes, Big CNG has the highest fuel use rates. Diesel's are lower and Small CNG's are the lowest.

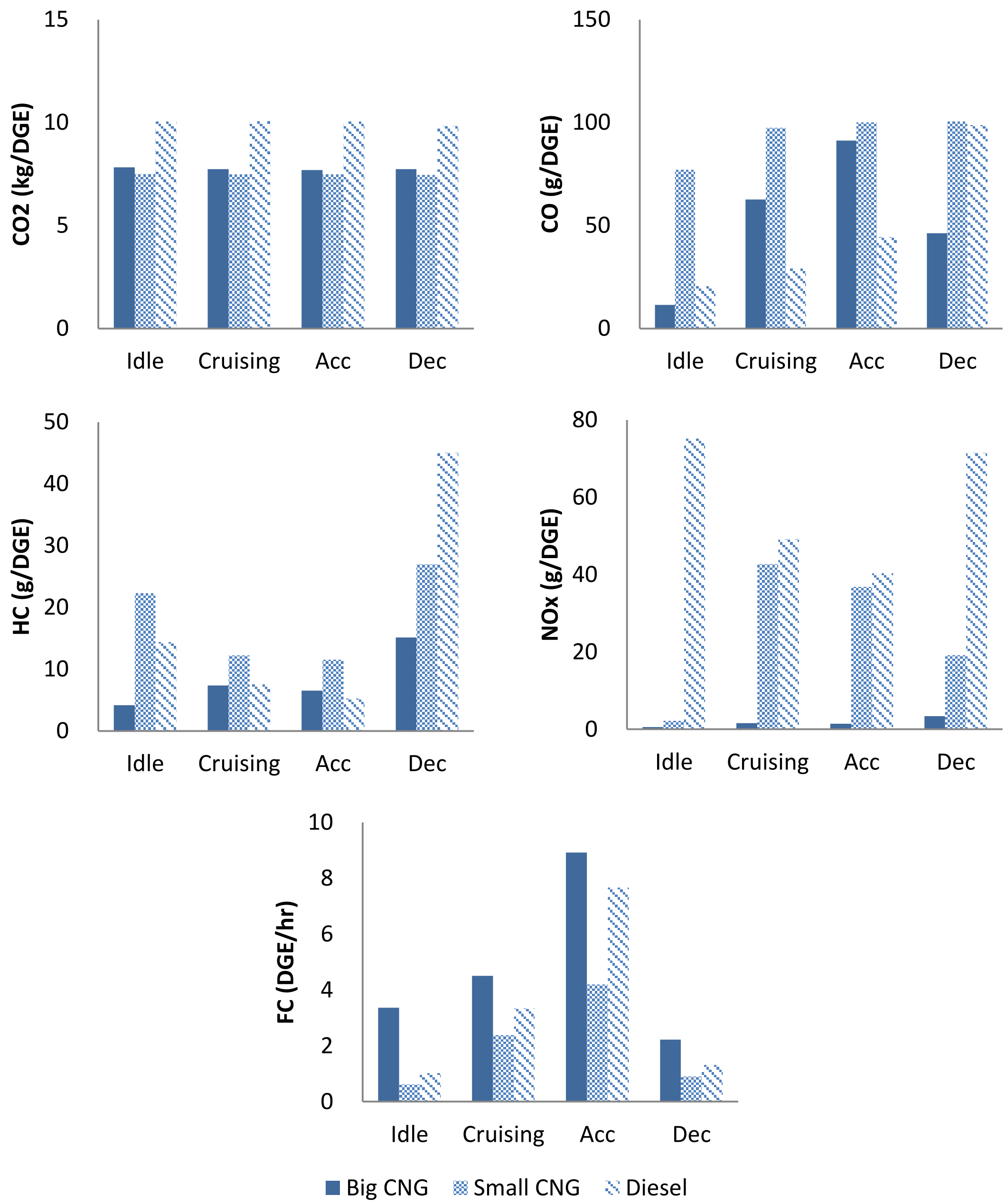


Figure 4.3 Average Mass per Fuel Used Emissions Rates per Operational Mode (Big CNG n=6; Small CNG n=5; Diesel n=3)

Figure 4.4 presents the average mass per distance emissions and fuel use rates per operational mode of the three bus types. All types of buses have a similar trend on all pollutant emissions rates and fuel use rates, in a sequence of acceleration, cruising and deceleration from the highest value to lowest values. The comparison was made among the bus type for each pollutant emission rates and fuel use rates as well.

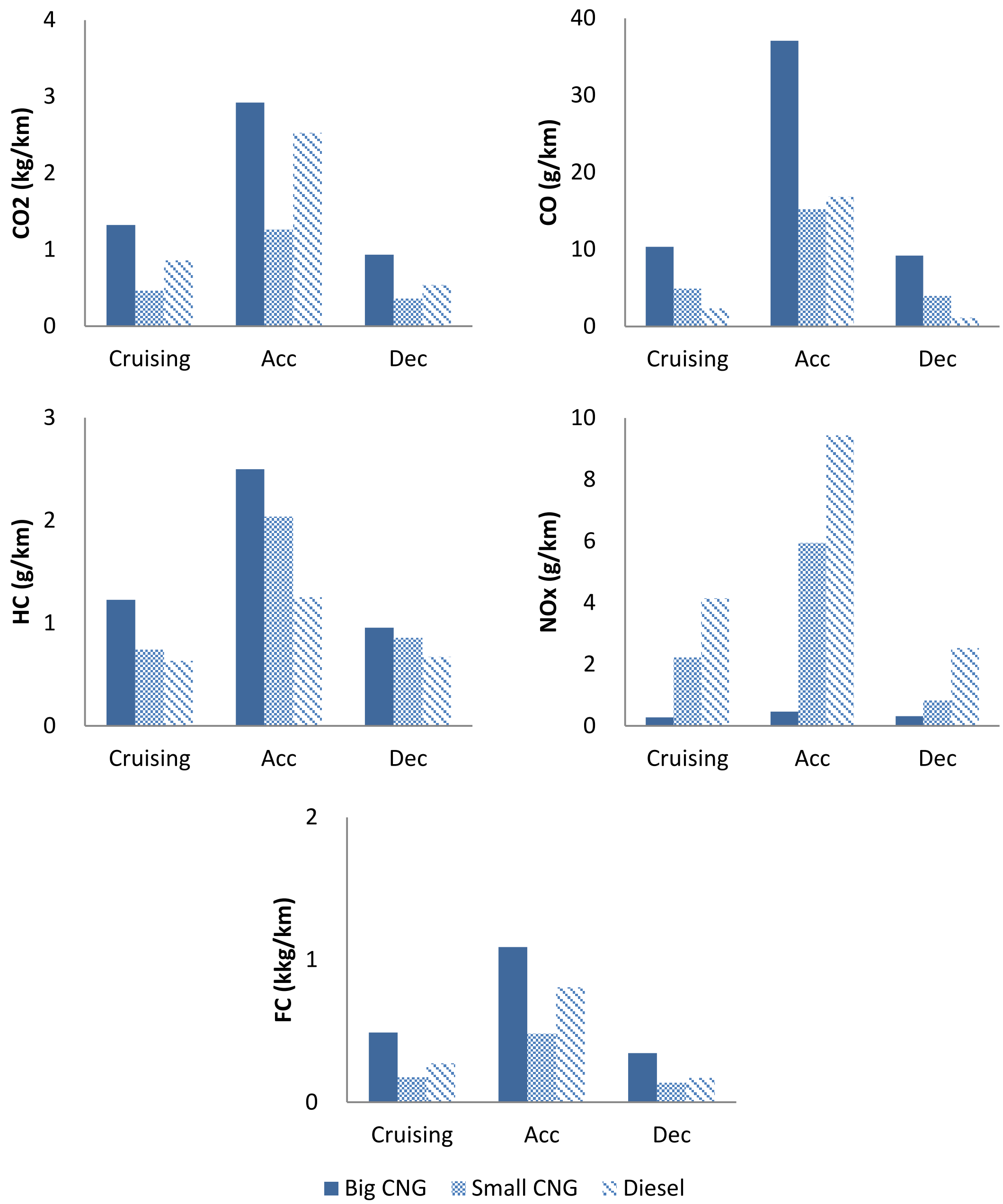
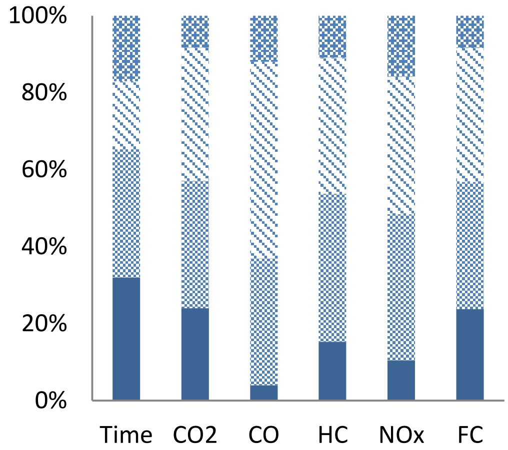


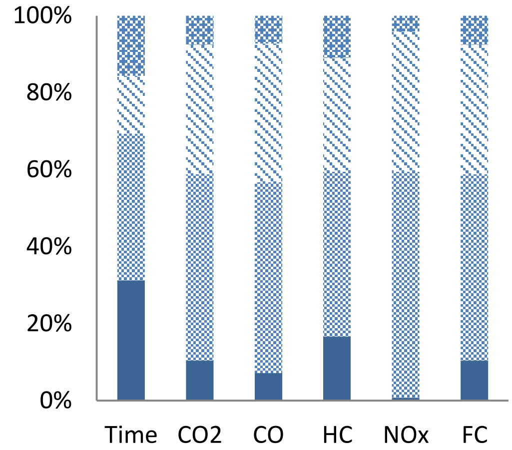
Figure 4.4 Average Mass per Distance Emissions and Fuel Use Rates per Operational Mode (Big CNG n=6; Small CNG n=5; Diesel n=3)

For CO_2 emission rates, Small CNG has lower values than Diesel on all three non-idling modes, but Big CNG has higher value than Diesel on all three modes. For CO emission rates, Big CNG has the highest values on three modes. Small CNG's values are lower. Diesel's values are the lowest. Small CNG and Diesel have similar values on acceleration mode. For HC emission rates, the comparison results are similar on the three modes. Big CNG has the highest value. Small CNG's values are lower and Diesel's values are the lowest. For NO_x emission rates, Diesel has the highest values on all three modes and Big CNG has much lower values when compared with Small CNG. For fuel use rates, on all three modes, Big CNG has the highest values. Diesel's values are lower values and Small CNG's values are the lowest.

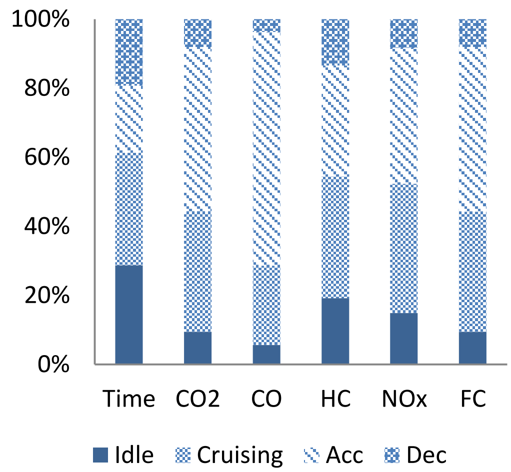
In order to assess the relative importance of each operational mode, the distribution of time, emissions, and fuel use on each mode of the three bus types are shown in Figure 4.5, respectively. As seen in Figure 4.5(a), for Big CNG, idling accounts for 32% of total time, but has a smaller proportion of emissions and fuel use, especially for CO and NO_x . Deceleration also accounts for a lower percentage of emissions and fuel use with its amount of time, especially for fuel use, CO_2 and HC. Conversely, cruising and acceleration account for a higher percentage of emissions and fuel use with their amounts of time. Especially for acceleration, it emitted 35% of the total emissions of CO_2, 51% of CO, 35% of HC, and 36% of NO_x with 18% of time. It also used 35 % of the total fuel. As seen in Figure 4 (b) and (c), Small CNG and Diesel show similar time, emissions and fuel use distributions with Big CNG.



Big CNG (n=6)



Small CNG (n=5)



Diesel (n=3)

Figure 4.5 Distribution of Time, Emissions and Fuel Use on Each Operational Mode

4.2.3. Engine Modal Comparison

In this research topic, the engine activity was categorized into 10 engine modes based on normalized RPM data. The percentage of time spent on each mode was calculated for each tested bus. Table 4.9 summarizes the percentage of time per engine mode for all tested Big CNG buses. The average percent time of each mode of these six buses was also calculated. As seen in Table 4.9, the amount of time has a general decreasing trend as the engine load increases (shown by the minimum to maximum orders of engine modes) of all Big CNG buses. However, all these buses spent less time on mode 1 and mode 3, compared with other low engine modes with high percentages of time.

Table 4.9 Percentage of Time per Engine Mode for Big CNG Buses

Mode	**1**	**2**	**3**	**4**	**5**	**6**	***Average***
1	4.3%	9.8%	5.2%	8.7%	8.6%	6.1%	*7.1%*
2	36%	30%	24%	23%	33%	29%	*29%*
3	3.3%	12%	3.0%	3.8%	4.3%	5.6%	*5.3%*
4	11%	21%	23%	17%	19%	31%	*20%*
5	16%	12%	13%	17%	14%	11%	*14%*
6	14%	9.2%	13%	13%	10%	9%	*11%*
7	8.5%	3.3%	10%	9.2%	6.1%	4.5%	*6.9%*
8	4.0%	1.7%	5.3%	5.7%	3.2%	2.4%	*3.7%*
9	2.1%	0.78%	3.0%	2.4%	1.6%	1.1%	*1.8%*
10	0.31%	0.03%	0.95%	0.61%	0.41%	0.11%	*0.40%*
							100%

The tables of percentage of time per each engine mode for Small CNG and Diesel buses are included in the Appendix. In order to compare the time distribution differences among bus types, the average percentage of time per engine mode for the three bus types was presented by histogram. As seen in Figure 4.6, for both Small CNG and Diesel, the average amount of time in the engine modes show a general decreasing trend as the engine loads increase, which is similar with the Big CNG. However, Small CNG and Diesel have the highest percentage of time in mode 1, corresponded with mode 2 of Big CNG. Small CNG buses spent much more time in mode 1, which is almost 48%, than Big CNG (7%) and Diesel (31%) buses. Furthermore, Small CNG and Diesel show a slight increasing trend during the mode 2 to the mode 4, but Big CNG spent much less time on mode 1 and 3 than other low engine modes.

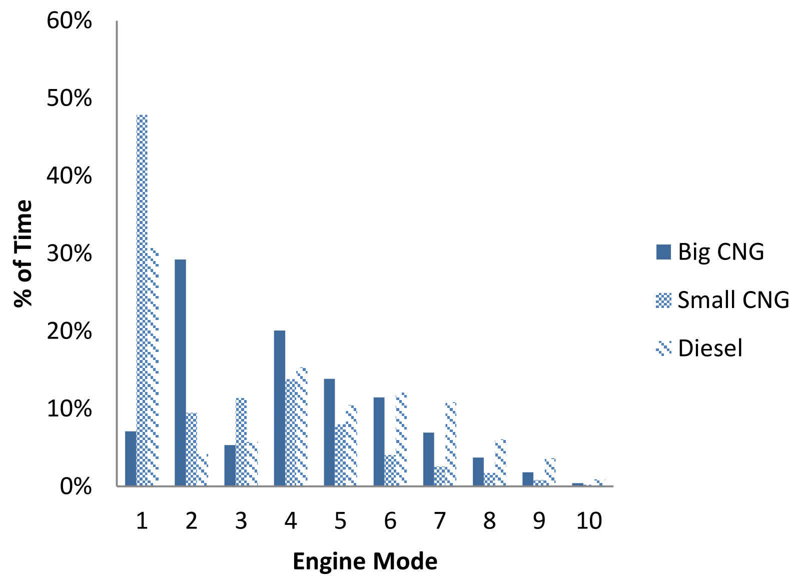


Figure 4.6 Average Percentage of Time per Engine Mode

The emissions and fuel use rates of the 10 engine modes are calculated for each tested bus. Figure 4.7 presents percent of time, and mass per time emissions and fuel use rates versus engine modes for Bus 1. The results of the other buses are presented in the Appendix. As seen in Figure 4.7, all pollutant emissions and fuel use rates have a general increasing trend as the engine loads increase. However, CO_2 emission rates and fuel use rates have a small decrease trend during mode 2 to mode 4; CO and NO_x emissions rates have a significant decrease at mode 10; and NO_x emission rates have a significant decrease from mode 1 to mode 2.

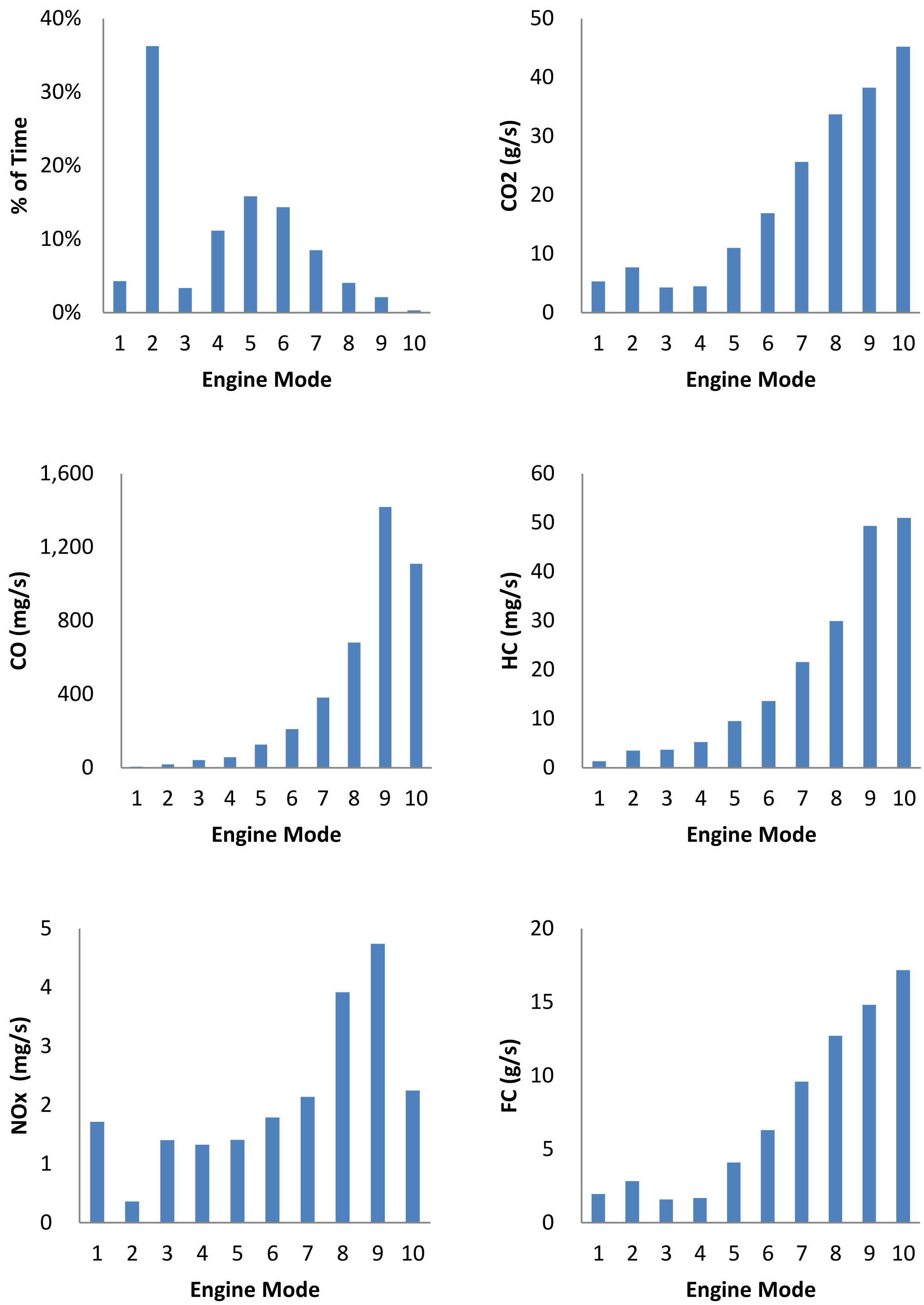


Figure 4.7 Percentage of Time, Mass per Time Emissions and Fuel Use Rates vs. Engine Modes for Bus 1

The average fuel use rates of each engine mode were calculated and compared among the three bus types. Table 4.10 presents the fuel use rates per engine mode for all Big CNG buses, and the average fuel use rate per each mode were calculated as well. Table 4.11 summarizes the average fuel use rates per engine mode for the three bus types. Similar analysis was also made on all the pollutant emissions rates, and the summary tables are included in the Appendix.

Table 4.10 Mass per Time Fuel Use Rates (g/s) per Engine Mode for Big CNG Buses

Engine Mode	Big CNG 1	2	3	4	5	6	*Average*
1	1.9	2.0	0.96	1.2	1.1	1.0	***1.4***
2	2.8	2.6	1.7	2.7	2.5	1.5	***2.3***
3	1.6	3.1	1.1	2.1	1.9	1.3	***1.8***
4	1.7	3.3	1.9	2.6	2.5	1.9	***2.3***
5	4.1	4.2	2.6	3.6	3.8	2.4	***3.4***
6	6.3	5.9	4.1	5.3	5.9	3.5	***5.1***
7	9.6	8.4	5.9	7.6	8.3	4.9	***7.5***
8	13	11	7.9	10	10	6.3	***9.7***
9	15	14	9.3	13	13	7.7	***12***
10	17	16	8.5	15	16	8.6	***13***

Table 4.11 Summary of Average Mass per Time Fuel Use Rates per Engine Mode

Engine Mode	Average Fuel Use Rates (g/s) Big CNG	Small CNG	Diesel
1	1.4	0.48	0.79
2	2.3	0.65	0.30
3	1.8	1.4	0.45
4	2.3	2.4	0.97
5	3.4	3.3	2.3
6	5.1	4.0	3.9
7	7.5	4.6	5.7
8	9.7	5.1	8.4
9	12	5.7	11
10	13	6.2	10

Figure 4.8 plots the average emissions and fuel use rates per engine mode for the three bus types. Based on Figure 4.7, the average emissions and fuel use rates for all the three bus types show a general increasing trend as the engine loads increase.

Specific comparisons on the emissions and fuel use rates of each mode are made among the three bus types. For CO_2 emission rates, Big CNG and Diesel have the comparable values on all 10 modes; Small CNG has comparable values with the other two bus types during mode 1 to mode 6, but lower values on the remaining modes. For CO emission rates, on the first five modes, the values of all three bus types are low (almost zero). On the last five modes, Big CNG has the highest values, and Small CNG is at the middle level between Big CNG and Diesel. For HC emission rates, Small CNG is comparable with Diesel on all 10 modes; Big CNG is also comparable with the other two bus types during the first five modes but has higher values during the last five modes.

For NO_x emission rates, on all 10 modes, Diesel has the highest values. Small CNG is at the middle level, and the Big CNG has much lower values (almost zero) than the other two bus types. Furthermore, the NO_x emission rates of Diesel show a decreasing trend from mode 1 to mode 2. For fuel use rates, Big CNG have the highest values; Small CNG and diesel have comparable fuel use rates on the first six modes, but fuel use rates of Diesel increase more rapidly during the last four modes. Diesel has higher fuel use rates than Small CNG during mode 7 to mode 10.

The weighted average emissions and fuel use rates were calculated for each mode of each tested bus by multiplying the percentage of time and emissions and fuel use rates for each mode. These results were then totaled for all engine modes in order to obtain the total weighted average emissions and fuel use rates. Table 4.12 presents the weighted average mass per time emissions and fuel use rates for Bus 1. The weighted average emissions and fuel use rates have the highest values in the middle level engine loads (mode 5 to mode 7). The high engine loads (mode 8 to mode 10) have the lowest weighted average emissions and fuel use rates, and the rates of the low engine loads (mode 1 to mode 4) are moderate. The weighted average emissions and fuel use rates of other tested buses are included in the Appendix. The results of those buses show the similar results.

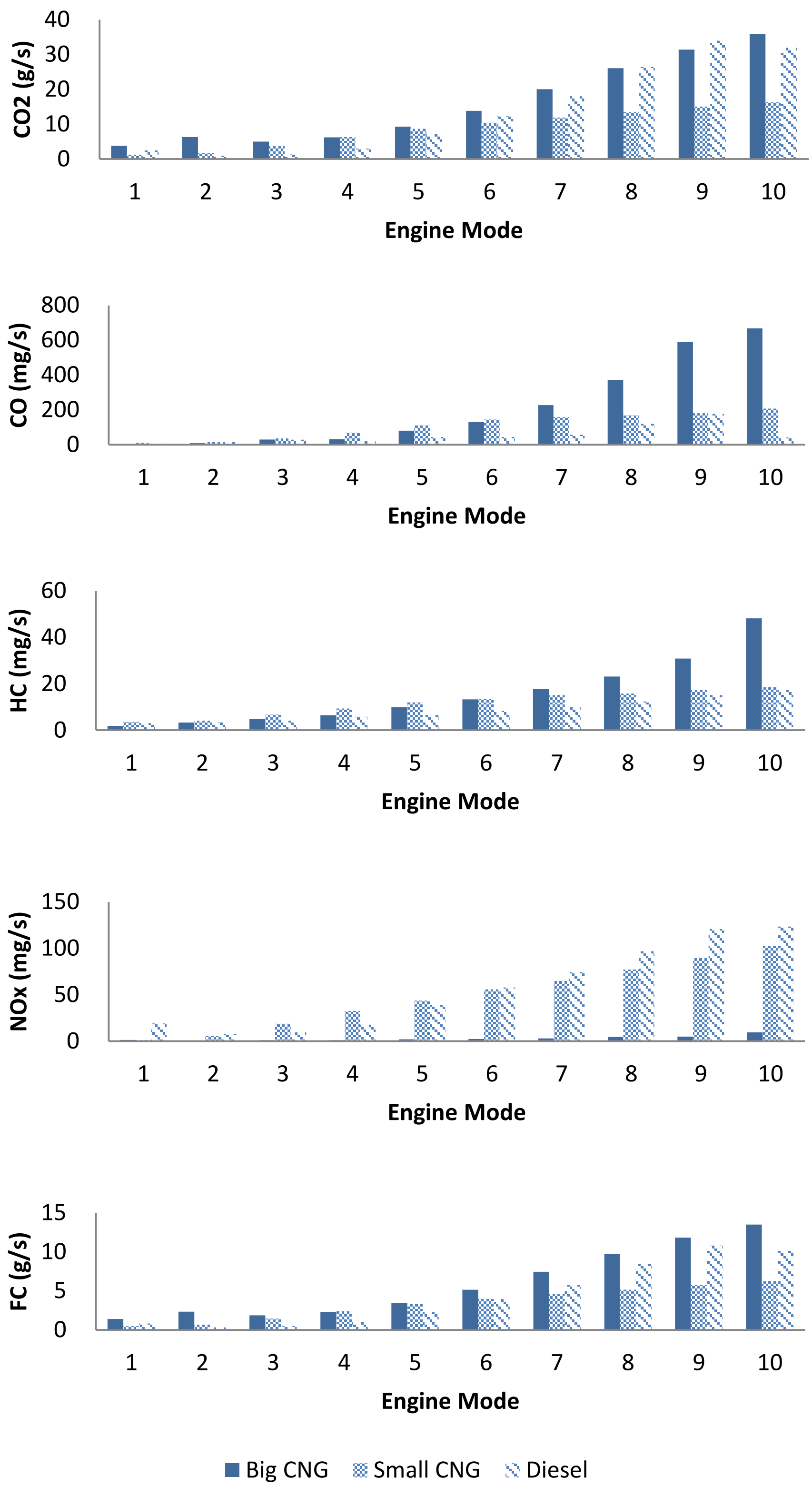


Figure 4.8 Average Mass per Time Emissions and Fuel Use Rates per Engine Mode

Table 4.12 Weighted Average Mass per Time Emissions and Fuel Use Rates for Bus 1

Mode	% of Time	Weighted Average Emissions and Fuel Use Rates				
		CO_2[g/s]	CO[mg/s]	HC[mg/s]	NO_x [mg/s]	FC[g/s]
1	4.3%	0.23	0.24	0.06	0.07	0.08
2	36%	2.8	6.7	1.3	0.13	1.0
3	3.3%	0.14	1.4	0.12	0.05	0.05
4	11%	0.49	6.4	0.59	0.15	0.18
5	16%	1.7	20	1.5	0.22	0.65
6	14%	2.4	30	1.9	0.26	0.90
7	8.5%	2.2	32	1.8	0.18	0.81
8	4.0%	1.4	27	1.2	0.16	0.51
9	2.1%	0.80	30	1.0	0.10	0.31
10	0.31%	0.14	3.4	0.16	0.01	0.05
Total	*100%*	*12*	*160*	*9.7*	*1.3*	*4.6*

Table 4.13 Summary of Weighted Average Mass per Time Fuel Use Rates

Mode	FC (g/s)								
	Big CNG			Small CNG			Diesel		
	% of time	Avg.	Weighted Avg.	% of time	Avg.	Weighted Avg.	% of time	Avg.	Weighted Avg.
1	7.1%	1.4	0.10	48%	0.48	0.23	31%	0.79	0.24
2	29%	2.3	0.68	9.5%	0.65	0.06	4.2%	0.30	0.01
3	5.3%	1.8	0.10	11%	1.4	0.16	5.7%	0.45	0.03
4	20%	2.3	0.46	14%	2.4	0.33	15%	0.97	0.15
5	14%	3.4	0.48	8.0%	3.3	0.26	10%	2.3	0.24
6	11%	5.1	0.59	4.1%	4.0	0.16	12%	3.9	0.48
7	6.9%	7.5	0.52	2.6%	4.6	0.12	11%	5.7	0.62
8	3.7%	9.7	0.36	1.8%	5.1	0.09	6.1%	8.4	0.51
9	1.8%	12	0.22	0.82%	5.7	0.05	3.6%	11	0.39
10	0.40%	13	0.05	0.23%	6.2	0.01	0.90%	10	0.09
Total			***3.6***			***1.5***			***2.8***

Table 4.14 Summary of Total Weighted Average Mass per Time Emissions and Fuel Use Rates

Bus Type	CO_2 (g/s)	CO (mg/s)	HC (mg/s)	NO_x (mg/s)	FC (g/s)
Big CNG	9.6	81	8.4	1.6	3.6
Small CNG	3.9	44	6.5	17	1.5
Diesel	8.7	37	6.5	40	2.8

The weighted average emissions and fuel use rates of each mode for each type of bus were calculated. Table 4.13 presents the summary of weighted average fuel use rates per engine mode for the three bus types. As seen in Table 4.13, the weighted average fuel use rates of bus types have the similar distribution with the individual tested buses: moderate engine loads (mode 5 to mode 7) have the highest values; high engine loads have the lowest values; and low engine loads (mode 1 to mode 4) are at the moderate level. The total weighted fuel use rates are calculated by the sum of the weighted fuel use rates for all 10 modes. The summary of weighted average emissions rates for the three bus types are included in the Appendix, which have the similar results with fuel use rates. The total weighted average emissions and fuel use rates for each bus type are summarized in Table 4.14.

4.3. Emissions and Fuel Use Predictive Models

Multiple linear regression (MLR) was used to develop the emissions and fuel use predictive models for all tested buses. Models were developed for the four gaseous pollutants (CO_2, CO, HC and NOx) and fuel use. In order to assess dependent relationships among emissions, fuel use and engine variables, correlation matrices were developed for each tested bus. In order to validate the models, two-third data were chosen as the training set, and the remaining one-third data was used for validation.

4.3.1. Correlation Matrix

Correlation matrices were developed for each tested bus and are included in the Appendix. Table 4.15, Table 4.16 and Table 4.17 present the average correlation coefficients for the Big CNG, Small CNG, and Diesel buses, respectively.

For the Big CNG buses, as seen in Table 4.15, CO_2 emissions and FC have a strong positive relationship with the engine activity variables of RPM, MAP, and LOAD. Among the other pollutants, CO and HC have moderate positive relationships with RPM and MAP. NO_x has weak relationships with all of the engine activity variables. The engine and vehicle activity variables, IAT and SPEED, have weak correlations with all pollutant emissions and FC. With the exception of NO_x versus IAT, all pollutant emissions versus vehicle activity variables have positive relationships; that is, as the vehicle activity variable increases, the pollutant emission rate increases. Furthermore, there are no strong interrelationships among the vehicle activity variables nor among the pollutant emission rates.

For the Small CNG buses, as seen in Table 4.16, all of the pollutant emission rates and FC have moderate-to-strong correlations with the engine activity variables RPM, MAF, and LOAD. For example, CO_2 and FC are nearly perfectly correlated with RPM and MAF and also are very strong with LOAD. The vehicle activity variable SPEED has moderate relationships with FC, CO_2, and NO_x but weak relationships with CO and HC. In contrast to the Big CNG buses, the Small CNG buses have a negative relationship with IAT, although it is very weak. With regard to inter-variable correlations, all of the engine variables except IAT have moderate-to strong relationships with one another; the correlations between RPM, MAF, and LOAD are particularly strong. Similarly, the inter-variable correlations among the pollutant emissions rates are moderate-to-strong, with NO_x versus CO_2 and HC versus CO_2 being the strongest.

For the Diesel buses, as seen in Table 4.17, similarly with Small CNG buses, all of the pollutant emission rates and FC had moderate-to-strong correlations with the engine activity variables RPM, MAP, and LOAD. SPEED has moderate correlations with all pollutant emission rates and FC, except CO; and IAT has weak correlations with all pollutant emission rates and FC. With regard to inter-variable correlations, as with Small CNG buses, all the engine variables have moderate to strong correlations except IAT. The correlations between RPM, MAP, and LOAD are particularly strong. The inter-variable correlations among the pollutant emissions rates are moderate-to-strong and the correlations between CO_2, HC and NO_x are particularly strong.

Table 4.15 Big CNG Average Correlation Matrix

	RPM	IAT	MAP	LOAD	SPEED	CO_2	CO	HC	NO_x	FC
RPM	1.00									
IAT	-0.03	1.00								
MAP	0.65	0.13	1.00							
LOAD	0.34	0.30	0.65	1.00						
SPEED	0.66	-0.30	0.40	-0.01	1.00					
CO_2	0.72	0.27	0.79	0.77	0.29	1.00				
CO	0.42	0.01	0.39	0.31	0.17	0.44	1.00			
HC	0.54	0.05	0.49	0.28	0.33	0.54	0.56	1.00		
NO_x	0.24	-0.13	0.22	0.20	0.10	0.21	0.24	0.23	1.00	
FC	0.72	0.26	0.79	0.77	0.30	1.00	0.48	0.55	0.22	1.00

Table 4.16 Small CNG Average Correlation Matrix

	RPM	IAT	MAF	LOAD	SPEED	CO_2	CO	HC	NO_x	FC
RPM	1.00									
IAT	-0.25	1.00								
MAF	0.95	-0.20	1.00							
LOAD	0.73	-0.10	0.87	1.00						
SPEED	0.62	-0.58	0.52	0.29	1.00					
CO_2	0.95	-0.20	0.99	0.87	0.51	1.00				
CO	0.53	-0.12	0.56	0.48	0.27	0.56	1.00			
HC	0.68	-0.10	0.72	0.67	0.30	0.74	0.39	1.00		
NO_x	0.73	-0.14	0.75	0.64	0.44	0.75	0.49	0.55	1.00	
FC	0.95	-0.20	0.99	0.87	0.51	1.00	0.57	0.74	0.75	1.00

Table 4.17 Diesel Average Correlation Matrix

	RPM	IAT	MAP	LOAD	SPEED	CO_2	CO	HC	NO_x	FC
RPM	1.00									
IAT	0.24	1.00								
MAP	0.76	0.25	1.00							
LOAD	0.58	0.18	0.87	1.00						
SPEED	0.69	0.26	0.51	0.27	1.00					
CO_2	0.72	0.21	0.97	0.91	0.38	1.00				
CO	0.40	0.06	0.39	0.45	0.15	0.43	1.00			
HC	0.68	0.18	0.70	0.56	0.33	0.69	0.34	1.00		
NO_x	0.71	0.21	0.92	0.80	0.41	0.93	0.39	0.70	1.00	
FC	0.72	0.21	0.97	0.91	0.38	1.00	0.45	0.69	0.93	1.00

4.3.2. Prediction Models using Multiple Linear Regression (MLR)

Predictive models of all pollutant emission rates and fuel use were developed based on engine variables for each tested buses. The engine variables contain RPM, IAT, MAP (MAF), LOAD and SPEED. Although IAT has weak correlations with all pollutant emission rates and fuel use, it was still added used as an input because it may still have some predictive power. The modeling process of one tested bus, Bus 1 (Big CNG), was explained step-by-step as example.

Two-thirds of the data (n=6431s) were selected as the modeling dataset of Bus 1. Then, a stepwise selection model was applied for each predictive model to determine if the engine variables were significant at α=0.05. Table 4.18 presents the result of the CO_2 predictive model. As seen in Table 4.18, all engine variables are needed, because all p-values are smaller than 0.05. It means all engine variables are significant in the model; additionally, the R^2 value increases as the variables enter.

Table 4.18 Stepwise Selection and VIF Test for Bus 1 CO_2 MLR Model

Step	Variable Entered	Variable Removed	R^2	P-value	VIF
1	LOAD		0.807	<.0001	2.72
2	RPM		0.889	<.0001	1.66
3	IAT		0.915	<.0001	2.85
4	SPEED		0.918	<.0001	2.80
5	MAP		0.920	<.0001	1.89

To check for multicollinearity, Variance Inflation Factors (VIF) are also calculated and displayed in Table 4.18 to quantify the severity of multicollinearity in the model. In this model, all independent variables have the VIF values less than five. It means no multicollinearity occurs in this model and no variables need to be removed. As a result, the stepwise selection results are the final results. For the other models, if some of the independent variables have VIF values greater than 5, some of variables need to be removed and stepwise selection should be made again until no multicollinearity happens and all independent variables are significant in the model. The MLR models of all pollutant emissions and fuel use of all three types of buses are presented in Table 4.19, Table 4.20 and Table 4.21 with R-square values.

Table 4.19 Summary of MLR Models for Big CNG Buses

Bus No.	Response	Equations	R^2
1	CO_2	$Y_1 = -20.0 + 0.0105X_1 + 0.402X_2 + 0.0211X_3 + 0.221X_4 - 0.0357X_5$	0.920
	CO	$Y_2 = -367 + 0.599X_1 - 12.2X_2 + 1.04X_3 + 4.01X_4 - 4.96X_5$	0.321
	HC	$Y_3 = -27.7 + 0.0236X_1 + 0.152X_2 + 0.0635X_3 + 0.0413X_4 - 0.150X_5$	0.514
	NO_x	$Y_4 = 3.46 + 0.00230X_1 - 0.224X_2 + 0.0389X_4 - 0.0140X_5$	0.225
	Fuel Use	$Y_5 = -7.54 + 0.00420X_1 + 0.140X_2 + 0.00838X_3 + 0.0830X_4 - 0.0160X_5$	0.921
2	CO_2	$Y_1 = -26.1 + 0.0126X_1 + 0.199X_2 + 0.0730X_3 + 0.146X_4 - 0.0199X_5$	0.868
	CO	$Y_2 = -353 + 0.195X_1 + 1.53X_3 + 1.29X_4 - 0.631X_5$	0.257
	HC	$Y_3 = -25.6 + 0.00957X_1 + 0.123X_2 + 0.162X_3 - 0.0510X_4$	0.310
	NO_x	$Y_4 = 8.26 + 0.00228X_1 - 0.198X_2 + 0.0123X_3 - 0.0378X_5$	0.0796
	Fuel Use	$Y_5 = -9.74 + 0.00472X_1 + 0.0729X_2 + 0.0277X_3 + 0.0540X_4 - 0.00753X_5$	0.871
3	CO_2	$Y_1 = -19.8 + 0.00842X_1 + 0.202X_2 + 0.0259X_3 + 0.129X_4 - 0.0127X_5$	0.920
	CO	$Y_2 = -162 + 0.361X_1 - 4.76X_2 + 0.383X_3 + 1.04X_4 - 2.48X_5$	0.237
	HC	$Y_3 = -30.7 + 0.0145X_1 + 0.325X_2 + 0.0681X_3 + 0.0149X_5$	0.495
	NO_x	$Y_4 = 6.39 + 0.00441X_1 - 0.243X_2 + 0.0360X_4 - 0.0480X_5$	0.182
	Fuel Use	$Y_5 = -7.36 + 0.00329X_1 + 0.0713X_2 + 0.0134X_3 + 0.0476X_4 - 0.00602X_5$	0.919
4	CO_2	$Y_1 = -22.4 + 0.0116X_1 + 0.247X_2 + 0.0464X_3 + 0.163X_4$	0.892
	CO	$Y_2 = -229 + 0.283X_1 - 3.22X_2 + 0.958X_3 + 0.784X_4 - 2.42X_5$	0.217
	HC	$Y_3 = -36.8 + 0.0290X_1 + 0.268X_2 + 0.161X_3 - 0.126X_4 - 0.0367X_5$	0.477
	NO_x	$Y_4 = 3.27 + 0.00220X_1 - 0.137X_2 + 0.0219X_4 - 0.0244X_5$	0.102
	Fuel Use	$Y_5 = -8.29 + 0.00437X_1 + 0.0887X_2 + 0.0174X_3 + 0.0603X_4$	0.892
5	CO_2	$Y_1 = -23.6 + 0.0119X_1 + 0.153X_2 + 0.0655X_3 + 0.167X_4$	0.911
	CO	$Y_2 = -275 + 0.199X_1 - 2.64X_2 + 2.26X_3 - 0.893X_4 - 1.38X_5$	0.324
	HC	$Y_3 = -14.0 + 0.0119X_1 + 0.0725X_3 - 0.0377X_4$	0.229
	NO_x	$Y_4 = 8.66 + 0.00235X_1 - 0.228X_2 + 0.00871X_3 + 0.0138X_4 - 0.0565X_5$	0.134
	Fuel Use	$Y_5 = -8.83 + 0.00444X_1 + 0.0556X_2 + 0.0252X_3 + 0.0616X_4$	0.912
6	CO_2	$Y_1 = -10.4 + 0.00784X_1 + 0.0341X_2 + 0.0457X_3 + 0.0806X_4 - 0.0486X_5$	0.716
	CO	$Y_2 = -73.9 + 0.0818X_1 - 0.725X_2 + 0.188X_3 + 0.350X_4 + 0.240X_5$	0.137
	HC	$Y_3 = -8.82 + 0.00426X_1 - 0.155X_2 + 0.102X_3 + 0.0205X_4 + 0.0207X_5$	0.221
	NO_x	$Y_4 = -9.05 + 0.00477X_1 - 0.170X_2 + 0.106X_3 + 0.0160X_4$	0.220
	Fuel Use	$Y_5 = -3.85 + 0.00291X_1 + 0.0118X_2 + 0.0169X_3 + 0.0296X_4 - 0.0176X_5$	0.717

*X_1 = RPM, X_2 = IAT, X_3 = MAP, X_4 = LOAD, X_5 = SPEED

Table 4.20 Summary of MLR Models for Small CNG Buses

Bus No.	Response	Equations	R^2
7	CO_2	$Y_1 = 0.955 – 0.0424X_2 + 0.159X_3 – 0.0173X_5$	0.945
	CO	$Y_2 = -8.64 + 2.63X_3 – 0.655X_5$	0.736
	HC	$Y_3 = 4.83 + 0.00423X_1 – 0.242X_2 – 0.0656X_5$	0.408
	NO_x	$Y_4 = -1.93 – 0.0839X_2 + 0.549X_3 – 0.0339X_5$	0.836
	Fuel Use	$Y_5 = 0.362 – 0.0163X_2 + 0.0611X_3 – 0.00692X_5$	0.946
8	CO_2	$Y_1 = -0.0000130 + 0.157X_3 – 0.000345X_5$	0.999
	CO	$Y_2 = -17.9 + 0.466X_2 + 2.20X_3 – 0.636X_4$	0.763
	HC	$Y_3 = 0.505 + 0.0617X_3 + 0.0343X_4 – 0.00542X_5$	0.577
	NO_x	$Y_4 = 0.816 + 0.491X_3 – 0.106X_4 – 0.0287X_5$	0.679
	Fuel Use	$Y_5 = -0.00645 + 0.000347X_2 + 0.0601X_3 – 0.000534X_4 – 0.000161X_5$	0.999
9	CO_2	$Y_1 = 0.02376 – 0.00200X_2 + 0.151X_3$	0.999
	CO	$Y_2 = 0.03912 – 0.00102X_2$	0.0013
	HC	$Y_3 = -3.56 + 0.219X_2 + 0.288X_3$	0.699
	NO_x	$Y_4 = -9.68 + 0.175X_2 + 0.550X_3 + 0.134X_5$	0.790
	Fuel Use	$Y_5 = 0.00687 – 0.000622X_2 + 0.0566X_3$	0.999
10	CO_2	$Y_1 = -0.0363 + 0.00346X_2 + 0.124X_3$	0.996
	CO	$Y_2 = 4.70 – 0.567X_2 + 5.87X_3 + 0.0704X_5$	0.953
	HC	$Y_3 = 5.11 – 0.179X_2 + 0.243X_3 – 0.0683X_5$	0.471
	NO_x	$Y_4 = -27.2 + 0.403X_2 + 2.43X_3 + 0.647X_5$	0.925
	Fuel Use	$Y_5 = -0.00783 + 0.000853X_2 + 0.0498X_3$	0.996
11	CO_2	$Y_1 = 0.00678 – 0.00131X_2 + 0.152X_3 – 0.00185X_5$	0.999
	CO	$Y_2 = 0.417 + 0.00626X_3$	0.009
	HC	$Y_3 = -1.86 + 0.0533X_2 + 0.190X_3 + 0.0140X_5$	0.846
	NO_x	$Y_4 = -3.44 + 0.0957X_2 + 0.0628X_3 + 0.0527X_5$	0.039
	Fuel Use	$Y_5 = 0.00151 – 0.000455X_2 + 0.0571X_3 – 0.000683X_5$	0.999

*X_1 = RPM, X_2 = IAT, X_3 = MAF, X_4 = LOAD, X_5 = SPEED

Table 4.21 Summary of MLR Models for Diesel Buses

Bus No.	Response	Equations	R^2
12	CO_2	$Y_1 = -12.6 - 0.0504X_2 + 0.229X_3 - 0.0604X_5$	0.972
	CO	$Y_2 = 3.11 - 0.165X_2 + 0.0882X_4 - 0.0219X_5$	0.121
	HC	$Y_3 = -4.15 + 0.0770X_2 + 0.0680X_3 + 0.00364X_5$	0.851
	NO_x	$Y_4 = -22.8 - 0.762X_2 + 0.765X_3 - 0.125X_5$	0.881
	Fuel Use	$Y_5 = -3.97 -0.0159X_2 + 0.0724X_3 - 0.0191X_5$	0.972
13	CO_2	$Y_1 = -28.3 + 0.00361X_1 - 0.0645X_2 + 0.287X_3 - 0.116X_5$	0.958
	CO	$Y_2 = 62.43 + 5.687X_4 - 2.08X_5$	0.147
	HC	$Y_3 = -3.97 + 0.00997X_1 - 0.0637X_2 + 0.0312X_3 - 0.114X_5$	0.278
	NO_x	$Y_4 = -64.8 - 0.0390X_2 + 0.792X_3 - 0.0673X_5$	0.813
	Fuel Use	$Y_5 = -9.09 + 0.00130X_1 - 0.0202X_2 + 0.0911X_3 - 0.0392X_5$	0.955
14	CO_2	$Y_1 = -19.9 - 0.0691X_2 + 0.241X_3 - 0.0656X_5$	0.948
	CO	$Y_2 = 34.7 + 0.0282X_1 - 1.66X_2 + 0.299X_4 + 0.0889X_5$	0.674
	HC	$Y_3 = 5.10 + 0.00836X_1 - 0.249X_2 + 0.0308X_4 - 0.0496X_5$	0.475
	NO_x	$Y_4 = -73.2 + 0.0109X_1 - 0.402X_2 + 0.947X_3 - 0.289X_5$	0.860
	Fuel Use	$Y_5 = -6.27 - 0.0231X_2 + 0.0763X_3 - 0.0207X_5$	0.948

*X_1 = RPM, X_2 = IAT, X_3 = MAP, X_4 = LOAD, X_5 = SPEED

Figure 4.9 presents four residual plots of Bus 1 CO_2 MLR model, which are residuals normal probability plot, residual versus fitted value, residual histogram, and residual versus observation orders. These four plots are used to checked normality and constant variance of residuals, which are required by MLR. Based on the normal probability plot and histogram, residuals are not perfectly normally distributed, but the trends are good. However, the last two plots indicate that residuals do not have constant variances, especially with fitted value. Usually transformation was applied at this situation in order to stabilize variance of residuals. However, because of the large sample sizes (n=6431 s), transformation can be ignored. Moreover, in this research, the MLR were developed for the purpose of estimation model only and not for finding the confidence interval or developing the hypothesis tests on the models. As a result, the MLR predictive models were developed without using the transformation.

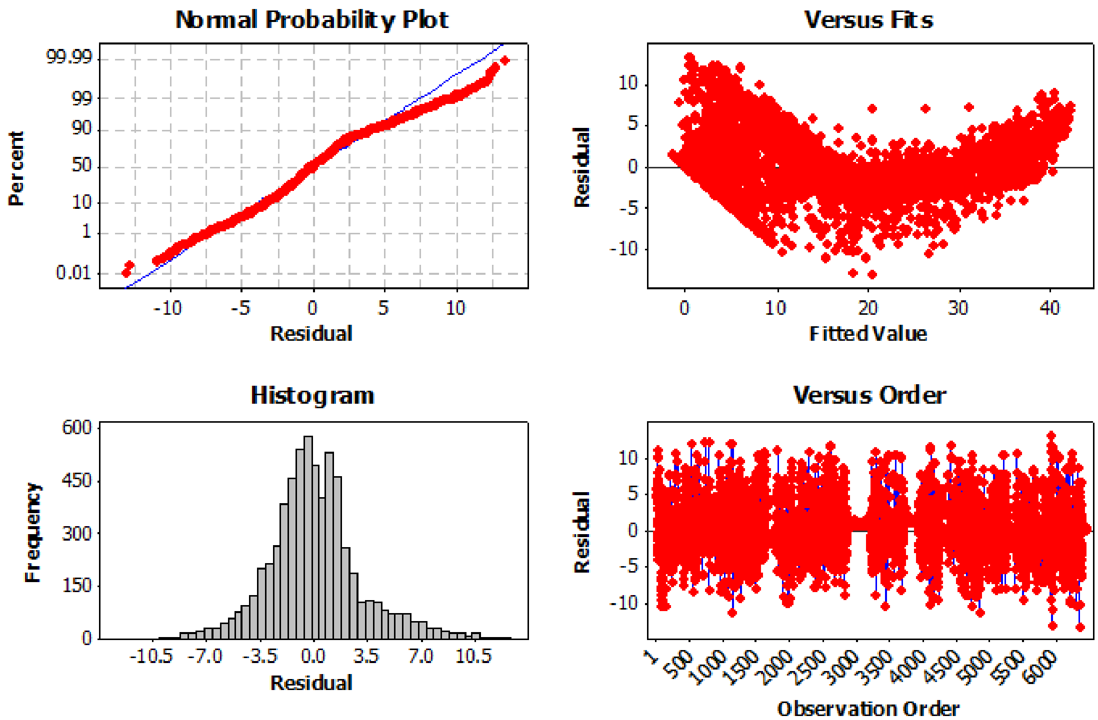


Figure 4.9 Residual Plots of Bus 1 CO_2 MLR Model

4.3.3. Model Validation

Model validation was made for all pollutant emissions and fuel use predictive models of each tested bus in order to assess the prediction performance of the models. For each model, the model was used to estimate the values of the remaining one-third data and then a scatter plot was made of the predicted values versus the actual values. After that, simple linear regression analysis was made between the predicted values and the actual values which displayed a trend line on the scatter plot with the equation containing the values of accuracy (m), bias (b), and precision (R^2).

The validation results of Bus 1 are presented in Figure 4.10 as an example of Big CNG buses. As seen in Figure 4.10, both CO_2 and FC models show high accuracy, low bias, and high precision; both CO and HC models show the moderate accuracy and precision but the bias of the CO model is high. The validation result of the NO_x model is not good. Although its bias is not high, its accuracy and precision are both low.

Figure 4.11 and Figure 4.12 present the validation results of Bus 7 and Bus 12 as an example of Small CNG buses and Diesel buses, respectively. Compared with Bus 1, Bus 7 and Bus 12 also have good predicted models for CO_2 and FC with high accuracy, low bias, and high precision. For Bus 7, its CO and NO_x models have moderate accuracy, bias and precision; its HC model has low accuracy, moderate bias, and low precision. For Bus 12, its HC and NO_x models also have high accuracy, low bias, and high precision; its CO model has low accuracy, moderate bias and low precision.

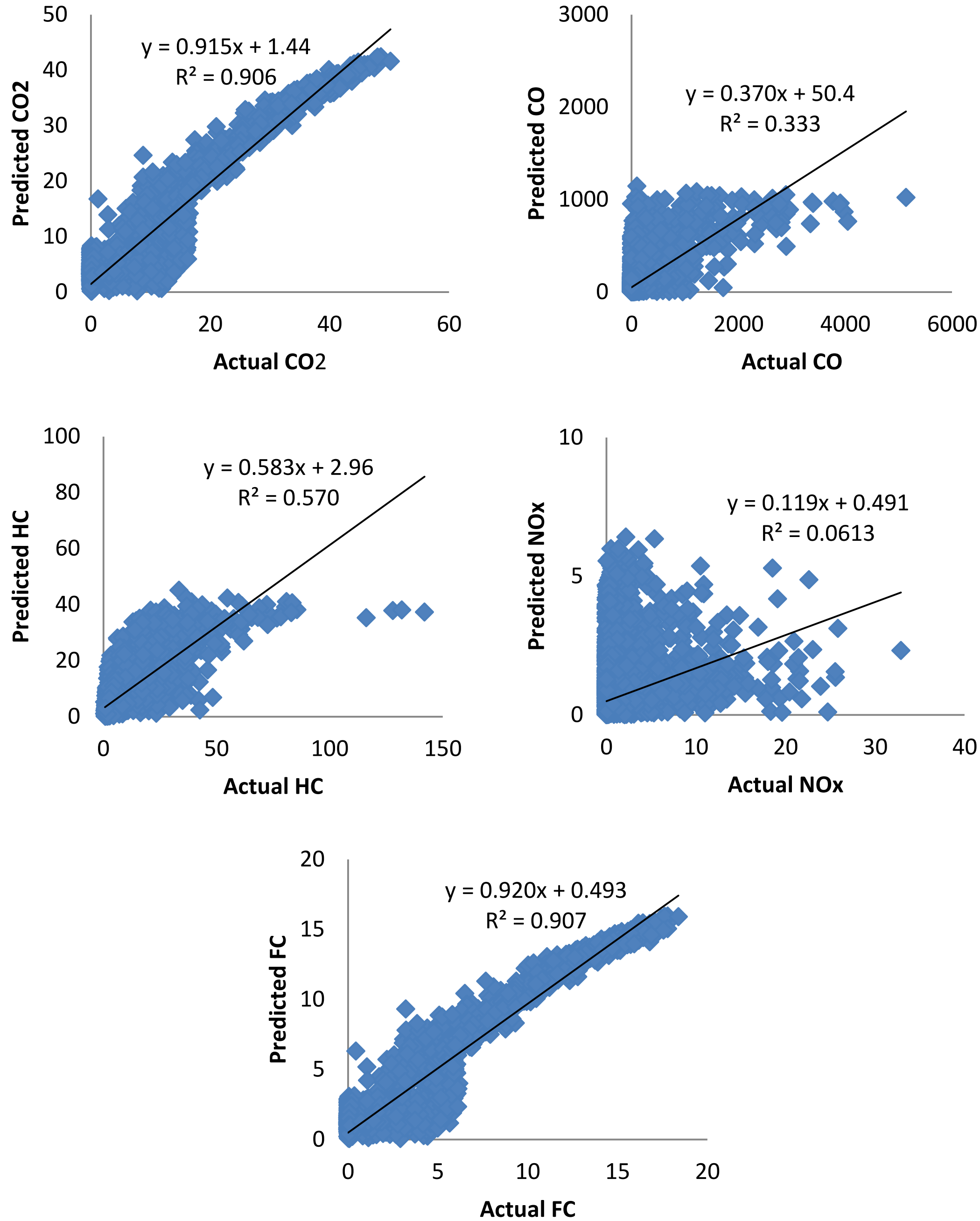


Figure 4.10 Model Validation for MLR of Emissions and Fuel Use Models of Bus 1

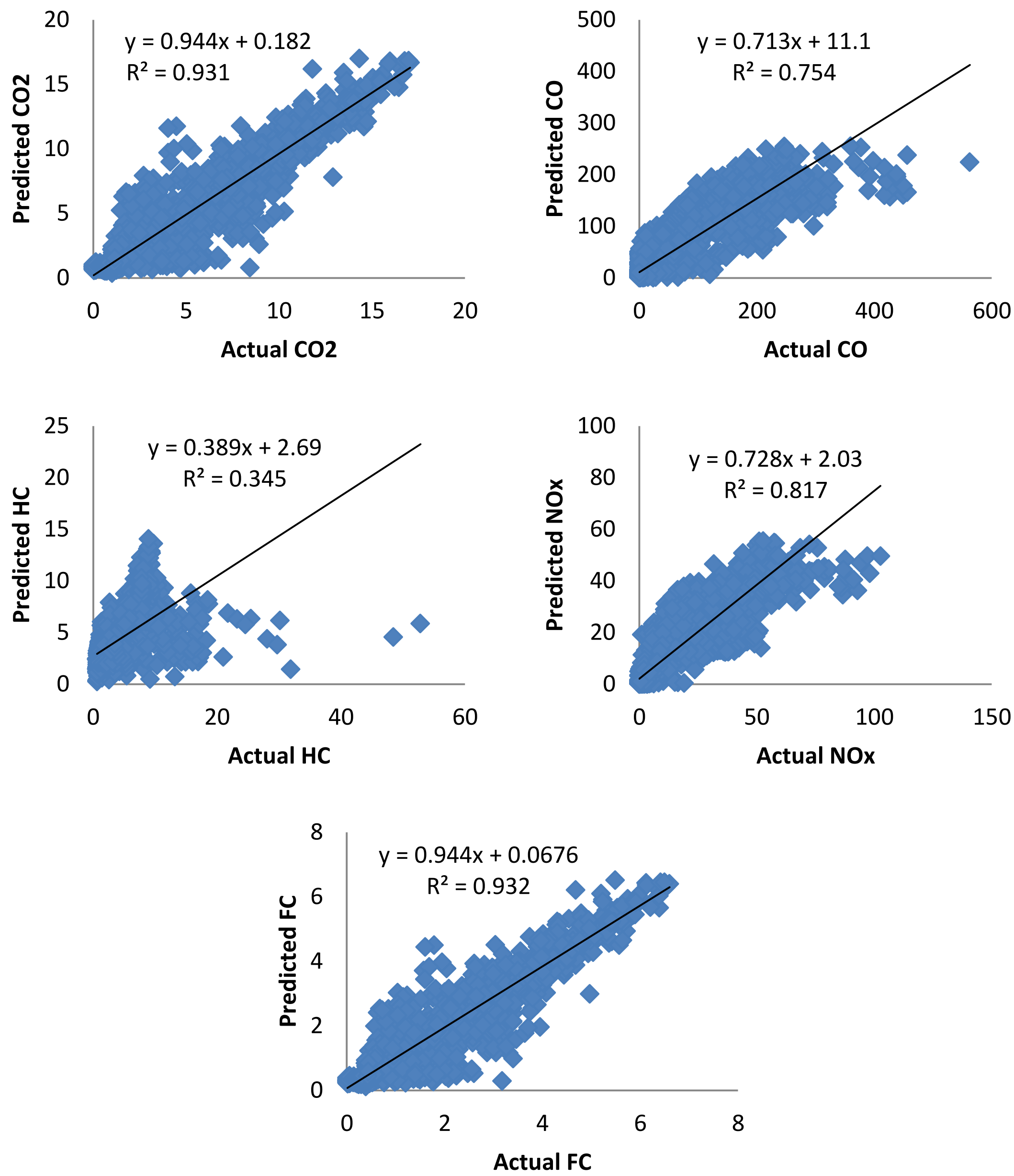


Figure 4.11 Model Validation for MLR of Emissions and Fuel Use Models of Bus 7

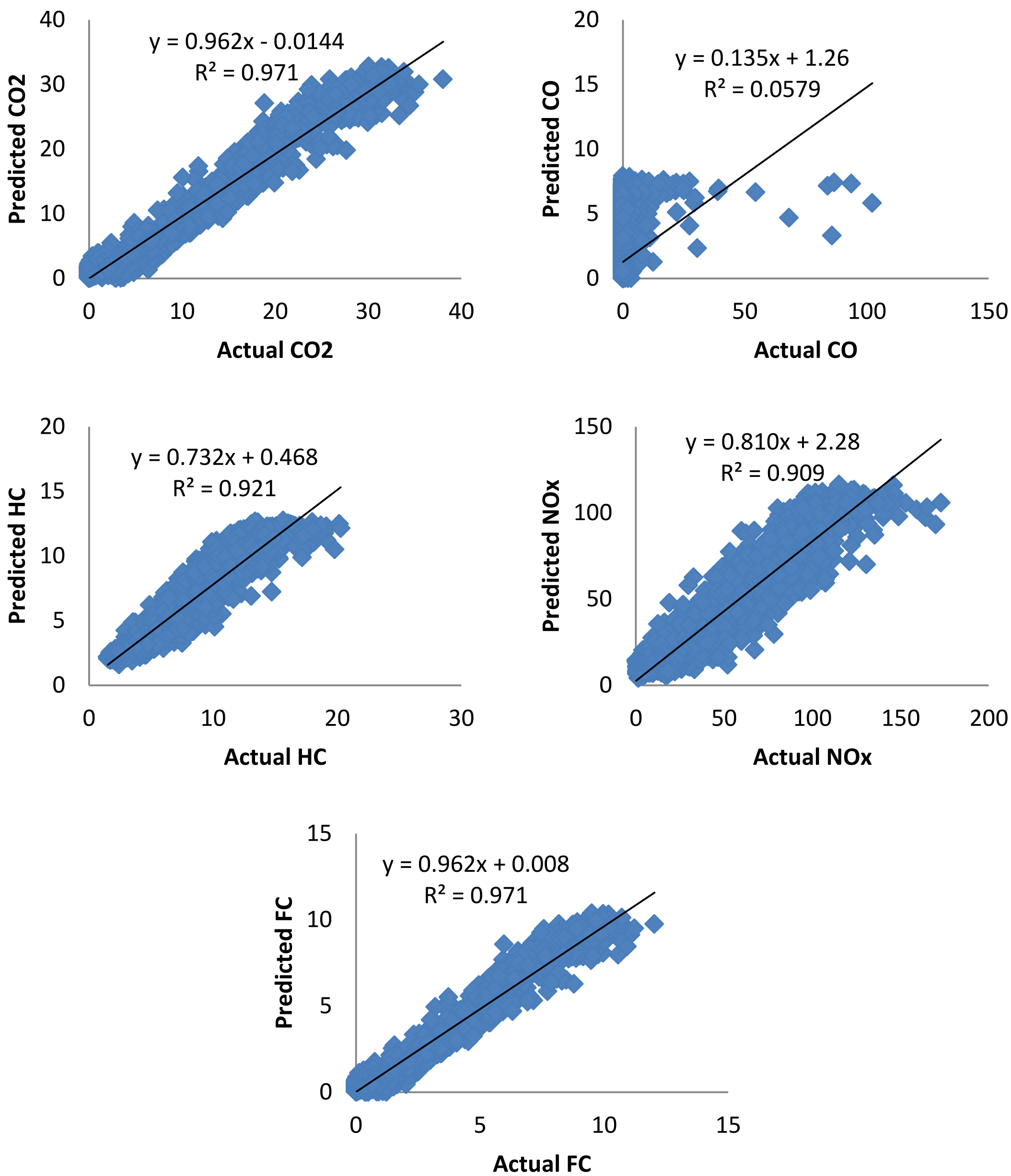


Figure 4.12 Model Validation for MLR of Emissions and Fuel Use Models of Bus 12

Table 4.22, Table 4.23 and Table 4.24 summarize the model validation results of all predicted models of the three bus types containing their accuracy, bias and precision. Their validation scatter plots are included in the Appendix. As seen in Table 4.22, for other tested Big CNG buses, they have similar model validation results with Bus 1 shown above. Most Big CNG buses have good CO_2 and FC models, moderate CO and HC models, and poor NO_x models, except Bus 5. The HC model of Bus 5 has low accuracy, high bias, and low precision.

Table 4.22 Summary of Model Validation for Big CNG Buses

Bus No.	Response	MLR		
		m	b	R^2
1	CO_2	0.915	1.44	0.906
	CO	0.370	50.4	0.333
	HC	0.583	2.96	0.570
	NO_x	0.120	0.520	0.061
	FC	0.920	0.493	0.907
2	CO_2	0.849	1.485	0.858
	CO	0.234	41.0	0.279
	HC	0.425	4.60	0.304
	NO_x	0.044	1.56	0.0399
	FC	0.851	0.568	0.863
3	CO_2	0.848	0.958	0.901
	CO	0.233	51.8	0.181
	HC	0.490	8.23	0.265
	NO_x	0.151	-0.0613	0.194
	FC	0.903	0.619	0.901
4	CO_2	0.901	0.940	0.870
	CO	0.197	62.5	0.164
	HC	0.494	9.85	0.469
	NO_x	0.0665	1.445	0.0527
	FC	0.902	0.375	0.869
5	CO_2	0.920	1.46	0.878
	CO	0.202	-5.48	0.257
	HC	-0.0033	5.82	0.00006
	NO_x	0.109	0.564	0.161
	FC	0.920	0.533	0.881
6	CO_2	0.941	1.33	0.833
	CO	0.199	23.025	0.146
	HC	0.887	1.53	0.245
	NO_x	0.429	2.20	0.0829
	FC	0.945	0.478	0.832

Compared with Big CNG buses, Small CNG buses show better model validation results in Table 4.23. All Small CNG buses have good CO_2 and FC models with high accuracy, low bias and high precision. Most Small CNG buses also have good CO and NO_x models, except Bus 9 and Bus 11. Because the CO emission rates of Bus 9 is almost zero, the CO model has a low R-square value, and the model validation is not available for this model. Similarly, CO and NO_x models of Bus 11 are not good, with low accuracy, high bias, and low precision.

Table 4.23 Summary of Model Validation for Small CNG Buses

Bus No.	Response	MLR		
		m	b	R^2
7	CO_2	0.944	0.182	0.931
	CO	0.713	11.1	0.754
	HC	0.389	2.69	0.345
	NO_x	0.728	2.03	0.817
	FC	0.944	0.0676	0.932
8	CO_2	0.998	0.0043	0.999
	CO	1.01	8.47	0.829
	HC	0.557	1.84	0.519
	NO_x	0.754	1.53	0.780
	FC	1.00	0.0009	0.999
9	CO_2	1.00	0.0143	0.999
	CO	-	-	-
	HC	0.632	3.05	0.682
	NO_x	0.764	1.93	0.840
	FC	1.00	0.0048	0.999
10	CO_2	1.16	-0.0073	0.994
	CO	1.12	7.16	0.963
	HC	0.482	5.36	0.304
	NO_x	1.04	2.03	0.931
	FC	1.16	-0.0012	0.994
11	CO_2	1.03	0.0275	0.999
	CO	0.0515	0.595	0.0954
	HC	1.11	1.20	0.837
	NO_x	0.0142	3.95	0.0031
	FC	1.04	0.0106	0.999

The models of Diesel buses show less variability among individual buses than CNG buses. As seen in Table 4.24, all Diesel buses have good CO_2, NO_x and FC models. All HC models have moderate accuracy, bias and precision. The CO model of Bus 14 is moderate, but the CO models of Bus 12 and Bus 13 are not good.

Table 4.24 Summary of Model Validation for Diesel Buses

Bus No.	Response	MLR		
		m	b	R^2
12	CO_2	0.962	-0.0144	0.971
	CO	0.135	1.26	0.0579
	HC	0.732	0.468	0.921
	NO_x	0.810	2.28	0.909
	FC	0.962	0.008	0.971
13	CO_2	0.918	0.400	0.962
	CO	0.149	65.9	0.186
	HC	0.507	3.02	0.690
	NO_x	0.785	7.76	0.811
	FC	0.914	0.164	0.958
14	CO_2	0.944	0.678	0.944
	CO	0.628	9.07	0.559
	HC	0.893	1.85	0.735
	NO_x	0.783	8.68	0.876
	FC	0.942	0.196	0.944

4.3.4. Variables Impact Analysis

In this research topic, the engine variables' impacts on each bus type's predictive models were assessed by the variable impact analysis. A variable impact table was made for each bus type by filling the order number of each engine variable given by the stepwise selection of each predictive model. The excluded engine variables were given number six as its order number. Then, the order numbers of each engine variable were summed as the impact parameters. Lower impact parameters mean the engine variables have higher impacts on the models.

Table 4.25 presents the variables impact results for Big CNG buses. It indicates that RPM has the least impact parameter (summation value), which means RPM has the highest impact on the predictive models in general. Both MAP and LOAD have the moderate impacts and the impacts of IAT and SPEED are the lowest.

Table 4.25 Variables Impact Results for Big CNG Buses

Bus NO.	Pollutants and FC	RPM	IAT	MAP	LOAD	SPEED
1	CO_2	2	3	5	1	4
	CO	2	4	5	1	3
	HC	1	5	3	4	2
	NO_x	1	2	6	3	4
	FC	2	3	5	1	4
2	CO_2	2	4	1	3	5
	CO	1	6	2	3	4
	HC	1	4	2	3	6
	NO_x	2	1	4	6	3
	FC	2	4	1	3	5
3	CO_2	3	4	1	2	5
	CO	1	4	5	3	2
	HC	1	3	2	6	4
	NO_x	1	3	6	2	4
	FC	3	4	1	2	5
4	CO_2	2	3	4	1	6
	CO	1	5	3	4	2
	HC	1	4	2	3	5
	NO_x	1	3	6	4	2
	FC	2	3	4	1	6
5	CO_2	3	4	1	2	6
	CO	2	5	1	3	4
	HC	1	6	2	3	6
	NO_x	1	3	5	2	4
	FC	3	4	1	2	6
6	CO_2	2	5	1	3	4
	CO	1	4	5	2	3
	HC	2	3	1	4	5
	NO_x	3	2	1	4	6
	FC	2	5	1	3	4
Sum		*52*	*113*	*87*	*84*	*129*

Table 4.26 Variables Impact Results for Small CNG Buses

Bus NO.	Pollutants and FC	RPM	IAT	MAF	LOAD	SPEED
7	CO_2	6	3	1	6	2
	CO	6	2	1	6	6
	HC	1	3	6	6	2
	NO_x	6	3	1	6	2
	FC	6	3	1	6	2
8	CO_2	6	6	1	6	2
	CO	6	3	1	2	6
	HC	6	6	1	2	3
	NO_x	6	6	1	2	3
	FC	6	2	1	3	4
9	CO_2	6	2	1	6	6
	CO	6	1	6	6	6
	HC	6	2	1	6	6
	NO_x	6	3	1	6	2
	FC	6	2	1	6	6
10	CO_2	6	2	1	6	6
	CO	6	3	1	6	2
	HC	6	2	1	6	3
	NO_x	6	3	1	6	2
	FC	6	2	1	6	6
11	CO_2	6	3	1	6	2
	CO	6	6	1	6	6
	HC	6	2	1	6	3
	NO_x	6	2	1	6	3
	FC	6	3	1	6	2
Sum		*145*	*75*	*35*	*135*	*93*

Table 4.26 presents the variable impact results for Small CNG buses. MAF has the much lower summation values than other variables; thus, it has much higher impacts than others on the Small CNG buses predictive models. Both IAT and SPEED have the moderate impacts, and RPM and LOAD have the lowest impacts. Although RPM and LOAD showed high correlation values with emissions and fuel use rates in the correlation matrices of Small CNG buses, they were usually

excluded from the Small CNG predictive buses. That is because multicorlinearity occurred around the RPM, MAF and LOAD in most Small CNG models, and RPM and LOAD had to be removed from the models to avoid this problem.

Table 4.27 shows the variable impact results of Diesel buses. Both MAP and SPEED have high impacts, and IAT has moderate impact. Similar with the Small CNG models, RPM and LOAD also have the lowest impacts on Diesel buses because of the multicorlinearity problems.

Table 4.27 Variables Impact Results for Diesel Buses

Bus NO.	Pollutants and FC	RPM	IAT	MAP	LOAD	SPEED
12	CO_2	6	3	1	6	2
	CO	6	3	6	1	2
	HC	6	3	1	6	2
	NO_x	6	3	1	6	2
	FC	6	3	1	6	2
13	CO_2	3	4	1	6	2
	CO	6	6	6	1	2
	HC	1	4	3	6	2
	NO_x	6	3	1	6	2
	FC	3	4	1	6	2
14	CO_2	6	3	1	6	2
	CO	1	3	6	2	4
	HC	1	4	6	3	2
	NO_x	3	4	1	6	2
	FC	6	3	1	6	2
	Sum	*66*	*53*	*37*	*73*	*32*

4.4. Emissions Inventory

In this research section, an emissions inventory was developed for the old diesel fleet and the current CNG fleet in order to assess the environmental benefits of the CNG buses. Table 4.28 presents the operation hour and fuel use data of each bus in the old fleet during 2009 to 2010. In

Table 4.28, the annual operation hour of each bus was estimated by the duration and total operational hour. For example, Bus 1530 has 24 months data, and its total operation hour is 5268 hours. The total operation hour was divided by the duration and multiplied by 12 months and the value was the annual operation hour of this bus. The annual fuel use of each bus was estimated in the same way based on the duration and the total fuel use data. The summation of the annual operation hour and fuel use of each bus was the total annual operation hour and fuel use for the whole diesel fleet.

Table 4.28 Operation Hour and Fuel Use Data of Diesel Fleet

Bus Plate	Duration (month)	Total OH (hr)	Annual OH (hr/yr)	Total FC (DGE)	Annual FC (DGE/yr)
1530	24	5,268	2,634	15,878	7,939
1544	24	3,790	1,895	10,696	5,348
1532	24	4,070	2,035	11,732	5,866
1531	24	4,473	2,237	13,389	6,695
1533	23	3,574	1,865	10,274	5,360
1534	24	3,136	1,568	9,003	4,502
1535	23	3,149	1,643	9,223	4,812
1536	24	3,255	1,628	9,995	4,998
1537	24	4,282	2,141	12,093	6,047
1538	24	3,812	1,906	11,611	5,806
1539	24	2,968	1,484	9,254	4,627
1540	24	2,883	1,442	7,738	3,869
1541	23	2,904	1,515	8,175	4,265
1542	20	3,413	2,048	10,167	6,100
1543	23	3,929	2,050	10,441	5,447
1545	21	1,904	1,088	4,693	2,682
1546	22	2,155	1,175	4,779	2,607
1548	16	1,041	781	2,778	2,084
1551	11	446	487	572	624
1552	24	1,087	544	1,904	952
1553	9	2,298	3,064	4,985	6,647
1554	9	2,110	2,813	4,550	6,067
Total	*464*	*65,947*	*38,041*	*183,930*	*103,341*

To calculate the annual emissions of each bus in the diesel fleet, the average emissions rates (g/DGE) of each bus were multiplied by its annual fuel use (DGE/yr). Table 4.29 presents the annual emissions and fuel use of each bus in the diesel fleet. It should be noted that only 1530, 1544 and 1532 were tested in this research. Thus, the emission rates of the other buses were estimated as the average emissions rates of these three tested buses. The summation of the annual emissions and fuel use of all buses were the total annual emissions and fuel use of the whole diesel fleet.

Table 4.29 Annual Emissions and Fuel Use of Diesel Fleet

Bus Plate	CO_2 (tons/yr)	CO (kg/yr)	HC (kg/yr)	NO_x (kg/yr)	FC (DGE/yr)
1530	79	20	48	365	7,939
1544	53	433	45	209	5,348
1532	59	153	45	340	5,866
1531	67	281	51	315	6,695
1533	54	225	41	252	5,360
1534	45	189	34	212	4,502
1535	48	202	37	226	4,812
1536	50	210	38	235	4,998
1537	60	254	46	284	6,047
1538	58	244	44	273	5,806
1539	46	194	35	217	4,627
1540	39	162	29	182	3,869
1541	43	179	32	200	4,265
1542	61	256	46	287	6,100
1543	54	229	41	256	5,447
1545	27	113	20	126	2,682
1546	26	109	20	123	2,607
1548	21	88	16	98	2,084
1551	6	26	5	29	624
1552	10	40	7	45	952
1553	66	279	51	312	6,647
1554	61	255	46	285	6,067
Total	*1,033*	*4,141*	*779*	*4,871*	*103,341*

For the CNG fleet, since there were no available operation hour and fuel use data, it was assumed that the CNG fleet had the same total annual operation hour as the diesel fleet (38041hours). Then, the total annual operation hour of the Big CNG fleet and the Small CNG fleet were determined by their proportions in the whole fleet. There are nine Big CNG buses and 10 Small CNG buses in the CNG fleet. Thus, the annual operation hour of the Big CNG fleet should be 9/19 of the total annual operation hour, which is 18,019 hours; and the 10/19 of the total should be the annual operation hour of the Small CNG fleet, which is 20,021 hours. After that, the annual operation hour of these two types of CNG fleets were multiplied by their average fuel use rates (Big CNG is

4.5 DGE/hr, Small CNG is 1.9 DGE/hr), in order to calculate their annual fuel use. The summation was the total annual fuel use of the CNG fleet. Based on the annual fuel use of the Big CNG and Small CNG fleet, the annual emissions were estimated in Table 4.30. For example, as seen in Table 4.30, for the Big CNG fleet, the average CO_2 emission rate is 7.7 kg/DGE, and the annual fuel use is 81,086 DGE/hr. Thus, the annual CO_2 emission of the Big CNG fleet is 7.7 kg/DGE multiplied by 81,086 DGE/hr, which is 624 tons/yr. The total annual emissions of the whole CNG fleet are the summation of the annual emissions of the Big and Small CNG fleets.

Table 4.30 Annual Emissions Estimation of CNG Fleet

	Average Emissions Rates				FC	Annual Emissions			
	CO_2 (kg/DGE)	CO (g/DGE)	HC (g/DGE)	NO_x (g/DGE)	(DGE/yr)	CO_2 (tons/yr)	CO (kg/yr)	HC (kg/yr)	NO_x (kg/yr)
Big CNG	7.7	62	6.6	1.3	81,086	624	5,027	535	105
Small CNG	7.5	97	14	36	38,041	285	3,690	533	1,369
Total					*119,127*	*910*	*8,717*	*1,068*	*1,475*

Table 4.31 presents the emissions inventory of the CNG fleet and the diesel fleet. As seen in Table 4.31, the CNG fleet emitted 14% less CO_2 and 70% less NO_x than the diesel fleet. However, the CNG fleet emitted 110% more CO and 37% more HC. Moreover, the CNG also used 15% more fuels (DGE/yr) than the diesel fleet.

Table 4.31 Emissions Inventory of CNG and Diesel Fleets

	CNG	Diesel	%
CO_2 (tons/yr)	910	1,033	-14%
CO (kg/yr)	8,717	4,141	110%
HC (kg/yr)	1,068	779	37%
NO_x (kg/yr)	1,475	4,871	-70%
FC (DGE/hr)	119,127	103,341	15%

CHAPTER V

CONCLUSIONS

5.1. Characterization of OSU Bus Fleet Data

5.1.1. Field Data Collection

The PEMS used for data collection measured real-world emission rates for CO_2, CO, HC and NO_x as well as fuel use data of both CNG buses and diesel buses. Based on these data, it was appropriate to make emissions comparisons between different fuels, operational modes and engine modes. The emission rates and fuel use measured by the PEMS can be compared with MOVES data in order to compare the two data sources.

Compared with laboratory data, real-world data collection was conducted in a challenging environment. For example, vibration of the tested bus sometimes caused a disconnection between the probes and the tailpipe. Cold weather froze the condensation in exhaust samples and blocked the gas analyzers of PEMS. Protocols for collecting real-world emissions and fuel use data should be developed.

5.1.2. Emissions Rates and Vehicle Activity Data

Summary statistics analysis showed that inter-vehicle variability exists in pollutant emissions rates and vehicle activity variables. This was true for the five Big CNG buses, the five Small CNG buses as well as the three Diesel buses, even though each of the Big CNG buses had the same manufacturer, model year, and engine specifications, and so do the Small CNG buses and the Diesel buses. The data variability even appeared on the same bus driving on two different routes. The study was somewhat limited in its ability to fully characterize the influence of route and weather on fuel use, emissions, and vehicle activity; however, the buses in each size category drove on routes that were of similar length and duration and under similar weather conditions. Although more data is needed to determine if the variability among the individual buses is statistically significant, this finding points toward a conclusion that individual buses may have their own unique emissions and fuel use rates on particular routes and particular weather conditions even if they have the same engine and vehicle specifications. The influence of the routes and weather should be assessed in future study.

5.2. Comparison of Emissions and Fuel Use Rates

5.2.1. CNG vs. Diesel Comparison

In the comparison between fuels, because the emissions rates were converted to mass per fuel used basis, the variability among individual buses in each type of bus was reduced. Both the Big CNG and Small CNG buses showed 25% lower average emission rate of CO_2 than the Diesel buses. Moreover, both types of CNG buses emitted less NO_x than Diesel buses. Especially for the Big CNG buses, their average NO_x emission rate was only equal to 2.8% of the Diesel buses' and the Small CNG buses also emitted 23% less than the Diesel buses per gallon fuel on average. There were mixed results for HC – the Small CNG buses had a 84% higher average emission rate than the Diesel buses but the Big CNG buses had 12 % lower rate the Diesel buses. Both CNG buses clearly had higher average emission rates of CO than the Diesel buses; the Big CNG buses had 48% higher rate and the Small CNG buses had 130% higher rate. Fuel use rates among the three types of buses were also compared. The Small CNG buses had a 63% lower average fuel use rate, but the Big CNG buses had a 45% higher average fuel use rate than the Diesel buses.

5.2.2. Operational Modal Comparison

In the comparisons among operational modes, the percent of time spent on each mode was quantified. All three types of buses spent more time on the idling and cruising modes than the acceleration and deceleration modes. The emissions and fuel use rates of each mode were compared for each type of bus on the basis of three different units to assess the impacts of operational modes on the emissions and fuel use rates. On mass per time basis, all pollutant emissions rates of all types of buses showed the similar trend that idling and deceleration modes had the lowest rates, the rates of the idling mode were higher, and the rates of the acceleration mode were the highest. On mass per distance basis, because of the limitation of the conversion, emissions rates were only compared among the three non-idling modes. All pollutant emissions rates showed the same trend of all three types of buses that the deceleration mode had the lowest rates, the rates of the cruising mode were higher, and the rates of the acceleration mode were the highest. On mass per fuel used basis, the results showed variability among not only pollutants but also bus types. For instance, for $NO_{x,}$ the diesel buses had the higher rates on the idle and deceleration modes than the cruising and acceleration modes; however, the Small CNG buses had the lower rates on the idle and deceleration modes than the cruising and acceleration modes. Moreover, the Big CNG buses had constant low rates among the four modes.

Fuel use rates were also compared among the four operation modes for each type of buses on mass per time basis, gallon per time basis, and mass per distance basis. The results showed a similar trend on all units for all types of buses. The idling and deceleration modes had the lowest rates (the fuel use rates were not analyzed on mass per distance basis), the rates of the cruising mode were higher, and the rates of the acceleration mode were the highest.

The distribution by operational modes of time, emissions and fuel use was analyzed for each type of buses to assess the relative importance of each operational mode. The results indicated that, for all three types of buses, the acceleration and cruising emitted more pollutants and used more fuels, compared with the idling and deceleration modes. Especially the acceleration mode, the tested buses usually spent 15% to 20% time on this mode, but emitted 30% to 70% pollutants and used 30% to 40% fuels. As a result, the total emissions and fuel use likely can be lower with less time in the acceleration mode. Moreover, although, generally, the idling mode emitted fewer pollutants and had lower fuel use than the three non-idling modes, it still emitted significant amounts of pollutants. For instance, the Big CNG buses emitted about 25% CO_2 during 30% of overall time on the idling mode. Thus, the total emissions and fuel use will likely decrease as the idling time decreases.

5.2.3. Engine Modal Comparison

In the engine modal comparisons, the data of each tested bus was categorized into 10 engine modes based on the normalized RPM data. Higher RPM values refer to higher engine loads. The percent of time spent on each mode was quantified for each tested bus firstly. Generally, the percent of time decreases as the engine modes increase (engine loads increase) for all tested buses. However, there was variability among the different types of buses. For instance, both the Small CNG and Diesel buses spent most time on the mode one, but the Big CNG buses spent most time on the mode 2. There was also variability among individual buses in each type of bus.

The emissions and fuel use rates of each mode were calculated for each tested bus. Then, the average emissions and fuel use rates of each mode for each type of bus were also calculated and compared. For all three types of buses, generally, the emissions and fuel use rates increases as the engine modes increases (engine loads increase), although there was still small variability among individual buses and the different types of buses. It may be concluded that all pollutant emissions and fuel uses rates of the tested buses had a general increasing trend as the engine modes increase (engine loads increase).

The weighted average emissions and fuel use rates of each mode were also calculated for each tested bus. Since the percent of time and emissions and fuel use rates had an opposite trend with the increase of the engine modes (engine loads increase), the results showed that, for all pollutants and fuel use of each tested bus, the weighted average emissions and fuel use rates had higher values in the middle engine modes and lower values in the low and high engine modes.

5.3. Emissions and Fuel Use Predictive Models

5.3.1. Correlation Matrix

Correlation matrix analysis showed that there were moderate-to-strong relationships between pollutant emissions rates and the vehicle activity variables, especially for the Small CNG buses. This is an encouraging finding because these relationships provide a good starting point for the development of predictive models using pollutant emissions rates as response variables and vehicle activity data as predictor variables. Although the results showed that engine intake air temperature (IAT) and vehicle speed (SPEED) had weak correlations with the pollutant emissions rates, this does not mean that those variables have no predictive power. Rather, it means that they likely contribute a smaller percentage of value to the response variable. The results also showed that there were strong interrelationships among the vehicle activity variables; thus, modelers must be aware of the possibility of multicollinearity among predictor variables. Although multicollinearity does not reduce the prediction effectiveness of the model, it does pose concerns with addressing how much of an impact a specific predictor variable has on the response variable.

5.3.2. Prediction Models using Multiple Linear Regression (MLR)

Predictive models were developed for each pollutant emission rate and fuel use rate of each tested bus based on two-thirds of the available data. The R-square value of each model was calculated to assess the appropriateness of the model. For Big CNG buses, their CO_2 and FC models had high R-square values, ranging from 0.7 to 0.9, which means that the engine variables could explain much variability of CO_2 and FC. Compared with CO_2 and FC models, the models of HC and CO were moderate with the R-values around 0.2 to 0.5, and the NO_x models were the ones with the lowest R-square values.

For Small CNG buses, their CO_2 and FC models were even better than the Big CNG's models, and their R-square values were all above 0.9. Their CO, HC and NO_x models were also better than Big CNG, however, there were variability among individual buses. For instance, three Small-CNG buses' CO models had high R-square values, but the other two buses' models had much lower R-square values.

For Diesel buses, as well as Big CNG and Small CNG buses, their CO_2 and FC models had high R-square values. The NO_x models also had high R-square values here. The CO and HC models had low R-square values and variability among individual buses.

Considering the characterizations of the emissions and fuel use data, there may be two reasons leading to the low R-square values of some models. First, the CV values indicated that there was significant inter-vehicle variability of some pollutant emissions rates. The high variability of the response variables (emissions rates) would lead to difficulty in using predictor variables (engine variables) to explain these variables. In other words, the models of these variables may have low R-square values. For instance, CO had the highest CV values of most tested buses. Thus, most CO models had lower R-square values than other pollutants models. Second, low values of the response variables may also lead to the low R-square values. For example, the Big CNG buses had much lower NO_x emission rates (almost zero) than Big CNG and Diesel buses. Because of these low emission rates, the NO_x models of Big CNG buses had the low R-square values. On the other hand, the NO_x models of Small CNG and Diesel buses were better because their NO_x emission rates were higher than Big CNG buses.

5.3.3. Model Validation

Model validation was conducted for each predictive model of each tested bus based on the remaining one-third available data. In this analysis, three statistic parameters were calculated to assess the predictive power of each model, which were accuracy (a), bias (b) and precision (R-square). Based on the results, all CO_2 and FC models showed high accuracy, high precision, and low bias. The HC models were moderate, and the CO and NOx models did not perform well. However, the NO_x models of Diesel buses perform well. Besides CO_2 and FC models, other pollutants models showed variability among bus type and individual buses.

5.3.4. Variables Impact Analysis

This study indicated which engine variables had the highest impacts on each type of buses' predictive models. In general, RPM had the highest impact on Big CNG buses models; MAF had the highest impact on Small CNG buses models; and MAP had the highest impact on Diesel buses. These results could be a good reference for engine variables selection of predictive model development in future study.

5.4. Emissions Inventory

Emissions Inventory was developed for the CNG fleet and the diesel fleet, respectively. Based on the inventory, the CNG fleet showed environmental benefits on the pollutants CO_2 and NO_x. However, the CNG fleet emitted more HC, and much more CO than the diesel fleet. Moreover, the CNG fleet had more fuel use than the diesel fleet.

CHAPTER VI

RECOMMENDATIONS AND FUTURE WORK

Some recommendations can be described as follows:

1. Data collection protocols should be developed. Foam boards should be placed under the main unit of PEMS to absorb the vibrations of the tested bus, in order to prevent the disconnection problems and physical damage. Moreover, when collecting data in winter, a heater should be used to keep the exhaust samples warm before the samples enter the main unit. That is because the freezing condensation exhaust samples may block the gas analyzers.
2. Since MLR models did not produce good predictive power for several pollutants' emissions rates, such as CO and NO_x, other statistical methods should be applied to these pollutants, like artificial neural network.
3. Predictive models should be developed for each operation mode. These specific models may produce stronger predictive power and higher accuracy than the general models.

4. This dissertation assessed the engine variable impacts on emissions and fuel use rates, but not evaluated environment and road conditions impacts. In future study, these impacts should be identified and quantified as well.
5. Because there is no available operation hour and fuel use data of the CNG fleet, the emissions inventory was developed based on several consumptions. In future study, the operation hour and fuel use data of the CNG fleet should be measured in order to develop more reliable emissions inventory of the CNG fleet.

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APPENDICES

The appendices provide data and calculation parts to support the results. The appendices were divided into several parts as follows:

Appendix A Tukey Test Results

Appendix B Operational Mode Dataset

Appendix C Engine Modal Comparison

Appendix D Correlation Matirx

Appendix E Model Validation

A) Appendix A: Tukey Test Results

This appendix present the Tukey Test results for the three bus types, respectively. The values in parentheses indicate there is no statistically significant difference between the two buses.

Table A.1. Tukey Test Results for Diesel Buses

CO_2	Bus 12	Bus 13	Bus 14
Bus 12			
Bus 13	3.2		
Bus 14	0.69	2.5	
CO	**Bus 12**	**Bus 13**	**Bus 14**
Bus 12			
Bus 13	83		
Bus 14	19	65	
HC	**Bus 12**	**Bus 13**	**Bus 14**
Bus 12			
Bus 13	4.4		
Bus 14	1.6	2.8	
NO_x	**Bus 12**	**Bus 13**	**Bus 14**
Bus 12			
Bus 13	8.1		
Bus 14	13	4.7	
FC	**Bus 12**	**Bus 13**	**Bus 14**
Bus 12			
Bus 13	1.1		
Bus 14	0.23	0.83	

*values in parentheses indicate there is no statistically significant difference between the two buses

Table A.2. Tukey Test Results for Big CNG Buses

CO_2 (g/s)	Bus 1	Bus 2	Bus 3	Bus 4	Bus 5	Bus 6
Bus 1						
Bus 2	2.3					
Bus 3	3.8	1.5				
Bus 4	0.95	1.4	2.8			
Bus 5	2.2	**(0.09)**	1.5	1.3		
Bus 6	6.2	3.9	2.5	5.3	4.0	

CO (mg/s)	Bus 1	Bus 2	Bus 3	Bus 4	Bus 5	Bus 6
Bus 1						
Bus 2	100					
Bus 3	70	33				
Bus 4	81	21	11			
Bus 5	77	26	**(6.7)**	**(4.6)**		
Bus 6	130	26	59	47	52	

HC (mg/s)	Bus 1	Bus 2	Bus 3	Bus 4	Bus 5	Bus 6
Bus 1						
Bus 2	4.3					
Bus 3	1.5	2.8				
Bus 4	8.2	12.6	9.8			
Bus 5	2.5	1.8	0.95	11		
Bus 6	6.7	2.4	5.2	15.0	4.2	

NO_x (mg/s)	Bus 1	Bus 2	Bus 3	Bus 4	Bus 5	Bus 6
Bus 1						
Bus 2	0.34					
Bus 3	0.17	**(0.17)**				
Bus 4	0.27	**(0.065)**	**(0.11)**			
Bus 5	**(0.023)**	0.36	0.19	0.30		
Bus 6	0.37	**(0.033)**	0.20	**(0.098)**	0.39	

FC (g/s)	Bus 1	Bus 2	Bus 3	Bus 4	Bus 5	Bus 6
Bus 1						
Bus 2	0.91					
Bus 3	1.4	0.51				
Bus 4	0.38	0.53	1.0			
Bus 5	0.86	**(0.048)**	0.56	0.48		
Bus 6	2.4	1.4	0.93	2.0	1.5	

*values in parentheses indicate there is no statistically significant difference between the two buses

Table A.3. Tukey Test Results for Small CNG Buses

CO_2	Bus 7	Bus 8	Bus 9	Bus 10	Bus 11
Bus 7					
Bus 8	1.5				
Bus 9	0.91	2.4			
Bus 10	1.3	2.7	0.35		
Bus 11	0.75	0.72	1.7	2.0	

CO	Bus 7	Bus 8	Bus 9	Bus 10	Bus 11
Bus 7					
Bus 8	**(2.6)**				
Bus 9	43	41			
Bus 10	86	89	130		
Bus 11	43	40	**(0.61)**	130	

HC	Bus 7	Bus 8	Bus 9	Bus 10	Bus 11
Bus 7					
Bus 8	**(0.13)**				
Bus 9	5.2	5.0			
Bus 10	3.3	3.2	1.9		
Bus 11	2.2	2.0	3.0	1.1	

NO_x	Bus 7	Bus 8	Bus 9	Bus 10	Bus 11
Bus 7					
Bus 8	1.3				
Bus 9	1.4	2.7			
Bus 10	33	32	34		
Bus 11	6.6	7.9	5.2	39	

FC	Bus 7	Bus 8	Bus 9	Bus 10	Bus 11
Bus 7					
Bus 8	0.55				
Bus 9	0.36	0.91			
Bus 10	0.42	0.97	**(0.055)**		
Bus 11	0.25	0.29	0.62	0.67	

*values in parentheses indicate there is no statistically significant difference between the two buses

B) Appendix B: Operational Mode Dataset

This appendix presents the operational mode dataset for each tested bus. The dataset contains the percent of time, emissions and fuel use rates on three different unit bases for each operational mode.

Table B.1. Bus 1 Operational Mode Dataset

Bus type: Big CNG; Bus ID: 1568; Route: Gray; Data: 03-19-2013																
Mode	Percent [%]	CO_2			CO			HC			NO_x			FC		
		g/s	kg/DGE	kg/km	mg/s	g/DGE	g/km	mg/s	g/DGE	g/km	mg/s	g/DGE	g/km	g/s	DGE/hr	kg/km
Idle	30%	8.1	7.8	--	19	18	--	3.8	3.7	--	0.25	0.24	--	3.0	3.7	--
Cruising	14%	13	7.7	1.3	160	98	17	9.9	5.9	1.0	1.4	0.81	0.14	4.8	6.0	0.50
Acc	28%	15	7.7	1.1	160	84	12	12	6.4	0.94	1.5	0.80	0.12	5.5	6.9	0.42
Dec	29%	14	7.6	1.9	290	160	41	13	7.2	1.8	2.2	1.2	0.31	5.3	6.6	0.73
Average		*12*	*7.7*	*1.7*	*160*	*99*	*22*	*9.7*	*6.1*	*1.4*	*1.3*	*0.83*	*0.19*	*4.6*	*5.8*	*0.65*

Table B.2. Bus 2 Operational Mode Dataset

Bus Type: Big CNG; Bus ID: 1568; Route: Orange; Date: 09-11-2013																
Mode	Percent [%]	CO_2			CO			HC			NO_x			FC		
		g/s	kg/DGE	kg/km	mg/s	g/DGE	g/km	mg/s	g/DGE	g/km	mg/s	g/DGE	g/km	g/s	DGE/hr	kg/km
Idle	38%	8.7	7.8	--	10.2	9.1	--	3.5	3.2	--	0.34	0.30	--	3.2	4.0	--
Cruising	45%	9.8	7.8	1.7	59	47	10	6.0	4.8	1.1	2.5	2.0	0.45	3.6	4.5	0.64
Acc	8%	23	7.7	4.6	290	97	58	14	4.9	2.9	2.6	0.90	0.53	8.4	11	1.7
Dec	8%	3.5	7.8	1.0	5.0	11	1.4	1.6	3.5	0.42	2.0	4.5	0.55	1.3	1.6	0.35
Average		*10*	*7.8*	*3.1*	*54.9*	*43*	*17*	*5.4*	*4.2*	*1.7*	*1.7*	*1.3*	*0.51*	*3.7*	*4.6*	*1.1*

Table B.3. Bus 3 Operational Mode Dataset

Bus Type: Big CNG; Bus ID: 1572; Route: Gray; Date: 09-19-2013																
Mode	**Percent [%]**	**CO_2**			**CO**			**HC**			**NO_x**			**FC**		
		g/s	**kg/DGE**	**kg/km**	**mg/s**	**g/DGE**	**g/km**	**mg/s**	**g/DGE**	**g/km**	**mg/s**	**g/DGE**	**g/km**	**g/s**	**DGE/hr**	**kg/km**
Idle	33%	5.6	7.8	--	11	15	--	4.0	5.6	--	0.21	0.28	--	2.1	2.6	--
Cruising	40%	9.1	7.7	0.79	96	81	8.3	9.9	8.4	0.85	1.5	1.3	0.13	3.4	4.3	0.29
Acc	14%	20	7.6	2.6	320	120	42	18	6.9	2.4	5.4	2.0	0.70	7.5	9.5	1.0
Dec	12%	0.83	7.8	0.12	2.5	23	0.36	2.5	23	0.37	0.48	4.5	0.07	0.3	0.38	0.04
Average		*8.5*	*7.7*	*1.3*	*88*	*79*	*13.3*	*8.2*	*7.4*	*1.2*	*1.5*	*1.3*	*0.23*	*3.2*	*4.0*	*0.48*

Table B.4. Bus 4 Operational Mode Dataset

Bus Type: Big CNG; Bus ID: 1566; Route: Scarlet; Date: 09-20-2013																
Mode	**Percent [%]**	**CO_2**			**CO**			**HC**			**NO_x**			**FC**		
		g/s	**kg/DGE**	**kg/km**	**mg/s**	**g/DGE**	**g/km**	**mg/s**	**g/DGE**	**g/km**	**mg/s**	**g/DGE**	**g/km**	**g/s**	**DGE/hr**	**kg/km**
Idle	20%	8.4	7.8	--	5.3	4.9	--	8.4	7.9	--	1.2	1.1	--	3.1	3.9	--
Cruising	51%	11	7.7	1.3	67	46	7.9	20	14	2.3	1.6	1.1	0.18	4.2	5.2	0.49
Acc	15%	25	7.7	3.8	280	86	43	34	10	5.1	3.2	1.0	0.48	9.4	12	1.4
Dec	15%	1.7	7.7	0.31	3.2	14	0.58	8.6	39	1.6	0.67	3.1	0.12	0.63	0.79	0.12
Average		*11*	*7.7*	*1.9*	*76*	*52*	*13*	*18*	*12*	*3.0*	*1.6*	*1.1*	*0.26*	*4.2*	*5.3*	*0.69*

Table B.5. Bus 5 Operational Mode Dataset

Bus Type: Big CNG; Bus ID: 1567; Route: White; Date: 09-27-2013																
Mode	**Percent [%]**	**CO_2**			**CO**			**HC**			**NO_x**			**FC**		
		g/s	**kg/DGE**	**kg/km**	**mg/s**	**g/DGE**	**g/km**	**mg/s**	**g/DGE**	**g/km**	**mg/s**	**g/DGE**	**g/km**	**g/s**	**DGE/hr**	**kg/km**
Idle	34%	7.7	7.8	--	10	10	--	2.8	2.9	--	0.40	0.41	--	2.8	3.5	--
Cruising	43%	9.9	7.7	1.4	80	62	11	9.2	7.2	1.3	1.5	1.2	0.21	3.7	4.6	0.52
Acc	13%	25	7.7	4.5	360	110	62	17	5.2	3.0	3.4	1.0	0.61	9.4	12	1.68
Dec	10%	1.5	7.8	0.33	4.6	24	1.0	2.6	14	0.58	0.87	4.5	0.19	0.55	0.70	0.12
Average		*10*	*7.7*	*2.4*	*81*	*62*	*19*	*7.2*	*5.6*	*1.7*	*1.3*	*1.0*	*0.31*	*3.7*	*4.7*	*0.88*

Table B.6. Bus 6 Operational Mode Dataset

Bus Type: Big CNG; Bus ID: 1569; Route: Orange; Date: 11-08-2013																
Mode	**Percent [%]**	**CO_2**			**CO**			**HC**			**NO_x**			**FC**		
		g/s	**kg/DGE**	**kg/km**	**mg/s**	**g/DGE**	**g/km**	**mg/s**	**g/DGE**	**g/km**	**mg/s**	**g/DGE**	**g/km**	**g/s**	**DGE/hr**	**kg/km**
Idle	36%	5.3	7.8	--	7.9	12	--	1.3	1.9	--	0.60	0.88	--	1.9	2.4	--
Cruising	7%	5.1	7.8	1.4	27	41	7.2	2.8	4.3	0.76	2.0	3.0	0.53	1.9	2.4	0.50
Acc	28%	6.3	7.8	0.87	42	53	5.9	4.5	5.6	0.63	2.3	2.8	0.32	2.3	2.9	0.32
Dec	29%	7.0	7.8	1.9	40	44	11	3.4	3.8	0.94	2.3	2.5	0.63	2.6	3.2	0.72
Average		*6.1*	*7.8*	*1.7*	*29*	*37*	*8.3*	*3.0*	*3.9*	*0.86*	*1.7*	*2.2*	*0.49*	*2.2*	*2.8*	*0.64*

Table B.7. Bus 7 Operational Mode Dataset

Bus Type: Small CNG; Bus ID: 1555; Route: Gray; Date: 03-21-2013																
Mode	**Percent [%]**	**CO_2**			**CO**			**HC**			**NO_x**			**FC**		
		g/s	**kg/DGE**	**kg/km**	**mg/s**	**g/DGE**	**g/km**	**mg/s**	**g/DGE**	**g/km**	**mg/s**	**g/DGE**	**g/km**	**g/s**	**DGE/hr**	**kg/km**
Idle	19%	1.1	7.6	--	4.0	26	--	2.4	16	--	0.18	1.2	--	0.43	0.54	--
Cruising	8%	4.1	7.5	0.43	45	82	4.7	4.6	8.4	0.48	11	20	1.2	1.6	2.0	0.16
Acc	37%	5.1	7.5	0.43	53	79	4.5	4.7	7.0	0.40	15	22	1.3	1.9	2.4	0.16
Dec	36%	4.1	7.5	0.91	53	97	12	4.4	8.0	0.97	10	19	2.3	1.6	2.0	0.35
Average		*3.9*	*7.5*	*0.57*	*43*	*83*	*6.3*	*4.2*	*8.0*	*0.61*	*10*	*20*	*1.5*	*1.5*	*1.9*	*0.22*

Table B.8. Bus 8 Operational Mode Dataset

Bus Type: Small CNG; Bus ID: 1558; Route: Blue; Date: 06-12-2014																
Mode	**Percent [%]**	**CO_2**			**CO**			**HC**			**NO_x**			**FC**		
		g/s	**kg/DGE**	**kg/km**	**mg/s**	**g/DGE**	**g/km**	**mg/s**	**g/DGE**	**g/km**	**mg/s**	**g/DGE**	**g/km**	**g/s**	**DGE/hr**	**kg/km**
Idle	31%	1.5	7.6	--	0.60	3.05	--	2.5	13	--	0.27	1.4	--	0.56	0.70	--
Cruising	48%	5.8	7.6	0.44	0.63	0.83	0.05	7.7	10	0.58	5.2	6.8	0.39	2.2	2.8	0.17
Acc	10%	12	7.6	1.6	0.88	0.55	0.11	16	9.9	2.0	9.5	5.9	1.2	4.6	5.8	0.59
Dec	11%	1.4	7.6	0.20	0.33	1.8	0.05	2.1	11	0.29	0.97	5.3	0.14	0.52	0.65	0.07
Average		*4.7*	*7.6*	*0.59*	*0.61*	*1.0*	*0.08*	*6.3*	*10*	*0.80*	*3.6*	*6.0*	*0.46*	*1.7*	*2.2*	*0.22*

Table B.9. Bus 9 Operational Mode Dataset

Bus Type: Small CNG; Bus ID: 1556; Route: Blue; Date: 09-13-2013																	
Mode	**Percent [%]**	**CO_2**			**CO**			**HC**			**NO_x**			**FC**		
		g/s	**kg/DGE**	**kg/km**	**mg/s**	**g/DGE**	**g/km**	**mg/s**	**g/DGE**	**g/km**	**mg/s**	**g/DGE**	**g/km**	**g/s**	**DGE/hr**	**kg/km**
Idle	29%	1.8	7.6	--	2.5	10	--	2.3	9.4	--	0.46	1.9	--	0.68	0.86	--
Cruising	49%	7.1	7.6	0.57	56	60	4.5	4.8	5.2	0.39	17	18	1.3	2.7	3.4	0.22
Acc	10%	12	7.5	1.6	120	78	16	8.5	5.5	1.2	30	20	4.1	4.4	5.5	0.60
Dec	12%	1.9	7.6	0.27	5.0	20	0.70	3.5	14	0.48	1.6	6.3	0.22	0.73	0.91	0.10
Average		*5.4*	*7.6*	*0.70*	*41*	*57*	*5.3*	*4.3*	*6.0*	*0.56*	*12*	*16*	*1.5*	*2.0*	*2.6*	*0.27*

Table B.10. Bus 10 Operational Mode Dataset

Bus Type: Small CNG; Bus ID: 1560; Route: Black ; Date: 10-08-2013																	
Mode	**Percent [%]**	**CO_2**			**CO**			**HC**			**NO_x**			**FC**		
		g/s	**kg/DGE**	**kg/km**	**mg/s**	**g/DGE**	**g/km**	**mg/s**	**g/DGE**	**g/km**	**mg/s**	**g/DGE**	**g/km**	**g/s**	**DGE/hr**	**kg/km**
Idle	36%	1.2	7.6	--	0.0	0.0	--	6.2	40	--	0.56	3.6	--	0.44	0.55	--
Cruising	40%	3.9	7.6	0.56	0.01	0.02	0.0	11	21	1.5	14	27	1.9	1.5	1.9	0.21
Acc	11%	7.5	7.6	1.6	0.02	0.02	0.0	19	19	4.0	26	26	5.4	2.8	3.5	0.60
Dec	12%	1.2	7.6	0.29	0.0	0.0	0.0	5.1	33	1.2	2.0	12	0.47	0.45	0.57	0.11
Average		*3.0*	*7.6*	*0.77*	*0.01*	*0.02*	*0.0*	*9.3*	*24*	*2.4*	*8.8*	*22*	*2.3*	*1.1*	*1.4*	*0.29*

Table B.11. Bus 11 Operational Mode Dataset

Bus Type: Small CNG; Bus ID: 1561; Route: Purple; Date: 12-20-2013																	
Mode	**Percent [%]**	**CO_2**			**CO**			**HC**			**NO_x**			**FC**		
		g/s	**kg/DGE**	**kg/km**	**mg/s**	**g/DGE**	**g/km**	**mg/s**	**g/DGE**	**g/km**	**mg/s**	**g/DGE**	**g/km**	**g/s**	**DGE/hr**	**kg/km**
Idle	41%	0.89	7.1	--	43	350	--	4.1	33	--	0.38	3.0	--	0.36	0.45	--
Cruising	45%	3.8	7.1	0.31	190	350	15	9.0	17	0.74	77	142	6.3	1.6	2.0	0.13
Acc	7%	7.4	7.1	1.1	360	340	55	17	16	2.6	115	110	18	3.0	3.7	0.46
Dec	7%	0.80	7.0	0.13	44	380	7.3	8.0	69	1.3	6.1	53.09	1.0	0.33	0.41	0.05
Average		*2.7*	*7.1*	*0.41*	*129*	*350*	*20*	*7.5*	*20*	*1.2*	*43*	*115*	*6.7*	*1.1*	*1.3*	*0.17*

Table B.12. Bus 12 Operational Mode Dataset

Bus Type: Diesel; Bus ID: 1530; Route: Gray; Date: 03-20-2013																	
Mode	**Percent [%]**	**CO_2**			**CO**			**HC**			**NO_x**			**FC**			
		g/s	**kg/DGE**	**kg/km**	**mg/s**	**g/DGE**	**g/km**	**mg/s**	**g/DGE**	**g/km**	**mg/s**	**g/DGE**	**g/km**	**g/s**	**DGE/hr**	**kg/km**
Idle	33%	1.6	10	--	0.15	0.93	--	2.0	12.25	--	13	80	--	0.52	0.58	--
Cruising	11%	9.5	10	0.98	1.9	2.0	0.20	5.4	5.8	0.56	39	41	4.0	3.0	3.4	0.31
Acc	28%	10	10	0.78	1.6	1.5	0.12	6.1	5.9	0.46	46	44	3.4	3.3	3.7	0.25
Dec	29%	9.8	10	1.4	3.9	4.0	0.56	5.4	5.6	0.79	41	42	6.0	3.1	3.5	0.45
Average		*7.2*	*10*	*1.1*	*1.8*	*2.6*	*0.27*	*4.5*	*6.3*	*0.67*	*33*	*46*	*4.9*	*2.3*	*2.6*	*0.34*

Table B.13. Bus 13 Operational Mode Dataset

Bus Type: Diesel; Bus ID: 1544; Route: Brown; Date: 07-10-2014																
Mode	**Percent [%]**	**CO_2**			**CO**			**HC**			**NO_x**			**FC**		
		g/s	**kg/DGE**	**kg/km**	**mg/s**	**g/DGE**	**g/km**	**mg/s**	**g/DGE**	**g/km**	**mg/s**	**g/DGE**	**g/km**	**g/s**	**DGE/hr**	**kg/km**
Idle	28%	4.0	10	--	19	47	--	7.1	18	--	22	55	--	1.3	1.4	--
Cruising	43%	9.8	10	0.82	55	57	4.6	9.0	9.2	0.75	45	46	3.8	3.1	3.5	0.26
Acc	15%	33	9.9	4.0	360	110	44	16	4.8	1.9	97	29	12	11	12	1.3
Dec	14%	0.70	9.7	0.10	11	150	1.6	4.5	62	0.66	5.5	75	0.81	0.23	0.26	0.03
Average		*10*	*10*	*1.4*	*85*	*81*	*12*	*8.9*	*8.5*	*1.2*	*41*	*39*	*5.6*	*3.3*	*3.8*	*0.45*

Table B.14. Bus 14 Operational Mode Dataset

Bus Type: Diesel; Bus ID: 1532; Route: Gray; Date: 07-16-2014																
Mode	**Percent [%]**	**CO_2**			**CO**			**HC**			**NO_x**			**FC**		
		g/s	**kg/DGE**	**kg/km**	**mg/s**	**g/DGE**	**g/km**	**mg/s**	**g/DGE**	**g/km**	**mg/s**	**g/DGE**	**g/km**	**g/s**	**DGE/hr**	**kg/km**
Idle	26%	3.0	10	--	4.1	14	--	3.9	13	--	27	90	--	0.95	1.1	--
Cruising	44%	8.8	10	0.78	25	29	2.2	6.6	7.6	0.59	52	60	4.7	2.8	3.1	0.25
Acc	15%	21	10	2.8	47	23	6.2	10	5.0	1.4	98	47	13	6.6	7.4	0.88
Dec	15%	0.52	9.7	0.08	7.5	140	1.1	3.6	68	0.55	5.2	97	0.79	0.17	0.19	0.03
Average		*7.9*	*10*	*1.1*	*20*	*26*	*2.9*	*6.0*	*7.7*	*0.86*	*46*	*58*	*6.5*	*2.5*	*2.8*	*0.36*

C) Appendix C: Engine Modal Comparison

This appendix presents the data supporting the engine modal comparison. Table C.1 to Table C 3 present the percent of time per engine mode for each bus type. Figure C.1 to Figure C 14 present the percent of time, emissions and fuel use rates of each engine mode for the tested buses. Table C.4 to Table C.8 summarizes the emissions and fuel use rates of each engine mode for each bus type. Table C.9 to Table C.22 present the weighted average emissions and fuel use rates of each engine mode for each tested bus. Table C.23 to Table C.27 summarized the weighted average emissions and fuel use rates of each engine mode for each bus type.

Table C.1. Percentage of Time per Engine Mode for Big CNG Buses

Mode	1	2	3	4	5	6	*Average*
1	4.3%	9.8%	5.2%	8.7%	8.6%	6.1%	*7.1%*
2	36%	30%	24%	23%	33%	29%	*29%*
3	3.3%	12%	3.0%	3.8%	4.3%	5.6%	*5.3%*
4	11%	21%	23%	17%	19%	31%	*20%*
5	16%	12%	13%	17%	14%	11%	*14%*
6	14%	9.2%	13%	13%	10%	9%	*11%*
7	8.5%	3.3%	10%	9.2%	6.1%	4.5%	*6.9%*
8	4.0%	1.7%	5.3%	5.7%	3.2%	2.4%	*3.7%*
9	2.1%	0.78%	3.0%	2.4%	1.6%	1.1%	*1.8%*
10	0.31%	0.03%	0.95%	0.61%	0.41%	0.11%	*0.40%*
							100%

Table C.2. Percentage of Time per Engine Mode for Small CNG Buses

Mode	7	8	9	10	11	*Average*
1	43%	44%	54%	53%	46%	*48%*
2	10%	8.3%	11%	9.6%	8.7%	*9.5%*
3	9.18%	7.8%	11%	12%	18%	*11%*
4	16%	15%	11%	13%	13%	*14%*
5	10%	9.4%	6.4%	7.6%	6.4%	*8.0%*
6	5.8%	5.3%	3.1%	2.1%	3.9%	*4.1%*
7	2.5%	5.0%	1.9%	1.2%	2.3%	*2.6%*
8	2.1%	3.6%	1.0%	0.73%	1.3%	*1.8%*
9	1.2%	1.6%	0.44%	0.50%	0.42%	*0.82%*
10	0.13%	0.49%	0.16%	0.15%	0.22%	*0.23%*
						100%

Table C.3. Percentage of Time per Engine Model for Diesel Buses

Mode	12	13	14	*Average*
1	43%	21%	28%	*31%*
2	3.4%	5.4%	3.7%	*4.2%*
3	4.6%	6.0%	6.6%	*5.7%*
4	6.8%	25%	14%	*15%*
5	8.5%	13%	9.6%	*10%*
6	12%	13%	11%	*12%*
7	10%	9.8%	13%	*11%*
8	5.9%	4.5%	7.7%	*6.1%*
9	4.1%	2.2%	4.5%	*3.6%*
10	0.86%	0.28%	1.6%	*0.90%*
				100%

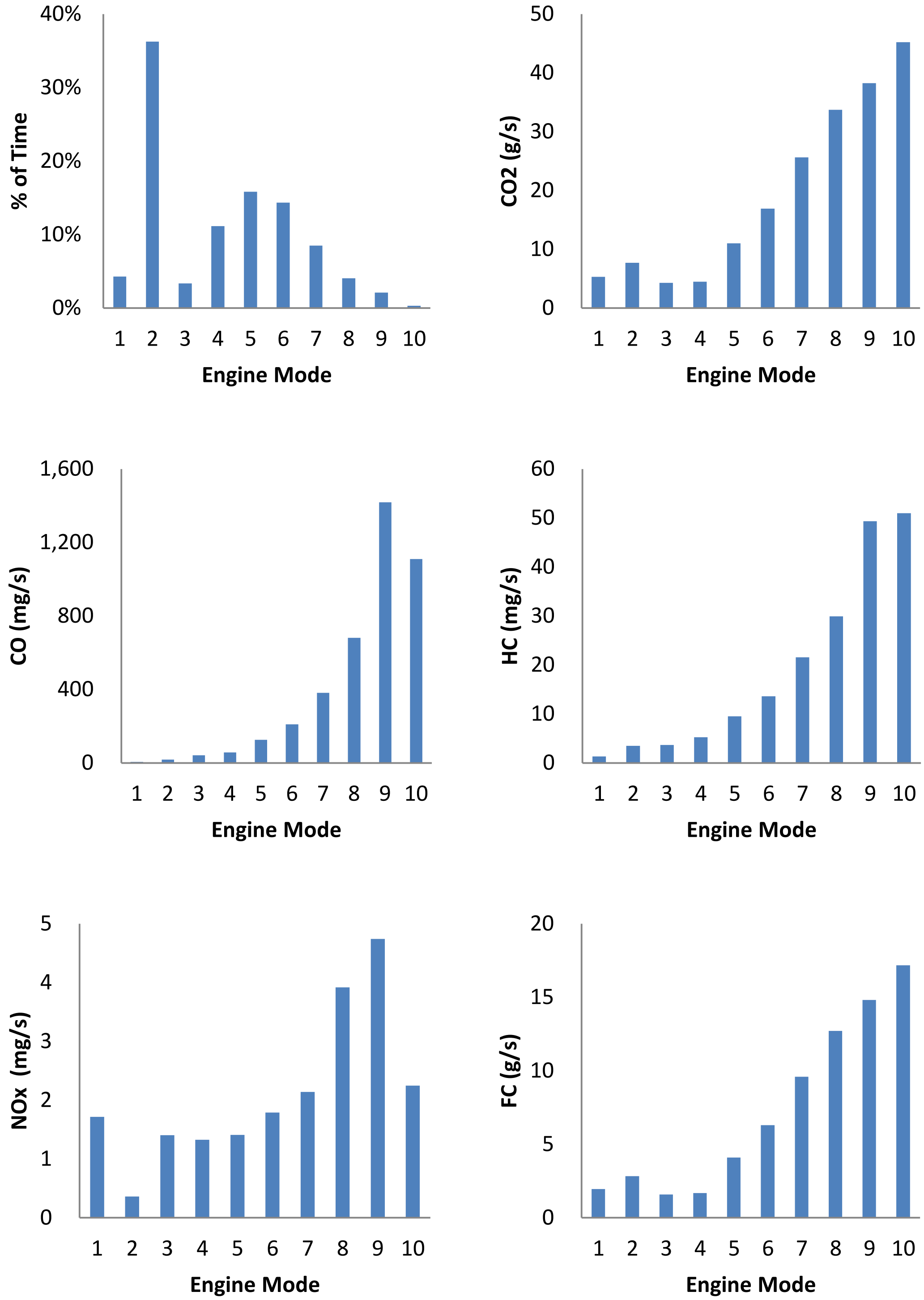

Figure C.1. Percentage of Time, Mass per Time Emissions and Fuel Use Rates vs. Engine Modes for Bus 1

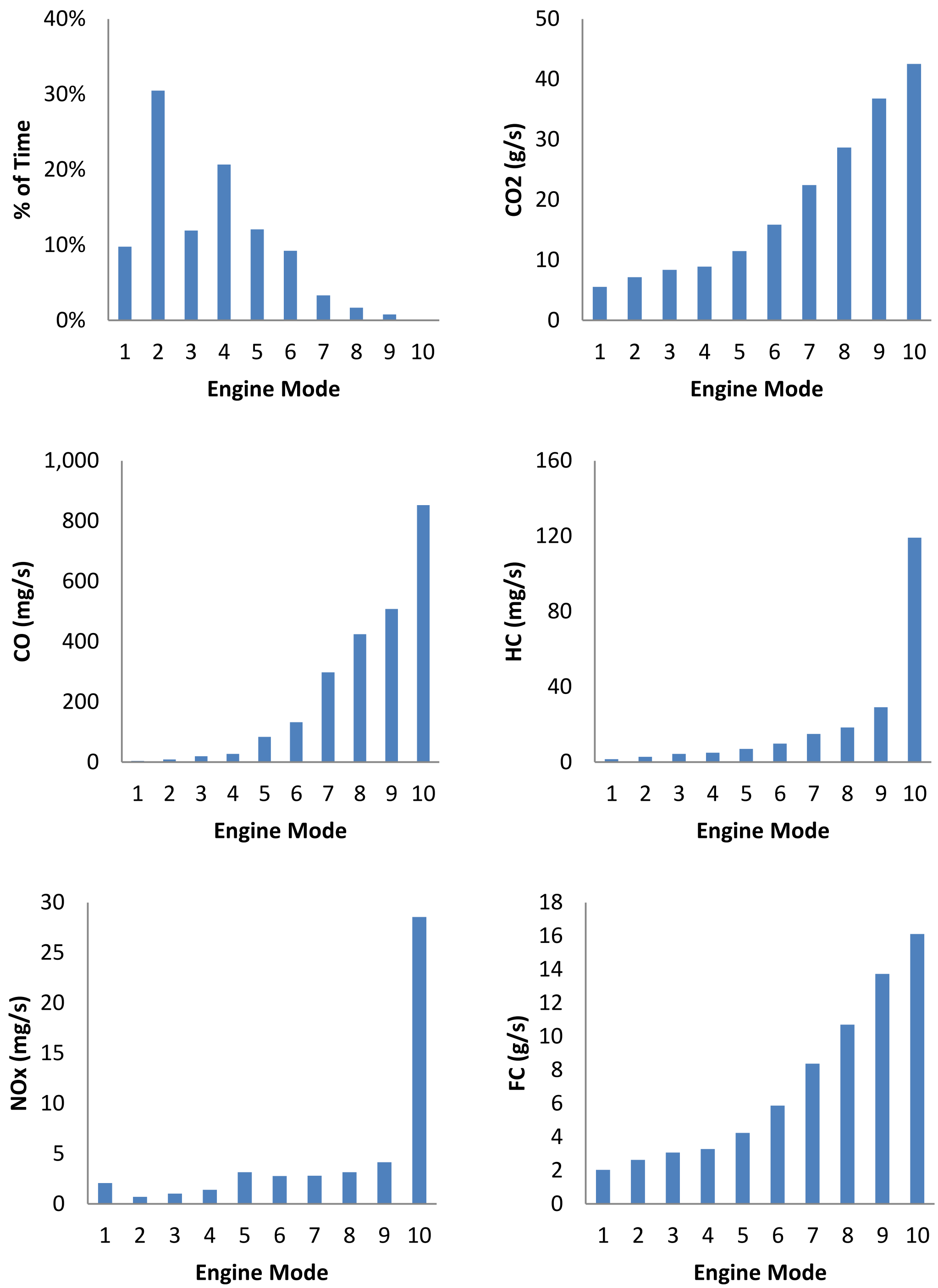

Figure C.2. Percentage of Time, Mass per Time Emissions and Fuel Use Rates vs. Engine Modes for Bus 2

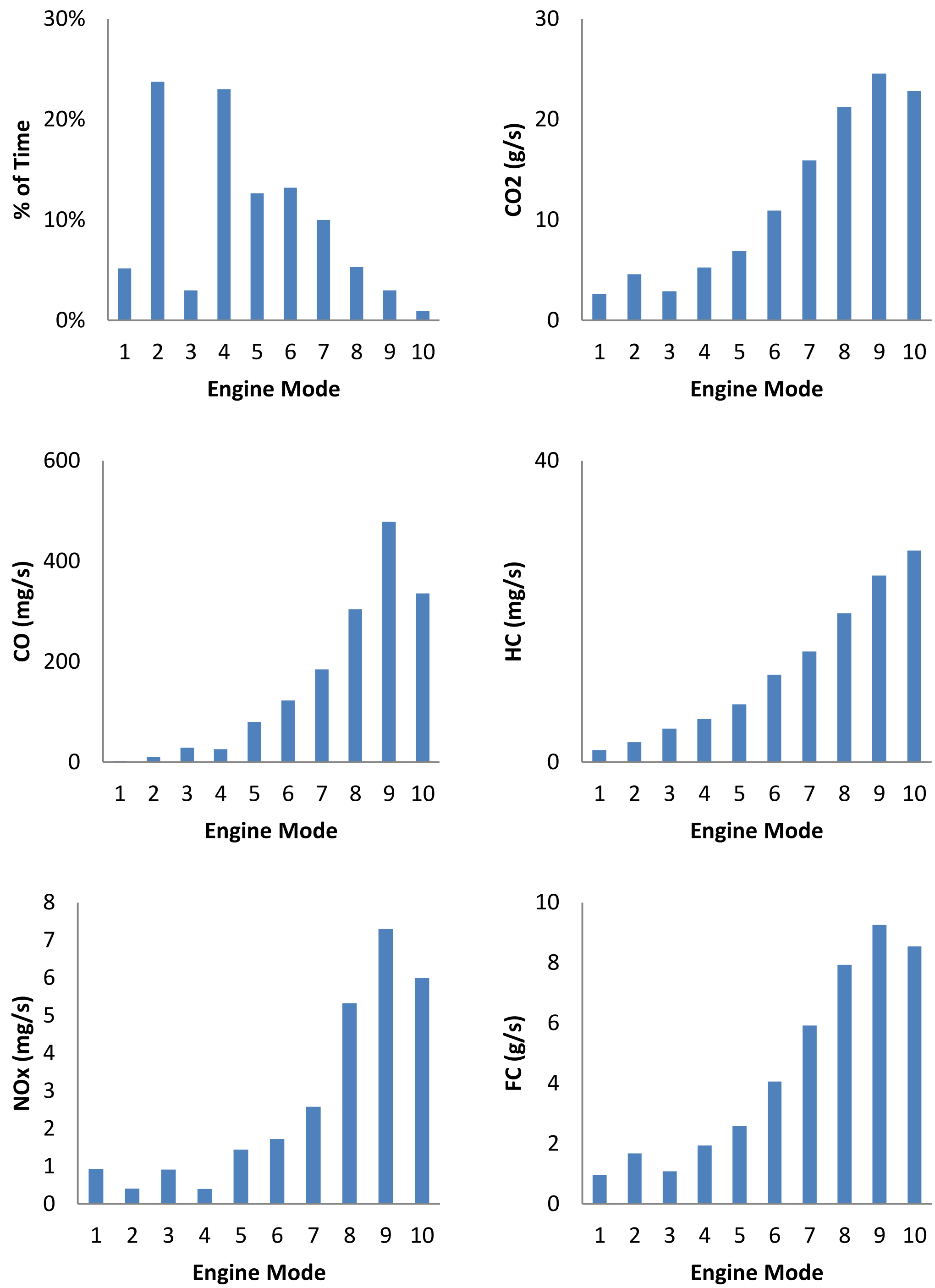

Figure C.3. Percentage of Time, Mass per Time Emissions and Fuel Use Rates vs. Engine Modes for Bus 3

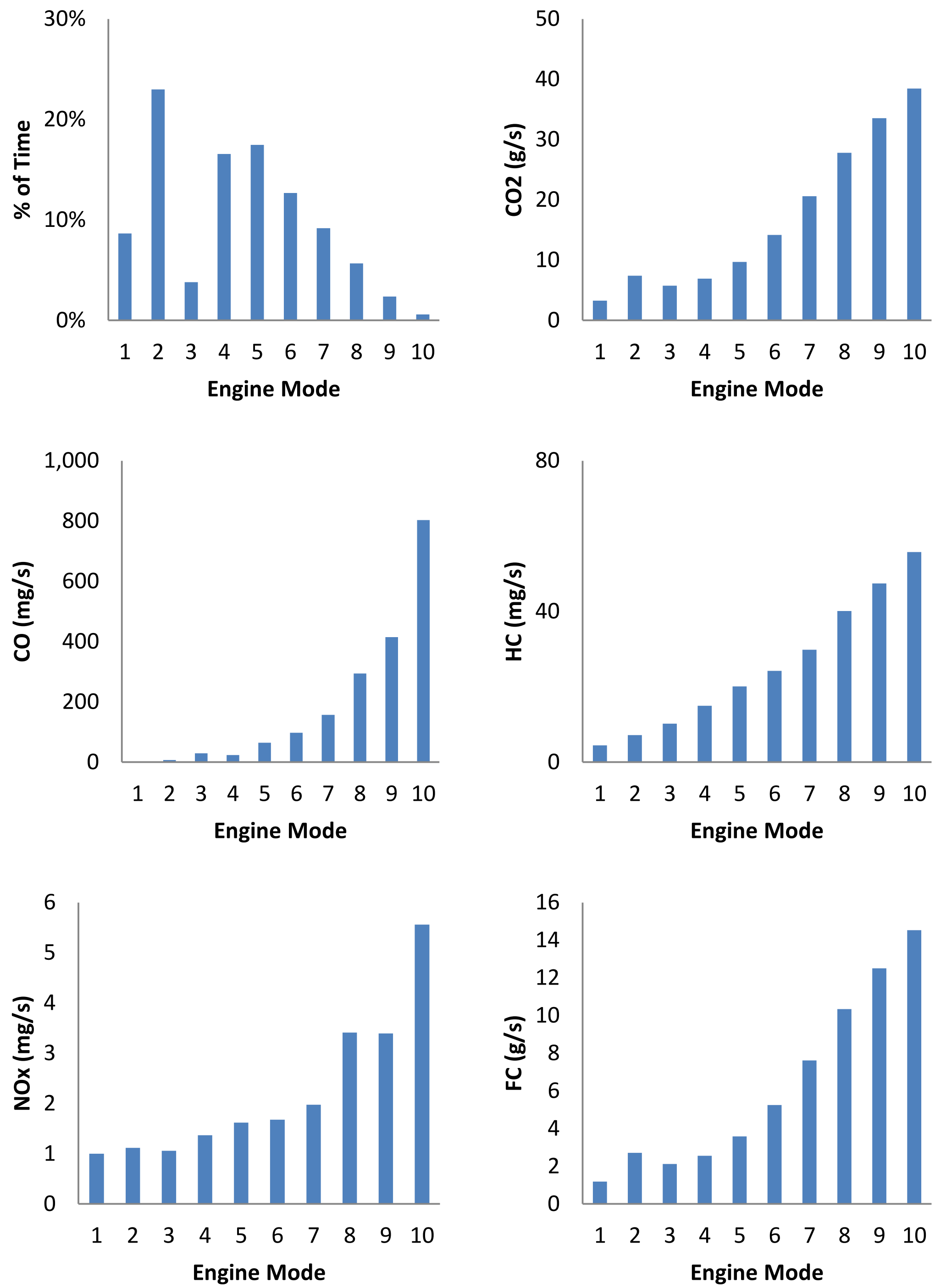

Figure C.4. Percentage of Time, Mass per Time Emissions and Fuel Use Rates vs. Engine Modes for Bus 4

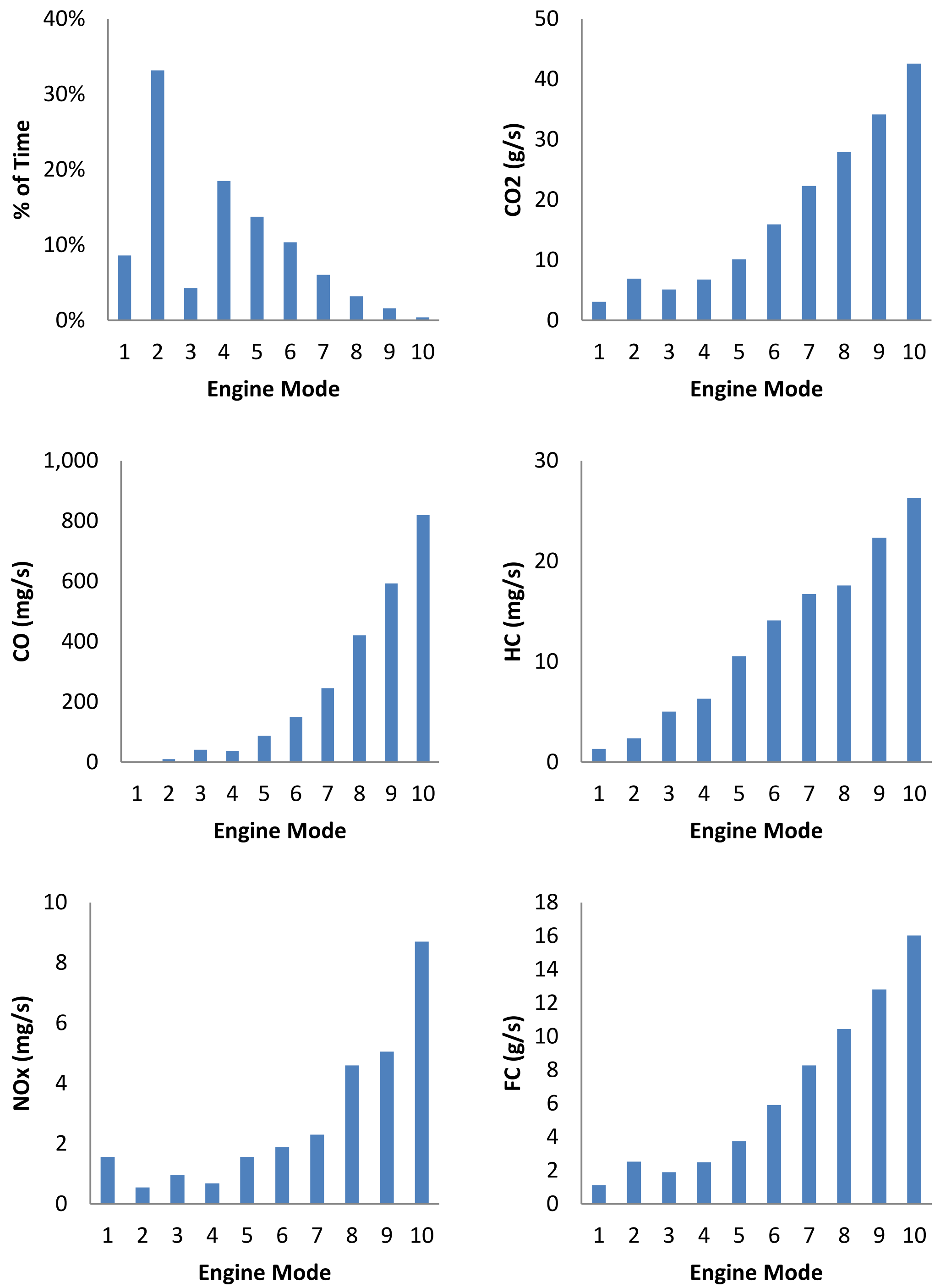

Figure C.5. Percentage of Time, Mass per Time Emissions and Fuel Use Rates vs. Engine Modes for Bus 5

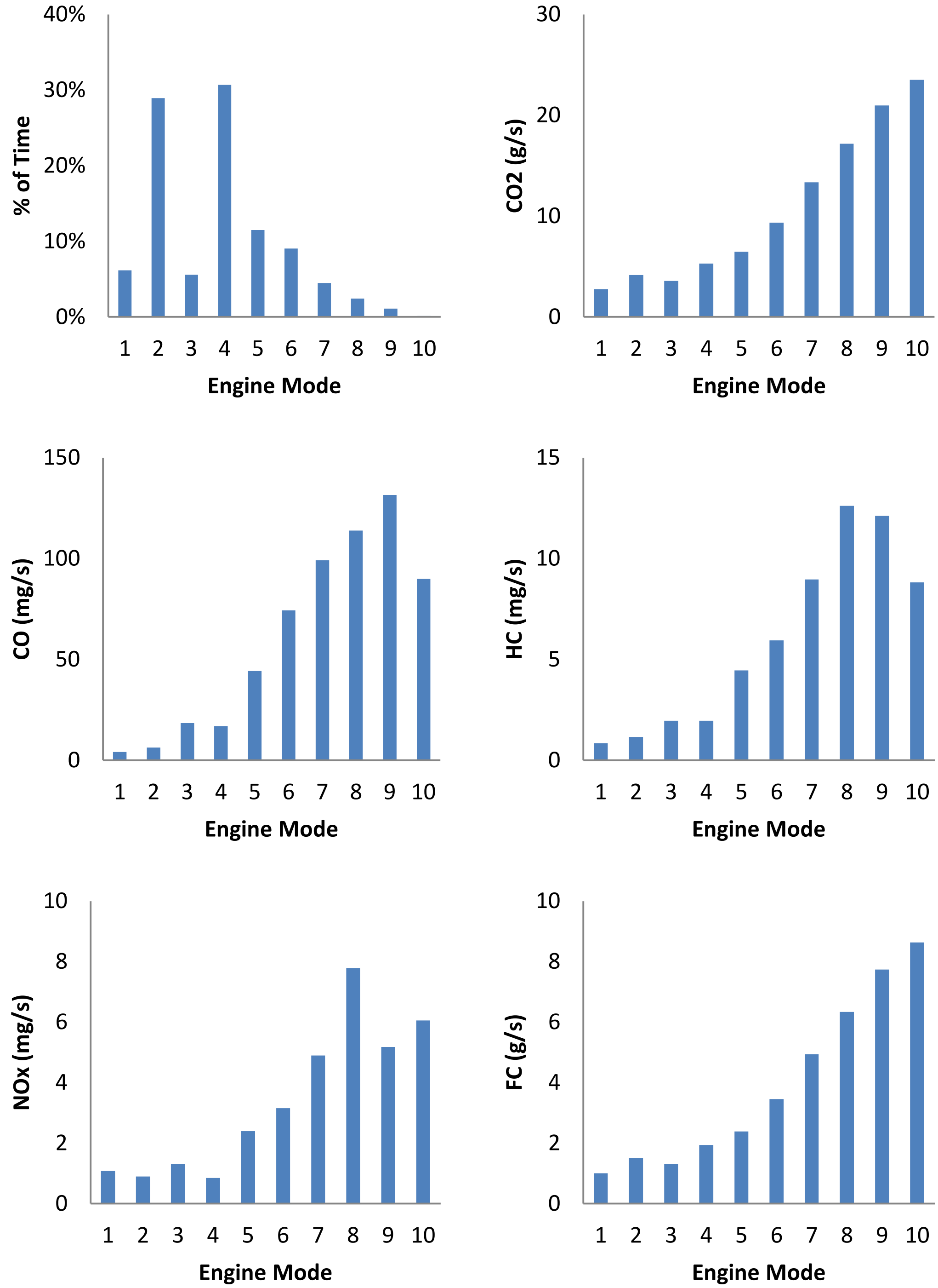

Figure C.6. Percentage of Time, Mass per Time Emissions and Fuel Use Rates vs. Engine Modes for Bus 6

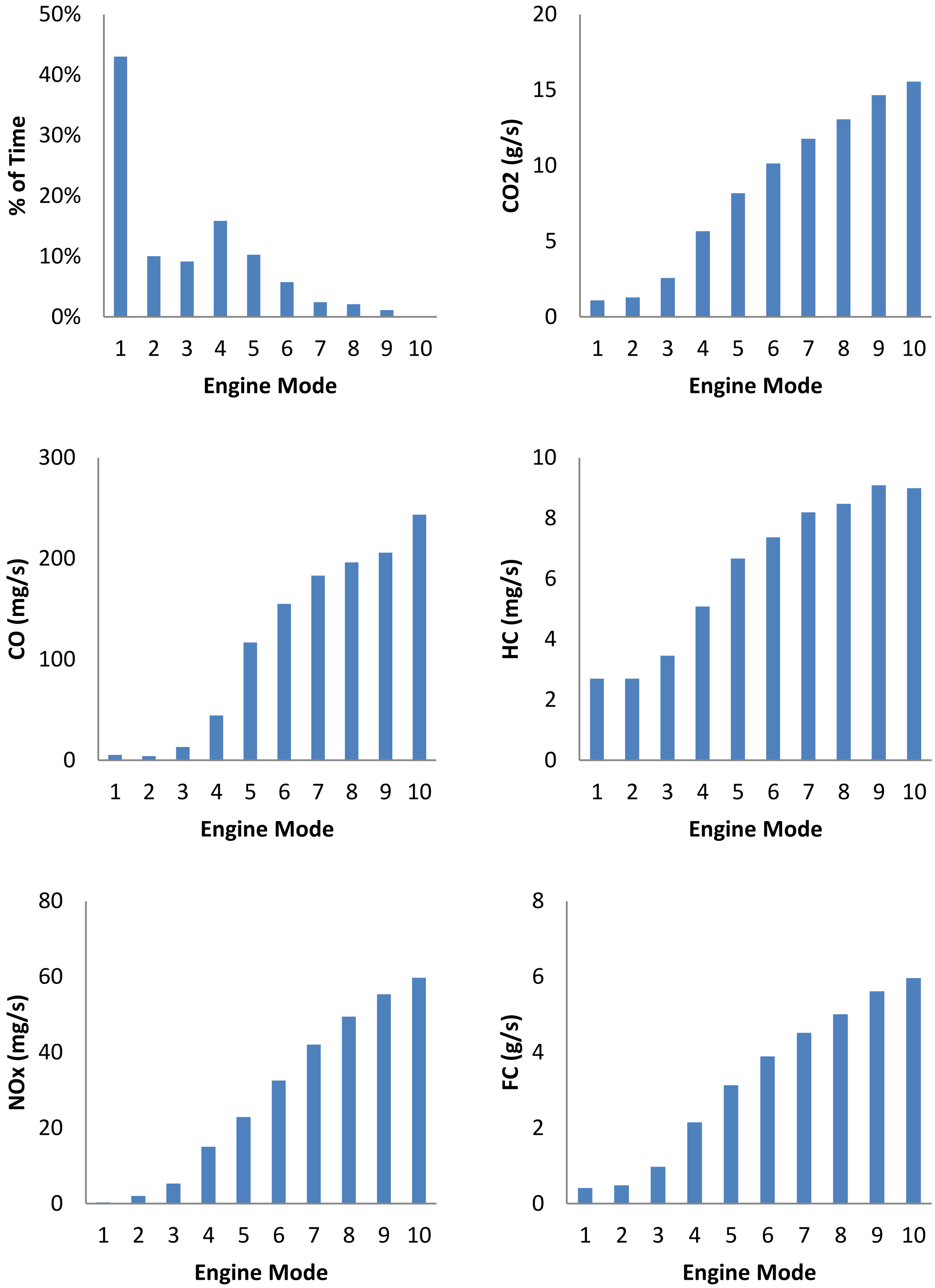

Figure C.7. Percentage of Time, Mass per Time Emissions and Fuel Use Rates vs. Engine Modes for Bus 7

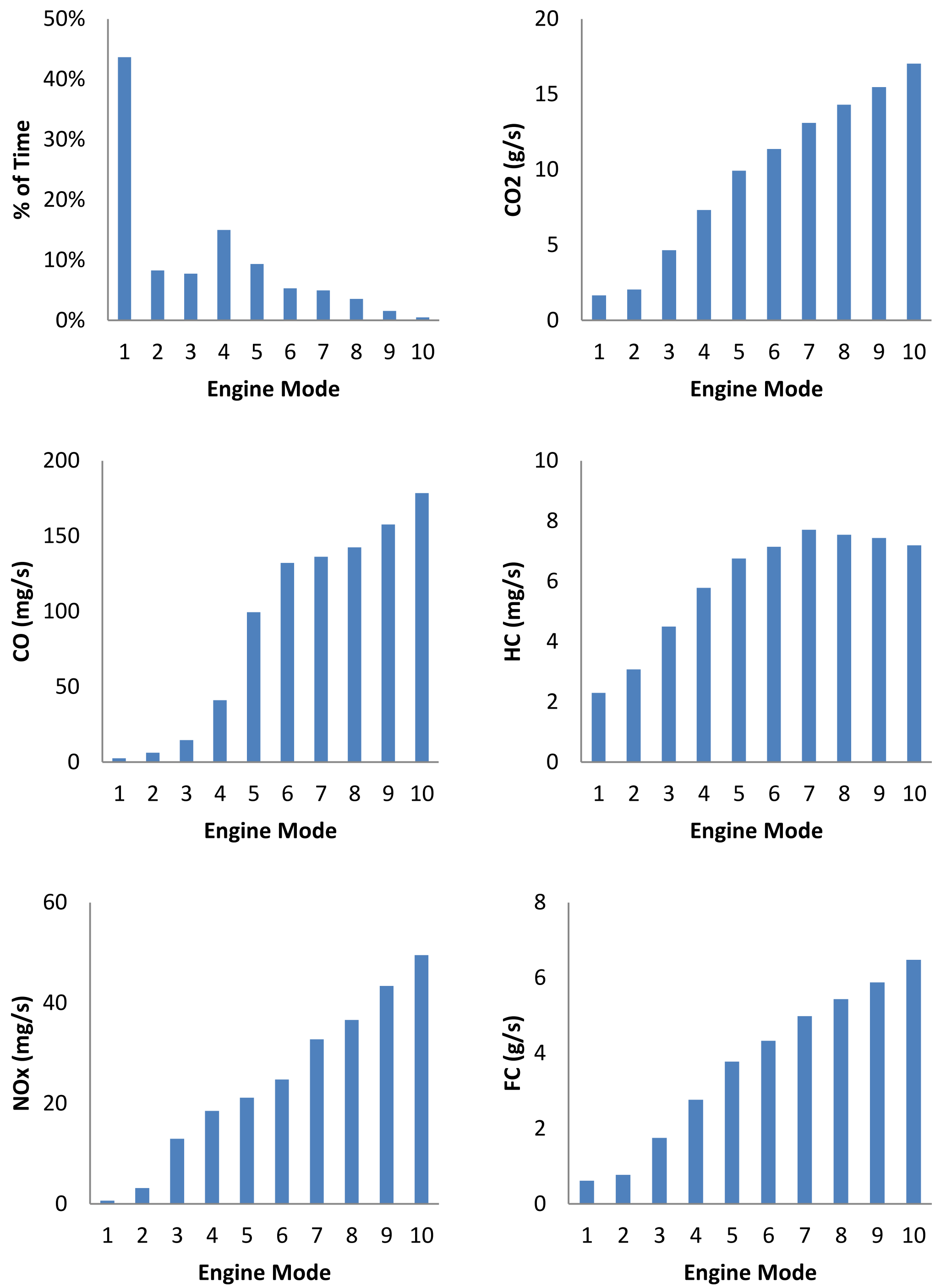

Figure C.8. Percentage of Time, Mass per Time Emissions and Fuel Use Rates vs. Engine Modes for Bus 8

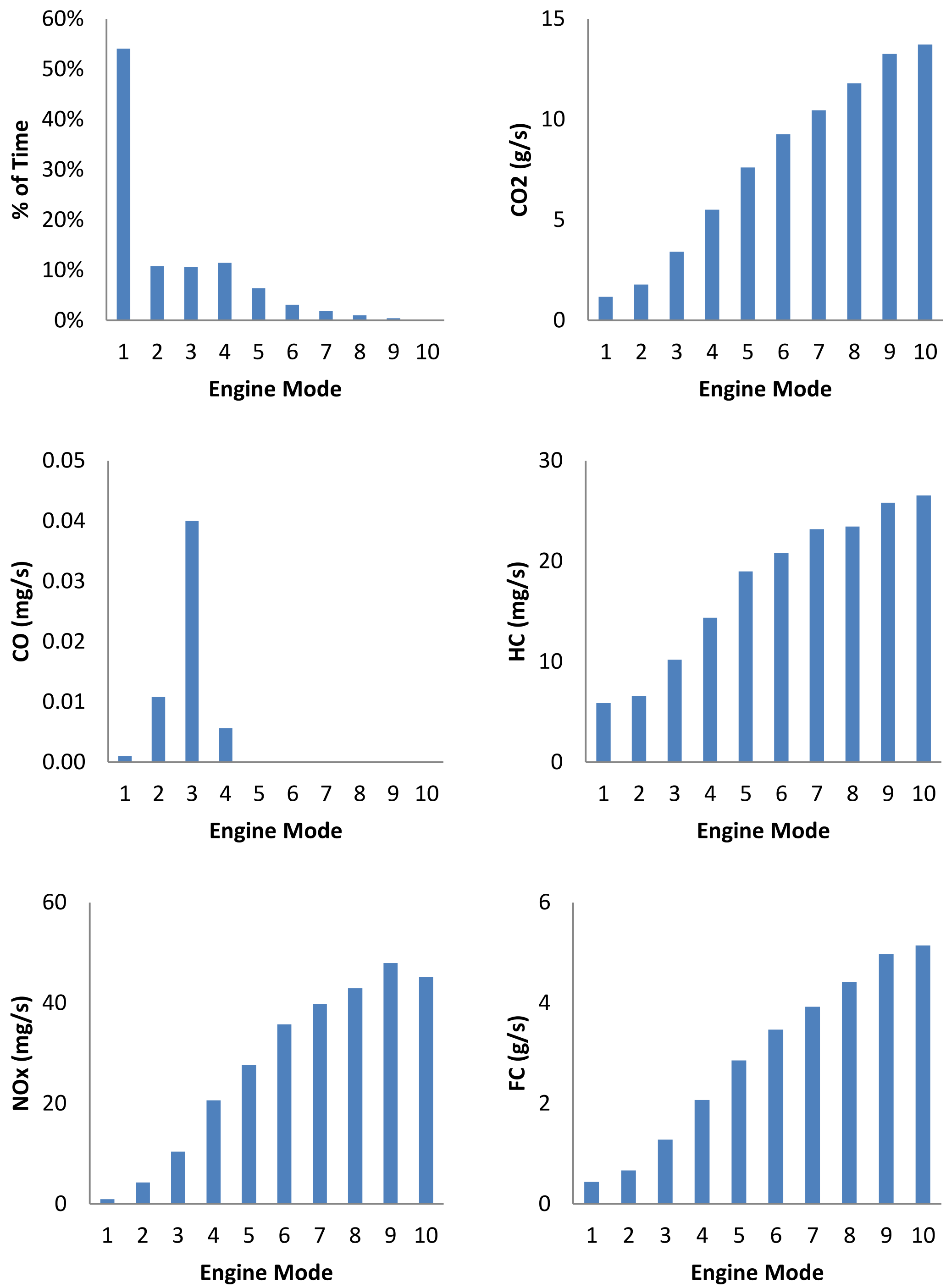

Figure C.9. Percentage of Time, Mass per Time Emissions and Fuel Use Rates vs. Engine Modes for Bus 9

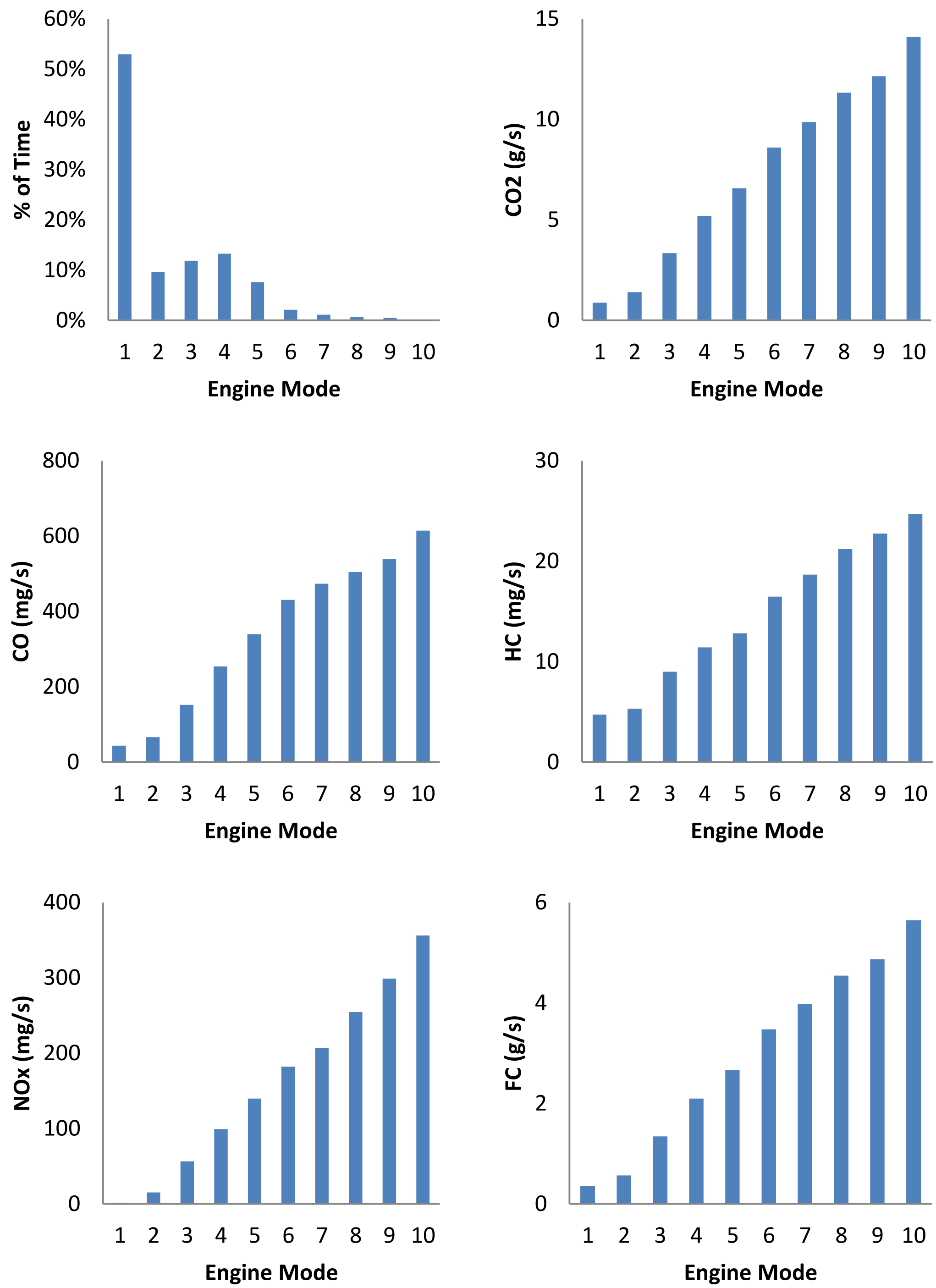

Figure C.10. Percentage of Time, Mass per Time Emissions and Fuel Use Rates vs. Engine Modes for Bus 10

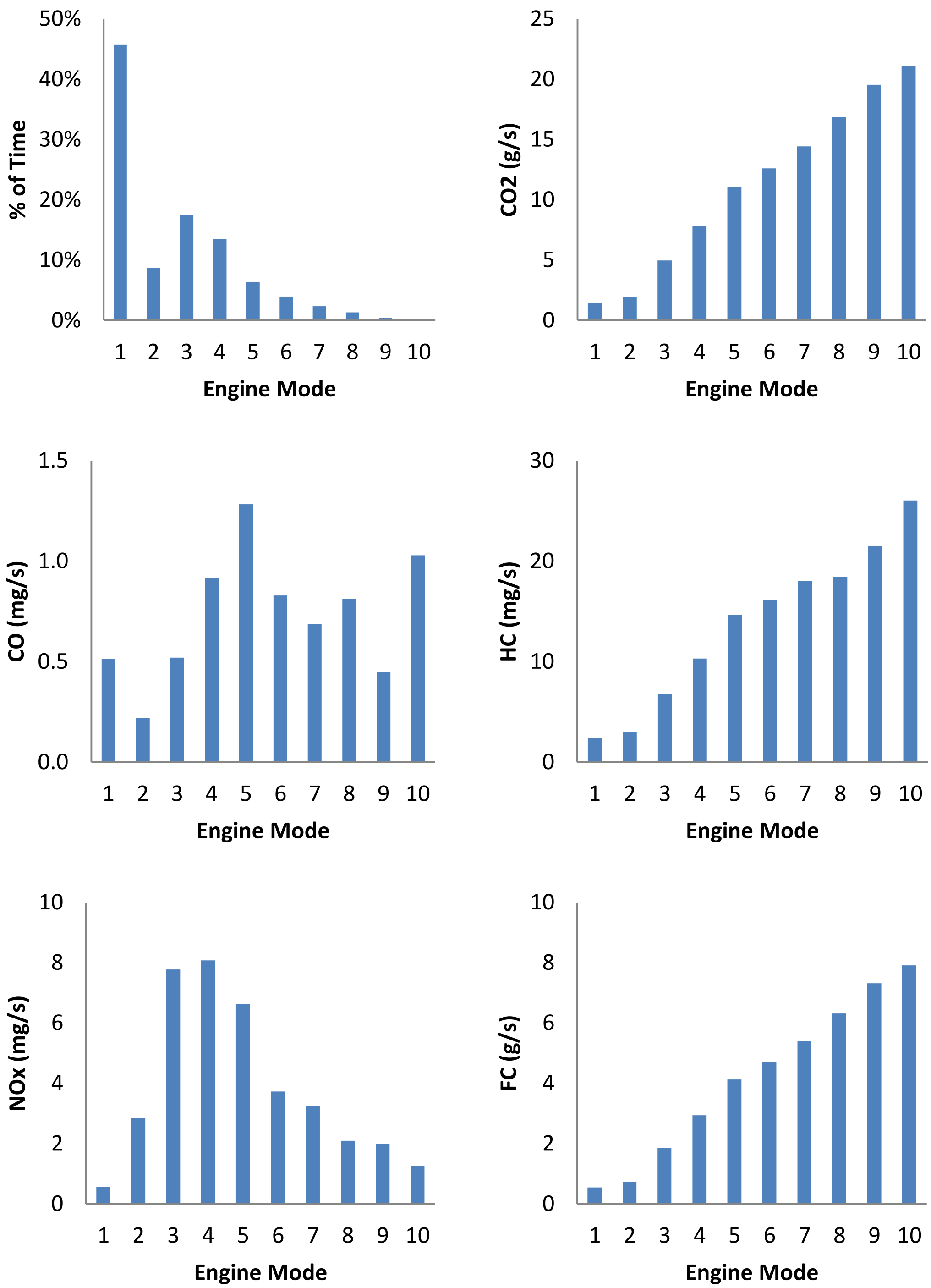

Figure C.11. Percentage of Time, Mass per Time Emissions and Fuel Use Rates vs. Engine Modes for Bus 11

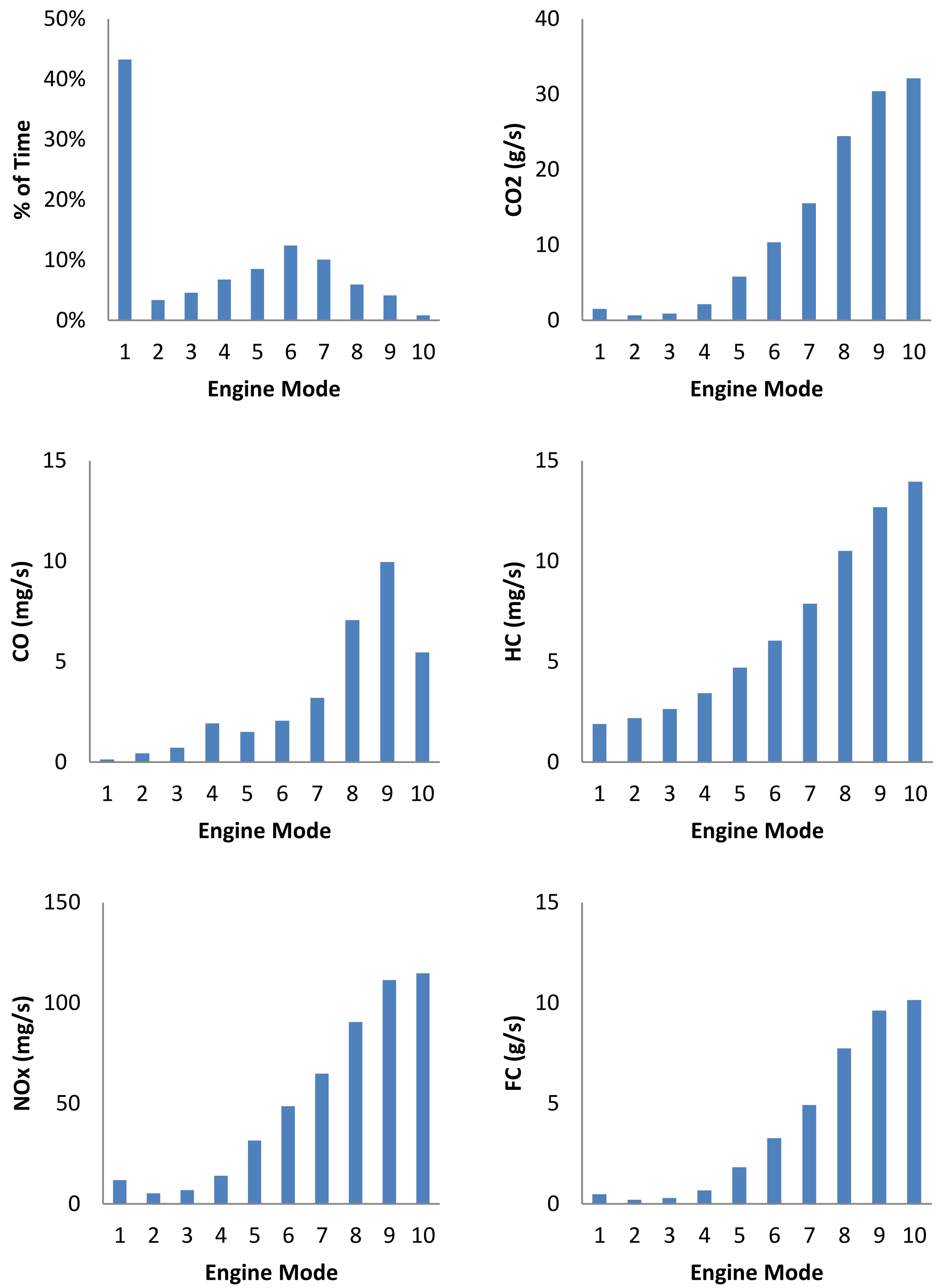

Figure C.12. Percentage of Time, Mass per Time Emissions and Fuel Use Rates vs. Engine Modes for Bus 12

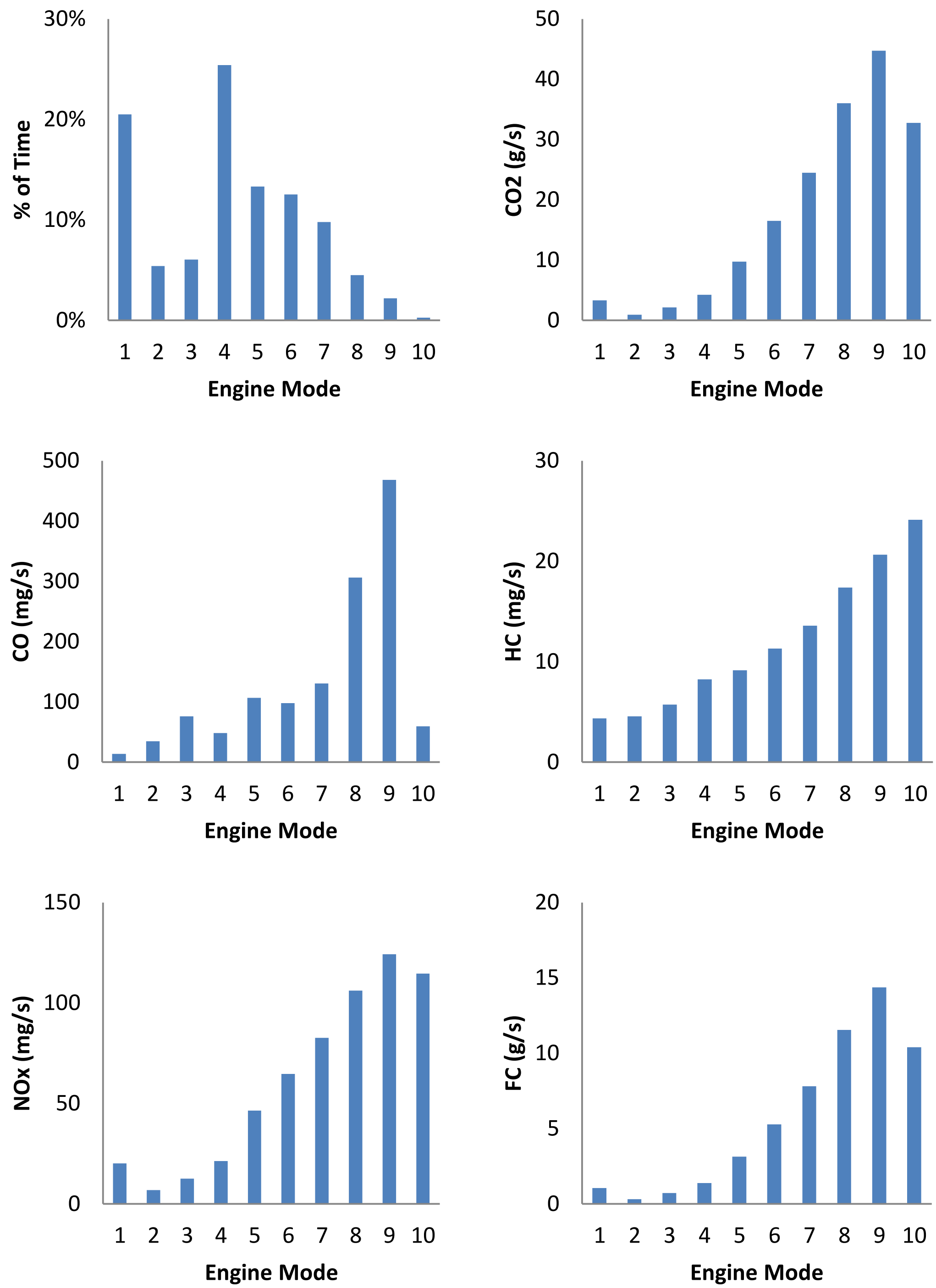

Figure C.13. Percentage of Time, Mass per Time Emissions and Fuel Use Rates vs. Engine Modes for Bus 13

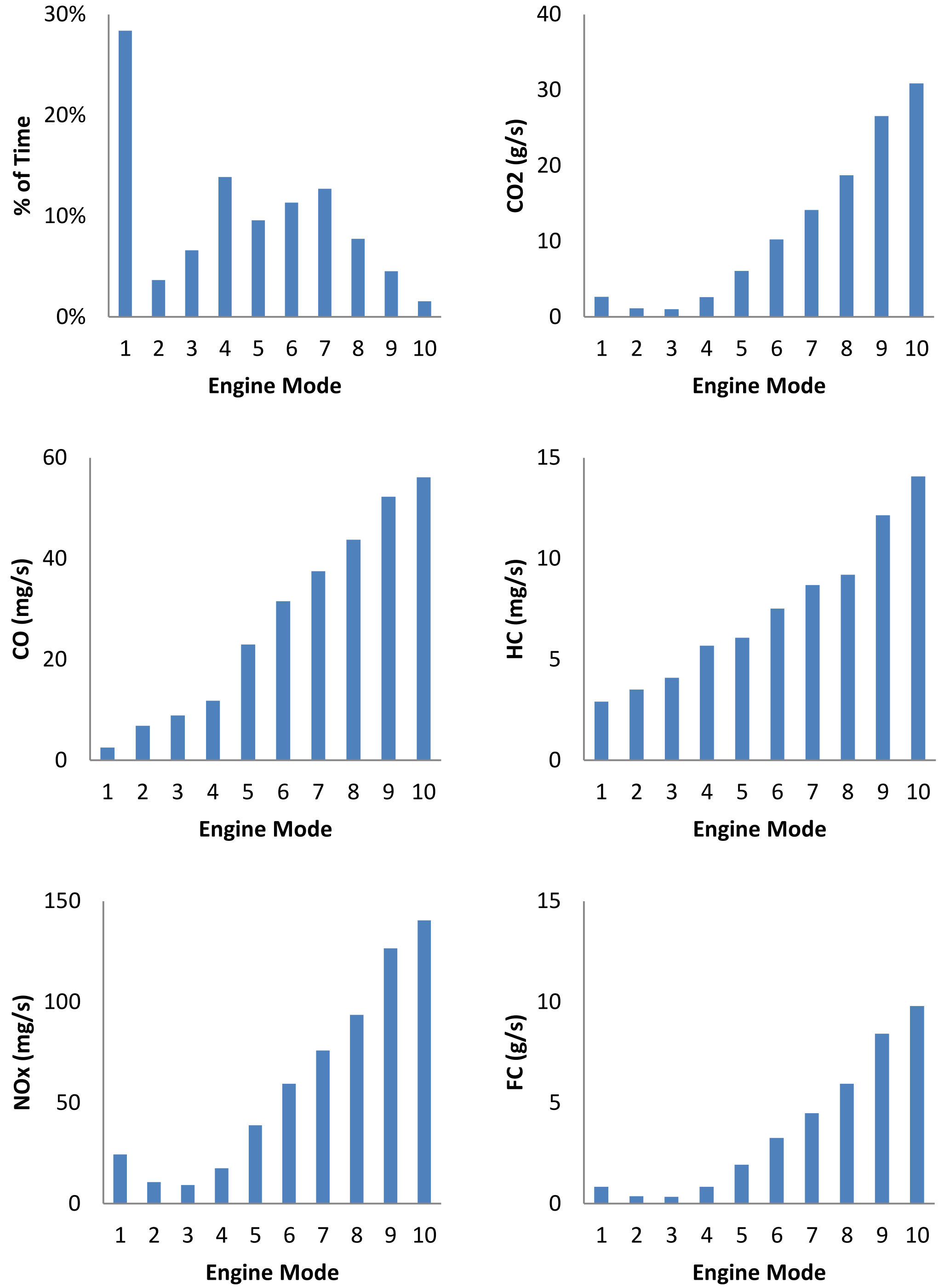

Figure C.14. Percentage of Time, Mass per Time Emissions and Fuel Use Rates vs. Engine Modes for Bus 14

Table C.4. Summary of Average Mass per Time CO_2 Rates per Engine Mode

Engine Mode	Average CO_2 Rates (g/s)		
	Big CNG	Small CNG	Diesel
1	3.8	1.3	2.5
2	6.3	1.7	0.92
3	5.0	3.8	1.4
4	6.3	6.3	3.0
5	9.3	8.7	7.2
6	14	10	12
7	20	12	18
8	26	13	26
9	31	15	34
10	36	16	32

Table C.5. Summary of Average Mass per Time CO Rates per Engine Mode

Engine Mode	Average CO Rates (mg/s)		
	Big CNG	Small CNG	Diesel
1	3.4	11	5.5
2	10	15	14
3	30	36	29
4	31	68	21
5	81	110	44
6	130	140	44
7	230	160	57
8	370	170	120
9	590	18	180
10	670	210	40

Table C.6. Summary of Average Mass per Time HC Rates per Engine Mode

Engine Mode	Average HC Rates (mg/s)		
	Big CNG	Small CNG	Diesel
1	1.9	3.6	3.1
2	3.3	4.1	3.4
3	4.9	6.8	4.1
4	6.5	9.4	5.8
5	9.9	12	6.6
6	13	14	8.3
7	18	15	10
8	23	16	12
9	31	17	15
10	48	19	17

Table C.7. Summary of Average Mass per Time NO_x Rates per Engine Mode

Engine Mode	Average NO_x Rates (mg/s)		
	Big CNG	Small CNG	Diesel
1	1.4	0.85	19
2	0.67	5.5	7.6
3	1.1	19	9.5
4	1.0	32	18
5	1.9	44	39
6	2.2	56	58
7	2.8	65	74
8	4.7	77	97
9	5.0	90	121
10	9.5	102	123

Table C.8. Summary of Average Mass per Time Fuel Use Rates per Engine Mode

Engine Mode	Average Fuel Use Rates (g/s)		
	Big CNG	Small CNG	Diesel
1	1.4	0.48	0.79
2	2.3	0.65	0.30
3	1.8	1.4	0.45
4	2.3	2.4	0.97
5	3.4	3.3	2.3
6	5.1	4.0	3.9
7	7.5	4.6	5.7
8	9.7	5.1	8.4
9	12	5.7	11
10	13	6.2	10

Table C.9. Weighted Average Mass per Time Emissions and Fuel Use Rates for Bus 1

Mode	% of Time	Weighted Average Emissions and Fuel Use Rates				
		CO2[g/s]	CO[mg/s]	HC[mg/s]	NO_x [mg/s]	FC[g/s]
1	4.3%	0.23	0.24	0.06	0.07	0.08
2	36%	2.8	6.7	1.3	0.13	1.0
3	3.3%	0.14	1.4	0.12	0.05	0.05
4	11%	0.49	6.4	0.59	0.15	0.18
5	16%	1.7	20	1.5	0.22	0.65
6	14%	2.4	30	1.9	0.26	0.90
7	8.5%	2.2	32	1.8	0.18	0.81
8	4.0%	1.4	27	1.2	0.16	0.51
9	2.1%	0.80	30	1.0	0.10	0.31
10	0.31%	0.14	3.4	0.16	0.01	0.05
Total	*100%*	*12*	*160*	*9.7*	*1.3*	*4.6*

Table C.10. Weighted Average Mass per Time Emissions and Fuel Use Rates for Bus 2

Mode	% of Time	Weighted Average Emissions and Fuel Use Rates				
		CO2[g/s]	CO[mg/s]	HC[mg/s]	NO_x [mg/s]	FC[g/s]
1	9.8%	0.55	0.38	0.15	0.20	0.20
2	30%	2.2	2.7	0.85	0.22	0.80
3	12%	1.0	2.4	0.52	0.12	0.37
4	21%	1.8	5.8	1.0	0.29	0.68
5	12%	1.4	10	0.86	0.38	0.51
6	9.2%	1.5	12	0.91	0.26	0.54
7	3.3%	0.75	9.9	0.50	0.09	0.28
8	1.7%	0.48	7.2	0.31	0.05	0.18
9	0.78%	0.29	3.9	0.23	0.03	0.11
10	0.03%	0.01	0.29	0.04	0.01	0.01
Total	*100%*	*10*	*55*	*5.4*	*1.7*	*3.7*

Table C.11. Weighted Average Mass per Time Emissions and Fuel Use Rates for Bus 3

Mode	% of Time	Weighted Average Emissions and Fuel Use Rates				
		CO2[g/s]	CO[mg/s]	HC[mg/s]	NO_x [mg/s]	FC[g/s]
1	5.2%	0.14	0.14	0.08	0.05	0.05
2	24%	1.1	2.3	0.63	0.10	0.40
3	3.0%	0.09	0.86	0.13	0.03	0.03
4	23%	1.2	6.0	1.3	0.09	0.45
5	13%	0.88	10	0.97	0.18	0.33
6	13%	1.4	16	1.5	0.23	0.54
7	10%	1.6	18	1.5	0.26	0.59
8	5.3%	1.1	16	1.0	0.28	0.42
9	3.0%	0.73	14	0.74	0.22	0.28
10	1.0%	0.22	3.2	0.27	0.06	0.08
Total	*100%*	*8.5*	*88*	*8.2*	*1.5*	*3.2*

Table C.12. Weighted Average Mass per Time Emissions and Fuel Use Rates Bus 4

Mode	% of Time	Weighted Average Emissions and Fuel Use Rates				
		CO2[g/s]	CO[mg/s]	HC[mg/s]	NO_x [mg/s]	FC[g/s]
1	8.7%	0.28	0.13	0.39	0.09	0.10
2	23%	1.7	1.7	1.6	0.26	0.62
3	3.8%	0.22	1.1	0.39	0.04	0.08
4	17%	1.1	3.9	2.5	0.23	0.42
5	17%	1.7	11	3.5	0.28	0.63
6	13%	1.8	12	3.1	0.21	0.67
7	9.2%	1.9	14	2.7	0.18	0.70
8	5.7%	1.6	17	2.3	0.19	0.59
9	2.4%	0.8	9.9	1.1	0.08	0.30
10	0.61%	0.23	4.9	0.34	0.03	0.09
Total	*100%*	*11*	*76*	*18*	*1.6*	*4.2*

Table C.13. Weighted Average Mass per Time Emissions and Fuel Use Rates for Bus 5

Mode	% of Time	Weighted Average Emissions and Fuel Use Rates				
		CO2[g/s]	CO[mg/s]	HC[mg/s]	NO_x [mg/s]	FC[g/s]
1	8.6%	0.27	0.22	0.11	0.13	0.10
2	33%	2.3	3.4	0.78	0.18	0.84
3	4.3%	0.22	1.8	0.22	0.04	0.08
4	19%	1.3	6.7	1.2	0.13	0.46
5	14%	1.4	12	1.5	0.22	0.52
6	10%	1.6	16	1.5	0.20	0.61
7	6.1%	1.3	15	1.0	0.14	0.50
8	3.2%	0.90	14	0.57	0.15	0.34
9	1.6%	0.55	9.6	0.36	0.08	0.21
10	0.41%	0.17	3.3	0.11	0.04	0.07
Total	*100%*	*10*	*81*	*7.2*	*1.3*	*3.7*

Table C.14. Weighted Average Mass per Time Emissions and Fuel Use Rates for Bus 6

Mode	% of Time	Weighted Average Emissions and Fuel Use Rates				
		CO2[g/s]	CO[mg/s]	HC[mg/s]	NO_x [mg/s]	FC[g/s]
1	6.1%	0.17	0.26	0.05	0.07	0.06
2	29%	1.2	1.8	0.33	0.26	0.44
3	5.6%	0.20	1.0	0.11	0.07	0.07
4	31%	1.6	5.2	0.60	0.26	0.60
5	11%	0.74	5.1	0.51	0.28	0.27
6	9.0%	0.84	6.7	0.54	0.28	0.31
7	4.5%	0.60	4.5	0.40	0.22	0.22
8	2.4%	0.42	2.8	0.31	0.19	0.15
9	1.1%	0.23	1.4	0.13	0.06	0.09
10	0.11%	0.03	0.10	0.01	0.01	0.01
Total	*100%*	*6.1*	*29*	*3.0*	*1.7*	*2.2*

Table C.15. Weighted Average Mass per Time Emissions and Fuel Use Rates for Bus 7

Mode	% of Time	Weighted Average Emissions and Fuel Use Rates				
		CO2[g/s]	CO[mg/s]	HC[mg/s]	NO_x [mg/s]	FC[g/s]
1	43%	0.47	2.3	1.2	0.15	0.18
2	10%	0.13	0.43	0.27	0.20	0.05
3	9.2%	0.24	1.2	0.32	0.49	0.09
4	16%	0.9	7.0	0.81	2.4	0.34
5	10%	0.84	12	0.68	2.4	0.32
6	5.8%	0.58	8.9	0.42	1.9	0.22
7	2.5%	0.29	4.5	0.20	1.0	0.11
8	2.1%	0.27	4.1	0.18	1.0	0.11
9	1.2%	0.17	2.4	0.11	0.64	0.07
10	0.13%	0.02	0.32	0.01	0.08	0.01
Total	*100%*	*3.9*	*43*	*4.2*	*10*	*1.5*

Table C.16. Weighted Average Mass per Time Emissions and Fuel Use Rates for Bus 8

Mode	% of Time	Weighted Average Emissions and Fuel Use Rates				
		CO_2[g/s]	CO[mg/s]	HC[mg/s]	NO_x [mg/s]	FC[g/s]
1	44%	0.72	1.1	1.0	0.29	0.27
2	8.3%	0.17	0.52	0.25	0.26	0.06
3	7.8%	0.36	1.1	0.35	1.0	0.14
4	15%	1.1	6.1	0.87	2.8	0.41
5	9.4%	0.93	9.3	0.63	2.0	0.35
6	5.3%	0.61	7.1	0.38	1.3	0.23
7	5.0%	0.65	6.8	0.38	1.6	0.25
8	3.6%	0.51	5.1	0.27	1.3	0.19
9	1.6%	0.24	2.5	0.12	0.69	0.09
10	0.49%	0.08	0.88	0.04	0.24	0.03
Total	*100%*	*5.4*	*41*	*4.3*	*12*	*2.0*

Table C.17. Weighted Average Mass per Time Emissions and Fuel Use Rates for Bus 9

Mode	% of Time	Weighted Average Emissions and Fuel Use Rates				
		CO_2[g/s]	CO[mg/s]	HC[mg/s]	NO_x [mg/s]	FC[g/s]
1	54%	0.63	0.0	3.2	0.53	0.24
2	11%	0.19	0.0	0.71	0.47	0.07
3	11%	0.36	0.0	1.1	1.1	0.14
4	11%	0.63	0.0	1.6	2.4	0.24
5	6.4%	0.48	0.0	1.2	1.8	0.18
6	3.1%	0.29	0.0	0.65	1.1	0.11
7	1.9%	0.20	0.0	0.44	0.76	0.07
8	1.0%	0.12	0.0	0.24	0.43	0.04
9	0.44%	0.06	0.0	0.11	0.21	0.02
10	0.16%	0.02	0.0	0.04	0.07	0.01
Total	*100%*	*3.0*	*0.01*	*9.3*	*8.8*	*1.1*

Table C.18. Weighted Average Mass per Time Emissions and Fuel Use Rates for Bus 10

Mode	% of Time	Weighted Average Emissions and Fuel Use Rates				
		CO2[g/s]	CO[mg/s]	HC[mg/s]	NO_x [mg/s]	FC[g/s]
1	53%	0.47	23	2.5	0.9	0.19
2	9.6%	0.14	6.4	0.51	1.5	0.05
3	12%	0.40	18	1.1	6.7	0.16
4	13%	0.69	34	1.5	13	0.28
5	7.6%	0.50	26	0.97	11	0.2
6	2.1%	0.18	9.2	0.35	3.9	0.07
7	1.2%	0.11	5.5	0.22	2.4	0.05
8	0.73%	0.08	3.7	0.15	1.9	0.03
9	0.50%	0.06	2.7	0.11	1.5	0.02
10	0.15%	0.02	0.93	0.04	0.54	0.01
Total	*100%*	*2.7*	*129*	*7.5*	*43*	*1.1*

Table C.19. Weighted Average Mass per Time Emissions and Fuel Use Rates for Bus 11

Mode	% of Time	Weighted Average Emissions and Fuel Use Rates				
		CO2[g/s]	CO[mg/s]	HC[mg/s]	NO_x [mg/s]	FC[g/s]
1	46%	0.67	0.23	1.1	0.26	0.25
2	8.7%	0.17	0.02	0.26	0.25	0.06
3	18%	0.87	0.09	1.2	1.4	0.33
4	13%	1.1	0.12	1.4	1.1	0.40
5	6.4%	0.71	0.08	0.94	0.42	0.26
6	3.9%	0.50	0.03	0.64	0.15	0.19
7	2.3%	0.34	0.02	0.42	0.08	0.13
8	1.3%	0.23	0.01	0.25	0.03	0.08
9	0.42%	0.08	0.0	0.09	0.01	0.03
10	0.22%	0.05	0.0	0.06	0.0	0.02
Total	*100%*	*4.7*	*0.61*	*6.3*	*3.6*	*1.7*

Table C.20. Weighted Average Mass per Time Emissions and Fuel Use Rates for Bus 12

Mode	% of Time	Weighted Average Emissions and Fuel Use Rates				
		CO2[g/s]	CO[mg/s]	HC[mg/s]	NO_x [mg/s]	FC[g/s]
1	43%	0.66	0.06	0.82	5.1	0.21
2	3.4%	0.02	0.01	0.07	0.18	0.01
3	4.6%	0.04	0.03	0.12	0.32	0.01
4	6.8%	0.15	0.13	0.23	0.95	0.05
5	8.5%	0.49	0.13	0.40	2.7	0.16
6	12%	1.3	0.26	0.75	6.0	0.41
7	10%	1.6	0.32	0.80	6.6	0.5
8	5.9%	1.5	0.42	0.62	5.4	0.46
9	4.1%	1.3	0.41	0.52	4.6	0.4
10	0.86%	0.28	0.05	0.12	0.99	0.09
Total	*100%*	*7.2*	*1.8*	*4.5*	*33*	*2.3*

Table C.21. Weighted Average Mass per Time Emissions and Fuel Use Rates for Bus 13

Mode	% of Time	Weighted Average Emissions and Fuel Use Rates				
		CO2[g/s]	CO[mg/s]	HC[mg/s]	NO_x [mg/s]	FC[g/s]
1	21%	0.68	2.8	0.89	4.1	0.22
2	5.4%	0.05	1.9	0.25	0.37	0.02
3	6.0%	0.13	4.6	0.35	0.76	0.04
4	25%	1.1	12	2.1	5.4	0.35
5	13%	1.3	14	1.2	6.2	0.42
6	13%	2.1	12	1.4	8.1	0.66
7	9.8%	2.4	13	1.3	8.1	0.76
8	4.5%	1.6	14	0.78	4.8	0.52
9	2.2%	0.98	10	0.45	2.7	0.32
10	0.28%	0.09	0.17	0.07	0.32	0.03
Total	*100%*	*10*	*85*	*8.9*	*41*	*3.3*

Table C.22. Weighted Average Mass per Time Emissions and Fuel Use Rates for Bus 14

Mode	% of Time	Weighted Average Emissions and Fuel Use Rates				
		CO2[g/s]	CO[mg/s]	HC[mg/s]	NO_x [mg/s]	FC[g/s]
1	28%	0.75	0.72	0.83	7.0	0.24
2	3.7%	0.04	0.25	0.13	0.39	0.01
3	6.6%	0.07	0.59	0.27	0.61	0.02
4	14%	0.36	1.6	0.79	2.4	0.12
5	9.6%	0.58	2.2	0.58	3.7	0.19
6	11%	1.2	3.6	0.85	6.7	0.37
7	13%	1.8	4.8	1.1	9.7	0.57
8	7.7%	1.5	3.4	0.71	7.2	0.46
9	4.5%	1.2	2.4	0.55	5.7	0.38
10	1.6%	0.48	0.88	0.22	2.2	0.15
Total	*100%*	*7.9*	*20*	*6.0*	*46*	*2.5*

Table C.23. Summary of Weighted Average Mass per Time CO_2 Rates

Mode	CO_2 (g/s)								
	Big CNG			Small CNG			Diesel		
	% of time	Avg.	Weighted Avg.	% of time	Avg.	Weighted Avg.	% of time	Avg.	Weighted Avg.
1	7.1%	3.8	0.27	48%	1.3	0.60	31%	2.5	0.77
2	29%	6.3	1.8	9.5%	1.7	0.16	4.2%	0.92	0.04
3	5.3%	5.0	0.27	11%	3.8	0.43	5.7%	1.4	0.08
4	20%	6.3	1.3	14%	6.3	0.87	15%	3.0	0.46
5	14%	9.3	1.3	8.0%	8.7	0.69	10%	7.2	0.76
6	11%	14	1.6	4.1%	10	0.42	12%	12	1.5
7	6.9%	20	1.4	2.6%	12	0.31	11%	18	2.0
8	3.7%	26	0.97	1.8%	13	0.24	6.1%	26	1.6
9	1.8%	31	0.57	0.8%	15	0.12	3.6%	34	1.2
10	0.40%	36	0.14	0.2%	16	0.04	0.90%	32	0.29
Total			***9.6***			***3.9***			***8.7***

Table C.24. Summary of Weighted Average Mass per Time CO Rates

Mode	CO (mg/s)								
	Big CNG			Small CNG			Diesel		
	% of time	Avg.	Weighted Avg.	% of time	Avg.	Weighted Avg.	% of time	Avg.	Weighted Avg.
1	7.1%	3.4	0.24	48%	11	5.0	31%	5.5	1.7
2	29%	10	3.0	9.5%	15	1.5	4.2%	14	0.58
3	5.3%	30	1.6	11%	36	4.1	5.7%	29	1.6
4	20%	31	6.3	14%	68	9.4	15%	21	3.2
5	14%	81	11	8.0%	110	8.9	10%	44	4.6
6	11%	130	15	4.1%	140	5.8	12%	44	5.3
7	6.9%	230	16	2.6%	160	4.1	11%	57	6.2
8	3.7%	370	14	1.8%	170	3.0	6.1%	120	7.2
9	1.8%	590	11	0.8%	180	1.5	3.6%	180	6.4
10	0.40%	670	2.7	0.2%	210	0.48	0.90%	40	0.36
Total			***81***			***44***			***37***

Table C.25. Summary of Weighted Average Mass per Time HC Rates

Mode	HC (mg/s)								
	Big CNG			Small CNG			Diesel		
	% of time	Avg.	Weighted Avg.	% of time	Avg.	Weighted Avg.	% of time	Avg.	Weighted Avg.
1	7.1%	1.9	0.13	48%	3.6	1.7	31%	3.1	0.94
2	29%	3.3	0.96	9.5%	4.1	0.39	4.2%	3.4	0.14
3	5.3%	4.9	0.26	11%	6.8	0.77	5.7%	4.1	0.24
4	20%	6.5	1.3	14%	9.4	1.3	15%	5.8	0.89
5	14%	9.9	1.4	8.0%	12	0.96	10%	6.6	0.70
6	11%	13	1.5	4.1%	14	0.55	12%	8.3	1.0
7	6.9%	18	1.2	2.6%	15	0.39	11%	10	1.1
8	3.7%	23	0.86	1.8%	16	0.28	6.1%	12	0.75
9	1.8%	31	0.56	0.8%	17	0.14	3.6%	15	0.55
10	0.40%	48	0.19	0.2%	19	0.04	0.90%	17	0.16
Total			***8.4***			***6.5***			***6.5***

Table C.26. Summary of Weighted Average Mass per Time NO_x Rates

Mode	NO_x (mg/s)								
	Big CNG			Small CNG			Diesel		
	% of time	Avg.	Weighted Avg.	% of time	Avg.	Weighted Avg.	% of time	Avg.	Weighted Avg.
1	7.1%	1.4	0.10	48%	0.85	0.41	30.7%	19	5.8
2	29%	0.67	0.20	9.5%	5.5	0.52	4.2%	7.6	0.32
3	5.3%	1.1	0.06	11%	19	2.1	5.7%	9.5	0.55
4	20%	1.0	0.20	14%	32	4.5	15.4%	18	2.7
5	14%	1.9	0.27	8.0%	44	3.5	10.5%	39	4.1
6	11%	2.2	0.25	4.1%	56	2.3	12.1%	58	7.0
7	6.9%	2.8	0.19	2.6%	65	1.7	10.9%	74	8.1
8	3.7%	4.7	0.17	1.8%	77	1.4	6.1%	97	5.9
9	1.8%	5.0	0.09	0.8%	90	0.73	3.6%	121	4.4
10	0.40%	9.5	0.04	0.2%	102	0.24	0.9%	123	1.1
Total			***1.6***			***17***			***40***

Table C.27. Summary of Weighted Average Mass per Time Fuel Use Rates

Mode	FC (g/s)								
	Big CNG			Small CNG			Diesel		
	% of time	Avg.	Weighted Avg.	% of time	Avg.	Weighted Avg.	% of time	Avg.	Weighted Avg.
1	7.1%	1.4	0.10	48%	0.48	0.23	31%	0.79	0.24
2	29%	2.3	0.68	9.5%	0.65	0.06	4.2%	0.30	0.01
3	5.3%	1.8	0.10	11%	1.4	0.16	5.7%	0.45	0.03
4	20%	2.3	0.46	14%	2.4	0.33	15%	0.97	0.15
5	14%	3.4	0.48	8.0%	3.3	0.26	10%	2.3	0.24
6	11%	5.1	0.59	4.1%	4.0	0.16	12%	3.9	0.48
7	6.9%	7.5	0.52	2.6%	4.6	0.12	11%	5.7	0.62
8	3.7%	9.7	0.36	1.8%	5.1	0.09	6.1%	8.4	0.51
9	1.8%	12	0.22	0.82%	5.7	0.05	3.6%	11	0.39
10	0.40%	13	0.05	0.23%	6.2	0.01	0.90%	10	0.09
Total			***3.6***			***1.5***			***2.8***

D) Correlation Matrix

This appendix presents the correlation matrix for each tested bus.

Table D.1. Bus 1 Correlation Matrix

	RPM	IAT	MAP	LOAD	SPEED	CO_2	CO	HC	NO_x	FC
RPM	1.00									
IAT	0.21	1.00								
MAP	0.65	0.47	1.00							
LOAD	0.49	0.53	0.71	1.00						
SPEED	0.72	0.12	0.37	0.11	1.00					
CO_2	0.68	0.60	0.78	0.90	0.31	1.00				
CO	0.44	0.10	0.40	0.43	0.10	0.46	1.00			
HC	0.63	0.31	0.60	0.54	0.27	0.67	0.82	1.00		
NO_x	0.28	-0.17	0.18	0.26	0.06	0.20	0.37	0.33	1.00	
FC	0.69	0.59	0.78	0.90	0.30	1.00	0.51	0.71	0.22	1.00

Table D.2. Bus 2 Correlation Matrix

	RPM	IAT	MAP	LOAD	SPEED	CO_2	CO	HC	NO_x	FC
RPM	1.00									
IAT	-0.27	1.00								
MAP	0.59	-0.16	1.00							
LOAD	0.17	0.11	0.55	1.00						
SPEED	0.64	-0.65	0.36	-0.11	1.00					
CO_2	0.72	0.03	0.76	0.66	0.27	1.00				
CO	0.44	-0.07	0.45	0.30	0.22	0.47	1.00			
HC	0.49	-0.06	0.47	0.16	0.27	0.49	0.58	1.00		
NO_x	0.19	-0.22	0.13	0.00	0.19	0.06	0.11	0.10	1.00	
FC	0.73	0.02	0.76	0.66	0.27	1.00	0.51	0.50	0.06	1.00

Table D.3. Bus 3 Correlation Matrix

	RPM	IAT	MAP	LOAD	SPEED	CO_2	CO	HC	NO_x	FC
RPM	1.00									
IAT	-0.04	1.00								
MAP	0.70	0.15	1.00							
LOAD	0.43	0.24	0.74	1.00						
SPEED	0.69	-0.26	0.49	0.16	1.00					
CO_2	0.72	0.27	0.85	0.85	0.36	1.00				
CO	0.41	-0.02	0.33	0.29	0.15	0.39	1.00			
HC	0.58	0.07	0.53	0.38	0.36	0.60	0.58	1.00		
NO_x	0.29	-0.10	0.24	0.27	0.06	0.27	0.26	0.16	1.00	
FC	0.73	0.26	0.85	0.85	0.36	1.00	0.44	0.62	0.28	1.00

Table D.4. Bus 4 Correlation Matrix

	RPM	IAT	MAP	LOAD	SPEED	CO_2	CO	HC	NO_x	FC
RPM	1.00									
IAT	0.11	1.00								
MAP	0.65	0.27	1.00							
LOAD	0.38	0.46	0.62	1.00						
SPEED	0.61	-0.15	0.37	-0.05	1.00					
CO_2	0.74	0.44	0.76	0.80	0.28	1.00				
CO	0.40	0.09	0.37	0.31	0.12	0.42	1.00			
HC	0.66	0.12	0.54	0.22	0.43	0.60	0.51	1.00		
NO_x	0.19	-0.04	0.18	0.21	0.02	0.20	0.20	0.11	1.00	
FC	0.74	0.44	0.77	0.80	0.28	1.00	0.46	0.61	0.20	1.00

Table D.5. Bus 5 Correlation Matrix

	RPM	IAT	MAP	LOAD	SPEED	CO_2	CO	HC	NO_x	FC
RPM	1.00									
IAT	-0.31	1.00								
MAP	0.69	-0.11	1.00							
LOAD	0.29	0.27	0.64	1.00						
SPEED	0.65	-0.68	0.36	-0.15	1.00					
CO_2	0.75	0.02	0.84	0.76	0.28	1.00				
CO	0.48	-0.07	0.52	0.36	0.21	0.53	1.00			
HC	0.49	-0.10	0.39	0.13	0.34	0.42	0.51	1.00		
NO_x	0.27	-0.12	0.28	0.23	0.09	0.24	0.34	0.12	1.00	
FC	0.76	0.02	0.84	0.76	0.28	1.00	0.56	0.44	0.25	1.00

Table D.6. Bus 6 Correlation Matrix

	RPM	IAT	MAP	LOAD	SPEED	CO_2	CO	HC	NO_x	FC
RPM	1.00									
IAT	0.13	1.00								
MAP	0.63	0.20	1.00							
LOAD	0.29	0.19	0.62	1.00						
SPEED	0.62	-0.18	0.44	0.01	1.00					
CO_2	0.68	0.23	0.72	0.66	0.27	1.00				
CO	0.35	0.00	0.29	0.19	0.25	0.36	1.00			
HC	0.37	-0.04	0.41	0.25	0.29	0.44	0.37	1.00		
NO_x	0.26	-0.12	0.31	0.24	0.19	0.31	0.16	0.54	1.00	
FC	0.68	0.23	0.72	0.65	0.27	1.00	0.39	0.45	0.31	1.00

Table D.7. Bus 7 Correlation Matrix

	RPM	IAT	MAF	LOAD	SPEED	CO_2	CO	HC	NO_x	FC
RPM	1.00									
IAT	-0.09	1.00								
MAF	0.95	-0.03	1.00							
LOAD	0.82	0.04	0.91	1.00						
SPEED	0.56	-0.60	0.50	0.33	1.00					
CO_2	0.95	-0.01	0.97	0.91	0.43	1.00				
CO	0.80	0.11	0.84	0.79	0.24	0.85	1.00			
HC	0.56	-0.10	0.53	0.53	0.19	0.62	0.54	1.00		
NO_x	0.89	-0.02	0.91	0.81	0.43	0.91	0.88	0.52	1.00	
FC	0.95	-0.01	0.97	0.91	0.43	1.00	0.86	0.62	0.91	1.00

Table D.8. Bus 8 Correlation Matrix

	RPM	IAT	MAF	LOAD	SPEED	CO_2	CO	HC	NO_x	FC
RPM	1.00									
IAT	-0.41	1.00								
MAF	0.95	-0.33	1.00							
LOAD	0.69	-0.16	0.86	1.00						
SPEED	0.62	-0.72	0.48	0.21	1.00					
CO_2	0.95	-0.32	1.00	0.85	0.47	1.00				
CO	0.09	-0.02	0.11	0.11	0.07	0.11	1.00			
HC	0.86	-0.24	0.91	0.79	0.42	0.91	0.12	1.00		
NO_x	0.18	-0.05	0.18	0.18	0.11	0.17	-0.08	0.30	1.00	
FC	0.95	-0.32	1.00	0.85	0.47	1.00	0.11	0.91	0.17	1.00

Table D.9. Bus 9 Correlation Matrix

	RPM	IAT	MAF	LOAD	SPEED	CO_2	CO	HC	NO_x	FC
RPM	1.00									
IAT	-0.35	1.00								
MAF	0.95	-0.30	1.00							
LOAD	0.61	-0.13	0.80	1.00						
SPEED	0.57	-0.70	0.47	0.16	1.00					
CO_2	0.95	-0.30	1.00	0.80	0.47	1.00				
CO	0.84	-0.21	0.87	0.62	0.40	0.86	1.00			
HC	0.67	-0.17	0.74	0.67	0.27	0.73	0.62	1.00		
NO_x	0.81	-0.25	0.84	0.64	0.40	0.83	0.71	0.65	1.00	
FC	0.95	-0.30	1.00	0.79	0.47	1.00	0.87	0.73	0.83	1.00

Table D.10. Bus 10 Correlation Matrix

	RPM	IAT	MAF	LOAD	SPEED	CO_2	CO	HC	NO_x	FC
RPM	1.00									
IAT	0.01	1.00								
MAF	0.96	0.03	1.00							
LOAD	0.76	0.05	0.89	1.00						
SPEED	0.63	-0.31	0.50	0.22	1.00					
CO_2	0.96	0.02	1.00	0.89	0.51	1.00				
CO	0.00	-0.07	0.00	-0.02	0.00	0.00	1.00			
HC	0.75	0.26	0.80	0.76	0.30	0.79	-0.01	1.00		
NO_x	0.87	0.05	0.89	0.74	0.53	0.88	-0.01	0.76	1.00	
FC	0.96	0.02	1.00	0.89	0.51	1.00	0.01	0.79	0.88	1.00

Table D.11. Bus 11 Correlation Matrix

	RPM	IAT	MAF	LOAD	SPEED	CO_2	CO	HC	NO_x	FC
RPM	1.00									
IAT	-0.44	1.00								
MAF	0.96	-0.39	1.00							
LOAD	0.79	-0.31	0.92	1.00						
SPEED	0.75	-0.60	0.66	0.50	1.00					
CO_2	0.95	-0.38	0.99	0.91	0.65	1.00				
CO	0.93	-0.40	0.97	0.90	0.65	0.98	1.00			
HC	0.57	-0.27	0.63	0.62	0.32	0.63	0.68	1.00		
NO_x	0.92	-0.42	0.95	0.83	0.75	0.95	0.94	0.52	1.00	
FC	0.95	-0.38	0.99	0.91	0.66	1.00	0.98	0.64	0.95	1.00

Table D.12. Bus 12 Correlation Matrix

	RPM	IAT	MAP	LOAD	SPEED	CO_2	CO	HC	NO_x	FC
RPM	1.00									
IAT	0.21	1.00								
MAP	0.82	0.24	1.00							
LOAD	0.68	0.18	0.89	1.00						
SPEED	0.70	0.22	0.49	0.26	1.00					
CO_2	0.79	0.20	0.98	0.93	0.36	1.00				
CO	0.28	-0.02	0.27	0.32	0.00	0.32	1.00			
HC	0.85	0.33	0.92	0.76	0.48	0.90	0.23	1.00		
NO_x	0.79	0.18	0.94	0.86	0.38	0.95	0.27	0.91	1.00	
FC	0.79	0.20	0.98	0.93	0.36	1.00	0.32	0.90	0.95	1.00

Table D.13. Bus 13 Correlation Matrix

	RPM	IAT	MAP	LOAD	SPEED	CO_2	CO	HC	NO_x	FC
RPM	1.00									
IAT	0.18	1.00								
MAP	0.73	0.14	1.00							
LOAD	0.51	0.09	0.84	1.00						
SPEED	0.66	0.10	0.48	0.24	1.00					
CO_2	0.68	0.12	0.97	0.87	0.34	1.00				
CO	0.19	0.03	0.18	0.37	-0.05	0.24	1.00			
HC	0.55	0.13	0.53	0.41	0.19	0.54	0.21	1.00		
NO_x	0.68	0.12	0.90	0.69	0.41	0.90	0.17	0.56	1.00	
FC	0.68	0.12	0.96	0.87	0.33	1.00	0.28	0.54	0.90	1.00

Table D.14. Bus 14 Correlation Matrix

	RPM	IAT	MAP	LOAD	SPEED	CO_2	CO	HC	NO_x	FC
RPM	1.00									
IAT	0.33	1.00								
MAP	0.73	0.39	1.00							
LOAD	0.55	0.28	0.87	1.00						
SPEED	0.71	0.45	0.57	0.32	1.00					
CO_2	0.70	0.32	0.96	0.93	0.43	1.00				
CO	0.73	0.17	0.72	0.65	0.49	0.75	1.00			
HC	0.65	0.10	0.65	0.52	0.32	0.63	0.58	1.00		
NO_x	0.67	0.32	0.92	0.84	0.44	0.94	0.72	0.63	1.00	
FC	0.70	0.32	0.96	0.93	0.43	1.00	0.75	0.63	0.94	1.00

E) Model Validation

This appendix presents the model validation results for each MLR model of each tested bus.

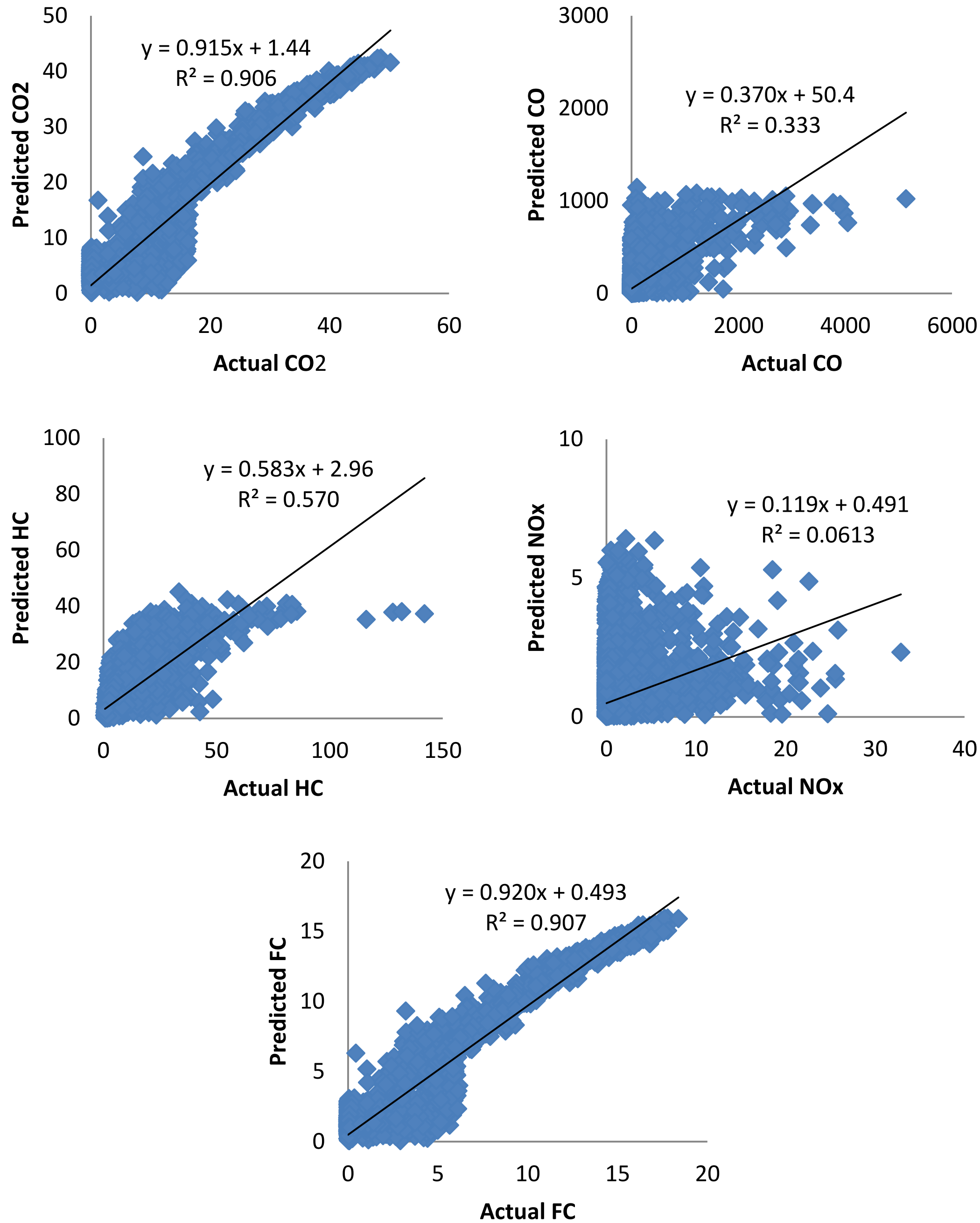

Figure E.1. Model Validation for MLR of Emissions and Fuel Use Models of Bus 1

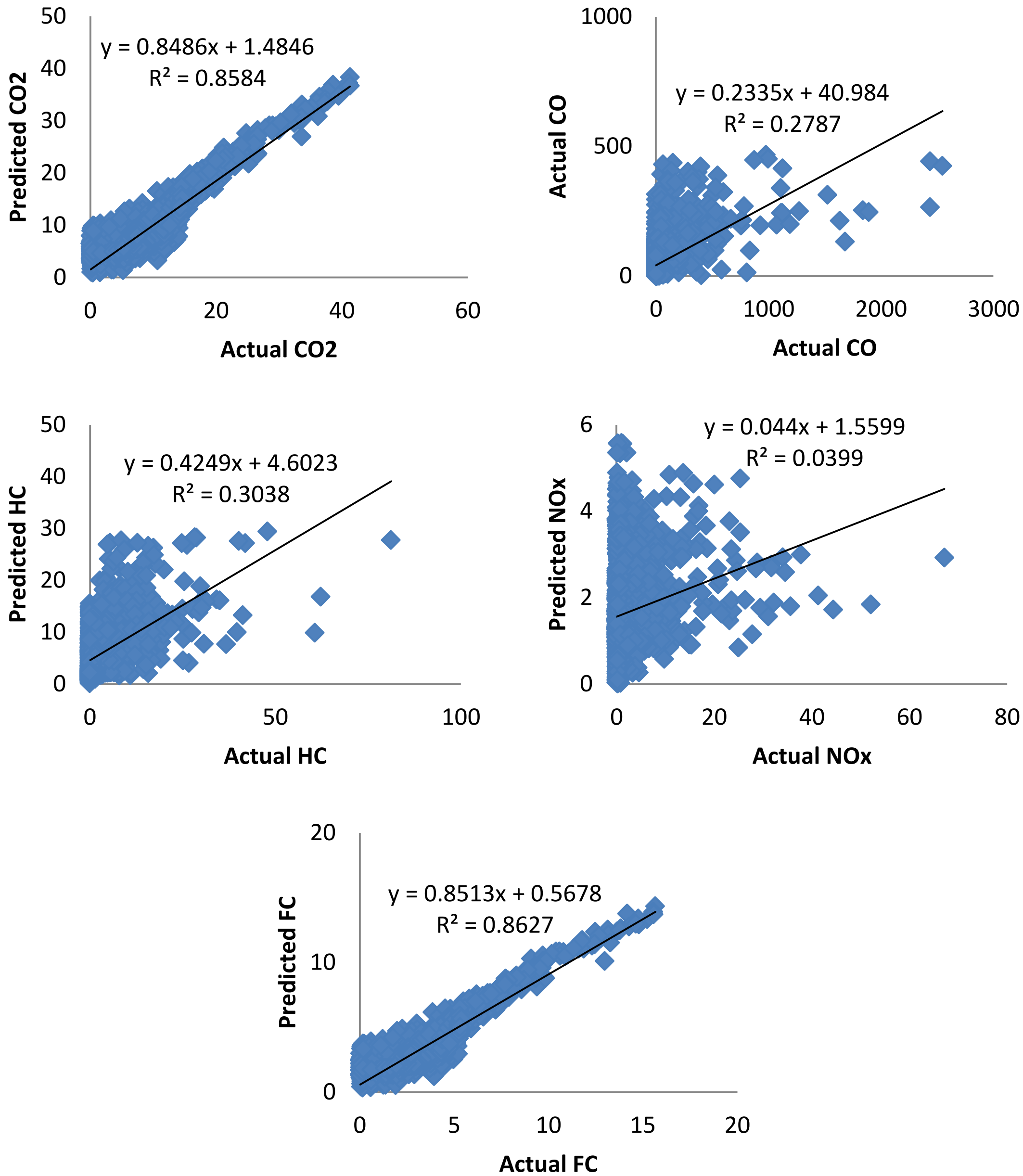

Figure E.2. Model Validation for MLR of Emissions and Fuel Use Models of Bus 2

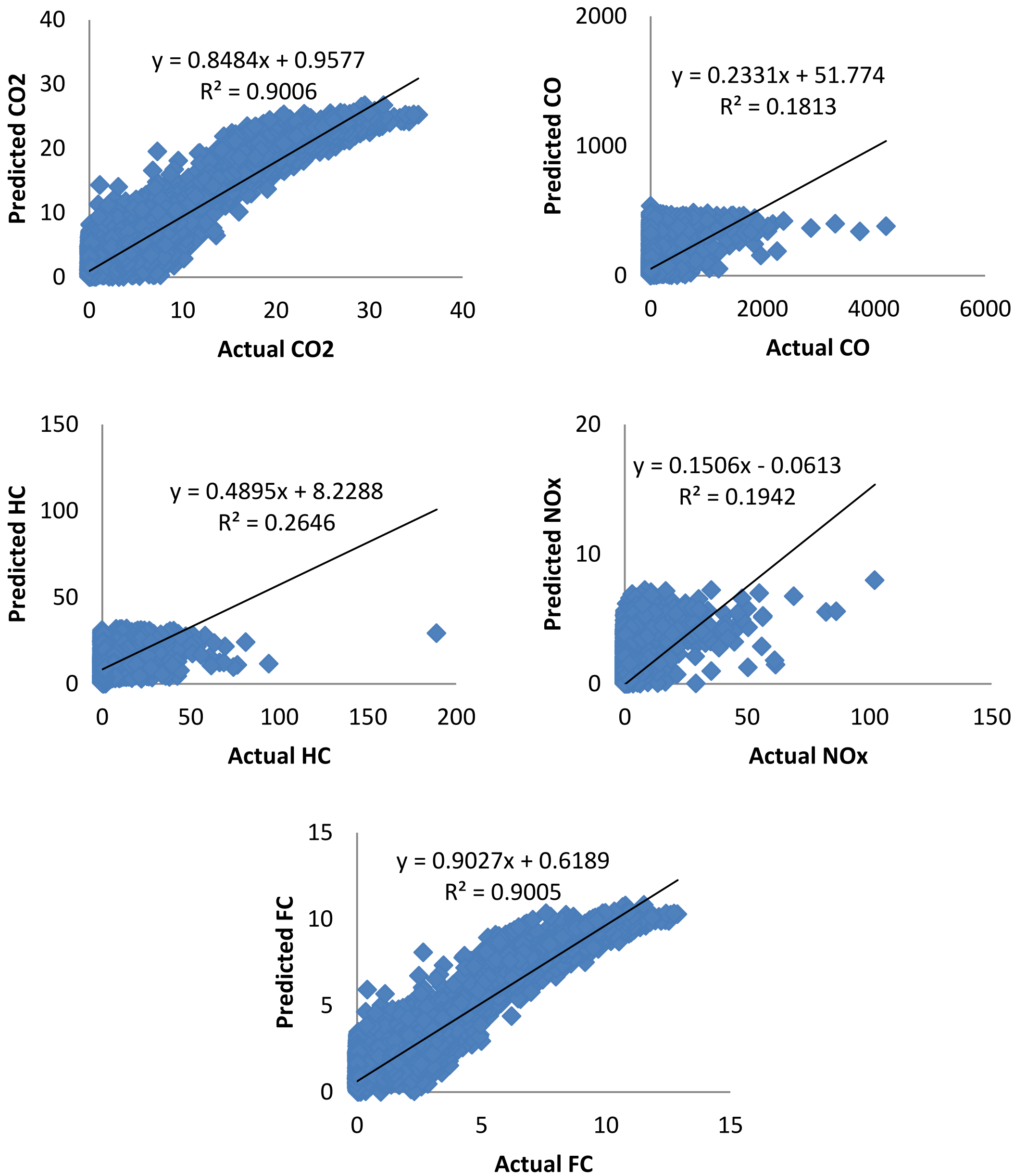

Figure E.3. Model Validation for MLR of Emissions and Fuel Use Models of Bus 3

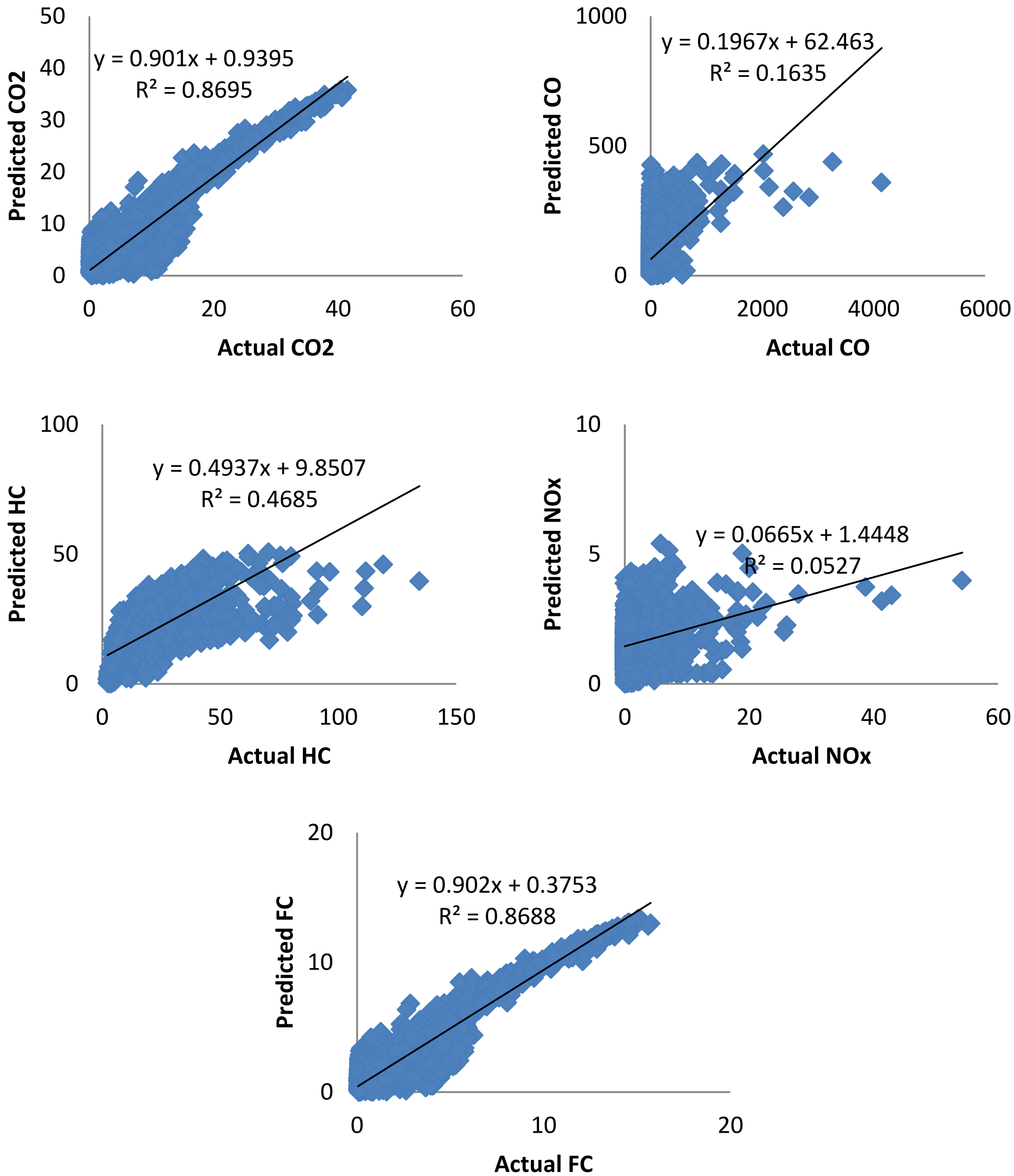

Figure E.4. Model Validation for MLR of Emissions and Fuel Use Models of Bus 4

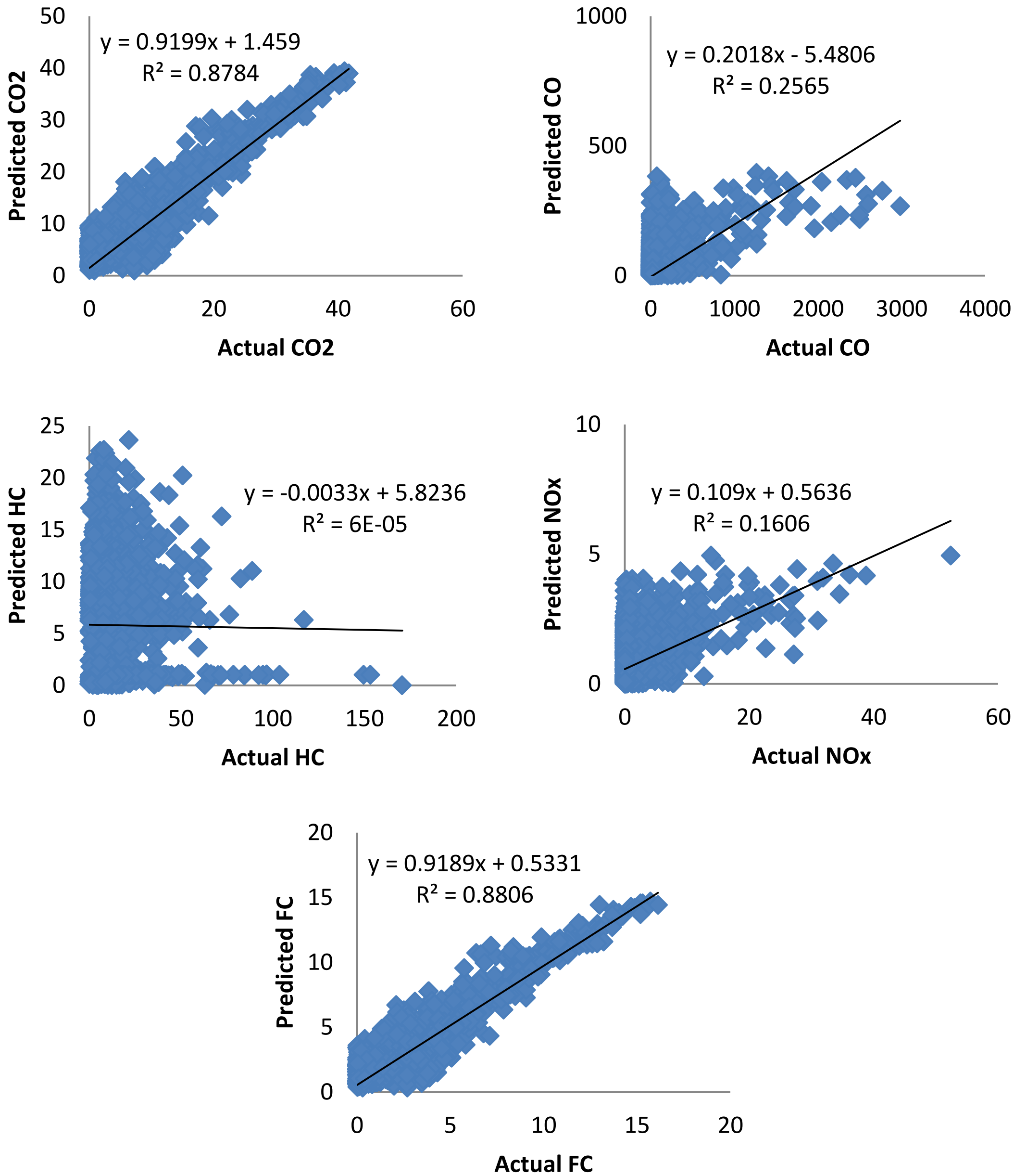

Figure E.5. Model Validation for MLR of Emissions and Fuel Use Models of Bus 5

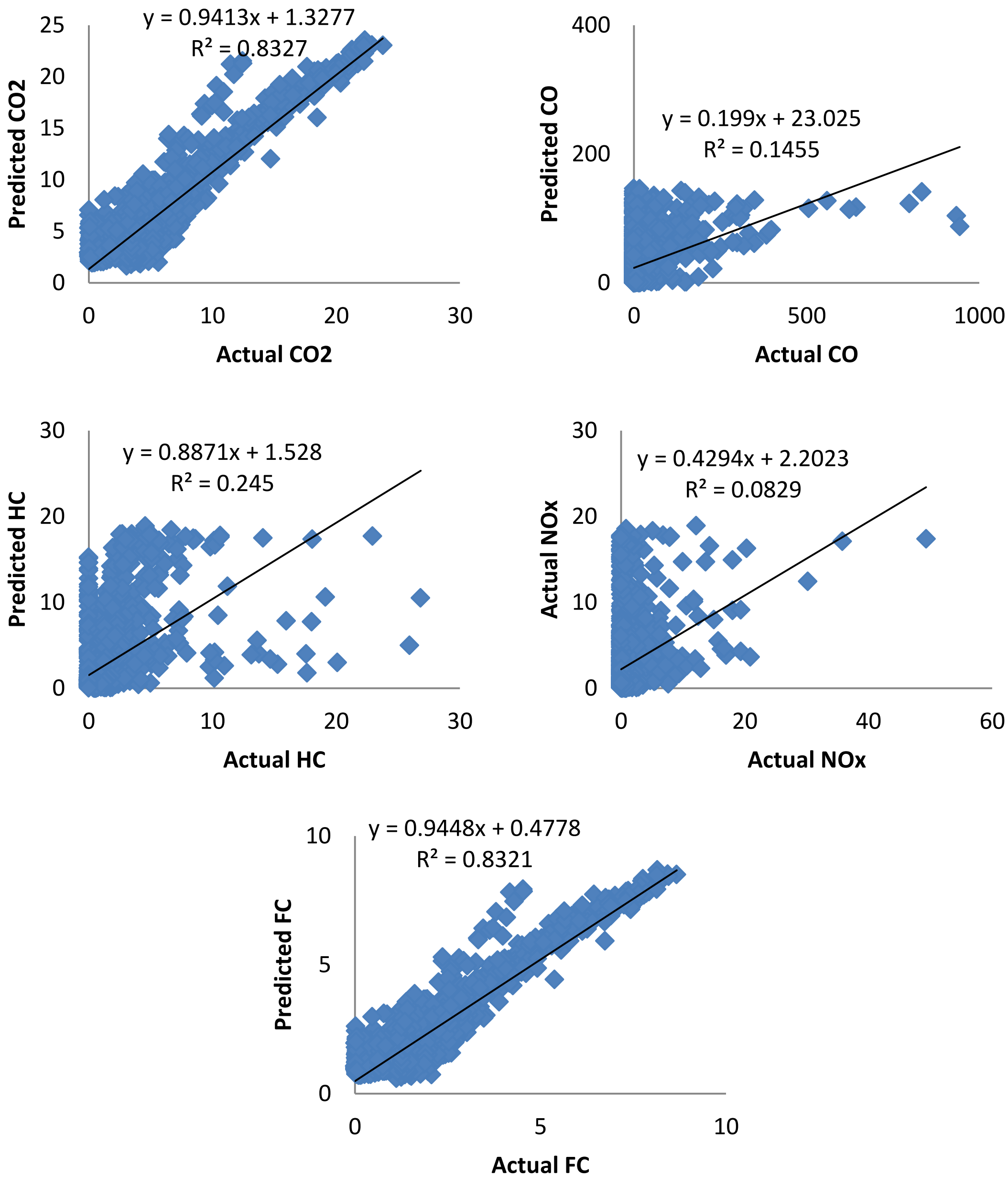

Figure E.6. Model Validation for MLR of Emissions and Fuel Use Models of Bus 6

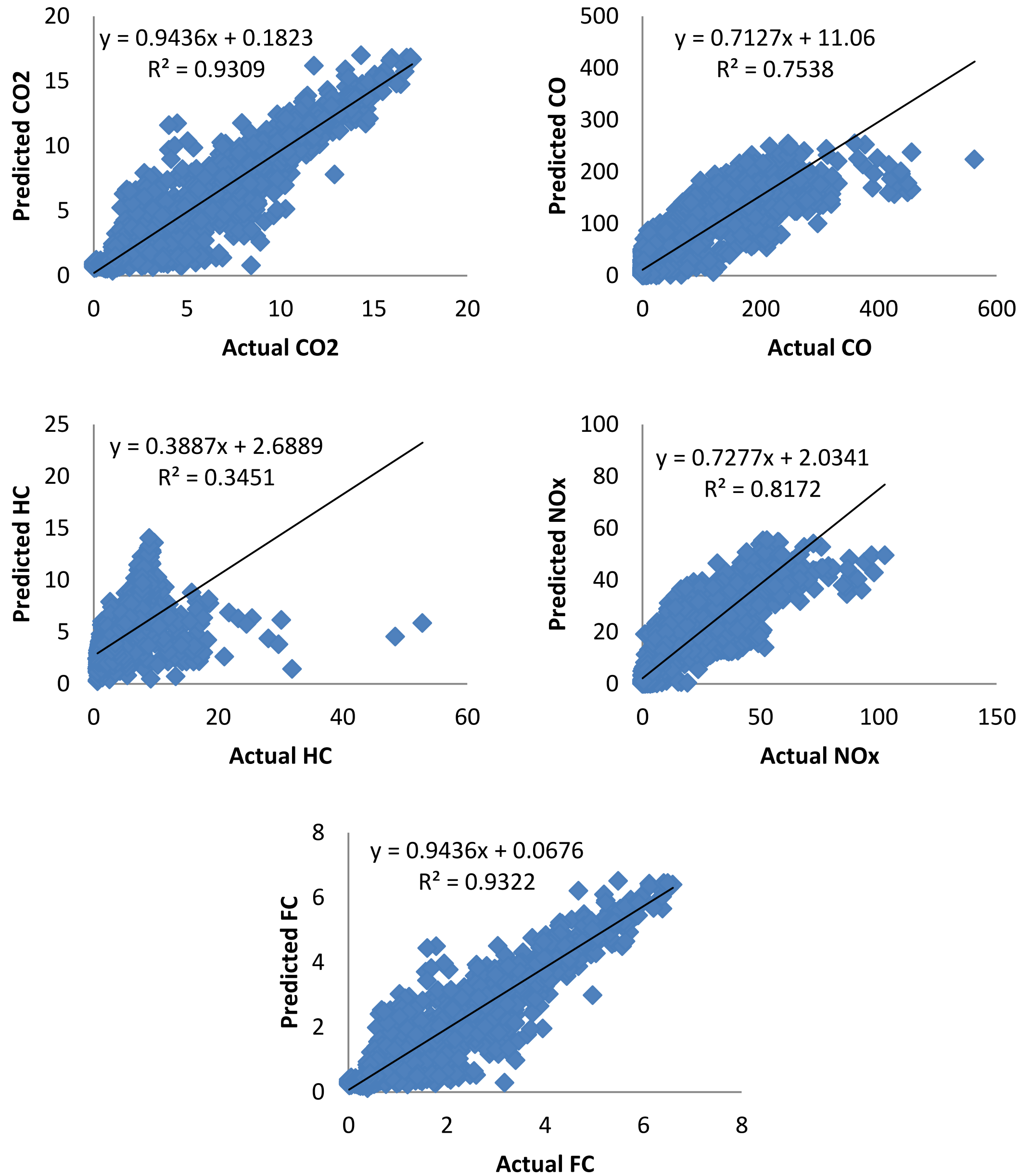

Figure E.7. Model Validation for MLR of Emissions and Fuel Use Models of Bus 7

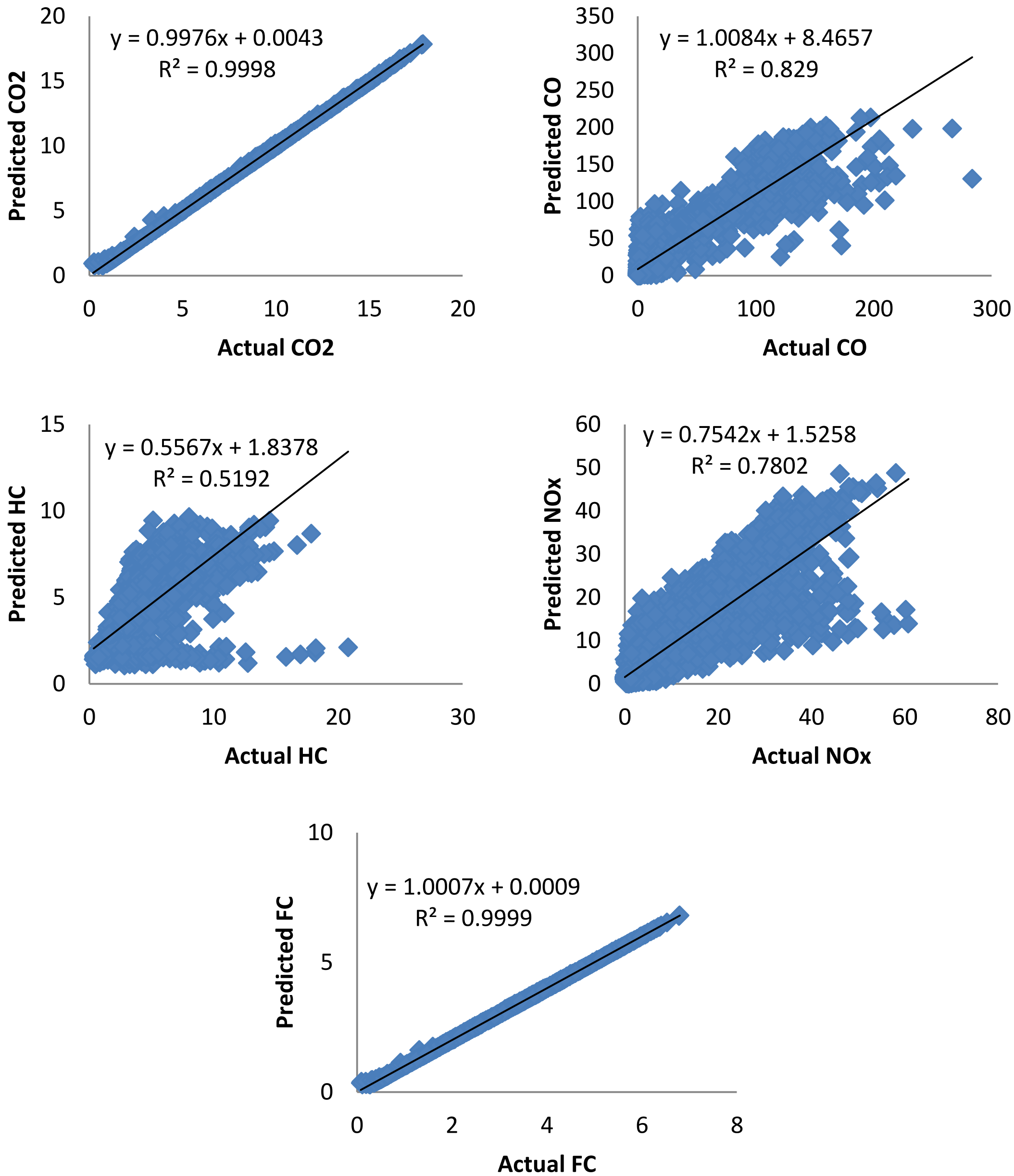

Figure E.8. Model Validation for MLR of Emissions and Fuel Use Models of Bus 8

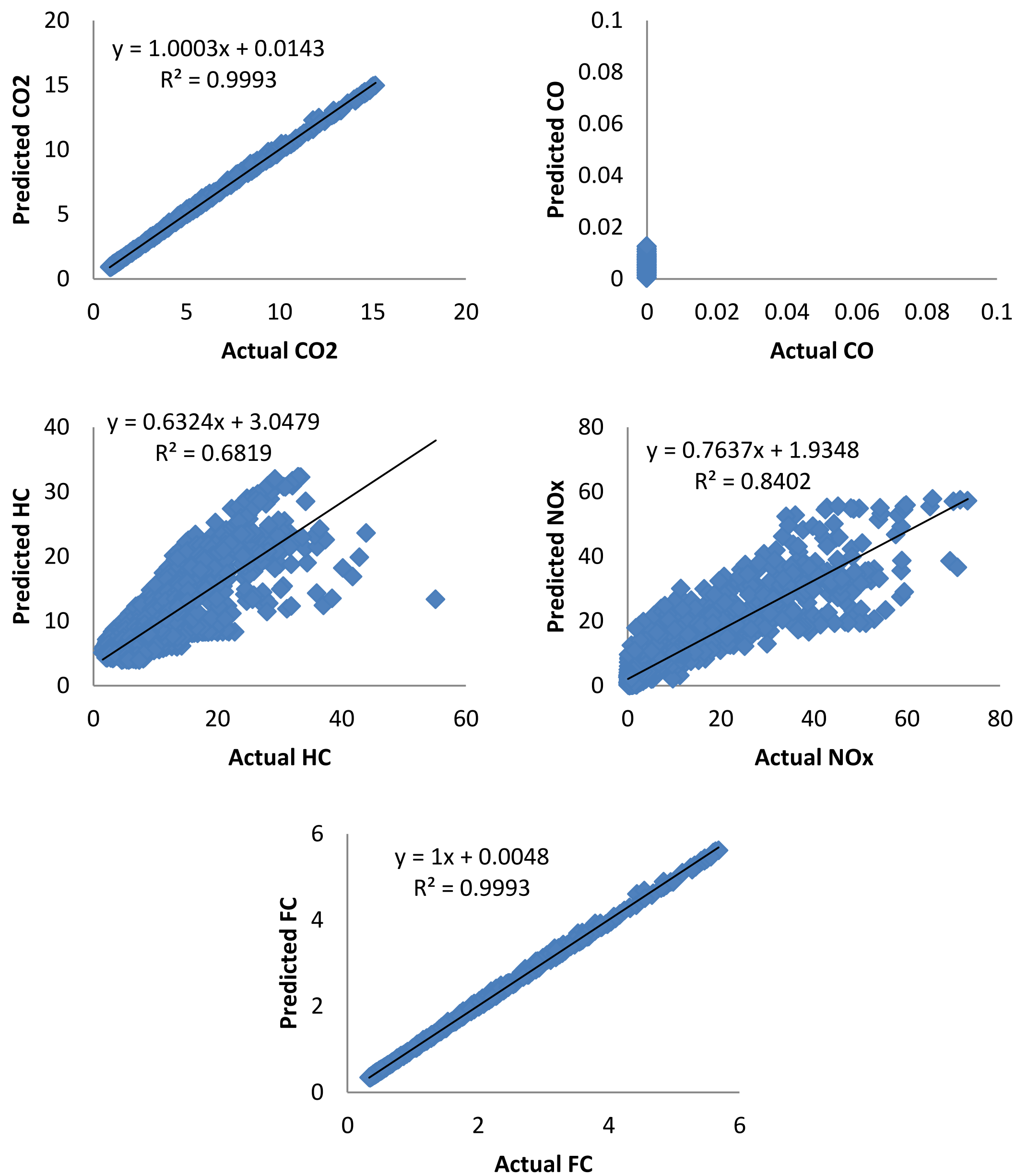

Figure E.9. Model Validation for MLR of Emissions and Fuel Use Models of Bus 9

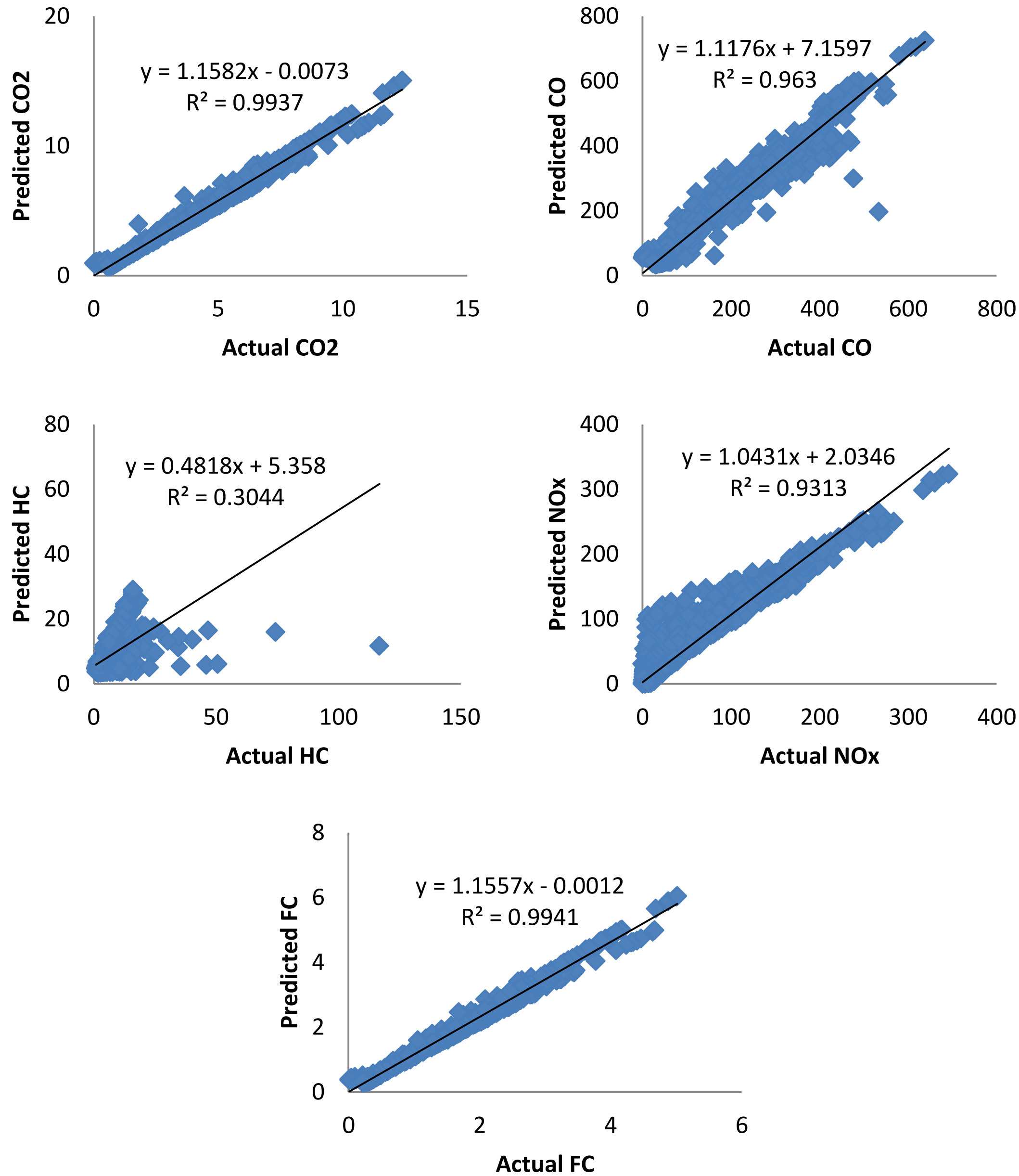

Figure E.10. Model Validation for MLR of Emissions and Fuel Use Models of Bus 10

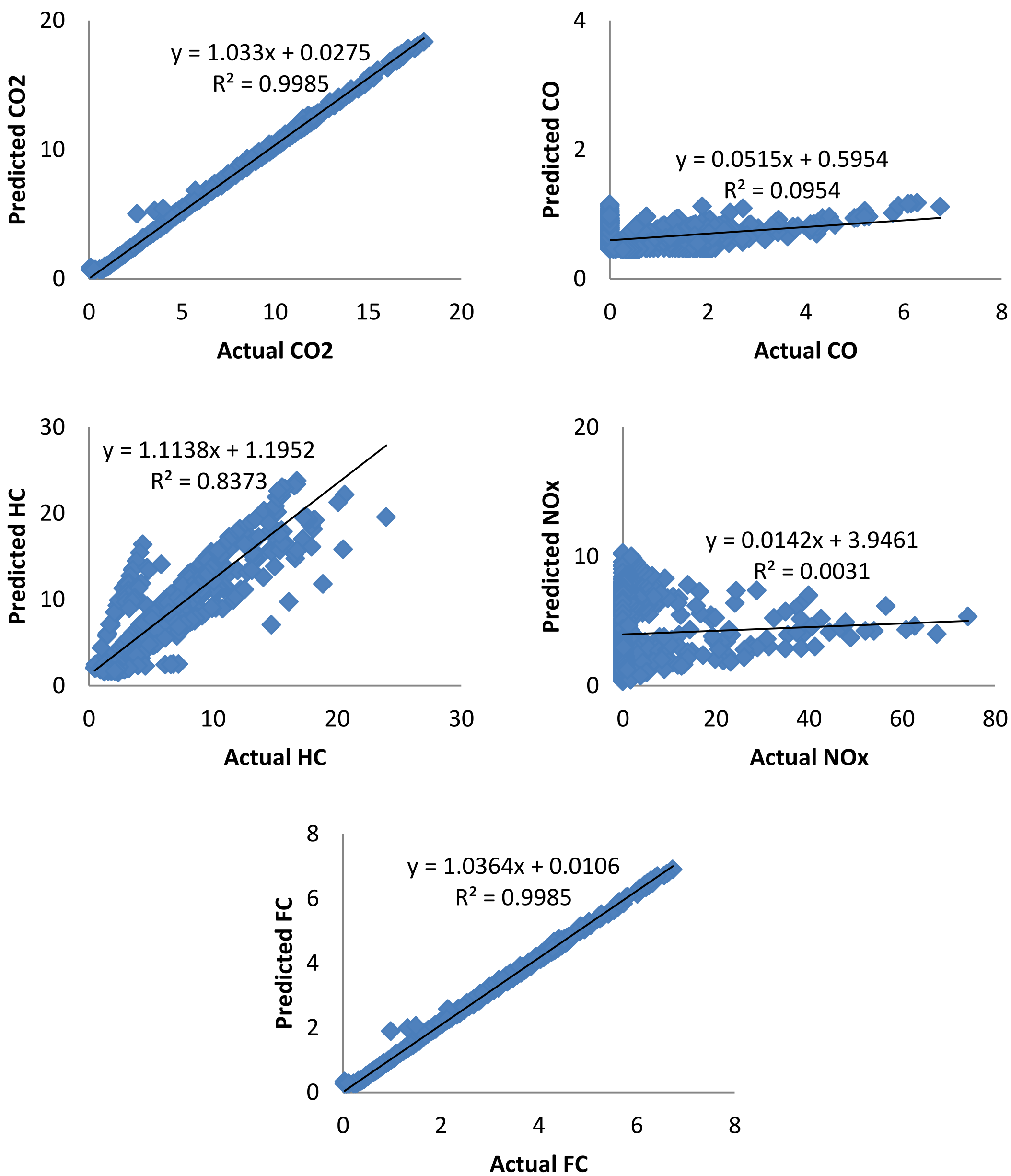

Figure E.11. Model Validation for MLR of Emissions and Fuel Use Models of Bus 11

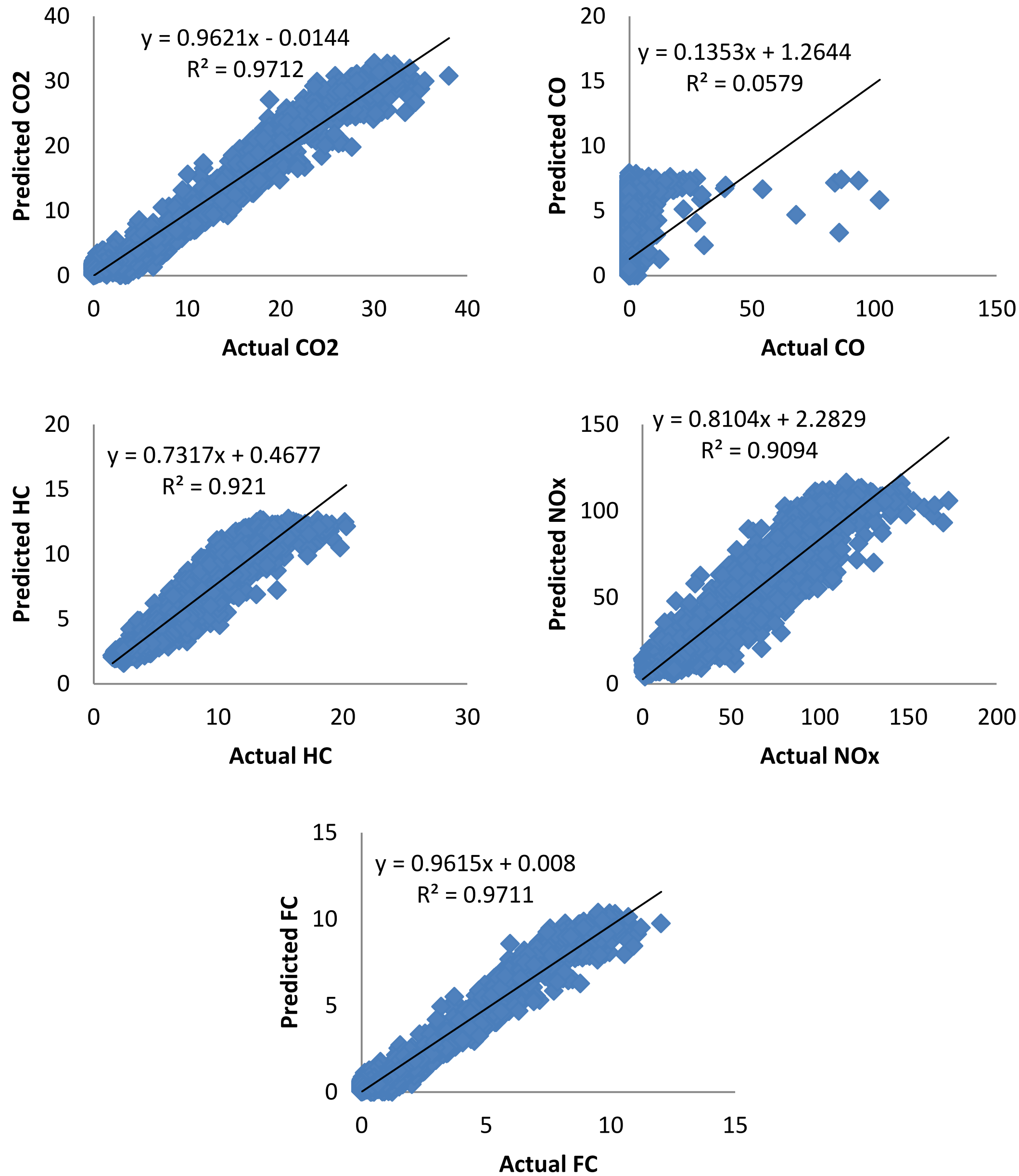

Figure E.12. Model Validation for MLR of Emissions and Fuel Use Models of Bus 12

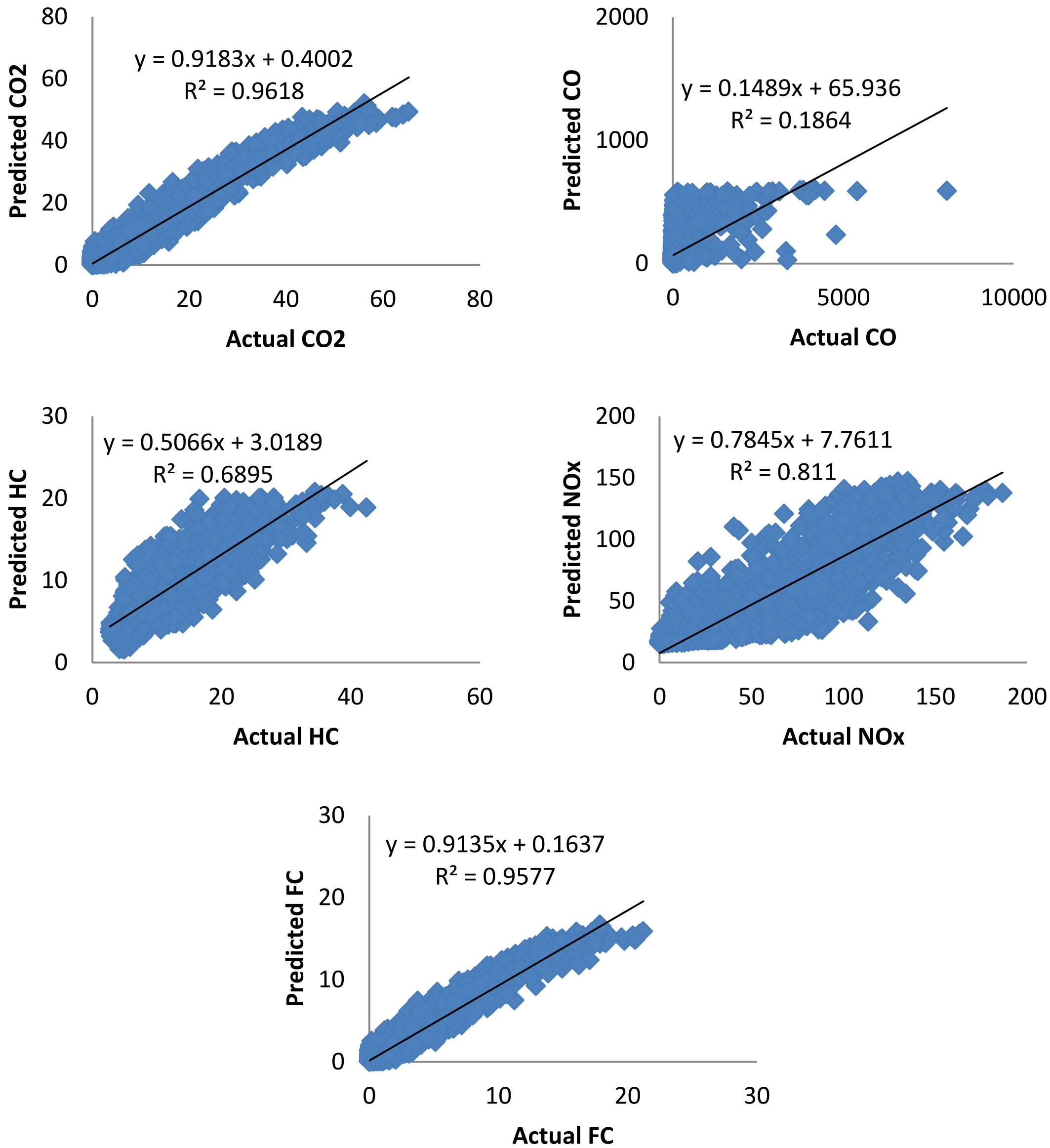

Figure E.13. Model Validation for MLR of Emissions and Fuel Use Models of Bus 13

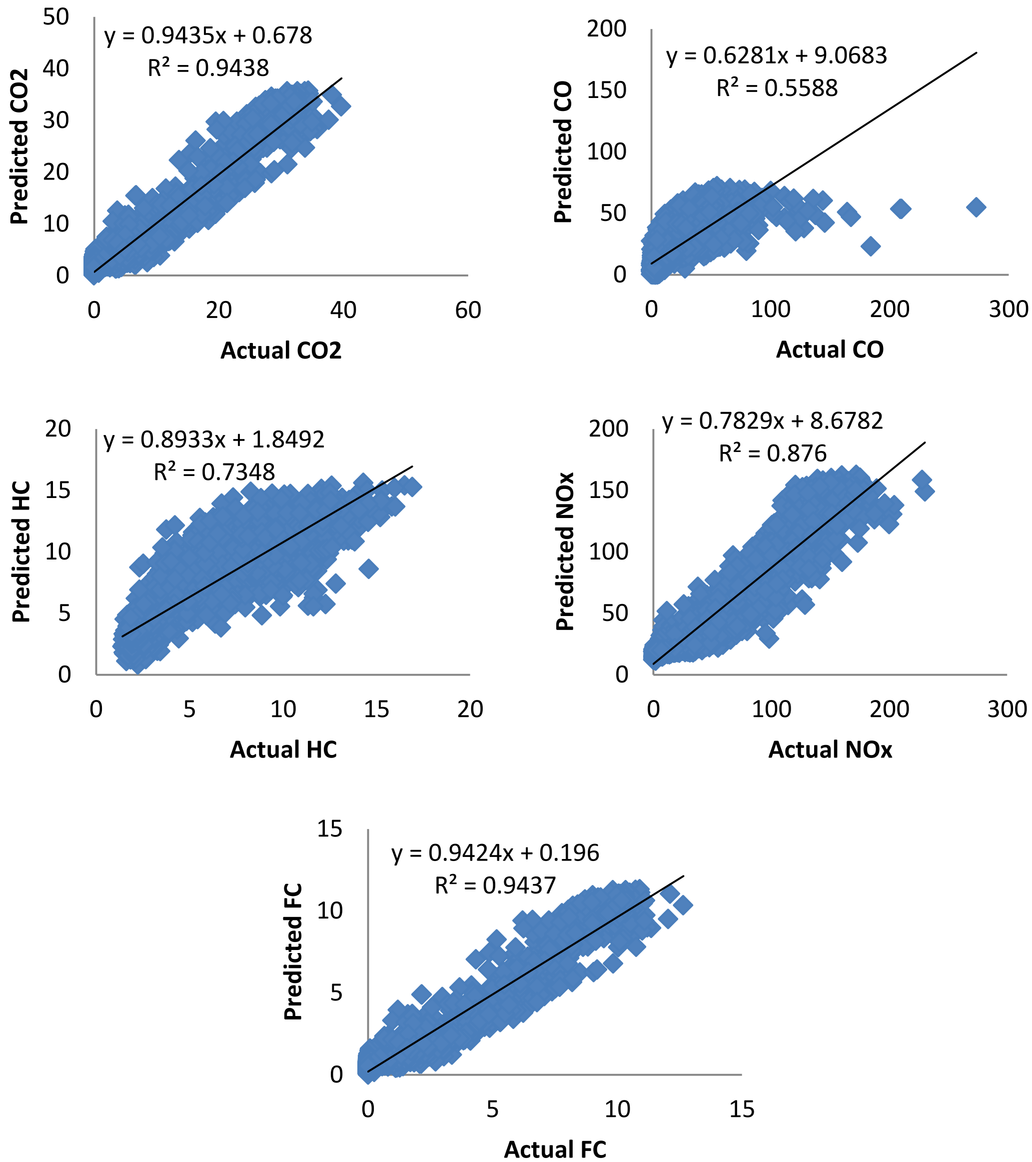

Figure E.14. Model Validation for MLR of Emissions and Fuel Use Models of Bus 14

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