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Non-parametric statistical evaluation of biodiesel emissions from transit buses

by

Abhisek Mudgal

A thesis submitted to the graduate faculty

in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Major: Civil Engineering (Transportation Engineering)

Program of Study Committee:
Shauna Hallmark, Major Professor
Konstantina Gkritza
Kasthurirangan Gopalakrishnan
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Iowa State University

Ames, Iowa

2009

DISCLAIMER

This document was used in partial fulfillment of the requirements set forth by Iowa State University for the degree of Master of Science. The numerical results and conclusions made in this report are interim steps and should not reflect the final and / or current views of the CenSARA, Iowa Department of Natural Resources, The Center for Transportation Research and Education (CTRE), or Iowa State University (ISU). The findings are restricted to the given engines, fuel blends, environmental conditions, routes and operation conditions.

DEDICATION

To the teachers who sacrifice their lives for the welfare of their students.

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LIST OF TERMS AND ABBREVIATIONS

BX	fuel with X% Biodiesel (e.g. B20 has 20% biodiesel and 80% conventional diesel)
B0	regular diesel
CAAA	Clean Air Act Amendments
CenSARA	Central States Air Resources Agencies
CO	Carbon monoxide
CO_2	Carbon dioxide
DOE	United States Department of Energy
EPA	United States Environmental protection agency
Emissions	NO_x, HC, CO, CO_2 and PM
HC	Hydro-carbons
NBB	National biodiesel board
NO_x	Oxides of nitrogen
NREL	National Renewable Energy Laboratory, Golden, CO
PEMS	Portable emission measurement system

PM	Particulate matter
Tier-1	Light-duty vehicles emissions standard (defined by CAAA in 1990) phased-in between 1994 and 1997
Tier-2	Light-duty vehicles emissions standard (defined by CAAA in 1990) phased-in between 2004 and 2009
VSP	vehicle specific power (W/kg)

Cetane number is the time period between the start of injection and start of combustion (ignition) of the fuel. Higher cetane number means shorter ignition delay i.e. the fuel would burn quickly.

Cloud point is the temperature at which a cloud of wax crystals first appear in a liquid when it is cooled under controlled conditions during a standard test (ASTM, 1991).

Flash point is the lowest temperature at which a flammable liquid can form an ignitable mixture in air.

Oxidation stability is the ability of a lubricant to resist natural degradation upon contact with oxygen.

Pour point is the temperature at which the fuel can no longer be poured due to gel formation (ASTM, 1996).

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ABSTRACT

Research on biodiesel emissions has been triggered by depleting fossil fuel resources and environmental protection concerns. However, vehicular emissions are inadequately understood and quantified because of large variations in individual vehicle emissions with changing operating conditions, engines and fuels. More research is needed to evaluate biodiesel emissions especially from heavy duty vehicles which include transit buses. Past research findings have been contradictory mostly in case of NO_x emissions. These make it essential to carry out further research especially with the help of on-road measurement devices which can capture the real-time variation in operating conditions, unlike dynamometers and remote sensing devices.

Emissions data were collected using a portable emission measurement system (PEMS) from three transit buses fueled with regular diesel (B0), 10% biodiesel (B10) and 20% biodiesel (B20). At an interval of one second, NO_x, HC, CO, CO_2 and particulate matter (PM) were recorded along with speed, acceleration, other engine parameters, and number of passengers for all the nine bus-fuel combinations. Emissions were found to exhibit auto-correlation and non-normal distributions, which necessitated a binning-based approach and the use of non-parametric statistics respectively for data analysis. Emission rates were not proportional to percentage of biodiesel. This was also seen when the same batch of biodiesel was tested using a dynamometer. Therefore, B10 and B20 were evaluated separately. The commonly used VSP formula was modified to account for passenger weight and load imparted by the use of air-conditioning. Emissions from each fuel were binned by speed and vehicle specific power (VSP). Emissions from each fuel were grouped by VSP into three bins. Emissions varied monotonically with VSP. Further, no significant change in result was obtained upon using the new formula. Statistical tests were performed to compare emissions from B10 and B20 to B0.

Evaluation of B10 revealed that NO_x, HC, CO, and CO_2 emission rates decreased for Tier-1 buses. For Tier-2 bus, NO_x, HC, CO_2 and PM emission rates increased while CO emission rates decreased. With B20, HC and PM emission rates decreased for all the buses. NO_x and CO, CO_2 results were contradictory. Decrease in PM emissions is very significant particularly for heavy duty vehicles in terms of freight demand. Decrease in HC is not significant for diesel engines. Likewise, inconsistency in CO emissions is also immaterial while inconsistency in NO_x emissions supports previous researches.

Keywords: biodiesel, data binning, diesel, emissions, on-road testing, non-parametric statistical tests, VSP.

CHAPTER 1. INTRODUCTION

1.1 Background

Road transportation is a major contributor to air pollution both on local and global scale. However, vehicular emissions are inadequately understood and quantified because of large variations in individual vehicle emissions with changing operating conditions, engines, and fuels. In general NO_x, HC, CO, CO_2 and PM emissions are considered where NO_x and HC contribute to formation of ozone and consequently smog, CO forms carboxyhemoglobin (inhibits the oxygen carrying capacity of oxygen). PM gives rise to respiratory problem such as bronchitis. CO_2 is responsible for global warming and climate change. To regulate vehicular pollution, two sets of emissions standards, Tier-1 and Tier-2, have been defined for light-duty vehicles in the CAAA of 1990. Tier-1 standard was phased-in progressively between 1994 and 1997, while Tier-2 had a phase-in implementation schedule from 2004 to 2009 (CBSII, 2008).

To assess the impact of these pollutants, appropriate assessment of the amount of emissions produced is necessary. However, incomplete understanding of emissions has led to contradicting results (Ropkins et al., 2007). This entails more research on vehicular emissions for various combinations of fuel, engine and operating conditions. The present research pertains to biodiesel emissions from transit buses with both Tier-1 and Tier-2 certified engines.

Reducing emissions from heavy duty diesel engines is one of the most important air quality concerns of the globe (EPA, 2008). The consequences of climate change due to release of

CO_2 is also a matter of worry. Even if hybrid and cleaner engines are being manufactured, millions of diesel engines already in use would continue to increase the concentration of pollutants (primarily NO_x and PM) in the atmosphere. This makes it even more necessary to have cleaner fuels which can be used in these existing heavy duty engines. Another concern for the road vehicle users is depleting fossil resources because of which there has been a continuous attempt to come up with an alternative source of energy. As ethanol is being considered for gasoline, biodiesel is considered an alternative to regular diesel.

1.1.1 Biodiesel

Vegetable oil was once seen as the economic alternative for diesel. Tests revealed that engines would fail prematurely when operating on fuel blends containing vegetable oil. But engines burning vegetable oil after trans-esterification with alcohols exhibit no such problem and even perform better by some measures than using diesel (Anthony, 2007). The technical process used in the formation of biodiesel is as follows:

Vegetable oil + alcohol (catalyst – NaOH) => Glycerol + Esters (Biodiesel)

1.1.1.1 Advantages of biodiesel

Biodiesel is biodegradable, non-toxic (in small quantity), non-hazardous fuel with high cetane number and high flash point (listed as combustible, not flammable). Biodiesel increases fuel lubricity, even when present in very small quantity, as shown by using a variety of bench scale test methods (NBB, 2008). National Renewable Energy Laboratory

(Sheehan et. al, 1998) estimated that use of soybean B100 in urban transit buses reduced net carbon dioxide emissions by 78.45 percent.

1.1.1.2 Disadvantages of biodiesel

Certain compounds in biodiesel can form crystals in the fuel at low temperature and this can cause undesired effects like plugging of fuel filters so that fuel cannot travel to the engine. The higher the pour point, greater is the scope for crystal formation in cold climate. Pour point is lower than cloud point. The cloud point and pour point of biodiesel are higher than conventional diesel fuel (Chetwynd et al., 2005). Cloud point of animal-fat diesel is still higher than that of soy diesel (Graboski et al., 1998). While biodiesel decreases the emissions of other pollutants, it increases the NO_x emissions (Fernando et al., 2006). For every 10 vol% of biodiesel that is blended into diesel fuel NO_x increased by 1% (EPA, 2002; Graboski et al., 1998). On the life cycle basis, research shows 13.35% increase in NO_x when the buses run on biodiesel as opposed to petroleum diesel (Agarwal, 2007). An important problem associated with biodiesel is poor oxidative stability. This is particularly true for soy-based biodiesel which has considerably higher levels of polyunsaturation (Wang et al., 2007).

1.1.2 Why consider B10 or B20?

Biodiesel has properties similar to mineral diesel, so it can operate in compression ignition (diesel) engine with very little or no engine modifications. Studies show that B20 has comparable fuel consumption, horsepower, torque, and haulage rates as conventional diesel fuel (Agarwal, 2007). CyRide, the transit bus agency, has been using B10 and not it was considering B20. The present study compares emissions from B0 (regular diesel) with that from B10 and B20. The concerns of global warming and air plooution are making it important to evaluate the emissions benefits of biodiesel especially the widely used blend – B20.

1.1.3 The Mechanics of Exhaust Emissions

Fuel combines with air (contains N2) and undergoes incomplete combustion producing byproducts of HC, CO, CO_2, and NO_x along with O_2 and CO_2 (Heywood, 1988). Air to fuel ratio (a/f ratio) is an important factor which determines the amount of pollutants produced during combustion. Typically, lean mixtures (high a/f ratio) produces higher NOx (particularly at hot conditions) and lower CO and HC emissions because of incomplete combustion. High power demand (high acceleration and load) which is associated with low a/f ratio, gives rise to higher CO and HC emissions while lower NO_x emissions (EPA, 2007). Emission control strategies focus on optimizing a/f ratio to its most efficient level (stoichiometry). Formation of PM is also associated with incomplete combustion and low a/f ratio. Generally, diesel PM consists of soot formed during combustion, heavy hydrocarbons condensed or adsorbed on the soot, and sulfates. The diesel combustion results in fuel-rich zones generating carbon particulates which adsorb organic compounds and sulfuric acids during the exhaust gas cooling and dilution process. A significant percentage (up to 40%) of heavy-duty diesel PM emissions come from the hydrocarbons which originate from the un-burnt lubricating oil. Any condition that either reduces the availability of oxygen (wither through poor mixing or operation at low a/f ratio), or the time for soot oxidation (such as retarding the combustion timing) can cause a very large increase in soot emissions (Faiz et al., 1996). In summary, vehicle emissions is greatly affected by a/f ratio which is highly variable. Figure 1.1 shows variation in emissions even during idling when the vehicle is not in motion. This depicts that formation of emissions is a complex phenomenon.

1.2 Motivation for this work

Biofuels have been suggested as a solution to reduce transportation-related air pollutants and global warming. However, emissions from biofuels, such as biodiesel, are not well understood. Combination of various factors like engine technology, vehicle age, vehicular maintenance, fuel, past and present operating conditions, climate and driver characteristics are highly correlated to emissions and should be evaluated to understand emissions better (Vijayan et al., 2008). Due to insufficient data biodiesel impact of NO_x has been inconclusive. Studies on biodiesel emissions (NO_x, in general) have often inconclusive and, sometimes contradictory (Hansen and Jensen, 1996;McDonald, 1995; Grägg, 1994). This is due to insufficient data. (EPA, 2002). More data collection and research is needed to assess the effects of different biodiesel blends on different engines (EPA, 2002; McCormick et al., 2006a). The present research would bring in new light on the use of biodiesel on transit buses in terms of effectiveness of reducing emissions of pollutants and green house gases (GHG) especially CO_2.

1.3 Research objective and Problem statement

Research indicates that biodiesel has benefits in terms of reducing emissions. The truth of this statement was considered by testing the given buses and fuel-blend combinations. The main objective of this research was to evaluate any significance change in emission rates when the transit buses are fueled with biodiesel as compared to regular diesel. To minimize the effect of variability inherent in on-road data collection, the emissions were divided into bins. The hypothesis tested was that the use of biodiesel would result in statistically significant reduction in emission rates of NO_x, HC, CO, CO_2 and PM. A deductive approach was taken to solve the problem.

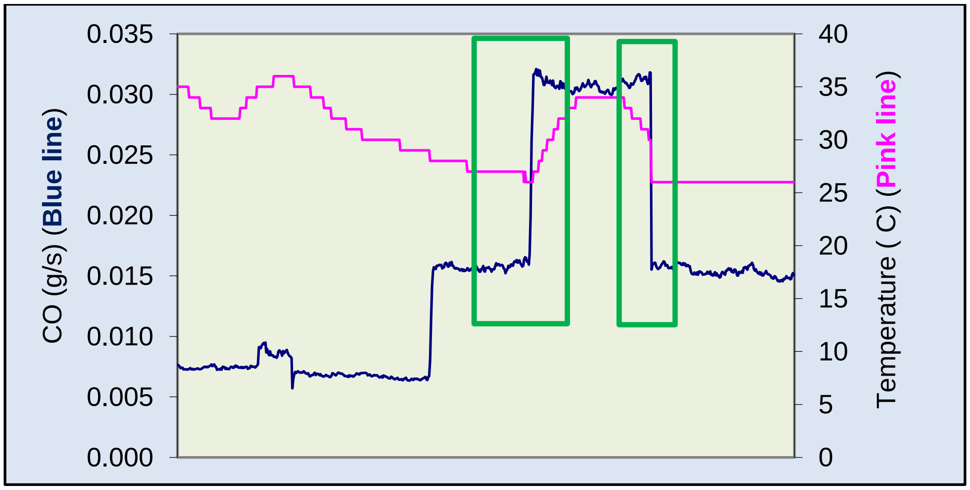


Figure 1.1: Variability during idling (emissions are correlated with change in temperature)

1.4 Thesis Organization

This thesis is divided into five chapters. The first Chapter introduces the background of the research, discussion on biodiesel (whose emissions are being evaluated in this work), and the mechanics of exhaust emissions. It also describes the motivation and contribution of this work and defines the research objective. The second chapter summarizes previous research on biodiesel emissions testing and analysis. Data collection methodology, study design and preparation of the final database are described in Chapter three. The results of data analysis are documented in Chapter four. The final Chapter summarizes the results of the analyses, discusses the limitation of the work, formulates conclusions, and presents recommendations for future research.

CHAPTER 2. LITERATURE REVIEW

This chapter deals with a review of various existing research works on emissions ranging from simple evaluations to development of models to explain variations of emissions. The following section elaborates research done on biodiesel emissions using dynamometer testing and PEMS.

2.1 Biodiesel Emissions testing

EPA (2002) performed a thorough analysis of the emission impacts of biodiesel using publicly available data collected prior to October 2002. They did a statistical analysis of the relationship between pollutants and biodiesel blends. No test engine was equipped with exhaust gas recirculation (EGR), NO_x adsorbers, or PM traps. About 98% of the vehicles consisted of 1997 or earlier model year engines. Biodiesel impacts on emissions varied depending both on the type of biodiesel (soybean, rapeseed, or animal fats) and regular diesel to which the biodiesel was added. Findings on non-road engines and light-duty vehicles could not be extended to heavy duty diesel engines. Based on engine dynamometer testing, B20 biodiesel leads to a small increase (i.e. 2 percent) in tailpipe NO_x emission rate, but decrease of 10 percent for PM, 11 percent for CO, and 21 percent for hydrocarbon (HC) tailpipe emission rates (EPA, 2002).

Mazzoleni et al (2007) conducted a field study on a fleet of 200 school buses to evaluate the effects of biodiesel use on gaseous and particulate matter fuel-based emission factors under real-world conditions using B0 and B20. They measured the emissions using a cross-plume vehicle exhaust remote sensing system (VERSS). Particulate matter emissions from school buses significantly increased (up to a factor of 1.8) with B20. This was because of high concentrations of free glycerin and reduced flash points in the B100 parent fuel. These were not in compliance with the U.S.A. ASTM D6751 biodiesel standard (finalized in December of 2001). Cold-start CO emissions and hot-stabilized HC emissions were also found to be higher with B20 while other tailpipe emissions (NO_x and PM) were not significantly different.

Ropkins et al (2007) compared emissions from B0 with that from B5. Using an On-Board Emissions Measurement System (OBS- 1300), data were collected on multiple replicates of three standardized on-road journeys - (1) a simple urban route; (2) a combined urban/interurban route; and, (3) an urban route subject to significant traffic management. Replacing diesel with a B5 resulted in significant increased in both NO_x emissions (8–13%) and fuel consumption (7–8%). Other emissions (CO, CO_2, and HC) did not differ significantly. Emissions were found to be more sensitive to journey/ drive cycle than to fuel.

Schumacher et al. (2001) compared emissions from two 60 DDC engines fueled with B0 and several blends of biodiesel (B20, B35, B65 and B100). Exhaust emission, fuel related properties and power/performance characteristics were studied while running the vehicles on the United States Code of the Federal Register 40 (CFR 40) transient testing procedures. Results show that use of B20, B35, B65 and B100 increased fuel consumption by 1.3%, 2.3%, 7.1%, and 12.7% respectively. NO_x emissions increased while THC, CO, and PM decreased with the percentage of biodiesel in the fuel. The increase in NO_x ranged from 1%–11.6% whereas reduction in CO ranged from approximately 9%–47%.

Knothe et al. (2005) did an exhaust emission testing on heavy-duty 2003 six-cylinder 14 L diesel engine supported by exhaust gas recirculation (EGR). Neat hydrocarbon fuels (B0) were tested in comparison to neat methyl esters including methyl soyate (commercial biodiesel, B100). They reported a change of -33%, -24%, +12% and -78% for NO_x, HC, CO and PM respectively when B100 was as compared to B0.

Farzaneh et al. (2008) investigated the impact of (biodiesel fuel) B20, cruise speed, and average acceleration rates on oxides of nitrogen (NO_x), hydrocarbons (HC), carbon monoxide (CO), and carbon dioxide (CO_2) emissions from diesel school buses. Result showed that NO_x and CO_2 emissions were not significantly different when biodiesel instead of diesel was used. On the other hand, HC emissions increased by 25.4- 28.8 % while CO emissions decreased by 23 - 33 %.

An emission testing study (Frey and Kim et al. 2005) was conducted on dump trucks with B0 and B20 using a portable emissions measurement system (PEMS). Results showed that average fuel use and CO_2 emission rates were approximately the same for the two fuels, but average emission rates of NO, CO, HC, and PM decreased by 10, 11, 22, and 10 percent, respectively, for B20 versus diesel. Emission rates from PEMS were consistent with that obtained through engine dynamometer tests. Results seem to be contrasting other studies.

Frey et al (2006) used a portable emissions monitor to measure emissions in 12 dump trucks. They tested each vehicle with B-20 comparing the emissions with that from petroleum diesel. A reduction of 1.6% for NO_x, 19% for CO, 22% for PM and 20% for HC was reported with use of the B20.

Vijayan et al. (2008) conducted a research on evaluating the effect of various factors on emissions from a transit bus running on diesel and 20 % biodiesel (or B20). They measured the emissions both at idling and at non-idling conditions. Emission comparison for buses showed that engine parameters such as engine rpm, maintenance history, engine temperatures, and engine technology influenced the emissions to a greater degree as compared to type of fuel used. This entails separate tests for each fuel, engine and environment configuration. For the same operation time, vehicles in idling mode produced higher average concentrations of carbon monoxide (CO), nitric oxide (NO), nitrogen dioxide (NO_2) and sulfur dioxide (SO_2) as compared to non-idling conditions. Further higher engine temperature resulted in a decrease in the concentration of these emissions by up to 30-42 %. Preventive maintenance reduced these emissions by 15-20 %. This was expected as higher temperature support combustion especially for NO_x. Higher emissions also corresponded to higher rpm (a measure of engine load).

The National Renewable Energy Laboratory (NREL, 2005) has evaluated the in-use performance of buses operating on B20. Out of a total of nine buses, four were fueled with B0 and the remaining with B20. A comparative study was done in terms of engine performance, component wear, fuel economy, vehicle maintenance, and emissions. No significant difference in fuel economy was observed between the two groups in on-road measurements. On the other hand, laboratory test results showed a decrease of 4 %, 29%, 24 %, 18 % and 4% in NO_x, HC, CO, PM and fuel economy respectively when using B20.

Frey et al. (2008a) also compared real-world emissions from non-road vehicles fueled with petroleum diesel (B0) and B20. Both time-based and fuel-based emission factors were estimated. Time-based emission factors were found to constantly increase with respect to engine manifold absolute pressure (MAP). Based on the study with limited number of vehicle, newer vehicle showed substantial emission benefits as compared to older ones. Emissions from loaded engines showed less variability in fuel-based emission rates than time-based emission rates. The average NO_x emissions showed insignificant 1.8 % decrease while average opacity (measure of PM), HC and CO emissions were found to significantly decrease by 18, 26, and 25 % respectively. On a fuel-basis, emission rates were found to be highly sensitive to idle versus non-idle operation.

Frey et al. (2008b) developed speed-acceleration modal emission rates for NO_x, HC, CO, CO_2 and PM from single rear axle and tandem dump trucks. Sensitivity analysis in terms of chassis type, vehicle load and fuel type was performed. CO_2, PM, NO and HC emissions were lower and CO emissions were higher for single rear axle trucks as compared to that for tandems. On average basis, PM, CO and HC emissions decreased significantly while no significant conclusion could be made for NO emissions. Increase in vehicle load increased the emissions by 34 % and 36 % for diesel and biodiesel respectively. In terms of fuel, with B20 the vehicles produced lower link-based emission rates of PM, NO, CO and HC as compared to diesel.

McCormick et al. (2006b) did a study to test whether emissions significantly varies when testing the entire vehicle rather than just the engine on a heavy-duty chassis dynamometer. They reviewed various chassis testing studies as well as portable emissions measurement system (PEMS) studies comparing B0 emissions with that of B20. From the recent published engine testing studies on B20 (comparing with B0), it was found that average change in NO_x

was -0.6% ± 2.0% (95 % confidence interval). Particularly for soy-derived biodiesel the average change ranged from 0.1% ± 2.7%. (95 % confidence interval) The vehicle tested comprised of eight heavy-duty diesel vehicles including three transit buses, two school buses, two class 8 trucks, and one motor coach. The PM, CO and HC emissions were found to decrease by 16 %, 17% and 12% respectively. Based on the published results and this study, it was found that there was no difference in emissions between engine and chassis testing. For NO_x emissions, it was found that individual engines may show a decrease or increase but on average there appears no change. EPA (2002) reported a small increase in NO_x emissions when using B20 instead of B0. McCormick et al. (2006b) argued that the results presented by EPA's 2002 report were biased in that the data included in the review pertained to engines from single manufacturer (DDC). Result specifically for transit buses showed NO_x reduced by 5.8% for one bus and by 3.9% for another. PM emission reductions ranged from 15 to 20% (90 % confidence). They recommended real-time data collection and analysis considering the effect of vehicle speed and horsepower and the rate of change of both (speed and horse power).

The following section deals with numerous methods used to analyze emissions data especially those obtained from on-road testing.

2.2 Evaluation of emissions using VSP

VSP, a surrogate for power demand, is generally defined as power per unit mass of the vehicle and is a function of vehicle speed, road grade and acceleration (Zhang, 2006). This section presents studies which used VSP for comparing emissions.

Frey et al. (2007) did a comparative study of fuel consumption and implication on emissions from diesel- and hydrogen transit buses. VSP based fuel modal averages rates were estimated and the comparison was based on these values. In comparison to diesel fuel consumption rate, hydrogen fuel consumption rate was found to be less sensitive to VSP as compared. It was found out that passenger load has a significant effect on fuel consumption only at middle and high-speed ranges. Passenger load had almost no effect on fuel consumption under very low speeds (<= 10 km/h).

Song et al. (2008a) studied the emission of a light duty gasoline vehicle around a toll station using a PEMS. Emissions data on both electronic toll collection (ETC) lanes and manual toll collection (MTC) lanes were compared. VSP was estimated and [-2, 2] was found to be a critical interval in the driving modes as well as emission rates. It was found that finer binning approach increase the accuracy of emission estimates.

Song et al. (2008b) developed a practical model to determine the level of fuel consumption for a traffic network as a function of real world driving activities and VSP. Analysis shows monotonic increase in fuel consumption rate with positive VSP. With negative bins, the fuel consumption rate remains somewhat low or constant. 97.7 percent of the data fell into the VSP interval of -20 to 20 kW/ton, which contribute 95.5 percent of the total fuel consumptions. The analysis was conducted within this interval.

Huai et al. (2005) estimated on-road NH_3 emissions from a light-duty vehicle using VSP binning as methodology as proposed by EPA’s MOVES. Piecewise linear regression models were estimated for each vehicles. Piecewise linear regression curve consisted of two linear slopes, an intercept, and a break point. This methodology was adopted because the variation in VSP was found to be different at lower values than at higher values. For a given bin, the data were averaged. Otherwise the large number of data points at low power would drive the regression without accounting for the behavior at higher VSP. The developed model was used to estimate the current NH3 emission inventory in the South Coast air basin.

2.3 Summary

In general, research works use both dynamometers and PEMS to measure and analyze NO_x, HC, CO, CO_2 and PM emissions and fuel consumptions. Both on-road and off-road tests on biodiesel emissions have been performed with special emphasis blend B20. Although there were some inconsistencies (particularly with respect to NO_x emissions) and wide variation in the findings, in general, biodiesel was reported to be cleaner than conventional diesel. Sometimes due to insufficient data, it was difficult to draw any conclusion as seen in case of NO_x (McCormick et al., 2006a; EPA, 2002). Few found newer engines to be cleaner than the older tier engines, while some studies reporting insignificant changes (Vijayan et al., 2008). Some researches implemented the VSP binning strategy and successfully compared emission rates. In this present study, biodiesel emissions were analyzed using VSP.

CHAPTER 3. DATA COLLECTION AND DATA PREPROCESSING

3.1 Emissions testing methodologies

The three most common methods for measuring vehicular emissions are – dynamometer testing, on-road remote sensing (RS), and using a portable emission measurement system (PEMS).

3.1.1 Dynamometer testing

Dynamometer testing is a standard laboratory emissions testing cycle defined by the EPA to provide simulated road loading of either the engine (engine dynamometer, Figure 3.1) or full power-train (chassis dynamometer, Figure 3.2). The advantage to dynamometer testing is that it allows repeatability and a controlled environment for testing. However, it suffers from inability to represent actual driving conditions and operation. The equipment is expensive and it is time consuming to test a large number of vehicles with this method.

Figure 3.1: Engine Dynamometer (source: http://www.cert.ucr.edu/photos/smHDDLTestFacility.jpg)

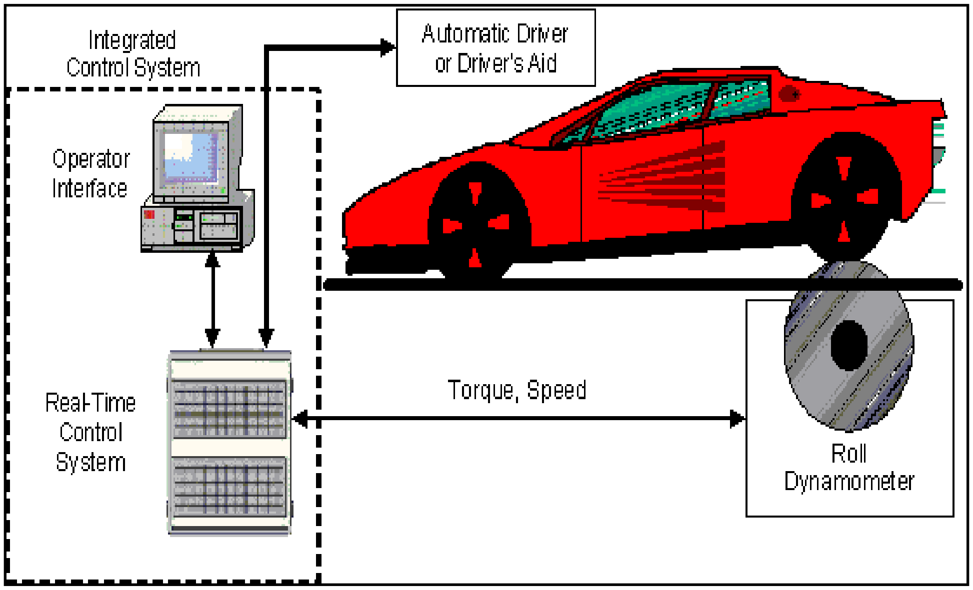


Figure 3.2: Chassis dynamometer testing (source: http//zone.ni.com)

3.1.2 Remote sensing

The remote sensing system uses an infrared (IR) absorption principle to measure emissions. It operates by continuously projecting an IR beam across a roadway (Figure 3.3). The unit also has a freeze-frame video camera and computer to record a color image of the rear of the tested vehicle, including the license plate. This allows the system to store emissions information for each vehicle, based on the license plate number (CABQ, 2008). Remote sensing enables the exhaust emissions of a motor vehicle to be measured as the vehicle passes by on the road. Non-dispersive infrared (IR) spectroscopy is used to measure concentrations of CO and HCs while dispersive ultraviolet (UV) spectroscopy employed in measuring NO_x.

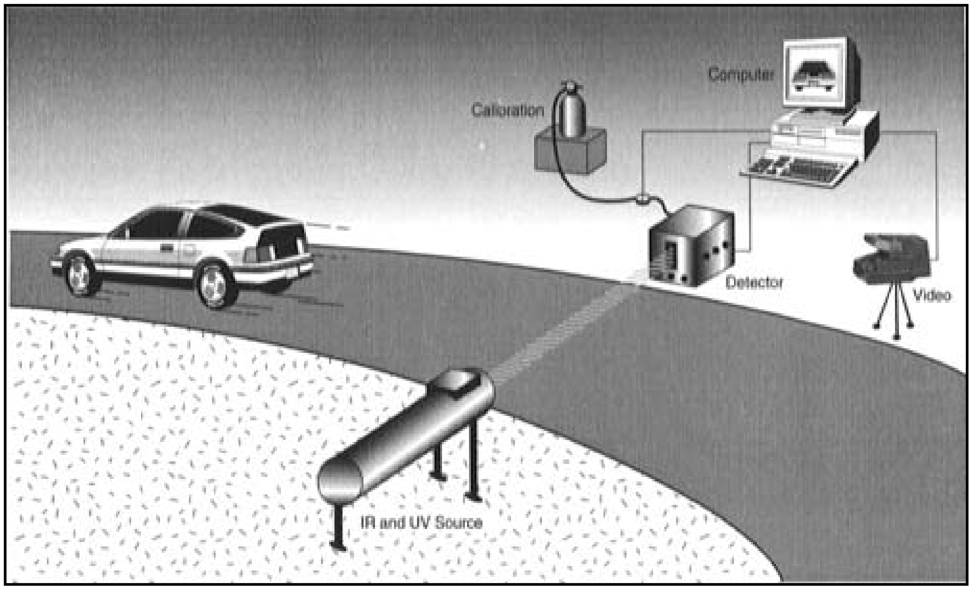


Figure 3.3: Typical layout of a Remote sensing device (Bishop, 1996).

Remote-sensing facilitates emissions measurement from a large number of vehicles simultaneously. The device is portable and can evaluate emissions directly on-road. However, since it is placed at a single location on a roadway, it only measures one point in time and does not account for vehicle speed and acceleration, air conditioning use or other vehicle parameters. Also, it is difficult to use this method for measuring emissions on multiple lanes with significant traffic flow, such as on arterials or freeways.

3.1.3 On-road testing using a portable measurement device

On-road testing is a real-time data collection methodology which involves measurements on the vehicle operating on an actual route, unlike dynamometer testing which assumes a speed profile in a laboratory setting. In the present study, on-road testing was performed using a portable emissions measurement system (PEMS in Figure 3.4). In this case, emissions were directly sampled from the tail pipe (Figure 3.5) of an operating vehicle into a system which analyses the exhaust and records the concentrations of the various emissions. Everything from the data analyzer to storage is integrated into a PEMS unit.

Figure 3.4: The PEMS (OEM2100^{TM} Montana System)

Figure 3.5: Extracting emission from the tail-pipe

3.1.3.1 Importance of on-road testing

Only on-road emissions data can capture emissions on a spatial dimension (Frey et al., 2002) such as on specific congested corridors and intersections. Traffic improvement at a given corridor/intersection cannot be evaluated with driving cycle-based models (National Research Council, 2000). Frey et al. (2002) pointed out that development of reliable new generation emissions models would require data both from real-world and laboratory measurements. The effects of different fuel formulations can be evaluated by collecting data for vehicles that use different fuel formulations or fuels. This is useful for the present research where the emissions from different fuel formulation have been tested on a real-time basis.

A PEMS provide the advantage of real time emissions with ability to perform micro-scale study (evaluating emissions from a single vehicle). Emissions study as a function of road grade and environmental condition and driver variability (Ahn et al., 2002; Frey et al., 1997) can be affectively done using PEMS. Research pertaining to investigation of the effect of signal timing on vehicle emissions (Unal, 2003), quantification of vehicle emissions hotspots (Unal, 2004), analysis of high occupancy vehicle lanes (Rilett, 2004) and measurement of off-highway construction equipment emissions (Vojtisek-Lom, 2003) have been successfully carried out using PEMS (OEM2100^{TM}). In addition, portability allows quick instrumentation and ability to perform tests at any place such as a hilly region. The system is designed to perform emission testing on any type of vehicle be it on-road or non-road, road or construction vehicle/equipment.

3.1.3.2 Limitations of on-road testing

On-road testing suffers from inherent variability due to many uncontrolled parameters (driver, road type and road curvatures) and lack of repeatability. Besides, numerous challenges in the form of equipment malfunction, adverse weather conditions, bus maintenance issues, running out of fuel, etc can seriously affect the data. Careful selection of variables and analysis methodology and taking precautions can take care of the variability to some extent but cannot eliminate it completely.

3.2 Description of the Equipment used

The measurement was carried out using OEM-2100, Montana system, a portable emissions measurement system (PEMS), manufactured by Clean Air Technologies International Inc. It comprises of an operating software, data acquisition hardware for engine data, gaseous pollutants, particulate matter (PM), and a global position system (Frey and Kim et al., 2005).

3.2.1 Raw variables measured

The system comprised of two parallel system of five-gas analyzers, a PM measurement system, an engine sensor array (measures rpm, manifold absolute pressure (MAP), and intake air temperature), a global position system (GPS), and an on-board computer which synchronizes the emissions, engine parameters and GPS data (location, speed, acceleration). HC, CO and CO_2 are estimated in using non-dispersive infrared (NDIR) analyzer. NO_x is measured by electrochemical cell whereas particulate matter (PM) concentration is quantified by means of a laser light scattering measurement subsystem. The sampling rate is 1 Hz. In raw data, the concentration of NO_x and HC are obtained in ppm, CO, CO_2 are expressed as % while PM is recorded in mg/m^3.

3.2.2 Estimation of concentration

The exhaust flow is estimated using the instantaneous vehicle speed, engine rpm, intake air temperature, intake air pressure and known parameters of the engine, such as engine displacement. This calculation is proprietary, but generally involves mass balance (CATI, 2007). Then using this intake air mass flow with the measured composition of intake air and exhaust air, and user-supplied composition of fuel, a second-by-second exhaust mass flow is calculated (Figure 3.6). Finally, NO_x, HC, CO, CO_2 are recorded in g/s while PM in mg/s.

3.2.3 Calibration

The gas analyzers were calibrated periodically (initially weekly and then daily because of large percentage of errors encountered due to heating up of the equipment) with a standard gas-cylinders provided by Parts Queen. There is a phenomenon called "zeroing" by which the two analyzers alternatively samples the ambient air (a reference gas) in order to prevent instrument bias. At any point of time, either one of the two analyzers samples the exhaust or both of them. When both the analyzers operate, the values are averaged.

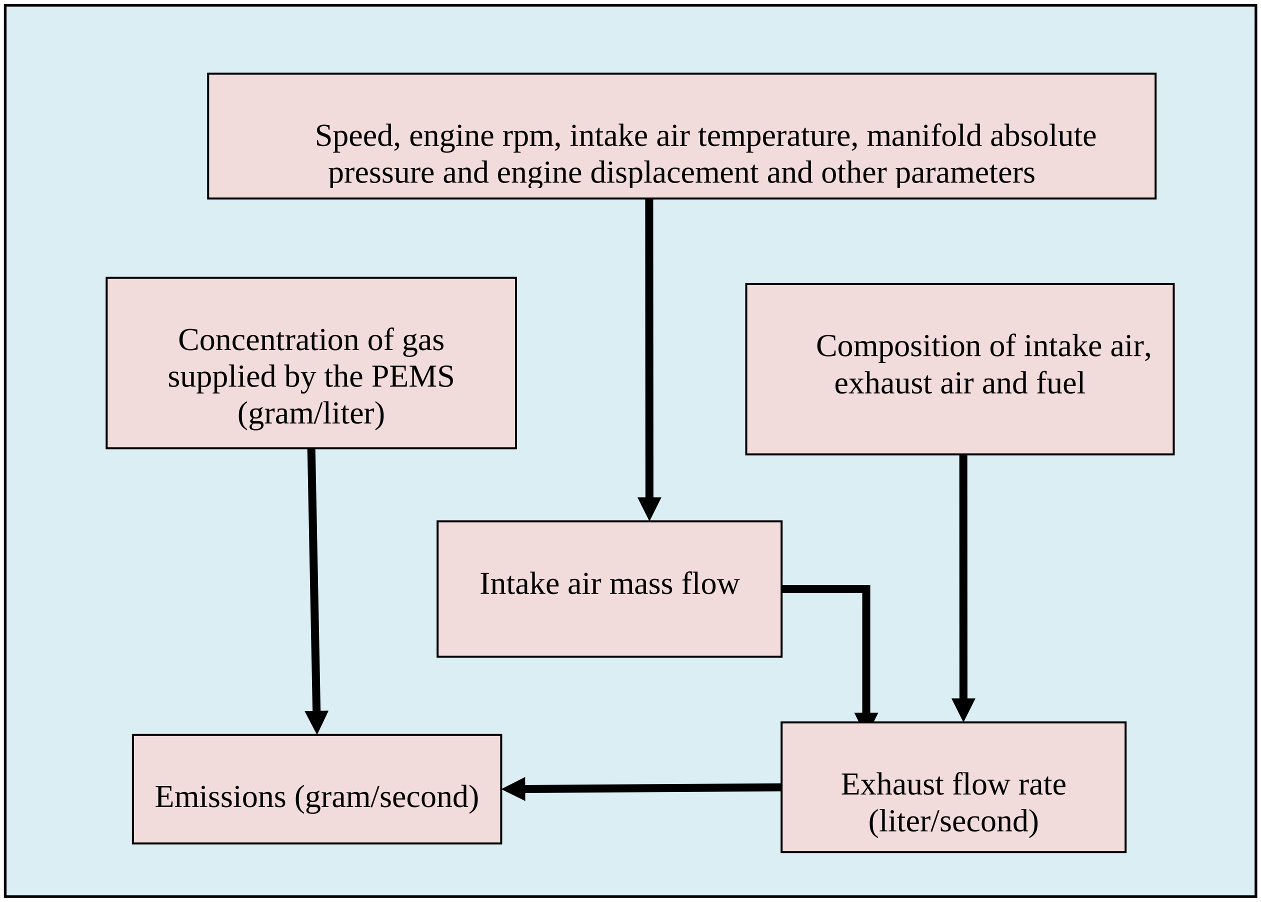


Figure 3.6: Block diagram showing how the concentration is estimated

3.2.4 Installation

It takes about 10 to 20 minutes to install the equipment on the vehicle. This task includes safe and convenient placement of the equipment, establishing a proper power source (in this study external battery was used), routing and fixing exhaust lines and placing the engine sensors on the respective parts of the engine system. Unless we changed the testing vehicle, the sample lines remained in the bus over night. Therefore, it took only five minutes to start the next day of testing with the same vehicle.

3.2.5 System Maintenance and trouble shooting

We interacted with CATI on a regular basis whenever we faced any problem with the functioning of PEMS. Buses were used for testing whose inspection and maintenance were handled by CyRide (local transit agency).

3.2.6 Validating OEM with dynamometer testing

Three light-duty vehicles (1997 Oldsmobile sedan, 1998 Plymouth Breeze and 1997 Chevy Blazer) were tested by (New York Department of Environmental Conservation (DEC) laboratory) using the I/M 240 and NYCC driving cycles (Rouphail et al., 2001). Emissions from two light-duty vehicles, a Mercury Grand Marquis and a Dodge full size pickup truck, were tested by EPA using both OEM2100^{TM} and a dynamometer equipment over FTP, US-606, NYCC, and FWY-HI driving cycles at Ann Arbor (MI). Comparison of the OEM 2100 and laboratory dynamometer results showed good correlation (R^2 = 0.90 to 0.99). The standard error was less than ten percent of mean emissions for all of the pollutants except hydrocarbon which had a standard error of 24 percent of mean emissions (Unal et el., 2001).

3.2.7 Instrument specifications

The dimensions of the equipment (LxWxH) are 23” x 18” x 9” (58cm x 46cm x 23cm). It weighs less than 38 lbs (< 21 kg) and uses a 12-14 V DC (12 V nominal), 6-9 Amperes power source. An external battery was used in this study as power source. The sample flow can be adjusted to 5 liters/minute nominal for each gas analyzer and 3.8 – 4.0 liters/minute for the PM sampler.

3.2.8 Operating conditions

For ambient conditions, the operating temperature and humidity are 25-100 ^oF, 0-90% RH, non-condensing and those at the instrument location are 40-95 ^oF, 0-90% RH, non-condensing.

3.2.9 Equipment warm-up

This is the time for which the equipment should be switched on before the actually tests. Warming-up is important for the following two reasons: (1.) it stabilizes the gas analyzers and allows for more accurate readings with minimal drifting, and (2.) prevents the gas phase constituents in the sampled exhaust from condensing onto the analyzer optics (CATI, 2007). The typical duration is 45 minutes although longer time is recommended for colder ambient conditions. Warming-up can also be done indoors before bringing the equipment to the vehicle but in that case it is recommended that there be a proper arrangement for ventilation.

3.2.10 System Placement

This section describes how the equipment and the engine scanner were set up.

3.2.10.1 The equipment

The system was placed at the back seat of the bus so that the passengers can safely enter and exit the bus with inconvenience (Figure 3.7). It was fastened to the seats to protect for losing connection or falling down while the bus was in operation.

Figure 3.7: The PEMS

Figure 3.8: Sample lines connected to the tailpipe of the bus

3.2.10.2 The sample lines

The sample lines (Figure 3.8) were connected to the tail-pipe of the engine exhaust present at the back of the bus.

3.2.10.3 The engine sensors

The engine sensor has the three components – an optical tachometer (measures rpm) a temperature probe (thermocouple) and a pressure transducer. The optical tachometer was placed on a magnetic mount and was directed towards the crankshaft pulley which spun at the same rate as the engine. The optical sensor measured the rpm by detecting a reflective tape attached to the crankshaft pulley (Figure 3.9). The temperature probe (Figure 3.10) was attached to the engine intake air manifold, at the point just before the air enters the engine. The pressure transducer (Figure 3.11) was mounted on the intake line. Each of these was connected to the digital data acquisition port as shown in the Figure 3.12.

3.2.11 The Global Positioning System (GPS)

Second-by-second speed, acceleration, and position (latitude and longitude) were obtained from the GPS which was connected to the PEMS and affixed to the roof of the bus. Acceleration (mph/s) was estimated as the difference in consecutive speeds (mph). Belliss (2004) found that the speed obtained from a GPS is within reasonable accuracy (0.53 m/s or 0.19 km/h).

Figure 3.9: Optical tachometer for measuring rpm

Figure 3.10: Temperature probe

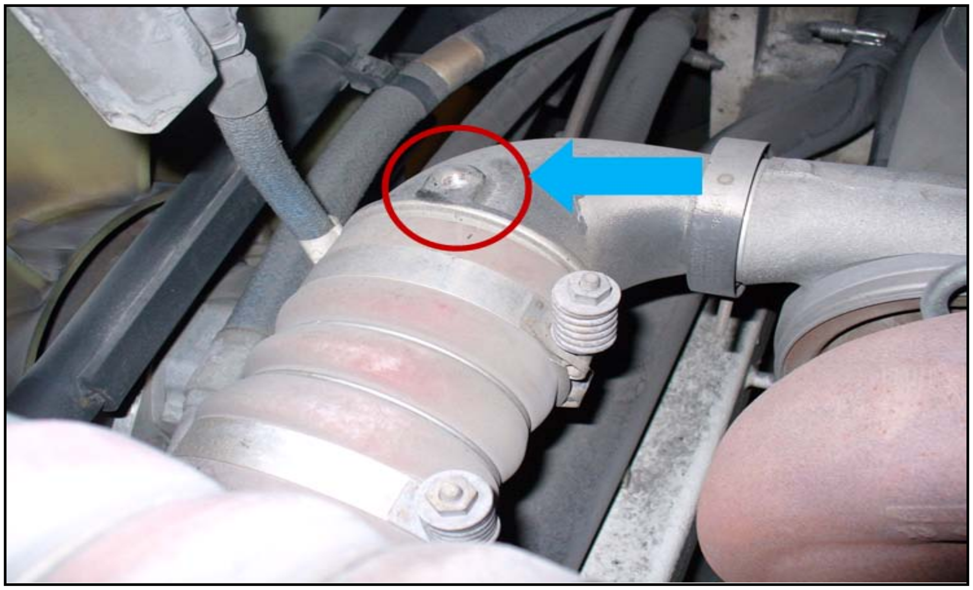


Figure 3.11: Site for pressure gage

Figure 3.12: Digital data acquisition port

3.2.12 Equipment Operation

After fixing the equipment appropriately making sure all the connections are proper, it is switched on and let run for few minutes and set for warming-up if not done before. While in operation, the equipment automatically samples the tail pipe exhaust, measures the concentration of the emissions and expel out the air back into the atmosphere. The emissions and engine data are stored in the memory. The equipment has a special feature called bag control which allows the data collector to label a particular test stage/vehicle activity so as to study/analyze it separately. Sometimes bad data may be tagged and eliminated from the dataset without spending time in identifying and separating the erroneous data. Similarly, idling events could also be separated and analyzed.

3.3 Study Design

This section deals with study design detailing the selection of vehicle, fuel, test-area, study period and various aspects of data collection. Frey et al. (2002) did a thorough job on identifying factors that influence on-road emissions measurements and developed strategies for data collection, quality assurance, reduction and vehicle activity (kinematic variables and engine parameters). Demonstration of analysis methods included macro-scale analysis of trip average emissions, micro-scale analysis of second-by-second emissions and meso-scale analysis of modal emission rates. This study forms the basis of methodologies for data collection and data cleaning used in the present study. Figure 3.14 shows a conceptual diagram of data collection.

3.3.1 Vehicle selection

Due to limited resources, only three buses (identification number – 971, 973 and 997) were tested. Figure 3.13 and Table 3.1 give the details.

Figure 3.13: CyRide Buses (source: http://www.cyride.com/about/Buses/001.htm)

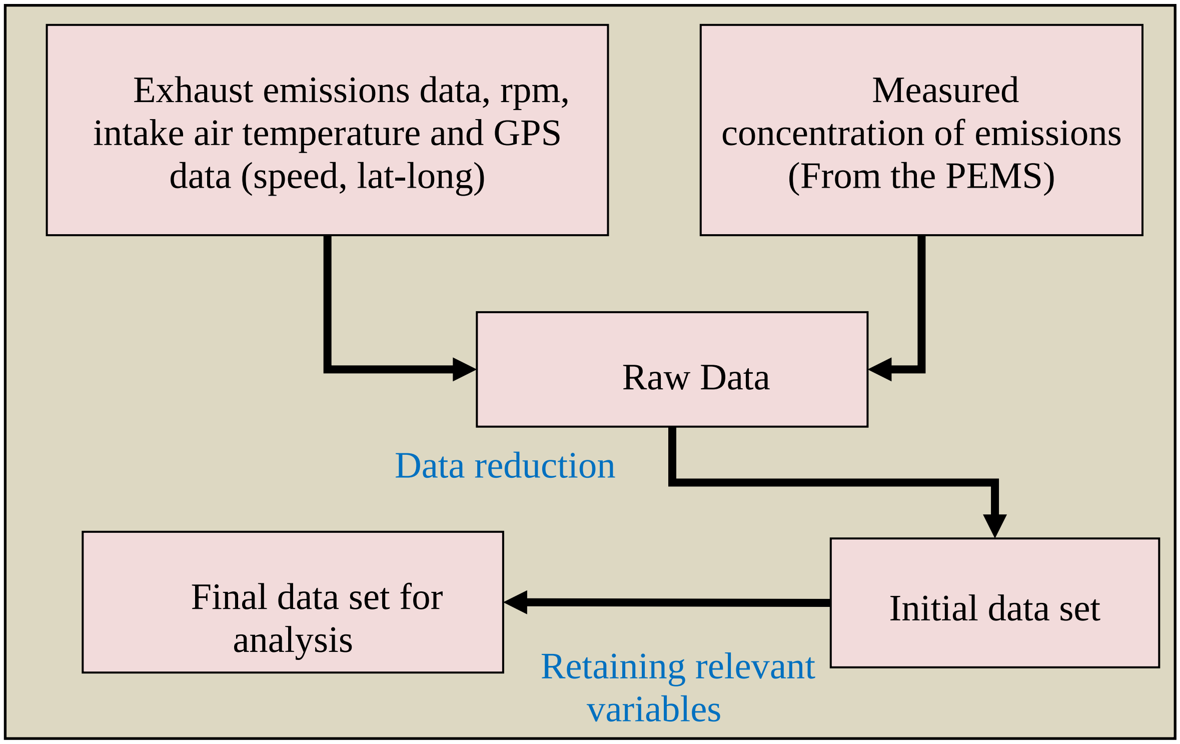


Figure 3.14: Conceptual diagram of data collection

Table 3.1: Bus specifications

Vehicle Identification Number	971 and 973	997
Engine standard (time frame)	Tier 1 (1998-2003)	Tier 2 (2004-2006)
Engine year	2002	2005
Vehicle model	V	VII
Vehicle make	Orion	
Gross weight	42000 lb	
Test weight	28000 lb or 12700.576 kg	
Cylinders	6	
Fuel delivery	electronic fuel injection	
Transmission	3 speed automatic	
Rated power	280 hp @ 1500 rpm	
Maximum torque	265 ft-lbs @ 1500 rpm	
Engine displacement	10.8	

3.3.2 Transit system

Buses (Vehicle identification numbers 971, 973 and 997) were provided by CyRide, the city bus system for Ames, Iowa. CyRide is in partnership with the city of Ames, Iowa State University, and ISU's Government of the Student Body. The transit system has 69 in-use buses and serves an average of 4,647,550 passengers as of Jun 08 (Cyride, 2008).

On a typical day, each bus was operated along a fixed combination of the four major routes (called study route) driven by a fixed driver. This study route covered the length and width of the city and included (1) Corridors with frequent-stops, (2) Arterial sections with high operating speeds, (3) Curved sections, and (4) Signalized corridors (Figure 3.15) which connects the campus to business area, apartments, schools, hospitals, malls and research centers. These are roads from 4 lane arterials to 2 lane roads with speed limit ranging from 25 to 45 mph. On few occasions, there were minor changes in routes because of road works and flood.

3.3.3 Study period

Long-term storage stability of diesel is commonly referred to as oxidative stability. Higher the oxidation stability, the longer is time the biodiesel would stay before reaching an out of specification condition (DOE, 2006). Therefore, the sooner the fuel is used the better it is for the engine and the environment.

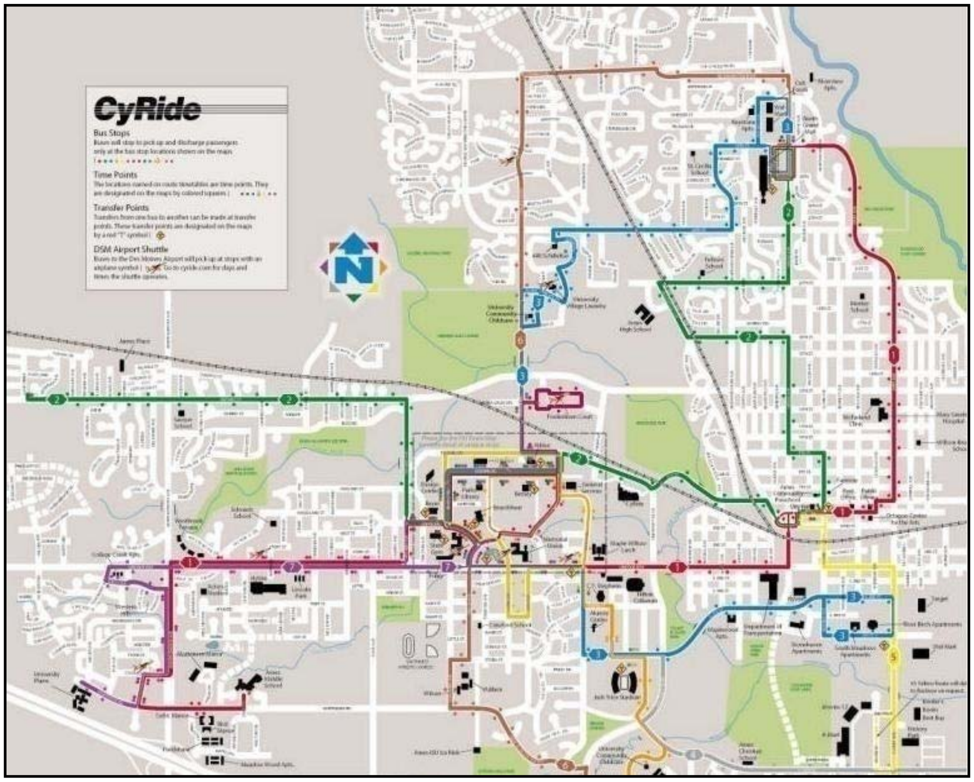


Figure 3.15: CyRide Bus network

CyRide does not use biodiesel during winter because it gels at low temperatures. Although the study was scheduled to begin in March’08, because of extreme weather it was postponed until the last week of April’08. The study continued till the first week of July’08. The old tier buses were tested during the spring (April’08 – June ’08) with the AC off. The Tier-2 bus was tested during the summer (June’08 – July’08) with the AC switched on. Study conducted over a long time and under different environment restricted any comparison of emissions across the buses. Tests were conducted between 7:30 am to 5:00 pm during the weekdays when the Iowa State University was in session.

3.3.4 Fueling

The buses were fueled at CyRide with blends of biodiesel provided by the Heart of Iowa Coop (meets ASTM standards). Some of the properties of the biodiesel used are presented in Table 3.2. All tests were carried out without any engine modification. Each bus was tested for regular low sulfur diesel (B0), 10 % biodiesel (B10) and 20% biodiesel (B20). Between subsequent fuel-replications, the fuel tank from each bus was emptied of the existing fuel to the extent it was practically possible. Each bus was tested on a particular fuel blend (B0, B10 or B20) for about 2-3 days before switching to the next blend. If the data for a particular day was found to be erroneous, the test for that fuel-bus combination was repeated before changing to the next fuel.

3.3.5 Driver

In general, a particular portion of the whole trip was driven by a particular driver. The drivers were cooperative in instrumenting the buses and informing the data-collector when the AC or heater was turned on. Further, they provided help in removing the equipment during the run when it had some technical problem.

Table 3.2: Fuel Specifications

Properties	Value
Relative Density @ 59 °F	0.85-0.90
Kinematic Viscosity @ 104 °F	1.9 – 6.0 mm^2/sec
Cloud point	32-54 °F
Oxidation Stability	3.0 hrs, minimum
Cetane number	47, minimum
Alcohol Control (A): Flashpoint	266°C, minimum

3.3.6 Data collected

3.3.6.1 Emissions, engine and spatial data

Data were recorded at an interval of one second. The emissions data included hot-stabilized NO_x, HC, CO, CO_2 (all in g/s) and PM (mg/s) while engine data comprised of engine rpm, intake temperature and intake pressure. Speed and latitude/longitude data were obtained from the GPS.

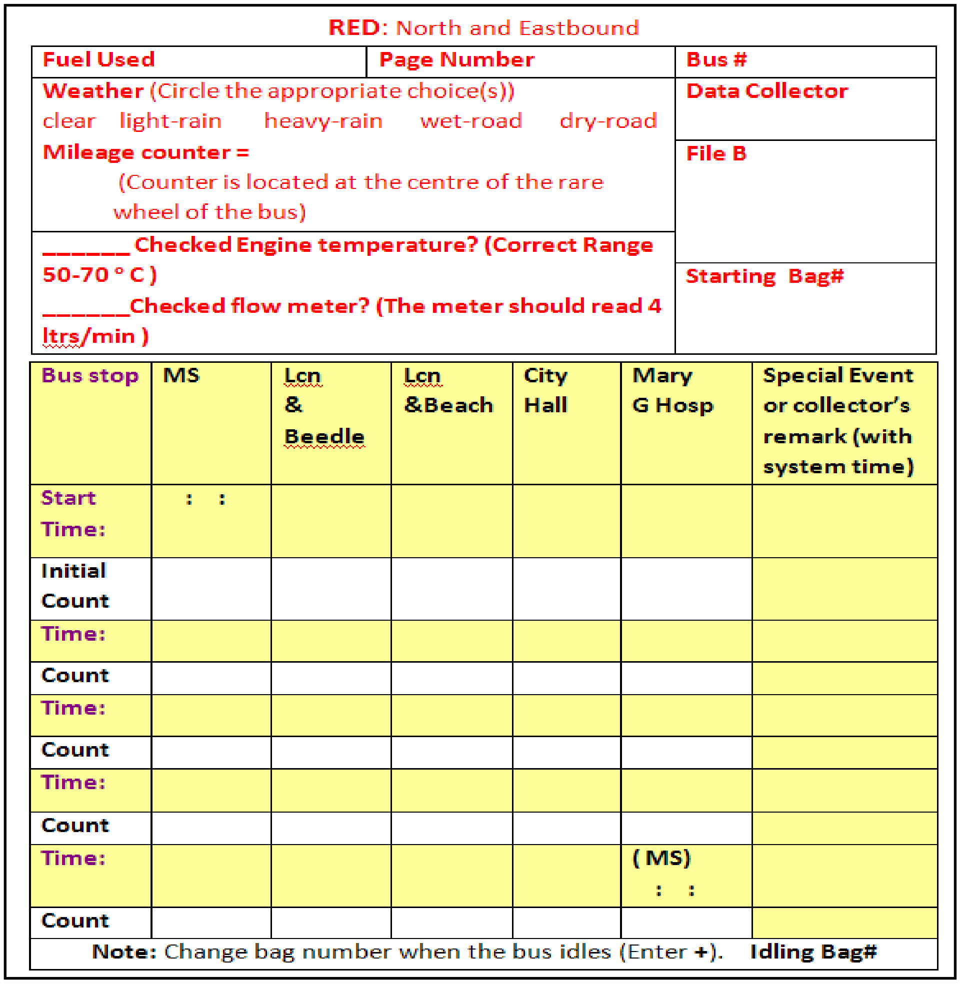
3.3.6.2 Other data

The total number of passengers (except the driver and the data collector which remained the same) present in the bus between each stop was manually counted and later entered into the database. The data collector would note down the time when the bus stopped. The passenger count was double checked using the time and the lat-long coordinate of the bus stop obtained from the GPS. EPA suggests 150 lb for an average passenger weight. A child was counted as a half-passenger. Figure 3.16 shows the final passenger data collection sheet.

In addition, road and weather conditions were was also noted down to make sure that conditions during all the tests remain identical.

3.4 Challenges faced during data collection

Any abnormality identified either during the course of testing or evaluating the raw data was flagged. The leading causes for abnormal data included analyzer “freezing,” inappropriate calibration (abnormal readings), failure of measuring devices (NDIR, in the



RED: North and Eastbound

Fuel Used	**Page Number**	**Bus #**
Weather (Circle the appropriate choice(s)) clear light-rain heavy-rain wet-road dry-road **Mileage counter =** (Counter is located at the centre of the rare wheel of the bus)		**Data Collector** **File B**
_______ Checked Engine temperature? (Correct Range 50-70 ° C) **_______Checked flow meter? (The meter should read 4 ltrs/min)**		**Starting Bag#**

Bus stop	**MS**	**Lcn & Beedle**	**Lcn &Beach**	**City Hall**	**Mary G Hosp**	**Special Event or collector's remark (with system time)**
Start Time:	: :					
Initial Count						
Time:						
Count						
Time:						
Count						
Time:						
Count						
Time:					(MS) : :	
Count						

Note: Change bag number when the bus idles (Enter **+**). **Idling Bag#**

Figure 3.16: Data collection sheet for passenger count

system, large discrepancies between the two parallel gas analyzers and system crashing (Frey et al, 2008a). Frey et al. (2001) and many others (Zhang, 2006) have published their experiences of using the PEMS, Montana system. Frey et al. (2001) found the fraction of invalid data to be 2.5-15% of the total on-road data. This pertains to equipment failure, wrongly placed sample and reference lines and improper calibration. This section describes the challenges faced during data collection. Through experience subsequent tests were done with specific considerations of these challenges.

3.4.1 Computer error

Sometimes the computer would freeze and the system had to be restarted which would create new data file. Freezing is due to a number of reasons which are beyond the scope of the present work.

3.4.2 Connection error

This implies the improper connection of either the physical sample lines or any electric wire on the system board inside. The reason for this kind of error is high vibration (Maldonado et al. 2006) and acceleration episodes. With subsequent testing, this problem was identified and somewhat controlled.

3.4.3 Negative emissions values

Frey et al. (2001) indicated that random measurement errors can result in negative values or values that are not statistically different from zero. This problem which is mainly associated with HC arises because of too low concentration of the gas in the sample. For small frequency and magnitude of negative values, the emissions measurements are assumed to be the same as zero (Frey et al., 2001). In the present work, these rows were eliminated from the final database after consultation with Clean Air Technologies Inc.

3.4.4 Emission spikes

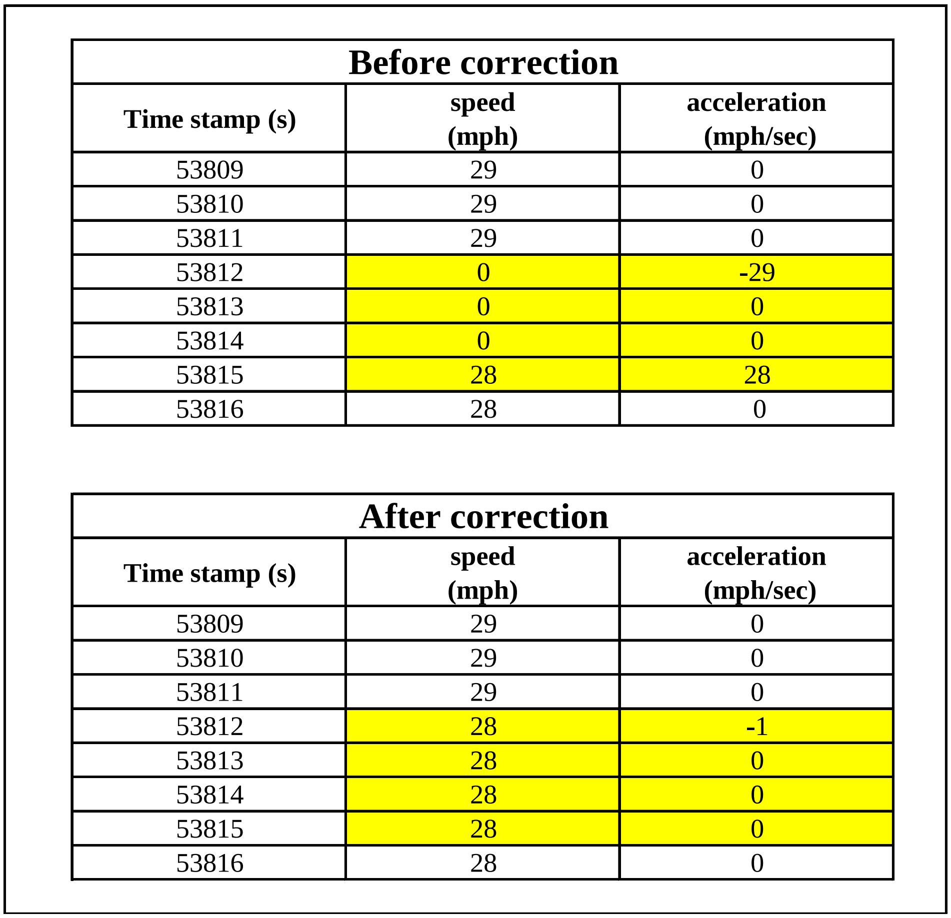
Sometimes due to equipment malfunctioning, the measurements would show very high values. This was due to improper calibration or failure of the analyzer as would be indicated by the system. This error was spotted during the data collection stage itself. Errors were marked with time stamps and later on the corresponding data would be discarded.

3.4.5 GPS losing satellite link

Speed was measured using a GPS. Sometimes, it (GPS) would lose contact with the satellites and the displayed speed would suddenly drop to a very small value indicating an acceleration of more than 10 mph/s which is abnormal (Zhang, 2006). When the problem was existed for a long stretch of time, tests were repeated. Otherwise, the data were interpolated to the nearest integer value (speed data is in integer form). This comprised of less than 1 % of data in all encountered cases. Further, because of random sampling, interpolation would not present any significant bias to the data (Zhang, 2006). This problem is similar to what Zhang (2006) described as speed drift. A better way to avoid this problem is to use a on-board speed sensors.

3.4.6 Synchronization errors

This occurs when there is a delay in the response of the gas sampling line and analyzer. Frey et al. (2001) suspected this to arise from obstructions in the gas sampling line. Time delay of the response of the analyzer can disrupt the equipment synchronization. Frey et al (2001) were able to find synchronization delay by looking at a plot of RPM and spikes in emissions. Synchronization errors were checked but no error was found in the data collected.



Before correction		
Time stamp (s)	speed (mph)	acceleration (mph/sec)
53809	29	0
53810	29	0
53811	29	0
53812	0	-29
53813	0	0
53814	0	0
53815	28	28
53816	28	0

After correction		
Time stamp (s)	speed (mph)	acceleration (mph/sec)
53809	29	0
53810	29	0
53811	29	0
53812	28	-1
53813	28	0
53814	28	0
53815	28	0
53816	28	0

Figure 3.17 :Data correction

3.4.7 Calibration problems

On many occasions discrepancies were found between the two analyzers' readings. Technician from Clean Air specified that this was likely due to poor ventilation in the room where calibration was performed. Future calibrations were done in open space. Improper calibration can also result in emissions spikes or negative emissions values. The equipment was calibrated every day before testing.

3.4.8 Exposure to extreme weather

Extreme winter and summer (hot) temperatures affect emissions. Restricting the data collection for each bus within similar weather conditions was a challenge. There were some hot days which influenced the equipment resulting in its failure to provide right measurements. Upon identifying the problem, the equipment was turned off after some period of data collection.

3.5 Precautions in data collection

Following are some precautions that can be taken to address the foregoing and other problems associated with on-road data collection (Frey et al., 2001).

1. Ensuring that the battery is sufficiently charged before the run.
2. Firmly fixing the data cable connection with duct tape.
3. Zeroing the instrument before each data collection run to avoid negative emissions readings
4. Checking and refreshing the gas analyzer display before the run to make sure that changes in the concentrations of all gases are appropriately reflected in the on-board computer display.
5. Zeroing in locations where the reference air is not stagnant or likely to be influenced significantly by emissions from other vehicles

3.6 Final emissions database

3.6.1 Initial data reduction

Frey et al. (2002) recommends data screening prior to performing data reduction. Discrepancies in data were identified through the following ways during the data collection stage.

1. Comparison of normal operation (moving along the routes) and idling data. (Concentration of emissions at idling emissions are lower)
2. Checking emissions spikes (Spike implies values more than 100 times the normal values).
3. Checking intake air temperature (measured by the temperature probe on the engine sensor) and rpm and MAP (normal temperature range is 50 – 70 ^{o} C).
4. Checking whether the emissions or GPS data were registered by the system ()

Data with errors and abnormality were tagged during data collection. After downloading the data to a spreadsheet, they were manually scanned for further errors. Erroneous rows thus identified were excluded from the database. Elimination of in- between rows can be justified by the following reasons.

1. Data for each bus-fuel combination was enormous. Therefore, deleting few rows would not make a significant difference.

2. Further, the study comprised of binning-based approach for data analysis which does not require data to be continuous.

3.6.2 Final clean-up

Each of the 3 buses was tested with B0, B10 and B20 for 2 days at the rate of 9 hours per day. This generated a total of about 162 (= 3 x 3 x 2 x 9) hours of initial raw data before screening. 89 hours of data were finally obtained (Table 3.3) while three hours of processed field data is sufficient for characterizing emission rates tests (Frey et al. 2008a).

Table 3.3: Data in (approximate) hours after final cleaning

	Fuel Blends			
Bus ID	B0	B10	B20	Total
971	16	11	7	33
973	8	13	14	35
997	5	10	4	20
Total	29	34	25	89

3.6.3 Retaining relevant variables

Table 3.4 shows all the variables that were measured by PEMS. Variables such as rpm, intake air temperature, and manifold absolute pressure were directly used by the PEMS for estimating emission rates. They were removed to minimize redundancy. Variables which were relevant and independent were then preserved.

BX signifies the biodiesel blend used by a bus for a given test. Vehicle specific power (VSP) defined in the next section was estimated for each row. The final database consisted of NO_x, HC, CO, CO_2 and PM as the emissions variables and BX, Speed, acceleration, passenger and VSP as the explanatory variables. For a given bus, data from all the three fuels were combined and stored in a single Microsoft Excel 2007 file.

Table 3.4: Variables retained after initial data cleaning

Vehicle and operation parameter	
BX	Categorical variable signifying Biodiesel blend (B0, B10, and B20)
Bpercent	Percentage of biodiesel (0%, 10%, or 20%)
Speed	Speed of the vehicle (Bus)
passenger	Number of passengers in the bus
T	Intake Air temperature
MAP	Manifold Absolute Pressure
Acceleration	Acceleration of the vehicle in mph/s = speed(t)- speed(t-1) , where t= time in sec
rpm	revolution per minute of the engine

3.6.4 VSP

VSP is defined as the instantaneous power per unit mass of the vehicle. This is a non-linear function of speed, acceleration, road grade which can characterize fuel consumption and emission rates (Jiménez-Palacios, 1999; Yu et al., 2008). Higher load, upward slope, air drag and use of air conditioning would require more power from the engine resulting in higher tailpipe emissions.

VSP has been routinely used for quantifying emissions especially in micro-scale analysis. It has been used for estimating emissions from light-duty gasoline vehicles as well a diesel transit buses (Frey et al., 2002; Zhai et al., 2006, Frey et al., 2007).

At each instance of time, the power generated by the engine is utilized in overcoming the rolling resistance and aerodynamic drag and in increasing the kinetic and potential energies of the vehicle. It has been found that emission models (e.g. MOBILE) which use average speed do not capture the effect of driving conditions. VSP which is a function of speed, acceleration and other variables can explain the effect of driving conditions on emissions better. The following equation 3.1 (Jiménez-Palacios, 1999) provides the derivation of VSP expression. Table 3.5 gives the explanation of the various parameters used this expression. F signifies force.

$$\mathrm{VSP} \;= \left(\frac{\mathrm{d}}{\mathrm{dt}}(\text{Kinetic energy} + \text{Potential energy}) + \mathrm{F_{rolling}} * \mathrm{v} + \mathrm{F_{aerodynamic}} * \mathrm{v}\right)/\mathrm{m}$$

$$= \frac{\mathrm{d}}{\mathrm{dt}}\left(\frac{1}{2}(1+\varepsilon).\mathrm{v}^2 + \mathrm{gh}\right) + \mathrm{C_R g.v} + \frac{1}{2}\rho\frac{\mathrm{C_D.A}}{\mathrm{m}}(\mathrm{v}+\mathrm{v_W})^2.\mathrm{v}$$

$$= \mathrm{v.}(\mathrm{a.}(1+\varepsilon) + \mathrm{g.grade} + \mathrm{g.C_R}) + \tfrac{1}{2}\rho\tfrac{\mathrm{C_D.A}}{\mathrm{m}}(\mathrm{v}+\mathrm{v_W})^2.\mathrm{v} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(Eq. 3.1)}$$

Using Equation 3.1, Frey et al. (2007) obtained equation 3.2 which they applied on transit buses to compare fuel consumption and emissions from hydrogen and diesel.

$$\mathrm{VSP} = \mathrm{v.}(\mathrm{a} + 0.092) + 0.00021 * \mathrm{v}^3 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(Eq. 3.2)}$$

Table 3.5: Parameters in VSP expression (source: Jiménez-Palacios, 1999)

Parameters	Explanation
ε	equivalent translational mass of the rotating components
v	velocity in m/s
a	acceleration in m/s2
grade	road grade or vertical rise/slope length
g	acceleration due to gravity = 9.81 m/s2
C_R	coefficient of rolling resistance (dimensionless),
C_D	drag coefficient (dimensionless)
A	frontal area of the vehicle
ρ	average density of air = 1.207 kg/m3 (at 20 0C = 68 0F)
v_w	headwind into the vehicle

3.6.5 Modified VSP – Derivation and Explanation

Research done by Frey et al. (2008b) found that increase in vehicle load increased the emissions by 34 % and 36 % for diesel and biodiesel respectively. The present work modified the VSP formula by including the dynamic weight of the vehicle and use of air conditioning. Dynamic weight is equal to the curb weight of the bus plus the total passenger load. In a transit bus the passenger load can change the weight of the vehicle considerably. Each passenger was assigned a weight of 150 lb or 68.04 kg (Borrell, 2006). The curb weight of the bus was 28000 lb. With 30 passengers, the additional weight is 30*150 or 4500 lb which is more than 16 % of the curb weight of the bus. In the present study, based on the particular bus tested the following values of various parameters are fed into equation 3.1 to obtain equation 3.3.

$\varepsilon = 0.1$, C_R = 0.01, C_D = 0.5, A= 7.96 m^2, ρ = 1.207 kg/m^3, road-grade = 0.0, (the road terrain was mostly flat), and the wind velocity, v_w was assumed to negligible (Orion, 2008).

$$\text{VSP(Without AC)} = v.(a + 0.092) + 2.04373/(M_0 + 68.04 * \text{passenger})\, v^3 \quad \text{……………………... (Eq. 3.3a)}$$

The dynamic weight, m= M_0 + 68.04*(passenger)

Where, M_0= curb weight of the bus = 28000(lb)* 0.45359 (kb/lb) = 12700.52 kg

The most significant of all accessory loads on the engine is identified to be vehicle air conditioning (AC) which is shown to increase both the fuel consumption and emissions. A study with dynamometer considered 10% increase in engine load to simulate the use of AC (NAP, 2000). The same was assumed to hold true for the present study, although it was based on on-road testing. One (Bus#997 with Tier-2 certification) of the buses was tested during the summer with the AC switched on throughout the study. VSP was multiplied by a factor of 1.10 (or 110%) in equation 3.3a to obtain equation 3.3b. In some previous research, humidity has been used as a parameter to model the effect of AC (National Research Council, 2000).

$$\text{VSP(With AC)} = 1.10 * (v.(a + 0.092) + 2.04373/(M_0 + 68.04 * \text{passenger})\, v^3) \text{……………….. (Eq. 3.3b)}$$

CHAPTER 4. DATA ANALYSIS

The main objective of this experimental study was to evaluate the impact of biodiesel (B0, B10, and B20) on emissions from transit buses. Hot stabilized emissions (NO_x, HC, CO, CO_2, and PM) data were collected from three transit buses using a PEMS that sampled the tail-pipe exhaust at an interval of one second.

4.1 Overview of analysis methodology

This section presents a summary of the overall methodology used in data analysis. Detailed results are presented later in the chapter. Firstly, the descriptive statistics were observed for both the explanatory variables (BX, Speed, acceleration, passenger and VSP) and the emissions wherein both failed to pass the *Anderson-Darling Normality* test. Next, cross-correlation coefficients (correlation between emissions and explanatory variables) were estimated to identify appropriate explanatory variables to characterize emissions. Data collected at equal intervals of time generally exhibit auto-correlations. Emissions were measured at an interval of 1 second and therefore had high auto-correlations (correlation between the values of a series and previous values of the same series). This required the use of time series models (models where previous instances of the dependent variable, X or the error terms,ε acts as an explanatory or independent variable e.g. $X(i) = \text{constant}*X(i-1) + \varepsilon$). However, given the blends of fuels used and the difference in operating conditions, it is difficult to come up with a general time series model which can represent the variation in emissions. However, autocorrelation can be reduced by dividing the emissions into bins such that emissions within each bin form an independent series (Frey et al., 2002). Emissions were plotted by binning them using both speed and VSP. With speed, emissions did not follow a monotonic trend and therefore distinguishing emissions across bins was difficult. However, emissions increased linearly across the VSP bins. This can provide some level of independency among disaggregated bins. Three emissions bins were created based on some criteria on VSP. Emissions from B10 and B20 were compared to B0 within these three bins. Emissions in each bin cannot be normally distributed because the observations in each bin were taken from population (emissions) which were not normally distributed as mentioned above. Therefore, a non-parametric test (Wilcoxon rank-sum test) was employed for comparing the emissions. Results are presented and discussed. Figure 4.1 describes the overall data analysis strategy.

4.2 Descriptive statistics

The **Anderson-Darling Normality test** (Stephens, 1974) is used to test whether a sample of data came from a population with a normal distribution. The Anderson-Darling Statistics is given by

$$A^2 = -N - \frac{2i-1}{N}\left(\ln\left(F(Y_i)\right) + \ln\left(1 - F(Y_{N=1-i})\right)\right) \qquad \text{(Eq. 4.1)}$$

where, F is the cumulative distribution function of the specified distribution, Y_i is the ordered data, N is the sample size while i varies from 1 to N. The test statistic is compared with the critical values of the theoretical distribution (dependent on which F is used) to determine the p-value.

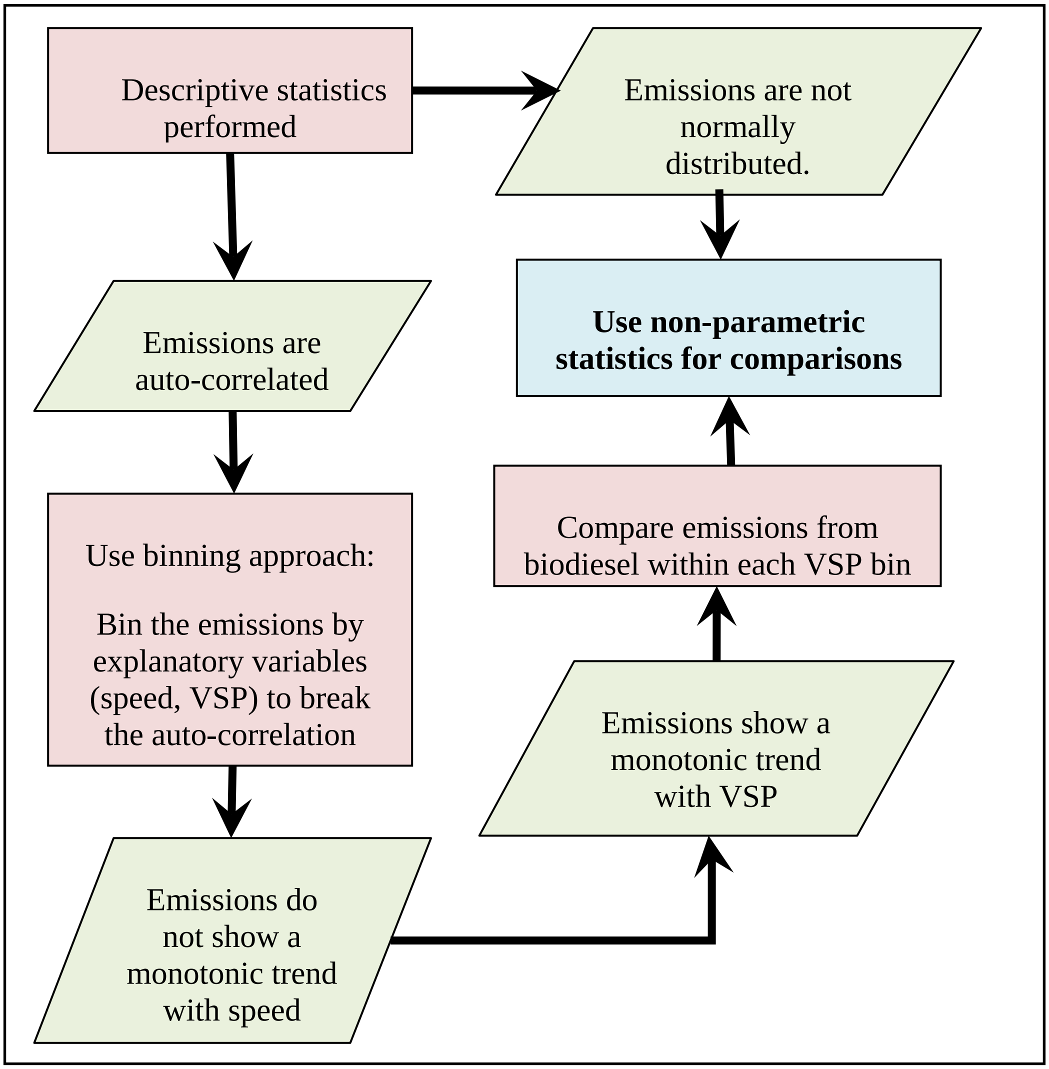


Figure 4.1: Conceptual diagram of data analysis methodology

The null hypothesis that the sample came from a normal distribution was rejected if p-values were less than the level of significance (0.05 in the present case). In this study, Anderson-Darling Normality tests were conducted using MINITAB-15® while descriptive statistics were obtained from JMP (version 7) software. Tables 4.1-4.2 present the descriptive statistics including the results from the test for normality. Coefficient of variation (CV) was calculated as (standard deviation)/(mean). Skewness is a measure of symmetry while kurtosis is a measure of whether the data are peaked or flat relative to a normal distribution (NIST, 2008). A distribution with heavier right tail shows positive skewness. A flatter distribution has positive kurtosis (Graphpad, 2008). For a normal distribution, both skewness and kurtosis are zero.

4.2.1 Descriptive statistics for the explanatory variables

Skewness, kurtosis and Anderson Darling Normality test statistics showed that the explanatory variables were not normally distributed. Distributions of speed (Table 4.1) were similar for all the three buses. Number of passenger ranged from 0 to about 40 for all the three buses. Acceleration (Table 4.3) was evenly distributed approximately around 0 mph/s. VSP values (Table 4.1) were concentrated on the positive side of the axis with the mean falling within 6-7 W/kg while the median was around 5 W/kg.

4.2.2 Descriptive statistics for emissions

This section presents the descriptive statistics with normality test (using *Anderson-Darling normality test*) for emissions (the dependent variables) from the three buses. All distributions (Tables 4.2) were skewed and failed to pass the Anderson-Darling normality tests (p value < 0.05). This implies that parametric tests which assume normal distribution of the data would not give reliable results. However, in previous studies, emissions were generally assumed to be normally distributed. Significant variation in the emissions is corroborated by high coefficient of variation (> 1). Descriptive statistics also showed that, in general, the distribution of emissions from all the three buses were similar.

Table 4.1: Descriptive statistics of the explanatory variables (SD = Standard Deviation)

Bus ID	Mean	$CV = \frac{\text{mean}}{\text{SD}}$	Median	Maximum	Skewness	Kurtosis	Anderson-Darling Normality test	
							A^2 (Eq. 4.1)	p-values
Speed in mph								
971	13.24	0.86	12	46	0.31	-1.21	3623.38	< 0.005
973	13.53	0.84	13	46	0.25	-1.27	3744.74	< 0.005
997	13.54	0.85	13	42	0.26	-1.28	2212.91	< 0.005
Number of passengers in the bus								
971	6.21	1.00	12	46	0.31	-1.21	3623.38	< 0.005
973	6.38	0.98	13	46	0.25	-1.27	3744.74	< 0.005
997	5.12	0.89	13	42	0.26	-1.28	2212.91	< 0.005
Acceleration in mph/s								
971	0.0053	269.64	0	19	-0.16	1.88	5391.28	< 0.005
973	0.0096	150.21	0	26	-0.15	2.8	6255.94	< 0.005
997	0.0020	712.95	0	9	-0.35	1.45	3459.19	< 0.005
VSP in Watt/kg								
971	6.13	1.14	4.39	91.8	0.77	0.29	4857.44	< 0.005
973	6.27	1.12	4.84	160	0.75	1.76	4554.50	< 0.005
997	6.87	1.13	5.07	50.5	0.63	-0.39	2735.22	< 0.005

Table 4.2: Descriptive statistics for emissions

Bus ID	Mean	$CV = \frac{\text{mean}}{\text{SD}}$	Median	Maximum	Skewness	Kurtosis	Anderson-Darling Normality test	
							A^2	p-values
NO_x (g/s)								
971	0.0318	0.89	0.023	0.248	1.77	4.06	5007.02	< 0.005
973	0.0436	0.98	0.029	0.432	2.01	5.42	6769.90	< 0.005
997	0.0597	1.07	0.036	0.426	1.9	3.56	5156.69	< 0.005
HC (g/s)								
971	0.0017	0.81	0.001	0.019	2.47	10.57	5472.76	< 0.005
973	0.0022	1.22	0.001	0.047	4.14	29.41	7474.82	< 0.005
997	0.0041	0.88	0.003	0.036	2.04	5.48	4007.74	< 0.005
CO (g/s)								
971	0.0014	1.29	0.00086	0.0312	3.42	20.77	8180.65	< 0.005
973	0.0028	0.97	0.00205	0.035	2.64	11.58	6219.44	< 0.005
997	0.0091	1.38	0.00455	0.2004	3.46	19.07	6311.00	< 0.005
CO_2 (g/s)								
971	2.685	1.32	1.298	29.347	2.66	8.45	11901.8	< 0.005
973	3.616	1.24	1.740	32.234	2.32	6.12	11187.7	< 0.005
997	10.061	1.06	5.001	53.75	1.62	1.87	5795.67	< 0.005
PM (mg/s)								
971	0.0664	2.00	0.02	1.83	3.82	18.84	21008.3	< 0.005
973	0.0658	1.76	0.03	1.96	4.27	25.63	18669.9	< 0.005
997	0.2321	1.55	0.10	3.77	3.15	11.48	10131.4	< 0.005

4.2.3 Emissions as a function of biodiesel blends

Figure 4.2 to 4.4 display the average emission rates at various biodiesel blends.

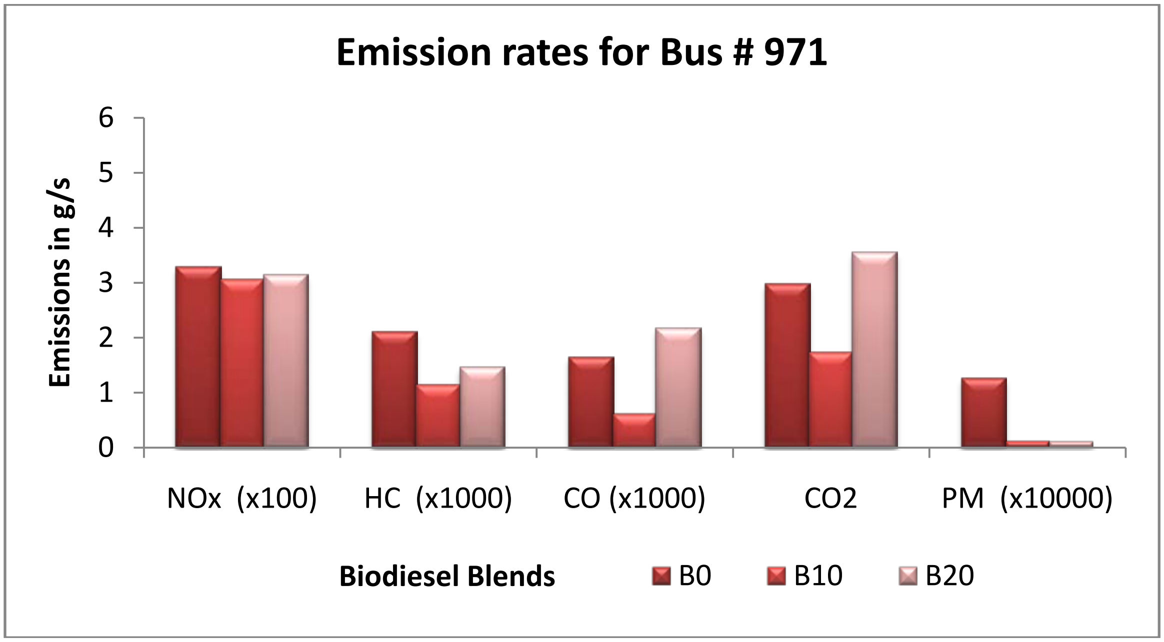


Figure 4.2: Emission rates (g/s) for Bus# 971

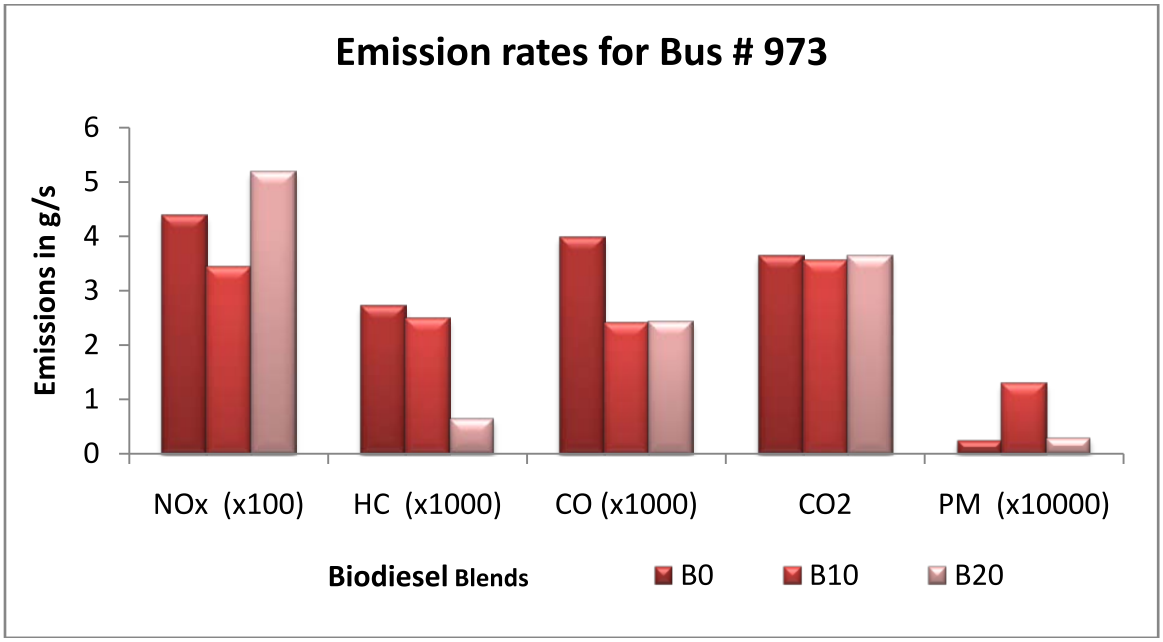


Figure 4.3: Emission rates (g/s) for Bus# 973

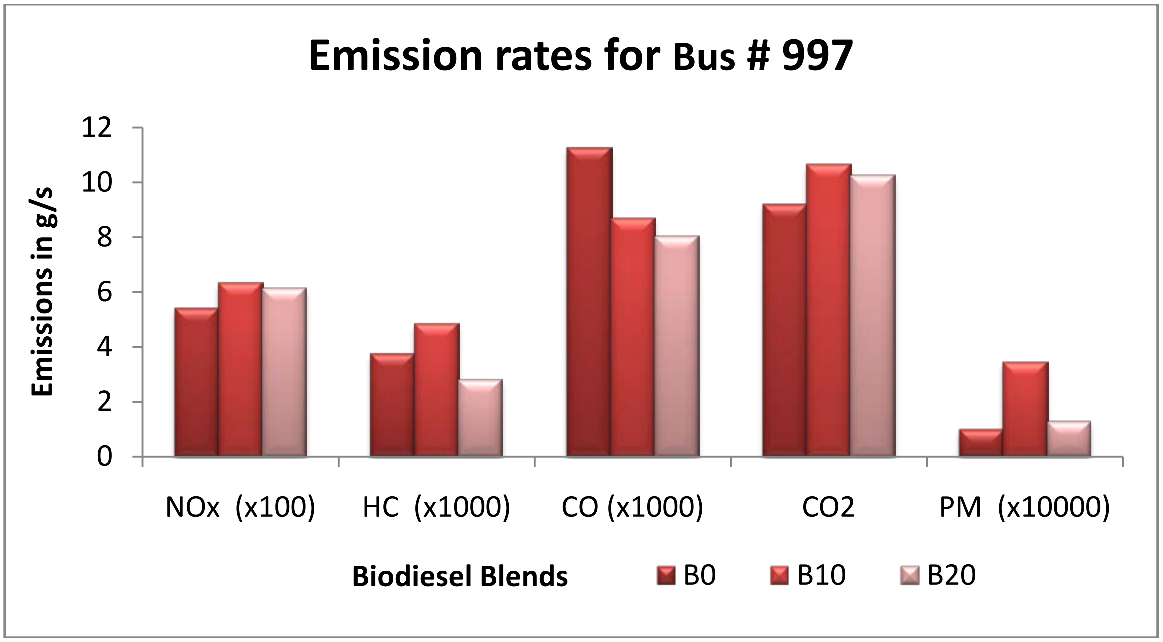


Figure 4.4: Emission rates (g/s) for Bus# 997

EPA (2002) found NO_x to increase by 1 % for every 10 % volume increase of biodiesel in regular diesel (Graboski 1998). It was expected that emissions from B10 to be somewhere in between that of B0 and B20. But results were contrary to this. Hallmark et al. (2008) also shows this with NO_x and HC when the same set of data was tested using a dynamometer system (Figure 4.5-4.6). This may either be due to the combustion reaction or something inherent to biodiesel itself. It is seen in chemical reactions how even a little change in the proportion of the reactants can change the reaction products. Also, data collected on different days had errors at different locations. Removal of these erroneous observations might have biased the data. The next section shows how emissions were checked for auto-correlation to see if emissions data were independent.

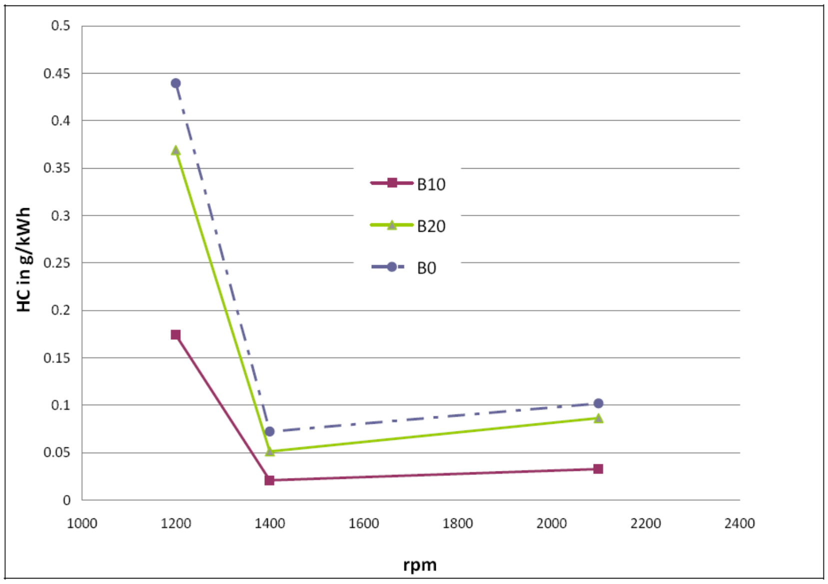


Figure 4.5: HC emissions at various rpm (Hallmark et al., 2008)

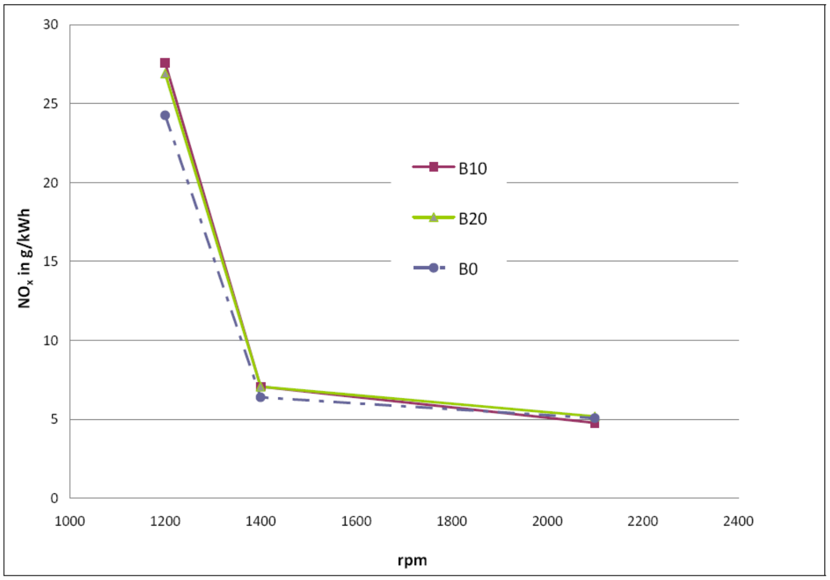


Figure 4.6: NO_x emissions at various rpm (Hallmark et al., 2008)

4.2.4 Auto-correlations in emissions

On-road emissions data have been found to be time series with statistically significant autocorrelations (Frey et al., 2002). This is because emissions at a particular second are dependent on activity and emissions in previous seconds (Zhang, 2006). To verify this, auto-correlation values were computed as shown in Tables 4.3. The table showed that the emissions are auto-correlated and therefore the observations are not independent of each other. Auto-correlation in emissions is handled through time series modeling. However, it is difficult to have a general time series model representing all the different trips. Even if the same model is used, the co-efficient may vary. In addition, the data from different days/driver/weather cannot be combined so as to produce a single time series. However, autocorrelations can be broken by binning the data into groups so that autocorrelation (or serial dependency) in each bin is reduced if not eliminated. Emissions were plotted with respect to various bins. Results are presented in the following section. Frey et al. (2002) removed the auto-correlations by binning the data and applied regression methods to data within each bin.

Table 4.3: Auto correlations for the three buses

	Bus # 971					Bus # 973					Bus # 997				
Time Lags (s)	NO_x	HC	CO_2	CO	PM	NO_x	HC	CO_2	CO	PM	NO_x	HC	CO_2	CO	PM
0	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
1	0.94	0.96	0.94	0.97	0.98	0.94	0.96	0.94	0.96	0.97	0.93	0.96	0.96	0.94	0.95
2	0.80	0.87	0.80	0.92	0.94	0.81	0.87	0.79	0.90	0.91	0.77	0.88	0.87	0.82	0.85
3	0.63	0.77	0.64	0.86	0.90	0.66	0.77	0.62	0.81	0.85	0.59	0.78	0.78	0.67	0.73
4	0.48	0.68	0.49	0.81	0.85	0.53	0.67	0.47	0.73	0.80	0.43	0.68	0.69	0.53	0.60
5	0.36	0.59	0.37	0.76	0.81	0.43	0.58	0.34	0.65	0.74	0.29	0.59	0.61	0.40	0.48
6	0.27	0.53	0.28	0.71	0.76	0.35	0.51	0.24	0.58	0.68	0.18	0.51	0.54	0.28	0.37
7	0.20	0.47	0.20	0.67	0.71	0.28	0.44	0.16	0.52	0.62	0.10	0.43	0.47	0.18	0.28
8	0.15	0.42	0.13	0.64	0.66	0.22	0.38	0.09	0.48	0.56	0.04	0.37	0.42	0.10	0.21
9	0.10	0.38	0.08	0.61	0.61	0.17	0.34	0.03	0.43	0.50	-0.01	0.32	0.37	0.03	0.15
10	0.06	0.35	0.04	0.58	0.56	0.13	0.30	-0.01	0.40	0.44	-0.04	0.28	0.33	-0.02	0.10

4.2.5 Emissions segregated by various bins

In a binning based approach, dependent variables (emissions in this case) are binned based on ranges of a given explanatory variable. Although it takes away some explanatory power, it helps to reduce the auto-correlation. Binning approaches are inbuilt with loss of explanatory power but provide increased convenience. It is intuitive and conducive for making macroscopic predictions (Frey et al., 2002). Further, EPA recommends the use of binning approach to relate vehicle activity and energy consumption so that the use of laboratory emission test results associated with VSP can be used (EPA, 2002). To choose appropriate explanatory variable, the correlation coefficients of the variables with emissions were estimated. Emissions were found to be correlated with speed and VSP (Table 4.4), and therefore these were used for binning the emissions.

Table 4.4: Correlation coefficients for Bus #971

Bus ID =>	Bus#971		Bus#973		Bus#997	
Emissions	speed	VSP	speed	VSP	speed	VSP
NO_x	0.26	0.59	0.23	0.55	0.11	0.48
HC	0.27	0.48	0.23	0.42	0.35	0.59
CO	0.23	0.33	0.29	0.46	0.07	0.33
CO_2	0.25	0.58	0.24	0.60	0.20	0.57
PM	0.22	0.31	0.31	0.43	0.12	0.42

4.2.5.1 Emissions by speed bins

Emissions were binned by various speed levels as defined in Table 4.5. Average emission rates from all the three buses were plotted with respect to these bins (Figure 4.7-4.9). Data for all the three fuels were combined to estimate the average values.

Table 4.5: Definition of Speedbin

Categorical variable	Value	Condition
Speedbin	1	speed < 5 mph
	2	5< speed <= 15
	3	15 < speed <=30
	4	speed > 30

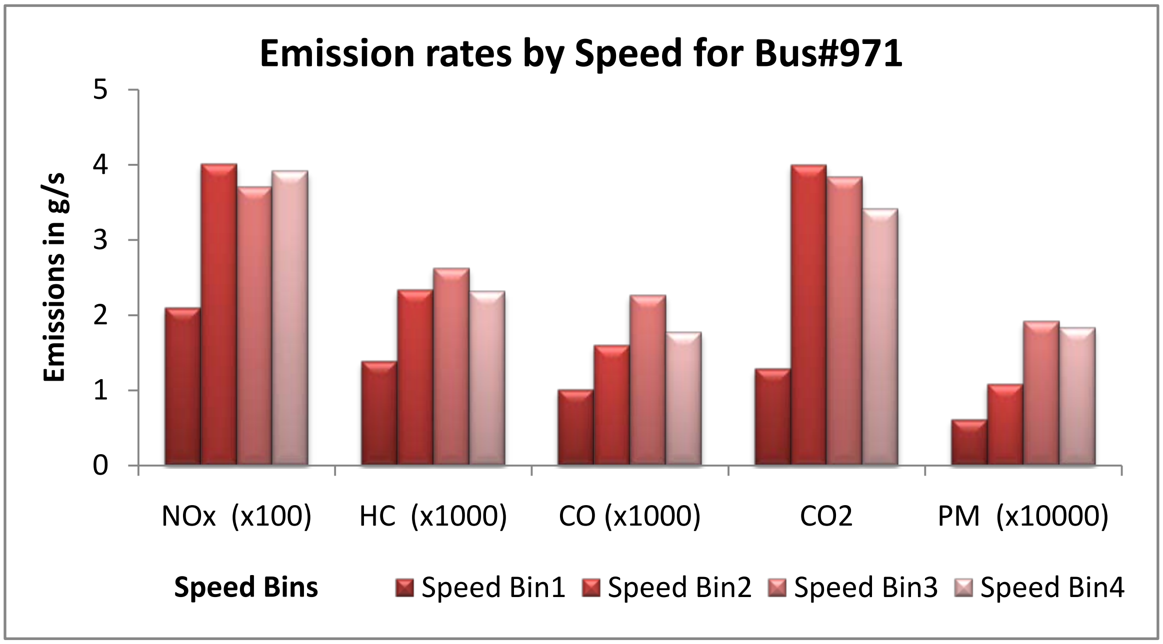


Figure 4.7 Emission rates (g/s) by Speed for Bus #971

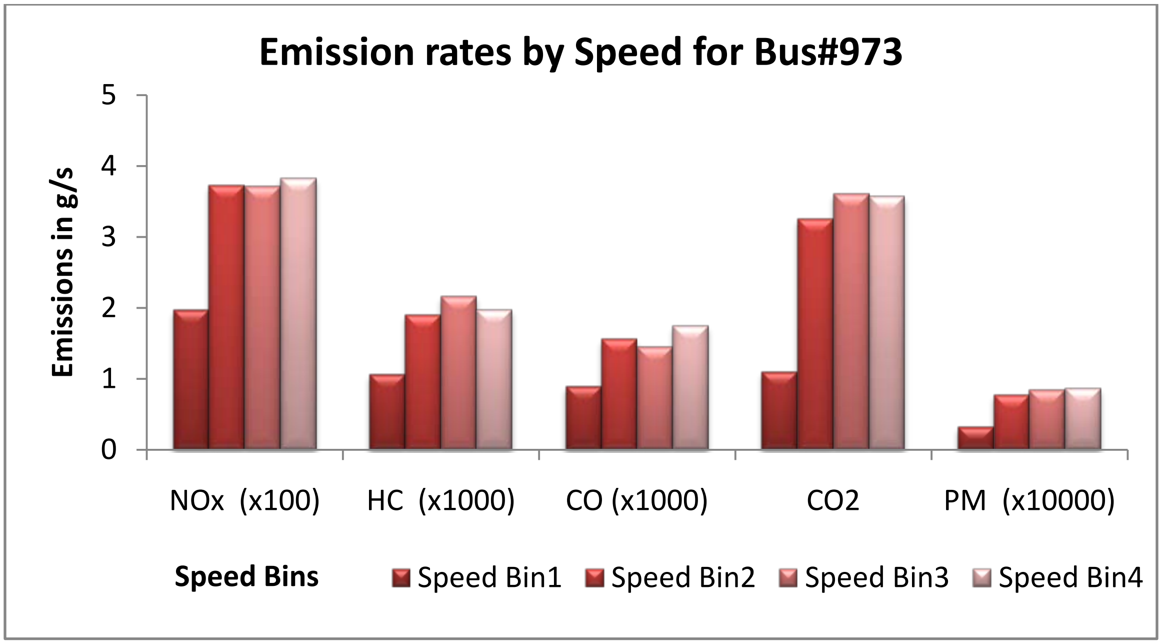


Figure 4.8: Emission rates (g/s) by Speed for Bus #973

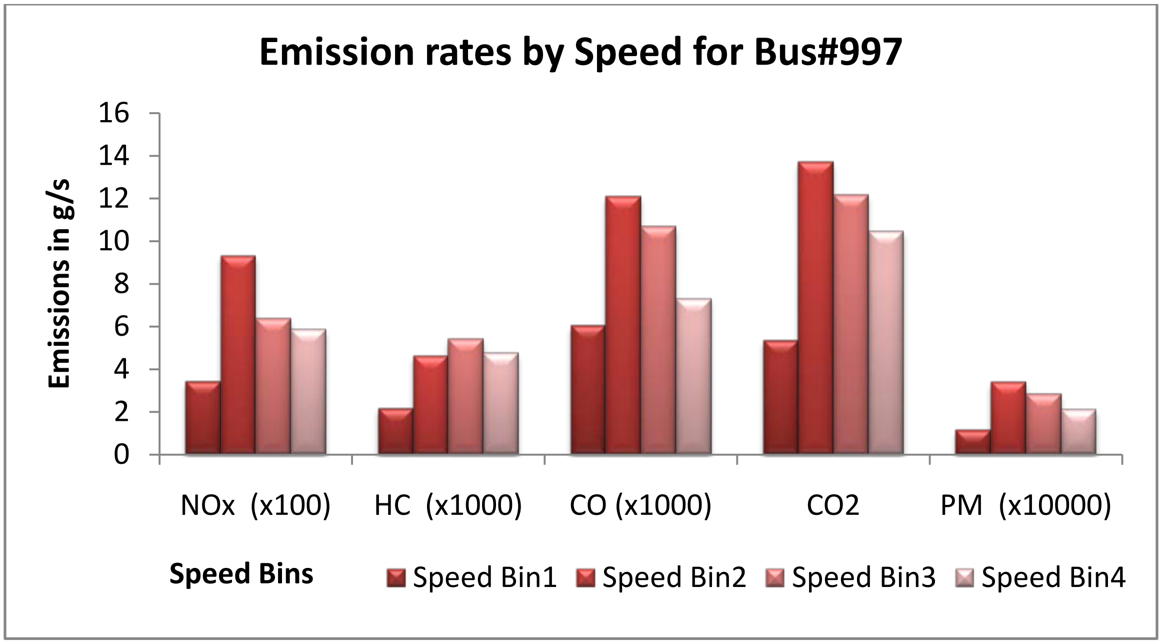


Figure 4.9: Emission rates (g/s) by Speed for Bus #997

Emissions did increase with speed for lower speeds (< 5 mph) but became flat or even decreased as the speed increased further. In other words, emissions trends across the bins were not monotonic. Previous research (Frey et al. 2002) found that the highest HC emission occurred when the speed was approximately 10 mph. The present research found this peak to be around 15-30 mph (Speed bin=3). Emissions binned by speed did not follow a monotonic trend and even became flat at high speeds. This decreases the chances that the emissions in each bin would differ significantly. Next, VSP was tried out for binning the emissions.

4.2.5.2 Emissions by VSP bins

VSP was chosen for creating bins because it takes into account speed, acceleration and other operative conditions within a single variable (Jiménez-Palacios 1999). Available literature has recommended lesser number of bins (Frey et al., 2002; Song et al., 2008a). Therefore, emissions were divided into three groups (or bins) as shown in Table 4.6. This definition was based on the following findings.

- About 97.7 % of VSP falls within -20 to 20 Watt/kg (Song et al., 2008b).
- From the present study, the mean and standard deviation of VSP were about 6.5 and 5.5 respectively (Table 4.1). This implies that the region around the mean ranged from VSP of 1 to 12.
- Distribution depicted VSP to be heavily tailed on the positive side (table 4.1). Therefore, three regions were chosen (Table 4.6). Emission rates were binned by both the unmodified and the modified VSP expressions (Equations 3.2 and 3.3 respectively).

Table 4.6: Definition of VSP bins

Categorical variable	Value	Condition (VSP in watt/kg)
VSP bin	1	VSP <= 0
	2	0 < VSP <= 10
	3	10 < VSP

Figures 4.10 to 4.12 shows average emission rates (combining data for all three fuels) with respect to unmodified VSP (Equation 3.2).

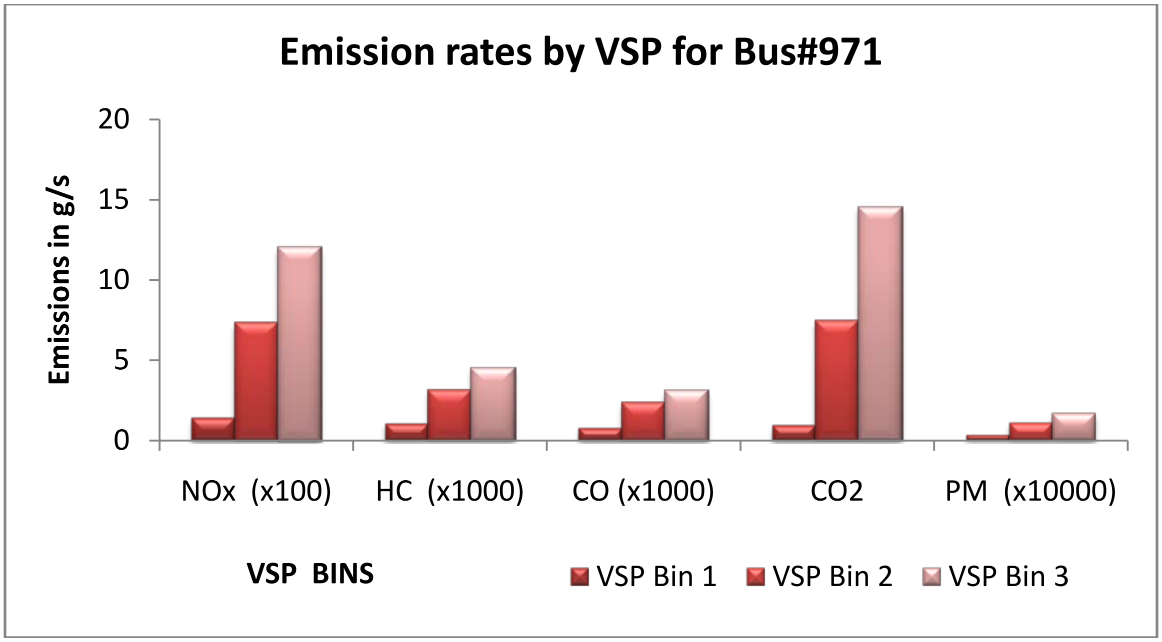


Figure 4.10: Emission rates (g/s) by VSP for Bus #971

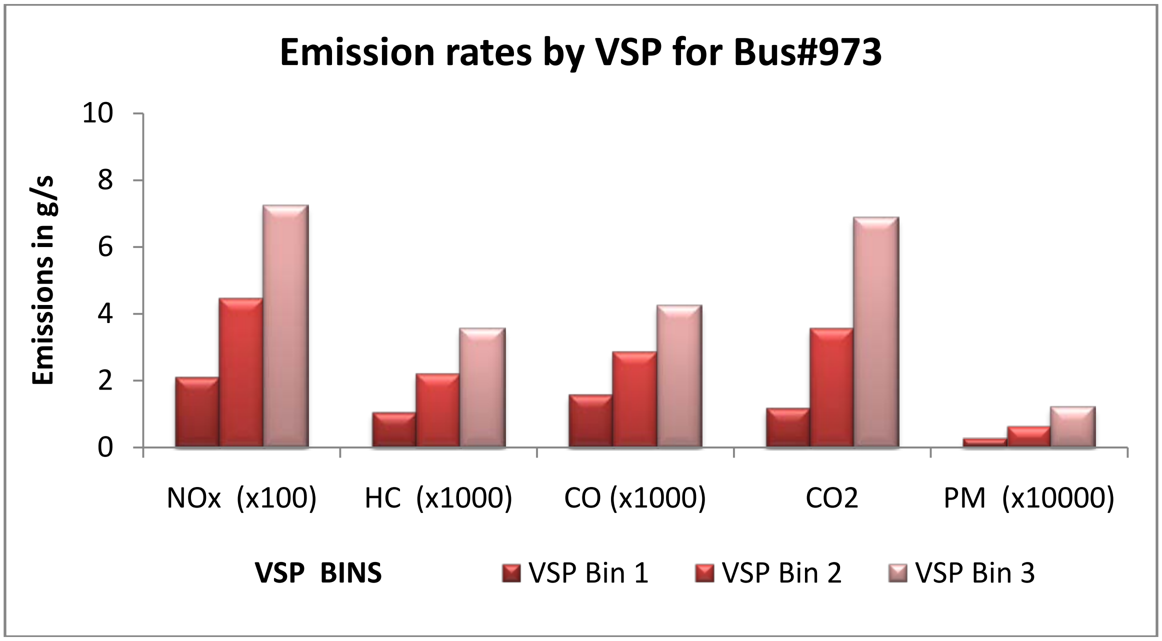


Figure 4.11: Emission rates (g/s) by VSP for Bus #973

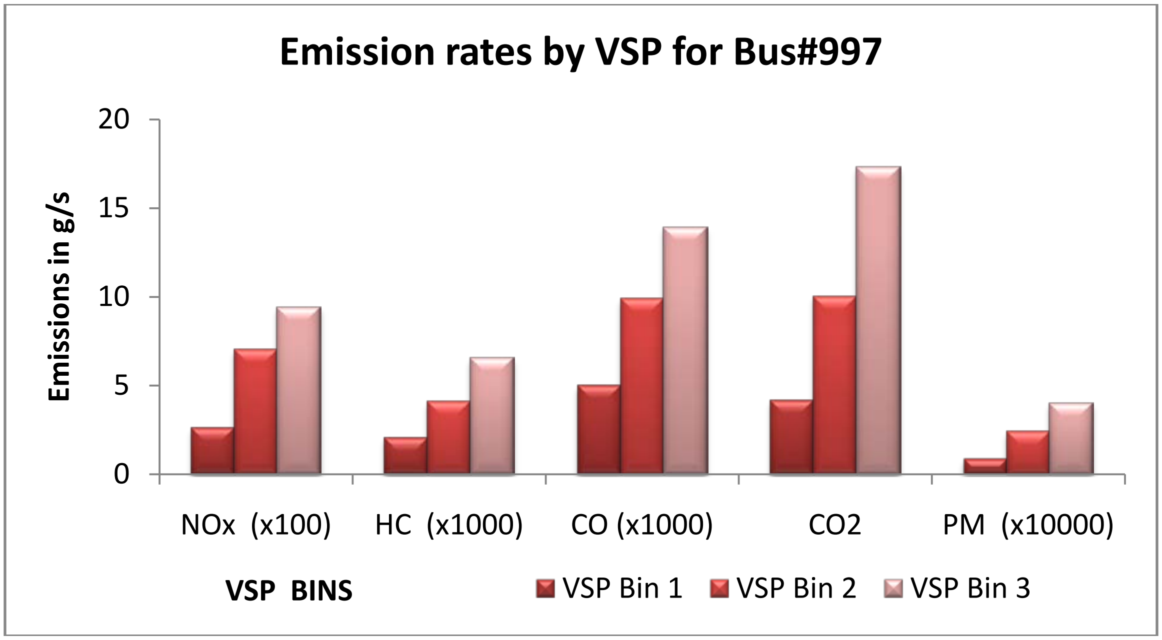


Figure 4.12: Emission rates (g/s) by VSP for Bus #997

Emissions increased monotonically with VSP in all cases. In essence, the higher the power demand, the higher the fuel consumption and emission rates are. Song et al. (2008b) found a monotonously increasing trend for fuel consumption which is proportional to emissions. Monotonic trend imparts some level of independency in emissions across the VSP bins.

With the modified VSP expression (Equation 3.3), emissions rates were not considerably different as compared to the original VSP expression (Equation 3.2). This means, passenger-load (weight of the passengers) and the use of air conditioning did not influence the power demand considerably. Frey (2007) found that there was no effect of passenger load on emissions under low speeds. The data in this study was dominated by lower speeds with median speed equal to 12 and this may be the reason for no effect.

Emissions from B0, B10 and B20 were evaluated at three levels of VSP or power demands. Originally, the emissions (series) were not normally distributed (as shown in section 4.4.2). Therefore, the binned or segregated samples from those series cannot be normally distributed. Hence, a non-parametric comparison test was used for the purpose of comparing the emissions. Emission rates (NO_x, HC, CO, CO_2 and PM) from B10 and B20 were compared to B0. The basic hypotheses tested were that presence of biodiesel in diesel (B0) changes the emission rates. Figure 4.11 gives a graphical description of how the emissions (only shown for NO_x) were binned. Other emissions (HC, CO, CO_2 and PM) were divided in a similar manner. The next section describes the statistical comparison test with results and discussions.

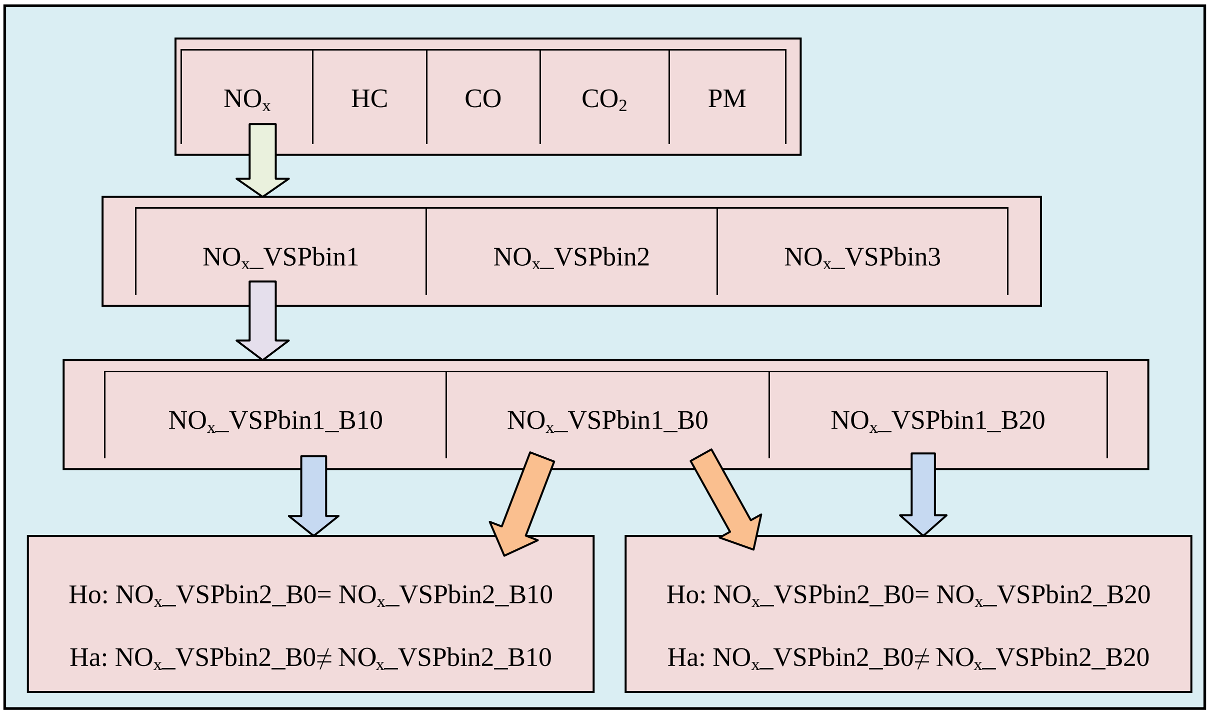


Figure 4.13: The sampling and binning strategy (bins are shown only for NO_x)

A total of 90 (=2 Comparisons* 3 bins* 5 Emissions* 3 Buses) comparison tests were conducted as shown by figure 4.13. Table 4.7 depicts the sample sizes used in hypothesis testing.

Table 4.7: Sample sizes used in the hypothesis testing for all the five emissions

Bus #	Fuel	VSPBIN1	VSPBIN2	VSPBIN3
971	B0	24804	31532	17593
	B10	16453	11199	11654
	B20	10407	5450	7691
973	B0	68367	25556	71749
	B10	19346	13535	14762
	B20	8917	5054	6251
997	B0	18951	19051	19020
	B10	35631	35603	35591
	B20	13290	13315	13274

4.3 Evaluation of emissions at various levels of power consumption

The *Wilcoxon rank-sum test* is a non-parametric test for assessing whether two samples of observations came from the same distribution or whether observation in the first sample is greater than the second. The requirements of using this test are that (1) the two samples should be independent, (2) the observations should be ordinal or continuous measurements, and (3) the populations of both the samples should be similar except for a shift (i.e.$f_1(x) = f_1(x+\delta)$). Wilcoxon test fails to give reliable result when there are differences in shape of the distributions of the two groups being compared. Statistical software, R was used for conducting Wilcoxon Rank Sum tests. A script was written in MATLAB-7® to customize the statistical tests.

The two samples (B0 and B10 or B0 and B20) were assumed to be independent as the data for different fuels were collected on different days and also emissions were binned which reduced auto-correlation. Emissions obtained from the PEMS are continuous measurements and descriptive statistics showed no considerable difference in distribution even among the three buses (section 4.4.2 and Appendix-1). In this way, all the three assumptions were satisfied. Following is a description of Wilcoxon rank sum test.

Wilcoxon rank sum test: First of all, the observation in each sample is ranked. The Wilcoxon test statistic W is the sum of the ranks of the population from which a sample came. Assuming that the two samples came from populations which have the same continuous distribution the mean and standard deviation of W are given by $\mu = m\,(m+n+1)/\,2$ and $\sigma=\sqrt{(m * n * (N + 1) / 12)}$ respectively. Here, N (or $m + n$) is the sum of the two sample sizes. The p-value is equal to twice the smallest tail value that is 2*P (N <=W) if $W < \mu$, or 2*P (N >=W) if $W > \mu$, where P is the probability function.

Using this test, medians were compared and tested for significance in difference. Emissions (median values) from B10 and B20 were compared to B0. The following two hypotheses were tested within each three VSP bin for each of the five emissions.

H_0: Emissions (B10) = Emissions (B0) vs. H_a: Emissions (B10) $\neq$ Emissions (B0)

H_0: Emissions (B20) = Emissions (B0) vs. H_a: Emissions (B20) $\neq$ Emissions (B0)

Tests were conducted at 5 % significance level. Based on which median is greater, it was inferred whether the emissions decreased, increased or did not change significantly (p-values

> 0.05) when B10 (Tables 4.8) or B20 (Tables 4.9) were used instead of B0. Details of test results are illustrated in Appendix B. Figures in parentheses signify p-values.

Table 4.8: Comparison of emission rates of B10 with B0 (Here, X_1* E-X_2 implies X_1 times 10 raised to the power –X_2)

Emissions	VSP bin 1 Inference (p-values)	VSP bin 2 Inference (p-values)	VSP bin 3 Inference (p-values)
Bus # 971			
NO_x	Increased (3.19E-3)	Decreased (< 2.20E-10)	Decreased (< 2.20E-10)
HC	Decreased (< 2.20E-10)	Decreased (< 2.20E-10)	Decreased (< 2.20E-10)
CO	Decreased (< 2.20E-10)	Decreased (< 2.20E-10)	Decreased (< 2.20E-10)
CO_2	Decreased (< 2.20E-10)	Decreased (< 2.20E-10)	Decreased (< 2.20E-10)
PM	Decreased (< 2.20E-10)	Decreased (< 2.20E-10)	Decreased (< 2.20E-10)
Bus # 973			
NO_x	Decreased (< 2.20E-10)	Decreased (< 2.20E-10)	Decreased (< 2.20E-10)
HC	Decreased (< 2.20E-10)	Decreased (6.99E-05)	Decreased (6.99E-05)
CO	Decreased (< 2.20E-10)	Decreased (< 2.20E-10)	Decreased (< 2.20E-10)
CO_2	Decreased (< 2.20E-10)	Decreased (2.67E-03)	Decreased (2.67E-03)
PM	Increased (< 2.20E-10)	Increased (< 2.20E-10)	Decreased (< 2.20E-10)
Bus # 997			
NO_x	No change (1.40E-01)	Increased (< 2.20E-10)	Increased (< 2.20E-10)
HC	Increased (< 2.20E-10)	Increased (< 2.20E-10)	Increased (< 2.20E-10)
CO	Decreased (< 2.20E-10)	Decreased (< 2.20E-10)	Decreased (< 2.20E-10)
CO_2	Increased (< 2.20E-10)	Increased (5.74E-04)	Increased (< 2.20E-10)
PM	Increased (< 2.20E-10)	Increased (< 2.20E-10)	Increased (< 2.20E-10)

Table 4.9: Comparison of emission rates of B20 with B0

Emissions	VSP bin 1 Inference (p-values)	VSP bin 2 Inference (p-values)	VSP bin 3 Inference (p-values)
Bus # 971			
NO_x	Decreased (< 2.20E-10)	Decreased (< 2.20E-10)	Decreased (< 2.20E-10)
HC	Decreased (< 2.20E-10)	Decreased (< 2.20E-10)	Decreased (< 2.20E-10)
CO	Increased (< 2.20E-10)	Increased (< 2.20E-10)	Increased (< 2.20E-10)
CO_2	No change (8.58E-1)	Increased (8.58E-04)	Increased (8.58E-4)
PM	Decreased (< 2.20E-10)	Decreased (< 2.20E-10)	Decreased (< 2.20E-10)
Bus # 973			
NO_x	Increased (< 2.20E-10)	Increased (< 2.20E-10)	Increased (< 2.20E-10)
HC	Decreased (< 2.20E-10)	Decreased (< 2.20E-10)	Decreased (< 2.20E-10)
CO	Decreased (< 2.20E-10)	Decreased (< 2.20E-10)	Decreased (< 2.20E-10)
CO_2	Increased (< 2.20E-10)	Decreased (1.47E-02)	Decreased (1.47E-02)
PM	Decreased (< 2.20E-10)	Decreased (< 2.20E-10)	Decreased (< 2.20E-10)
Bus # 997			
NO_x	Increased (< 2.20e-10)	No change (1.96e-01)	Increased (9.39e-14)
HC	Decreased (< 2.20e-10)	Decreased (< 2.20e-10)	Decreased (< 2.20e-10)
CO	Decreased (< 2.20e-10)	Decreased (< 2.20e-10)	Decreased (< 2.20e-10)
CO_2	Increased (< 2.20e-10)	No change (1.13e-01)	Increased (< 2.20e-10)
PM	Decreased (< 2.20e-10)	Increased (1.30e-08)	Increased (< 2.20e-10)

Evaluation of B10 in comparison to B0 (Table 4.8): In general, all emissions decreased for all the three VSP bins for Bus #971. Results from Bus# 973, showed that NO_x, CO, CO_2 and HC emissions decreased for all bins. PM emissions decreased only at VSP bin3 while increased at lower VSP bins (VSP bin1, VSP bin2). Past research (EPA, 2002) showed similar results except for NO_x emissions which increased. In general, NO_x, HC, CO_2 and PM emissions increased while CO emissions decreased for Bus#997. In summary, with B10 as fuel, results from both the older buses (971, 973) showed decrease in NO_x, HC, CO, and CO_2 emissions while there was inconsistency in PM emissions. All emissions except CO increased when Bus # 997 was fueled with B10.

Evaluation of B20 in comparison to B0 (Table 4.9): For Bus#971, NO_x, HC and PM emissions decreased, while CO and CO_2 emissions increased. This is corroborated with other studies (Frey et al., 2008). NO_x and CO_2 emissions increased while HC, CO and PM emissions decreased when Bus#973 was tested. For Bus#997, NO_x and CO_2 emissions increased. HC, CO and PM emissions decreased. In short, when B20 was used as fuel, HC and PM emissions decreased while in general, CO_2 emissions increased for all the three buses. NO_x and CO emissions showed contradictory results. These results corroborated previous findings where emissions results were contradictory (Ropkins et al., 2007). In general, past research shows similar trends with HC, PM and CO_2 emissions (EPA, 2002; McCormick, 2006; Frey, 2008a).

4.4 Summary and findings

Average emissions trends from B0 to B10 were different (mostly opposite) from the trends from B10 to B20. In other words, emissions were not proportional to % of biodiesel in regular diesel. Existing research shows that tail-pipe emissions (NO_x, HC, CO, CO_2, and PM) are time series with significant auto-correlation. In addition, they exhibit non-normal distributions. These observations necessitated a binning-based approach and the use of non-parametric statistics respectively for data analysis. In general, previous research have assumed emissions data to be normally distributed and compared the mean emissions. The present work used a non-parametric method of comparing the emissions from the different fuels. Emissions were not proportional to speed. Vehicle specific power (VSP) which takes speed and acceleration into account has been shown to explain emissions better. VSP formula was modified to include passenger weight and air-conditioning usage load. Results did not differ significantly when this modified VSP expressions were used (eq. 3.3). This may be attributed to the fact that the passenger load was low most of the time. Rows corresponding to VSP Bin of 1, 2 and 3 were separated and three emissions bins were obtained. Hypotheses tests were conducted on whether the presence of biodiesel in diesel (B0) changes the emission rates. Emission rates (or simply emissions) from both B10 and B20 were statistically compared with emissions from B0. Results obtained from using non-parametric method of statistical testing were comparable with previous studies.

With B10 as fuel, results from both the older buses (971, 973) showed decrease in NO_x, HC, CO, and CO_2 emissions while inconsistency in PM emissions. All emissions except CO increased when Bus # 997 was fueled with B10. This shows variability in on-road emissions from older to newer engine. Large variation in the measurement might be due to the presence of other factors effecting emissions, such as engine condition, driver aggressiveness, and weather conditions (Frey, 2000).

When B20 was used, HC and PM emissions decreased while CO_2 emissions increased for all the three buses. NO_x and CO emissions showed contradictory results. These corroborated previous findings where emissions results for NO_x emissions were contradictory (Ropkins et al., 2007). In general, past research shows similar trends with HC and PM. Results for B20 were much more consistent across the three buses. This can be a useful finding since most engines are fueled with B20 and consequently most of the studies have tested emissions from B20.

CHAPTER 5. CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

Based on the on-road data collection and findings obtained in this research, the following conclusions can be made.

1. On-road emissions are characterized by significant variability because of a lot of real-time variables ranging from driving to environment conditions.

2. Neither the emissions nor the explanatory variables are normally distributed. This restricts the use of various statistical methods which entail normally distributed data. This necessitates the use of non-parametric statistical methods such as Wilcoxon rank sum test, Kruskal Wallis test etc. Use of non-parametric tests provides consistent results with other research findings.

3. Emissions are not proportional to the percentage of biodiesel in the fuel mixture. This was also found by dynamometer tests (Hallmark, 2008) which used the same batch of biodiesel as this study. In addition, results for B10 were inconsistent across old and new engines. Results for B20 were consistent among the three buses (with both Tier-1 and Tier-2 engines).

4. Average emissions do not follow a monotonic trend with speed; they show peak at intermediate speeds. Emissions, however, vary monotonically with VSP.

5. For all practical purposes, increase in passengers (with median of 13) and air conditioning usage may not considerably change the emission rates.

6. CO_2, HC, and PM emissions decreased when B20 was used instead of B0. This corroborated previous studies. Decrease in PM emissions is very significant because heavy duty vehicles (uses diesel) are responsible for most of the PM emissions. Therefore, in this era of soaring fuel prices along with high freight transportation demand, biodiesel is likely to play an important role in fighting environmental pollution.

7. Gasoline engine is the major source of HC and CO emissions (EPA, 2007; National Research Council, 2000). Therefore, decrease in HC emissions is not very significant for diesel engines. Likewise, inconsistency in CO emissions is also immaterial. Inconsistency in NOx emissions continues to encourage more researches and more controlled environment for testing.

5.2 Contributions to the state-of-art

The project has provided valuable insights to a number of aspects related to biodiesel, on-road testing and analysis methodology.

1. It adds knowledge to the understanding of the effect of biodiesel on emissions with varying fuel, engine, passenger load and air conditioning usage.

2. The work offers support to emissions models such as MOVES (the latest version for the EPA emissions model), which uses the VSP function for predicting emission

rates. For a transit bus, passenger load and the use of air conditioning do not significantly change the emissions and therefore they can be modeled accordingly.

3. The findings in this study have provided support to previous studies on B20.
4. The study corroborated the complexity of engine combustion through the illustration of idling emissions.
5. This study has brought important insights into improving on-road data collection and handling numerous errors.
6. The study established the use of non-parametric statistics for comparing emission rates.
7. This works has highlighted the important of non-parametric statistics for analyzing emissions data.

5.3 Challenges and Limitations

Emissions involve a lot of variation even with a single engine-fuel combination as seen in the study. This observed variability in repeated measurements for individual vehicles may not be due to limitations of the test methods themselves (Bishop et al., 1996). In this work, the variability in emissions may be due to the environmental conditions as the data collection period ranged from spring to summer which involves a large variation in temperature of the atmosphere and the pavement. Furthermore, the NDIR method used for detecting HC appears to be sensitive to vibration (Norbeck et al., 2001; Andros Inc, 2003). Vibration is natural in a transit bus running on local busy roads. Variability in emissions might also be due to difference in drivers who operated the buses (Holmen et al., 1997). A limitation of this research was that only two Tier-1 buses and one Tier-2 bus could be tested due to constraints of resources.

5.4 Recommendations for future research

Based on the above gaps in previous research and challenges faced in this work, the following can be considered for future research.

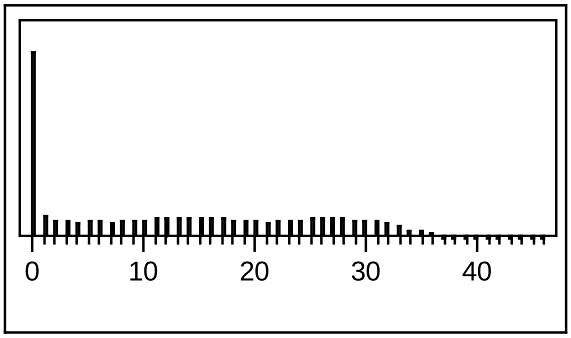
1. B20 results for two buses were reasonably similar to one another but little different from the third bus. More number of buses with same Tier engine and operating conditions can be tested to understand whether the inconsistency in results across buses is statistically justified. Also, more tests are required because typically on-road testing data have considerable percentage of erroneous data. Data can be collected such that variation in driving conditions is minimized. This can be achieved by having a single driver and a uniform route.

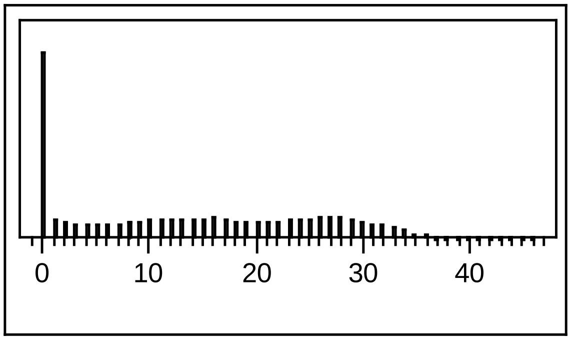
2. Data collection using an on-road emissions measurement device (PEMS) is subjected to numerous failures such as equipment malfunctioning due to extreme weather conditions, loss of satellite link with the GPS, inappropriate sampling etc. These can be tackled by avoiding data collection in extreme weather conditions, use of on-board speed sensor, and making sure that emissions are sampled from the relatively clean ambient air. Testing may be done within a short duration to make sure the problem of

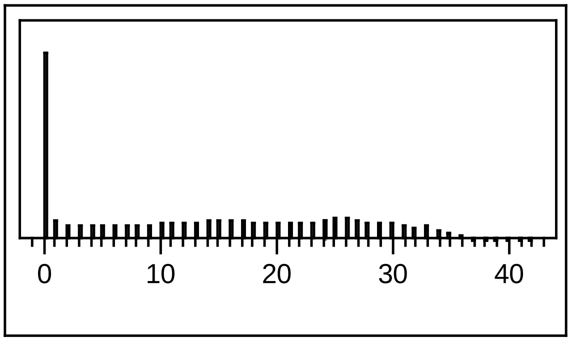
poor oxidation stability (see List of Terms and abbreviations, page number- ix) of biodiesel (due to long storage) does not bias the data.

3. More research is needed on emissions from B10. Further, research is needed on several blends of biodiesels to get a clearer understanding of emissions as function of percentage of biodiesel in the fuel mixture.
4. Data collection is time and energy consuming process. Given the complexity of the emissions formation, non-linear emissions models may be developed which can provide the required estimations.
5. Future research may consider analyzing idling emissions measured through a PEMS.
6. Tests may be conducted on heavy duty trucks by varying the load at different biodiesel blends.
7. New methods to account for dynamic load in VSP expression may be developed.

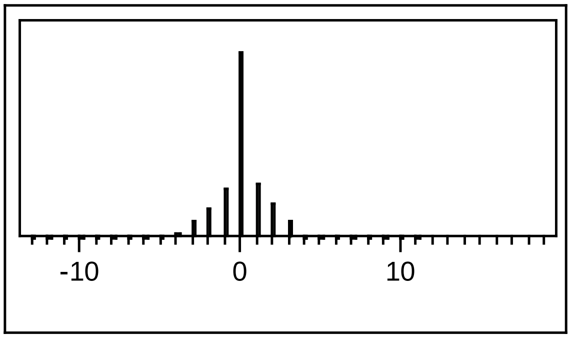
APPENDIX A. DISTRIBUTIONS OF VARIABLES


Bus#971: Speed (mph)

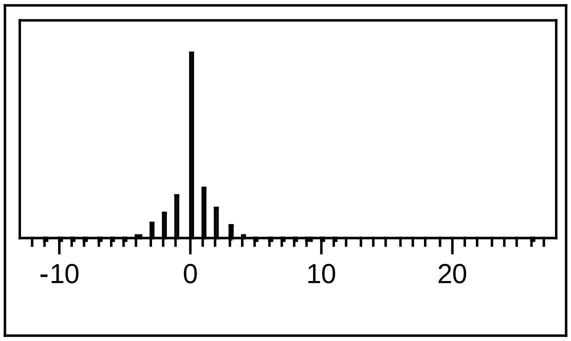

Bus#973: Speed (mph)


Bus#997: Speed (mph)

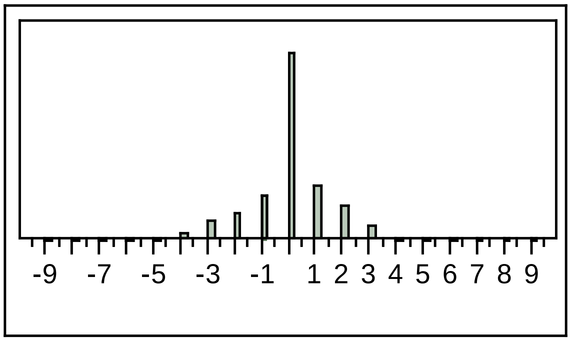
Bus#971: Acceleration (mph/s)

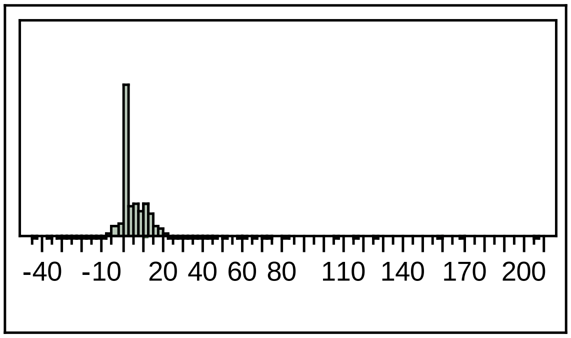


Bus#973: Acceleration (mph/s)

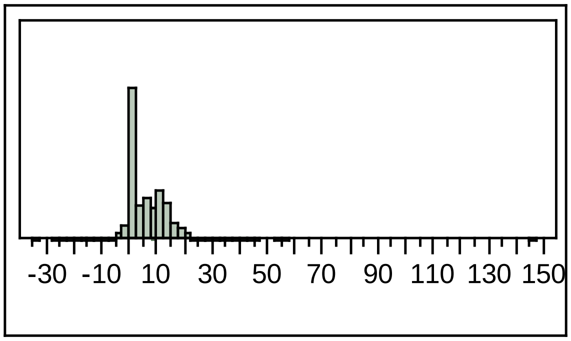


Bus#997: Acceleration (mph/s)

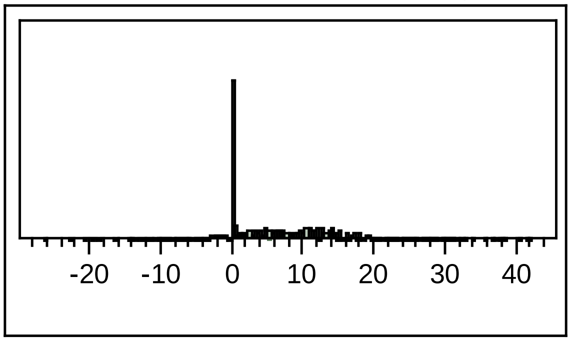




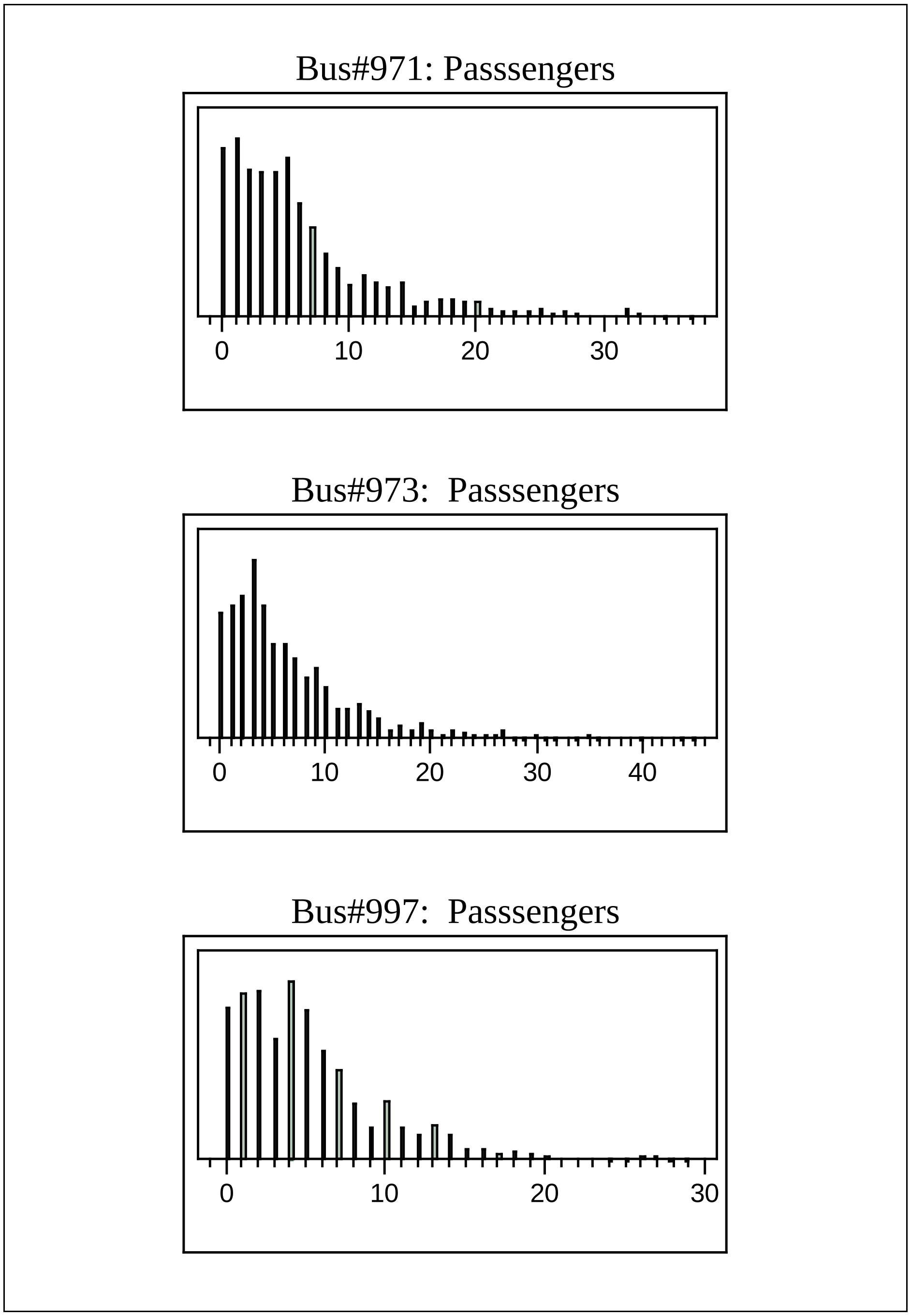
Bus#971: VSP (Watt/Kg)



Bus#973: VSP (Watt/Kg)



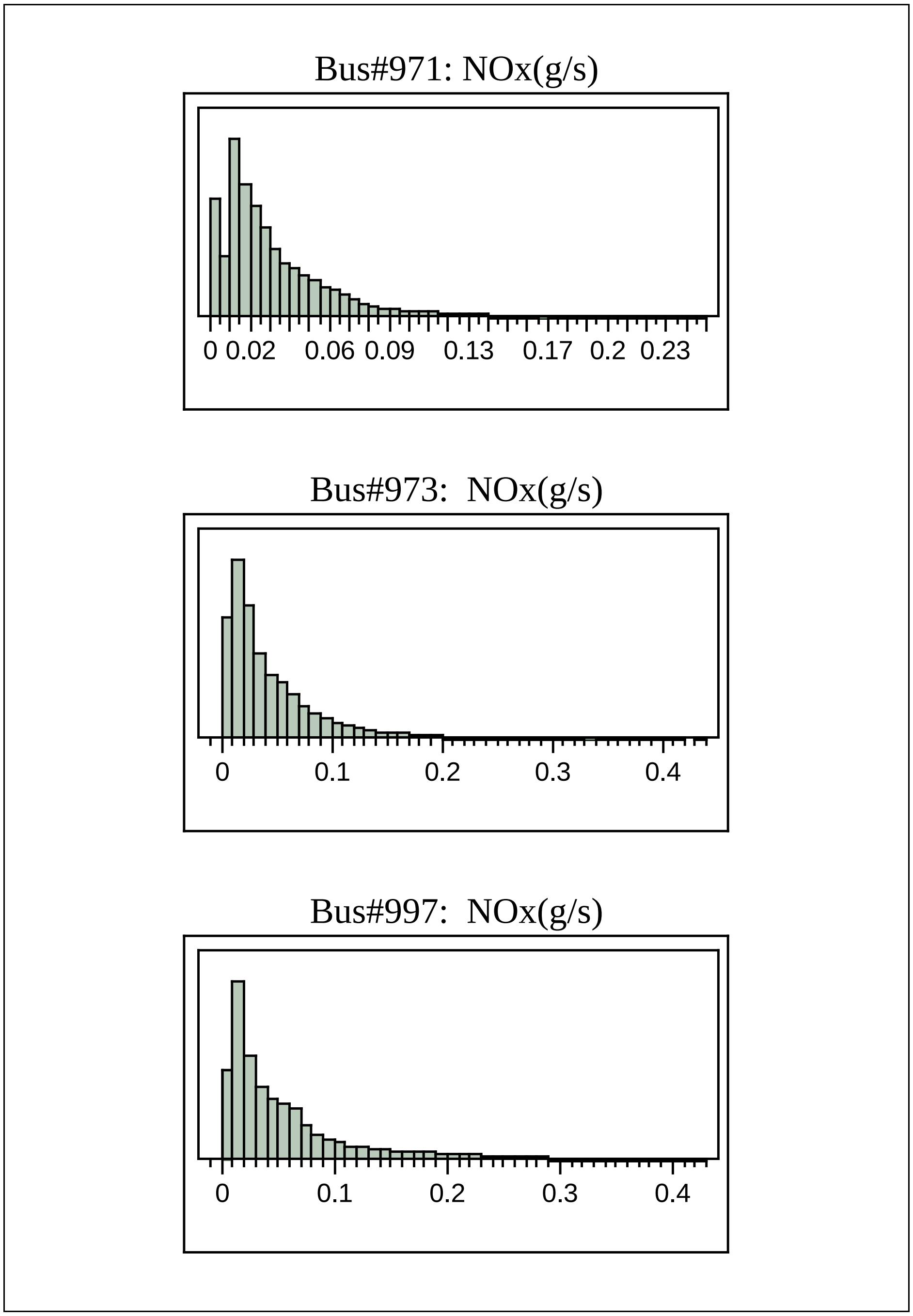
Bus#997: VSP (Watt/Kg)

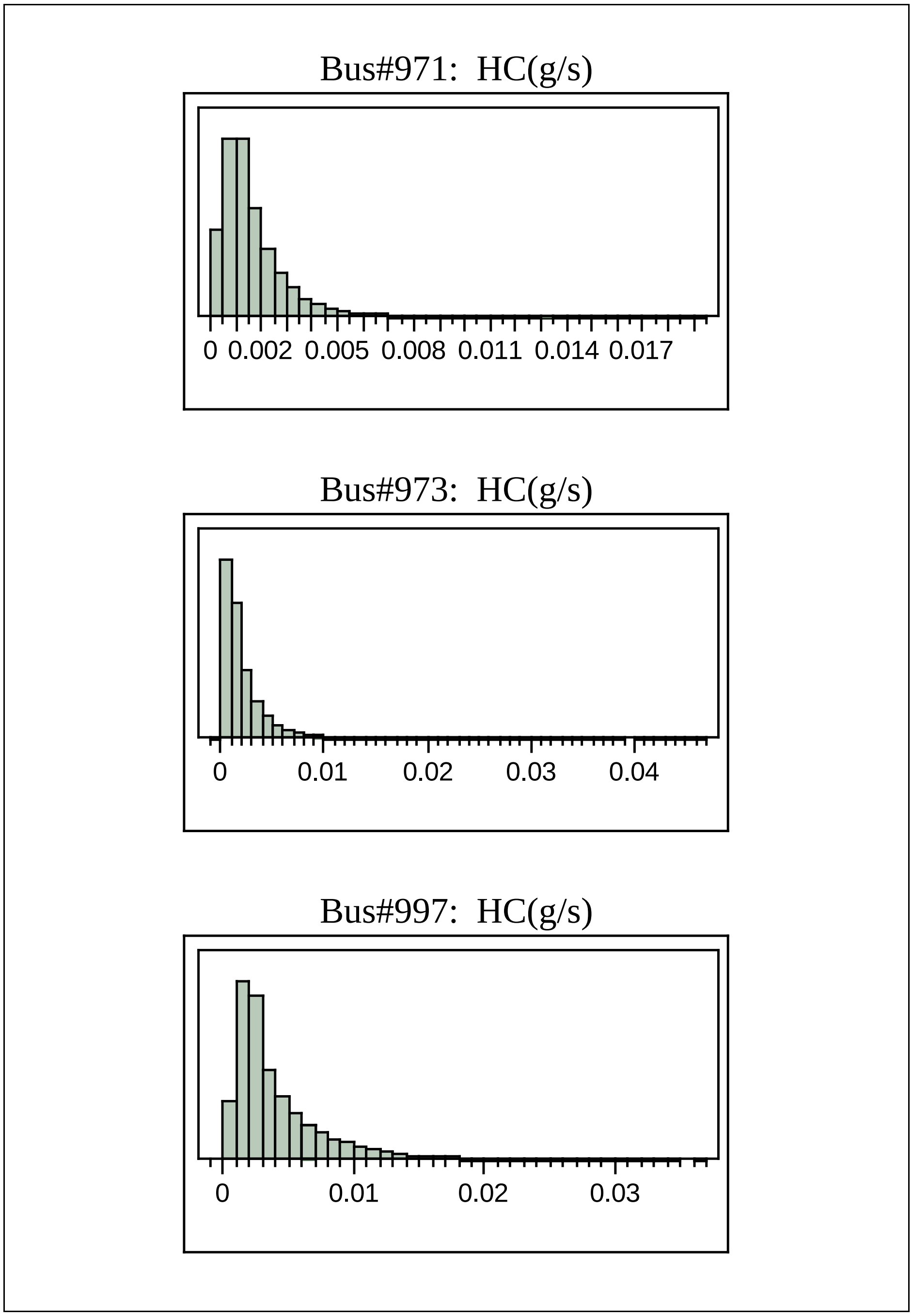


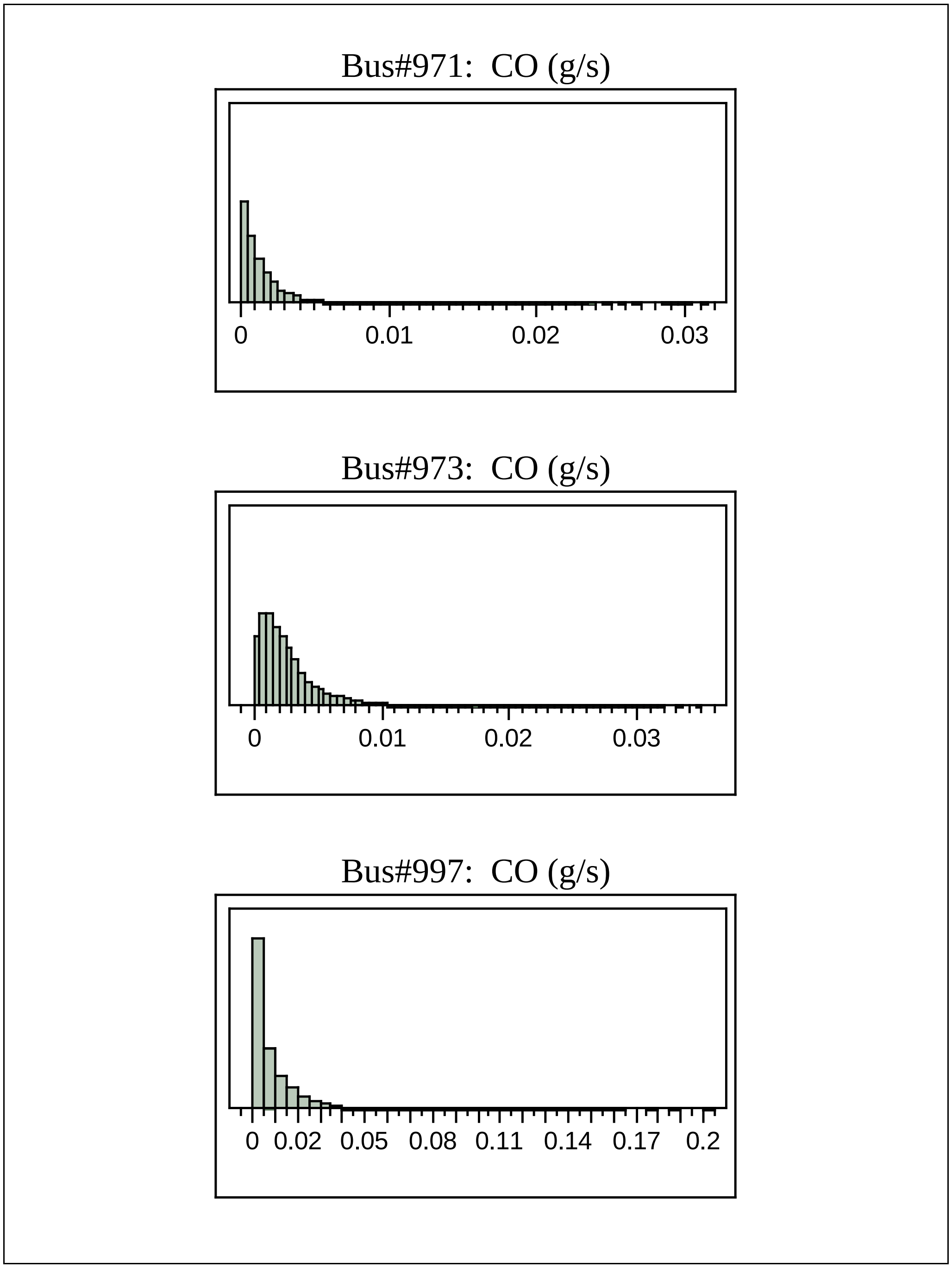
Bus#971: Passsengers

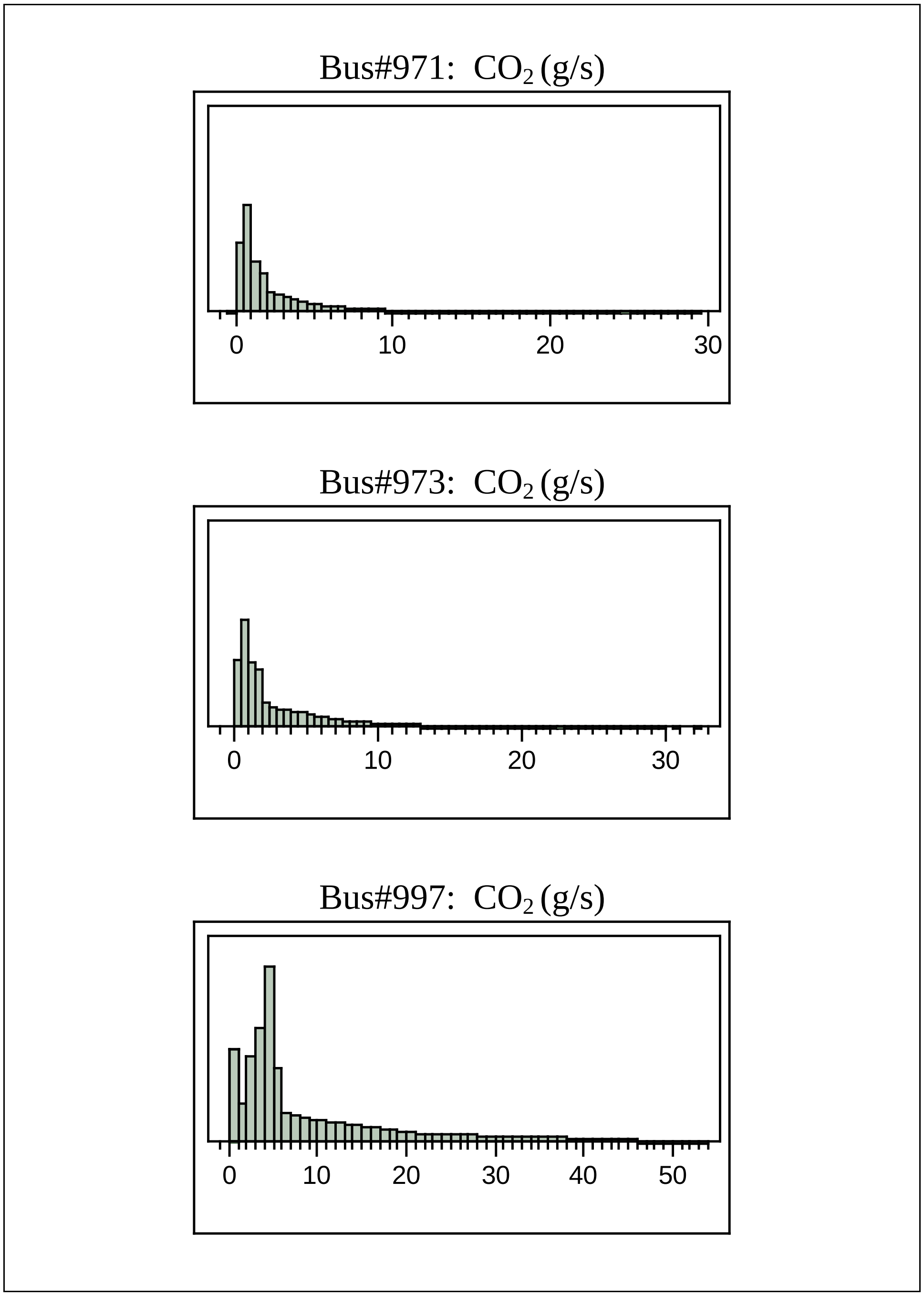
Bus#973: Passsengers

Bus#997: Passsengers


Bus#971: NOx(g/s)
0
0.02
0.06
0.09
0.13
0.17
0.2
0.23
Bus#973: NOx(g/s)
0
0.1
0.2
0.3
0.4
Bus#997: NOx(g/s)
0
0.1
0.2
0.3
0.4


Bus#971: HC(g/s)
0
0.002
0.005
0.008
0.011
0.014
0.017
Bus#973: HC(g/s)
0
0.01
0.02
0.03
0.04
Bus#997: HC(g/s)
0
0.01
0.02
0.03

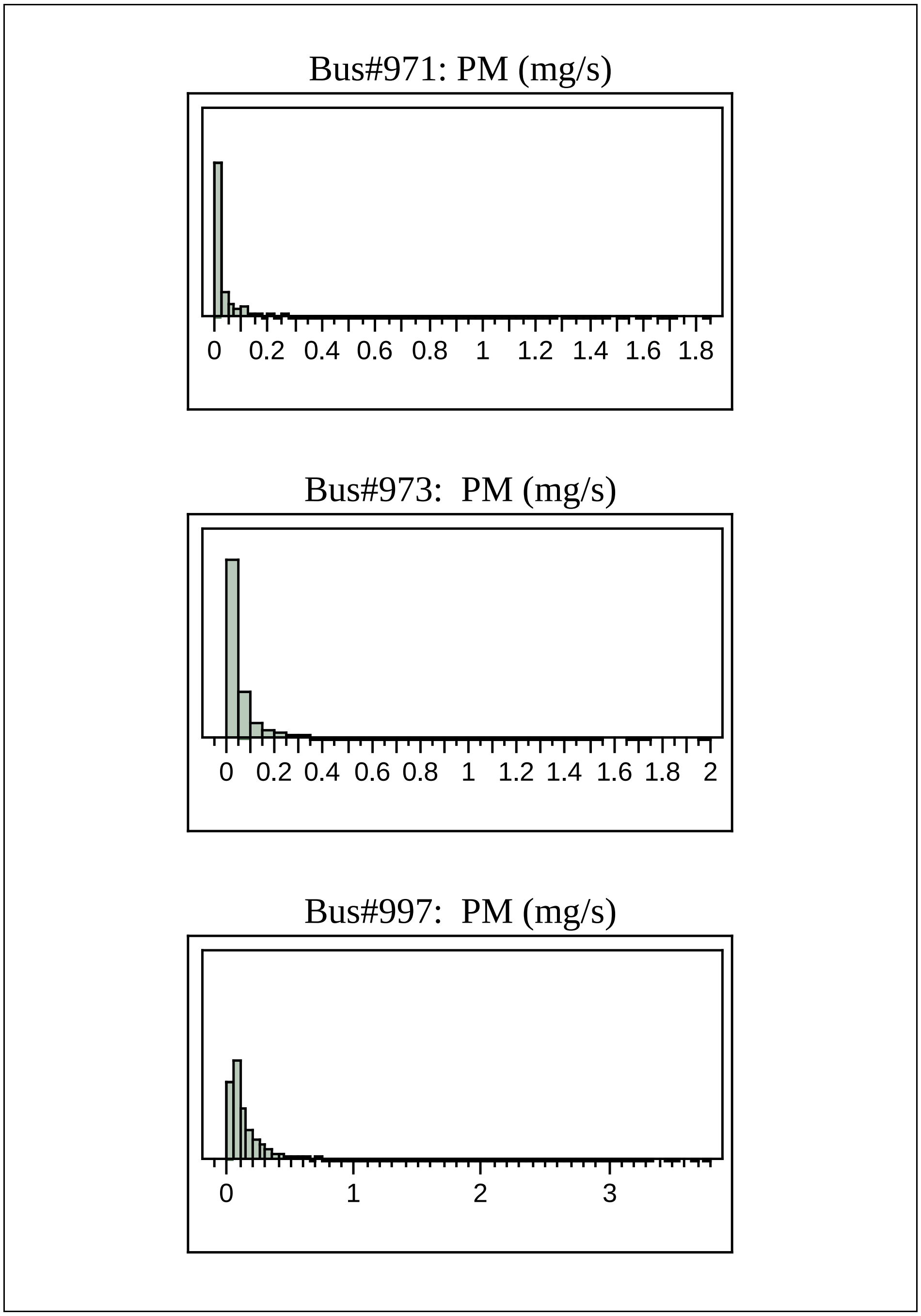

Bus#971: CO (g/s)
0
0.01
0.02
0.03
Bus#973: CO (g/s)
0
0.01
0.02
0.03
Bus#997: CO (g/s)
0
0.02
0.05
0.08
0.11
0.14
0.17
0.2



Bus#971: CO_2 (g/s)

Bus#973: CO_2 (g/s)

Bus#997: CO_2 (g/s)



Bus#971: PM (mg/s)

Bus#973: PM (mg/s)

Bus#997: PM (mg/s)

APPENDIX B. EXAMPLE OF WILCOXON RANK SUM TEST

- The difference in location is the difference in median between the first sample A and the second sample B, in wicoxon.exact (A,B,conf.int=TRUE)
- W is the Wilcoxon statistics
- *Con.int* gives the 95 % confidence interval of the*difference in median.
- The statistics were evaluated by R (statistical software).
- The function was used 3*5*3*3 or 135 times.
- A particular example is shown with the following parameters for BUS ID = 971.

Emissions considered = NO_x , VSP BIN=1, Fuels = B0 vs. B10 (comparison)

Hypothesis: H_0: NOx emissions for B0 fuel = NOx emissions for B10 fuel

H_a : NOx emissions for B0 fuel ≠ NOx emissions for B10 fuel

R command (function): **wilcox.exact**(NOxB10,NOxB0, conf.int = TRUE)

RESULTS:

Data: NOxB0 and NOxB10 (NO_x emissions from fuel B0 and B10 respectively)

W = 638863228, **p-value** = 0.003185

Alternative hypothesis: true mu is not equal to 0

95 percent confidence interval: [6.3046×10^{-05}, 4.2615×10^{-04}]

Sample estimates: difference in location = 0.0002854888
[This is **Median (NOxB10) –Median (NOxB0)]**

Conclusion: NO_x emissions from B10 fuel are not equal to but higher than NO_x emissions from B0 fuel.

BIBLOGRAPHY

1. Agarwal, A. K. (2007). Biofuels (Alcohols and Biodiesel) Applications as Fuels for Internal Combustion Engines. *Progress in Energy and Combustion Science, Vol. 33, No. 3* , 233-271.

2. Ahn, K., Rakha, H., Trani, A., & Van Aerde, M. (2002). Estimating vehicle fuel consumption and emissions based on instantaneous speed and acceleration levels. *ASCE Journal of Transportation Engineering* .

3. Antony, R. (2008). *Biodiesel Performance, Costs, and use*. Retrieved April 7, 2008, from http://www.eia.doe.gov/oiaf/analysispaper/biodiesel/

4. ASTM. (1991). *ASTM D2500-91*. Standard Test Method of Cloud Point of Petroleum Products. *American Society for Testing and Material*.

5. ASTM. (1996). ASTM D97-96a Standard Test Method of Pour Point of Petroleum Products. *American Society for Testing and Material*.

6. Belliss, G. (2004). Detailed speed and travel time surveys using low cost GPS equipment. *IPENZ Transportation Group Technical Conference.*

7. Bishop, G. A., Stedman, D. H., & Ashbaugh, L. (1996). Motor Vehicle Emissions Variability. *Journal of Air and Waste Management Association 46-7* , 667-675.

8. Borrell, E. R., McKain, D. L., Paramo, V. H., Wayne, W. S., Vergara, W., Barnett, R. A., et al. (2006). Evaluation of Emissions from New and In-Use Transit Buses in Mexico City, Mexico. *Transportation Research Record: Journal of the Transportation Research Board,* No. 1987 , pp. 42-53.

9. CABQ. (2008). *Remote Sensing - Vehicular pollution management*. Retrieved Nov 30, 2008, from http://www.cabq.gov/aircare/rst.html

10. CATI. (2007). *OEM-2100 Montana System*: Operation Manual. Buffalo, New York: Clean Air Technology Inc.

11. CATI. (2000). *OEM-2100 Portable Onboard Mobile Emissions Monitor working projects.* Retrieved July 12, 2000, from Clean Air Technologies Inc.: http://www.cleanairt.com/main.html

12. CBSII. (2008). *Understanding Emissions Regulations.* Retrieved Nov 30, 2008, from CBS Interactive Inc.:

    http://findarticles.com/p/articles/mi_m3012/is_9_183/ai_108098150/prin

13. Chetwynd, T., MacIsaac, N., & Mugaas, A. S. (2005). *Econ 5253 Project Cycle Analysis*. Wilson Fuels and the Biodiesel Project , p. 11.

14. Clark, T. (1998). *GPS determination of course and speed*. Retrieved Nov 30, 2008, from http://www.aprs.net/vm/gps_cs.htm

15. Conover, W. J. (1980). *Practical Nonparametric Statistics (3rd Ed.)*. Wiley Series in Probability and Statistics.

16. Cyride. (2008). *About Cyride*. Retrieved Sep 30, 2008, from http://www.cyride.com/about/about.html

17. EPA. (October 2002). A Comprehensive Analysis of Biodiesel Impacts on Exhaust Emissions. *US Environmental Protection Agency*.

18. EPA. (2008a). *Automobile Exhaust emissions*. Retrieved Nov 30, 2008, from http://www.epa.gov/nrmrl/pubs/600r98097/600R98097chap2.pdf

19. EPA. (2008b). *National Clean Diesel Campaign*. Retrieved Nov 30, 2008, from http://www.epa.gov/cleandiesel

20. Faiz, A., Weaver, C. S., & Walsh, M. P. (1996). Air Pollution from Motor Vehicles: Standards and Technologies for Controlling Emissions. Washington, D.C.: *World Bank Publications.*

21. Farzaneh, M., Zietsman, J., Perkinson, D., & Spillane, D. (2008). Comparative field evaluation of biodiesel impact on hot stabilized emissions from school buses. *Submitted to the 87th Transportation Research Board Annual Meeting.* Washington D.C.: Transportation Research Board.

22. Fernando, S., Hall, C., & Jha, S. (2006). NO_x Reduction from Biodiesel Fuels. *Energy and Fuels, Vol. 20* , 378-382.

23. Frey, H. C. (1997). Variability and Uncertainty in Highway Vehicle Emission Factors. *Oct 28-30, Emission Inventory: Planning for the Future* (pp. 208-219). Pittsburgh, Pennsylvania: Air and Waste Management Association.

24. Frey, H., Rouphail, N., Unal, A., & Colyar, J. (2000). Emissions and Traffic Control: An Empirical Approach. *March 27-29, CRC On-Road Vehicle Emissions Workshop.* San Diego, California.

25. Frey, H. C., Rouphail, N. M., Unal, A., & Colyar, J. D. (2001). Emissions Reduction Through Better Traffic Management: An Empirical Evaluation Based Upon On-Road Measurements. *North Carolina State University*. Raleigh, NC.

26. Frey, H. C., Unal, A., & Chen, J. (2002). Recommended Strategy for On-Board Emission Data Analysis and Collection for the New Generation Model. Department of Civil Engineering, *North Carolina State University*. Raleigh, NC.

27. Frey, H., & Kim, K. (2005). Operational Evaluation of Emissions and Fuel Use of B20 Versus Diesel Fueled Dump Trucks. Federal Highway Administration FHWA/NC/2005-07. Center for Transportation and the Environment, *North Carolina State University*, Raleigh, NC.

28. Frey, H. C., Rouphail, N. Z., Zhai, H., Farias, T. L., & Goncalves, G. A. (2007). Comparing real-world fuel consumption for diesel- and hydrogen-fueled transit buses and implication for emissions. *Transportation Research Part D: Transport and Environment (12) 4* , 281-291.

29. Frey, H. C., Rouphail, N. M., & Zhai, H. (2008). Link-Based Emission Factors for Heavy-Duty Diesel Trucks Based on Real-World Data. *Submitted to Transportation Research Board 2008 87th Annual Meeting*. Washington D.C.: Transportation Research Board.

30. Frey, H., William, R., Kim, K., Pang, S., & Lewis, P. (2008a). Comparison of Real-World Emissions of B20 Biodiesel Versus Petroleum Diesel for Selected Nonroad Vehicles and Engine Tiers. *Transportation Research Record: Journal of the Transportation Research Board* , 33-42.

31. Frey, H. C., WRasdorf, W., Kim, K., Pang, S. L., & Lewis, P. (2008b). Comparison of Real World Emissions of Backhoes, Front-End Loaders, and Motor Graders for B20 Biodiesel vs. Petroleum Diesel and for Selected Engine Tiers. *Submitted to the 87th Transportation Research Borard 2008 Annual Meeting*. Washington D.C.: Transportation Research Borard.

32. Graboski, M. S., & McCormick, R. L. (1998). Combustion of Fat and Vegetable Oil Derived Fuels in Diesel engines. *Progress in Energy and Combustion Science 24-2* , 125-164.

33. Gragg, K. (1994). Effects of Environmentally Classified Diesel Fuels, RME and Blends of Diesel Fuel and RME on the Exhaust Emissions. *Sweden: Motor Test Center Report 9209 b.*

34. Graphpad. (2008). *Graphpad Software*. Retrieved Nov 14, 2008, from http://www.graphpad.com

35. Hallmark, S., Kong, S. C., Mudgal, A., Orellana, M., & Kroeger, D. (2008). Evaluation of On-road and Laboratory Engine Dynamometer Emission Tests to Compare the Emission Reduction Potential of Different Biodiesel Blends. *Center for Transportation Research and Education*. Ames, IA.

36. Hansen, H. K., & Jensen, M. G. (1996). Chemical and biological characteristics of Exhaust Emissions from a Di Diesel Engine Fuelled with Rapeseed Oil Methyl Ester (RME). *Society of Automotive Engineers, SAE paper 971689* .

37. Hess, M. A., Haas, M. J., & Foglia, T. E. (2007). Attempts to reduce NOx exhaust emissions by using reformulated biodiesel. *Fuel Processing Technology 88* , 693-699.

38. Heywood, J. B. (1988). *Internal combustion engine fundamentals.* McGraw-Hill.

39. Holmen, B. A., & Niemeier, D. A. (1998). Characterizing the effect of driver variability on real-world vehicle emissions. *Transportation research-D* 3-2 , 117-128.

40. Inc., A. (2008). *Concentrations Measurement and Span Calibration using n-Hexane and Propane in the ANDROS 6602/6800 Automotive Exhaust Gas Analyzer*. Retrieved Nov 30, 2008, from http://www.andros.com/hmDownloads.htm

41. Jiménez-Palacios, J. L. (1999). Understanding and Quantifying Motor Vehicle Emissions with Vehicle. *Massachusetts Institute of Technology*, Cambridge.

42. Knothe, G., Sharp, C. A., & Ryan, T. W. (2006). Exhaust emissions of biodiesel, petrodiesel, neat methyl esters, and alkanes in a new techonology engine. *Energy and Fuel (20)* , 403-8.

43. L. G. Schumacher, W. M. (2001). Biodiesel emissions data from series 60 DDC engines. *American Society of Agricultural Engineers, Vol. 44(6)* , 1465–1468.

44. *Lubicity benefits*. (n.d.). Retrieved 11 26, 2008, from National Biodiesel Board: http://www.biodiesel.org/pdf_files/fuelfactsheets/Lubricity.PDF

45. Mazzoleni, C., Kuhns, H. D., Moosmüller, H., Witt, J., Nussbaum, N. J., Oliver Chang, M.-C., et al. (2007). A case study of real-world tailpipe emissions for school buses using a 20% biodiesel blend. *Science of The Total Environment, Volume 385, Issue 1-3* , 146-159.

46. McCormick, R. L., Alleman, T., Barnitt, R., Clark, W., Hayes, B., Ireland, J., et al. (2006a). Biodiesel R&D at National Renewable Energy Labratory. *February 5-8, National Biodiesel Conference & Expo,*. San Diego: California.

47. McCormick, R. L., Williams, A., Ireland, J., Brimhall, M., & Hayes, R. R. (October, 2006b). Effetcs of biodiesel blends on vehicle emissions. *National Renewable Energy Laboratory* NREL/MP-540-4 0 55 4. Golden, Colorado.

48. Mcdonald, J. (1995). Emission Characteristics of Soy Methyl Ester Fuels in an IDI Compression Ignition Engine. *Society of Automotive Engineers, SAE paper 950400* .

49. Miller, J. W., Durbin, T., Johnson, K., & Cocker, D. (2006). Evaluation of Portable Emissions Measurement Systems (PEMS) for Inventory Purposes and the Not-To-Exceed Heavy-Duty Diesel Engine Regulation. College of Engineering-*Center for Environmental Research and Technology*. Riverside, California.

50. National Research Council. (2000). Modeling Mobile-Source Emissions. *National Academy Press*. Washington, D.C.

51. Neave, H., & Worthington, P. (1998). *Distribution Free Tests.* Unwin Hyman.

52. NIST. (2008). *Measure of skewness and kurtosis.* Retrieved Nov 11, 2008, from National Institute of Standards and Technology: http://www.itl.nist.gov/div898/handbook/eda/section3/eda35b.htm

53. Norbeck, J., Miller, J., Welch, W., Smith, M., Johnson, K., & Pankratz, D. (2001). Develop On-Road System for Emissions Measurement from Heavy-Duty Trucks. *University of California at Riverside* 0012-AP-20906-005-FR. Riverside, California.

54. Orion. (2008). *Orion International - Products*. Retrieved Nov 30, 2008, from http://www.dcbusna.com/orion/0-867-584008-1-584011-1-0-0-0-0-1-10595-584008-0-0-0-0-0-0-0.html

55. Qu, Y., Holmen, B. A., & Ravishanker, N. (2008). Predicting Light-Duty Gasoline Vehicle On-Road Particle Number Concentrations From Gas Concentrations Using Time-Series Cross-Section Regression. *Submitted to the 87th Transportation Research Board Annual Meeting.* Washington D.C.

56. Ropkins, K., Quinn, R., Beebe, J., Li, H., Daham, B., Tate, J., et al. (2007). Real-world comparison of probe vehicle emissions and fuel consumption using diesel and 5% biodiesel (B5) blend. *Science of The Total Environment, Volume 376, Issue 1-3* , 267-284.

57. Rouphail, N. M., Frey, H. C., Colyar, J., & Unal, A. (2001). Vehicle Emissions and Traffic Measures: Exploratory Analysis of Field Observations at Signalized Intersections. *80th Annual Meeting of the Transportation Research Board.* Washington DC.

58. Schumacher, L. G., Marshal, W., Krahl, J., Wetherell, W. B., & Grabowski, M. S. (2006). Biodiesel emissions data from series 60 DDC engines. *Trans ASAE 44(6)* , 1465-8.

59. Sheehan, J., Camobreco, V., Duffield, J., Graboski, M., & Shapouri, H. (1998). Life Cycle Inventory of Biodiesel and Petroleum Diesel for Use in an Urban Bus: Final Report, *NREL/SR-580-24089. National Renewable Energy Laboratory*. Golden, CO.

60. Song. (2008). Emission Analysis at a Toll Station in Beijing Using PEMS' Measurement. *Submitted to the 87th Transportation Research Board Annual Meeting.* Washington D.C.

61. Song, G., Yu, L., & Wang, Z. (2008). A Practical Modeling approach for Evaluation of Fuel Efficiency for Road traffic. *Submitted to the 87th Transportation Research Board Annual Meeting.* Washington D.C.

62. Stephens, M. A. (1974). EDF statistics for goodness of fit and some comparisons. *Journal of the American Statistical Association (69)* , pp. 730-737.

63. Unal, A., Frey, H. C., Rouphail, N. M., & Colyar, J. D. (2001). Hot spot analysis of real world vehicle emissions based upon a portable on-board measurement system. *Abstract# 42159 . North Carolina State University*. Raleigh, North Carolina.

64. Vijayan, A., Kumar, A., & Abraham, M. (2008). Experimental analysis of vehicle operation parameters affecting emission behavior of public transport buses operating on alternative diesel fuels. *Submitted to the 87th Transportation Research Board Annual Meeting.* Washington D.C.

65. Wang, A., Clark, B., O' Salley, S., & Simon Ng, K. Y. (2007). Oxidative stability of 20% soy-based biodiesel (B20) in ultra-low sulfur diesel. *May 13-16, 98th AOCS Annual Meeting.* Quebec City, Canada.

66. Wang, A., H., T., Bradley, C., J., W., Salley, S. O., & Simon Ng, K. Y. (2007). Oxidative Stability of 20% Soy-based Biodiesel (B-20) in Ultra-low Sulfur Diesel. *5-*7 November, International Congress on Biodiesel: *The Science and The Technologies*. Vienna,Austria.

67. Washington, S., P., Karlaftis, M., G., Mannnering, F. L. (2003). *Statistical and Econometric Methods for Transportation Data Analysis*. Chapman & Hall/CRC

68. Yu, L., Wang, Z., Qiao, F., & Qi, Y. (2008). Vehicle Emission Characteristics-based Approach to the Development and Evaluation of Driving Cycles for Classified Roads. *Submitted to the 87th Transportation Research Board Annual Meeting*. Washington D.C.