Evaluation of On-road and Laboratory Engine Dynamometer Emission Tests to Compare the Emission Reduction Potential of Different Biodiesel Blends

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16. Abstract

Biodiesels are often marketed as being cleaner than regular diesel for emissions. Emission test results depend on the biodiesel blend, but laboratory tests suggest that biodiesels decrease particulate matter, carbon monoxide, hydrocarbons, and air toxins when compared to regular diesel. Results for the amount of oxides of nitrogen (NO_x) have been less conclusive.

Tests have not evaluated the commonly available ranges of biodiesel blends in the laboratory. Additionally, little information is available from on-road studies, so the effectiveness of using biodiesels to reduce actual emissions is unknown. A more complex relationship exists between engine operation and the rate of emission production than is typically evaluated using engine or chassis dynamometer tests. On-road emissions can vary dramatically because emissions are correlated to engine mode. Additionally, activity such as idling, acceleration, deceleration, and operation against a grade can produce higher emissions than more stable engine operating modes. Since these modes are not well captured in a laboratory environment, understanding on-road relationships is critical in evaluating the emissions reductions that may be possible with biodiesels. More tests and quantifications of the effects of different blends on engine and vehicle performance are required to promote widespread use of biodiesel.

The objective of this research was to conduct on-road and laboratory tests to compare the emission impacts of different blends of biodiesel to regular diesel fuel under different operating conditions. The team conducted engine dynamometer tests as well as on-road tests that utilized a portable emissions monitoring system that was used to instrument transit buses. Regular diesel and different blends of biodiesel were evaluated during on-road engine operation by instrumenting three in-use transit buses, from the CyRide system of Ames, Iowa, along existing transit routes. Evaluation of transit buses was selected for this study rather than heavy-duty trucks since transit buses have a regular route. This way, emissions for each of the biodiesel blends could be compared across the same operating conditions.

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EVALUATION OF ON-ROAD AND LABORATORY ENGINE DYNAMOMETER EMISSION TESTS TO COMPARE THE EMISSION REDUCTION POTENTIAL OF DIFFERENT BIODIESEL BLENDS

Final Report
August 2008

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EXECUTIVE SUMMARY

Biodiesels are often marketed as being cleaner than regular diesel for emissions. Emission test results depend on the biodiesel blend, but laboratory tests suggest that biodiesels decrease particulate matter, carbon monoxide, hydrocarbons, and air toxins when compared to regular diesel. Results for oxides of nitrogen (NO_x) have been less conclusive.

Tests have not evaluated the commonly available ranges of biodiesel blends in the laboratory. Additionally, little information is available from on-road studies, so the effectiveness of using biodiesels to reduce actual emissions is unknown. A more complex relationship exists between engine operation and the rate of emission production than is typically evaluated using engine or chassis dynamometer tests. On-road emissions can vary dramatically since emissions are correlated to engine mode and activity such as idling, acceleration, deceleration, and operation against a grade produce higher emissions than more stable engine operating modes. Since these modes are not well captured in a laboratory environment, understanding on-road relationships is critical in evaluating the emissions reductions that may be possible with biodiesels. More tests and quantifications of the effects of different blends on engine and vehicle performance are required to promote widespread use of biodiesel.

The objective of this research was to conduct on-road and laboratory tests to compare the emission impacts of different blends of biodiesel to regular diesel fuel under different operating conditions. The team conducted engine dynamometer tests as well as on-road tests that utilized a portable emissions monitoring system that was used to instrument transit buses. Regular diesel and different blends of biodiesel were evaluated during on-road engine operation by instrumenting three in-use transit buses, from the CyRide system in Ames, Iowa, along existing transit routes. Evaluation of transit buses was selected for this study rather than heavy-duty trucks because transit buses have a regular route. This way, emissions for each of the biodiesel blends can be compared across the same operating conditions.

Summary for On-road Tests

The three different types of diesel and biodiesel were evaluated in three in-service transit buses using a portable emissions monitor (B-0, B-10, and B-20). Two buses, Bus 973 and 971, fall into the 1998-2003 diesel engine emissions standard time frame. Data were collected for the two buses during spring-like conditions (April and May 2008 with cooler temperatures). The third bus, Bus 997, falls into the 2004-2006 diesel engine emissions standard time frame and data was collected during summer conditions (June and July 2008 with hot and humid conditions and regular air conditioning use).

Simple comparison of the three fuels for each pollutant of interest for each bus were made by mode (idle, steady state, acceleration, deceleration) and speed range. Averages are in g/s. Results for Bus 973 indicates that average NO_x emissions were generally lower for B-10 than for B-0 but higher for B-20. Mixed results were found for Bus 971 with NO_x emissions higher for some speed ranges and modes for B-10 and B-20 than for B-0 but emissions were lower in some cases.

Average NO_x emissions were usually higher for both B-10 and B-20 than for B-0 for all modes and speed ranges for Bus 997.

Average HC emissions were lower for B-10 and B-20 than for Bus 973 for all modes and speed ranges and for Bus 971 except HC emissions during deceleration. HC emissions for B-20 were lower for Bus 997 than for B-0 but HC emissions for B-10 were higher than for B-0. Carbon monoxide emissions were lower for both B-10 and B-20 than for B-0 for all modes and speed ranges for Bus 973 and 997. However, while B-10 CO emissions were lower than B-0, B-20 emissions were higher than B-0 for Bus 971.

Results for carbon dioxide were mixed for Bus 973. Average CO_2 emissions were similar or slightly higher for both biodiesel blends than for regular diesel for idling, steady state, and deceleration while they were slightly lower in most cases for acceleration. CO_2 emissions were generally lower for B-10 than for B-0 but were higher for B-20 for idling, steady state, and acceleration while results were mixed for deceleration for Bus 971. CO_2 emissions were similar for Bus 997 as for Bus 973 with similar or slightly higher average emissions for B-10 and B-20 than for B-0 during idling, steady state, and deceleration while results were inconclusive for deceleration. PM emissions were much higher for B-10 than for B-0 for Bus 973 and Bus 997 for all modes and speed ranges while B-20 PM emissions were similar or slightly higher. For Bus 971, the two biodiesel blends resulted in significantly lower PM emissions than B-0 for all modes and speed ranges.

A summary of the results of the statistical model are presented in the table below. Emissions by bus by fuel types, pollutant, and mode are presented in the table. Evidence of difference in emissions means (g/s) was found for all the buses for all the studied pollutants for almost all the compared fuel types and the different driving modes. However, in some cases differences in estimated means were small. Number 1 represents the highest estimated mean emissions. In most cases the results were statistically significant. So for instance, B-10 had the highest mean NO_x emissions (g/s) for Bus 971. In all cases emissions were highest while the bus was in acceleration mode.

Table. Summary of model results by bus and pollutant for fuel and mode

		NOx		HC		CO		CO2		PM	
Bus	**Ranking**	**Fuel**	**Mode**	**Fuel**	**Mode**	**Fuel**	**Mode**	**Fuel**	**Mode**	**Fuel**	**Mode**
971	**1**	B10	Accel	B0	Accel	B20	Accel	B20	Accel	B0	Accel
	2	B0	Steady	B20	Steady	B0	Steady	B0	Steady	B10	Steady
	3	B20	Idle	B10	Decel	B10	Idle	B10	Idle	B20	Decel
	4		Decel		Idle		Decel		Decel		Idle
973	**1**	B20	Accel	B0	Accel	B20	Accel	B20	Accel	B10	Accel
	2	B0	Steady	B10	Steady	B0	Steady	B0	Steady	B20	Steady
	3	B10	Idle	B20	Decel	B10	Idle	B10	Idle	B0	Decel
	4		Decel		Idle		Decel		Decel		Idle
977	**1**	B20	Accel	B10	Accel	B0	Accel	B10	Accel	B10	Accel
	2	B0	Steady	B0	Steady	B10	Steady	B20	Steady	B20	Steady
	3	B10	Idle	B20	Decel	B20	Idle	B0	Idle	B0	Idle

	4		Decel		Idle		Decel		Decel		Decel	

Results of the descriptive statistics and statistical modeling are fairly consistent. NOx, HC, CO, emissions for results are generally consistent with what has been reported for biodiesels. PM emissions were much lower for one bus for B-10 and B-20 which is consistent with other studies but for the other two buses, PM emissions for biodiesels were either higher or similar to those for regular diesel.

Summary for Laboratory Tests

The effects of biodiesel blends on engine performance and exhaust emissions were investigated and verified by the laboratory engine testing. Various engine load conditions that are representative of the operation of the present engine class were tested. Results indicate that increases in NO_x and decrease in soot, CO, and HC emissions are obtained by using biodiesel blends. Engine test results show that the increased NO_x emissions using B-10 and B-20 are approximately the same for the three load conditions studied. In general, soot emissions were reduced by using B-10 and B-20. However, soot emissions are approximately the same for three fuels at the 1,200 rpm light load condition, under which the soot emissions are already relatively low and it is hard to distinguish among them. The CO emissions decrease as the biodiesel contents increase. However, a clear trend of declining HC emissions was not observed with increased biodiesel contents. Both B-10 and B-20 produced lower HC emissions than B-0, but B-20 produced higher HC emissions than B-10.

In general, the trends of increasing NO_x emissions and decreasing soot, CO, and HC emissions are obtained by using biodiesel blends. There are only a few operating points for which a clear trend is not observed. Although certain trends may be expected, it should be noted that the emission results for various biodiesel blends may vary due to differences in specific engine operating conditions and fuel properties. This study followed the test protocol described above, and the results obtained were consistent throughout the testing. The general effects of biodiesel on engine performance have been observed.

1. INTRODUCTION

1.1 Background

Heavy-duty vehicles, including buses, make up approximately 4% of the on-road vehicle fleet. In contrast, they account for more than 8% of vehicle miles traveled on roadways in the United States and consume more than 22% of the total fuel used by on-road vehicles (USDOT 2006). Heavy-duty vehicles are estimated to contribute a significant proportion of regulated ambient emissions, which includes particulate matter (PM), carbon monoxide (CO), oxides of nitrogen (NO_x), and volatile organic compounds (VOC). The U.S. Environmental Protection Agency (USEPA) estimates the contribution of highway vehicles is 32% of NO_x emissions, with heavy-duty vehicles responsible for up to 38% of that amount (USEPA 2000). Other studies indicate that heavy-duty vehicles contribute as much NO_x as passenger vehicles (Sawyer 2000). The total estimated highway vehicle contribution to VOCs is 30%, 9% of which comes from heavy-duty vehicles. Heavy-duty vehicles also contribute 13% of the carbon monoxide emissions attributed to highway vehicles. Nationally, heavy-duty vehicles are also responsible for 65% and 75% of the on-road vehicle contribution to PM_{10} and $PM_{2.5}$, respectively (USEPA 2000).

A significant emphasis has been placed on the development and use of biorenewable fuels to improve air quality. Biofuels have received attention as a sustainable energy source and for their potential in lessening U.S. dependence on foreign oil and thus enhancing national security. The feedstock to produce biofuels is produced locally, and thus the use of biofuels will also enhance the local economy. A number of states are moving towards setting Renewable Fuels Standards (RFS). Iowa is setting the most aggressive standard with a RFS of 25% by 2020 (Green Car Congress 2007). Use of biodiesel is of particular interest because of the contribution heavy-duty vehicles make to emissions. Additionally, fleets of vehicles, such as transit vehicles or trucking fleets, may be more readily targeted for use of biofuels since they often have their own refueling facilities. Consequently, as agencies review their options for meeting air quality goals, they are more frequently considering use of biodiesel (USEPA 2002). In 2005, approximately 75 million gallons of biodiesel were sold in the U.S. (National Biodiesel Board 2006).

Biodiesel will also provide numerous advantages in terms of fuel preparation and engine operation. Biodiesel blends are simple to prepare and use in that they require no specific handling considerations. Biodiesel is biodegradable and essentially free of sulfur and aromatics, and thus it has the potential to reduce certain harmful pollutants. Biodiesel has a better lubricity and can reduce the wear of engine parts. Biodiesel is also easy to ignite due to its higher cetane number, which is an indicator of the ease of auto-ignition in a compression-ignition engine. Therefore, the engine operability will not suffer when biodiesel blends are used. On the other hand, there are also potential downsides associated with the use of biodiesel blends, including lower energy content, cleansing effects, cold weather operation, and material compatibilities. Nonetheless, with cautious fuel procurement and management, these downsides can be overcome and biodiesel can be an attractive alternative to regular diesel fuel.

1.2 Emission Impacts of Biodiesels

Tailpipe emissions for all fuels depend on a number of factors, including vehicle characteristics (i.e., size, weight, engine type, engine age, maintenance, etc.), operating characteristics (i.e., speed, acceleration, load, etc.), and fuel characteristics (i.e., Reid vapor pressure, sulfur content, etc.). Emissions from biodiesels also depend on the type of material used to produce the biodiesel, such as soybean, cottonseed oil, or rapeseed oil.

Several studies have evaluated the emission impacts of biodiesel. USEPA (2002) analyzed data from other sources that were collected using methods similar to those of the Federal Test Procedure. They indicated that a 20% biodiesel blend (B-20) is expected to require 2.2% more fuel to provide the same energy as regular diesel, but engine dynamometer tests suggest that B-20 will reduce hydrocarbon (HC) emissions by 21.1%, CO emissions by 11.0%, and PM by 10.1% while increasing NO_x by 2% (USEPA 2002). A linear relationship between emissions and increasing fractions of biodiesel (USEPA 2002) was developed, as shown in Figure 1-1.

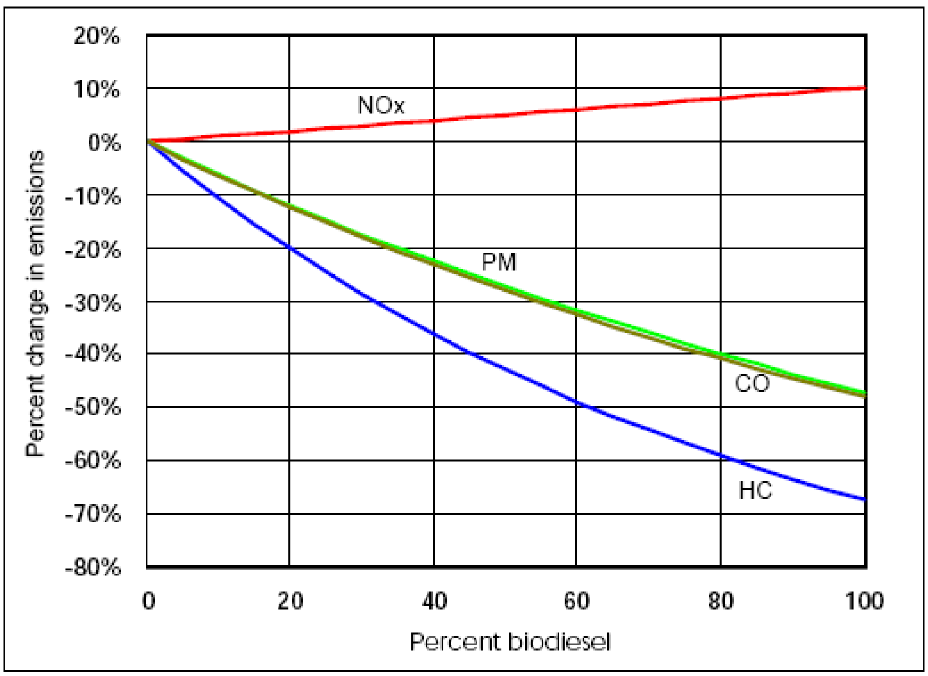

Figure 1-1. Average emission impacts of biodiesels for heavy-duty vehicle engines (USEPA 2002)

McCormick et al. (2006) evaluated the effect of regular diesel and B-20 in various types of heavy-duty vehicles using a chassis dynamometer. The authors evaluated three transit buses and found a 2% reduction in fuel economy. They also reported a 3.7%–5.8% reduction in NO_x, a 17.4%–33.0% reduction in PM, and an 18.6%–26.8% reduction in CO. Results were statistically significant at the 95% confidence level for CO and NO_x and 10% for PM. McCormick et al. (2006) also tested two Class 8 trucks and found an increase in NO_x of 2.1% and 3.6%, a reduction in PM of 19.4% and 34.7%, and a 6.9% and 15.3% decrease in CO. Two conventional school buses were also tested. The authors reported a 0.7% decrease (not statistically significant) and 6.2% increase in NO_x, a 2.5% increase (not statistically significant) and 24.0% decrease in NO_X, and a 9.5% increase in CO for one bus and 22.6% decrease for the other. Unless indicated otherwise, results were significant at the 90% level of significance.

McCormick et al. (2005) also evaluated biodiesel from grease and tallow and found that NO_x increased by 3% for B20, with decreases of 25% for PM.

Mazzoleni et al. (2007) used a gaseous remote sensor to measure on-road emissions for 200 school buses. The authors evaluated the buses using regular petroleum diesel and B20. They determined that there was no statistically significant difference in CO and NO_x hot stabilized emissions between the two fuel types. However, they found that hot stabilized PM emissions increased 1.8 times with B20. Hot stabilized HC emissions were 23% higher with B20.

Frey et al. (2006) used a portable emissions monitor to measure emissions in 12 dump trucks. The authors tested each vehicle with B-20 and 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 B-20.

Ropkins et al. (2007) instrumented a Ford Mondeo and measured emissions with regular diesel and a B-5 blend. The authors collected data on replicates of three standardized trips. They found an 8%–13% reduction in NO_x. They also found that emissions were associated with driving events.

Proc et al. (2006) discussed a study that evaluated nine identical transit buses where five were operated exclusively on B-20 and four operated exclusively on regular diesel for two years. Over the course of the study, each bus accumulated around 100,000 miles. The buses using B20 were compared to the buses using regular diesel. Proc et al. (2006) found no difference in in-use fuel economy between the buses using B-20 and regular diesel. Laboratory tests did, however, show a 2% reduction in fuel economy. The researchers also conducted laboratory chassis dynamometer tests to evaluate emissions. They used the City-Suburban Heavy Vehicle Cycle for testing because it was similar to the buses' actual routes. The buses were evaluated using two different drivers. The researchers found that for both buses, emissions for B20 were lower in terms of NOx, total HC, CO, and PM than for regular diesel. Results were statistically significant at the 95% level of significance.

Grabowski et al. (2003) performed a detailed analysis of the effect of biodiesel composition on engine emissions from a 1991 DDC series 60 diesel engine. As compared to certification diesel, reduction in PM was found to depend only upon the fuel oxygen content (roughly 2.5% for B-20 blends and 12% for neat biodiesels). Although in all cases NO_x emissions increased, the change was different for different biodiesel feedstocks. NO_x emission from certification fuel was found to be 4.59 ± 0.053 g/bhp-h, whereas PM emissions averaged 0.261 ± 0.019 g/bhp-h.

Schumacher et al. (2006) compared two 60 DDC engines using B-20, B-35, B-65, and B-100. The United States Code of the Federal Register (CFR) Title 40 transient testing procedure was used. Results showed that fueling with B20 increased fuel consumption by 1.3%, 2.3%, 7.1%, and 12.7% for B-35, B-65, and B-100, respectively. NO_x emissions increased, while total HC, CO, and PM decreased with the fraction of biodiesel in the fuel mixture. The increase in NO_x was found to be between 1% and 12%, whereas CO reductions ranged from approximately 9%–47% when fueling with biodiesel and biodiesel blends.

Knothe et al. (2006) conducted an emission study on a heavy-duty 2003 six-cylinder 14 L diesel engine supported by exhaust gas recirculation. Neat hydrocarbon fuels and neat methyl esters including methyl soyate (commercial biodiesel) were tested. PM emissions were reduced by about 77%, while NO_x emissions increased by about 12% compared to the base fuel (petrodiesel).

Farzaneh et al. (2008) studied the impact of B-20, cruise speed, and average acceleration rates on NO_x, HC, CO, and CO_2 emissions from diesel school buses. Results showed that NO_x and CO_2 emissions were not significantly different when biodiesel was used in place of diesel. HC emissions increased by 25.4%–28.8%, while CO emissions decreased by 23%–33%.

There are other data on emissions from mobile engines burning biodiesel, such as laboratory testing of truck engines (Sharp et al. 2000; Alam et al. 2004), field testing of bus engines (Souligny et al. 2004), and tractor engines (Bouche et al. 2000). In summary, these data show a linear increase in nitrogen oxide (NOx) emissions with increasing proportions of biodiesel. It has been suggested that the increase in NOx is due to injection timing differences caused by the low compressibility of biodiesel. Research that used spray chamber testing showed a one-crank-angle-degree shift in using B-100, i.e., the actual start of injection was earlier (Szybist and Boehman 2003). The shift in injection timing resulted in an earlier ignition by four crank angle degrees that caused a higher combustion temperature in the cylinder and produced more NO_x emissions. Other research indicates that the increase in NO_x emissions is due to the lack of soot radiation that causes a higher flame temperature in the cylinder when oxygenated fuel such as biodiesel is used (Chen et al. 2006). In any case, various NO_x reduction strategies have been proposed, including retarding the injection timing setting, cooling the intake charge, introducing fuel additives and blending, and using exhaust gas recirculation to lower the combustion temperature (Yoshimoto and Tamaki 2001; McCormick et al. 2002; Szybist et al. 2003).

Greenhouse gas emissions have also been evaluated for biodiesel and, in general, use of biodiesel results in lower CO_2 emissions. Mazzoleni et al. (2007) indicate that there is no net addition of CO_2 in the atmosphere when using biodiesel. Biodiesel contains carbon extracted by the photosynthesis process from atmospheric CO_2 using solar radiation as an energy source. During combustion, the carbon is re-released to the atmospheric as CO_2. The National Renewable Energy Laboratory (Sheehan et al. 1998) estimated that use of soybean B-100 in urban transit buses reduces net CO_2 emissions by 78.5%. Beer et al. (2002) evaluated different types of alternative fuels in heavy vehicles including compressed natural gas, ethanol, and biodiesel. The authors conducted a life-cycle assessment and found that B20 resulted in 17.7% lower CO_2 emissions and B-100 resulted in 56.8% lower CO_2 emissions than regular diesel.

2. PROJECT SCOPE

2.1 Need for Research

Biodiesels are often marketed as being cleaner than regular diesel for emissions. Emission test results depend on the biodiesel blend, but laboratory tests suggest that biodiesels decrease particulate matter, carbon monoxide, hydrocarbons, and air toxins when compared to regular diesel. Results for NO_x have been less conclusive (USEPA 2002).

Tests have not evaluated the commonly available ranges of biodiesel blends in the laboratory. Additionally, little information is available from on-road studies, so the effectiveness of using biodiesels to reduce actual emissions is unknown. A more complex relationship exists between engine operation and the rate of emission production than is typically evaluated using engine or chassis dynamometer tests. On-road emissions can vary dramatically since emissions are correlated to engine mode and activity such as idling, acceleration, deceleration, and operation against a grade produce higher emissions than more stable engine operating modes (Pierson et al. 1996; Cicero-Fernandez et al. 1997; Enns et al. 1994; CARB 1997; Le Blanc et al. 1995). Since these modes are not well captured in a laboratory environment, understanding on-road relationships is critical in evaluating the emissions reductions that may be possible with biodiesels.

2.2 Project Objectives

More tests and quantifications of the effects of different blends on engine and vehicle performance are required to promote widespread use of biodiesel. The objective of this research was to conduct on-road and laboratory tests to compare the emission impacts of different blends of biodiesel to regular diesel fuel under different operating conditions. The team conducted engine dynamometer tests as well as on-road tests which utilized a portable emissions monitoring system (PEMS) that was used to instrument transit buses. Regular diesel and different blends of biodiesel were evaluated during on-road engine operation by instrumenting three in-use transit buses, from the CyRide transit system in Ames, Iowa, along existing transit routes. Evaluation of transit buses was selected for this study rather than heavy-duty trucks because transit buses have a regular route. Therefore, emissions for each of the biodiesel blends could be compared across the same operating conditions. CyRide was already using 10% biodiesel and was considering use of 20%.

The remainder of the report summarizes the data collection methodology, analysis, and results for the engine dynamometer and on-road tests. The on-road testing is discussed in Section 3 of this report, and the dynamometer tests are discussed in Section 4.

Initially, the team attempted to compare the portable emissions monitoring system to the dynamometer. The team conducted an early test in which they attempted to attach the PEMS to the dynamometer. Since the engine being tested for this study was located inside a laboratory, the exhaust was vented from the engine by way of a series of pipes. The PEMS probe should have been placed parallel to the venting exhaust. However, within the given exhaust configuration, the probe could only be placed perpendicular to the exhaust flow. Initial comparison of the PEMS and dynamometer using this configuration resulted in widely disparate readings. The team believes this was because the probe was not able to directly sample the exhaust stream. The team considered other alternatives so that the probe could directly sample the exhaust stream, but this could not be done without reconfiguring the engine venting set up. As a result, the comparison could not be conducted, given project resources and practical considerations.

3. ON-ROAD TESTING USING A PORTABLE EMISSIONS MONITORING SYSTEM

On-road emissions were evaluated for three in-use transit buses from the Ames, Iowa, transit service using regular diesel (B-0), a 10% biodiesel blend (B-10), and 20% blend (B-20). Emissions were evaluated from April 2008 to July 2008 using a PEMS as described in the following sections.

3.1 Description of PEMS Equipment

The on-road emissions testing was conducted using a PEMS. The system is portable, as shown in Figure 3-1, and is approximately the size of a small suitcase. The OEM 2100 Universal Montana System from Clean Air Technologies (www.cleanairt.com) measures second-by-second mass emissions from vehicles with electronically controlled sparked ignition and compression ignition engines. The unit provides NO_x, HC, CO, CO_2, O_2, and PM readings for diesel vehicles. Pollutant concentrations are obtained from a standard sample probe inserted into the tailpipe, as shown in Figure 3-1. These data are combined with the theoretical exhaust flow data, calculated using engine parameters read from the vehicle's engine control unit.

Figure 3-1. PEMS (left shows system size, right shows tailpipe probe installed in passenger vehicle)

The Montana System is equipped with a computer and can be quickly installed (5–20 min) on a variety of vehicles, without physical modification to the vehicle. The system is designed for a range of testing scenarios, from short tests in the laboratory to extended field testing on fleet vehicles. The system can be safely installed in vehicles and has been used during revenue service routes on transit buses (Clean Air Technologies 2006). The system also has a global positioning system (GPS) to record the spatial position of the vehicle being tested. This can be used to locate where the vehicle was on the roadway during testing. Information about the roadway, such as grade, can be linked to emissions production. The equipment to extract engine data is used to record characteristics such as speed, acceleration, and throttle position. These characteristics have also been shown to influence vehicle emissions and are key components in assessing emission productions.

HC, CO, CO_2, O_2, and NO_x concentrations are sampled using a dual five-gas analyzer system. The analyzers self calibrate in the field using ambient air as a benchmark. Particulate matter concentration is quantified using a laser light scattering measurement subsystem. Speed, engine revolutions per minute (RPM), intake air pressure (manifold absolute pressure), and other engine operating parameters are collected to determine intake air mass flow. Using intake air mass flow, the known composition of intake air, measured composition of exhaust, and user-supplied composition of fuel, a second-by-second exhaust mass flow is calculated. The exhaust mass flow is multiplied by the concentrations of different pollutants to provide emissions in grams per second (Clean Air 2007). The system synchronizes the different data streams (second by second engine data, emissions, and GPS).

Frey and Rouphail (2003) have conducted a number of on-road emissions tests using the OEM 2100 and indicate that the precision and accuracy of the equipment is comparable to that of laboratory instrumentation. They indicate that CO and CO_2 are accurate to within 10% when compared to the measurement of average emission rates for dynamometer tests. They also indicate that NO is measured using an electrochemical cell in the PEMS and report that NO reported as equivalent NO^2 was accurate to ± 10%. PM is measured using a light-scattering method, which, according to Frey, is analogous to opacity and as such can be used to make relative comparisons of PM. The researchers caution, however, that it cannot be used to characterize the absolute magnitude of PM emissions (Frey et al. 2008).

Additionally, the equipment was calibrated each evening using the procedure outlined in the equipment manual (Clean Air 2007).

3.2 Buses Evaluated

CyRide is the city bus system for Ames, Iowa, and is operated through collaboration between the city and Iowa State University (ISU). CyRide has 10 fixed routes that serve a large portion of Ames and ISU (CyRide 2007). The fixed routes operate every day of the year except Thanksgiving, Christmas, and New Year’s Day. Figures for fall 2007 indicate that CyRide has an average of 4,314,151 passengers per year (CyRide 2007).

U.S. diesel engine standards cover 1991–1993, 1994–1997, 1998–2003, and 2004–2006 (USEPA 1997). The most recent diesel standards took effect in 2007 for diesel vehicles over 8,500 pounds (USEPA 2000). CyRide had vehicles from the 1998 to 2003 standard time frame and buses from the 2004 to 2006 standard time frame. Due to resource constraints, only two buses from the 1998–2003 standard time and one bus from the 2004–2006 standard time frame were evaluated. Two of the buses evaluated had 2002 six cylinder 280 HP 10.8 liter engines, and the third had a 2005 six cylinder 280 HP 10.8 liter engine. All had gross vehicle weights of 42,000 lbs and had automatic transmissions.

3.3 Bus Route Information

CyRide rotates buses into and off the system to meet peak travel demands. Buses are driven over several routes according to a prescribed schedule, depending on when the bus comes into and leaves the system. Each bus tested was evaluated over the same route pattern. This route pattern utilizes the same driver unless that driver is sick or scheduled for vacation. The route pattern used for testing started around 7:30 a.m. and returned to the garage around 5:30 p.m. The route pattern consisted of the following:

- A section with significant stops and starts at lower speeds (15–25 mph)—this portion of the route goes through the ISU campus
- A short section with significant stops and starts at lower speeds (15–25 mph)—this portion of the route goes through the Ames downtown area
- A section through a residential area
- An arterial section with regularly spaced signals
- An arterial section with signals spaced at greater distances (up to a mile)

Grade could not be collected because the route pattern covered such a large distance. As a result, grade was not incorporated into the model. However, no significant grade was present over any of the routes. The entire route pattern was characterized by fairly flat terrain.

Occasionally, there were minor changes in routes due to construction and some flooding that occurred in June 2008. This consisted of a small portion of the whole route and can be safely assumed not to affect the data.

3.4 Fuel

Fuel was purchased from Heart of Iowa Cooperative (HOIC), a supplier of biodiesel. The facility was capable of blending different fractions of biodiesel. A portable fuel tank was rented to use for the duration of the project because the HOIC biodiesel facility was 10 miles from Ames in Roland, Iowa, and fueling vehicles at the site was not practical. Fuel was purchased from HOIC for both the on-board and laboratory engine dynamometer tests. Because three buses were tested and repeat testing was necessary in a number of instances, the tank would have been filled with the same fuel blend on more than one occasion For the dynamometer tests, 30 gallons of each fuel blend were extracted from the same fuel tank used for the transit buses during one of the times that the tank was filled with that blend. Thus, the same fuel was evaluated in both the on-road and laboratory tests. The soy blend used in the diesel fuel by the HOIC was obtained from the Cargill Plant in Iowa Falls, Iowa. Cargill processed the soy oil meeting ASTM standards. HOIC then blended the soy and diesel fuel, according to the applicable standards. The base fuel was regular ultra low–sulfur diesel.

Before the fuel replication and between all subsequent fuel replications, the fuel tank from each bus was emptied of the existing fuel as much as possible and refilled with the fuel blend for the next replication. When the fuel blends were changed in the portable storage tank, the tank was also emptied before being refilled with the next blend. CyRide has a service truck with battery-operated pumps that was used to pump fuel out of the bus tank and portable storage tank. CyRide used the remaining pumped fuel in other non-test buses.

3.5 Testing Methodology for On-road

Each bus was evaluated over three replications. Each replication consisted of testing the bus for several working weekdays with the same fuel. Due to the nature of the equipment and the fact that the testing was conducted on-road with actual in-service transit buses, multiple problems could result that could have affected data, such as equipment malfunction, adverse weather conditions, bus maintenance issues, etc. To start, each bus was tested for two days for each replication. Data for each day of testing were checked, and, if problems had occurred that compromised the accuracy of the data for a large portion of the day, the data were discarded and data were collected for an additional day. For instance, during one day of testing, the temperature probe slipped and came in contact with the engine and was burned. The error wasn't noticed until data had been collected for the day. Since temperature is used to calculate engine flow rate, it was determined that an inaccurate reading would have a significant impact on the data. The data were discarded and recollected once a new temperature probe was obtained. Data for each day were evaluated, as will be discussed in Section 3.6. In several cases, due to equipment malfunction and other problems, buses were tested for three or four days. In all cases, at least one day of usable data were available, and in most cases two days of usable data resulted.

Buses were tested with B-0, B-10, and B-20. A description of the fuel is provided in Section 3.4. CyRide had been using a 2% (approximately) biodiesel blend when the testing started, so each bus was drained of the existing fuel and refilled before the first replication. Fuel was drained from each bus before the start of the next replication. Data were collected from April 22 to May 30, 2008, for the two 2002 buses (Bus 971 and 973). During this period, moderate spring-like temperatures were present. Data were collected from June 23 to July 9, 2008, for the 2005 bus (Bus 997). During this time, higher temperatures and humidity were present, and air conditioning was used on the bus. As a result, emissions for each bus were collected under similar temperature and environmental conditions.

A member of the research team was present with the equipment on the bus the entire time data were being collected. As a result, the team member was able to monitor the equipment and, in some cases, could determine problems early enough that they could be corrected without compromising a large portion of the data collected for the day. The team member also recorded the number of passengers who entered or exited the bus at each stop so that the total number of passengers could be included in the analysis.

The equipment was installed before the bus left the garage for its first run around 7:30 a.m. and was removed each evening when the bus returned to the garage around 5:30 p.m. The on-board equipment was removed at the end of the day and then hooked back up the following day. The accessory equipment (hoses and parts that attach to the vehicle engine) remained on the bus through the entire replication. The PEMS was recalibrated each evening as per specification in the PEMS operating manual (Clean Air 2007).

In all cases, data were collected while ISU classes were in session. During holidays and semester breaks, loading patterns are different, and in some cases routes are changed or omitted. As a result, data were collected while ISU classes were in session to ensure consistency.

3.6 Data Preparation and Quality Assurance for On-road

A significant amount of manual data preparation was necessary to prepare the data for analysis. Quality assurance was also necessary. Since there are a large number of errors that can occur with PEMS, each row of data in each sheet was manually checked. The data preparation and quality assurance methodologies are described in the following paragraphs.

3.6.1 Data Preparation

The PEMS is capable of storing a large amount of data in a single file. Within a file, data can be identified as a "bag." The equipment software allows the data collector to mark the beginning and end of an activity of interest. The set of data is indicated within the data file as a bag with a specific number. Data collectors attempted to start and end a bag for each route during the day. However, an individual bag could be an individual bag. For example, the buses have specific points along the route when they stop and wait if they get ahead of schedule. Long periods of idling were also indicated as individual bags. Locations where the buses stopped and idled for long periods of time were not included in the analysis. The data collector would also observe the data on the screen for any discrepancy.

Each individual bus route was extracted and imported into a geographic information system (ArcView GIS). This was done so that bus stops could be identified and passenger loading associated with the emission data file could be entered as shown in Figures 3-2 and 3-3. Additionally, data collectors had indicated the time the bus made each stop. As a result, bus stops could be lined up temporally and spatially and passenger loading could be entered.

Plotting data in ArcView GIS also allowed data to be viewed spatially. This allowed additional error checking, as described in the following section. It was also possible to see how emissions and other parameters were changing over the course of a bus route, as shown in Figures 3-4 and 3-5.

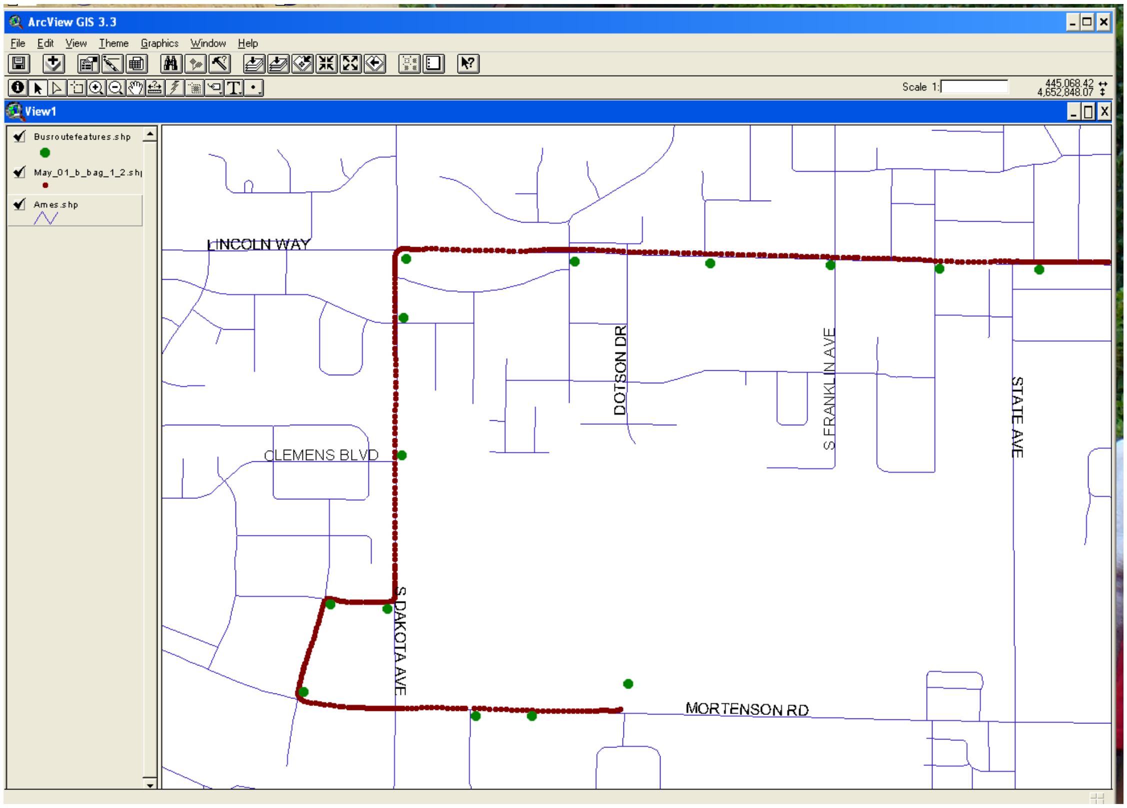

Figure 3-2. Bus route with bus stops

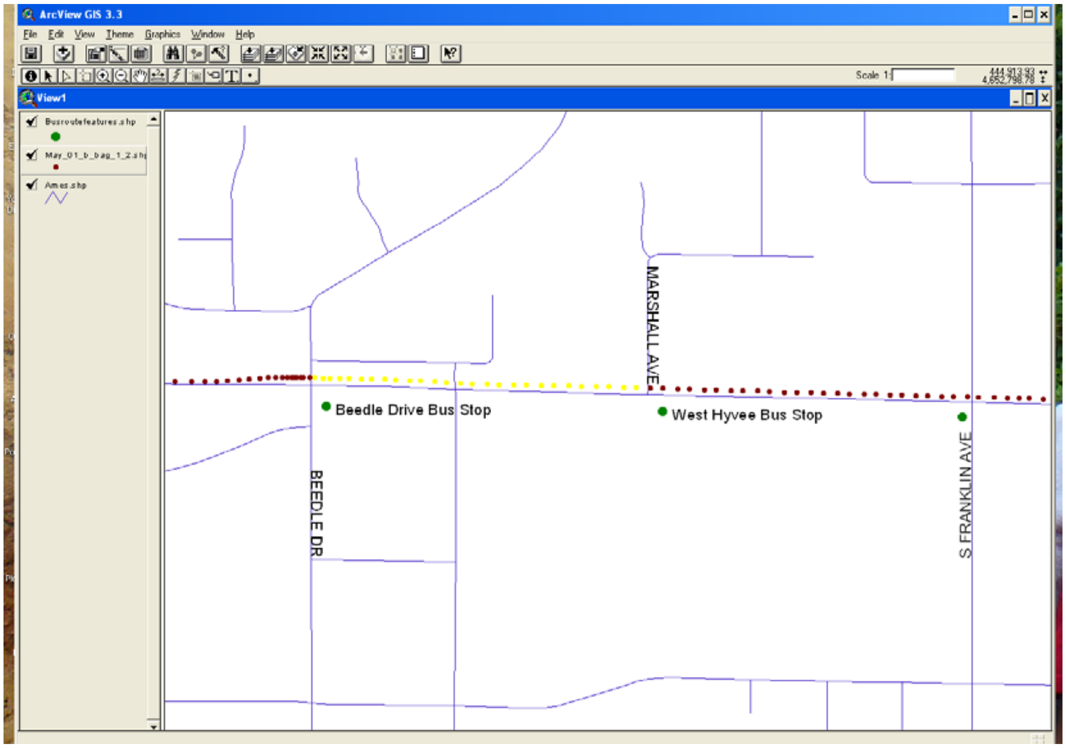

Figure 3-3. Locating bus stops to enter passenger loads

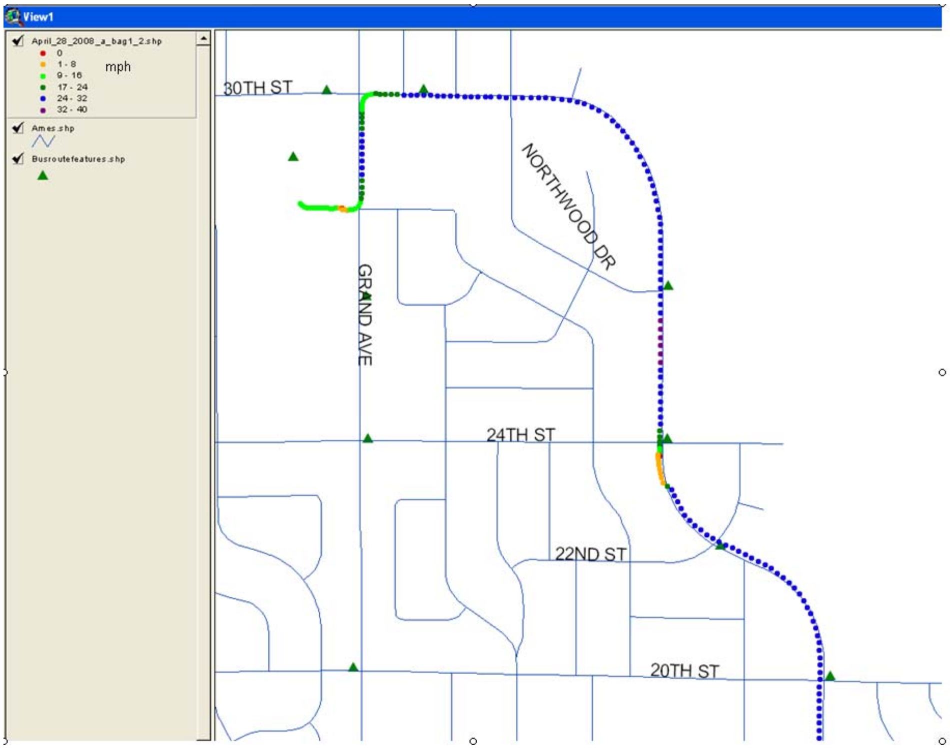

Figure 3-4. Speeds for Bus 1-A along route (mph)

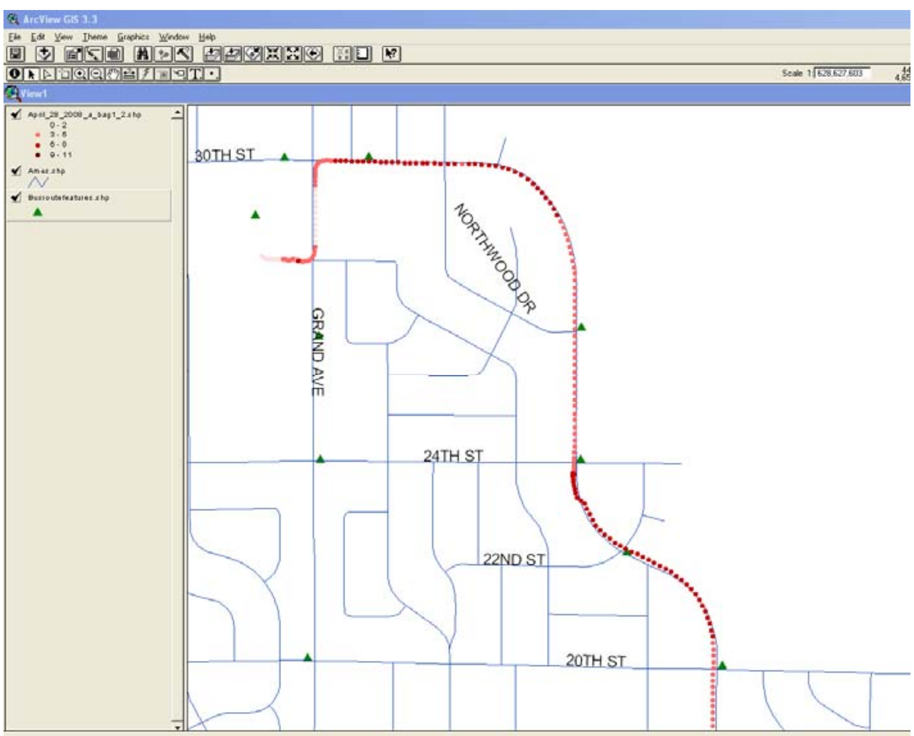

Figure 3-5. HC for Bus 1-A along route (ppm)

3.6.2 Potential Errors

Potential errors in the datasets have been discussed by Frey et al. (2001) and others who have used similar equipment. Potential errors were also discussed as they arose with Clean Air Technologies during the course of data collection.

Frey et al. (2001) have conducted a number of studies with the same equipment used in this study (Montana OEM). The authors discuss data quality assurance and common errors that can occur with the system. They also indicate times when other conditions are outside the range of normal activity. Each dataset was reviewed for the errors and conditions and, when warranted, the data were discarded.

Frey et al. (2001) reported an error rate in the data of 2.5%–15%. The leading causes were inter-analyzer discrepancies, analyzer freezing, and air leaking (which is manifested in very low pollutant concentrations). They compared parallel gas analyzer concentrations and discarded the data if measurements differed by a set threshold value for each pollutant. The authors also discarded data if the gas analyzer failed to update on a second-by-second basis or if oxygen levels were beyond a normal range leading to concentration values below detection limits for most pollutants. The researchers indicated that these three errors affected approximately 6.3% of the raw data (Frey et al. 2008).

Other errors and conditions according to Frey et al. (2001) are provided in the following paragraphs. The team evaluated each row of data in each data file to determine whether any of the following problems had occurred. The following paragraphs also indicate whether an individual problem occurred and how any problems were addressed in the data quality assurance.

3.6.2.1 Abnormal Traffic Conditions

Abnormal traffic conditions are when surrounding traffic is affected by activities that are outside the range of normal operation. This would include an accident or incident, such as a stalled vehicle interrupting traffic flow for an extended period of time. (During the course of the testing, no abnormal traffic conditions were noted.)

3.6.2.2 Zeroing

Zeroing occurs when the gas analyzer automatically measures ambient air every 10 minutes to prevent instrument drift. Problems can also occur when the monitors zero in on an area with very high ambient emissions, resulting in artificially low emission measurements during a run. Negative emissions can be avoided by zeroing in on areas where air is stagnant or large concentrations of pollution are not present. This problem was noted, as discussed under the section titled “Negative Emissions Values.”

3.6.2.3 Computer Errors

Since the computer is integrated into the system, synchronization issues between the computer and analyzers did not occur. However, there may be issues such as the computer freezing up, problems in the electronic circuitry, and so on.

Computer problems were also noted. It was not uncommon for the system to freeze. Clean Air Technologies indicated the proper procedure to follow when the system froze. Since data collectors were present, this problem was usually spotted immediately and the system was restarted. Because the system saves the data file, there was only one case in which more than a few minutes of data were lost. However, in one case an entire afternoon was lost because the emissions output file was damaged.

3.6.2.4 Engine Analyzer Errors

Engine analyzer errors occur when communication is lost between the equipment physically attached to the vehicle and the on-board system. This problem occurred several times when the probe became detached from the equipment. The problem could be spotted by the data collectors and corrected on-board.

3.6.2.5 Gas Analyzer Errors

Gas analyzer errors happen when zeroing occurs during a run and no engine or emissions data are recorded during the zeroing event, which leads to data gaps. The researchers found on some occasions that the values for one or more pollutants may be frozen during a run because of some type of error in the gas analyzer computer interface.

Frey et al. (2001) suggest that many gas analyzer errors can be avoided by zeroing the instrument before each data collection run. The authors also suggest checking and refreshing the gas analyzer display before the run to make sure that the changes in the concentrations of gases are appropriately displayed in the on-board display (Frey et al. 2001).

Gas analyzer errors were not noted. The equipment was calibrated each evening.

3.6.2.6 Negative Emissions Values

Due to random measurement errors, concentrations (especially HC with diesel emissions) can have negative values or values that are not statistically different from zero. This occurs during zeroing when the reference air has significant amounts of a pollutant, resulting in negative emissions. Frey et al. 2001 indicated that when negative values occurred that could not be attributed to measurement error the emissions were assumed to be zero. If the frequency and magnitude of zero or negative values was large, the authors led to suspect that there was a problem with the run. In that case, the run was discarded.

The problem of negative emissions values was noted during the study. When pollution concentrations were less than zero, those data cells were not used (indicated as “NA” within the data row). This was a common problem with HC emissions. In a discussion with Clean Air Technologies, Frey et al. (2001) indicated that since HC emissions in diesel engines are low to start with, this problem is common. Frey et al. (2001) suggested that these values be included as zero, and this solution was discussed, but the researchers decided to discard those data cells.

3.6.2.7 Synchronization Errors

Synchronization errors occur when there is a delay in the response of the gas sampling line and analyzer. Frey et al. (2001) suspect that this was due to blockages in the gas sampling line. Time delay of the response of the gas analyzer may increase, leading to a discrepancy in the synchronization of the gas analyzer and engine data streams. Frey et al. (2001) were able to find synchronization delay by looking at a plot of RPM and spikes in emissions. They describe a method to correct the problem in Frey et al. (2001).

Frey et al. (2002) also found that a drift in emissions data can occur due to instrument error. To determine when this occurred, they plotted the data and checked for abnormal values (Frey et al. 2002).

Synchronization errors were checked by occasionally plotting NO_x emissions against engine RPM, as suggested by Frey et al. (2002) and as shown in Figure 3-6. NO_x was multiplied by a factor of three for plotting purposes. Spikes in NO_x should correspond with spikes in RPM. No synchronization problems were noted.

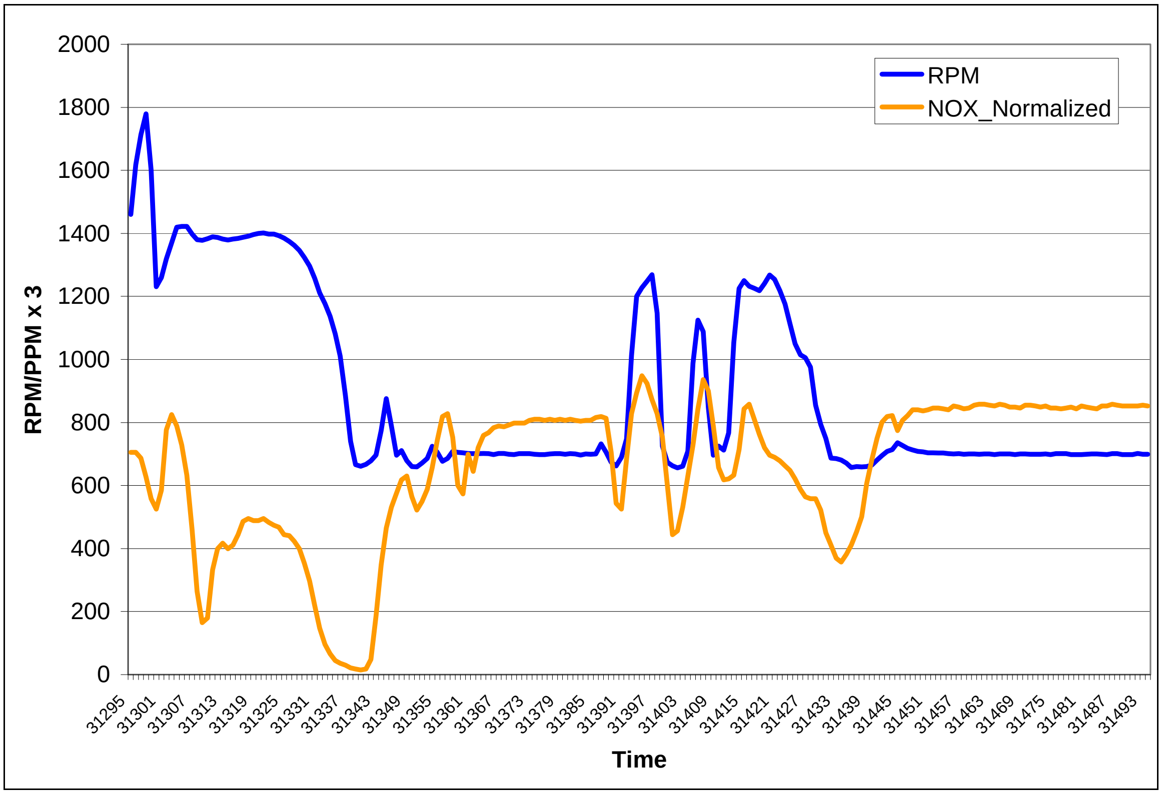

Figure 3-6. Plot of RPM versus NO_x to check for synchronization (NO_x was multiplied by a factor of 3 for graphing purposes)

Other errors the team found during the course of the study include the following:

3.6.2.8 Calibration Problems

The team found discrepancies between the two sensor readings. Clean Air Technologies indicated that this was likely due to poor ventilation in the room where the calibration was taking place. They suggested doing the calibration on the bus when all the equipment was set up rather than completing it inside.

3.6.2.9 Equipment Malfunction

Several equipment malfunctions occurred over the course of the data collection. For instance, the team was initially using the bus engine as the power source. However, an electrical surge damaged the internal computer and the team purchased a battery to be used as the power source instead. In another instance, the temperature probe came in contact with the engine and was damaged, resulting in false engine temperature readings. Hoses also occasionally came loose, and fuses were blown. The team checked all readings regularly (both while collecting data and while examining the output file) and so were able to spot problems before losing much data.

3.6.2.10 Emission Spikes

In several cases, emission values from one of the two sensors would spike to abnormally high values. For instance, HC values spiked to 100 times the normal values. The team could not determine the source of the error. However, the error itself was easy to spot, and all data for that time period were discarded.

3.6.2.11 GPS Losing Satellite Link

Sometimes, due to loose connections from the power source, the GPS would lose contact with the satellites. Since the speed and spatial data was provided by the GPS, data gathered while the GPS was not receiving any signal were discarded.

3.7 Analysis Methodology for On-road

Numerous data files were created for each replication, depending on how frequently the data collector started a new file and whether the system froze. Data were output from the PEMS in the form of a Microsoft Excel spreadsheet. Data for each data file were quality checked using the methods discussed in the previous sections. A final data file was created for each bus and each fuel type for data analysis. The data file may have contained data for more than one day. The amount of data available for each replication (B-0, B-10, B-20) was compared for each bus. Data files for each bus were adjusted so that data for all three replications contained similar amounts of data for the same time periods. Since the buses were driven over a set route/driver pattern that varied over the course of the day, it was decided that including more data for one time period for one replication over another could skew the data. For instance, if the final B-0 and B-20 datasets for one bus contained two full days of data each, and the final B-10 data sets only contained one full day plus data from the morning for another day, then the afternoon data for the B0 and B20 datasets would have been removed. In the final analysis, data were analyzed for the entire day rather than by time period. This prevented oversampling of one situation.

The team, including a graduate student from the ISU Department of Statistics, reviewed all available literature about methods used by other researchers to analyze PEMS data, and a professor from ISU's Department of Statistics was consulted. The following methodology, described in the following sections, was selected to evaluate the data.

Emissions are for hot, stabilized emissions. The buses were started at approximately 7:00 a.m. and were at the first bus stop of the day by 7:30. Emissions for the first half hour were removed from the analysis to ensure that the vehicle was fully warmed up.

A model was developed for each of the pollutants of interest. Each row in each of the data files represents one second of data. The following independent variables were included in the analysis:

3.7.1 Fuel type

The type of fuel was included as an independent variable (B-0, B-10, or B-20).

3.7.2 Speed

Vehicle emissions are correlated to speed. Speed was obtained from the GPS in the PEMS. The best method to obtain speed and acceleration would have been to use an on-board diagnostic system (OBD), which directly measures engine parameters. However, none of the buses were OBD-capable. As a result, the speed and acceleration values were those calculated from the GPS. Accuracy of speed and acceleration from a GPS depends on several factors, including spatial accuracy of the GPS, signal quality, number of satellites, signal blockage, etc. . A study by Yoon et al (2005) developed speed/acceleration profiles for transit buses in Atlanta using GPS data. Based on other studies they found that speed from GPS receivers is as accurate as speed obtained from conventional distance measuring devices except at speeds less than 5 miles per hour when compared with vehicle speed sensors.

Speed was categorized for the descriptive statistics in 5 mph speed bins and was categorized for the statistical analysis as shown in Table 3-1.

Table 3-1. Speed categories used in analysis

Speed	Speed Category
≤ 5 mph	1
5 < mph ≤ 15	2
15 < mph ≤ 25	3
25 < mph ≤ 35	4
mph > 35	5

3.7.2 Acceleration Mode

Vehicle emissions are also correlated to acceleration. Acceleration data were also obtained from the GPS. Acceleration was also obtained from the GPS. Acceleration is reported as the change in speed between subsequent seconds. The accuracy of the acceleration measurements is directly correlated to the accuracy of speed. Since acceleration at lower speeds may have some inaccuracies and evaluating speed at each acceleration value would have required a large amount of data, a dummy variable, *mode*, was used as an aggregate measure for acceleration. Mode was assigned to each row of data according to the convention shown in Table 3-2.

Table 3-2. Mode categories used in analysis

Mode	Speed (mph) and Acceleration Range (mph/s)
Idle (1)	speed = 0 and acceleration = 0
Steady state (2)	Speed > 0 and acceleration = 0
Acceleration (3)	Speed > 0 and acceleration > 0
Deceleration (4)	Speed > 0 and acceleration < 0

3.7.3 Passengers

The number or range of passengers present on the bus was another variable. This did not include the bus driver or data collector since this remained consistent across data collection.

In the statistical model, the variable "passengers" was categorized using the convention shown in Table 3-3.

Table 3-3. Passenger categories used in analysis

Number of passengers	Passenger category
$0 < p \leq 5$	1
$5 < p \leq 10$	2
$10 < p \leq 20$	3
$p > 20$	4

3.7.4 Vehicle Specific Power

Vehicle specific power (VSP) mode has been utilized by Scora and Barth (2006), Frey et al. (2007), and others. VSP is a measure of vehicle loading. Barth et al. (2006) define VSP using Equation 3-1.

$$VSP = v[1.1a + 9.81(\text{atan}(\sin(grade))) + 0.132] + 0.000302v^3 \qquad \text{(Equation 3-1)}$$

Where:

VSP = vehicle specific power (kW/ton)
v = vehicle speed (m/second)
a = acceleration (m/second^2)
$grade$ = road grade (radians)

Frey et al. (2007) used VSP to evaluate emissions for transit buses using Equation 3-2. The authors defined eight VSP modes (Table 3-4) and estimated modal fuel use and emission rates for each of eight modes.

$$VSP = V \times (a + g \times \sin(grade) + 0.092) + 0.00021 \times V^3 \qquad \text{(Equation 3-2)}$$

Where:

VSP = vehicle specific power (kW/ton)
V = the speed at which the vehicle is traveling (m/s)
a = the acceleration of the vehicle (m/second^2)
grade = road grade (decimal fraction)
0.092 = rolling resistance coefficient
0.00021 = drag term coefficient

Table 3-4. Definition of VSP bin for transit buses (Frey et al. 2007)

VSP Range(kw/ton)	VSP Bin	VSP Range(kw/ton)	VSP Bin
VSP<=0	1	6=<VSP<8	5
0<VSP<2	2	8=<VSP<10	6
2=<VSP<4	3	10=<VSP<13	7
4=<VSP<6	4	VSP>=13	8

Variables which are highly correlated were not evaluated together in the models. So for instance, VPS which is a function of speed and acceleration was not included when speed was included.

The data were disaggregated by the different independent variables for each bus and fuel type and histograms plotted to observe trends. It was decided that the data in general were gamma distributed. As an illustration, histograms that show the conditional distribution for NO_x, HC, CO, and CO_2 for Bus 973 are shown in Figures 3-7. Data for each bus and fuel were also separated by vehicle mode (idle, steady state, acceleration, and deceleration) to make sure that the data still followed a gamma distribution. Figure 3-8 provide plots showing the fitted curve using gamma distribution for HC for Bus 973 for acceleration. Since the data were determined to be gamma distributed, regular tests that assume normality could not be applied.

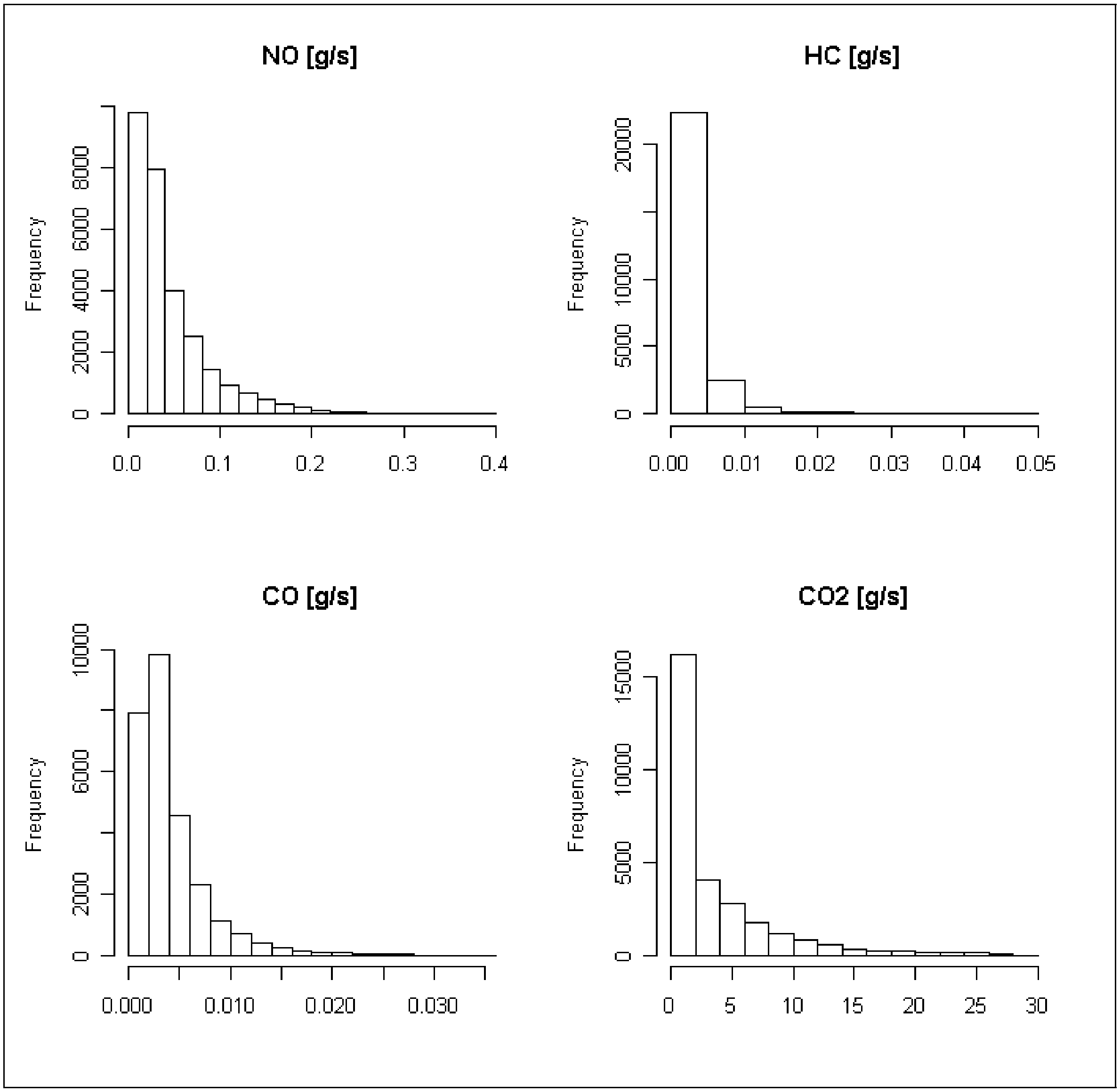

Figure 3-7. Histograms showing conditional distribution by pollutant for Bus 973

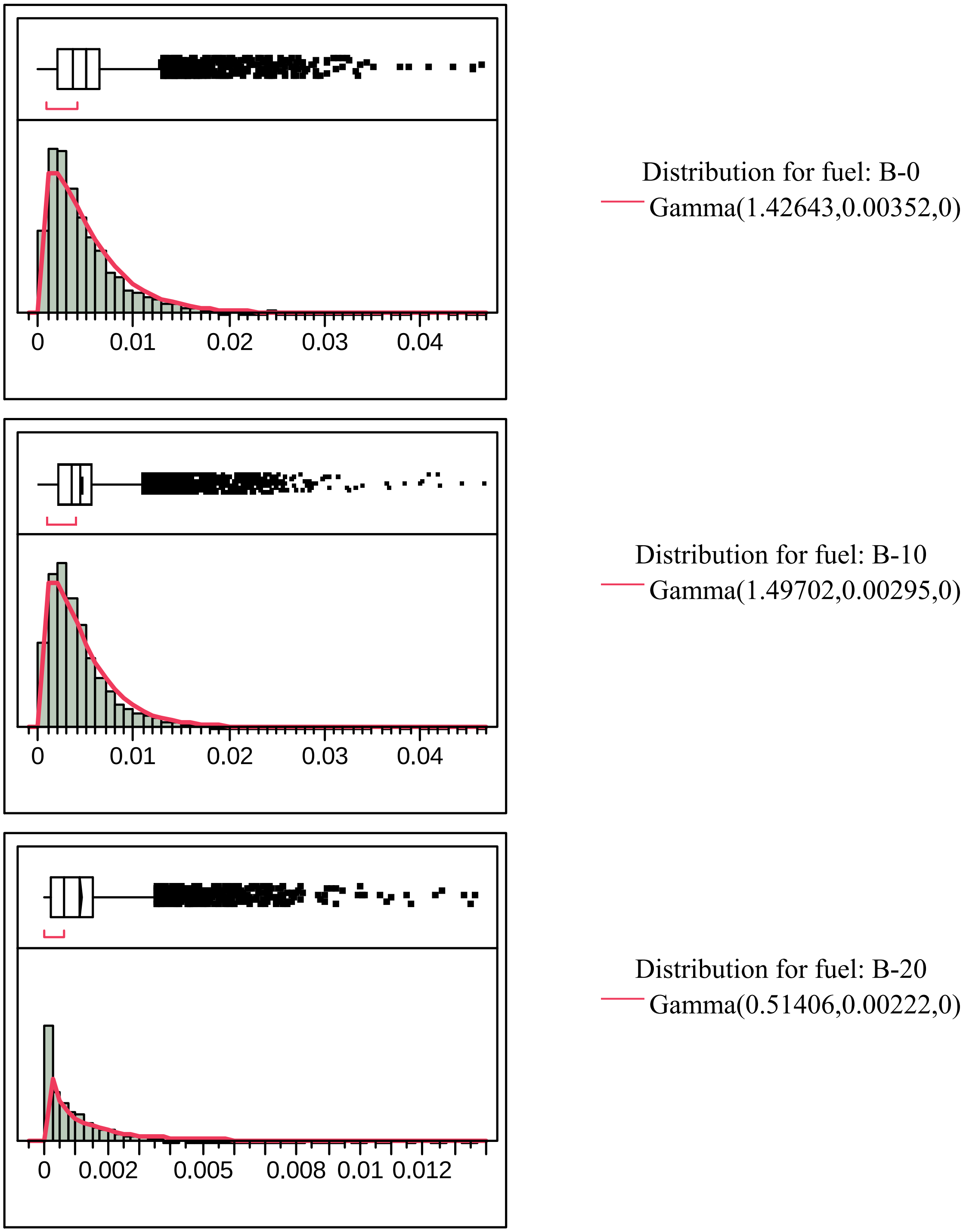

Figure 3-8: Fitted camma distributions for Bus 973 in acceleration by fuel type

The first model considered was a time series analysis. However, a time series analysis is dependent on having a continuous time series and there were a number of missing values in the data due to data cleansing. Additionally there was a large amount of variability in the data which makes it difficult to fit a time series model. The next natural choice of models which was selected was a generalized linear model where the response has a gamma distribution and the explanatory variables are included in the linear predictor. The model uses the inverse as a link function.

The model specification is provided in Equation 3-3 and 3-4.

$$y_i \mid \alpha, \beta \sim Gamma(\alpha, \beta) \qquad \text{(Equation 3-3)}$$

Where:

$$E(y_i \mid \alpha, \beta) = \mu = \frac{\alpha}{\beta} \qquad \text{(Equation 3-4)}$$

The link function in this model is $\eta = \frac{1}{\mu} = X\beta$,

Therefore, $\mu = \frac{1}{X\beta}$

The model was created using SAS proc genmod. Proc genmod uses maximum likelihood estimation to obtain parameter estimators. A model was fitted for each bus and each pollutant giving 15 different models. The model fitting was performed using SAS proc genmod. In this case the model specified in SAS was:

η = int + mode + fuel + speed + passengers + fuel * mode + fuel * speed + pass*fuel

(Equation 3-5)

Some additional information about the model is provided in the following paragraphs.

The Wald test was used to indicate whether parameters are significant. Wald theory is based on asymptotic normality of (in particular) maximum likelihood estimators. The (1-α)100% Wald confidence interval for a parameter β is defined as $\hat{\beta} \pm z_{1-\alpha/2}\hat{\sigma}$,

Where,

z_p is the 100*p*th percentile of the standard normal distribution

$\hat{\beta}$ is the parameter estimate

$\hat{\sigma}$ is the estimate of its standard error

Least-square means of the response, also known as adjusted or marginal means can be computed for each *classification* or *qualitative* effect in the model. Examples of qualitative effects in our model are *mode* (four levels: idle, steady, acceleration, deceleration) and *fuel* (3 levels: B0, B10 and B20). Least-square means (LSM) are predicted population margins or within-effect level means adjusted for the other effects in the model. If the design is balanced, the LSM equal the observed marginal means. Our study is highly unbalanced, and thus the LSM of the any response variable for any effect level will not coincide with the simple within-effect level mean response.

When the response variable has been transformed prior to fitting the model, the LSM is computed in the transformed scale and must be then transformed back into the original scale. If we have maximum likelihood estimators of the regression coefficients, we can easily compute the LSM in the original scale, simply by applying the inverse transformation. For example, in our case we have $g(\mu)=\frac{1}{\mu}=X\beta$, and the LSM in the transformed scale is given by $L'\hat{\beta}$ (where L is simply a vector of coefficients). We can compute the LSM in the original scale as follows:

$$LSM_{original} = g^{-1}\left(LSM_{transformed}\right) = g^{-1}\left(L'\hat{\beta}\right) = \frac{1}{L'\hat{\beta}}$$

To obtain the standard error of the LSM $_{original}$ we used the Delta Method.

Given any non-linear function H of some scalar-valued random variable θ, $H(\theta)$ and given σ^2, the variance of θ, we can obtain an expression for the variance of $H(\theta)$ as follows

$$Var[H(\theta)] = \left[\frac{\partial H(\theta)}{\partial \theta}\right]^2 \sigma^2$$

In our case, we used the inverse transformation and obtained a least square mean in the transformed scale that we denoted as $L'\hat{\beta}$, with estimated variance $\sigma^2{}_{L'\beta}$. The estimate of the mean in the original scale is obtained by applying the inverse transformation to the LSM:

$$\hat{m} = LSM_{original=} \frac{1}{\left(L'\hat{\beta}\right)}$$

Now, the variance of $\hat{m}$ is given by

$$\sigma^2_{\hat{m}} = \left[\frac{\partial 1/\left(L'\hat{\beta}\right)}{\partial L'\hat{\beta}}\right]^2 \sigma^2_{L'\hat{\beta}} = \frac{1}{\left(L'\hat{\beta}\right)^4}\hat{\sigma}^2_{L'\hat{\beta}}$$

Given a point estimate of the LSM in the original scale an approximation to its variance, and using asymptotic normality, we can compute an approximate 100(1-α)% confidence interval for the true mean in the original scale in the usual manner

$$95\%CI(\hat{m}) = \hat{m} \pm 2 * \hat{\sigma}_{\hat{m}}$$

Results are presented in Section 3.8.2.

3.8 Results for On-road

The first section provides a summary of descriptive statistics. Data were evaluated to determine general trends. The second section discusses results of the statistical modeling.

3.8.1 Descriptive Statics for On-Road

Data were plotted to evaluate general trends.

3.8.1.1 Descriptive Statistic Results for Bus 973

Data were plotted by mode and speed range and VSP bin as shown in Figures 3-9 to 3-19 for Bus 973. Results for Bus 973 indicate that in general NO_x emissions are lower for B-10 than for B-0 for all modes and most speed ranges with higher emissions for B-20 than for B-0. A downward trend exists for HC emissions which are slightly lower for B-10 than for B-0 and are significantly lower for B-20 than for B-0 or B-10 for all modes and speed ranges. CO emissions are lower for both B-10 and B-20 than for B-0. In some cases emissions are lower for B-20 than for B-10 and in other cases CO emissions are lower for B-10 than B-20. In most cases, CO_2 emissions are lower for B-10 and B-20 than for B-0 except for steady state where B-10 emissions are lower but B-20 emissions are higher than for B-0. PM was similar for B-0 and B-20 but PM emissions were much higher than expected for B-10 for all modes and all speed ranges.

Overall, evaluation of the plotted data indicates that emissions (except for HC) are much higher for acceleration mode than for all other modes for all speed ranges and fuel types.

Idle

Steady State

Acceleration

Deceleration

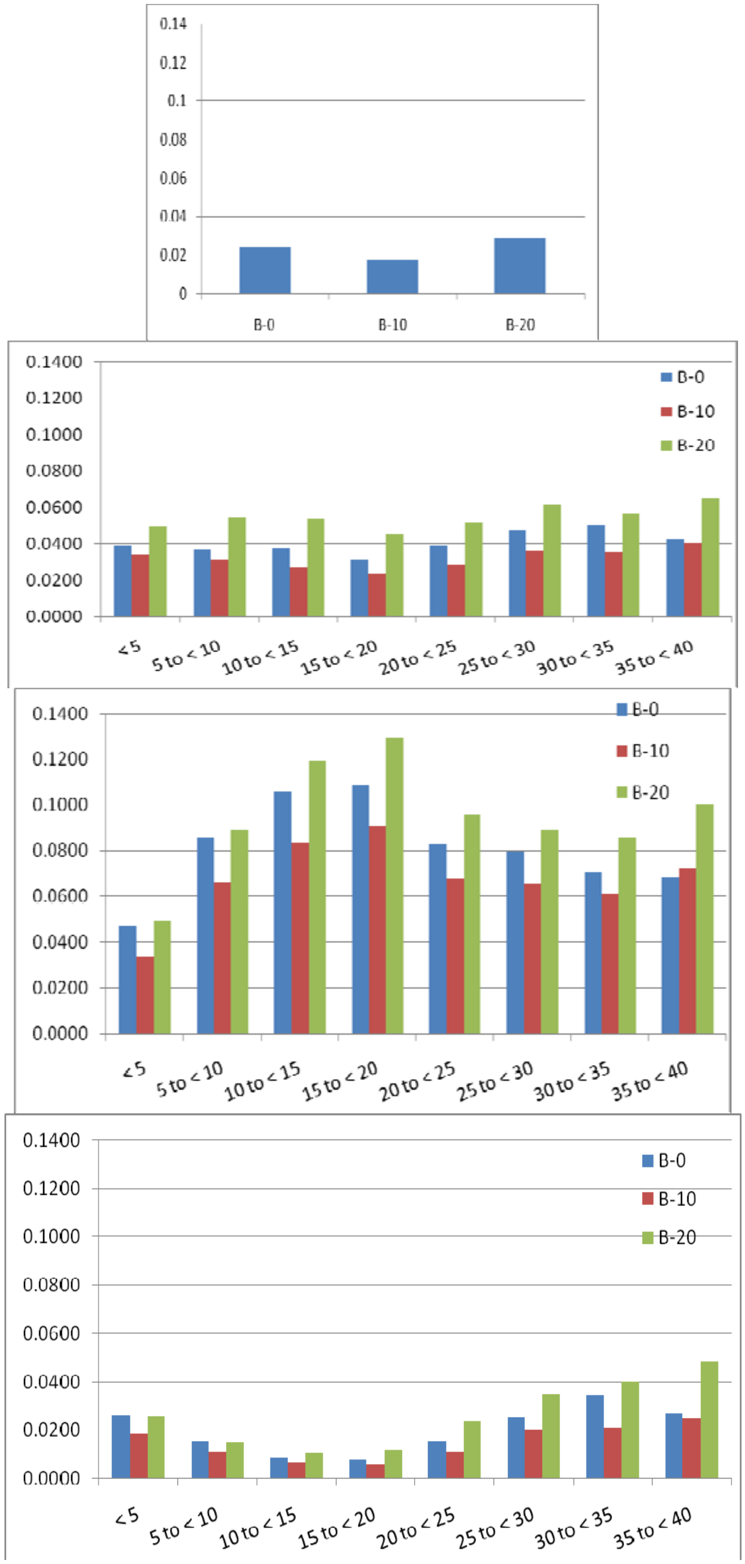

Figure 3-9. NO_x Emissions (g/s) for Bus 973 by Mode and Speed (mph)

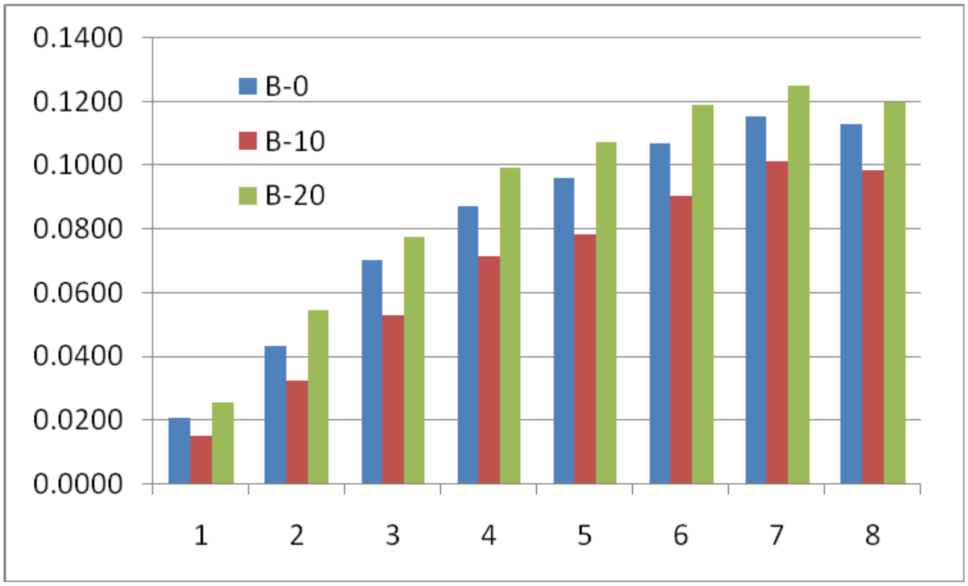

Figure 3-10. NO_x emissions (g/s) for Bus 973 by VSP bin

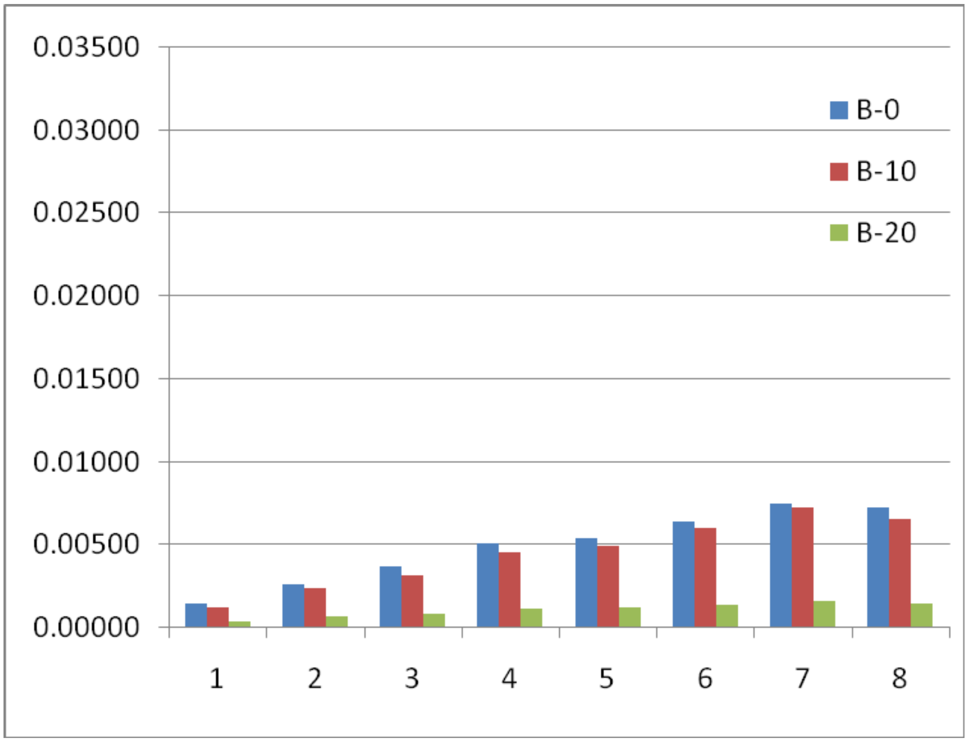

Figure 3-11. HC emissions (g/s) for Bus 973 by VSP bin

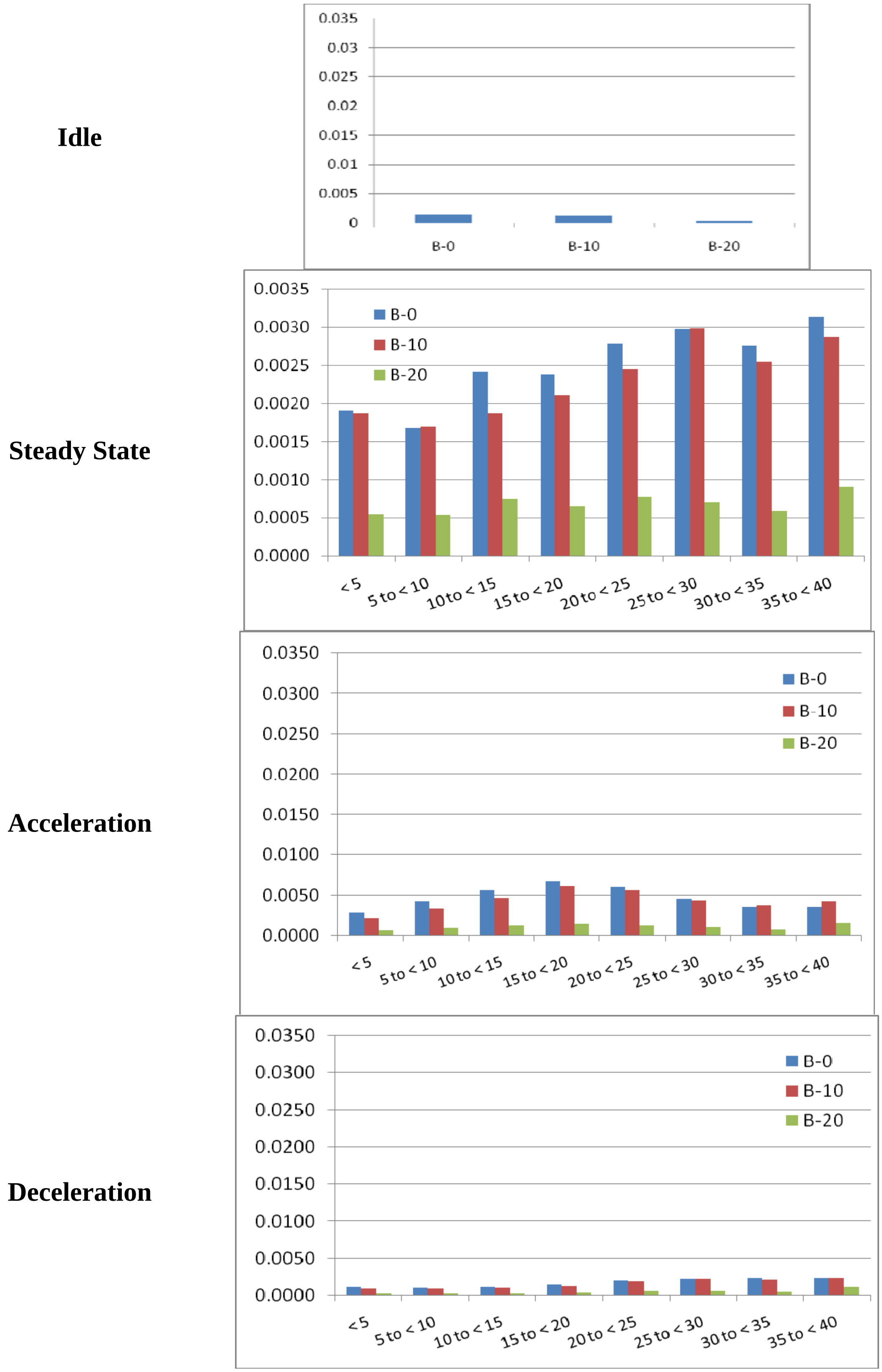

Figure 3-12. HC emissions (g/s) for Bus 973 by mode and speed (mph)

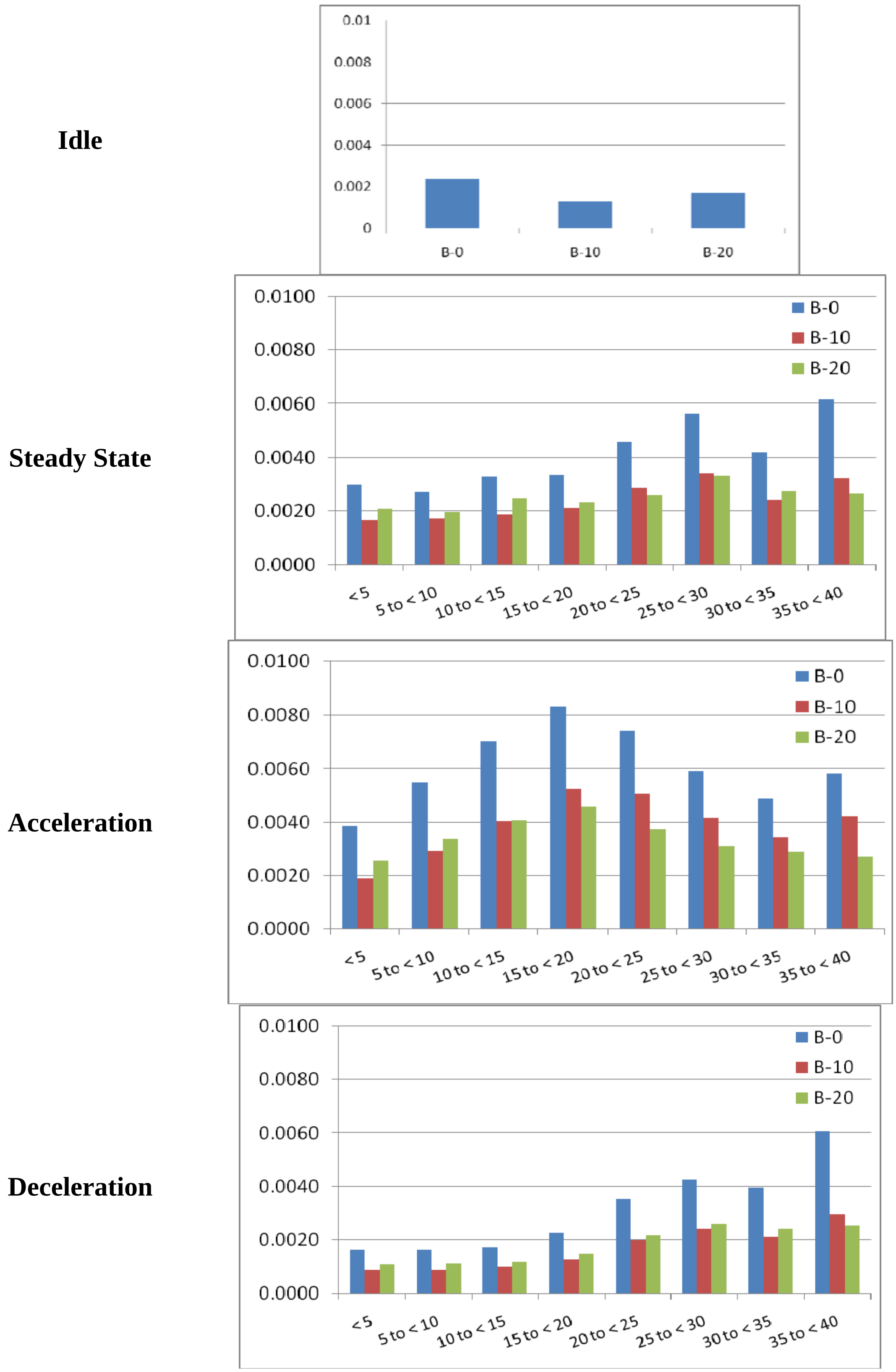

Figure 3-13: CO Emissions (g/s) for Bus 973 by Mode and Speed (mph)

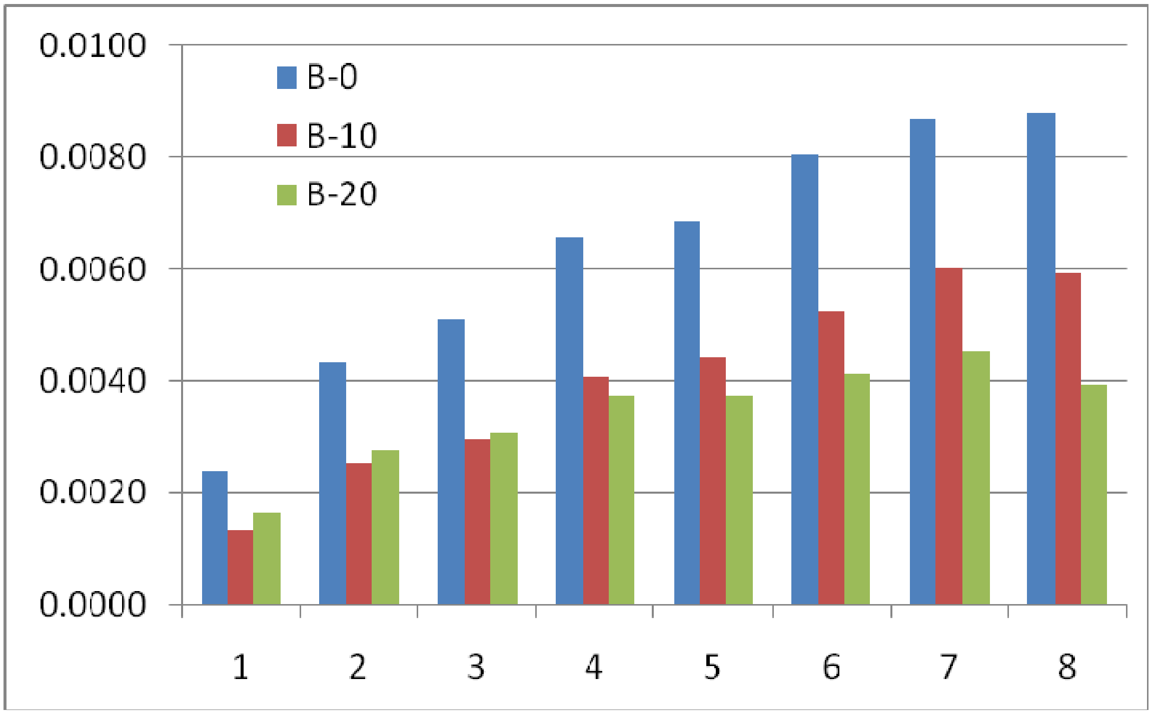

Figure 3-14. CO emissions (g/s) for Bus 973 by VSP bin

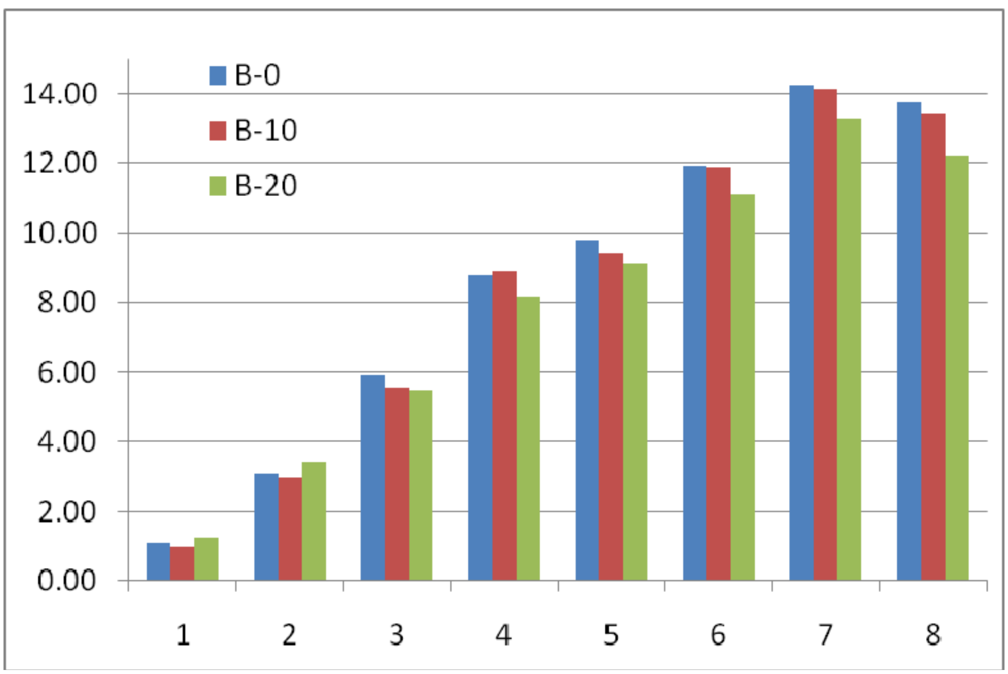

Figure 3-15 CO_2 emissions (g/s) for Bus 973 by VSP bin

Idle

Steady State

Acceleration

Deceleration

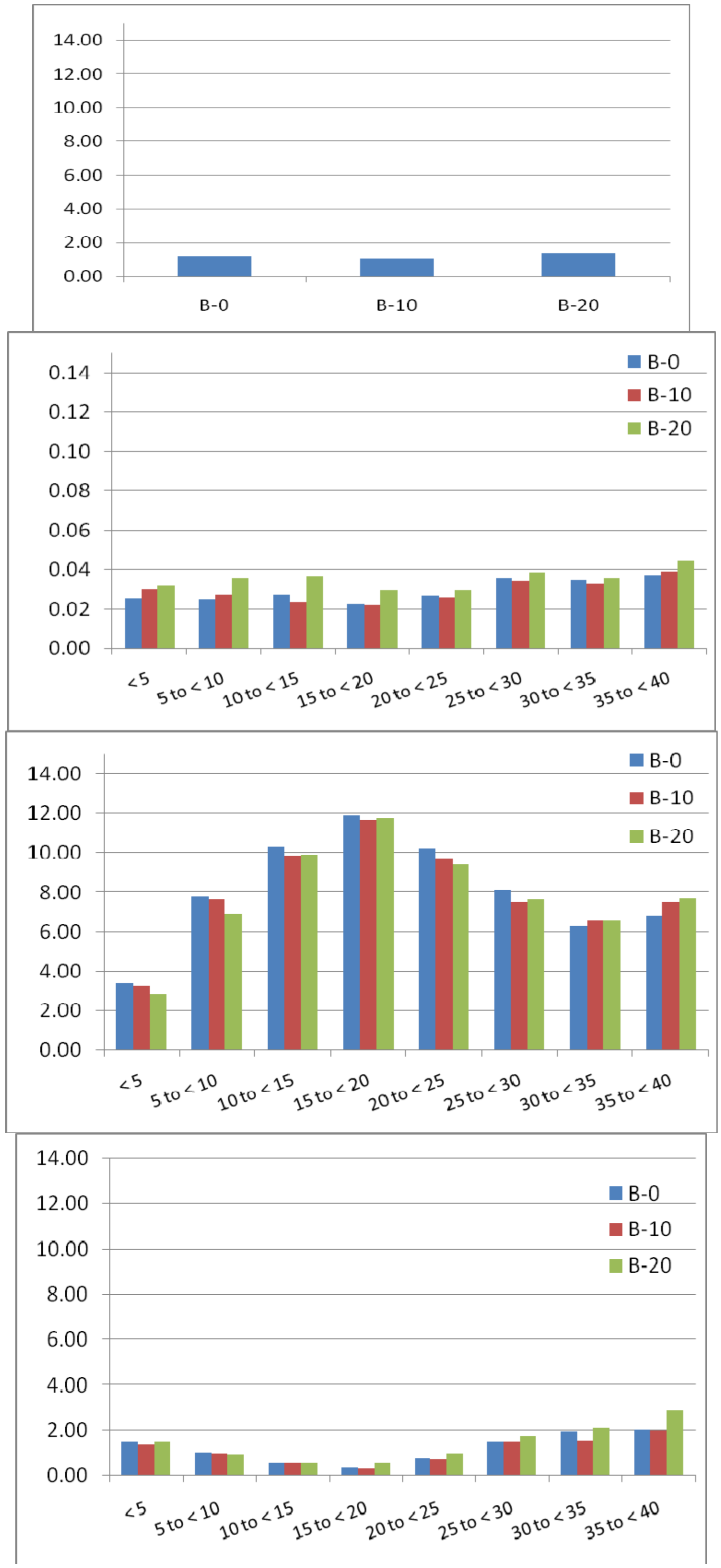

Figure 3-16. CO_2 emissions (g/s) for Bus 973 by mode and speed (mph)

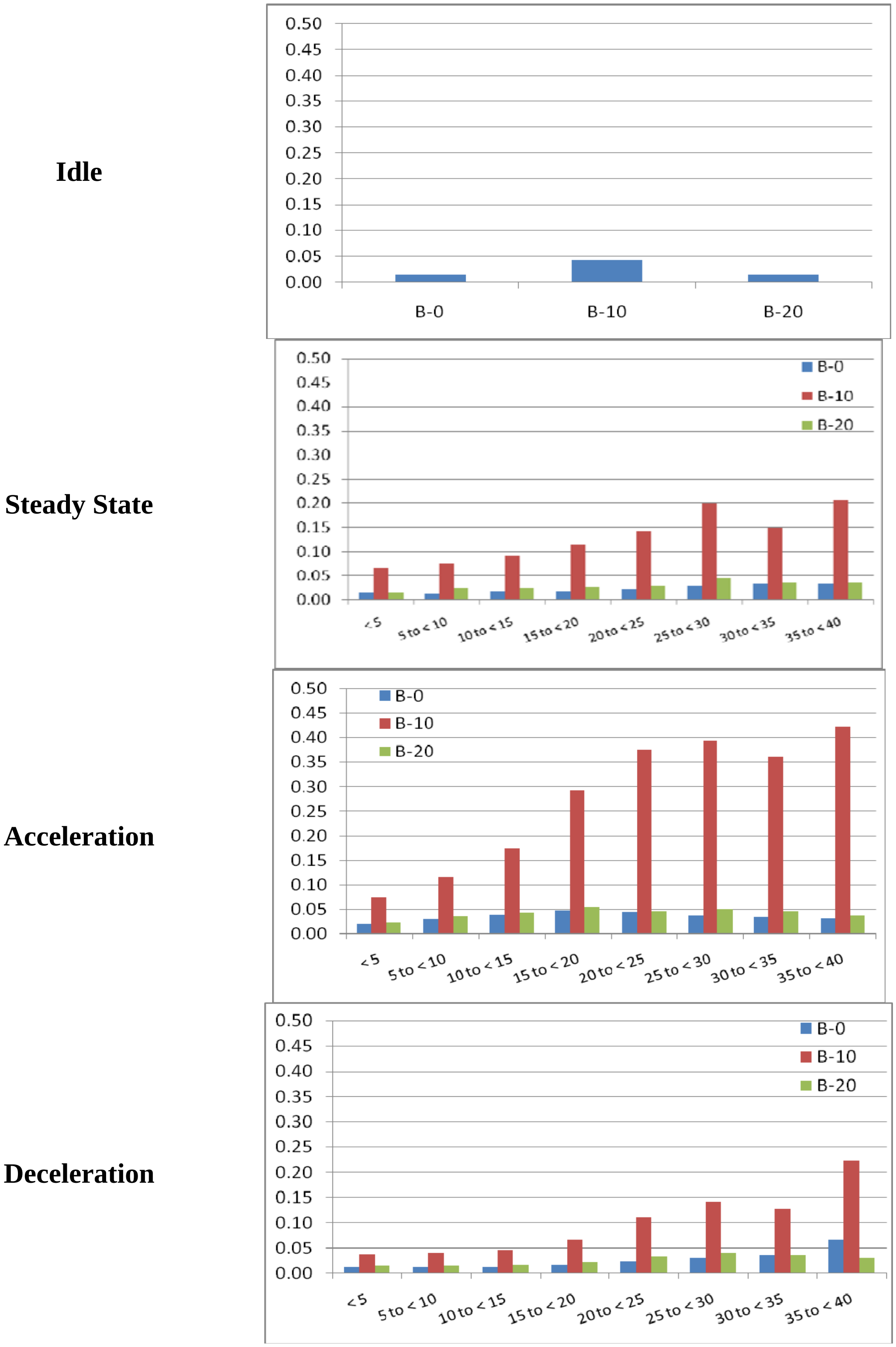

Figure 3-17. PM emissions (mg/s) for Bus 973 by mode and speed (mph)

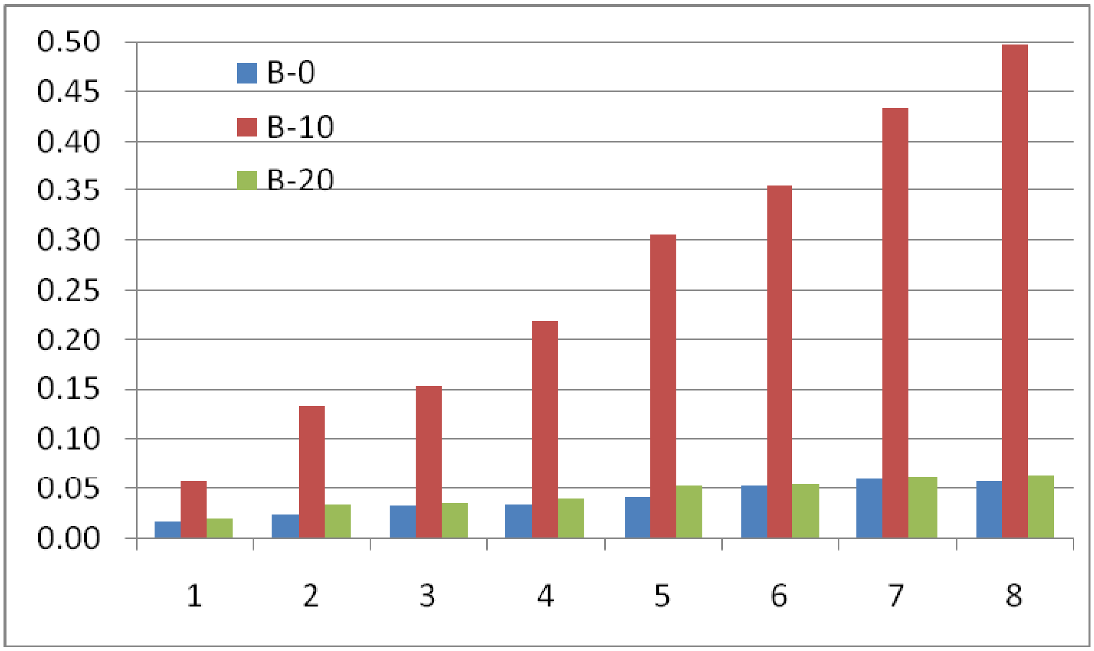

Figure 3-18. PM emissions (mg/s) for Bus 973 by VSP bin

3.8.1.2 Descriptive Statistic Results for Bus 971

Data were plotted by mode and speed range and VSP bin as shown in Figures 3-19 to 3-28 for Bus 971. Results for Bus 971 suggest no specific trend exists in NO_x emissions due to the different biodiesel blends. Results for steady state are mixed while NO_x emissions are lower B-10 than for B-0 and B-20 for acceleration mode. For deceleration, NO_x emissions are higher for B-10 than for either B-0 or B-20. Results are similar for idle conditions for all three fuels.

HC emissions for B-10 and B-20 are much lower than for B-0 for all modes except for deceleration where B-10 emissions are lower than B-0 but B-20 emissions are higher. CO emissions are much lower for B-10 than for B-0 but B-20 emissions are higher than for B-0 for all modes and speed ranges. Results are mixed for CO_2 emissions for deceleration and no general conclusions can be drawn. CO_2 emissions are generally lower for B-10 but higher for B-20 than for B-0 for acceleration, deceleration, and idling. PM emissions are similar and much lower for B-10 and B-20 for all modes and all speed ranges than for B-0.

Idle

Steady State

Acceleration

Deceleration

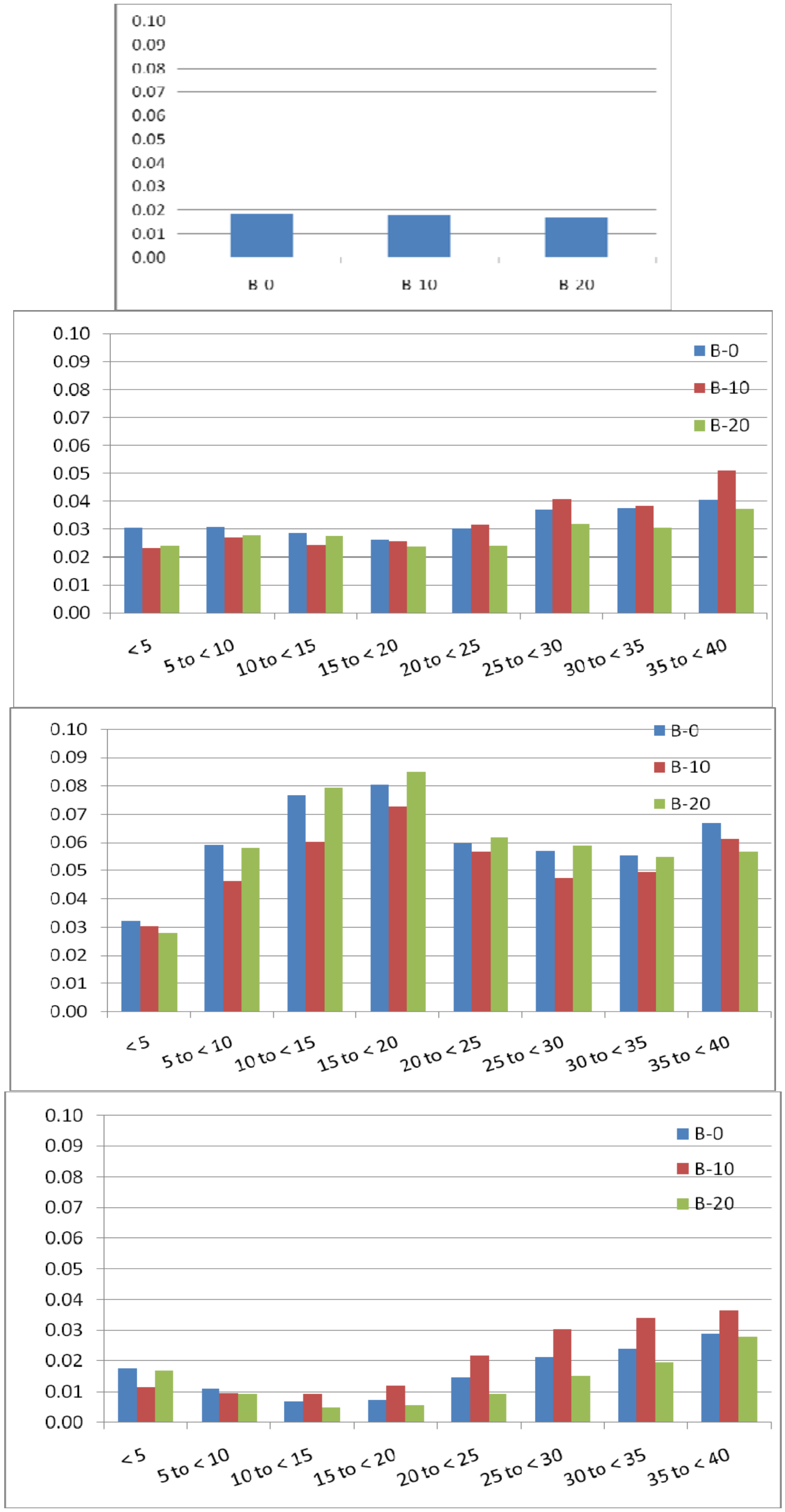

Figure 3-19. NO_x emissions (g/s) for Bus 971 by mode and speed (mph)

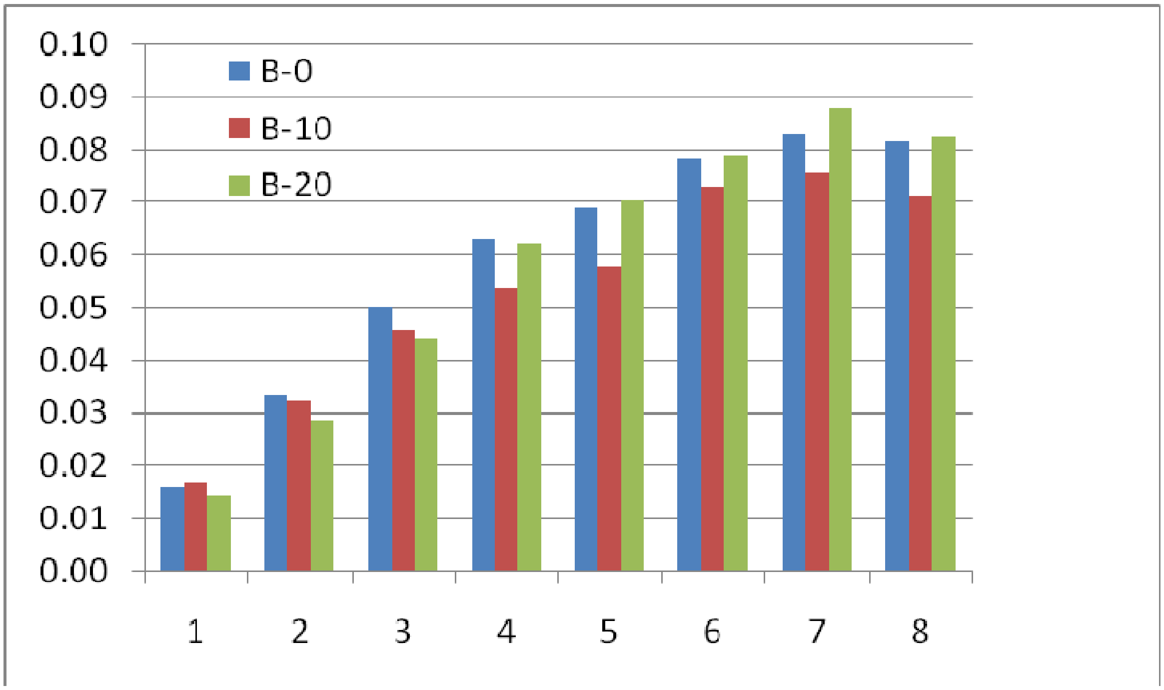

Figure 3-20. NO_x emissions (g/s) for Bus 971 by VSP bin

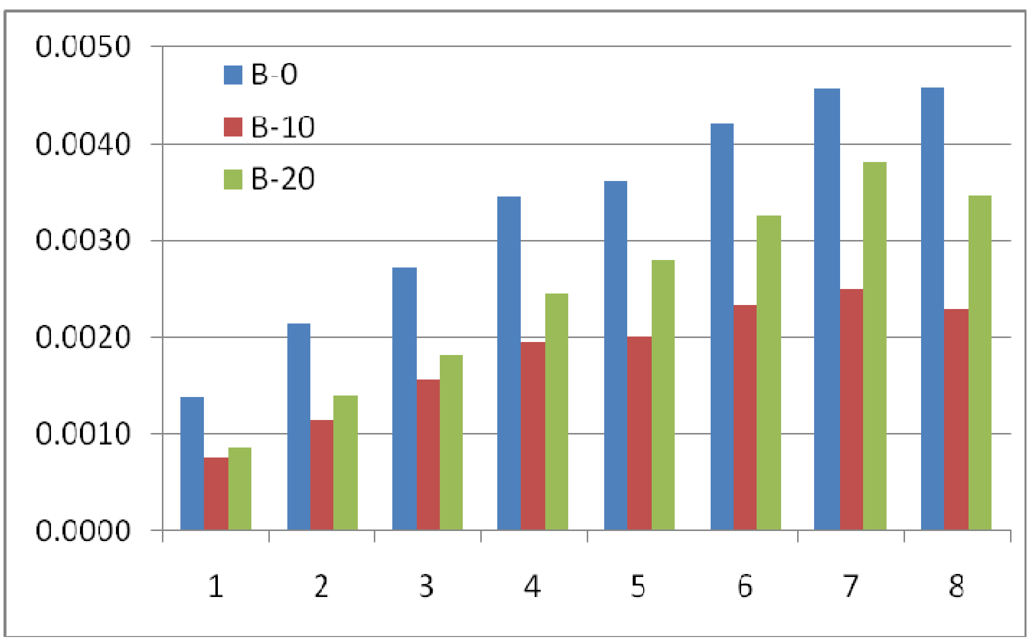

Figure 3-21. HC emissions (g/s) for Bus 971 by VSP bin

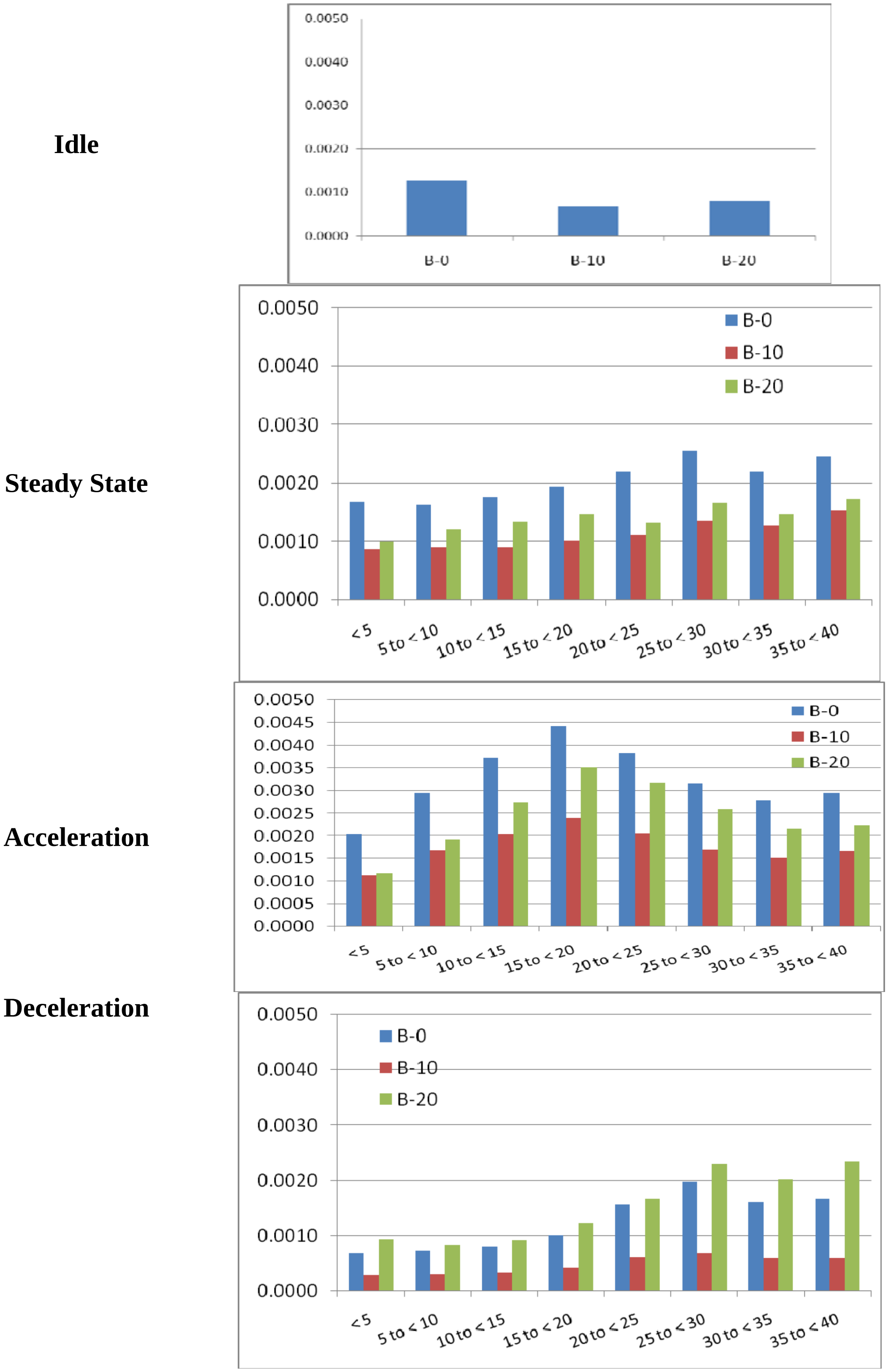

Figure 3-22. HC emissions (g/s) for Bus 971 by mode and speed (mph)

Idle

Steady State

Acceleration

Deceleration

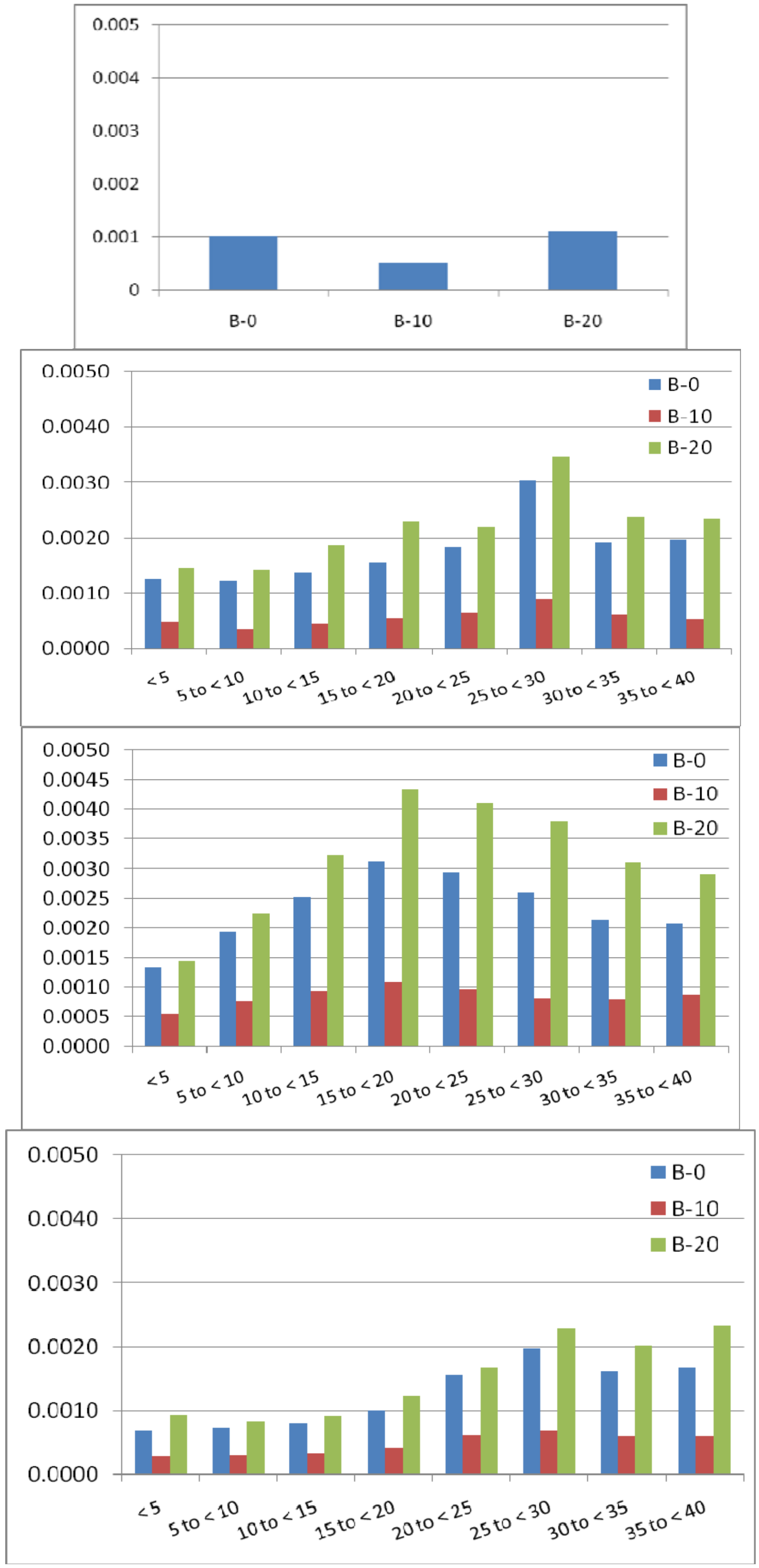

Figure 3-23. CO emissions (g/s) for Bus 971 by mode and speed (mph)

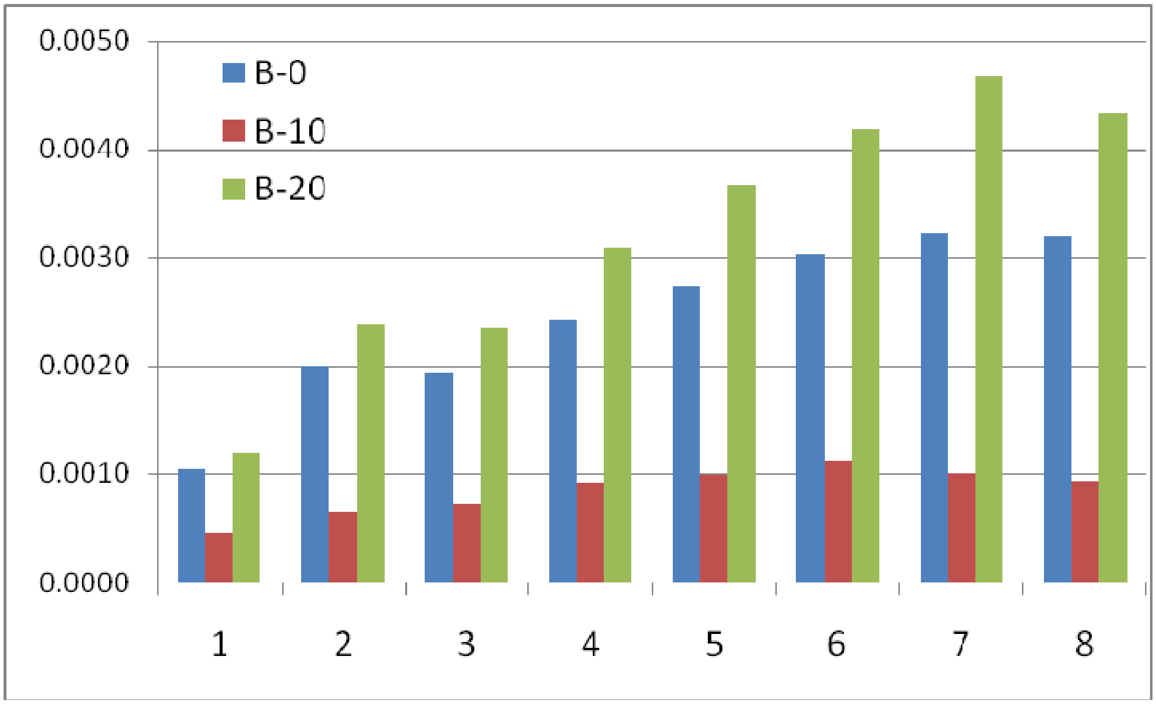

Figure 3-24. CO emissions for Bus 971 by VSP bin

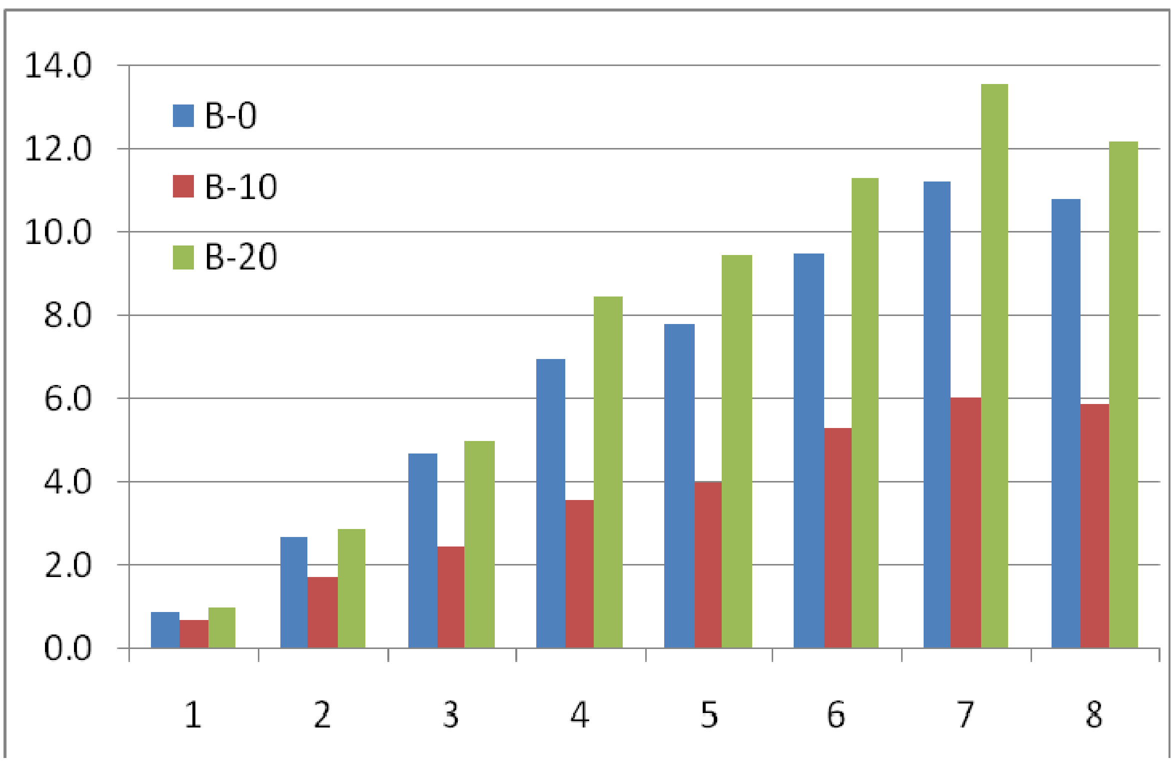

Figure 3-25. CO_2 emissions for Bus 971 by VSP bin

Idle

Steady State

Acceleration

Deceleration

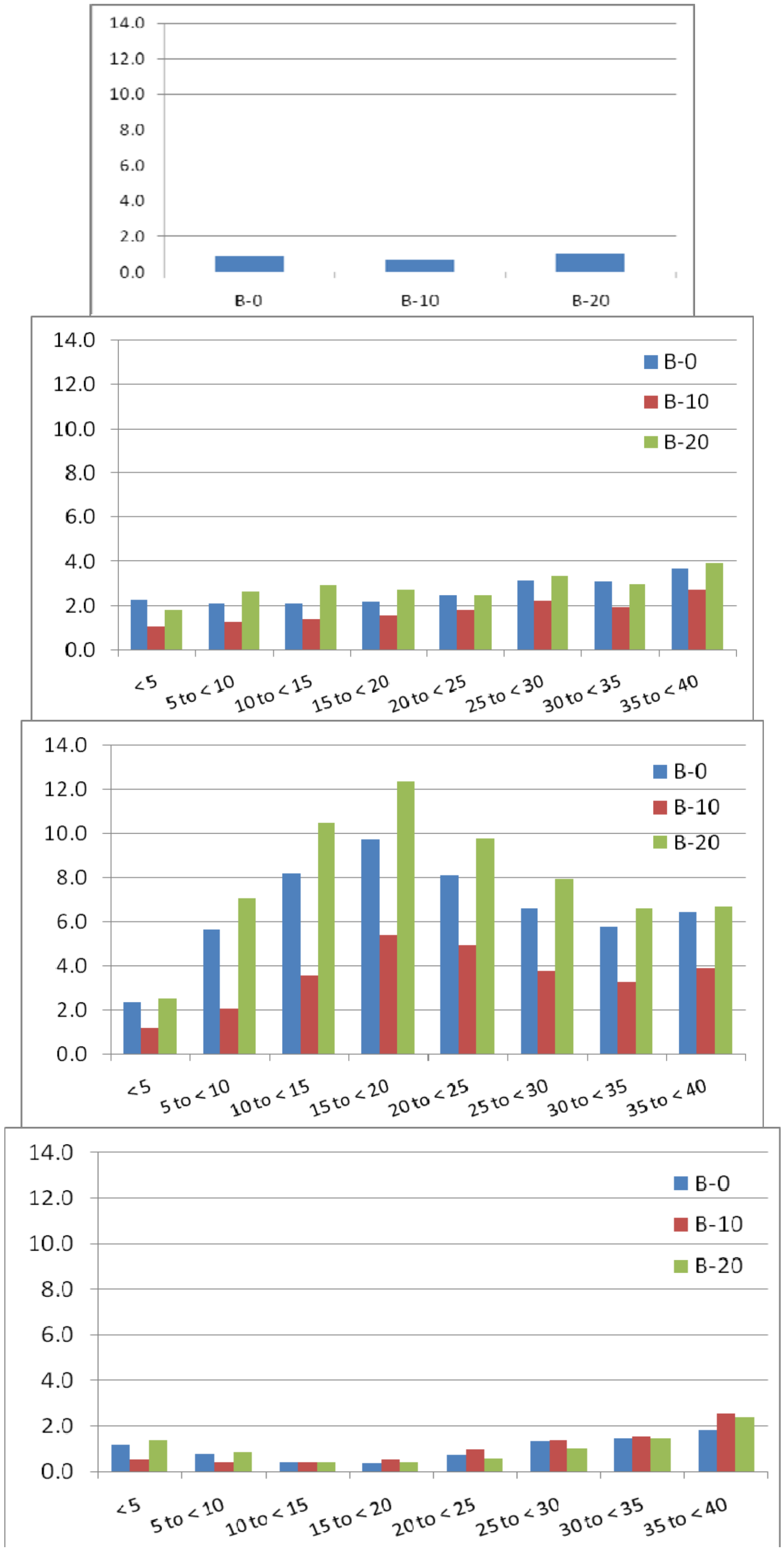

Figure 3-26. CO_2 emissions (g/s) for Bus 971 by mode and speed (mph)

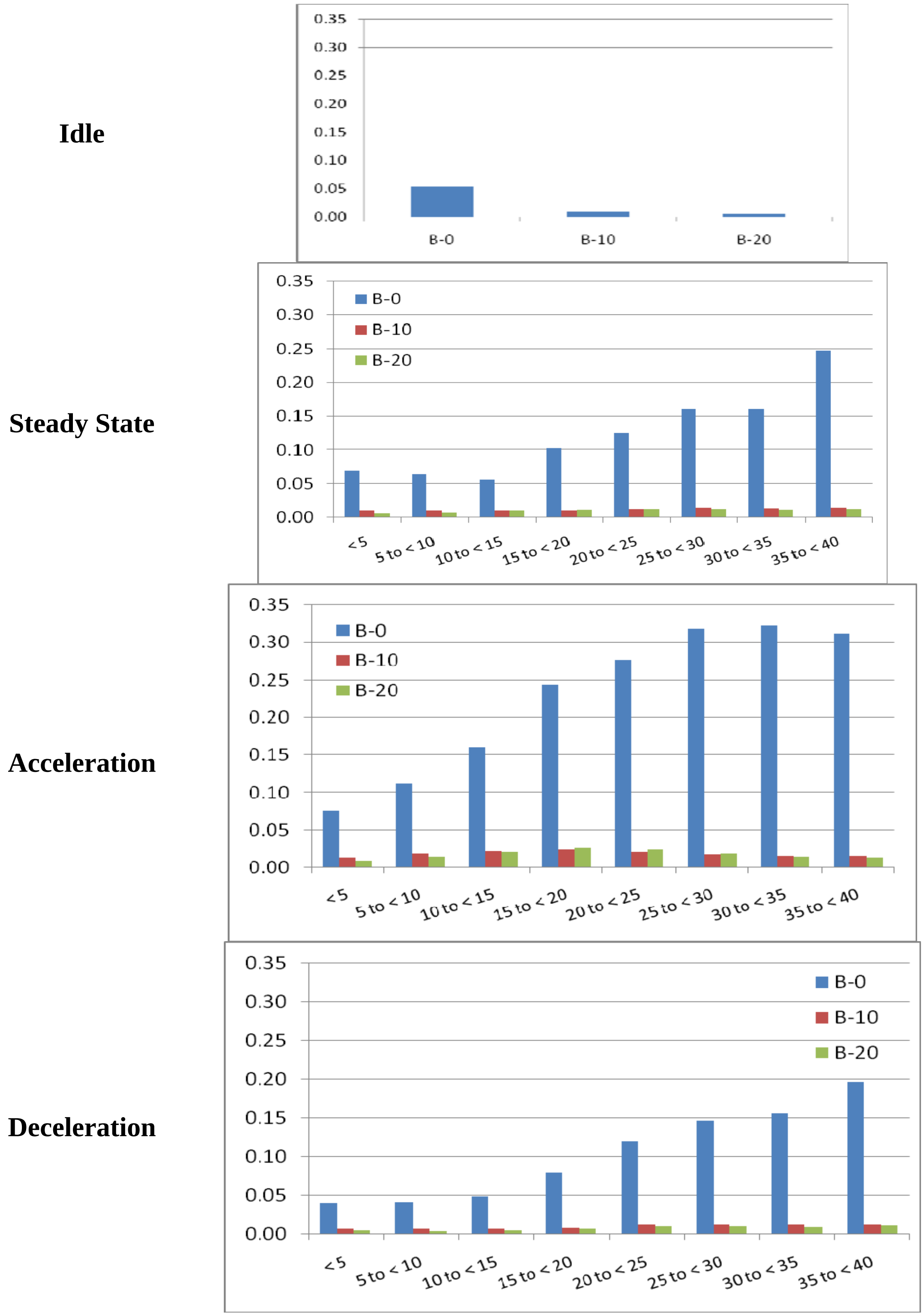

Figure 3-27. PM emissions (mg/s) for Bus 971 by mode and speed (mph)

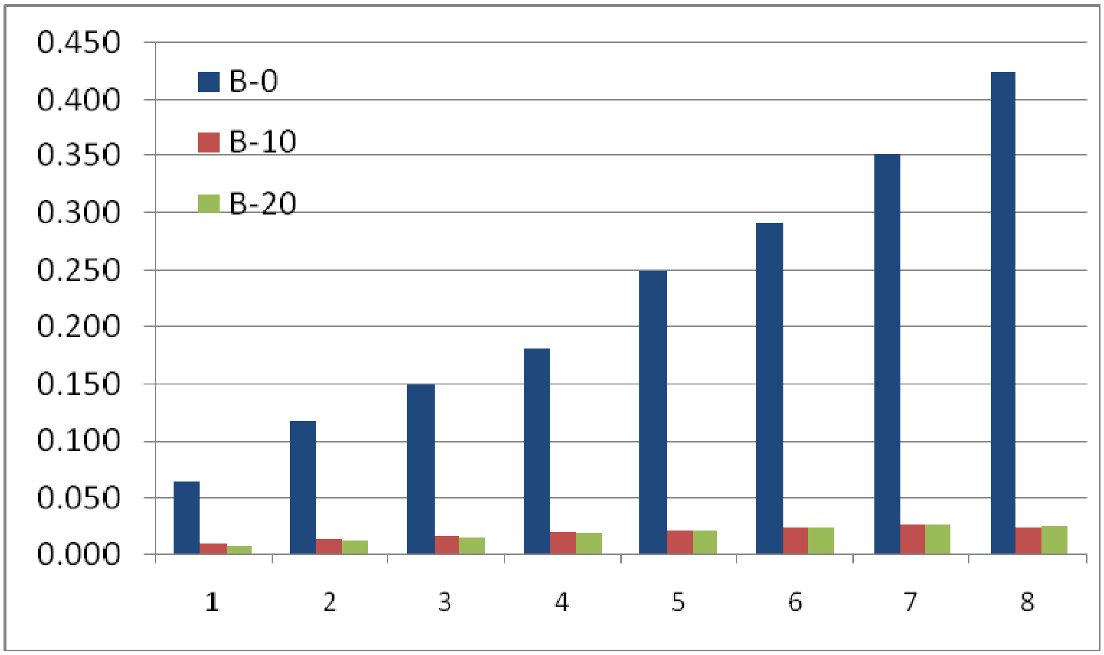

Figure 3-28. PM emissions (mg/s) for Bus 971 by VSP bin

3.8.1.3 Descriptive Statistic Results for Bus 997

Data were plotted by mode and speed range and VSP bin as shown in Figures 3-28 to 3-38 for Bus 997. Results for Bus 997 suggest that NO_x emissions increased for both B-10 and B-20 for all modes and all speed ranges. In some cases B-20 emissions are higher for a specific speed range by mode and in other cases B-10 emission are higher.

HC emissions for B-10 are higher than for B-0 in for all modes and speed ranges while B-20 HC emissions are much lower than for B-0. This was unexpected since HC emissions are usually expected to be lower for biodiesel. Carbon monoxide emissions were lower for B-10 than for B-0 and were lower for B-20 than for B-10 in all cases.

Results are mixed for CO_2 emissions but CO_2 emissions are generally higher for both B-10 and B-20 than for B-0. In most cases, CO_2 emissions for B-10 were higher for than for B-20. PM emissions for B-20 were slightly higher than or similar to those for B-0 for all modes and speed ranges while PM emissions were much higher for B-10 than for B-0 for all modes and speed ranges.

Idle

Steady State

Acceleration

Deceleration

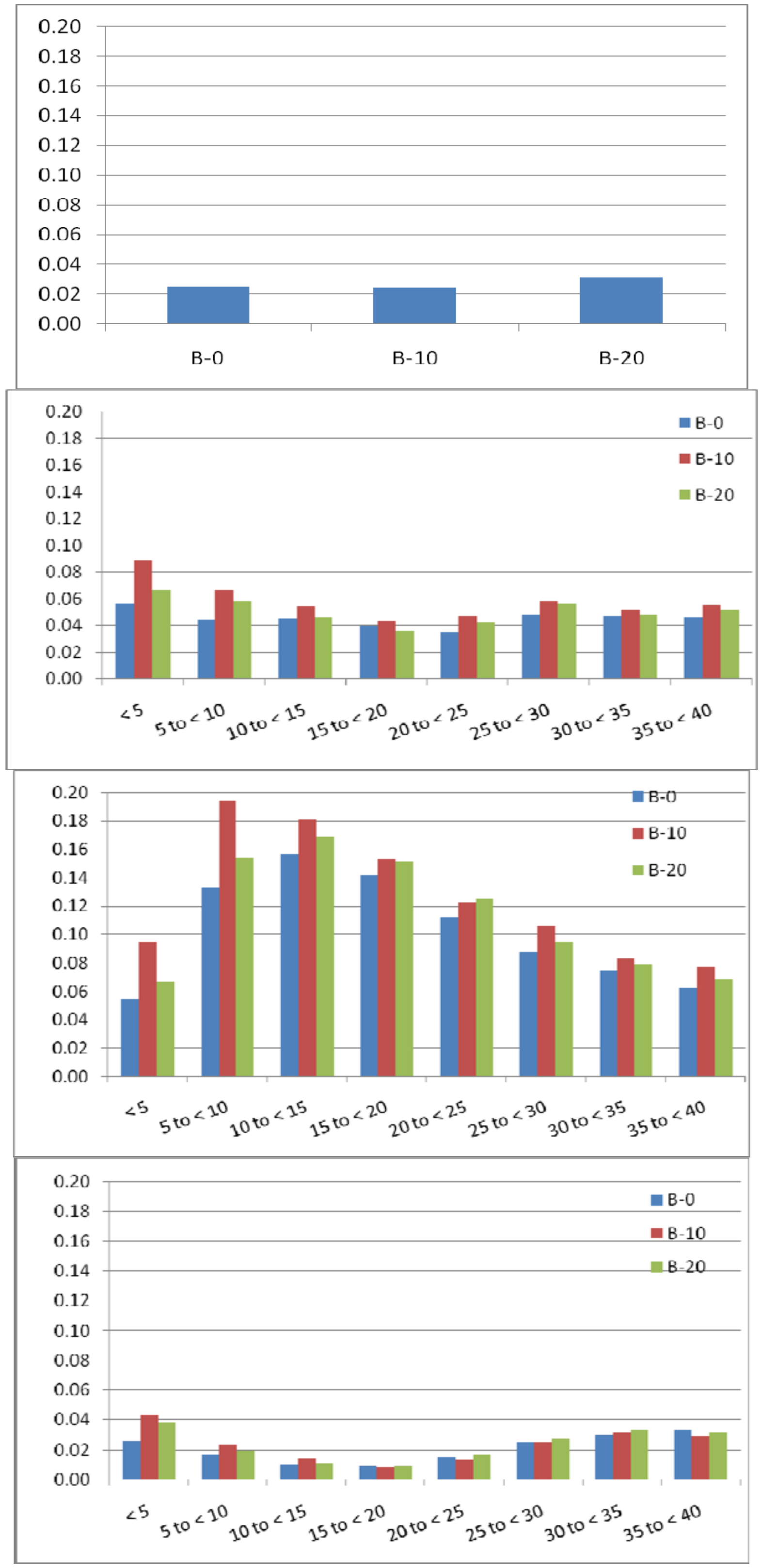

Figure 3-29. NO_x emissions (g/s) for Bus 997 by mode and speed (mph)

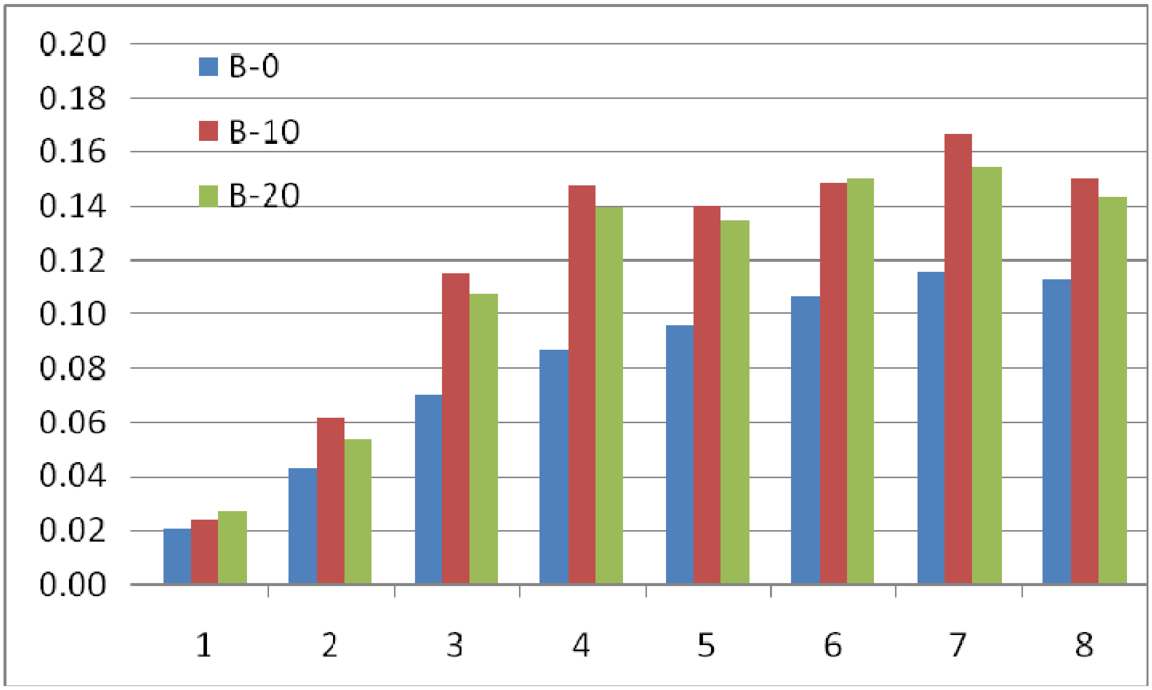

Figure 3-30. NO_x emissions (g/s) for Bus 997 by VSP bin

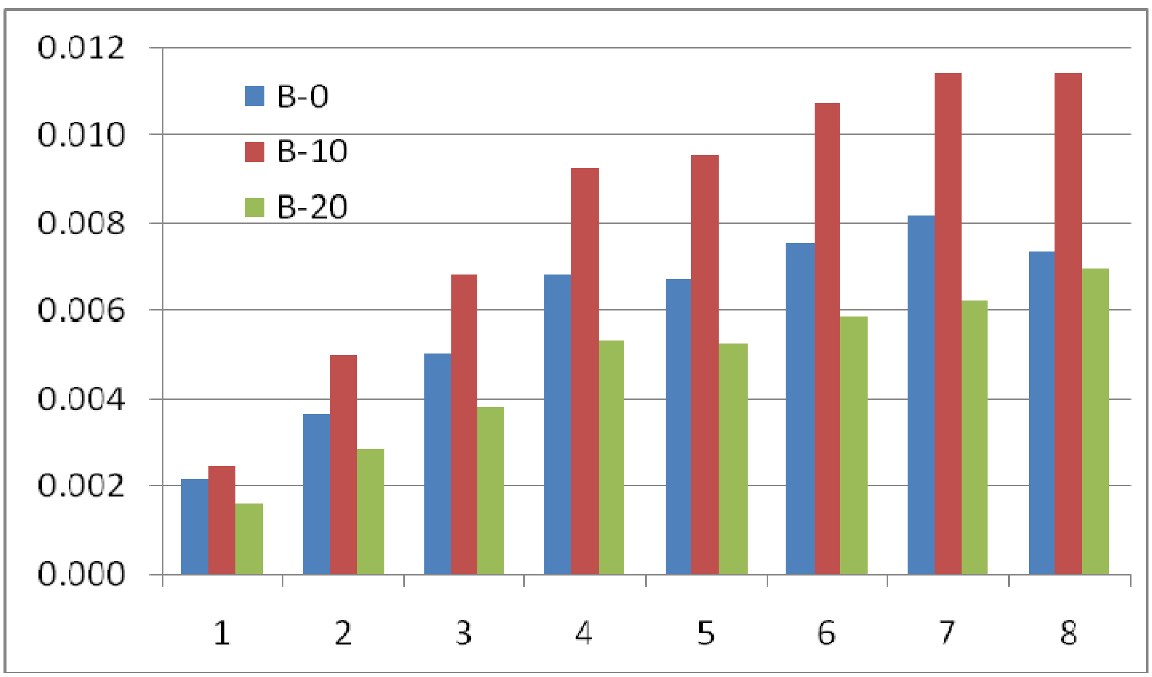

Figure 3-31. HC emissions (g/s) for Bus 997 by VSP bin

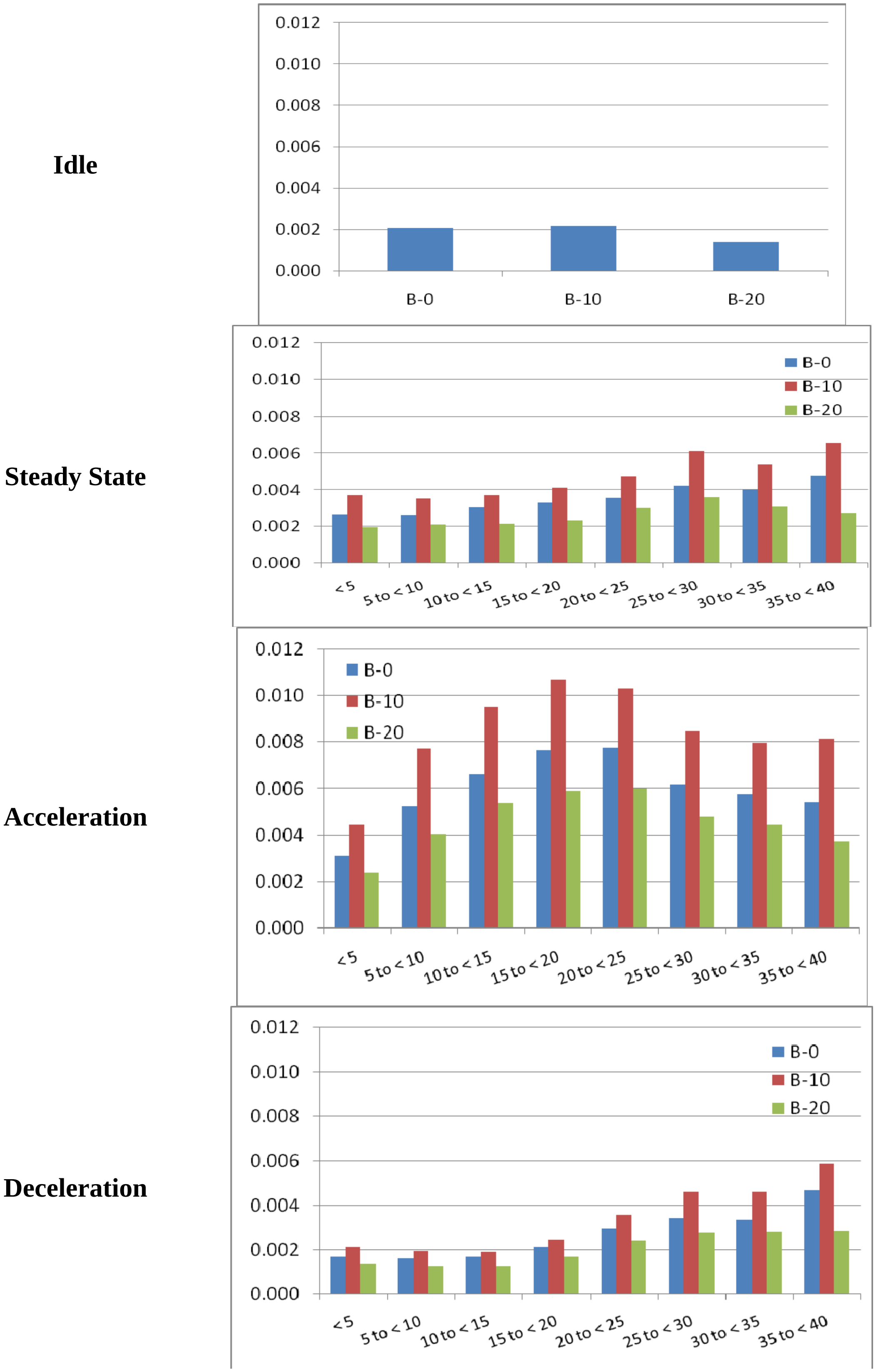

Figure 3-32. HC emissions for Bus 997 by mode and speed (mph)

Idle

Steady State

Acceleration

Deceleration

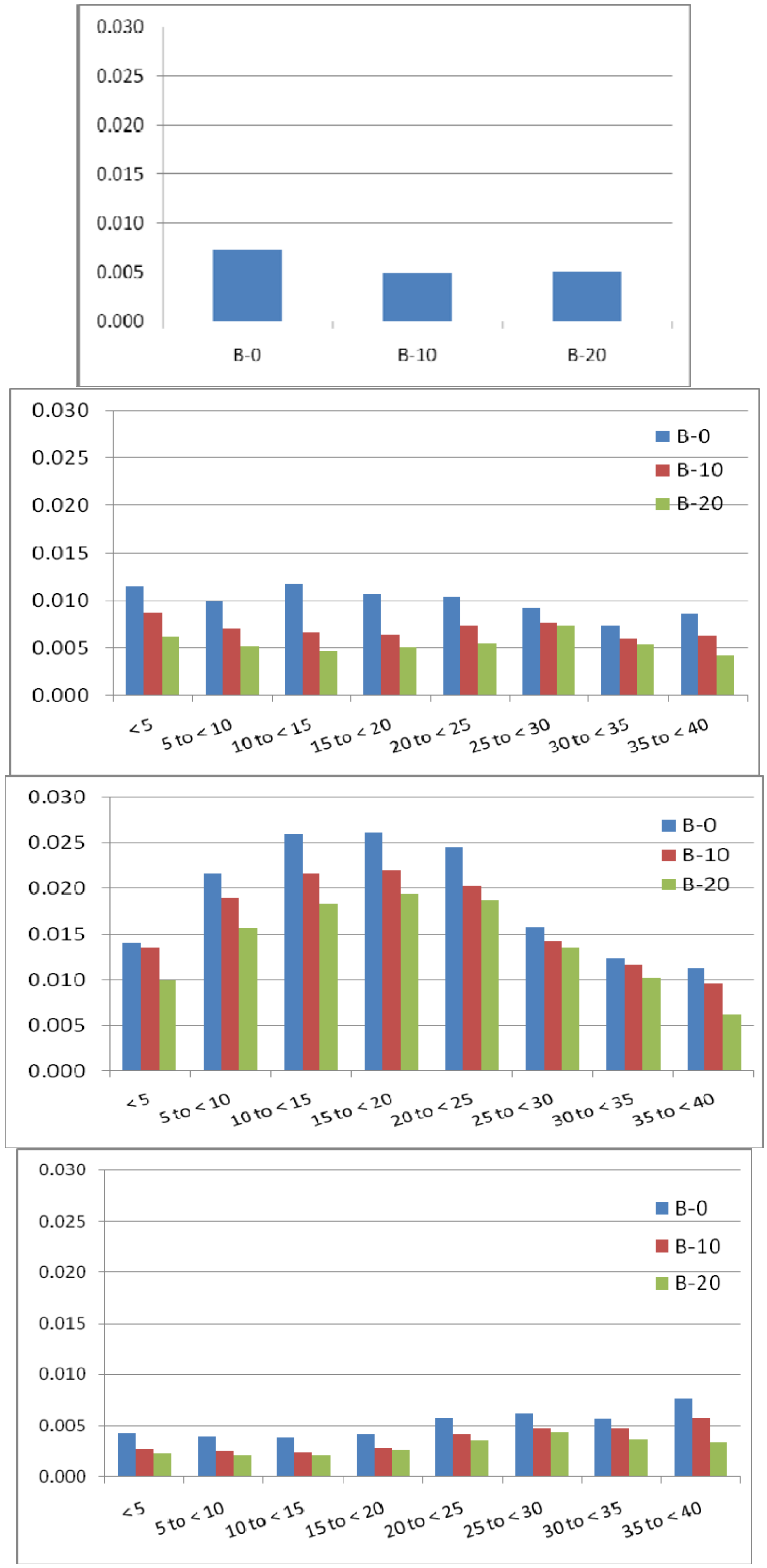

Figure 3-33. CO emissions for Bus 997 by mode and speed (mph)

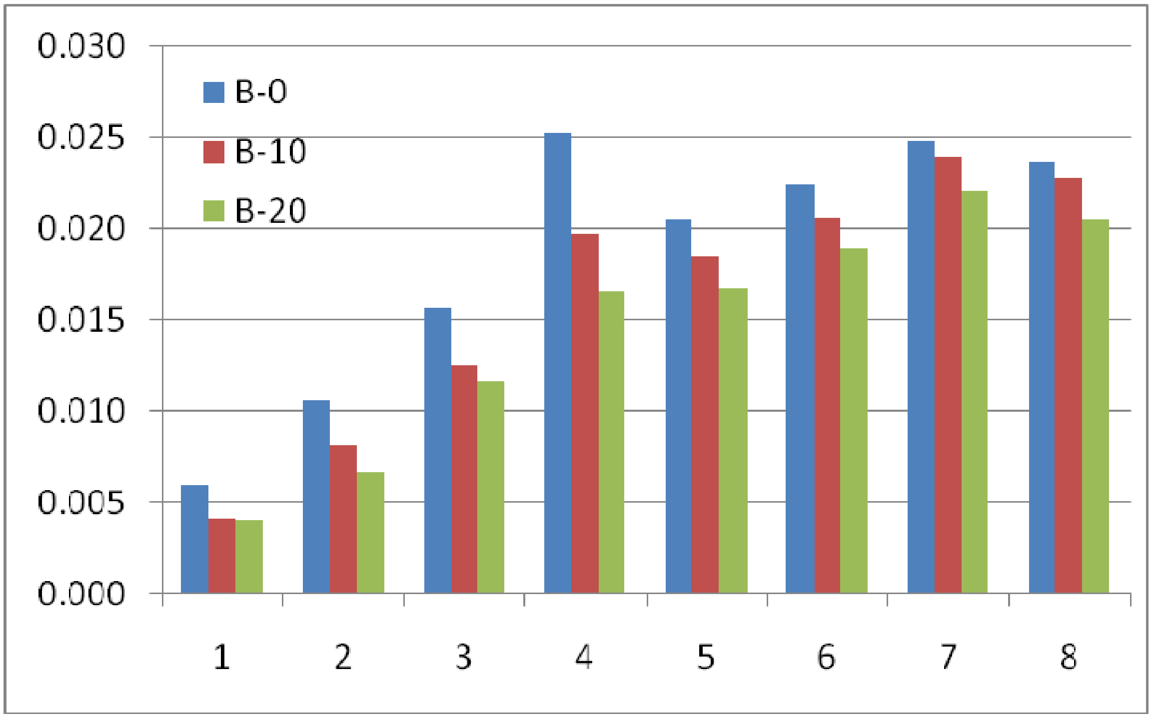

Figure 3-34. CO emissions (g/s) for Bus 997 by VSP bin

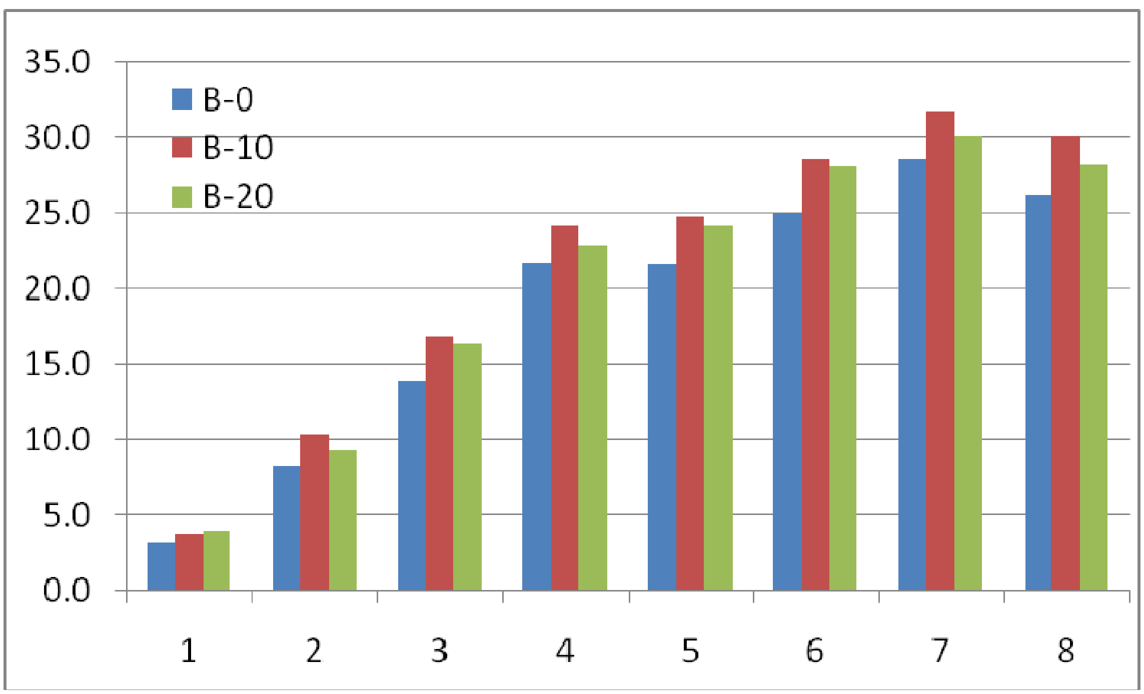

Figure 3-35. CO_2 emissions (g/s) for Bus 997 by VSP bin

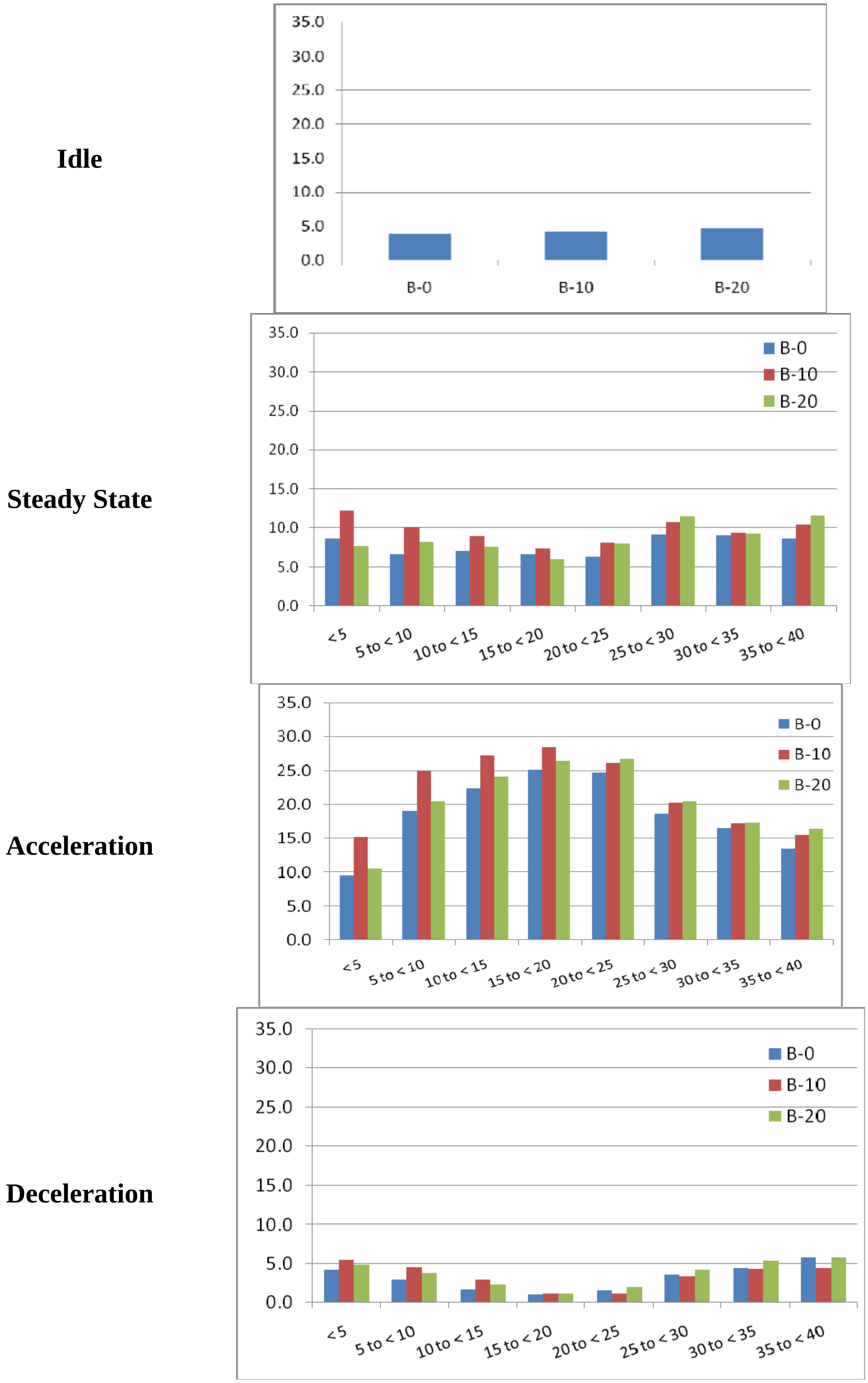

Figure 3-36. CO_2 emissions (g/s) for Bus 997 by mode and speed (mph)

Idle

Steady State

Acceleration

Deceleration

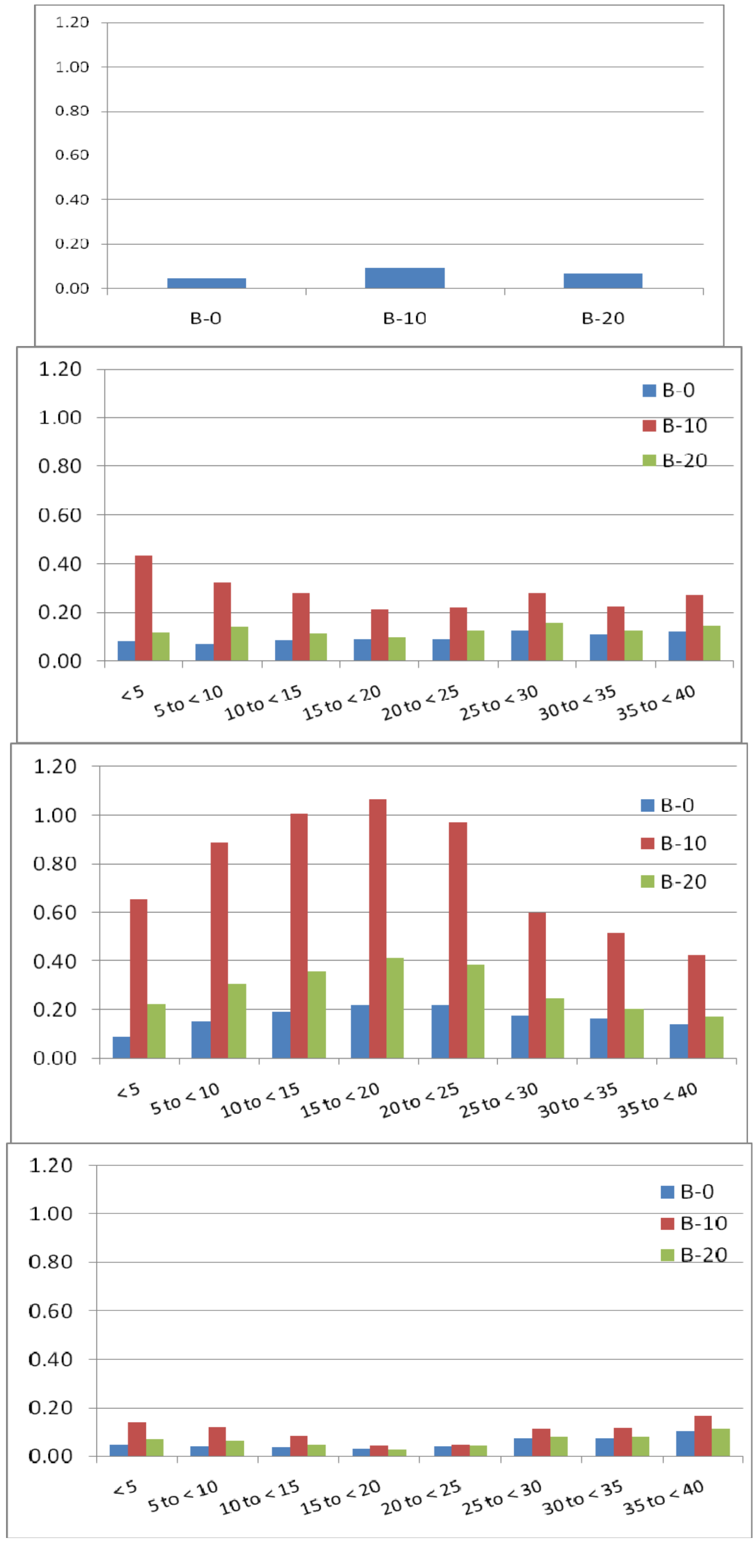

Figure 3-37. PM emissions (mg/s) for Bus 997 by mode and speed (mph)

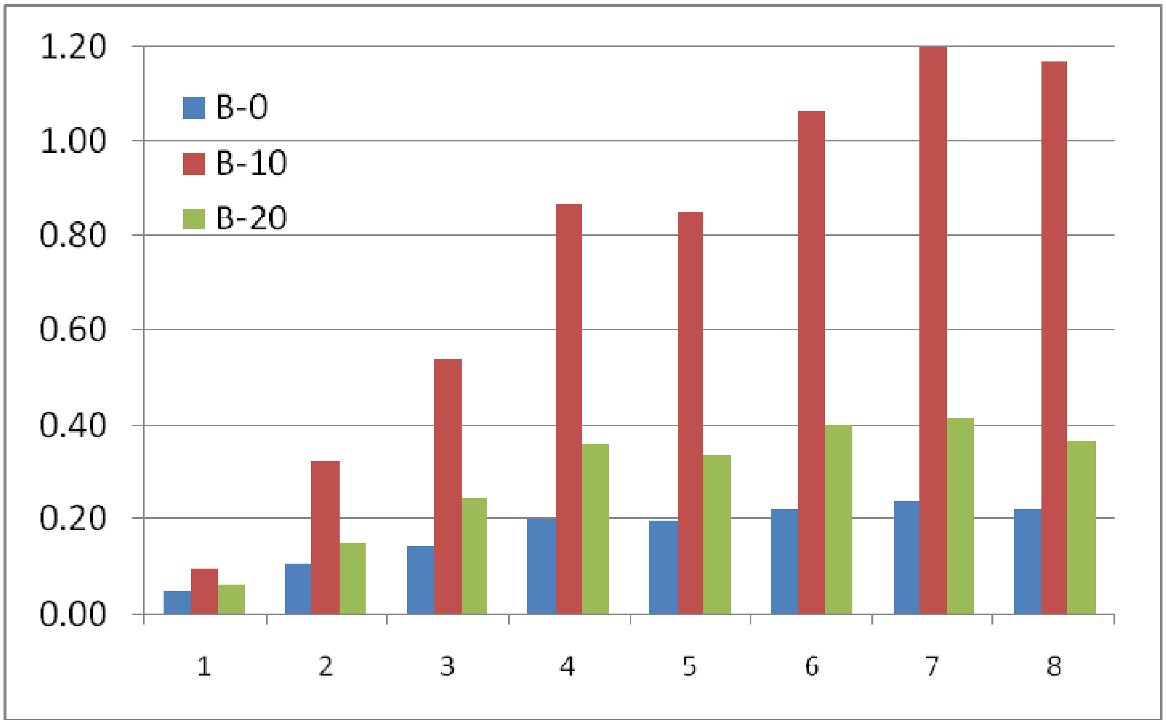

Figure 3-38. PM emissions (mg/s) for Bus 997 by VSP bin

3.8.2 Model Results for On-Road

3.8.2.1 Model Results for Bus 973

A generalized linear model where the response has a gamma distribution and the explanatory variables are included in the linear predictor was used to fit a model for each pollutant of interest.

Nitrogen Oxides. Table 3-5 to 3-9 provide model results for NO_x for Bus 973. As shown in Table 3-6, all the parameter comparisons and interactions are significant except for "passengers" and the interaction "B-0 and speed". Table 3-9 provides the least square means. As shown, B-20 has the highest estimated mean NO_X emissions followed by B-0. B-10 has the lowest NO_X emissions. Mean NO_x emissions (g/s) for B-10 are 17.2% lower than B-20 and B-10 emissions are 26.8% lower than for B-0. Emissions while the bus is in acceleration mode have the highest emissions, while emissions during deceleration mode are the lowest.

Table 3-5. Parameter information for NO_x (Bus 973)

Parameter	Effect	Fuel	Mode
Prm1	Intercept		
Prm2	mode		1
Prm3	mode		2
Prm4	mode		3
Prm5	mode		4
Prm6	fuel	B0	
Prm7	fuel	B10	
Prm8	fuel	B20	
Prm9	speed		
Prm10	pass		
Prm11	fuel*mode	B0	1
Prm12	fuel*mode	B0	2
Prm13	fuel*mode	B0	3
Prm14	fuel*mode	B0	4
Prm15	fuel*mode	B10	1
Prm16	fuel*mode	B10	2
Prm17	fuel*mode	B10	3
Prm18	fuel*mode	B10	4
Prm19	fuel*mode	B20	1
Prm20	fuel*mode	B20	2
Prm21	fuel*mode	B20	3
Prm22	fuel*mode	B20	4
Prm23	speed*fuel	B0	
Prm24	speed*fuel	B10	
Prm25	speed*fuel	B20	
Prm26	pass*fuel	B0	
Prm27	pass*fuel	B10	
Prm28	pass*fuel	B20	
Number of observations		133,652	

Table 3-6. Analysis of parameter estimates for NO_x (Bus 973)

Parameter			Estimate	Standard Error	Wald 95% Confidence Limits		Chi-Square	Pr > ChiSq
Intercept			48.4152	0.3540	47.7214	49.1091	18704.1	<.0001
mode	1		-14.0139	0.4177	-14.8325	-13.1953	1125.80	<.0001
mode	2		-27.9397	0.3613	-28.6478	-27.2316	5980.71	<.0001
mode	3		-36.5954	0.3424	-37.2665	-35.9243	11423.5	<.0001
mode	4		0.0000	0.0000	0.0000	0.0000	.	.
fuel	B0		11.2111	0.6449	9.9471	12.4751	302.21	<.0001
fuel	B10		33.3259	0.6461	32.0595	34.5922	2660.52	<.0001
fuel	B20		0.0000	0.0000	0.0000	0.0000	.	.
speed			-0.1136	0.0065	-0.1263	-0.1009	306.80	<.0001
pass			0.0561	0.0107	0.0351	0.0770	27.49	<.0001
fuel*mode	B0	1	-3.8679	0.7863	-5.4090	-2.3269	24.20	<.0001
fuel*mode	B0	2	-5.3176	0.6663	-6.6234	-4.0117	63.70	<.0001
fuel*mode	B0	3	-9.1137	0.6249	-10.3385	-7.8888	212.67	<.0001
fuel*mode	B0	4	0.0000	0.0000	0.0000	0.0000	.	.
fuel*mode	B10	1	-9.5653	0.7868	-11.1073	-8.0232	147.81	<.0001
fuel*mode	B10	2	-18.6917	0.6654	-19.9958	-17.3876	789.17	<.0001
fuel*mode	B10	3	-27.7527	0.6243	-28.9762	-26.5291	1976.20	<.0001
fuel*mode	B10	4	0.0000	0.0000	0.0000	0.0000	.	.
fuel*mode	B20	1	0.0000	0.0000	0.0000	0.0000	.	.
fuel*mode	B20	2	0.0000	0.0000	0.0000	0.0000	.	.
fuel*mode	B20	3	0.0000	0.0000	0.0000	0.0000	.	.
fuel*mode	B20	4	0.0000	0.0000	0.0000	0.0000	.	.
speed*fuel	B0		0.0003	0.0120	-0.0232	0.0238	0.00	0.9800
speed*fuel	B10		-0.0688	0.0112	-0.0907	-0.0469	37.87	<.0001
speed*fuel	B20		0.0000	0.0000	0.0000	0.0000	.	.
pass*fuel	B0		-0.1337	0.0158	-0.1647	-0.1027	71.41	<.0001
pass*fuel	B10		-0.0612	0.0162	-0.0930	-0.0294	14.25	0.0002
pass*fuel	B20		0.0000	0.0000	0.0000	0.0000	.	.
Scale			1.7098	0.0061	1.6979	1.7218		

Table 3-7. Wald statistics for type 3 analysis for NO_x (Bus 973)

Source	DF	Chi-Square	Pr > ChiSq
mode	3	56802.3	<.0001
fuel	2	4575.23	<.0001
speed	1	740.35	<.0001
pass	1	1.79	0.1813
fuel*mode	6	4013.20	<.0001
speed*fuel	2	42.13	<.0001
pass*fuel	2	71.41	<.0001

Table 3-8. Least square means of the transformed data for NO_x (Bus 973)

Effect	Fuel	mode	Estimate	Standard Error	Chi-Square	Pr > ChiSq	Confidence Limits	
fuel	B0		33.3959	0.1727	37381	<.0001	33.0573	33.7344
fuel	B10		45.6430	0.1737	69054	<.0001	45.3025	45.9834
fuel	B20		27.6377	0.1087	64681	<.0001	27.4247	27.8507
mode		1	42.8969	0.2165	39253	<.0001	42.4725	43.3212
mode		2	25.4457	0.1163	47894	<.0001	25.2178	25.6736
mode		3	12.5043	0.0548	52121	<.0001	12.3970	12.6117
mode		4	61.3885	0.2663	53146	<.0001	60.8666	61.9104

Table 3-9 Least square means (g/s) of the original data for NO_x (Bus 973)

Effect	fuel	mode	Estimate	SE	LowerCL	UpperCL
fuel	B0		0.029944	.000154875	0.029634	0.030254
fuel	B10		0.021909	.000083374	0.021742	0.022076
fuel	B20		0.036182	.000142268	0.035898	0.036467
mode		1	0.023312	.000117662	0.023076	0.023547
mode		2	0.039299	.000179574	0.038940	0.039658
mode		3	0.079972	.000350296	0.079272	0.080673
mode		4	0.016290	.000070660	0.016148	0.016431

Hydrocarbons. The model for hydrocarbons is shown in Tables 3-10 to 3-14. As shown in Table 3-11 and 3-12, all the variables and all effects are significant. Table 3-14 provides the estimated least square means for hydrocarbons. As shown, mean HC emissions are highest for B-

0, followed by B-10. B-20 has the lowest HC emissions. Mean HC emissions (g/s) for B-10 are 74.3% lower than for B-0 and B-10 emission are 11.7% lower. Emissions are also highest while the bus is in acceleration mode and lowest while the bus is idling.

Table 3-10. Parameter information for HC (Bus 973)

Parameter	Effect	fuel	mode
Prm1	Intercept		
Prm2	mode		1
Prm3	mode		2
Prm4	mode		3
Prm5	mode		4
Prm6	fuel	B0	
Prm7	fuel	B10	
Prm8	fuel	B20	
Prm9	speed		
Prm10	pass		
Prm11	fuel*mode	B0	1
Prm12	fuel*mode	B0	2
Prm13	fuel*mode	B0	3
Prm14	fuel*mode	B0	4
Prm15	fuel*mode	B10	1
Prm16	fuel*mode	B10	2
Prm17	fuel*mode	B10	3
Prm18	fuel*mode	B10	4
Prm19	fuel*mode	B20	1
Prm20	fuel*mode	B20	2
Prm21	fuel*mode	B20	3
Prm22	fuel*mode	B20	4
Prm23	speed*fuel	B0	
Prm24	speed*fuel	B10	
Prm25	speed*fuel	B20	
Prm26	pass*fuel	B0	
Prm27	pass*fuel	B10	
Prm28	pass*fuel	B20	
Number of observations		96,586	

Table 3-11. Analysis of parameter estimates for HC (Bus 973)

Parameter			DF	Estimate	Standard Error	Wald 95% Confidence Limits		Chi-Square	Pr > ChiSq
Intercept			1	2444.239	35.5709	2374.522	2513.957	4721.70	<.0001
mode	1		1	472.2523	49.1230	375.9731	568.5315	92.42	<.0001
mode	2		1	-761.443	36.7401	-833.453	-689.434	429.53	<.0001
mode	3		1	-1408.52	32.7942	-1472.79	-1344.24	1844.72	<.0001
mode	4		0	0.0000	0.0000	0.0000	0.0000	.	.
fuel	B0		1	-1707.45	36.4599	-1778.91	-1635.99	2193.14	<.0001
fuel	B10		1	-1630.46	36.1585	-1701.33	-1559.59	2033.30	<.0001
fuel	B20		0	0.0000	0.0000	0.0000	0.0000	.	.
speed			1	-13.4027	0.9542	-15.2729	-11.5325	197.29	<.0001
pass			1	13.3894	1.6408	10.1734	16.6055	66.59	<.0001
fuel*mode	B0	1	1	-435.602	50.5205	-534.621	-336.584	74.34	<.0001
fuel*mode	B0	2	1	516.1644	37.7192	442.2361	590.0926	187.26	<.0001
fuel*mode	B0	3	1	964.8898	33.6704	898.8971	1030.883	821.22	<.0001
fuel*mode	B0	4	0	0.0000	0.0000	0.0000	0.0000	.	.
fuel*mode	B10	1	1	-414.974	50.0496	-513.069	-316.879	68.75	<.0001
fuel*mode	B10	2	1	487.4667	37.3409	414.2799	560.6534	170.42	<.0001
fuel*mode	B10	3	1	920.0136	33.3374	854.6734	985.3538	761.59	<.0001
fuel*mode	B10	4	0	0.0000	0.0000	0.0000	0.0000	.	.
fuel*mode	B20	1	0	0.0000	0.0000	0.0000	0.0000	.	.
fuel*mode	B20	2	0	0.0000	0.0000	0.0000	0.0000	.	.
fuel*mode	B20	3	0	0.0000	0.0000	0.0000	0.0000	.	.
fuel*mode	B20	4	0	0.0000	0.0000	0.0000	0.0000	.	.
speed*fuel	B0		1	9.4287	0.9745	7.5187	11.3387	93.61	<.0001
speed*fuel	B10		1	7.4407	0.9662	5.5470	9.3343	59.31	<.0001
speed*fuel	B20		0	0.0000	0.0000	0.0000	0.0000	.	.
pass*fuel	B0		1	-16.8265	1.6506	-20.0616	-13.5913	103.92	<.0001
pass*fuel	B10		1	-12.7927	1.6565	-16.0392	-9.5461	59.64	<.0001
pass*fuel	B20		0	0.0000	0.0000	0.0000	0.0000	.	.
Scale			1	1.2782	0.0052	1.2680	1.2885		

Table 3-12. Wald statistics for type 3 analysis for HC (Bus 973)

Source	DF	Chi-Square	Pr > ChiSq
mode	3	9872.76	<.0001
fuel	2	4456.12	<.0001
speed	1	560.02	<.0001
pass	1	40.09	<.0001
fuel*mode	6	2019.10	<.0001
speed*fuel	2	135.84	<.0001
pass*fuel	2	280.63	<.0001

Table 3-13. Least square means of the transformed data for HC (Bus 973)

Effect	fuel	mode	Estimate	Standard Error	Chi-Square	Pr > ChiSq	Confidence Limits	
fuel	B0		497.2399	3.0882	25925	<.0001	491.1871	503.2926
fuel	B10		563.0096	2.5083	50381	<.0001	558.0934	567.9258
fuel	B20		1936.752	13.1750	21610	<.0001	1910.930	1962.575
mode		1	1442.325	13.1764	11982	<.0001	1416.499	1468.150
mode		2	826.6984	7.2426	13029	<.0001	812.5032	840.8936
mode		3	473.3812	4.1296	13140	<.0001	465.2874	481.4751
mode		4	1253.598	10.7885	13502	<.0001	1232.453	1274.743

Table 3-14. Least square means (g/s) of the original data for HC (Bus 973)

Effect	fuel	Mode	Estimate	SE	LowerCL	UpperCL
fuel	B0		.002011102	.00012490	.001986121	.002036082
fuel	B10		.001776169	.000007913	.001760342	.001791995
fuel	B20		.000516328	.000003512	.000509304	.000523353
mode		1	.000693325	.000006334	.000680657	.000705993
mode		2	.001209631	.000010597	.001188436	.001230826
mode		3	.002112462	.000018428	.002075606	.002149319
mode		4	.000797704	.000006865	.000783974	.000811434

Carbon Monoxide. Table 3-15 to 3-19 provide model results. As shown in Table 3-16 and 3-17, all the parameters were significant, except the interaction of “B-20 and deceleration mode” and “B-10 and idling mode” indicating there is no evidence of differences in means between B-10 fuel and deceleration mode. Table 3-19 provides the least square means (g/s) and indicates that B-0 had the highest CO emissions followed by B-20 (estimated mean is 34.7% lower than for B-0). B-10 has the lowest mean CO emissions (estimated mean is 43.0% lower than B-0). As shown, emissions are also highest while the bus is accelerating and lowest when the bus is in deceleration.

Table 3-15. Parameter information for CO (Bus 973)

Parameter	Effect	fuel	mode
Prm1	Intercept		
Prm2	mode		1
Prm3	mode		2
Prm4	mode		3
Prm5	mode		4
Prm6	fuel	B0	
Prm7	fuel	B10	
Prm8	fuel	B20	
Prm9	speed		
Prm10	pass		
Prm11	fuel*mode	B0	1
Prm12	fuel*mode	B0	2
Prm13	fuel*mode	B0	3
Prm14	fuel*mode	B0	4
Prm15	fuel*mode	B10	1
Prm16	fuel*mode	B10	2
Prm17	fuel*mode	B10	3
Prm18	fuel*mode	B10	4
Prm19	fuel*mode	B20	1
Prm20	fuel*mode	B20	2
Prm21	fuel*mode	B20	3
Prm22	fuel*mode	B20	4
Prm23	speed*fuel	B0	
Prm24	speed*fuel	B10	
Prm25	speed*fuel	B20	
Prm26	pass*fuel	B0	
Prm27	pass*fuel	B10	
Prm28	pass*fuel	B20	
Number of Observations		127,358	

Table 3-16. Analysis of parameter estimates for CO (Bus 973)

Parameter			Estimate	Standard Error	Wald 95% Confidence Limits		Chi-Square	Pr > ChiSq
Intercept			674.3356	6.3965	661.7988	686.8724	11114.1	<.0001
mode	1		-93.9931	7.7287	-109.141	-78.8451	147.90	<.0001
mode	2		-230.789	6.3919	-243.317	-218.261	1303.70	<.0001
mode	3		-346.235	5.8602	-357.721	-334.749	3490.76	<.0001
mode	4		0.0000	0.0000	0.0000	0.0000	.	.
fuel	B0		-211.069	8.3210	-227.378	-194.760	643.41	<.0001
fuel	B10		144.7419	9.5213	126.0806	163.4033	231.10	<.0001
fuel	B20		0.0000	0.0000	0.0000	0.0000	.	.
speed			-3.6897	0.1881	-4.0584	-3.3210	384.65	<.0001
pass			2.0844	0.3085	1.4798	2.6891	45.65	<.0001
fuel*mode	B0	1	48.8939	10.5309	28.2537	69.5340	21.56	<.0001
fuel*mode	B0	2	74.7021	8.3387	58.3584	91.0457	80.25	<.0001
fuel*mode	B0	3	96.8199	7.6346	81.8563	111.7834	160.83	<.0001
fuel*mode	B0	4	0.0000	0.0000	0.0000	0.0000	.	.
fuel*mode	B10	1	13.1392	12.2264	-10.8241	37.1024	1.15	0.2825
fuel*mode	B10	2	-65.6947	9.4522	-84.2207	-47.1688	48.31	<.0001
fuel*mode	B10	3	-119.076	8.7037	-136.135	-102.017	187.17	<.0001
fuel*mode	B10	4	0.0000	0.0000	0.0000	0.0000	.	.
fuel*mode	B20	1	0.0000	0.0000	0.0000	0.0000	.	.
fuel*mode	B20	2	0.0000	0.0000	0.0000	0.0000	.	.
fuel*mode	B20	3	0.0000	0.0000	0.0000	0.0000	.	.
fuel*mode	B20	4	0.0000	0.0000	0.0000	0.0000	.	.
speed*fuel	B0		0.1353	0.2390	-0.3332	0.6037	0.32	0.5714
speed*fuel	B10		-3.3310	0.2510	-3.8230	-2.8390	176.08	<.0001
speed*fuel	B20		0.0000	0.0000	0.0000	0.0000	.	.
pass*fuel	B0		-1.4196	0.3679	-2.1405	-0.6986	14.89	0.0001
pass*fuel	B10		1.7427	0.4131	0.9330	2.5524	17.80	<.0001
pass*fuel	B20		0.0000	0.0000	0.0000	0.0000	.	.
Scale			1.1982	0.0042	1.1899	1.2065		

Table 3-17. Wald statistics for type 3 analysis

Source	DF	Chi-Square	Pr > ChiSq
Mode	3	16578.8	<.0001
Fuel	2	2489.41	<.0001
speed	1	2401.25	<.0001
pass	1	205.16	<.0001
fuel*mode	6	1096.37	<.0001
speed*fuel	2	284.16	<.0001
pass*fuel	2	87.34	<.0001

Table 3-18. Least square means of the transformed data

Effect	fuel	mode	Estimate	Standard Error	Chi-Square	Pr > ChiSq	Confidence Limits	
fuel	B0		307.1364	1.8600	27266	<.0001	303.4908	310.7820
fuel	B10		538.7877	2.4747	47402	<.0001	533.9374	543.6380
fuel	B20		470.4611	2.0708	51613	<.0001	466.4023	474.5198
mode		1	529.1686	3.4886	23009	<.0001	522.3311	536.0060
mode		2	374.6974	1.9594	36568	<.0001	370.8570	378.5378
mode		3	248.8303	1.2650	38693	<.0001	246.3510	251.3097
mode		4	602.4840	3.1166	37370	<.0001	596.3755	608.5925

Table 3-19. Least square means (g/s) of the original data

Effect	Fuel	Mode	Estimate	SE	LowerCL	UpperCL
fuel	B0		.003255882	.000019718	.003216447	.003295318
fuel	B10		.001856019	.000008525	.001838969	.001873068
fuel	B20		.002125574	.000009356	.002106862	.002144287
mode		1	.001889757	.000012458	.001864841	.001914674
mode		2	.002668820	.000013956	.002640908	.002696733
mode		3	.004018803	.000020431	.003977942	.004059664
mode		4	.001659795	.000008586	.001642623	.001676967

Carbon dioxide. Model results for CO_2 for Bus 973 are provided in Tables 3-20 to 3-24. Table 3-21 and 3-22 indicates that 14 of the 18 parameters comparisons were significant. As shown, the interaction between the variable "passenger" and fuel type was not significant. Results also show that there is no evidence of differences in means between the comparison of "B-20 and deceleration mode" and "B-0 and idling mode", "B-0 and speed", and "B-10 and speed". Table 3-24 provides the estimated least square means. As indicated, B-20 has the highest estimated mean CO_2 emissions (g/s) followed by B-0 (B-0 is 9.8% lower than B-20. B-10 has the lowest mean emissions (8.3% lower than B-0). Also as indicated emissions are highest when the bus is in acceleration mode and lowest when the bus is decelerating.

Table 3-20. Parameter information for CO_2 (Bus 973)

Parameter	Effect	fuel	mode
Prm1	Intercept		
Prm2	mode		1
Prm3	mode		2
Prm4	mode		3
Prm5	mode		4
Prm6	fuel	B0	
Prm7	fuel	B10	
Prm8	fuel	B20	
Prm9	speed		
Prm10	pass		
Prm11	fuel*mode	B0	1
Prm12	fuel*mode	B0	2
Prm13	fuel*mode	B0	3
Prm14	fuel*mode	B0	4
Prm15	fuel*mode	B10	1
Prm16	fuel*mode	B10	2
Prm17	fuel*mode	B10	3
Prm18	fuel*mode	B10	4
Prm19	fuel*mode	B20	1
Prm20	fuel*mode	B20	2
Prm21	fuel*mode	B20	3
Prm22	fuel*mode	B20	4
Prm23	speed*fuel	B0	
Prm24	speed*fuel	B10	
Prm25	speed*fuel	B20	
Prm26	pass*fuel	B0	
Prm27	pass*fuel	B10	
Prm28	pass*fuel	B20	
Number of observations		133,611	

Table 3-21. Analysis of parameter estimates for CO_2 (Bus 973)

Parameter			Estimate	Standard Error	Wald 95% Confidence Limits		Chi-Square	Pr > ChiSq
Intercept			0.9249	0.0068	0.9116	0.9382	18677.6	<.0001
mode	1		-0.1650	0.0085	-0.1817	-0.1483	375.42	<.0001
mode	2		-0.5974	0.0070	-0.6110	-0.5838	7385.54	<.0001
mode	3		-0.7734	0.0067	-0.7865	-0.7603	13410.6	<.0001
mode	4		0.0000	0.0000	0.0000	0.0000	.	.
fuel	B0		0.0901	0.0115	0.0676	0.1127	61.37	<.0001
fuel	B10		0.1607	0.0099	0.1412	0.1801	261.25	<.0001
fuel	B20		0.0000	0.0000	0.0000	0.0000	.	.
speed			-0.0017	0.0001	-0.0018	-0.0015	410.82	<.0001
pass			-0.0005	0.0001	-0.0008	-0.0003	19.56	<.0001
fuel*mode	B0	1	0.0124	0.0153	-0.0175	0.0424	0.66	0.4163
fuel*mode	B0	2	-0.0524	0.0119	-0.0757	-0.0291	19.47	<.0001
fuel*mode	B0	3	-0.0954	0.0114	-0.1177	-0.0732	70.54	<.0001
fuel*mode	B0	4	0.0000	0.0000	0.0000	0.0000	.	.
fuel*mode	B10	1	0.0569	0.0132	0.0310	0.0828	18.52	<.0001
fuel*mode	B10	2	-0.1099	0.0102	-0.1300	-0.0898	115.14	<.0001
fuel*mode	B10	3	-0.1633	0.0098	-0.1825	-0.1441	277.66	<.0001
fuel*mode	B10	4	0.0000	0.0000	0.0000	0.0000	.	.
fuel*mode	B20	1	0.0000	0.0000	0.0000	0.0000	.	.
fuel*mode	B20	2	0.0000	0.0000	0.0000	0.0000	.	.
fuel*mode	B20	3	0.0000	0.0000	0.0000	0.0000	.	.
fuel*mode	B20	4	0.0000	0.0000	0.0000	0.0000	.	.
speed*fuel	B0		-0.0001	0.0001	-0.0004	0.0002	0.44	0.5077
speed*fuel	B10		-0.0002	0.0001	-0.0004	0.0001	2.28	0.1310
speed*fuel	B20		0.0000	0.0000	0.0000	0.0000	.	.
pass*fuel	B0		0.0002	0.0002	-0.0002	0.0005	0.97	0.3258
pass*fuel	B10		0.0006	0.0002	0.0002	0.0009	11.38	0.0007
pass*fuel	B20		0.0000	0.0000	0.0000	0.0000	.	.
Scale			1.5921	0.0056	1.5811	1.6032		

Table 3-22. Wald statistics for type 3 analysis for CO_2 (Bus 973)

Source	DF	Chi-Square	Pr > ChiSq
mode	3	80958.6	<.0001
fuel	2	735.47	<.0001
speed	1	1129.55	<.0001
pass	1	17.04	<.0001
fuel*mode	6	1132.13	<.0001
speed*fuel	2	2.28	0.3197
pass*fuel	2	12.00	0.0025

Table 3-23. Least square means of the transformed data for CO_2 (Bus 973)

Effect	fuel	mode	Estimate	Standard Error	Chi-Square	Pr > ChiSq	Confidence Limits	
Fuel	B0		0.5714	0.0033	30886	<.0001	0.5650	0.5777
Fuel	B10		0.6230	0.0026	57814	<.0001	0.6179	0.6281
Fuel	B20		0.5151	0.0022	55853	<.0001	0.5108	0.5193
Mode		1	0.8412	0.0042	40235	<.0001	0.8330	0.8494
Mode		2	0.3316	0.0015	48421	<.0001	0.3286	0.3345
Mode		3	0.1234	0.0006	47262	<.0001	0.1223	0.1245
Mode		4	0.9831	0.0044	48913	<.0001	0.9744	0.9918

Table 3-24. Least square means (g/s) of the original data for CO_2 (Bus 973)

Effect	fuel	mode	Estimate	SE	LowerCL	UpperCL
fuel	B0		1.75023	0.009959	1.73031	1.77015
fuel	B10		1.60509	0.006675	1.59174	1.61844
fuel	B20		1.94147	0.008215	1.92504	1.95790
mode		1	1.18876	0.005926	1.17690	1.20061
mode		2	3.01589	0.013706	2.98847	3.04330
mode		3	8.10374	0.037276	8.02919	8.17830
mode		4	1.01722	0.004599	1.00803	1.02642

Particulate Matter. Model results for PM for Bus 973 are provided in Tables 3-25 to 3-29. Table 3-26 and 3-27 indicates that the variable "passenger" was not significant and the interaction of "fuel and passenger" was not significant". The interactions of "B-0 and steady state mode" and "B-20 and deceleration mode" were also not significant. The estimated least square means for PM is shown in Table 3-9. As indicated, mean PM emissions (g/s) are highest for B-10 followed by B-20. B-0 has the lowest emissions. Estimated mean emissions for B-0 are

75.0% lower than for B-10 and 16.3% lower than B-0. PM emissions were highest while the bus was in acceleration model and lowest when the bus was in deceleration mode.

Table 3-25. Parameter information for PM (Bus (973)

Parameter	Effect	fuel	mode
Prm1	Intercept		
Prm2	mode		1
Prm3	mode		2
Prm4	mode		3
Prm5	mode		4
Prm6	fuel	B0	
Prm7	fuel	B10	
Prm8	fuel	B20	
Prm9	pass		
Prm10	fuel*mode	B0	1
Prm11	fuel*mode	B0	2
Prm12	fuel*mode	B0	3
Prm13	fuel*mode	B0	4
Prm14	fuel*mode	B10	1
Prm15	fuel*mode	B10	2
Prm16	fuel*mode	B10	3
Prm17	fuel*mode	B10	4
Prm18	fuel*mode	B20	1
Prm19	fuel*mode	B20	2
Prm20	fuel*mode	B20	3
Prm21	fuel*mode	B20	4
Prm22	pass*fuel	B0	
Prm23	pass*fuel	B10	
Prm24	pass*fuel	B20	
Number of Observations		133661	

Table 3-26. Analysis of parameter estimates for PM (Bus (973)

Parameter			DF	Estimate	Standard Error	Wald 95% Confidence Limits		Chi-Square	Pr > ChiSq
Intercept			1	43.0921	0.5256	42.0619	44.1222	6721.74	<.0001
mode	1		1	24.3149	0.8773	22.5955	26.0343	768.23	<.0001
mode	2		1	-13.9685	0.5867	-15.1185	-12.8186	566.84	<.0001
mode	3		1	-20.4736	0.5534	-21.5583	-19.3889	1368.54	<.0001
mode	4		0	0.0000	0.0000	0.0000	0.0000	.	.
fuel	B0		1	8.4304	0.9956	6.4790	10.3819	71.70	<.0001
fuel	B10		1	-28.7161	0.5490	-29.7921	-27.6402	2736.29	<.0001
fuel	B20		0	0.0000	0.0000	0.0000	0.0000	.	.
pass			1	0.0633	0.0327	-0.0007	0.1274	3.76	0.0525
fuel*mode	B0	1	1	-7.7289	1.6390	-10.9413	-4.5165	22.24	<.0001
fuel*mode	B0	2	1	-1.3920	1.1331	-3.6127	0.8288	1.51	0.2193
fuel*mode	B0	3	1	-7.7913	1.0369	-9.8236	-5.7590	56.46	<.0001
fuel*mode	B0	4	0	0.0000	0.0000	0.0000	0.0000	.	.
fuel*mode	B10	1	1	-15.4423	0.9289	-17.2630	-13.6216	276.34	<.0001
fuel*mode	B10	2	1	6.1291	0.6103	4.9329	7.3253	100.85	<.0001
fuel*mode	B10	3	1	10.1131	0.5756	8.9849	11.2412	308.70	<.0001
fuel*mode	B10	4	0	0.0000	0.0000	0.0000	0.0000	.	.
fuel*mode	B20	1	0	0.0000	0.0000	0.0000	0.0000	.	.
fuel*mode	B20	2	0	0.0000	0.0000	0.0000	0.0000	.	.
fuel*mode	B20	3	0	0.0000	0.0000	0.0000	0.0000	.	.
fuel*mode	B20	4	0	0.0000	0.0000	0.0000	0.0000	.	.
pass*fuel	B0		1	0.5754	0.0608	0.4563	0.6945	89.68	<.0001
pass*fuel	B10		1	-0.0296	0.0332	-0.0946	0.0354	0.80	0.3714
pass*fuel	B20		0	0.0000	0.0000	0.0000	0.0000	.	.
Scale			1	0.6643	0.0022	0.6600	0.6685		

Table 3-27. Wald statistics for type 3 analysis for PM (Bus (973)

Source	DF	Chi-Square	Pr > ChiSq
mode	3	7841.45	<.0001
fuel	2	12464.3	<.0001
pass	1	145.38	<.0001
fuel*mode	6	1889.01	<.0001
pass*fuel	2	138.27	<.0001

Table 3-28. Least square means of the transformed data for PM (Bus (973)

Effect	fuel	mode	Estimate	Standard Error	Chi-Square	Pr > ChiSq	Confidence Limits	
fuel	B0		48.9787	0.3883	15911	<.0001	48.2177	49.7398
fuel	B10		12.2665	0.0794	23888	<.0001	12.1110	12.4221
fuel	B20		40.9784	0.2453	27905	<.0001	40.4976	41.4592
mode		1	54.5402	0.4577	14200	<.0001	53.6432	55.4373
mode		2	25.5596	0.2179	13760	<.0001	25.1325	25.9866
mode		3	18.2494	0.1535	14125	<.0001	17.9484	18.5503
mode		4	37.9491	0.3158	14442	<.0001	37.3302	38.5680

Table 3-29. Least square means (g/s) of the original data for PM (Bus (973)

Effect	fuel	mode	Estimate	SE	LowerCL	UpperCL
fuel	B0		0.02042	.000161864	0.02009	0.02074
fuel	B10		0.08152	.000527463	0.08047	0.08258
fuel	B20		0.02440	.000146084	0.02411	0.02470
mode		1	0.01834	.000153865	0.01803	0.01864
mode		2	0.03912	.000333527	0.03846	0.03979
mode		3	0.05480	.000461055	0.05387	0.05572
mode		4	0.02635	.000219269	0.02591	0.02679

3.8.2.2 Model Results for Bus 971

A generalized linear model where the response has a gamma distribution and the explanatory variables are included in the linear predictor was used to fit a model for each pollutant of interest.

Nitrogen Oxides. Table 3-30 to 3-34 provide model results for NO_x for Bus 971. Results presented in Table 3-31 and 3-32 indicate that the variable "Passengers" is the only main effect that is not significant. Table 3-32 shows that the interactions of "B-10 and speed" and "fuel and passengers" are also not significant. Table 3-34 provides the least squares estimate of the mean. As shown, B-10 had the highest mean NO_x emissions (g/s) followed by B-0 (2.7% lower). B-20 has the lowest mean NO_x emissions (12.5% lower than B-0). Additionally, results show that emissions are highest while the bus is in acceleration mode while the lowest mean emissions result while the bus is in deceleration mode.

Table 3-30. Parameter information for NO_x (Bus 971)

Parameter	Effect	fuel	mode
Prm1	Intercept		
Prm2	mode		1
Prm3	mode		2
Prm4	mode		3
Prm5	mode		4
Prm6	fuel	B0	
Prm7	fuel	B10	
Prm8	fuel	B20	
Prm9	speed		
Prm10	pass		
Prm11	fuel*mode	B0	1
Prm12	fuel*mode	B0	2
Prm13	fuel*mode	B0	3
Prm14	fuel*mode	B0	4
Prm15	fuel*mode	B10	1
Prm16	fuel*mode	B10	2
Prm17	fuel*mode	B10	3
Prm18	fuel*mode	B10	4
Prm19	fuel*mode	B20	1
Prm20	fuel*mode	B20	2
Prm21	fuel*mode	B20	3
Prm22	fuel*mode	B20	4
Prm23	speed*fuel	B0	
Prm24	speed*fuel	B10	
Prm25	speed*fuel	B20	
Prm26	pass*fuel	B0	
Prm27	pass*fuel	B10	
Prm28	pass*fuel	B20	

Table 3-31. Analysis of parameter estimates for NO_x (Bus 971)

Parameter			Estimate	Standard Error	Wald 95% Confidence Limits		Chi-Square	Pr > ChiSq
Intercept			92.1390	0.8638	90.4460	93.8320	11377.8	<.0001
mode	1		-32.7929	1.0053	-34.7633	-30.8224	1063.97	<.0001
mode	2		-53.6033	0.8986	-55.3646	-51.8420	3558.07	<.0001
mode	3		-73.2122	0.8418	-74.8621	-71.5622	7563.14	<.0001
mode	4		0.0000	0.0000	0.0000	0.0000	.	.
fuel	B0		-14.9917	0.9948	-16.9416	-13.0419	227.10	<.0001
fuel	B10		-20.0467	0.9969	-22.0007	-18.0927	404.33	<.0001
fuel	B20		0.0000	0.0000	0.0000	0.0000	.	.
speed			-0.1729	0.0133	-0.1990	-0.1467	167.84	<.0001
pass			-0.0174	0.0270	-0.0703	0.0355	0.41	0.5196
fuel*mode	B0	1	9.2947	1.1698	7.0019	11.5874	63.13	<.0001
fuel*mode	B0	2	10.4560	1.0331	8.4310	12.4809	102.42	<.0001
fuel*mode	B0	3	15.1142	0.9668	13.2193	17.0090	244.41	<.0001
fuel*mode	B0	4	0.0000	0.0000	0.0000	0.0000	.	.
fuel*mode	B10	1	15.4496	1.1881	13.1210	17.7783	169.09	<.0001
fuel*mode	B10	2	21.9140	1.0327	19.8900	23.9380	450.30	<.0001
fuel*mode	B10	3	27.8423	0.9654	25.9502	29.7345	831.77	<.0001
fuel*mode	B10	4	0.0000	0.0000	0.0000	0.0000	.	.
fuel*mode	B20	1	0.0000	0.0000	0.0000	0.0000	.	.
fuel*mode	B20	2	0.0000	0.0000	0.0000	0.0000	.	.
fuel*mode	B20	3	0.0000	0.0000	0.0000	0.0000	.	.
fuel*mode	B20	4	0.0000	0.0000	0.0000	0.0000	.	.
speed*fuel	B0		-0.0303	0.0162	-0.0620	0.0014	3.50	0.0613
speed*fuel	B10		-0.2974	0.0173	-0.3313	-0.2634	294.92	<.0001
speed*fuel	B20		0.0000	0.0000	0.0000	0.0000	.	.
pass*fuel	B0		0.0762	0.0302	0.0169	0.1354	6.34	0.0118
pass*fuel	B10		0.0422	0.0315	-0.0195	0.1039	1.80	0.1798
pass*fuel	B20		0.0000	0.0000	0.0000	0.0000	.	.
Scale			1.8741	0.0070	1.8605	1.8879		

Table 3-32. Wald statistics for type 3 analysis for NO_x (Bus 971)

Source	DF	Chi-Square	Pr > ChiSq
Mode	3	46203.1	<.0001
Fuel	2	228.09	<.0001
Pass	1	1868.16	<.0001
Fuel*mode	1	3.73	0.0535
pass*fuel	6	1261.23	<.0001

Table 3-33. Least square means of the transformed data for NO_x (Bus 971)

Effect	fuel	mode	Estimate	Standard Error	Chi-Square	Pr > ChiSq	Confidence Limits	
fuel	B0		43.6287	0.1555	78695	<.0001	43.3238	43.9335
fuel	B10		42.4083	0.1652	65917	<.0001	42.0846	42.7321
fuel	B20		49.8375	0.2643	35556	<.0001	49.3194	50.3555
mode		1	52.3096	0.2686	37937	<.0001	51.7832	52.8359
mode		2	34.0410	0.1596	45473	<.0001	33.7282	34.3539
mode		3	17.9610	0.0779	53209	<.0001	17.8084	18.1136
mode		4	76.8543	0.3513	47873	<.0001	76.1659	77.5428

Table 3-34. Least square means (g/s) of the original data for NO_x (Bus 971)

Effect	Fuel	Mode	Estimate	SE	LowerCL	UpperCL
Fuel	B0		0.022921	.000081706	0.022757	0.023084
Fuel	B10		0.023580	.000091844	0.023397	0.023764
Fuel	B20		0.020065	.000106412	0.019852	0.020278
Mode		1	0.019117	.000098149	0.018921	0.019313
Mode		2	0.029376	.000137760	0.029101	0.029652
Mode		3	0.055676	.000241367	0.055193	0.056159
Mode		4	0.013012	.000059468	0.012893	0.013131

Hydrocarbons. The model for carbon monoxide indicates that parameters mode, fuel type, number of passengers, and speed were statistically significant. Table 3-35 to 3-39 provide model results. As shown in Table 3-36 and 3-37, all of the main effects are significant except for the interaction between fuel type and mode. Table 3-39 provides the least squares means (g/s) which indicate that for Bus 971, B-0 had the highest mean HC emissions, followed by B-20. B-10 had the lowest HC emission values. Estimated mean HC emissions for B-20 are 36.1% and emissions for B-10 are 45.6% lower than for B-0. Acceleration also has the highest and idling had the lowest mean emissions.

Table 3-35. Parameter information for HC (Bus 971)

Parameter	Effect	fuel	mode
Prm1	Intercept		
Prm2	mode		1
Prm3	mode		2
Prm4	mode		3
Prm5	mode		4
Prm6	fuel	B0	
Prm7	fuel	B10	
Prm8	fuel	B20	
Prm9	speed		
Prm10	pass		
Prm11	fuel*mode	B0	1
Prm12	fuel*mode	B0	2
Prm13	fuel*mode	B0	3
Prm14	fuel*mode	B0	4
Prm15	fuel*mode	B10	1
Prm16	fuel*mode	B10	2
Prm17	fuel*mode	B10	3
Prm18	fuel*mode	B10	4
Prm19	fuel*mode	B20	1
Prm20	fuel*mode	B20	2
Prm21	fuel*mode	B20	3
Prm22	fuel*mode	B20	4
Prm23	speed*fuel	B0	
Prm24	speed*fuel	B10	
Prm25	speed*fuel	B20	
Prm26	pass*fuel	B0	
Prm27	pass*fuel	B10	
Prm28	pass*fuel	B20	
Number of Observations			120,081

Table 3-36. Analysis of parameter estimates for HC (Bus 971)

Parameter			Estimate	Standard Error	Wald 95% Confidence Limits		Chi-Square	Pr > ChiSq
Intercept			1154.856	10.3800	1134.511	1175.200	12378.3	<.0001
mode	1		57.0525	14.1700	29.2799	84.8252	16.21	<.0001
mode	2		-311.108	10.8290	-332.332	-289.883	825.36	<.0001
mode	3		-652.499	9.4528	-671.026	-633.972	4764.76	<.0001
mode	4		0.0000	0.0000	0.0000	0.0000	.	.
fuel	B0		-400.730	11.2547	-422.789	-378.671	1267.76	<.0001
fuel	B10		226.7075	13.6242	200.0044	253.4105	276.89	<.0001
fuel	B20		0.0000	0.0000	0.0000	0.0000	.	.
speed			-7.9459	0.2675	-8.4703	-7.4215	882.10	<.0001
pass			7.1958	0.6377	5.9459	8.4457	127.33	<.0001
fuel*mode	B0	1	-29.2869	15.3742	-59.4198	0.8460	3.63	0.0568
fuel*mode	B0	2	137.1726	11.7407	114.1612	160.1841	136.50	<.0001
fuel*mode	B0	3	284.1532	10.2301	264.1027	304.2038	771.52	<.0001
fuel*mode	B0	4	0.0000	0.0000	0.0000	0.0000	.	.
fuel*mode	B10	1	4.1572	18.8395	-32.7676	41.0819	0.05	0.8254
fuel*mode	B10	2	11.8783	14.2236	-15.9995	39.7560	0.70	0.4037
fuel*mode	B10	3	-21.5385	12.3654	-45.7743	2.6972	3.03	0.0815
fuel*mode	B10	4	0.0000	0.0000	0.0000	0.0000	.	.
fuel*mode	B20	1	0.0000	0.0000	0.0000	0.0000	.	.
fuel*mode	B20	2	0.0000	0.0000	0.0000	0.0000	.	.
fuel*mode	B20	3	0.0000	0.0000	0.0000	0.0000	.	.
fuel*mode	B20	4	0.0000	0.0000	0.0000	0.0000	.	.
speed*fuel	B0		2.8053	0.2980	2.2213	3.3893	88.65	<.0001
speed*fuel	B10		-1.8619	0.3799	-2.6065	-1.1174	24.02	<.0001
speed*fuel	B20		0.0000	0.0000	0.0000	0.0000	.	.
pass*fuel	B0		-7.6920	0.6648	-8.9949	-6.3890	133.89	<.0001
pass*fuel	B10		-8.0602	0.7389	-9.5084	-6.6120	118.99	<.0001
pass*fuel	B20		0.0000	0.0000	0.0000	0.0000	.	.
Scale			2.5813	0.0099	2.5619	2.6008		

Table 3-37. Wald statistics for type 3 analysis for HC (Bus 971)

Source	DF	Chi-Square	Pr > ChiSq
mode	3	31653.5	<.0001
Fuel	2	7389.79	<.0001
speed	1	3245.46	<.0001
pass	1	58.58	<.0001
Fuel*mode	6	3119.36	<.0001
speed*fuel	2	285.02	<.0001
pass*fuel	2	139.50	<.0001

Table 3-38. Least square means of the transformed data for HC (Bus 971)

Effect	fuel	mode	Estimate	Standard Error	Chi-Square	Pr > ChiSq	Confidence Limits	
fuel	B0		554.0822	1.5939	120848	<.0001	550.9583	557.2061
fuel	B10		1017.802	3.3046	94859	<.0001	1011.325	1024.279
fuel	B20		866.7930	3.9345	48534	<.0001	859.0815	874.5046
mode		1	1055.995	5.1357	42278	<.0001	1045.930	1066.061
mode		2	745.8955	3.0834	58517	<.0001	739.8521	751.9389
mode		3	442.3586	1.7373	64833	<.0001	438.9535	445.7636
mode		4	1007.320	4.0430	62075	<.0001	999.3953	1015.244

Table 3-39. Least square means (g/s) of the original data for HC (Bus 971)

Effect	fuel	mode	Estimate	SE	LowerCL	UpperCL
fuel	B0		.001804786	.000005192	.001794403	.001815170
fuel	B10		.000982510	.000003190	.000976130	.000988890
fuel	B20		.001153678	.000005237	.001143204	.001164151
mode		1	.000946974	.000004606	.000937763	.000956185
mode		2	.001340670	.000005542	.001329586	.001351755
mode		3	.002260610	.000008878	.002242853	.002278366
mode		4	.000992734	.000003985	.000984765	.001000703

Carbon monoxide. The model for carbon monoxide indicates that parameters mode, fuel type, number of passengers, and speed were statistically significant. Table 3-40 to 3-44 provide model results. Tables 3-41 and 3-42 indicate that all the parameters were significant, except mode 1 which indicates that there is no evidence of differences in means between idle and deceleration modes. Table 3-44 provides the estimated least square means. As indicated average CO emissions (g/s) for B-20 are higher than for B-0 for Bus 971 (B-0 estimated mean emissions are 9.3% lower than for B-20). B-10 has the lowest CO emissions (59.2% lower than for B-0). Acceleration mode also has the highest mean emissions for CO followed by steady state. CO emissions are lowest when the bus is decelerating.

Table 3-40. Parameter information for CO (Bus 971)

Parameter	Effect	fuel	Mode
Prm1	Intercept		
Prm2	mode		1
Prm3	mode		2
Prm4	mode		3
Prm5	mode		4
Prm6	fuel	B0	
Prm7	fuel	B10	
Prm8	fuel	B20	
Prm9	mph		
Prm10	pass		
Prm11	fuel*mode	B0	1
Prm12	fuel*mode	B0	2
Prm13	fuel*mode	B0	3
Prm14	fuel*mode	B0	4
Prm15	fuel*mode	B10	1
Prm16	fuel*mode	B10	2
Prm17	fuel*mode	B10	3
Prm18	fuel*mode	B10	4
Prm19	fuel*mode	B20	1
Prm20	fuel*mode	B20	2
Prm21	fuel*mode	B20	3
Prm22	fuel*mode	B20	4
Prm23	mph*fuel	B0	
Prm24	mph*fuel	B10	
Prm25	mph*fuel	B20	
Prm26	pass*fuel	B0	
Prm27	pass*fuel	B10	
Prm28	pass*fuel	B20	
Number of Observations			117,203

Table 3-41. Analysis of parameter estimates for CO (Bus 971)

Parameter			Estimate	Standard Error	Wald 95% Confidence Limits		Chi-Square	Pr > ChiSq
Intercept			818.3327	14.4265	790.0573	846.6080	3217.66	<.0001
Mode	1		4.9890	19.4793	-33.1898	43.1679	0.07	0.7979
Mode	2		-275.652	14.1148	-303.317	-247.988	381.39	<.0001
Mode	3		-425.905	12.9840	-451.353	-400.456	1075.98	<.0001
Mode	4		0.0000	0.0000	0.0000	0.0000	.	.
Fuel	B0		259.5434	18.6191	223.0507	296.0362	194.31	<.0001
Fuel	B10		1841.798	37.7183	1767.871	1915.725	2384.40	<.0001
Fuel	B20		0.0000	0.0000	0.0000	0.0000	.	.
Mph			-7.9004	0.3717	-8.6289	-7.1718	451.73	<.0001
Pass			15.8507	1.0255	13.8407	17.8607	238.89	<.0001
fuel*mode	B0	1	-118.026	24.8763	-166.783	-69.2695	22.51	<.0001
fuel*mode	B0	2	-61.9679	18.2561	-97.7492	-26.1866	11.52	0.0007
fuel*mode	B0	3	-54.5391	16.8295	-87.5243	-21.5540	10.50	0.0012
fuel*mode	B0	4	0.0000	0.0000	0.0000	0.0000	.	.
fuel*mode	B10	1	-775.692	45.4856	-864.842	-686.542	290.83	<.0001
fuel*mode	B10	2	-316.378	37.9320	-390.724	-242.033	69.57	<.0001
fuel*mode	B10	3	-697.159	33.9399	-763.680	-630.638	421.93	<.0001
fuel*mode	B10	4	0.0000	0.0000	0.0000	0.0000	.	.
fuel*mode	B20	1	0.0000	0.0000	0.0000	0.0000	.	.
fuel*mode	B20	2	0.0000	0.0000	0.0000	0.0000	.	.
fuel*mode	B20	3	0.0000	0.0000	0.0000	0.0000	.	.
fuel*mode	B20	4	0.0000	0.0000	0.0000	0.0000	.	.
mph*fuel	B0		-2.4764	0.5004	-3.4573	-1.4956	24.49	<.0001
mph*fuel	B10		-16.0993	1.1709	-18.3943	-13.8044	189.04	<.0001
mph*fuel	B20		0.0000	0.0000	0.0000	0.0000	.	.
pass*fuel	B0		-16.7180	1.1303	-18.9333	-14.5026	218.76	<.0001
pass*fuel	B10		-16.0437	1.8022	-19.5760	-12.5114	79.25	<.0001
pass*fuel	B20		0.0000	0.0000	0.0000	0.0000	.	.
Scale			0.6548	0.0023	0.6504	0.6593		

Table 3-42. Wald statistics for CO (Bus 971)

Source	DF	Chi-Square	Pr > ChiSq
mode	3	3951.37	<.0001
Fuel	2	3229.61	<.0001
mph	1	1204.95	<.0001
Pass	1	62.97	<.0001
fuel*mode	6	624.03	<.0001
mph*fuel	2	192.13	<.0001
pass*fuel	2	220.95	<.0001

Table 3-43. Least square means of the transformed data for CO (Bus 971)

Effect	gas	mode	Estimate	Standard Error	Chi-Square	Pr > ChiSq	Confidence Limits	
gas	B0		702.0540	4.0723	29721	<.0001	694.0724	710.0355
gas	B10		1719.000	11.0902	24025	<.0001	1697.264	1740.736
gas	B20		636.9293	5.6082	12898	<.0001	625.9374	647.9213
mode		1	1069.199	11.4969	8648.9	<.0001	1046.666	1091.733
mode		2	960.3491	8.2562	13530	<.0001	944.1672	976.5309
mode		3	685.6461	5.4912	15590	<.0001	674.8835	696.4087
mode		4	1362.116	10.7726	15988	<.0001	1341.003	1383.230

Table 3-44. Least square means (g/s) of the original data for CO (Bus 971)

Effect	Fuel	Mode	Estimate	SE	LowerCL	UpperCL
Fuel	B-0		.001424392	.000008262	.001407867	.001440916
Fuel	B-10		.000581734	.000003753	.000574227	.000589240
Fuel	B-20		.001570033	.000013824	.001542384	.001597682
mode		1	.000935279	.000010057	.000915166	.000955393
mode		2	.001041288	.000008952	.001023384	.001059192
mode		3	.001458478	.000011681	.001435117	.001481840
mode		4	.000734152	.000005806	.000722539	.000745764

Carbon dioxide. Model results for CO_2 for Bus 971 are provided in Tables 3-45 to 3-49. As shown in tables 3-46 and 3-47, 10 out of 15 parameters comparisons were significant. Model results indicate that while mean CO_2 emissions for B-20 were higher than for B-0 there is no evidence of differences in means between B-0 and B-20. Model results indicate that the variable "passenger" in this case was not significant. The interactions between other mode and fuel combinations were significant. Table 3-49 provides the final estimates of the mean. The estimated mean CO_2 emissions (g/s) for B-10 were lower than B-0 (25.6%) and results are statistically significant. As indicated, CO_2 emissions are highest while the bus is in acceleration mode followed by steady state while emissions are lowest for deceleration.

Table 3-45. Parameter information for CO_2 (Bus 971)

Parameter	Effect	fuel	mode
Prm1	Intercept		
Prm2	mode		1
Prm3	mode		2
Prm4	mode		3
Prm5	mode		4
Prm6	fuel	B0	
Prm7	fuel	B10	
Prm8	fuel	B20	
Prm9	pass		
Prm10	fuel*mode	B0	1
Prm11	fuel*mode	B0	2
Prm12	fuel*mode	B0	3
Prm13	fuel*mode	B0	4
Prm14	fuel*mode	B10	1
Prm15	fuel*mode	B10	2
Prm16	fuel*mode	B10	3
Prm17	fuel*mode	B10	4
Prm18	fuel*mode	B20	1
Prm19	fuel*mode	B20	2
Prm20	fuel*mode	B20	3
Prm21	fuel*mode	B20	4
Prm22	pass*fuel	B0	
Prm23	pass*fuel	B10	
Prm24	pass*fuel	B20	
Number of observations		123,098	

Table 3-46. Analysis of parameter estimates for CO_2 (Bus 971)

Parameter			Estimate	Standard Error	Wald 95% Confidence Limits		Chi-Square	Pr > ChiSq
Intercept			1.1446	0.0117	1.1217	1.1675	9613.04	<.0001
mode	1		-0.2054	0.0149	-0.2346	-0.1763	190.64	<.0001
mode	2		-0.8082	0.0121	-0.8320	-0.7845	4445.99	<.0001
mode	3		-1.0267	0.0117	-1.0496	-1.0039	7735.23	<.0001
mode	4		0.0000	0.0000	0.0000	0.0000	.	.
fuel	B0		0.0249	0.0142	-0.0029	0.0527	3.07	0.0795
fuel	B10		0.2865	0.0160	0.2551	0.3180	319.03	<.0001
fuel	B20		0.0000	0.0000	0.0000	0.0000	.	.
pass			0.0001	0.0002	-0.0004	0.0005	0.06	0.8063
fuel*mode	B0	1	0.0934	0.0186	0.0570	0.1298	25.31	<.0001
fuel*mode	B0	2	-0.0089	0.0148	-0.0379	0.0200	0.37	0.5450
fuel*mode	B0	3	-0.0055	0.0142	-0.0333	0.0224	0.15	0.7011
fuel*mode	B0	4	0.0000	0.0000	0.0000	0.0000	.	.
fuel*mode	B10	1	0.2194	0.0219	0.1765	0.2623	100.34	<.0001
fuel*mode	B10	2	-0.0858	0.0168	-0.1187	-0.0530	26.19	<.0001
fuel*mode	B10	3	-0.1160	0.0161	-0.1475	-0.0845	52.06	<.0001
fuel*mode	B10	4	0.0000	0.0000	0.0000	0.0000	.	.
fuel*mode	B20	1	0.0000	0.0000	0.0000	0.0000	.	.
fuel*mode	B20	2	0.0000	0.0000	0.0000	0.0000	.	.
fuel*mode	B20	3	0.0000	0.0000	0.0000	0.0000	.	.
fuel*mode	B20	4	0.0000	0.0000	0.0000	0.0000	.	.
pass*fuel	B0		0.0013	0.0003	0.0007	0.0018	21.26	<.0001
pass*fuel	B10		-0.0004	0.0004	-0.0011	0.0004	0.96	0.3280
pass*fuel	B20		0.0000	0.0000	0.0000	0.0000	.	.
Scale			1.5597	0.0057	1.5485	1.5710		

Table 3-47. Wald statistics for type 3 analysis for CO_2 (Bus 971)

Source	DF	Chi-Square	Pr > ChiSq
mode	3	66448.0	<.0001
fuel	2	2654.86	<.0001
pass	1	7.51	0.0061
fuel*mode	6	575.08	<.0001
pass*fuel	2	37.76	<.0001

Table 3-48. Least square means of the transformed data for CO_2 (Bus971)

Effect	fuel	mode	Estimate	Standard Error	Chi-Square	Pr > ChiSq	Confidence Limits	
fuel	B0		0.6873	0.0029	57908	<.0001	0.6817	0.6929
fuel	B10		0.9235	0.0042	48771	<.0001	0.9153	0.9317
fuel	B20		0.6348	0.0038	27314	<.0001	0.6273	0.6424
mode		1	1.1494	0.0056	41580	<.0001	1.1384	1.1605
mode		2	0.4108	0.0020	43061	<.0001	0.4069	0.4147
mode		3	0.1834	0.0009	44508	<.0001	0.1817	0.1851
mode		4	1.2506	0.0059	44392	<.0001	1.2390	1.2622

Table 3-49. Least square means (g/s) of the original data for CO2 (Bus 971)

Effect	fuel	mode	Estimate	SE	LowerCL	UpperCL
fuel	B-0		1.45492	0.006046	1.44282	1.46701
fuel	B-10		1.08281	0.004903	1.07300	1.09261
fuel	B-20		1.57522	0.009531	1.55616	1.59429
mode		1	0.86999	0.004267	0.86145	0.87852
mode		2	2.43427	0.011731	2.41081	2.45773
mode		3	5.45284	0.025846	5.40114	5.50453
mode		4	0.79961	0.003795	0.79202	0.80720

Particulate Matter. Model results for PM for Bus 971 are provided in Tables 3-50 to 3-54. Results provided in Table 3-51 and 3-52 indicate that all the parameters are significant except for the variable “passengers” which is not significant. Table 3-54 provides the least square means for PM. As shown, mean estimated PM emissions (g/s) were highest for B-0 followed by B-10 (B-10 estimated mean emissions are 87.4% lower). B-20 has the lowest emissions (90.4% lower than B-0). Also as shown, PM emissions while the bus is in acceleration mode are higher than any other mode while idling has the lowest PM emissions.

Table 3-50. Parameter information for PM (Bus 971)

Parameter	Effect	fuel	Mode
Prm1	Intercept		
Prm2	mode		1
Prm3	mode		2
Prm4	mode		3
Prm5	mode		4
Prm6	fuel	B0	
Prm7	fuel	B10	
Prm8	fuel	B20	
Prm9	pass		
Prm10	fuel*mode	B0	1
Prm11	fuel*mode	B0	2
Prm12	fuel*mode	B0	3
Prm13	fuel*mode	B0	4
Prm14	fuel*mode	B10	1
Prm15	fuel*mode	B10	2
Prm16	fuel*mode	B10	3
Prm17	fuel*mode	B10	4
Prm18	fuel*mode	B20	1
Prm19	fuel*mode	B20	2
Prm20	fuel*mode	B20	3
Prm21	fuel*mode	B20	4
Prm22	pass*fuel	B0	
Prm23	pass*fuel	B10	
Prm24	pass*fuel	B20	

Table 3-51. Analysis of parameter estimates for PM (Bus 971)

Parameter			DF	Estimate	Standard Error	Wald 95% Confidence Limits		Chi-Square	Pr > ChiSq
Intercept			1	145.5803	2.4492	140.7800	150.3805	3533.24	<.0001
mode	1		1	50.5546	3.8941	42.9224	58.1869	168.54	<.0001
mode	2		1	-55.2088	2.7731	-60.6439	-49.7737	396.37	<.0001
mode	3		1	-90.4382	2.4910	-95.3205	-85.5559	1318.12	<.0001
mode	4		0	0.0000	0.0000	0.0000	0.0000	.	.
fuel	B0		1	-134.039	2.4539	-138.849	-129.230	2983.77	<.0001
fuel	B10		1	-36.6733	2.8417	-42.2429	-31.1038	166.56	<.0001
fuel	B20		0	0.0000	0.0000	0.0000	0.0000	.	.
pass			1	-0.5052	0.1357	-0.7713	-0.2391	13.85	0.0002
fuel*mode	B0	1	1	-44.7368	3.9032	-52.3868	-37.0867	131.37	<.0001
fuel*mode	B0	2	1	49.6135	2.7781	44.1685	55.0584	318.94	<.0001
fuel*mode	B0	3	1	82.4864	2.4958	77.5948	87.3780	1092.34	<.0001
fuel*mode	B0	4	0	0.0000	0.0000	0.0000	0.0000	.	.
fuel*mode	B10	1	1	-37.8397	4.4403	-46.5425	-29.1369	72.62	<.0001
fuel*mode	B10	2	1	22.5676	3.2355	16.2261	28.9092	48.65	<.0001
fuel*mode	B10	3	1	30.6823	2.9022	24.9941	36.3704	111.77	<.0001
fuel*mode	B10	4	0	0.0000	0.0000	0.0000	0.0000	.	.
fuel*mode	B20	1	0	0.0000	0.0000	0.0000	0.0000	.	.
fuel*mode	B20	2	0	0.0000	0.0000	0.0000	0.0000	.	.
fuel*mode	B20	3	0	0.0000	0.0000	0.0000	0.0000	.	.
fuel*mode	B20	4	0	0.0000	0.0000	0.0000	0.0000	.	.
pass*fuel	B0		1	0.7909	0.1361	0.5243	1.0576	33.80	<.0001
pass*fuel	B10		1	0.7540	0.1554	0.4494	1.0585	23.55	<.0001
pass*fuel	B20		0	0.0000	0.0000	0.0000	0.0000	.	.
Scale			1	0.5935	0.0020	0.5896	0.5974		

Table 3-52. Wald statistics for type 3 analysis for PM (Bus 971)

Source	DF	Chi-Square	Pr > ChiSq
mode	3	6458.63	<.0001
fuel	2	18258.3	<.0001
pass	1	0.04	0.8507
fuel*mode	6	4648.12	<.0001
pass*fuel	2	33.99	<.0001

Table 3-53. Least square means of the transformed data for PM (Bus 971)

Effect	fuel	mode	Estimate	Standard Error	Chi-Square	Pr > ChiSq	Confidence Limits	
fuel	B0		11.3647	0.0719	24964	<.0001	11.2237	11.5056
fuel	B10		90.5152	0.6049	22394	<.0001	89.3297	91.7007
fuel	B20		118.7022	1.0701	12304	<.0001	116.6048	120.7997
mode		1	111.7652	1.1733	9074.3	<.0001	109.4656	114.0647
mode		2	57.5876	0.5900	9526.8	<.0001	56.4312	58.7439
mode		3	36.0207	0.3406	11185	<.0001	35.3532	36.6883
mode		4	88.7360	0.9089	9531.2	<.0001	86.9546	90.5175

Table 3-54. Least square means (g/s) of the original data for PM (Bus 971)

Effect	fuel	mode	Estimate	SE	LowerCL	UpperCL
fuel	B0		0.087992	.000556915	0.086878	0.089106
fuel	B10		0.011048	.000073826	0.010900	0.011196
fuel	B20		0.008424	.000075949	0.008273	0.008576
mode		1	0.008947	.000093926	0.008759	0.009135
mode		2	0.017365	.000177909	0.017009	0.017721
mode		3	0.027762	.000262498	0.027237	0.028287
mode		4	0.011269	.000115432	0.011039	0.011500

3.8.2.3 Model Results for Bus 997

A generalized linear model where the response has a gamma distribution and the explanatory variables are included in the linear predictor was used to fit a model for each pollutant of interest for Bus 997.

Nitrogen Oxides. Table 3-55 to 3-59 provide model results for NO_x for Bus 997. Table 3-56 and 3-57 provides results for the analysis of parameter estimates and Wald Statistics. As shown, all the main parameters are significant. The interaction comparison between “B-0 and idle mode”, “B-10 and steady state mode”, “passenger and fuel”, and “B-0 and speed” were not significant. Table 3-59 provides the least square mean estimates for NO_x. As shown, B-20 had the highest estimated mean NO_x emissions (g/s) followed by B-10. B-0 has the lowest emissions. B-0 estimated mean emissions are 12.1% lower than B-20 and 15.0% lower than B-10.

Table 3-55. Parameter information for NO_x (Bus 997)

Parameter	Effect	fuel	mode
Prm1	Intercept		
Prm2	mode		1
Prm3	mode		2
Prm4	mode		3
Prm5	mode		4
Prm6	fuel	B0	
Prm7	fuel	B10	
Prm8	fuel	B20	
Prm9	speed		
Prm10	pass		
Prm11	fuel*mode	B0	1
Prm12	fuel*mode	B0	2
Prm13	fuel*mode	B0	3
Prm14	fuel*mode	B0	4
Prm15	fuel*mode	B10	1
Prm16	fuel*mode	B10	2
Prm17	fuel*mode	B10	3
Prm18	fuel*mode	B10	4
Prm19	fuel*mode	B20	1
Prm20	fuel*mode	B20	2
Prm21	fuel*mode	B20	3
Prm22	fuel*mode	B20	4
Prm23	speed*fuel	B0	
Prm24	speed*fuel	B10	
Prm25	speed*fuel	B20	
Prm26	pass*fuel	B0	
Prm27	pass*fuel	B10	
Prm28	pass*fuel	B20	
Number of observations		71844	

Table 3-56. Analysis of parameter estimates for NO_x (Bus 997)

Parameter			DF	Estimate	Standard Error	Wald 95% Confidence Limits		Chi-Square	Pr > ChiSq
Intercept			1	45.5086	0.5636	44.4039	46.6133	6519.52	<.0001
mode	1		1	-13.8985	0.6517	-15.1758	-12.6211	454.79	<.0001
mode	2		1	-26.7604	0.5927	-27.9220	-25.5988	2038.72	<.0001
mode	3		1	-38.8688	0.5456	-39.9380	-37.7995	5076.09	<.0001
mode	4		0	0.0000	0.0000	0.0000	0.0000	.	.
fuel	B0		1	9.2255	0.8115	7.6350	10.8159	129.25	<.0001
fuel	B10		1	-3.1163	0.6626	-4.4149	-1.8177	22.12	<.0001
fuel	B20		0	0.0000	0.0000	0.0000	0.0000	.	.
speed			1	0.0547	0.0089	0.0372	0.0722	37.58	<.0001
pass			1	0.0971	0.0250	0.0482	0.1460	15.13	0.0001
fuel*mode	B0	1	1	-0.9255	0.9720	-2.8305	0.9795	0.91	0.3410
fuel*mode	B0	2	1	-6.6929	0.8517	-8.3622	-5.0236	61.75	<.0001
fuel*mode	B0	3	1	-7.8161	0.7887	-9.3619	-6.2703	98.21	<.0001
fuel*mode	B0	4	0	0.0000	0.0000	0.0000	0.0000	.	.
fuel*mode	B10	1	1	12.8421	0.7996	11.2750	14.4092	257.97	<.0001
fuel*mode	B10	2	1	-0.0299	0.6970	-1.3960	1.3361	0.00	0.9658
fuel*mode	B10	3	1	1.8390	0.6424	0.5799	3.0981	8.19	0.0042
fuel*mode	B10	4	0	0.0000	0.0000	0.0000	0.0000	.	.
fuel*mode	B20	1	0	0.0000	0.0000	0.0000	0.0000	.	.
fuel*mode	B20	2	0	0.0000	0.0000	0.0000	0.0000	.	.
fuel*mode	B20	3	0	0.0000	0.0000	0.0000	0.0000	.	.
fuel*mode	B20	4	0	0.0000	0.0000	0.0000	0.0000	.	.
speed*fuel	B0		1	-0.0305	0.0123	-0.0545	-0.0065	6.19	0.0129
speed*fuel	B10		1	0.0709	0.0104	0.0505	0.0914	46.37	<.0001
speed*fuel	B20		0	0.0000	0.0000	0.0000	0.0000	.	.
pass*fuel	B0		1	-0.0440	0.0295	-0.1019	0.0139	2.21	0.1368
pass*fuel	B10		1	-0.1130	0.0267	-0.1654	-0.0606	17.88	<.0001
pass*fuel	B20		0	0.0000	0.0000	0.0000	0.0000	.	.
Scale			1	1.9961	0.0098	1.9770	2.0154		

Table 3-57. Wald statistics for type 3 analysis for NO_x (Bus 997)

Source	DF	Chi-Square	Pr > ChiSq
mode	3	45705.2	<.0001
fuel	2	346.86	<.0001
speed	1	233.29	<.0001
pass	1	18.72	<.0001
fuel*mode	6	805.68	<.0001
speed*fuel	2	120.37	<.0001
pass*fuel	2	26.94	<.0001

Table 3-58. Least square means of the transformed data for NO_x (Bus 997)

Effect	fuel	mode	Estimate	Standard Error	Chi-Square	Pr > ChiSq	Confidence Limits	
fuel	B0		31.5911	0.1875	28380	<.0001	31.2236	31.9586
fuel	B10		27.7813	0.1204	53284	<.0001	27.5454	28.0171
fuel	B20		26.8595	0.1751	23517	<.0001	26.5162	27.2028
mode		1	38.7649	0.2205	30918	<.0001	38.3328	39.1970
mode		2	19.6898	0.1256	24575	<.0001	19.4436	19.9360
mode		3	7.8300	0.0446	30826	<.0001	7.7426	7.9174
mode		4	48.6911	0.2832	29565	<.0001	48.1361	49.2461

Table 3-59. Least square means (g/s) of the original data for NO_x (Bus 997)

Effect	fuel	Mode	Estimate	SE	LowerCL	UpperCL
fuel	B0		0.03165	.000187902	0.03128	0.03203
fuel	B10		0.03600	.000155938	0.03568	0.03631
fuel	B20		0.03723	.000242777	0.03675	0.03772
mode		1	0.02580	.000146709	0.02550	0.02609
mode		2	0.05079	.000323973	0.05014	0.05144
mode		3	0.12771	.000727415	0.12626	0.12917
mode		4	0.02054	.000119443	0.02030	0.02078

Hydrocarbons. Table 3-60 to 3-64 provide model results for hydrocarbons for Bus 997. Tables 3-61 and 3-62 show the results for the analysis of parameter estimates and Wald Statistics. As indicated all parameters and effects are statistically significant except for the interaction between "B-10 and idle mode" as compared to "B-10 and deceleration mode". Estimates for the least square mean for HC are provided in Table 3-64. As indicated, mean HC emissions (g/s)were higher for B-10 than for B-0 and were lower for B-20 than for B-0. Estimated mean emissions for B-0 are 15.6% lower than for B-10 and 24.9% lower for B-20 than for B-0. HC emissions were highest when the bus was in acceleration mode and lowest when the bus was idling.

Table 3-60. Parameter information for HC (Bus 997)

Parameter	Effect	fuel	mode
Prm1	Intercept		
Prm2	mode		1
Prm3	mode		2
Prm4	mode		3
Prm5	mode		4
Prm6	fuel	B0	
Prm7	fuel	B10	
Prm8	fuel	B20	
Prm9	speed		
Prm10	pass		
Prm11	fuel*mode	B0	1
Prm12	fuel*mode	B0	2
Prm13	fuel*mode	B0	3
Prm14	fuel*mode	B0	4
Prm15	fuel*mode	B10	1
Prm16	fuel*mode	B10	2
Prm17	fuel*mode	B10	3
Prm18	fuel*mode	B10	4
Prm19	fuel*mode	B20	1
Prm20	fuel*mode	B20	2
Prm21	fuel*mode	B20	3
Prm22	fuel*mode	B20	4
Prm23	speed*fuel	B0	
Prm24	speed*fuel	B10	
Prm25	speed*fuel	B20	
Prm26	pass*fuel	B0	
Prm27	pass*fuel	B10	
Prm28	pass*fuel	B20	
Number of observations			68,662

Table 3-61. Analysis of parameter estimates for HC (Bus 997)

Parameter			DF	Estimate	Standard Error	Wald 95% Confidence Limits		Chi-Square	Pr > ChiSq
Intercept			1	640.3952	6.9109	626.8501	653.9402	8586.79	<.0001
mode	1		1	87.1470	9.8592	67.8234	106.4706	78.13	<.0001
mode	2		1	-172.348	7.0116	-186.091	-158.606	604.20	<.0001
mode	3		1	-335.356	6.2210	-347.549	-323.163	2905.95	<.0001
mode	4		0	0.0000	0.0000	0.0000	0.0000	.	.
fuel	B0		1	-145.625	8.1964	-161.690	-129.561	315.66	<.0001
fuel	B10		1	-234.087	7.3810	-248.553	-219.620	1005.82	<.0001
fuel	B20		0	0.0000	0.0000	0.0000	0.0000	.	.
speed			1	-4.9043	0.1838	-5.2645	-4.5440	711.88	<.0001
pass			1	-3.4083	0.5584	-4.5028	-2.3137	37.25	<.0001
fuel*mode	B0	1	1	-108.138	11.5622	-130.799	-85.4760	87.47	<.0001
fuel*mode	B0	2	1	27.3562	8.3531	10.9844	43.7279	10.73	0.0011
fuel*mode	B0	3	1	64.0934	7.4084	49.5732	78.6136	74.85	<.0001
fuel*mode	B0	4	0	0.0000	0.0000	0.0000	0.0000	.	.
fuel*mode	B10	1	1	-25.2437	10.5865	-45.9928	-4.4945	5.69	0.0171
fuel*mode	B10	2	1	28.5632	7.5102	13.8435	43.2828	14.46	0.0001
fuel*mode	B10	3	1	94.6434	6.6762	81.5584	107.7284	200.97	<.0001
fuel*mode	B10	4	0	0.0000	0.0000	0.0000	0.0000	.	.
fuel*mode	B20	1	0	0.0000	0.0000	0.0000	0.0000	.	.
fuel*mode	B20	2	0	0.0000	0.0000	0.0000	0.0000	.	.
fuel*mode	B20	3	0	0.0000	0.0000	0.0000	0.0000	.	.
fuel*mode	B20	4	0	0.0000	0.0000	0.0000	0.0000	.	.
speed*fuel	B0		1	1.2280	0.2165	0.8038	1.6523	32.19	<.0001
speed*fuel	B10		1	2.2787	0.1943	1.8979	2.6594	137.59	<.0001
speed*fuel	B20		0	0.0000	0.0000	0.0000	0.0000	.	.
pass*fuel	B0		1	4.1269	0.5989	2.9531	5.3006	47.49	<.0001
pass*fuel	B10		1	2.6421	0.5696	1.5256	3.7585	21.51	<.0001
pass*fuel	B20		0	0.0000	0.0000	0.0000	0.0000	.	.
Scale			1	2.8445	0.0145	2.8161	2.8731		

Table 3-62. Wald statistics for type 3 analysis for HC (Bus 997)

Source	DF	Chi-Square	Pr > ChiSq
mode	3	22442.1	<.0001
fuel	2	2167.98	<.0001
speed	1	2471.68	<.0001
pass	1	32.17	<.0001
fuel*mode	6	728.44	<.0001
speed*fuel	2	177.30	<.0001
pass*fuel	2	64.30	<.0001

Table 3-63. Least square means of the transformed data for HC (Bus 997)

Effect	fuel	mode	Estimate	Standard Error	Chi-Square	Pr > ChiSq	Confidence Limits	
fuel	B0		339.0646	1.5922	45352	<.0001	335.9440	342.1851
fuel	B10		286.0338	1.0024	81427	<.0001	284.0692	287.9985
fuel	B20		451.2078	2.7207	27503	<.0001	445.8753	456.5403
mode		1	499.8216	3.2007	24386	<.0001	493.5484	506.0949
mode		2	303.4264	1.7041	31706	<.0001	300.0866	306.7663
mode		3	174.6917	0.9732	32218	<.0001	172.7842	176.5992
mode		4	457.1351	2.4740	34143	<.0001	452.2862	461.9840

Table 3-64. Least square means (g/s) of the original data for HC (Bus 997)

Effect	fuel	mode	Estimate	SE	LowerCL	UpperCL
fuel	B0		.002949291	.000013849	.002921593	.002976989
fuel	B10		.003496090	.000012252	.003471587	.003520594
fuel	B20		.002216274	.000013364	.002189546	.002243001
mode		1	.002000714	.000012812	.001975090	.002026337
mode		2	.003295692	.000018509	.003258674	.003332709
mode		3	.005724369	.000031892	.005660586	.005788152
mode		4	.002187537	.000011839	.002163860	.002211215

Carbon Monoxide. Table 3-65 to 3-69 provide model results for carbon monoxide for Bus 997. Table 3-66 provides results of the analysis of parameter estimates and Table 3-67 provides the Wald statistics. As shown all the parameters and effects are significant except for speed and the interaction between "B-20 and deceleration mode", "B-10 and steady state mode", and "passengers and B-10". The estimated least square means for carbon monoxide are shown in

Table 3-69. As indicated, CO emissions (g/s) are highest for B-0, followed by B-10 and are lowest for B-20. Estimated mean emissions are 29.4% lower for B-10 and 37.4% lower for B-20 than for B-20. The estimated mean CO emissions are highest when the bus is in acceleration mode and lowest for deceleration.

Table 3-65. Parameter information for CO (Bus 997)

Parameter	Effect	fuel	mode
Prm1	Intercept		
Prm2	mode		1
Prm3	mode		2
Prm4	mode		3
Prm5	mode		4
Prm6	fuel	B0	
Prm7	fuel	B10	
Prm8	fuel	B20	
Prm9	speed		
Prm10	pass		
Prm11	fuel*mode	B0	1
Prm12	fuel*mode	B0	2
Prm13	fuel*mode	B0	3
Prm14	fuel*mode	B0	4
Prm15	fuel*mode	B10	1
Prm16	fuel*mode	B10	2
Prm17	fuel*mode	B10	3
Prm18	fuel*mode	B10	4
Prm19	fuel*mode	B20	1
Prm20	fuel*mode	B20	2
Prm21	fuel*mode	B20	3
Prm22	fuel*mode	B20	4
Prm23	speed*fuel	B0	
Prm24	speed*fuel	B10	
Prm25	speed*fuel	B20	
Prm26	pass*fuel	B0	
Prm27	pass*fuel	B10	
Prm28	pass*fuel	B20	
Number of observations		71,311	

Table 3-66. Analysis of parameter estimates for CO (Bus 997)

Parameter			DF	Estimate	Standard Error	Wald 95% Confidence Limits		Chi-Square	Pr > ChiSq
Intercept			1	366.2006	6.9609	352.5575	379.8437	2767.64	<.0001
mode	1		1	-174.315	7.5910	-189.193	-159.436	527.31	<.0001
mode	2		1	-190.772	7.3890	-205.255	-176.290	666.59	<.0001
mode	3		1	-302.591	6.7212	-315.765	-289.418	2026.82	<.0001
mode	4		0	0.0000	0.0000	0.0000	0.0000	.	.
fuel	B0		1	-151.095	7.8578	-166.496	-135.694	369.74	<.0001
fuel	B10		1	-65.3215	7.9944	-80.9902	-49.6529	66.76	<.0001
fuel	B20		0	0.0000	0.0000	0.0000	0.0000	.	.
speed			1	-0.3511	0.1103	-0.5673	-0.1349	10.13	0.0015
pass			1	1.3803	0.3208	0.7515	2.0090	18.51	<.0001
fuel*mode	B0	1	1	98.1168	8.7066	81.0522	115.1814	127.00	<.0001
fuel*mode	B0	2	1	79.9956	8.3493	63.6312	96.3600	91.80	<.0001
fuel*mode	B0	3	1	134.9584	7.5830	120.0960	149.8207	316.75	<.0001
fuel*mode	B0	4	0	0.0000	0.0000	0.0000	0.0000	.	.
fuel*mode	B10	1	1	67.6448	8.8546	50.2902	84.9994	58.36	<.0001
fuel*mode	B10	2	1	20.6928	8.4810	4.0703	37.3152	5.95	0.0147
fuel*mode	B10	3	1	44.4664	7.7214	29.3327	59.6002	33.16	<.0001
fuel*mode	B10	4	0	0.0000	0.0000	0.0000	0.0000	.	.
fuel*mode	B20	1	0	0.0000	0.0000	0.0000	0.0000	.	.
fuel*mode	B20	2	0	0.0000	0.0000	0.0000	0.0000	.	.
fuel*mode	B20	3	0	0.0000	0.0000	0.0000	0.0000	.	.
fuel*mode	B20	4	0	0.0000	0.0000	0.0000	0.0000	.	.
speed*fuel	B0		1	0.5347	0.1308	0.2783	0.7910	16.71	<.0001
speed*fuel	B10		1	0.5120	0.1271	0.2629	0.7611	16.23	<.0001
speed*fuel	B20		0	0.0000	0.0000	0.0000	0.0000	.	.
Pass*fuel	B0		1	-1.8938	0.3390	-2.5581	-1.2294	31.22	<.0001
Pass*fuel	B10		1	0.5114	0.3482	-0.1711	1.1938	2.16	0.1420
Pass*fuel	B20		0	0.0000	0.0000	0.0000	0.0000	.	.
Scale			1	0.8152	0.0037	0.8079	0.8226		

Table 3-67. Wald statistics for type 3 analysis for CO (Bus 997)

Source	DF	Chi-Square	Pr > ChiSq
mode	3	14672.6	<.0001
fuel	2	601.68	<.0001
speed	1	0.00	0.9639
pass	1	57.11	<.0001
fuel*mode	6	924.92	<.0001
speed*fuel	2	19.02	<.0001
pass*fuel	2	198.82	<.0001

Table 3-68. Least square means of the transformed data for CO (Bus 997)

Effect	fuel	mode	Estimate	Standard Error	Chi-Square	Pr > ChiSq	Confidence Limits	
fuel	B0		126.3080	1.1352	12381	<.0001	124.0832	128.5329
fuel	B10		179.0038	1.2053	22057	<.0001	176.6415	181.3661
fuel	B20		201.5951	2.0820	9375.3	<.0001	197.5144	205.6758
mode		1	179.6716	1.7176	10942	<.0001	176.3051	183.0381
mode		2	141.5226	1.3988	10236	<.0001	138.7810	144.2642
mode		3	55.9494	0.5139	11854	<.0001	54.9422	56.9566
mode		4	298.7323	2.7901	11464	<.0001	293.2638	304.2008

Table 3-69. Least square means (g/s) of the original data for CO (Bus 997)

Effect	fuel	mode	Estimate	SE	LowerCL	UpperCL
fuel	B0		0.007917	.000071153	0.007775	0.008059
fuel	B10		0.005586	.000037616	0.005511	0.005662
fuel	B20		0.004960	.000051230	0.004858	0.005063
mode		1	0.005566	.000053208	0.005459	0.005672
mode		2	0.007066	.000069841	0.006926	0.007206
mode		3	0.017873	.000164159	0.017545	0.018202
mode		4	0.003347	.000031265	0.003285	0.003410

Carbon Dioxide. Table 3-70 to 3-74 provide model results for carbon dioxide for Bus 997. Table 3-71 provides results of the analysis of parameter estimates and Table 3-72 shows the Wald Statistics. As indicated, the variable “passengers” is the only main effect that is not significant. Several interactions are not significant in this model: “B-0 and idle mode”, “B-10 and steady state mode”, “B-10 and acceleration mode”, and “B-0 and speed”. All the rest of parameters are significant. Estimates of the least squares means are given in Table 3-74. As shown, B-10 has the highest estimated mean CO_2 emissions (g/s) followed by B-20. Estimated mean emissions for B-0 are 15.0% lower than for both B-10 and B-20. Mean CO_2 emissions are highest when the bus is in acceleration mode and lowest when the bus is in deceleration mode.

Table 3-70. Parameter information for CO_2 (Bus 997)

Parameter	Effect	fuel	mode
Prm1	Intercept		
Prm2	mode		1
Prm3	mode		2
Prm4	mode		3
Prm5	mode		4
Prm6	fuel	B0	
Prm7	fuel	B10	
Prm8	fuel	B20	
Prm9	speed		
Prm10	pass		
Prm11	fuel*mode	B0	1
Prm12	fuel*mode	B0	2
Prm13	fuel*mode	B0	3
Prm14	fuel*mode	B0	4
Prm15	fuel*mode	B10	1
Prm16	fuel*mode	B10	2
Prm17	fuel*mode	B10	3
Prm18	fuel*mode	B10	4
Prm19	fuel*mode	B20	1
Prm20	fuel*mode	B20	2
Prm21	fuel*mode	B20	3
Prm22	fuel*mode	B20	4
Prm23	speed*fuel	B0	
Prm24	speed*fuel	B10	
Prm25	speed*fuel	B20	
Prm26	pass*fuel	B0	
Prm27	pass*fuel	B10	
Prm28	pass*fuel	B20	
Number of observations		71,807	

Table 3-71. Analysis of parameter estimates for CO_2 (Bus 997)

Parameter			DF	Estimate	Standard Error	Wald 95% Confidence Limits		Chi-Square	Pr > ChiSq
Intercept			1	0.3242	0.0041	0.3161	0.3323	6185.18	<.0001
mode	1		1	-0.1120	0.0048	-0.1213	-0.1027	551.99	<.0001
mode	2		1	-0.2013	0.0042	-0.2096	-0.1930	2250.72	<.0001
mode	3		1	-0.2695	0.0040	-0.2774	-0.2616	4495.17	<.0001
mode	4		0	0.0000	0.0000	0.0000	0.0000	.	.
fuel	B0		1	0.0573	0.0059	0.0457	0.0689	93.61	<.0001
fuel	B10		1	-0.0203	0.0049	-0.0298	-0.0107	17.27	<.0001
fuel	B20		0	0.0000	0.0000	0.0000	0.0000	.	.
speed			1	-0.0006	0.0001	-0.0007	-0.0005	115.73	<.0001
pass			1	0.0004	0.0002	0.0001	0.0007	5.23	0.0223
fuel*mode	B0	1	1	-0.0079	0.0071	-0.0217	0.0060	1.24	0.2663
fuel*mode	B0	2	1	-0.0453	0.0061	-0.0573	-0.0334	55.23	<.0001
fuel*mode	B0	3	1	-0.0540	0.0058	-0.0654	-0.0427	86.83	<.0001
fuel*mode	B0	4	0	0.0000	0.0000	0.0000	0.0000	.	.
fuel*mode	B10	1	1	0.0440	0.0058	0.0327	0.0553	58.44	<.0001
fuel*mode	B10	2	1	0.0010	0.0050	-0.0089	0.0109	0.04	0.8431
fuel*mode	B10	3	1	0.0061	0.0048	-0.0032	0.0155	1.65	0.1987
fuel*mode	B10	4	0	0.0000	0.0000	0.0000	0.0000	.	.
fuel*mode	B20	1	0	0.0000	0.0000	0.0000	0.0000	.	.
fuel*mode	B20	2	0	0.0000	0.0000	0.0000	0.0000	.	.
fuel*mode	B20	3	0	0.0000	0.0000	0.0000	0.0000	.	.
fuel*mode	B20	4	0	0.0000	0.0000	0.0000	0.0000	.	.
speed*fuel	B0		1	0.0001	0.0001	-0.0001	0.0002	0.68	0.4081
speed*fuel	B10		1	0.0007	0.0001	0.0006	0.0008	115.03	<.0001
speed*fuel	B20		0	0.0000	0.0000	0.0000	0.0000	.	.
pass*fuel	B0		1	-0.0002	0.0002	-0.0006	0.0002	1.04	0.3075
pass*fuel	B10		1	-0.0004	0.0002	-0.0007	-0.0000	4.78	0.0287
pass*fuel	B20		0	0.0000	0.0000	0.0000	0.0000	.	.
Scale			1	1.6908	0.0082	1.6748	1.7069		

Table 3-72. Wald statistics for type 3 analysis for CO_2 (Bus 997)

Source	DF	Chi-Square	Pr > ChiSq
mode	3	38652.1	<.0001
fuel	2	391.68	<.0001
speed	1	153.34	<.0001
pass	1	7.22	0.0072
fuel*mode	6	366.40	<.0001
speed*fuel	2	171.33	<.0001
pass*fuel	2	6.20	0.0450

Table 3-73. Least square means of the transformed data for CO_2 (Bus 997)

Effect	fuel	mode	Estimate	Standard Error	Chi-Square	Pr > ChiSq	Confidence Limits	
fuel	B0		0.2027	0.0013	22891	<.0001	0.2001	0.2054
fuel	B10		0.1723	0.0008	43141	<.0001	0.1707	0.1739
fuel	B20		0.1724	0.0013	18993	<.0001	0.1699	0.1749
mode		1	0.2329	0.0015	23534	<.0001	0.2299	0.2359
mode		2	0.1168	0.0008	23253	<.0001	0.1153	0.1183
mode		3	0.0474	0.0003	25250	<.0001	0.0468	0.0480
mode		4	0.3329	0.0021	25279	<.0001	0.3288	0.3370

Table 3-74. Least square means (g/s) of the original data for CO_2 (Bus 997)

Effect	fuel	mode	Estimate	SE	LowerCL	UpperCL
fuel	B0		4.9327	0.03260	4.8675	4.9979
fuel	B10		5.8032	0.02794	5.7473	5.8591
fuel	B20		5.8005	0.04209	5.7163	5.8847
mode		1	4.2935	0.02799	4.2375	4.3495
mode		2	8.5641	0.05616	8.4518	8.6764
mode		3	21.1060	0.13282	20.8404	21.3717
mode		4	3.0041	0.01889	2.9664	3.0419

Particulate Matter. Model results for PM for Bus 997 are provided in Tables 3-75 to 3-79. Table 3-76 provides results of the analysis of parameter estimates and Table 3-77 shows the Wald Statistics. As indicated, all the parameters were significant except for "passengers", and the interactions between "B-0 and acceleration mode", "B-0 and steady state mode", and "B-0 and fuel". Table 3-79 provides estimates of the least square means for the data. As shown, B-10 has the highest mean PM emissions (g/s) followed by B-20. B-0 has the lowest PM emissions (53.7% lower than for B-0 and 26.2% lower than for B-20). PM emissions are also highest when the bus is in acceleration mode and lowest while in deceleration mode.

Table 3-75. Parameter information for PM (Bus 997)

Parameter	Effect	fuel	mode
Prm1	Intercept		
Prm2	mode		1
Prm3	mode		2
Prm4	mode		3
Prm5	mode		4
Prm6	fuel	B0	
Prm7	fuel	B10	
Prm8	fuel	B20	
Prm9	speed		
Prm10	pass		
Prm11	fuel*mode	B0	1
Prm12	fuel*mode	B0	2
Prm13	fuel*mode	B0	3
Prm14	fuel*mode	B0	4
Prm15	fuel*mode	B10	1
Prm16	fuel*mode	B10	2
Prm17	fuel*mode	B10	3
Prm18	fuel*mode	B10	4
Prm19	fuel*mode	B20	1
Prm20	fuel*mode	B20	2
Prm21	fuel*mode	B20	3
Prm22	fuel*mode	B20	4
Prm23	speed*fuel	B0	
Prm24	speed*fuel	B10	
Prm25	speed*fuel	B20	
Prm26	pass*fuel	B0	
Prm27	pass*fuel	B10	
Prm28	pass*fuel	B20	
Number of observations		71, 885	

Table 3-76. Analysis of parameter estimates for PM (Bus 997)

Parameter			DF	Estimate	Standard Error	Wald 95% Confidence Limits		Chi-Square	Pr > ChiSq
Intercept			1	18.2371	0.2057	17.8339	18.6402	7860.49	<.0001
mode	1		1	-1.9245	0.2610	-2.4361	-1.4130	54.38	<.0001
mode	2		1	-9.5767	0.2166	-10.0011	-9.1522	1955.46	<.0001
mode	3		1	-14.0555	0.1995	-14.4466	-13.6644	4962.17	<.0001
mode	4		0	0.0000	0.0000	0.0000	0.0000	.	.
fuel	B0		1	3.7689	0.3046	3.1719	4.3659	153.10	<.0001
fuel	B10		1	-8.0196	0.2205	-8.4517	-7.5874	1322.91	<.0001
fuel	B20		0	0.0000	0.0000	0.0000	0.0000	.	.
mspeed			1	-0.0183	0.0034	-0.0250	-0.0117	29.49	<.0001
pass			1	-0.1765	0.0079	-0.1919	-0.1610	501.23	<.0001
fuel*mode	B0	1	1	2.1970	0.4143	1.3849	3.0090	28.12	<.0001
fuel*mode	B0	2	1	-0.5777	0.3161	-1.1972	0.0418	3.34	0.0676
fuel*mode	B0	3	1	-0.5364	0.2914	-1.1075	0.0348	3.39	0.0657
fuel*mode	B0	4	0	0.0000	0.0000	0.0000	0.0000	.	.
fuel*mode	B10	1	1	3.1197	0.2855	2.5601	3.6792	119.41	<.0001
fuel*mode	B10	2	1	2.9950	0.2321	2.5401	3.4500	166.52	<.0001
fuel*mode	B10	3	1	4.8353	0.2143	4.4153	5.2554	509.01	<.0001
fuel*mode	B10	4	0	0.0000	0.0000	0.0000	0.0000	.	.
fuel*mode	B20	1	0	0.0000	0.0000	0.0000	0.0000	.	.
fuel*mode	B20	2	0	0.0000	0.0000	0.0000	0.0000	.	.
fuel*mode	B20	3	0	0.0000	0.0000	0.0000	0.0000	.	.
fuel*mode	B20	4	0	0.0000	0.0000	0.0000	0.0000	.	.
mspeed*fuel	B0		1	-0.0855	0.0059	-0.0970	-0.0741	213.29	<.0001
mspeed*fuel	B10		1	0.0294	0.0035	0.0226	0.0363	71.06	<.0001
mspeed*fuel	B20		0	0.0000	0.0000	0.0000	0.0000	.	.
pass*fuel	B0		1	0.1802	0.0119	0.1570	0.2035	230.20	<.0001
pass*fuel	B10		1	0.1758	0.0080	0.1601	0.1916	477.42	<.0001
pass*fuel	B20		0	0.0000	0.0000	0.0000	0.0000	.	.
Scale			1	2.0535	0.0101	2.0338	2.0733		

Table 3-77. Wald statistics for type 3 analysis for PM (Bus 997)

Source	DF	Chi-Square	Pr > ChiSq
mode	3	32287.1	<.0001
fuel	2	7707.96	<.0001
mspeed	1	351.99	<.0001
pass	1	209.01	<.0001
fuel*mode	6	1670.73	<.0001
mspeed*fuel	2	612.46	<.0001
pass*fuel	2	479.06	<.0001

Table 3-78. Least square means of the transformed data for PM (Bus 997)

Effect	fuel	mode	Estimate	Standard Error	Chi-Square	Pr > ChiSq	Confidence Limits	
fuel	B0		14.5090	0.0831	30500	<.0001	14.3462	14.6719
fuel	B10		6.7119	0.0297	50921	<.0001	6.6536	6.7702
fuel	B20		10.6972	0.0683	24509	<.0001	10.5633	10.8312
mode		1	15.8735	0.1038	23387	<.0001	15.6701	16.0769
mode		2	7.2549	0.0485	22399	<.0001	7.1599	7.3499
mode		3	3.4033	0.0225	22812	<.0001	3.3591	3.4475
mode		4	16.0258	0.0983	26581	<.0001	15.8332	16.2185

Table 3-79. Least square means (g/s) of the original data for PM (Bus 997)

Effect	Fuel	Mode	Estimate	SE	LowerCL	UpperCL
fuel	B0		0.06892	.000394652	0.06813	0.06971
fuel	B10		0.14899	.000660245	0.14767	0.15031
fuel	B20		0.09348	.000597130	0.09229	0.09468
mode		1	0.06300	.000411945	0.06217	0.06382
mode		2	0.13784	.000920980	0.13600	0.13968
mode		3	0.29383	.001945450	0.28994	0.29772
mode		4	0.06240	.000382729	0.06163	0.06316

3.8.2.4 Summary of Model Results

Results of the emissions evaluation by fuel type and mode are summarized in Table 3-80. As shown, emissions by Bus by fuel types, pollutant, and mode are presented. Number 1 represents the highest estimated mean emissions (g/s). In most cases the results were statistically significant. So for instance, B-10 had the highest mean NO_x emissions for Bus 971. In all cases emissions were highest while the bus was in acceleration mode.

Table 3-80. Summary of model results by bus and pollutant for fuel and mode

Bus	Ranking	NOx		HC		CO		CO2		PM	
		Fuel	Mode	Fuel	Mode	Fuel	Mode	Fuel	Mode	Fuel	Mode
971	1	B10	Accel	B0	Accel	B20	Accel	B20	Accel	B0	Accel
	2	B0	Steady	B20	Steady	B0	Steady	B0	Steady	B10	Steady
	3	B20	Idle	B10	Decel	B10	Idle	B10	Idle	B20	Decel
	4		Decel		Idle		Decel		Decel		Idle
973	1	B20	Accel	B0	Accel	B20	Accel	B20	Accel	B10	Accel
	2	B0	Steady	B10	Steady	B0	Steady	B0	Steady	B20	Steady
	3	B10	Idle	B20	Decel	B10	Idle	B10	Idle	B0	Decel
	4		Decel		Idle		Decel		Decel		Idle
977	1	B20	Accel	B10	Accel	B0	Accel	B10	Accel	B10	Accel
	2	B0	Steady	B0	Steady	B10	Steady	B20	Steady	B20	Steady
	3	B10	Idle	B20	Decel	B20	Idle	B0	Idle	B0	Idle
	4		Decel		Idle		Decel		Decel		Decel

Evidence of difference in emissions means was found for all the buses for all the studied pollutants for almost all the compared fuel types and the different driving modes. In some cases differences in estimated means were small. The ability to detect small differences in means is in part due to the high number of observations. Whether practical differences in emissions exist should be considered when applying model results.

4. LABORATORY DYNAMOMETER ENGINE TESTING

4.1 Data Collection

Laboratory engine testing was performed on a diesel engine using B-0, B-10, and B-20. Emissions were evaluated using a gaseous emission analyzer and a smoke meter, as described in the following sections.

4.2 Description of Equipment

A John Deere diesel engine (model 4045) was used in this study. The engine is a four-cylinder, 4.5 L turbocharged engine and has a modern common-rail fuel injection system that can achieve a high injection pressure. The engine is coupled with a dynamometer that controls the engine speed and torque during the steady-state test, as shown in Figure 4-1. The engine system is controlled by operators from the controlled room, as also shown in Figure 4-1.

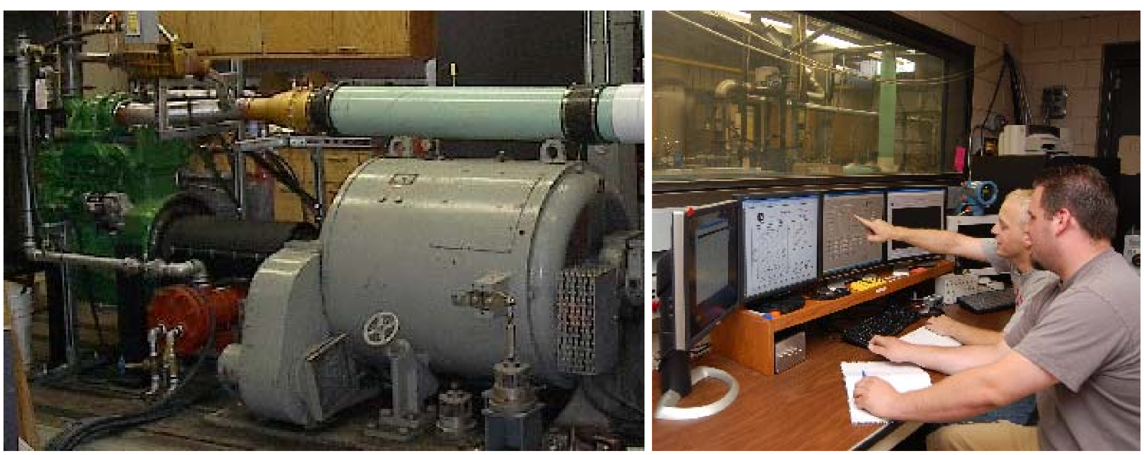

Figure 4-1. Test engine, dynamometer, and the control room in the engine laboratory

Gaseous emissions were measured using a HORIBA MEXA 7100DEGR emission analyzer. The gaseous emissions to be recorded included CO, total unburned HC, NO_x, CO_2, and O_2. The analyzer was calibrated before each test using various bottled calibration gas with a gas divider. The particulate emissions were measured using an AVL 415S smoke meter. Figure 4-2 shows the emission analyzer and calibration gas bottles.

(a) Emissions analyzer (b) Calibration gas bottles

Figure 4-2. Layout of the emission analyzer and calibration gas bottles

The laboratory equipment to record engine operating conditions and the exhaust emissions analyzer meet the requirements in CFR Title 40, Section 1065. The dynamometer records engine speed and torque (CFR 1065.110 and 210) in a continuous operating mode, which is one of the standard procedures for diesel engine testing (CFR 1065.150). Operating conditions, including intake air (CFR 1065.125), exhaust (CFR 1065.130), gas temperature, and pressure (CFR 1065.215), are all recorded using proper sensors. A fuel flow meter (CFR 1065.220), intake air flow meter (CFR 1065.225), and an exhaust gas recirculation device (CFR 1065.127) are also implemented. The fuel consumption and emissions data are reported as g/bhp-hr, which is the same unit that federal regulations use.

For emissions measurements, a gas divider (CFR 1065.248) is used to blend calibration gases for analyzer calibration. Most importantly, the gaseous emissions analyzer uses methods that are specified in CFR 1065, including the following:

- Non-dispersive infra-red analyzer for CO and CO2 (CFR 1065.250)
- Flame ionization detector for total HC (CFR 1065.260)
- Chemiluminescent detector for NO/NO2 (CFR 1065.270)
- Magnetopneumatic detector for O2 (CFR 1065.280)

The sampling lines for HC and NO_x measurements are heated to meet the testing requirements. The operating conditions, sampling frequency, accuracy, and repeatability of the above analyzers meet the specifications of CFR 1065.205.

4.3 Engine Operating Conditions

Engine performance and emissions data were recorded for three engine operating conditions, including peak torque (1,400 rpm, 220 ft-lbs), rated power (2,100 rpm, 187 ft-lbs), and light load (1,200 rpm, 30 ft-lbs). These three conditions are the representative load conditions corresponding to the present engine class. Steady-state tests were performed for each load condition.

A data acquisition system was used to acquire engine performance data in the laboratory. The data system is capable of acquiring fueling rate, engine power, and all the emissions data automatically. The data were averaged over the duration of each individual test. The data were then analyzed to assess each of the emissions with respect to the fuel type.

4.4 Fuel

The diesel-biodiesel blends were supplied by Western Central Cooperative, a supplier of biodiesel blends. The facility was capable of blending different fractions of biodiesel. Three different fuels were used, including B0, B10, and B20. Ultra low–sulfur diesel fuel was used as the base diesel fuel for blending with biodiesel. The fuel used in the laboratory was the same as that used in CyRide test (see Section 3.4 in this report). For the dynamometer tests, an appropriate amount of fuel was extracted from the same fuel tank used for the transit buses so that the same fuel was evaluated.

4.5 Testing Procedure

Engine testing was performed for the three different fuels. Various preliminary tests were performed for data evaluation and engine performance assessment. The final engine testing was carried out based on the following procedure:

4.5.1 Replication 1

Ultra low–sulfur diesel fuel (i.e., B0) was used for this test. The emissions analyzer was warmed up and calibrated at the beginning of each day. A gas divider was used to blend the calibration gas for calibration. For each day of engine testing, the engine was warmed up until steady state conditions were reached, approximately one hour as determined by steady coolant and oil temperature readings. The engine continued to run at the steady state condition for one hour for stabilization. After the stabilization, the engine was tested on one load condition over two hours for power and emissions measurements. Engine data within the two-hour test period for a specific load were analyzed and reported.

Since each load resulted in different engine operating conditions, e.g., coolant temperatures, different load conditions would require different days of testing. At the beginning of each day, the emissions analyzer and engine were warmed up in the same way.

4.5.2 Replication 2

B10 was used for this test. The emissions analyzer and engine were warmed up and stabilized at the beginning of each test day. The test protocol was the same as in Replication 1, except that the fuel was B10. After Replication 2 was finished, the engine was run using B0 for a period of time to stabilize the engine and to reach the previous steady state conditions achieved using B0. The transition time was at least two hours, or as long as it took to re-establish the steady state conditions. This was also to eliminate the effects of residual biodiesel in the fuel system.

4.5.3. Replication 3

B20 was used for this test. The emissions analyzer and engine were warmed up and stabilized at the beginning of each test day. The test protocol was the same as Replication 1, except that the fuel was B20. After Replication 3 was finished, the engine was run using B0 for at least two hours, or as long as it took to re-establish the steady state conditions achieved using B0. This was also to eliminate the effects of residual biodiesel in the fuel system.

Data from each replication were evaluated in terms of emissions by load. Emissions were measured in terms of engine loads in units of g/kW-hr. As a result, the emission measurement was the mass of emissions per unit of fuel energy burned. Increased engine loading translates into additional fuel energy used and higher emissions. As a result, relationships between engine loading and emissions can be derived for each fuel blend.

4.6 Engine Test Results

The equipment used in the engine laboratory meets the engine testing requirements laid out in CFR Title 40, Section 1065 in terms of recording dynamometer data and measuring gaseous emissions using an emission analyzer methodology. The emission data are reported in g/kW-hr such that the data are normalized by engine load and size.

The results of engine testing are shown in Figures 4-3 to 4-6 for NO_x, soot, CO, and HC, respectively. The engine test results show that the increased NO_x emissions using B-10 and B-20 are approximately the same for the three load conditions studied. In general, soot emissions were reduced by using B-10 and B-20. However, soot emissions are approximately the same for three fuels at the 1,200 rpm light load condition, under which the soot emissions are already relatively low and it is hard to distinguish among them. The CO emissions decrease as the biodiesel contents increase. However, a clear trend of declining HC emissions was not observed with increased biodiesel contents. Both B-10 and B-20 produced lower HC emissions than B-0, but B-20 produced higher HC emissions than B-10.

In general, the trends of increasing NO_x emissions and decreasing soot, CO, and HC emissions are obtained by using biodiesel blends. There are only a few operating points for which a clear trend is not observed. Although certain trends may be expected, it should be noted that the emission results for various biodiesel blends may vary due to differences in specific engine operating conditions and fuel properties. This study followed the test protocol described above, and the results obtained were consistent throughout the testing. The general effects of biodiesel on engine performance have been observed.

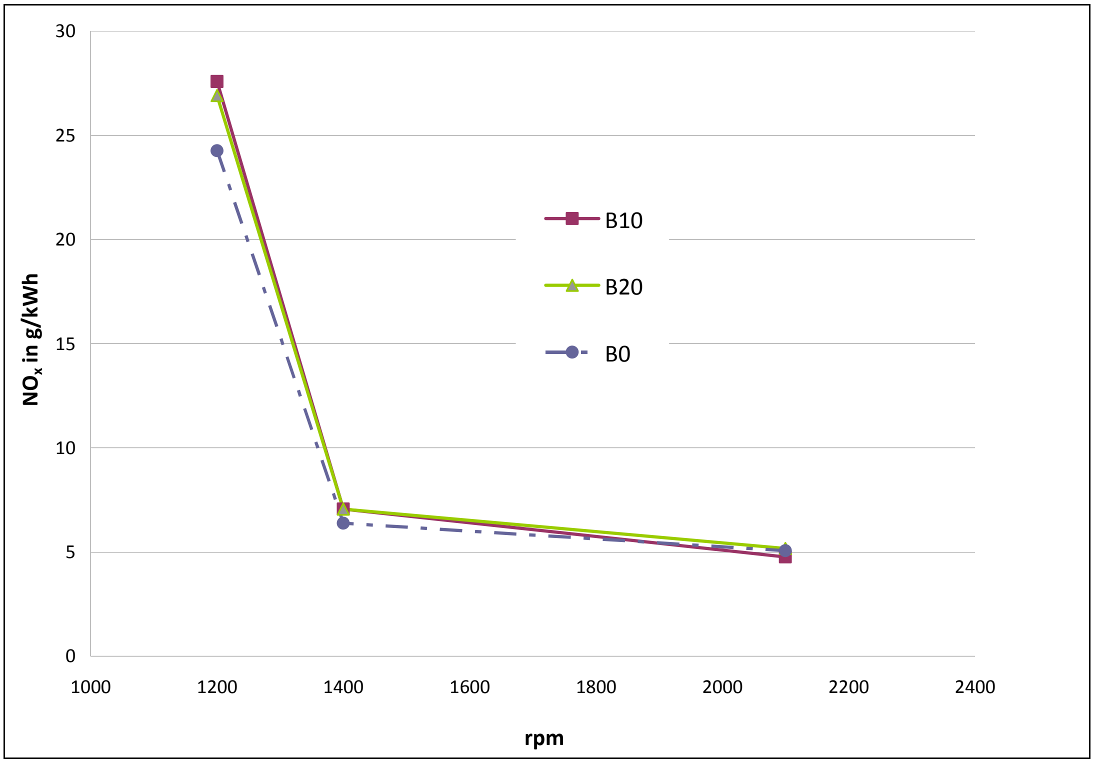

Figure 4-3. NOx emissions corresponding to each operating condition

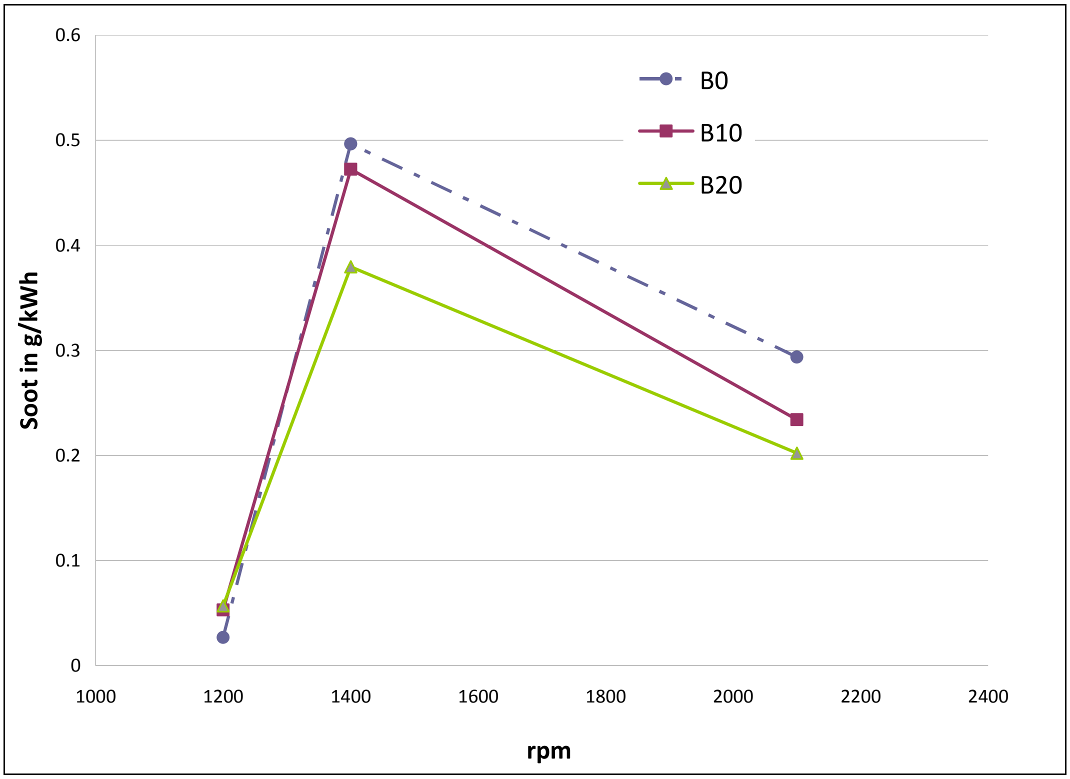

Figure 4-4. Soot emissions corresponding to each operating conditions

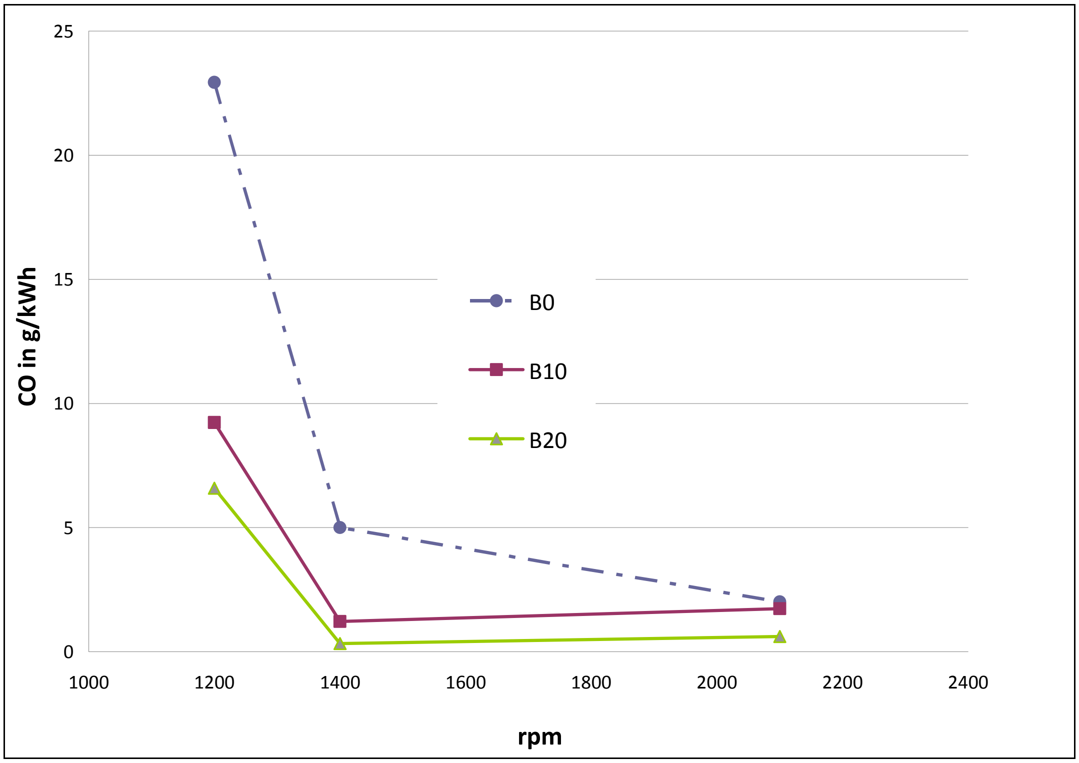

Figure 4-5. CO emissions corresponding to each operating conditions

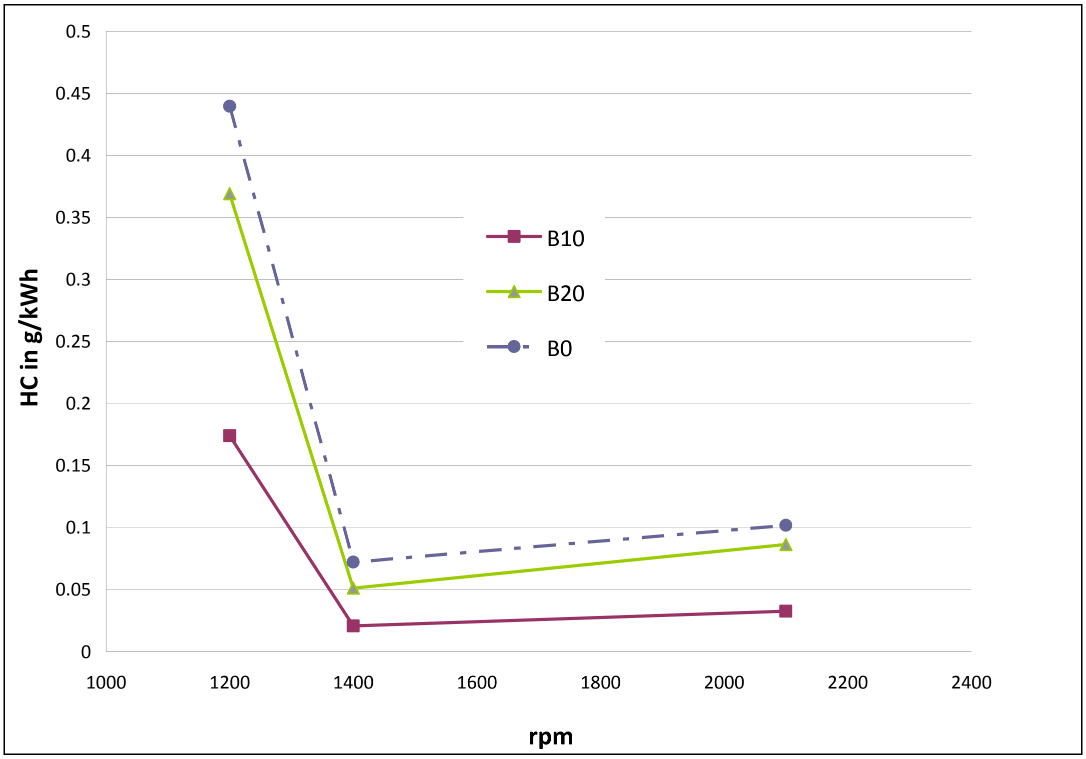

Figure 4-6. HC emissions corresponding to each operating conditions

6. SUMMARY

This study evaluated the emissions impacts of different biodiesel blends on emissions using a laboratory dynamometer testing and on-road testing of transit buses using a portable emissions monitor. Regular ultra low sulfur diesel (B-0) and two biodiesel blends were evaluated (B-10 and B-20).

6.1 Summary for On-road Tests

The three different types of diesel and biodiesel were also evaluated in three in-service transit buses using a portable emissions monitor. Two buses, Bus 973 and 971, fall into the 1998-2003 diesel engine emissions standard time frame. Data were collected for the two buses during spring-like conditions (April and May 2008 with cooler temperatures). The third bus, Bus 997, falls into the 2004-2006 diesel engine emissions standard time frame and data was collected during summer conditions (June and July 2008 with hot and humid conditions and regular air conditioning use).

Simple comparison of the three fuels for each pollutant of interest for each bus were made by mode (idle, steady state, acceleration, deceleration) and speed range. Averages are in g/s. Results for Bus 973 indicate that average NO_x emissions were generally lower for B-10 than for B-0 but higher for B-20. Mixed results were found for Bus 971 with NO_x emissions higher for some speed ranges and modes for B-10 and B-20 than for B-0 but emissions were lower in some cases. Average NO_x emissions were usually higher for both B-10 and B-20 than for B-0 for all modes and speed ranges for Bus 997.

Average HC emissions (g/s) were lower for B-10 and B-20 than for Bus 973 for all modes and speed ranges and for Bus 971 except HC emissions during deceleration. HC emissions for B-20 were lower for Bus 997 than for B-0 but HC emissions for B-10 were higher than for B-0. Carbon monoxide emissions were lower for both B-10 and B-20 than for B-0 for all modes and speed ranges for Bus 973 and 997. However, while B-10 CO emissions were lower than B-0, B-20 emissions were higher than B-0 for Bus 971.

Results for carbon dioxide were mixed for Bus 973. Average CO_2 emissions were similar or slightly higher for both biodiesel blends than for regular diesel for idling, steady state, and deceleration while they were slightly lower in most cases for acceleration. CO_2 emissions were generally lower for B-10 than for B-0 but were higher for B-20 for idling, steady state, and acceleration while results were mixed for deceleration for Bus 971. CO_2 emissions were similar for Bus 997 as for Bus 973 with similar or slightly higher average emissions for B-10 and B-20 than for B-0 during idling, steady state, and deceleration while results were inconclusive for deceleration. PM emissions were much higher for B-10 than for B-0 for Bus 973 and Bus 997 for all modes and speed ranges while B-20 PM emissions were similar or slightly higher. For Bus 971, the two biodiesel blends resulted in significantly lower PM emissions than B-0 for all modes and speed ranges.

A summary of the results of the statistical model are presented in Table 6-1. As shown, emissions by Bus by fuel types, pollutant, and mode are presented. Evidence of difference in emission means (g/s) was found for all the buses for all the studied pollutants for almost all the compared fuel types and the different driving modes. However, in some cases differences in estimated means were small. Number 1 represents the highest estimated mean emissions. In most cases the results were statistically significant. So for instance, B-10 had the highest mean NO_x emissions (g/s) for Bus 971. In all cases emissions were highest while the bus was in acceleration mode.

Table 6-1. Summary of model results by bus and pollutant for fuel and mode

Bus	Ranking	NOx		HC		CO		CO2		PM	
		Fuel	Mode	Fuel	Mode	Fuel	Mode	Fuel	Mode	Fuel	Mode
	1	B10	Accel	B0	Accel	B20	Accel	B20	Accel	B0	Accel
971	2	B0	Steady	B20	Steady	B0	Steady	B0	Steady	B10	Steady
	3	B20	Idle	B10	Decel	B10	Idle	B10	Idle	B20	Decel
	4		Decel		Idle		Decel		Decel		Idle
	1	B20	Accel	B0	Accel	B20	Accel	B20	Accel	B10	Accel
973	2	B0	Steady	B10	Steady	B0	Steady	B0	Steady	B20	Steady
	3	B10	Idle	B20	Decel	B10	Idle	B10	Idle	B0	Decel
	4		Decel		Idle		Decel		Decel		Idle
	1	B20	Accel	B10	Accel	B0	Accel	B10	Accel	B10	Accel
977	2	B0	Steady	B0	Steady	B10	Steady	B20	Steady	B20	Steady
	3	B10	Idle	B20	Decel	B20	Idle	B0	Idle	B0	Idle
	4		Decel		Idle		Decel		Decel		Decel

The ability to detect small differences in means is in part due to the high number of observations. Whether practical differences in emissions exist should be considered when applying model results.

Results of the descriptive statistics and statistical modeling are fairly consistent. NOx, HC, CO, emissions for results are generally consistent with what has been reported for biodiesels. PM emissions were much lower for one bus for B-10 and B-20 which is consistent with other studies but for the other two buses, PM emissions for biodiesels were either higher or similar to those for regular diesel.

6.2 Summary for Laboratory Tests

The effects of biodiesel blends on engine performance and exhaust emissions were investigated and verified by the laboratory engine testing. Various engine load conditions that are representative of the operation of the present engine class were tested. Results indicate that increases in NO_x and decrease in soot, CO, and HC emissions are obtained by using biodiesel blends. Engine test results show that the increased NO_x emissions using B-10 and B-20 are approximately the same for the three load conditions studied. In general, soot emissions were reduced by using B-10 and B-20. However, soot emissions are approximately the same for three fuels at the 1,200 rpm light load condition, under which the soot emissions are already relatively low and it is hard to distinguish among them. The CO emissions decrease as the biodiesel contents increase. However, a clear trend of declining HC emissions was not observed with increased biodiesel contents. Both B-10 and B-20 produced lower HC emissions than B-0, but B-20 produced higher HC emissions than B-10.

In general, the trends of increasing NO_x emissions and decreasing soot, CO, and HC emissions are obtained by using biodiesel blends. There are only a few operating points for which a clear trend is not observed. Although certain trends may be expected, it should be noted that the emission results for various biodiesel blends may vary due to differences in specific engine operating conditions and fuel properties. This study followed the test protocol described above, and the results obtained were consistent throughout the testing. The general effects of biodiesel on engine performance have been observed.

7. LIMITATIONS OF STUDY

Several limitations were present that may affect project results. Since the study included on-road testing, it was impossible to control for or include many environmental, vehicle, and driver variables. As discussed, data were collected during the same time period for each bus so that weather variations could be minimized. A log was kept of hour-by-hour temperature, wind speed, and precipitation information. However, it was not possible to collect enough data to test differences in environmental variables. Additionally, each bus was tested over the same route pattern to control for roadway and driver differences. However, although no adverse congestion or traffic events were noted, traffic can vary significantly. Drivers may also drive differently on different days, and driver variability can significantly influence emissions.

The nature of the PEMS equipment also introduces variability in the data. The equipment was checked and calibrated regularly, and data were carefully checked. However, it is not possible to find or correct all possible errors.

Fuel quality may also vary. Fuel was purchased from the same supplier, but differences may still result. In addition, biodiesel can also degrade over time, because biodiesel has poor oxidation stability. This problem is more pronounced for soy-based biodiesel (Wang et al. 2007). Once the biodiesel blends were purchased, the fuels remained in the temporary storage tank for less than two weeks in all cases. However, it was not possible to control how long batches of biodiesel had been stored by the supplier.

Finally, in the dynamometer study the amounts of particulates were measured using a smoke meter. The test results were obtained by measuring the opacity of the filter paper to determine the soot concentration. In contrast, a more rigorous and comprehensive particulate emission measurement is obtained by using a dilution tunnel with an appropriate procedure to obtain the mass of all the particulate matters, including various compounds. Therefore, without the direct measurement of the mass of all particulate matters, the results of particulate emissions in this study are limited to the soot emissions.

8. BENEFITS OF PROJECT

A better understanding of the environmental impacts of biodiesel will assist agencies in the Central States Air Resources Agencies Association (CenSARA) area in modeling baseline emissions when biodiesel use is prevalent and will aid them in forecasting the emission reduction potential of economic or policy shifts resulting in increased use of biodiesel. The promotion of biodiesels has important economic implications for many of the states within the CenSARA region since many of the states have agricultural based economies.

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