Evaluation of In-Use Fuel Economy and On-Board Emissions for Hybrid and Regular CyRide Transit Buses

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16. Abstract

The objective of this project was to evaluate the in-use fuel economy and emission differences between hybrid-electric and conventional transit buses for the Ames, Iowa transit authority, CyRide. These CyRide buses were deployed in the fall of 2010.

Fuel economy was compared for the hybrid and control buses. Several older bus types were also available and were included in the analysis. Hybrid buses had the highest fuel economy for all time periods for all bus types. Hybrid buses had a fuel economy that was 11.8 percent higher than control buses overall, 12.2 percent higher than buses with model years 2007 and newer, 23.4 percent higher than model years 2004 through 2006, 10.2 percent higher than model years 1998 through 2003, 38.1 percent higher than model years 1994 through 1997, 36.8 percent higher than model years 1991 through 1993, and 36.8 percent higher for model years pre-1991.

On-road emissions were also compared for three of the hybrid buses and two control buses using a portable emissions monitor. On-average, carbon dioxide, carbon monoxide, and hybrid carbon emissions were much higher for the control buses than for the hybrid buses. However, on average nitrogen oxide emissions were higher for the hybrid buses.

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1. Executive Summary

1.1 Purpose of Study

Fuel costs are a significant portion of transit agency budgets. Hybrid technology offers an attractive option and has the potential to reduce operating costs for agencies significantly. The main impetuses behind use of hybrid transit vehicles are fuel savings and reduced emissions.

Laboratory tests have indicated that hybrid transit buses can have significantly higher fuel economy and lower emissions compared to conventional transit buses. However, the number of studies is limited and laboratory tests may not represent actual driving conditions given that in-use vehicle operation differs from laboratory test cycles.

Hybrid transit buses require a significant investment for transit agencies and early estimates of cost savings have not materialized to the extent that transit agencies expected. To justify the expenditure, agencies require more quantitative information about the on-road fuel economy and other costs for hybrid buses.

The objective of this project was to evaluate the in-use fuel economy and emission differences between hybrid-electric and conventional transit buses for the Ames, Iowa transit authority, CyRide. These CyRide buses were deployed in the fall of 2010.

Given the CyRide hybrid buses were first generation, some adjustments were made up until mid-summer of 2011. As a result, on-road fuel economy was evaluated over a 12 month period for the 12 hybrid transit and 7 control buses.

The hybrid diesel buses are 2010 Gillig low-floor buses with 280 HP and inline six-cylinder engines. The control buses are 2008/2010 Gillig low-floor diesel buses also with 280 HP and inline six-cylinder engines.

Fuel economy comparisons were also provided for several older bus types. Emissions were tested on-road using a portable emissions measurement system (PEMS).

1.2 Fuel Economy Assessment

Fuel economy for the hybrid buses was compared to regular buses. Data were collected as follows.

CyRide buses are usually fueled at the end of their service day when they return to the garage and technicians note the amount of fuel used (in gallons) and the odometer reading. CyRide’s fuel blend averages two percent biodiesel and buses are all fueled from the same tank.

Fuel and odometer data were provided to the team weekly or bi-weekly in a hard copy format and were entered into a separate worksheet for each bus. Each row of data represented one fueling period (which was usually one day).

Bus drivers record the number of passengers who embark on the bus each day manually, but do not record disembarking passengers or the time that riders enter the bus. As a result, total passengers per day (ridership) is available but not the number of passengers riding the bus at a given time.

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. Drivers are assigned to a particular route and buses are rotated through all routes. As a result, it was assumed that buses were randomly distributed across routes during the study period. The routes traveled by a bus during a fueling period are also recorded.

Initially the team recorded ridership and route pattern for each bus for each fueling period. However, entering this information manually for each bus and fueling period was far beyond project resources. As a result, it was decided to enter bus ridership and route pattern for one week each month for all buses. Consequently, the analysis described in section 1.2.1, which assessed vehicle operation variables, included only a sample of fueling periods. A more simplistic analysis of only fuel economy included all observations as described in section 1.2.1.

Fuel economy is highly correlated to vehicle operation (amount of time spent in a particular speed/acceleration range). As a result, global positioning system (GPS) data were collected for several different buses at several different times periods.

Data specific to each route were identified and this information was used to compute average speed metrics including average speed, average running speed, average acceleration, average deceleration, percent of time spent in acceleration, idle, or deceleration, and number of stops for each route.

Variables for each fueling period were obtained by weighting the corresponding variable by the number of times a particular route was driven during the fueling period.

Season was also included by assigning months in Iowa where weather is similar (spring, summer, fall, and winter) so that a measure of environmental characteristics could be included.

1.2.1 General Fuel Economy Analysis and Results

The researchers conducted a simplistic analysis that compared average fuel economy, bus type, and season without including vehicle operation variables first. This allowed analysis that included all fueling intervals for the 12 month period; whereas, the full analysis described in section 1.2.2 included only a sampling of fueling intervals.

In addition, because data for buses other than the control buses were also collected, the general analysis evaluated several types of buses. Buses other than the control and hybrid buses were grouped by model year corresponding to US diesel standards. Average fuel economy in miles per gallon (mpg) was calculated for each bus group overall and by season. A total of 5,746 observations were available for the 12 month analysis period.

Hybrid buses had the highest fuel economy for all time periods for all bus types. Hybrid buses had a fuel economy that was 11.8 percent higher than control buses overall and 12.2 percent higher than buses with model years 2007 and newer, 23.4 percent higher than model years 2004 through 2006, 10.2 percent higher than model years 1998 through 2003, 38.1 percent higher than model years 1994 through 1997, 36.8 percent higher than model years 1991 through 1993, and 36.8 percent higher for model years pre-1991.

Differences between groups of buses also varied by season. The hybrid buses had an average fuel economy that was 13.3 percent higher than control buses for fall, 16.4 percent higher for spring, 8.6 percent higher for summer, and 13.3 percent higher for winter.

Fuel economy was highest for almost all bus types in the spring. In addition, average fuel was lower in the summer for most bus types. In particular, average fuel economy for the hybrid buses was 14.4 percent higher for the spring than summer.

1.2.2 Fuel Economy Analysis with Vehicle Activity and Results

The researchers conducted a second analysis that included ridership and aggregate vehicle activity variables such as average speed, average acceleration, and so forth. Due to the significant amount of data reduction required to obtain or manually record the ridership and vehicle activity variables, only hybrid and control vehicles were included in the analysis. In addition, only one week of data was included for each bus. This resulted in 759 observations.

The researchers used a log-normal model to model fuel economy and bus characteristics. The best-fit model indicated that the covariates bus type, number of passengers per route, average running speed, average acceleration, average deceleration, percentage of time spent in acceleration, and season were statistically significant.

The model also indicated that season was relevant and that regular buses have an expected fuel economy that is 9.1 percent lower than hybrid buses. Fuel economy in the summer is 12.5 percent lower than expected in the spring while fuel economy in the fall is 3.1 percent lower than expected in the spring and fuel economy in the winter is 4.2 percent lower than expected in the spring.

Model results also showed that fuel economy is correlated positively with running speed. Consequently, as running speed increases, fuel economy also increases.

Fuel economy is correlated negatively with the number of passengers per route, average acceleration, average deceleration, and percent of time spent in acceleration. As a result, as the number of passengers per route, average acceleration, or average deceleration increases, fuel economy decreases.

1.3 Emissions Analysis

Emissions data were collected on-road using a PEMS, the Axion System from Clean Air Technologies International, Inc. (CATI). The system samples hydrocarbon (HC), carbon monoxide (CO), carbon dioxide (CO_2), and nitrogen oxide (NO_x) concentrations using a dual five-gas analyzer system. The system also has a GPS that reports speed and position. Data are output at one-second intervals.

Data were collected for three hybrid and two control buses. Testing of three control buses was planned originally. However, the equipment malfunctioned during data collection and there was not sufficient time to collect data for the third control bus.

Each bus was instrumented with the PEMS and emissions were collected for at least one operating bus day. The researchers evaluated each bus tested over the same route pattern. Each 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 number of passengers embarking or disembarking at each stop was collected by an on-board data collector so that passenger load could be included.

Vehicle emissions are correlated to instantaneous engine load demand, which is a function of factors such as speed, acceleration, road grade, and air conditioning use. Vehicle-specific power (VSP) has been used as a proxy variable for power demand or engine load. VSP is the instantaneous power per unit mass of the vehicle and passengers and is a function of velocity, acceleration, mass, grade, and road load coefficients. VSP was calculated for each row of data.

The instananeous data were stratified into the defined VSP bins and average emission rates and standard error were calculated for each bus for each pollutant.

At the lower VSP bin ranges, CO_2 emissions were low and comparable for the two bus types with differences within 0.2 g/s. In the middle VSP bin ranges, emissions were higher for control buses with differences between 0.3 and 0.4 g/s (9.4 to 27.3 percent higher). In the higher VSP ranges, emissions were significantly higher for control buses than for hybrid buses with differences between 0.7 and 2.7 g/s higher (15.0 to 97.0 percent higher).

Average CO emissions were higher for control buses than hybrid buses for all VSP bins. At the lower ranges, emissions were 0.5 to 0.9 mg/s higher for control buses compared to hybrid buses (86.4 to 142.2 percent higher). For all other VSP bins, control buses had CO emissions that were higher than hybrid buses by 1.0 to 3.1 mg/s (1.35 to 3.07 times higher).

Average HC emissions were higher for control buses than hybrid buses in all cases. Differences were less marked in the lower VSP ranges with increases between 0.3 and 0.8 mg/s. Control buses had HC emissions 1.2 to 1.8 mg/s higher in the mid-VSP ranges (68.5 to 131.0 percent higher). In the higher VSP ranges, HC emissions were much higher for control buses than hybrid buses by 2.3 to 3.0 mg/s (94.2 to 182.8 percent higher).

Average NO_x emissions were similar for the hybrid and control buses in the lower VSP ranges. In some cases, the control bus had higher NO_x emissions and in other cases, the hybrid bus had higher NO_x emissions. However, differences were within 0.7 mg/s. In the higher VSP bins, hybrid bus NO_x emissions are higher than the control bus. Differences ranged from 0.8 to 3.5 mg/sec (18.4 to 40.1 percent) higher.

1.4 Acknowledgments

The team would like to thank the Iowa Energy Center for funding this project and William Haman, the project monitor. We would also like to thank CyRide for all of their assistance in giving feedback, providing data, setting up emission and GPS data collection, and allowing us to conduct the study. In particular, we would like to thank Sheri Kyras, James Rendall, and Rich Leners for their assistance.

2. Introduction

Fuel costs are a significant portion of transit agency budgets. Hybrid buses offer an attractive option and have the potential to reduce operating costs for agencies significantly. Hybrid technology has been available in the transit market for some time.

More than 1,200 hybrid buses were in regular service in North America in more than 40 transit agencies as of 2009 (Transport Canada 2011). The majority are regular 40 foot buses, although some smaller (20 foot) shuttle buses and larger articulated (60 foot) buses are also in service. New York, New York had approximately 1,000 hybrid buses as of 2009 (Maynard 2009) and approximately 33 percent of Toronto, Canada's buses were hybrids in 2009 (Transport Canada 2011).

Hybrid technology offers an attractive option and has the potential to reduce operating costs significantly for agencies. The main impetuses behind use of hybrid transit vehicles are fuel savings and reduced emissions.

Wayne et al. (2009) estimated that use of diesel-electric hybrid buses in 15 percent of the US transit fleet could reduce fuel consumption by 50.7 million gallons of diesel annually. However, purchase of hybrid transit buses requires a significant investment for transit agencies given that a hybrid bus costs approximately 50 to 70 percent more than a conventional diesel bus (Hybrid Center 2010).

In addition, early estimates of cost savings may not have materialized to the extent that transit agencies expected. Other costs such as the cost of replacing the battery and reduced maintenance are also concerns that have not been substantiated in studies. To justify the expenditure, agencies require more quantitative information about the likely fuel economy, maintenance, and other costs/benefits with hybrid buses.

This report summarizes the results of a study that evaluated fuel economy and emissions for hybrid transit and control buses as part of the Ames, Iowa Transit Agency, CyRide. Fuel economy comparisons were also provided for several older bus types.

2.1 Background

A number of costs are important for transit agencies to consider in making the decision to invest in hybrid technology. A summary of known costs from the literature was cataloged in a companion technical brief titled Assessing the Costs for Hybrid versus Regular Transit Buses and that document provides information for transit agencies in considering this investment.

The study documented in this report focused on differences in fuel economy and emissions for hybrid-electric transit versus conventional buses. As a result, only information related to these two topics is covered in this report. The following sections summarize a survey of the literature relevant to differences in fuel economy and emissions for hybrid-electric buses compared to conventional transit buses.

2.1.1 General Fuel Economy Estimates

Actual savings depend on usage and fuel costs, but improved fuel economy is the main savings associated with use of hybrid transit buses. Early estimates of fuel savings for hybrid buses over conventional buses were based on laboratory studies that demonstrated significant fuel savings.

Laboratory tests, in general, have indicated that the fuel economy of hybrid transit buses is significantly better than for regular buses. Chassis dynamometer tests were conducted for 10 low-floor hybrid buses and 14 conventional high-floor diesel transit buses run by New York City Transit (Chandler and Walkowicz 2006).

Buses were evaluated over three driving cycles including the Central Business District (CBD), the New York bus cycle, and the Manhattan cycle. The operating costs, efficiency, emissions, and overall performance were also compared while both types of buses were operating on similar routes. The evaluation found that fuel economy was 48 percent higher for the hybrid buses.

A study by Battelle (2002) tested emissions using a dynamometer for one diesel hybrid-electric bus and two regular diesel buses (with and without catalyzed diesel particulate filters/DPFs). The researchers reported that fuel economy for the hybrid bus was 54 percent higher than the two regular diesel buses.

In another study, two buses were tested using a dynamometer at the National Renewable Energy Laboratory (NREL) Refuel facility in Golden, Colorado. One bus was a conventional diesel and the other was a hybrid bus and both were tested over several drive cycles including Manhattan, Orange County Transit A, CBD, and King County Metro. Results indicated 30.3 percent lower fuel use for the KCM cycle, 48.3 percent lower for the CBD cycle, 50.6 percent lower for the OCTA cycle, and 74.6 percent lower for the Manhattan cycle. Fuel economy was reported as miles per gallon.

In another study, Clark et al. (2006) evaluated six transit buses with traditional diesel engines, two powered by spark-ignited compressed natural gas (CNG), and one hybrid transit bus in Mexico City, Mexico using a mobile heavy-duty emissions testing lab. Buses were tested over a driving cycle representative of Mexico City transit bus operation, which was developed using GPS data from in-use transit buses. Depending on how fuel economy was evaluated, the hybrid bus ranked fourth and first in fuel economy.

Transport Canada (2011) summarized several studies that compared fuel economy for several transit agencies in Canada. In one laboratory study using the Manhattan Test Cycle, a reduction in fuel consumption of 36 percent resulted for hybrid buses as compared to regular buses.

Results of a test track study showed a 28 percent fuel reduction for hybrid transit buses compared to regular buses when the buses were operated at an average speed of 10 km/h with 10 stops per kilometer. As average speed increased, the differences in fuel consumption were smaller.

In a later test track study, results showed an average reduction of 28 percent in fuel use. However, the study also reported that the Toronto Transit Corporation, which has about 500 hybrid buses, was only achieving a reduction of 10 percent for in-use fuel consumption.

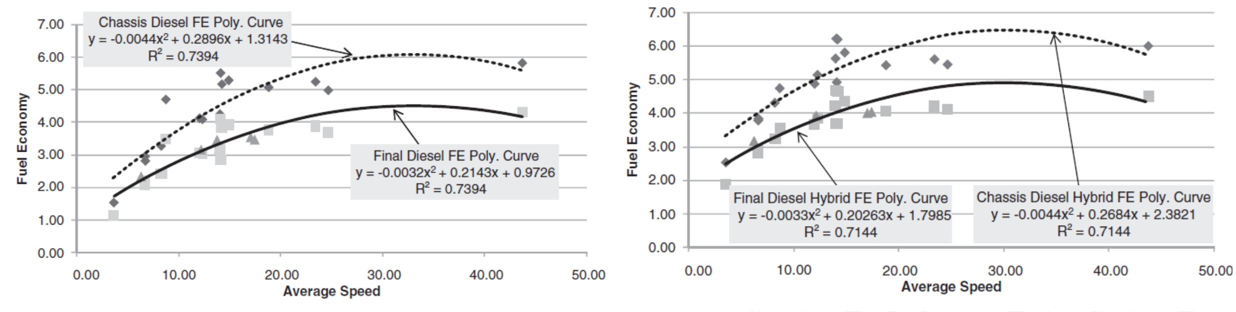
The Federal Transit Administration (FTA 2000) published a report on the status, current issues, and benefits of hybrid bus technology. The report summarized the experiences from four transit agencies in the US and found that hybrid buses had better fuel efficiency and accelerating and handling experience.

The overall fuel economy increases for New York City, Cedar Rapids, Iowa, and Los Angeles, California transit agencies were 18 percent, 15 percent, 5 percent, respectively. These values were significantly lower than fuel economy estimates that have been reported in laboratory studies.

Barnitt and Gonder (2011) collected school bus drive cycle data for a first-generation plug-in hybrid electric vehicle (PHEV) school bus and a conventional school bus. Both buses were tested over several different driving cycles to represent a range of driving activity.

When in charge-depleting mode, the PHEV had a fuel savings of more than 30 percent for the Ruban Dynamometer Driving Schedule for Heavy Duty Vehicles and Rowan University Composite School Bus drive cycles. Fuels savings of more than 50 percent were noted for the hybrid school bus for the Orange County Bus cycle. When in charge-sustaining mode, smaller fuel savings were noted.

Clark et al. (2009) evaluated chassis dynamometer and in-use fuel economy data for both hybrid-electric and conventional diesel buses and developed a relationship between speed and fuel economy as shown in Figure 2-1.



Conventional bus | Hybrid electric

Figure 2-1: Relationship between speed and fuel economy by bus type

2.1.2 Reduced Emissions

Reduced emissions are the second main benefit attributed to hybrid buses and a number of studies have indicated a substantial reduction in pollutants for hybrid buses over regular transit buses.

Wayne et al. (2009) conducted an evaluation scenario comparing use of hybrid transit buses to regular transit buses. The authors estimated that use of diesel-electric hybrid buses in just 15 percent of the US transit fleet could reduce annual emissions by 1,800 tons of carbon monoxide (CO), 400 tons of hydrocarbons (HC), 4,400 tons of nitrogen oxides (NO_x), 200 tons of particulate matter (PM), and 491,400 tons of carbon dioxide (CO_2).

Chandler et al. (2002) conducted chassis dynamometer tests for 10 low-floor hybrid buses and 14 conventional high-floor diesel transit buses run by New York City Transit (NYCT). The buses were tested over three driving cycles: the Central Business District (CBD), New York bus cycle, and the Manhattan cycle. The operating costs, efficiency, emissions, and overall performance were also compared while both types of buses were operating on similar routes.

Data were collected from 1999 through 2001. Results indicate that, for the CBD cycle, emissions for the hybrid transit buses were 97 percent lower for CO, 36 percent lower for NO_x, 43 percent lower for HC, 50 percent lower for PM, and 19 percent lower for CO_2. Results from the NY bus cycle showed a decrease of 56 percent for CO, 44 percent for NO_x, 77 percent for PM, and 40 percent for CO_2. HC emissions, however, increased by 88 percent for the hybrid buses. With the Manhattan cycle, the researchers found a decrease for the hybrid buses of 98 percent for CO, 44 percent for NO_x, 28 percent for HC, 99 percent for PM, and 33 percent for CO_2.

Emission tests for one diesel hybrid-electric bus and two diesel buses (Orion V, with and without DPFs) were evaluated using a dynamometer in Ottawa Canada (Battelle 2002).

The buses were tested on the CBD cycle using ultra-low sulfur diesel (ULSD) #1 fuel. The researchers indicated that the hybrid bus had 94 percent lower emissions for CO, 49 percent lower emissions for NO_x, 120 percent higher emissions for HC, 93 percent lower emissions for PM, and 37 percent lower emissions for CO_2 than the diesel bus without a catalyzed DPF.

Emissions for the hybrid bus compared to the diesel bus with the catalyzed DPF installed were 38 percent lower for CO, 49 percent lower for NO_x, 450 percent higher for HC, 60 percent lower for PM, and 38 percent lower for CO_2. Tests were conducted in February 2000.

In another study, two buses (one from a conventional diesel fleet and another from a hybrid fleet) were tested using a dynamometer at the National Renewable Energy Laboratory (NREL) ReFUEL facility in Golden, Colorado (Chandler and Walkowicz 2006).

The buses were tested over several drive cycles including Manhattan, Orange County Transit A, CBD, and King County Metro. Tests were conducted in May and June 2005. Results are shown in Table 2-1 for each drive cycle.

Table 2-1: Summary of NREL study showing hybrid versus regular bus percentages

Cycle	CO	NO_x	HC	PM	CO_2
Manhattan	NS	-38.7	NS	-92.6	-43.8
OCTA	-32.0	-28.6	NS	-50.8	-34.5
CBD	-48.0	-26.6	-75.2	-97.1	34.8
KCM	-59.5	-17.8	-56.3	NS	-24.1

NS = not statistically significant (data source: Chandler and Walkowicz 2006)

The table shows the percentage difference in emissions among the buses. Emissions were reported in grams per mile. As indicated, emissions were lower in all cases for the hybrid bus, except for the cases where the differences were not statistically significant (indicated as NS in the table).

Clark et al. (2006) evaluated six transit buses with traditional diesel engines, two powered by spark-ignited compressed natural gas (CNG), and one hybrid transit bus in Mexico City using a transportable heavy-duty emissions testing lab. Buses were tested over a driving cycle representative of Mexico City transit bus operation, which was developed using GPS data from in-use transit buses.

Depending on how emissions were compared, the hybrid bus and one of the CNG buses had the lowest NO_x emissions of the nine buses tested. Particulate emissions from the hybrid bus were less than 10 percent of the average PM emissions for the diesel-powered buses. The hybrid bus and one of the CNG buses had the lowest CO emissions, and the hybrid bus and buses equipped with CRT exhaust after-treatment had hydrocarbon emissions that were below the detectable limit of the instrument used.

Shorter et al. (2005) used a chase vehicle sampling strategy to measure NO_x from 170 in-use New York City transit buses. The authors sampled emissions from conventional diesel buses, diesel buses with continuously regenerating technology, diesel hybrid-electric buses, and CNG buses. The authors found that NO_x emissions from CNG buses and hybrid buses were comparable. NO_x emissions for the hybrid buses were approximately half of those for conventional transit buses.

In contrast, Jackson and Holmen (2009) collected second-by-second particle number (PN) emissions from four conventional and one hybrid transit buses in Connecticut over six pre-defined test routes that had multiple road types and ranges of driving conditions. For most of the routes, few differences were noted between the conventional and hybrid transit buses. However, the hybrid had higher emission rates on two routes with steep uphill grades, and PN emissions were 51 percent higher on one route and 24 percent higher on the other.

Choi and Frey (2010) evaluated emissions for a parallel-hybrid diesel-electric school bus (PHSB) and conventional school bus using a portable emissions monitor. Results were presented by type of route.

Depending on the route, the researchers found 1.4 to 8.7 percent lower $C0_2$ tailpipe emissions for the PHSB than for the conventional school bus; 3.3 to 8.5 lower NOx emissions; a 0.1 to 3.6 percent reduction in HC tailpipe emissions for all except one route (with that route having 0.4 percent higher HC emissions than the PHSB); a 0.6 to 5.4 reduction for CO tailpipe emissions; a 1.3 to 8.7 percent decrease in sulfur dioxide ($S0_2$) tailpipe emissions; and a 5.1 to 17 percent decrease in PM tailpipe emissions.

Wayne et al. (2004) evaluated three transit vehicles: a series drive hybrid-electric bus, conventional drive diesel-powered buses, and a conventional drive liquid nitrogen gas- (LNG-) powered bus. The researchers evaluated the buses on a dynamometer over several cycles.

In all cases, the conventional diesel-powered bus had the highest NOx emissions. The hybrid had the lowest NOx emissions, which were 52 percent, 60 percent, 42 percent, and 45 percent lower for the Manhattan, urban dynamometer driving schedule (UUDS), OCTA, and CBD, respectively.

PM emissions were about 90 percent lower for all cycles. The hybrid electric bus had CO emissions that were 73 percent, 47 percent, 82 percent, and 72 percent lower for the Manhattan, UDDS, OCTA, and CBD drives, respectively. CO emissions for the hybrid bus were below the detectable range for the equipment and were reported as 98 percent lower than the conventional diesel bus.

Although significant reductions in emissions have been reported, it is difficult to allocate costs to pollutant reduction. One factor in selection of the hybrid technology is political, social, and environmental pressure to reduce emissions, improve health, and conserve energy.

Social costs associated with reduction in emissions and improved health are difficult to quantify, making it difficult to include emission reduction in long-term cost analyses. However, agencies in non-attainment areas for criteria pollutants have some methods to quantify costs.

A report by the Transit Cooperative Research Program (TCRP 2000), for instance, estimated a value of $1,000 per ton of NO_x reduced and a $3,000 per ton for VOCs. In addition, one problem for use of cost-reduction benefits involving pollutants is that cost savings are not usually accrued to the transit agency, making it more difficult to assess long-term agency costs/benefits.

2.2 Project Objectives

Laboratory tests have indicated that hybrid transit buses can have significantly higher fuel economy compared to conventional transit buses. However, the number of studies is limited and laboratory tests may not represent actual driving conditions given in-use vehicle operation differs from laboratory test cycles.

Several initial studies have suggested that the fuel economy savings reported in laboratory tests may not be realized on-road.

The objective of this project was to evaluate the in-use fuel economy and emission differences between hybrid-electric and conventional transit buses for the Ames, Iowa transit authority, CyRide. The buses were deployed in the fall of 2010. The team began tracking the buses July 1, 2011 and continued tracking the buses through August 31, 2012.

The project also developed outreach materials, which can be used by Iowa agencies and others to determine the feasibility of using hybrid transit buses and make long-term investment decisions. This information is found in a supporting document entitled Assessing the Costs for Hybrid versus Regular Transit Buses.

2.3 Study Background

CyRide, the city bus system for Ames, is operated through collaboration between the city and Iowa State University (ISU). CyRide reported 5,447,289 passengers for fiscal year 2011 and posted 1,185,089 revenue miles (CyRide 2012).

CyRide operates about 79 buses and purchased 12 hybrid transit buses, as shown in Figure 2-2, using a Transportation Investments Generating Economic Recovery (TIGER) grant.

Figure 2-2: CyRide's hybrid bus, termed a "CYBRID"

The grants were made available pursuant to the American Recovery and Reinvestment Act of 2009, which funded programs to decrease energy use and reduce greenhouse gas emissions. The grant allowed funds to offset purchase of the hybrid buses but not to evaluate them.

An evaluation of the buses was important because there is no well-documented information about the pay-off for hybrid buses that can be used by Iowa agencies considering a similar investment. As a result, the Iowa Energy Center (IEC) sponsored this research, which evaluated the fuel efficiency and emission impacts of the hybrid buses.

In addition to the 12 hybrid buses, 7 regular diesel buses were selected from among regular diesel buses in the CyRide fleet. These control buses were selected because they have very similar bus specifications to the hybrid buses in terms of manufacturer, model year, and engine size. Bus specifications are listed in Table 2-2.

Table 2-2: Specifications of both hybrid diesel buses and conventional diesel buses

	Hybrid Diesel Buses	Conventional Diesel Buses
Bus Number	118, 119, 120, 121, 122, 123, 124, 429, 430, and 431	819, 820, 821, 822, 126, 127, and 128
Model Year	2010	2008/2010
Capital Cost	$521,970	$367,115
Manufacture	Gillig Hybrid	Gillig
Bus Type	Low Floor	Low Floor
Engine	Cummins '10 ISL 280 HP, inline six-cylinder	Cummins '10 ISL 280 HP, inline six-cylinder
Transmission	Voith DIWA Parallel Hybrid	Voith D864.5 4-speed
After treatment	Catalyzed Particulate Filter (CPF)	Catalyzed Particulate Filter (CPF)
Governed Speed	65 mph	65 mph
Start Date	6/28/2010	6/28/2010
Frontal Area	113.5 x 102 foot	113.5 x 102 foot
Length x Height	40 foot x 138 in.	40 foot x 138 in.
Curb Weight	29,500 lbs	25,000 lbs

Fuel economy was also tracked for other buses in the CyRide fleet, although those buses vary in characteristics. Comparison to other buses was done so that CyRide could compare the hybrids to the rest of their fleet, as well as assess how much improvement was gained over buses that were replaced by the hybrid buses.

Other buses were grouped into model years corresponding to US diesel standards given that engines from years with the same engine standards would have similar emission control technology, which can affect fuel consumption. Buses were grouped as shown in Table 2-3.

Table 2-3: Specifications for other buses tracked for fuel economy

Standard Year	Buses	Bus Types
Pre-1991	941, 942, 943, 17, 18, 967, 990	GMC—1973; Orion V—1989
1991-1993	111,112, 113, 115, 116, 117	Gillig Phantom —1993
1994-1997	139, 140, 141, 142, 143, 933, 934	Gillig Phantom—1996; Gillig Phantom—1997
1998-2003	944, 945, 946, 947; 953; 954; 955; 956; 957; 958, 970; 971, 972; 973; 974, 975, 976, 977	Gillig Low Floor—1999; Orion V—2000; Orion V—2002
2004-2006	1, 2, 3, 4, 994, 995, 996, 997	Orion V—2005; Orion VII—2006
2007+	819, 820, 821, 822	Gillig Low Floor—2008

US diesel engine standards cover 1991 through 1993, 1994 through 1997, 1998 through 2003, 2004 through 2006, and 2007 and higher (USEPA 2012). Buses were included if they were operated for the majority of at least two months. Several buses were used for only a very limited period during the analysis period and were not included in the analysis.

2.3.1 Bus Route Information

CyRide operates with 12 fixed routes. The fixed routes operate every day of the year except for Thanksgiving, Christmas, and New Year's Day. CyRide rotates buses into and off the system to meet peak travel demands. Buses are driven over several routes according to a prescribed schedule (route pattern), depending on when each bus comes into and leaves the system. In general, the buses are cycled randomly through the various route patterns.

2.3.2 Updates to Hybrid Buses

The hybrid-electric buses were in use by fall 2010. Initially, CyRide was not finding that the hybrid buses were performing as expected. The hybrid buses were the first ones in production and, as a result, experienced some early issues. Consequently, the manufacturer made several adjustments.

Major adjustments that were made in June 2011 and early July 2011 were to fix the brake pedals, which affects the capture of regenerative energy directly. Programming was also adjusted to increase fuel economy as noted in Table 2-4.

Table 2-4: Bus fixes/adjustments

Date	Fix/Adjustment
6/22/2011	Fixed electronic brake pedals on two buses
7/5/2011	Fixed electronic brake pedals on two buses
7/15/2011	Fixed rest of brake pedals and installed new programming for all buses
9/12/2011	Fixed all braking pedals on all buses
12/9/2011	Replaced two software programs, changed the shifting routing on eight buses, changed braking pedal on four buses
12/30/2011	Braking pedal charging software
2/10/2012	Minor changes for transmission

The team collected data prior to July 2011. However, given fairly significant changes occurred in June and July, the researchers did not include the earlier data in their final analysis.

3. Fuel Economy Analysis

3.1 Data Collection

Data to be included in the fuel economy analysis were either recorded by CyRide (i.e., fuel use) and reported to the research team or collected by the team (i.e., GPS data).

3.1.1 Data Reported by CyRide

CyRide buses are usually fueled at the end of the service day when returned to the garage. Each time a bus is fueled is referred to as a fueling period. CyRide technicians note the amount of fuel used in gallons and the odometer reading in miles for each fueling period. Differences in odometer readings between fueling periods represents the operating mileage during the period (between fueling), which in most cases was one day.

CyRide uses an average of a two-percent-blend of biodiesel. Buses are all fueled from the same tank. Fuel and odometer data were provided to the team each week in a hard-copy format. Data were entered manually into a spreadsheet with date, bus number, fuel used, and odometer reading. One row of data represented one fueling period.

In addition to fuel used and odometer readings, the team originally thought that technicians also kept track of maintenance events and all major changes to all buses. Maintenance includes preventive maintenance, unscheduled maintenance, and road calls (date of repair, labor hours, number of days out of service, odometer reading, parts replaced, parts cost, and description of problems reported and actual repair performed).

However, due to the method used by CyRide to maintain regular maintenance, this data could not be extracted without significant effort by CyRide, which was already expending a number of resources to provide fueling information and assisting with emissions testing and other project-related data collection. As a result, although the original intent was to track maintenance for the hybrid and control buses and compare differences in costs, it was not feasible to do so.

CyRide also tracks the following other variables, which were also made available to the team in hard copy.

Route: 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. Drivers are assigned to a particular route.

By law, buses are rotated through all routes so that no route within the service area consistently receives older buses for social equity reasons. As a result, it was assumed that buses were somewhat randomly distributed across routes during the study period.

The number of routes and the specific routes covered by each bus for each fueling period were reported by CyRide.

Ridership: Because most passengers (ISU students) are free riders, CyRide does not have an automated fare system. Consequently, CyRide does not track riders by stop. Bus drivers record (manually) the number of passengers who enter the bus, but do not record location or time of embarkation or disembarkation. Given that no temporal information was provided, actual load could not be ascertained.

The team received the ridership logs for each bus and data recorders had to sum the number of passengers for each bus from the hard-copy log.

3.1.2 Data Collected by the Team

Variables such as traffic operation, road characteristics (i.e., grade), and weather will affect fuel economy. Roadway and traffic characteristics could not be collected realistically. Weather was indicated by season of the year. Quarters were designated using the following convention, which aggregates months where weather conditions were most likely to be similar in Iowa:

- Winter: December, January, and February
- Spring: March, April and May
- Summer: June, July, and August
- Fall: September, October, and November

Fuel economy is highly correlated to vehicle operation (amount of time spent in a particular speed/acceleration range). As a result, GPS data were collected to provide some measure of vehicle operation.

Ideally, GPS data would have been collected for each vehicle on a daily basis. However, given the analysis period was over 12 months and data were collected for more than 70 buses, it was not feasible to purchase sufficient GPS equipment to record data for every bus every day. In addition, the resources to download GPS data and reduce data for even the 12 test and 7 control buses on a daily basis were not feasible.

It was decided to collect data for several different buses at several different time periods using GPS data. Data specific to each route were identified and this information was used to compute average speed metrics for each route as described in the following section.

Six GPS data loggers (CP-Q 1100 Ps) were installed on a sample of buses as shown in the Table 3-1.

Table 3-1: GPS data collection

Dates	Duration	Buses						Routes
Nov. 29, 2011 ~ Dec. 12, 2011	10 days	126	127	128	129	130	131	1, 2, 3, 6 , 21, 23
Feb. 20, 2012 ~ Feb. 24, 2012	5 days	136	997	953	974	976	977	5, 7, 22
April 23, 2012 ~ April 27, 2012	5 days	128	129	130	997	976	977	7, 22

The data logger had a 40 hour battery life and memory storage up to 400,000 records (rows of data). GPS data were collected for the six buses at three different intervals so that the data collected would be representative of different times of the year.

Data were collected 19 days over the following times:

- November 29, 2011 ~ December 12, 2011
- February20, 2012 ~ February 24, 2012
- April 23, 2012 ~ April 27, 2012

The data loggers were installed, as shown in Figure 3-1, on the buses each morning and collected data during normal bus operation.

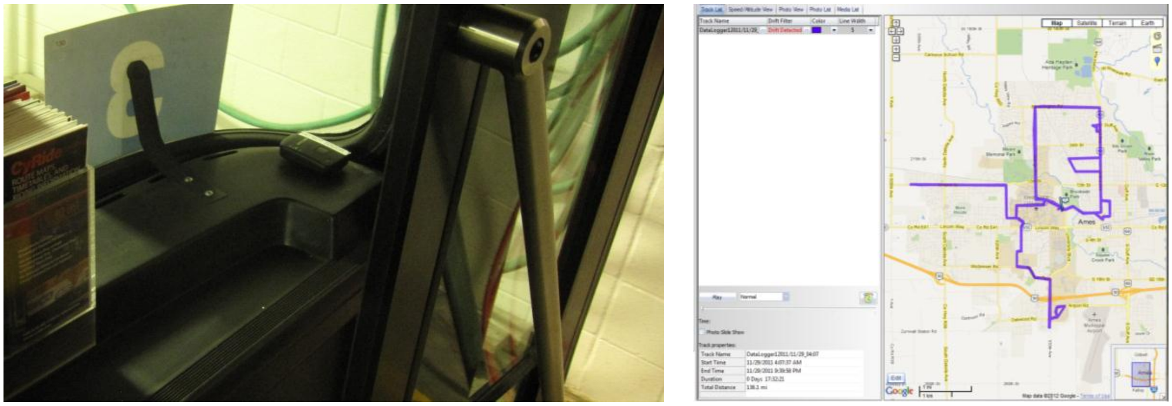


Figure 3-1: GPS data logger installed in bus (left) and GPS data integrated in a GIS (right)

At the end of each service day, the GPS data were downloaded into a geographic information system (GIS) and checked for data quality issues. Data were reported at one-second intervals (1 Hz). Although the buses were supposed to operate over a scheduled route pattern, some unexpected events occurred occasionally. The GPS data were inspected visually and route pattern deviations noted. For example, if a bus terminated a route and returned to the garage, that trip was eliminated.

Data points corresponding to each route were determined by overlaying route maps and GPS runs. This information was used to disaggregate data by route.

Given the way CyRide assigns buses for the range of route patterns, each bus traversed a majority of the routes several times over the course of the 20 days. Overall, 65 drivers were recorded during the 20 day GPS data collection.

Average Speed: Speed in miles per hour (mph) was an output from the GPS and was reported for each 1 second interval. Belliss (2004) evaluated the accuracy of several commercial GPS data loggers and found the accuracy of speeds was within 0.12 mph, while the accuracy of acceleration was within 0.22 mph/s. Average speed for each CyRide route was calculated by averaging speed across all of the data points and all runs, which corresponded to a particular route.

Average Running Speed: Average running speed in mph was calculated by removing data points where speed was equal to 0 and then averaging speed across all of the data points and all runs, which corresponded to a particular route. As a result, average running speed did not include time spent idling.

Acceleration: Acceleration in miles per hour per second (mph/s) for each data point was calculated as the change in speed over the change in time from the previous data point. Average acceleration was calculated by averaging acceleration across all of the data points and all runs, which corresponded to a particular route. Data points when acceleration was less than or equal to 0 (deceleration or idle) were not included.

Deceleration: Deceleration in mph/s for each data point was calculated as the change in speed over the change in time from the previous data point. Average deceleration was calculated by deceleration across all of the data points and all runs, which corresponded to a particular route. Data points when acceleration was greater than or equal to 0 (acceleration or idle) were not included.

Percent Acceleration: The amount of time spent in acceleration for each route was calculated by dividing the number of data points for a particular route where acceleration was ≥ 1 mph/s by the total data points for the route. The threshold of 1 mph/s was selected given visual inspection of the data suggested that values less than 1 mph/s were “noise” rather than representing actual acceleration.

Percent Deceleration: The amount of time spent in deceleration for each route was calculated by dividing the number of data points for a particular route where acceleration was ≤ -1 mph/s by the total data points for the route. The threshold of -1 mph/s was selected for the same reason given above.

Percent Cruise: The amount of time spent in cruise was calculated by dividing the number of data points for a particular route where speed > 0 and the speed differential between two successive data points was ≤ 1 mph/s by total data points for the route.

Percent Idle: The amount of time spent idling was calculated by dividing the number of data points for a particular route where speed was ≤ 1 mph/s and the speed differential between two successive data points was ≤ 1 mph/s by total data points for the route.

Total Stops: Total number of stops was calculated by summing all incidents where the bus came to a complete stop.

Variables for each fueling period were obtained by weighting the corresponding variable by the number of times a particular route was driven during the fueling period.

3.1.3 Data Reduction

Data were entered by fueling period by bus. Consequently, each row of data (observation) was one fueling period for a particular bus. Bus number, date, fuel used, and odometer reading were available for all observation periods included.

Data were reviewed to ensure data quality. Outliers were identified and, if they appeared to indicate erroneous data, the data were removed. For instance, odometer readings or fuel economy that clearly did not make sense were removed.

Initially, the team recorded ridership and route pattern for each bus for each fueling period. After several months, it became obvious that entering this information manually for each bus and fueling period was far beyond project resources. Entering ridership and route data for each bus for each fueling period required approximately 60 minutes. Given this time commitment greatly exceeded project results, it was decided to enter bus ridership and route pattern for one week each month for all buses. Consequently, the full statistical analysis included only a sample of fueling periods. However, a more simplistic analysis of only fuel economy included all observations.

3.2 General Fuel Economy Analysis and Results

In addition to the hybrid and control buses, other buses were grouped by model year corresponding to US diesel standards as shown in Table 3-2. Data were further disaggregated by season as described by section 3.1.2. Fuel economy (in miles per gallon/mpg) for each observation was calculated by dividing miles driven during the fueling period by total gallons used.

Average fuel economy was calculated for each bus group overall and by season and results are shown in Figure 3-2.

Average fuel economy by bus group by season is shown along with the standard error. As shown, hybrid buses had the highest fuel economy for all time periods. Hybrid buses had a fuel economy that was 11.8 percent higher than control bus for all times periods and 12.2 percent higher than buses with model years 2007 and newer, 23.4 percent higher than model years 2004 through 2006, 10.2 percent higher than model years 1998 through 2003, 38.1 percent higher than model years 1994 through 1997, 36.8 percent higher for model years 1991 through 1993, and 36.8 percent higher for model years pre-1991.

Differences between groups of buses also varied by season. Fuel economy was highest for almost all bus types in the spring. In addition, average fuel was lowest in the summer for most bus types. In particular, average fuel economy for the hybrid buses was 14.4 percent higher for spring than for summer.

The hybrid bus had an average fuel economy that was 1.3 percent higher than control buses for fall, 16.4 percent higher for spring, 8.6 percent higher for summer, and 13.3 percent higher for winter.

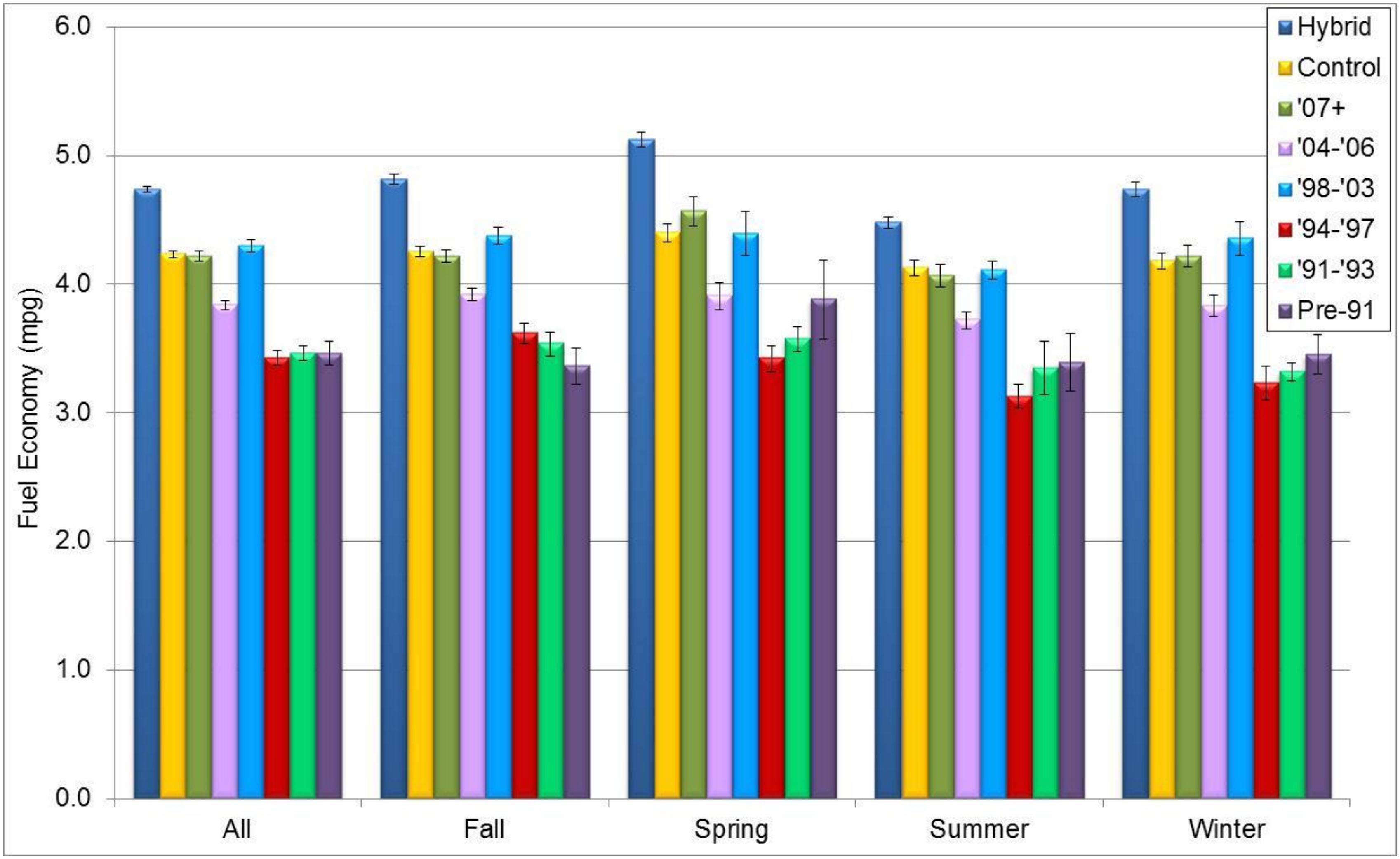


Figure 3-2: Average fuel economy (miles per gallon) by season by bus group

3.3 Fuel Economy Analysis with Vehicle Activity

A second analysis was conducted that included ridership and aggregate vehicle activity variables as described in section 3.1. Due to the significant amount of data reduction to obtain the ridership and vehicle activity variables, only hybrid and control vehicles were included in the analysis.

In addition, as noted in section 3.1, due to the significant amount of data reduction to include these variables, only one week of data was available for each bus. This resulted in 759 observations (rows of data).

A lognormal model was developed using the variables noted in Table 3-2.

Table 3-2: Explanatory variables used in fuel economy model

Variable	Description
Bus Type	Type of bus
Route	Number of routes driven during fueling period
Passengers	Number of passengers during fueling period
Season	Winter (December, January, February) Spring (March, April, May) Summer (June, July, August) Fall (September, October, November)
AvgSpeed	Average speed (mph) weighted over routes driven during fueling period
AvgRunSpeed	Average running speed (mph) weighted over routes driven during fueling period
Accel	Average acceleration (mph/s) weighted over routes driven during fueling period
Decel	Average deceleration (mph/s) weighted over routes driven during fueling period
PerAccel	Average amount of time spent in acceleration weighted over routes driven during fueling period
PerDecel	Average amount of time spent in deceleration weighted over routes driven during fueling period
PerIdle	Average amount of time spent in idling weighted over routes driven during fueling period
Stops	Average number of stops weighted over routes driven during fueling period
Pass/Route	Average number of passengers per route weighted over routes driven during fueling period

The model was fit to the aggregated data and mileage was used as an offset as indicated in equation 3-1:

$$\log(y_j) = \log(z_j) + \sum_i \beta_i x_{ij} + \varepsilon_j \qquad \textbf{(3-1)}$$

where y_j is the amount of fuel consumed for a bus j for a particular fueling period, z_j is the mileage driven during the fueling period and x_{ij} represent covariates. The final model included covariates, which were statistically significant at the 90 percent level of confidence.

The final model statistics are provided in Table 3-3.

Table 3-3: Best-fit model parameters

Parameter	Estimate	Pr < | z |
Intercept	1.279	0.333
Bus type (Regular vs. Hybrid)	-0.095	1.63e-12
Pass/Route	-0.002	0.009
AvgRunSpeed	0.068	0.002
Accel	-2.300	0.023
Decel	-1.985	3.54e-06
PerAccel	-3.372	0.0795
Summer vs. Spring	-0.134	4. 98e-11
Fall vs. Spring	-0.032	0.082
Winter vs. Spring	-0.043	0.013

The impact of the covariates can interpreted in the following way. The difference between regular bus and hybrid bus fuel economy is given by the following:

$e^{(-0.095)} = 0.909$

so, regular buses have fuel economy that is (1-0.909) or 9.1 percent lower than hybrid buses. This result is similar to the result for the more simplistic analysis, which showed that the fuel economy of control buses was 10.6 percent lower than the hybrid buses.

The impact of summer versus spring is given by the following:

$e^{(-0.134)} = 0.875$

so, expected fuel economy in the summer is (1-0.875) or 12.5 percent lower than expected fuel economy in the spring. This result is similar to the results for the simple analysis, which showed that fuel economy for hybrid buses was 12.6 percent lower in the spring than in the summer and 6.3 percent lower in the summer than spring for control buses.

The impact of fall versus spring is given by the following:

$e^{(-0.032)} = 0.967$

so, expected fuel economy in the fall is (1-0.967) or 3.1 percent lower than expected fuel economy in the spring. Results for the more simplistic analysis showed that hybrid buses had 6.0 percent fuel economy for fall compared to spring and control buses had 3.4 percent lower.

The impact of winter versus spring is given by:

$e^{(-0.043)} = 0.958$

so expected fuel economy in the winter is (1-0.958) or 4.2 percent lower than expected fuel economy in the spring. For the more simplistic analysis, fuel economy was 7.5 percent and 5.0 percent lower for winter than spring for hybrid and control buses, respectively.

Model results also indicate that fuel economy is correlated positively with running speed. Consequently, as running speed increases, fuel economy also increases.

Fuel economy is correlated negatively with the number of passengers per route, average acceleration, average deceleration, and percent of time spent in acceleration. As a result, as the number of passengers per route increases, average acceleration increases, or average deceleration increases, fuel economy decreases.

4. On-Road Emissions Analysis

Although not within the mission of the Iowa Energy Center, CyRide had requested an emissions analysis given this information is also required by the TIGER program. The goal of the TIGER grants was both improved fuel economy and reduction of greenhouse gas emissions. Other Iowa agencies that utilize similar grants would also need to demonstrate the emissions impacts of the investment.

4.1 On-Road Emissions Data Collection

Data were collected using a portable emissions monitoring system (PEMS), the Axion System from Clean Air Technologies International, Inc. (CATI) (www.cleanairt.com) as shown in Figure 4-1.

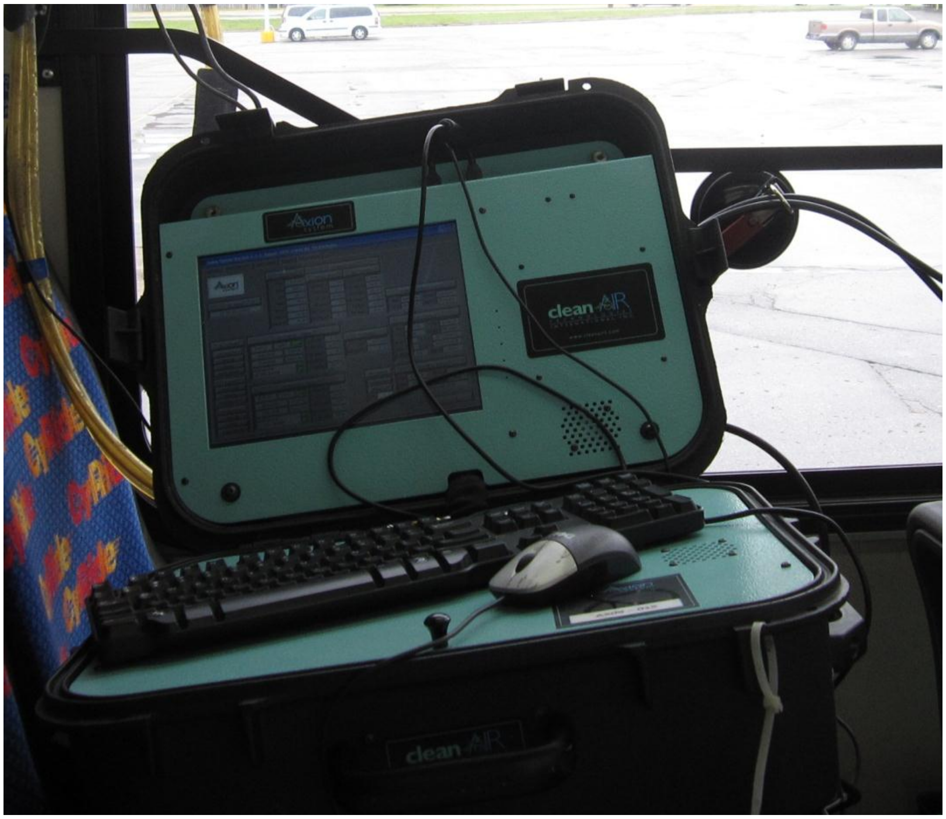


Figure 4-1: PEMS installed on CyRide bus

The PEMS is equipped with a computer and can be installed quickly 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.

The system also has a GPS to record the spatial position of the vehicle being tested, which can be used to locate where the vehicle was on the roadway during testing.

HC, CO, CO_2, O_2, and NO_x concentrations are sampled using a dual five-gas analyzer system using a tailpipe probe as shown in Figure 4-2.

Figure 4-2: PEMS tailpipe probe on CyRide bus

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) conducted a number of on-road emissions tests using the OEM 2100 and indicated that the precision and accuracy of the equipment is comparable to that of laboratory instrumentation. The authors indicated that CO and CO_2 are accurate to within 10 percent when compared to the measurement of average emission rates for dynamometer tests. The researchers also indicate that NO is measured using an electrochemical cell in the PEMS and reported that NO reported as equivalent NO^2 was accurate to ± 10 percent. 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 (Frey et al. 2008).

Data were collected for three hybrid and two control buses (see Figure 4-3).

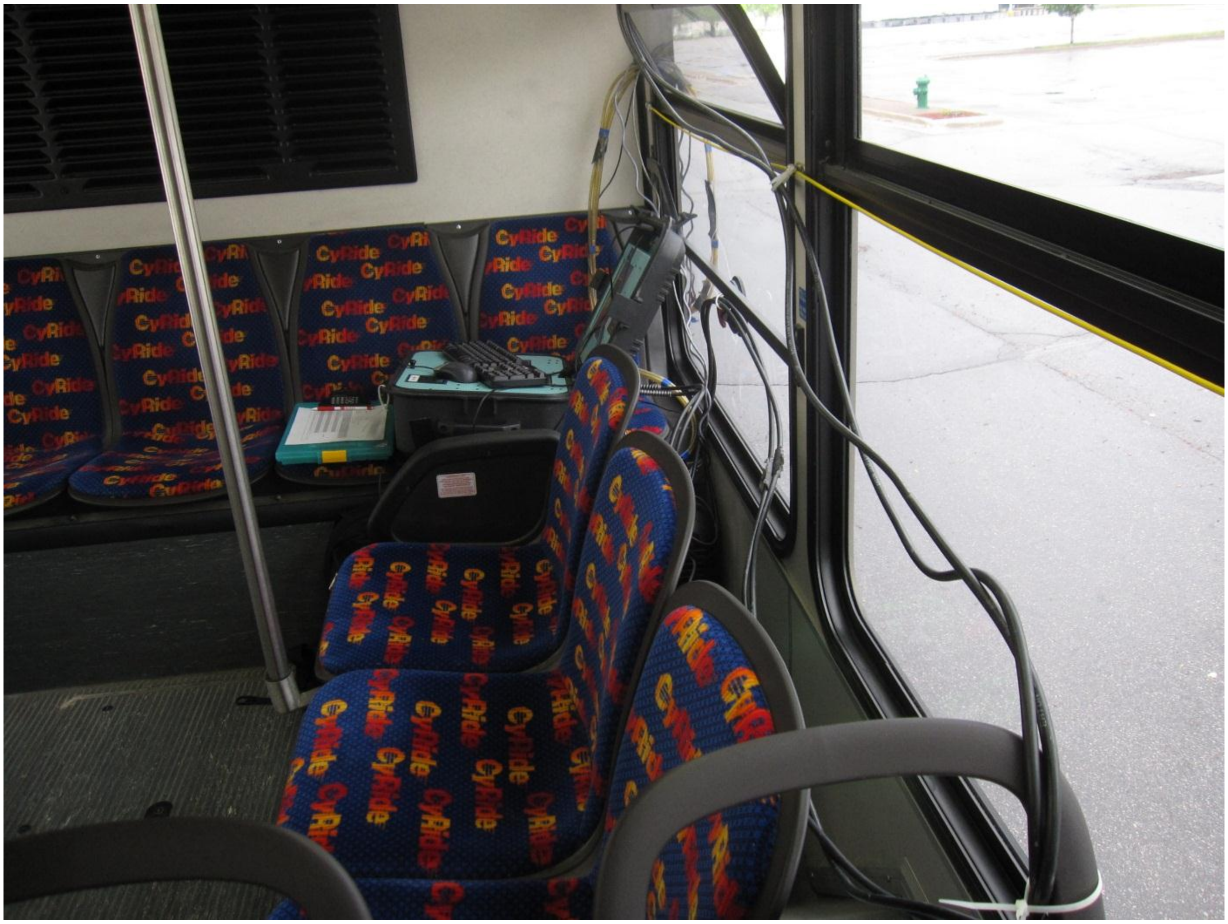


Figure 4-3: PEMS installed on CyRide bus

Originally, testing three control buses was planned. However, the equipment malfunctioned during data collection for the third control bus and the PEMS had to be shipped back to the manufacturer. By the time the equipment could be fixed, it was well into summer and weather conditions were significantly different from when data were collected for the other buses (early spring).

Each bus was instrumented with the PEMS and emissions were collected for at least one operating bus day. In some cases, issues arose with the equipment and data were collected additional days.

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 each 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 (shown in Figure 4-4) used for testing started around 7:30 a.m. and returned to the garage around 5:30 p.m.

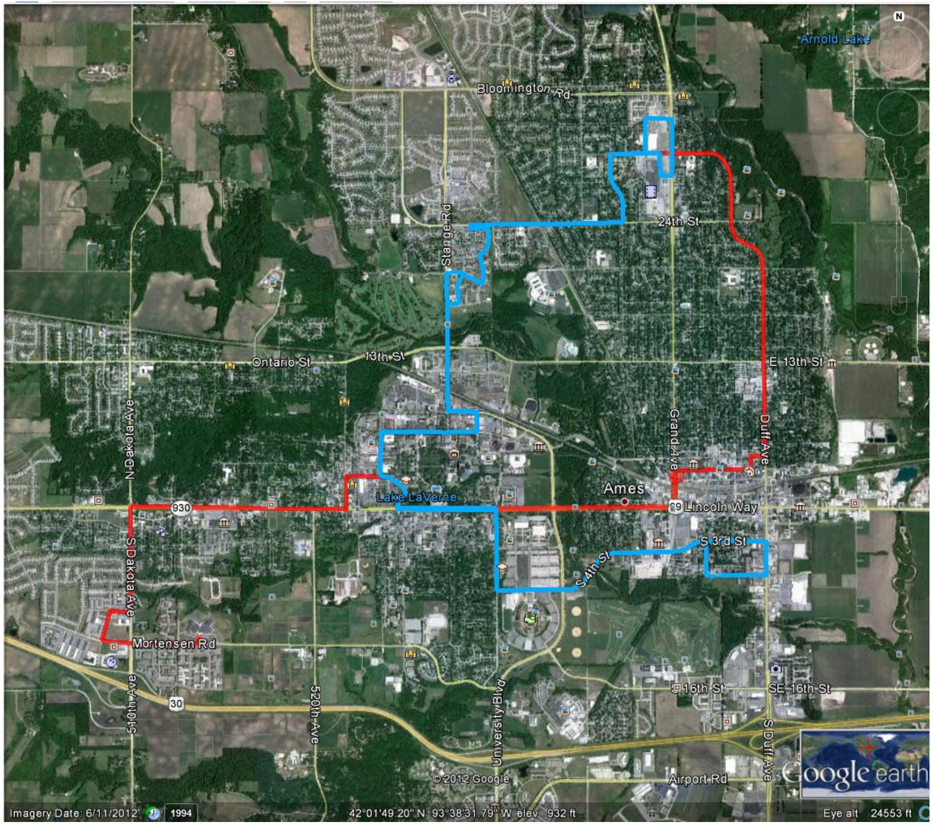


Figure 4-4: Route pattern used for emissions analysis

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 section through a residential area
- An arterial section with regularly-spaced signals

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.

A data collector was present with the equipment at all times. The data collector monitored the equipment for problems and also recorded information such as time and number of passengers who entered or exited the bus at each stop. Data were collected approximately from 8 a.m. to 4:30 p.m. each day. All emissions data were collected in April 2012.

The PEMS was cleaned and calibrated according to manufacturer specifications, which was typically every one to two days. Data were downloaded at the end of each day of data collection.

4.2 On-Road Emissions Data Reduction

The PEMS outputs emissions, GPS, and other data, such as manifold absolute pressure (MAP), on a second-by-second basis. A worksheet was created for each bus using output from the PEMS. Each observation output (row) represented one second of data. Speed and acceleration were calculated by the system's GPS.

Ridership data were collected to the nearest second and were synchronized with the PEMS datasets using time stamp and bus stop. As a result, each row of data had a corresponding passenger load.

Each worksheet was reviewed to ensure data quality. Because a large number of errors can occur with PEMS, each row of data in each sheet was checked manually. The data preparation and quality assurance methodologies are described below. Data were corrected when possible and invalid data were removed when they could not be resolved.

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 CATI during the course of data collection.

Frey et al. (2001) have conducted a number of studies with equipment similar to that used in this study. 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 to 15 percent. The leading causes were inter-analyzer discrepancies, analyzer freezing, and air leaking (which is manifested in very low pollutant concentrations). The authors 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 percent of the raw data (Frey et al. 2008).

4.2.1 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 below under Negative Emissions Values.

4.2.2 Computer Errors

Because 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 noted. It was not uncommon for the system to freeze. CATI indicated the proper procedure to follow when the system froze. Given data collectors were present, this problem was usually spotted immediately and the system was restarted. Because the system saves the data file, there were no instances of lost data.

4.2.3 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 a number of instances when the equipment reported NA instead of the corresponding emission value. When this occurred, the entire row of data was removed.

4.2.4 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 0. This occurs during zeroing when the reference air has significant amounts of a pollutant, resulting in negative emissions.

Frey et al. (2001) indicated when negative values occurred that could not be attributed to measurement error, the emissions were assumed to be 0. If the frequency and magnitude of 0 or negative values was large, the authors were led to suspect 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 0, those data cells were not used. This was a common problem with HC emissions. In a discussion with CATI, they indicated that because 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 0, and this solution was discussed, but the researchers decided to discard the data cells.

4.2.5 Equipment Malfunction

Several equipment malfunctions occurred over the course of the data collection. Hoses also came loose occasionally, and fuses blew. 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.

4.2.6 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.

4.3 Emissions Analysis

Vehicle emissions are correlated to instantaneous engine load demand, which is a function of factors such as speed, acceleration, road grade, and air conditioning use. Vehicle-specific power (VSP) has been used as a proxy variable for power demand or engine load (Frey et al. 2007, Zhai et al. 2008). VSP is the instantaneous power per unit mass of the vehicle.

Huai et al. (2005) indicate that the advantages of using VSP as an independent variable for studying hot-stabilized emissions are that specific power can be measured directly, it captures most of the dependence of emissions on engine operating parameters, and certification driving cycles can be specified in VSP.

After passenger data were entered and data quality assurance was completed, VSP was calculated for each row of data using equation 4-1 (USEPA 2010):

$$\mathrm{VSP} = (\mathrm{A}/M)*v + (\mathrm{B}/M)*v^2 + (\mathrm{C}/M)*v^3 + (a + g*\sin ø)*v \qquad \textbf{(4-1)}$$

where:

VSP = vehicle specific power in kW/metric ton
v = velocity in meters/second
M = mass in metric tons
g = acceleration due to gravity (9.8 m/sec^2)
a = acceleration in meters/second^2
sinø = fractional road grade
A = road load coefficients for rolling resistance (kilowatt Second/meter)
B = road load coefficients for rotating resistance (kilowatt Second^2/meter^2)
C = road load coefficients for drag resistance (kilowatt Second^3/meter^3)

Road load coefficients were obtained from the MOVES user guide for transit buses (USEPA 2010) where A = 1.0944 kW-s/m, B = 0, and C = 0.003587. The bus mass was provided by the manufacturer as listed in Table 2-2. Each passenger was assumed to weigh 150 pounds (0.068 metric tons) as used by O'Keefe et al. (2002) and others. Road grade was not collected and could not be included in the calculations.

Emission rate, speed, and acceleration are reported by the PEMS in one-second intervals. The number of passengers between stops was recorded so the passenger load by time was also known. VSP was calculated for each one-second inteval using equation 4-1.

VSP bins were developed by taking into account that bins should have a statistically significantly different average emission rate from each other and no single mode should dominate the estimate of total emissions, as suggested by Zhai et al. (2008). Based on these considerations, VSP bins were defined using a preliminary analysis of the data for all pollutants considered. The same bin definitions were used for all pollutants and buses to facilitate comparison. The final bins are shown in Table 4-1.

Table 4-1: Bins used to evaluate bus emissions by VSP range

Bin Definition	VSP Bin Range
≤ 10	VSP < -10.5
-10 to 0	-10.5 <= VSP < 0
0	0 <= VSP < 0.5
1	0.5 <= VSP < 1.5
2	1.5 <= VSP < 2.5
3	2.5 <= VSP < 3.5
4	3.5 <= VSP < 4.5
5	4.5 <= VSP < 5.5
6	5.5 <= VSP < 6.5
7	6.5 <= VSP < 7.5
8	7.5 <= VSP < 8.5
9	8.5 <= VSP < 9.5
10	9.5 <= VSP < 10.5
11	10.5 <= VSP < 11.5
12 +	11.5 <= VSP

The instananeous data were stratifyied into the defined VSP bins and average modal emission rates and standard error were calculated for each bus for each pollutant.

Data were averaged for each VSP bin for each bus and standard error was calculated using equation 4-2:

$$SE = \sigma/N^{0.5} \qquad \textbf{(4-2)}$$

where:

SE = standard error
σ = standard deviation
N = sample size

4.4 Emissions Results

Results are presented by pollutant in the following sections. Both hybrid and control buses had DPFs. PM emissions were low enough that practical differences between buses could not be determined. In addition, the PEMS measures PM using a light-scattering method and, as such, cannot be used to make relative comparisons of PM. Consequently, results for PM are not shown.

4.4.1 Carbon Dioxide

Results for carbon dioxide ($C0_2$) are shown in Figure 4-5.

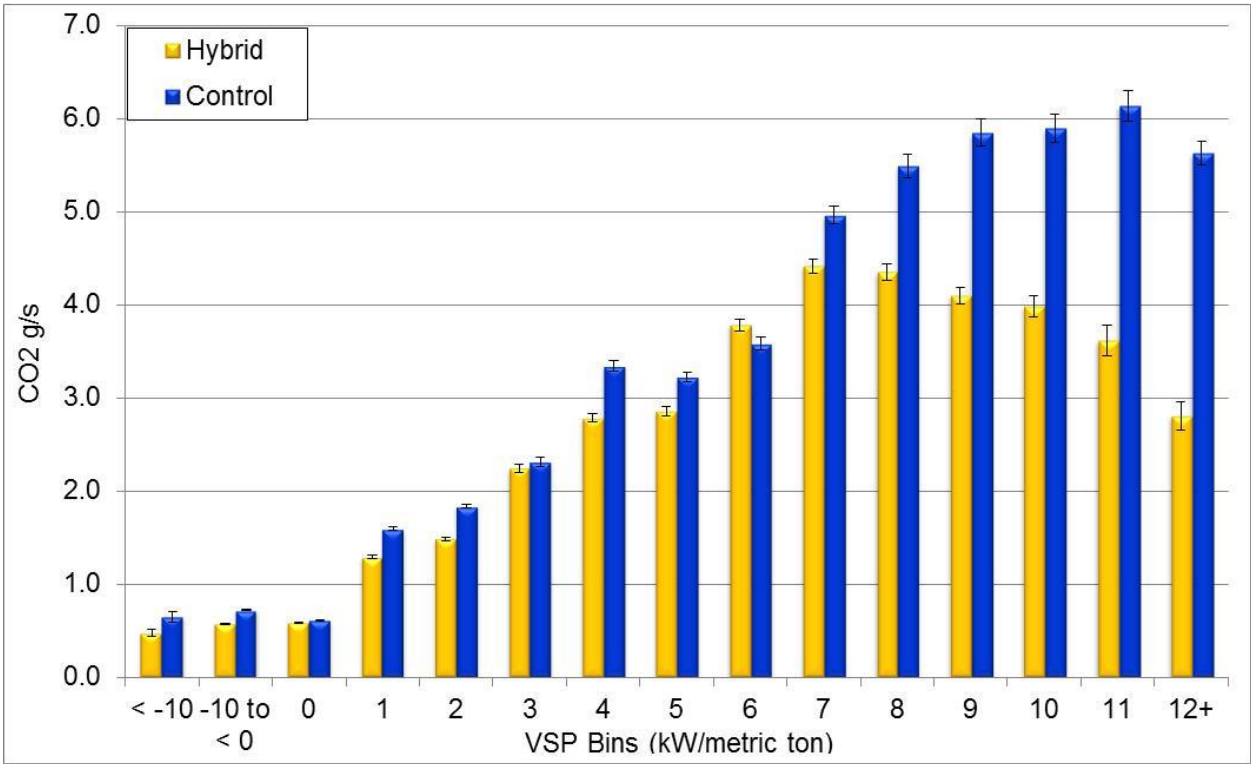


Figure 4-5: CO_2 emissions by VSP and bus type

At the lower VSP categories (≤ 10, - 10 to < 0, 0, 3, and 6) CO_2 emissions were within 0.2 g/s. Emissions were between 0.3 and 0.6 grams/second higher for control buses than for hybrid buses with differences ranging from 12.3 to 23.4 percent for bins 4, 5, and 7. In the higher VSP ranges, emissions were significantly higher for control buses than for hybrid buses with differences between 1.17 and 2.8 g/s higher (26.1to 100.5 percent higher).

CO_2 emissions are lowest in the lower VSP bins for both bus types. However, while CO_2 emission are highest in the mid-VSP ranges for hybrid buses (bins 6 through 9), they are highest for control buses in the higher VSP bins (bins 8 through 12+).

4.4.2 Carbon Monoxide

Carbon monoxide (CO) emissions in milligrams per second are shown by VSP bin in Figure 4-6.

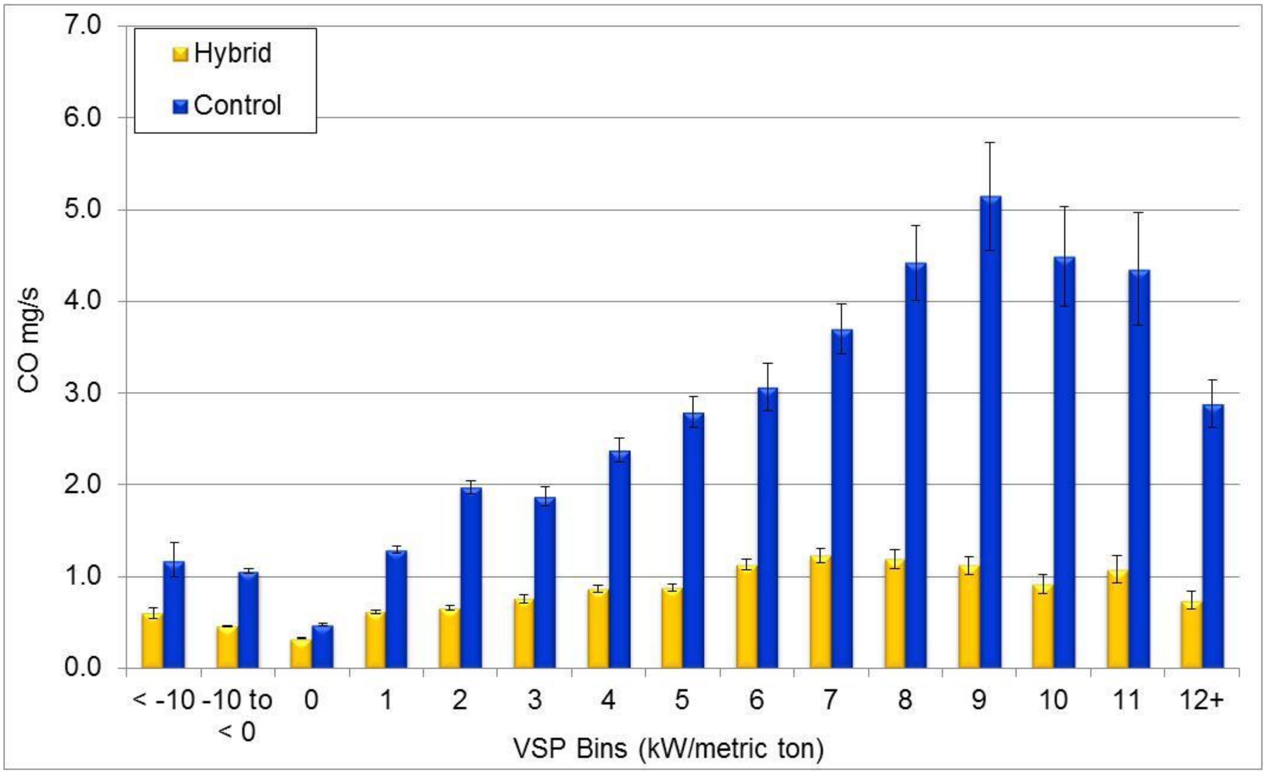


Figure 4-6: CO emissions by VSP and bus type

Emissions were within 0.1 mg/s for the VSP bin 0 and emissions were 0.6 to 0.7 mg/s higher for control buses compared to hybrid buses for bins ≤ 10, - 10 to < 0, and 1 (86.4 to 142.2 percent higher). For all other VSP bins, control buses had CO emissions that were higher than hybrid buses by 1.3 to 4.0 mg/s (1.5 to 3.9 times higher).

CO emissions vary only moderately over most VSP bins for the hybrid buses. Emissions are lowest in lower VSP bins and peak in VSP bins 6 through 9. Emissions, however, only range from 0.9 to 2.8 mg/s. In contrast, CO emissions for control buses are much lower in the smaller VSP bins and then steadily increase in the higher VSP bins. CO emissions vary much more significantly with ranges of 0.5 to 2.0 mg/s in the lower VSP bins and 3.1 to 4.4 mg/s in the higher ranges.

4.4.3 Hydrocarbons

Average hydrocarbon emissions in milligrams per second by VSP bin are shown in Figure 4-7.

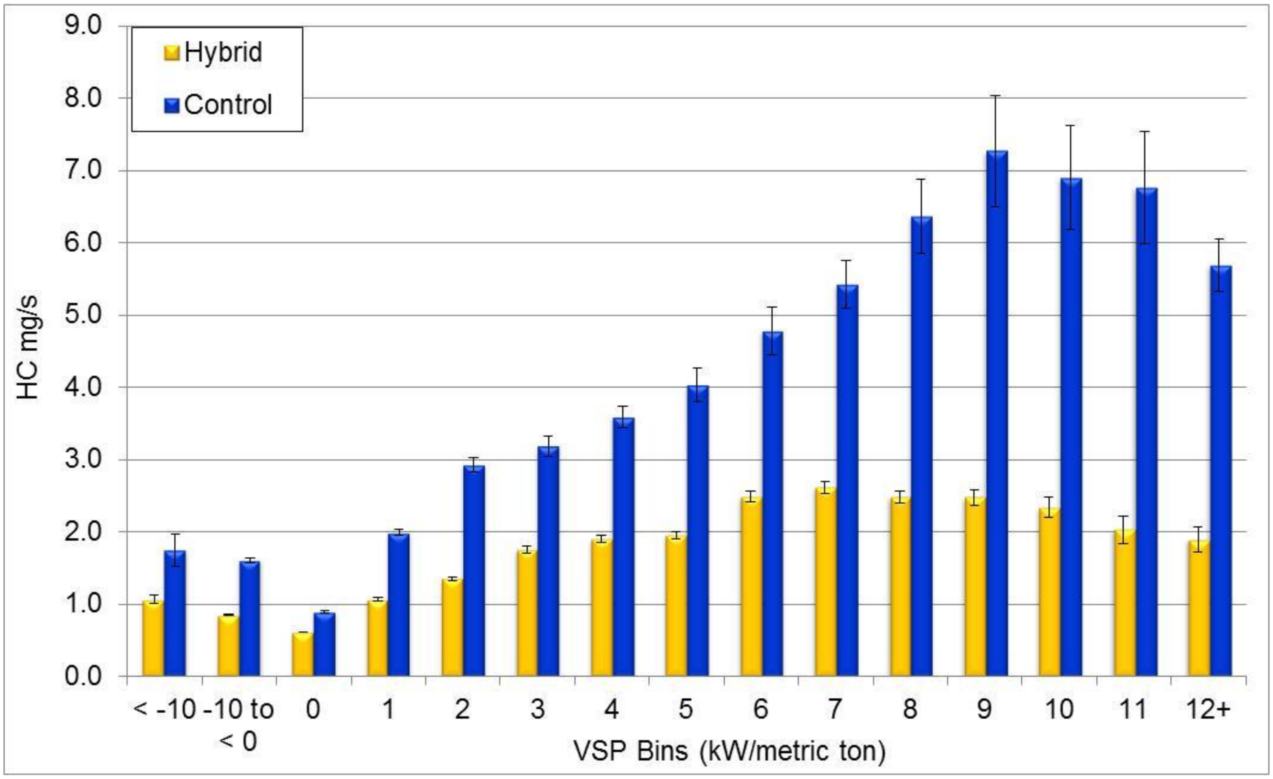


Figure 4-7: HC emissions by VSP and bus type

In all cases, control buses had higher HC emissions than hybrid buses. Differences are less marked in the lower VSP ranges with increases between 0.3 and 0.8 mg/s for negative and 0 VSP bins. Control buses have HC emissions that are 0.9 to 2.1 mg/s higher in VSP bins1 through 5 (80.0 to 115.6 percent higher). In the higher VSP ranges, emissions are higher for control buses than hybrid buses by 2.3 to 4.8 mg/s (92.5 to 231.8 percent higher).

In addition, emissions are highest for both bus types for the mid-range VSP bins (6 to 11) and lowest for the lower VSP bins. HC emissions peak in VSP bin 9 for the control bus with emissions in a similar range for VSP bins 6, 7, 8, 10, 11, and 12+. HC emissions peak in VSP bins 6 and 7 for the hybrid buses and then gradually decrease in the higher bins.

4.4.4 Nitrogen Oxides

Average nitrogen oxide emissions in milligram per second are shown in Figure 4-8 by VSP bin.

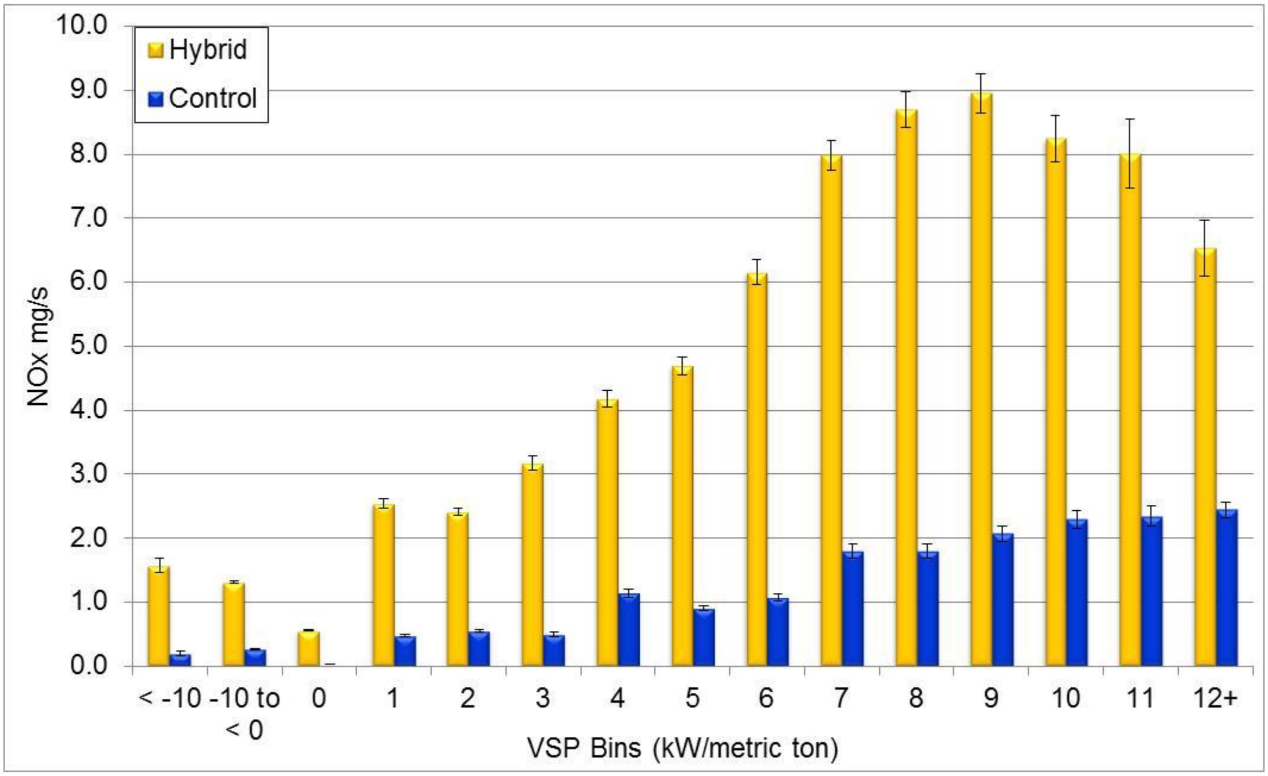


Figure 4-8: NO_x emissions by VSP and bus type

As shown, in the lower VSP bins (≤ 10 through 3), NO_x emissions are moderately higher for the hybrid than for the control buses. Differences range from 0.5 to 2.7 mg/s (79.5 to 95.2 percent). Differences in the higher VSP bins range from 3.0 to 6.9 mg/s (62.6 to 80.7 percent) higher for hybrid buses than for control buses.

NO_x emissions are lowest in the lower VSP bins and peak in VSP bins 7 through 10 for hybrid buses. Emissions then decrease in bins 11 and 12. Emissions for the lower VSP bins increase consistently from the lower VSP bins through the higher VSP bins.

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