AIR-POLLUTANT EMISSIONS FROM CONVENTIONAL DIESEL, HYBRID DIESEL-ELECTRIC, AND COMPRESSED NATURAL GAS FUELED BUSES: COMPARATIVE ON-ROAD ANALYSIS

Which technology is best from an air quality perspective?

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AIR-POLLUTANT EMISSIONS FROM CONVENTIONAL DIESEL, HYBRID DIESEL-ELECTRIC AND COMPRESSED NATURAL GAS FUELED BUSES: COMPARATIVE ON-ROAD ANALYSIS

FINAL REPORT
To

Cache Valley Transit District

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INTRODUCTION

At the request of Cache Valley Transit District (CVTD) a study was performed comparing the levels of carbon dioxide (CO_2), carbon monoxide (CO), hydrocarbons (HC), and oxides of nitrogen (NO_X) discharged in the emissions of a conventional diesel bus, a hybrid diesel-electric bus and a compressed natural gas (CNG) bus- all three being new models equipped with the latest in emissions-control technology for their respective engine types. The study was conducted over the first half of 2011, outside of a laboratory setting using on-board instrumentation to measure and record levels of in-tailpipe, air pollutant output on a regular bus route with changing grades and frequent stops and also on a flatter more continuous semirural bus route. In addition to bus testing, a sample of personal automobiles driven along the examined bus routes was tested and included in the study. The details and findings of this study are provided in this document.

BACKGROUND

Cache Valley Transit District is a transportation agency that provides fare-free public transportation for citizens of communities throughout the Cache County, Utah region including regularly scheduled connections into the adjacent Franklin County, Idaho. At the start of 2011, CVTD acquired several new buses to expand their fleet. Owing to the local air quality issues, they chose to broaden their fleet with hybrid diesel-electric buses to see if this newer technology could help to reduce the use of fossil fuels and thus better the air quality of Cache Valley. These buses were put into regular service during the last part of February 2011.

CVTD approached Dr. Randy Martin, an Environmental Engineering Professor at Utah State University (USU), seeking unbiased air-pollution emissions information about diesel, hybrid diesel-electric and CNG vehicles that will aid them in making future decision regarding the further expansion of their fleet and facilities including the ability to include local, on-road information from an air quality perspective. Arrangements were then made for this on-road emissions analysis to be performed.

Vehicle Descriptions

The CVTD buses, both hybrid and conventional diesel, were manufactured by Gillig and are powered by Cummins engines (1). The 40-foot conventional diesel buses are equipped with the 2010 Cummins ISL9 engine and feature a state-of-the-art emissions control system called the Cummins Aftertreatment System (CAS) (2). The CAS consists of three main components. The first component is a diesel particulate filter (DPF), which traps carbon and takes in the products of diesel fuel combustion, namely nitrogen monoxide (NO) and diatomic oxygen (O_2), and through a series of chemical reactions, including a reaction with the carbon, releases CO_2 and NO_X. The second component is a decomposition reactor with a diesel exhaust fluid dosing valve, which sprays a light mist of Diesel Exhaust Fluid (DEF) into the hot exhaust gas, forming ammonia (NH_3). The third and last component is a selective catalytic reduction catalyst which provides an environment where the remaining NO_X and the NH_3 can react to form diatomic nitrogen (N_2) and water (H_2O) before leaving the system. The CAS is purported to reduce levels of emissions (especially NO_X) to “near-zero levels” (3). A part of this system that does not seem to be listed on the Cummins website, but that should be noted, is the DPF regeneration process, where the carbon and other particulates that get trapped in the DPF are literally burned out of the filter. This regeneration occurs automatically and approximately every two-weeks.

The CVTD hybrid diesel-electric buses are equipped with the Cummins ISB6.7 engine – which is a smaller diesel engine than the conventional diesel buses engines – and are run with hybrid drive systems manufactured by General Motors' (GM) Allison Division (1). The hybrid buses also feature the CAS.

The CNG Aggie Shuttle Bus is powered by a Cummins ISLG 8.9L engine. The ISLG 8.9L engine is the compressed natural gas version of the Cummins ISL engine.

The following (Table 1) shows the year, make, and model of each automobile included in the personal vehicles sample. These particular vehicles were selected solely on availability from a volunteer pool.

YEAR	MAKE	MODEL
1993	Toyota	Camry
1995	Toyota	Previa
1997	Mitsubishi	Galant
1997	Chrysler	Town & Country
2000	Nissan	Xterra
2002	Subaru	Outback
2003	GMC	Yukon
2007	Dodge	RAM 1500
2010	Pontiac	G6

Table 1. Tested personal vehicles.

EPA URBAN BUS EMISSIONS STANDARDS INFORMATION

The Environmental Protection Agency (EPA) issues emissions standards for heavy-duty vehicles and urban buses in units of grams/brake horsepower-hour (g/bhp-hr) (4). For ease of comparison in this study these values will be converted to g/mile using an EPA correction factor of 3.25 bhp-hr/mile. This correction factor is derived assuming a diesel fuel density of 7.11 lb/gal, a brake specific fuel consumption value of 0.372 lb/hp-hr, a vehicle fuel economy of 5.9

mpg, and an average vehicle speed of 48 mph (5). Note that these converted emissions values are not specific for any bus tested here, but are considered close approximations. The following table (Table 2) displays the EPA emission standards for non-methane hydrocarbons (NMHC), CO, and NO_X. The EPA has not, at the time of this study, issued a standard for CO_2 emissions.

Pollutant	Standard (g/mile)
CO	50.38
NO_X	0.650
NMHC	0.455

Table 2. EPA urban bus emissions standards.

RESEARCH OBJECTIVES

The purpose of this study is to provide CVTD with unbiased comparisons of conventional diesel, hybrid diesel-electric, and CNG bus emissions under real operating conditions. This was to be achieved by:

1. Collection of on-road emissions data from the targeted vehicle types,
2. Processing and compiling the air pollutant emissions data into equivalent units grams per mile (g/mile), and
3. Comparison of this study's data with previous local studies and those found in recent scientific literature.

Research Questions

- Is the purchase of a hybrid diesel-electric bus over a conventional diesel bus an effective way to reduce air pollution in the Cache Valley region?
- How do the emissions from a CNG bus compare to those from a conventional diesel and a diesel hybrid?

- How do the emissions from newly acquired CVTD buses compare to EPA Emission Standards?
- Considering the results from the personal vehicle sample, how many bus passengers would be required to produce a net reduction in the overall emissions to the local air shed?

METHODOLOGY

TEST MATRIX

To help ensure accurate results, it was decided that the emissions sampling should be conducted on a randomized basis. The buses were selected and tested for the most part on different days in no particular order with respect to bus type, day of week or time of day. This randomized basis also provided a check for consistency in the equipment. In theory, like test should align with like test. In other words one test from a specific bus type should turn out similar to a second. For example, the data from a CNG test-run should compare more closely with another CNG test-run than with the data from either a hybrid or diesel test-run. If this was not the case then it may indicate that the equipment may need maintenance or re-calibration.

It was also decided that the buses should be evaluated on two actual CVTD routes. Route #4 and the Franklin County Connection Route were selected based on characteristic differences. Route #4 is a one of the shortest routes, totaling an approximate 6.36 miles circling, from the CVTD transit center, up around USU campus before returning to the transit center (see Figure 1 below)(6). Route #4 also features many changes in grade and frequent stops. This type of route, in theory, is conducive to ideal performance from the hybrid diesel-electric buses because of the frequent stops that allow the bus' electrical systems to recharge often and the changes in the road grade would challenge the bus' operating parameters.

Figure 1. Map of CVTD Route #4

The Franklin County Connection route is quite the opposite of Route #4. It is the longest CVTD route at approximately 63.8 miles round-trip. It runs from the Transit Center Northbound on Highway 91 into Preston, Idaho and then back again, making a stop in Lewiston, Utah on both the out and back legs of the trip (see Figure 2 below)(7). It features semirural flat terrain with highway speeds and few stops. The hybrid diesel-electric buses are not typically run by CVTD on this route due to these conditions which don't optimize their electrical systems' potential.

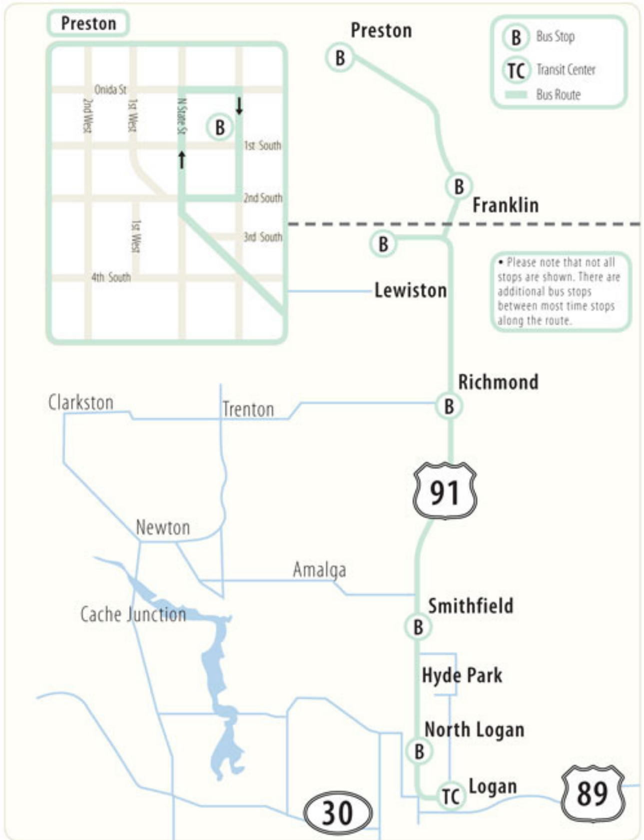

Figure 2. CVTD Map of Franklin County Connection.

Thirdly, it was decided, owing to the fact that Aggie Shuttle buses do not run on the exact CVTD routes, to evaluate the CNG Aggie Shuttle bus on the Stadium Express route which runs between the USU stadium parking lot and the Taggart Student Center (TSC) turn-a-bout. This route is approximately 2.33 miles and involves a long uphill segment from the stadium parking lot to the TSC and a similar downhill segment on the return trip. It was determined that three replicate test-runs per bus, per route would be sufficient to give a statistically-defensible glimpse of the emissions output of each bus.

An additional part of the test matrix was the plan to test a broad sample of USU student and faculty vehicles to add a group of personal vehicles to the comparison. These vehicles were evaluated on Route #4 to replicate similar run conditions; however, only one run was made per vehicle.

EQUIPMENT

An Autologic 5-Gas Analyzer was used to quantify the in-tailpipe concentrations of NO_x, HC, CO, CO_2 and H_2O_{vapor} in units of parts per million (ppm) or percent (%), as appropriate. The Autologic 5-Gas Analyzer was used in combination with a Hewlett Packard (HP) iPAQ handheld computer and AutoGas software (Figure 3 below). A 5 liter tank of Praxair calibration gas for emissions testing was used to calibrate the 5-Gas Analyzer following manufacturer's recommendations. A handheld Garmin ETrex Global Positioning System (GPS) was used to measure actual time and distance of each route. A Kestrel 4000 Pocket Weather Meter was used to measure barometric pressure and in-tailpipe exhaust gas velocity and a handheld infrared IR thermometer was used to measure tailpipe temperatures. For the CVTD bus tests, a laptop computer was used with Cummins brand diagnostic software to record the engine speed in revolutions per minute (RPMs) throughout the run. During other test runs, engine RPMs were manually recorded.

TEST PROCEDURE

Pre-run

Before each test run the 5-Gas Analyzer and the GPS were installed and setup on the target vehicle. The 5-Gas Analyzer was connected directly into the bus' power sources via a maintenance panel at the rear of the buses or operated by a secondary battery connection. The 5-Gas Analyzer's sample hose and probe were run out through an access port and into the tailpipe (Figure 3). The exhaust diffuser hoods on the diesel and hybrid buses were removed before inserting the 5-Gas Analyzer's sample probe into the exhaust pipes. Lastly, after the instruments were in place, the 5-Gas Analyzer was zero-calibrated and leak checked through features of the AutoGas software.

Figure 3. Test set-up. (Clockwise from top left: sample hose position, electrical panel, sample probe inserted, HP handheld display).

On-Run

At the beginning of each test run, the AutoGas program on the handheld computer was set to record the in-tailpipe concentrations of the targeted gases at a sample rate of one measurement every five seconds. During the run, as required, an observer would manually record the engine speed (RPMs) by using the bus' tachometers approximately once every 60 seconds. As previously noted, a laptop computer was used instead of an observer on the CVTD buses with diagnostic software to record the engine speed at that same rate.

Post-Run

After the run, the instruments were removed from the vehicle and measurements of tail-pipe exhaust gas velocity and temperature were made and recorded with the engine at idle speed.

The idle RPMs and measurement of the tail-pipe diameter were also recorded at that time.

OTHER FIELD PROCEDURES

The 5-Gas Analyzer was calibrated using the Praxair calibration gas in at least two-week intervals, which is twice as frequent at the manufacturer's recommended re-calibration interval, to insure accurate gas measurement. Furthermore, the instruments filter bowl was cleaned and the filter was replaced conservatively more frequently than the manufacturer requirements suggest.

DATA PROCESSING

The raw data collected by the AutoGas software were transferred into a PC spreadsheet for evaluation and processing. HC and NO_X data were collected as ppm concentrations whereas CO and CO_2 concentrations were collected as % volume. All of the data were converted from those original values into units of g/mile for comparative purposes. For example, one of the collected data points for a CO_2 reading was 11.49 (%Vol). The following equation was used to convert this value into g/m^3:

$$g/_{m^3} = \frac{11.49}{\frac{100 * P_{bar} * MW}{R * T}}$$

where P_{bar} (atm) is the barometric pressure, MW is the molecular weight of CO_2 (44 g gmol^{-1}), R (m^3 atm K^{-1} gmol^{-1}) is the ideal gas constant, and T (K) is the exhaust temperature. The result of the above example is 110.7 g/m^3 of CO_2.

Next, this value was multiplied by the average volumetric flow rate of exhaust gas output divided by the mileage of the given route to turn out a result in grams per mile (g/mile). These values were derived from the post-test tailpipe measurements and the mileage information collected from the installed on-board GPS.

The molecular weights used for these calculations of HC, NO_X, CO_2, and CO were 78.11 g $gmol^{-1}$ (benzene), 30 g $gmol^{-1}$ (assuming all exhausted NO_X was in the form of NO), 44 g $gmol^{-1}$, and 28 g $gmol^{-1}$, respectively, for all diesel and gasoline fueled vehicles in the study. It should be noted that for the CNG bus 16 g $gmol^{-1}$, the molecular weight of methane (CH_4), was used for the molecular weight of HC, since methane is the primary HC species found in compressed natural gas emissions.

The engine speed, tailpipe diameter, and tailpipe temperature measurements were used to calculate the exhaust gas flow rate. This was done by first finding the exhaust gas velocity at the average engine speed for the run and then multiplying this number by the area of the tailpipe opening, which produces the flow-rate over time of the exhaust gas in m^3/s.

RESULTS

The following graphs were created from the data collected and processed as described above. The error bars on each of the following figures represent on a 95% confidence interval about the calculated mean.

Figures 4-7 (below) display the data collected from the testing of the personal vehicles. These data are discussed initially to show the variety of vehicle-to-vehicle emissions found, before ultimate comparison with the various bus emissions. As can be seen, there were significant differences in the pollutant emissions across the tested vehicles and across the tested pollutants. It is interesting to note that the Pontiac G6, the newest vehicle (refer back to Table

1), showed the greatest emissions for CO_2 and HCs, and had the second highest CO emissions. Although from a statistical standpoint, the G6's emissions were indistinguishable from the seemingly greater emissions of the tested Mitsubishi Gallant. It is also of interest to point out that excess emissions of CO and/or HCs, which are often indicative of fuel-rich combustion, are not necessarily associated with high NO_X emissions, which are more often associated with more stoichiometric or fuel-lean combustion coupled catalytic converter failure.

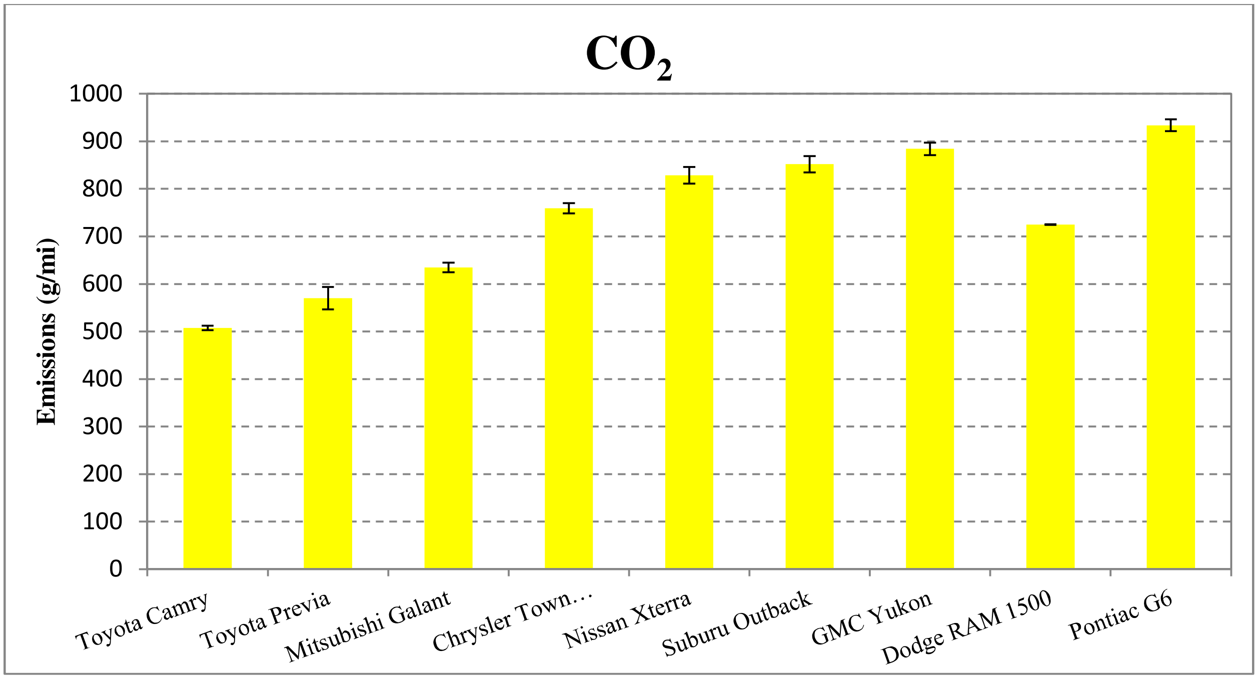

Figure 4. CO_2 Personal vehicle comparison.

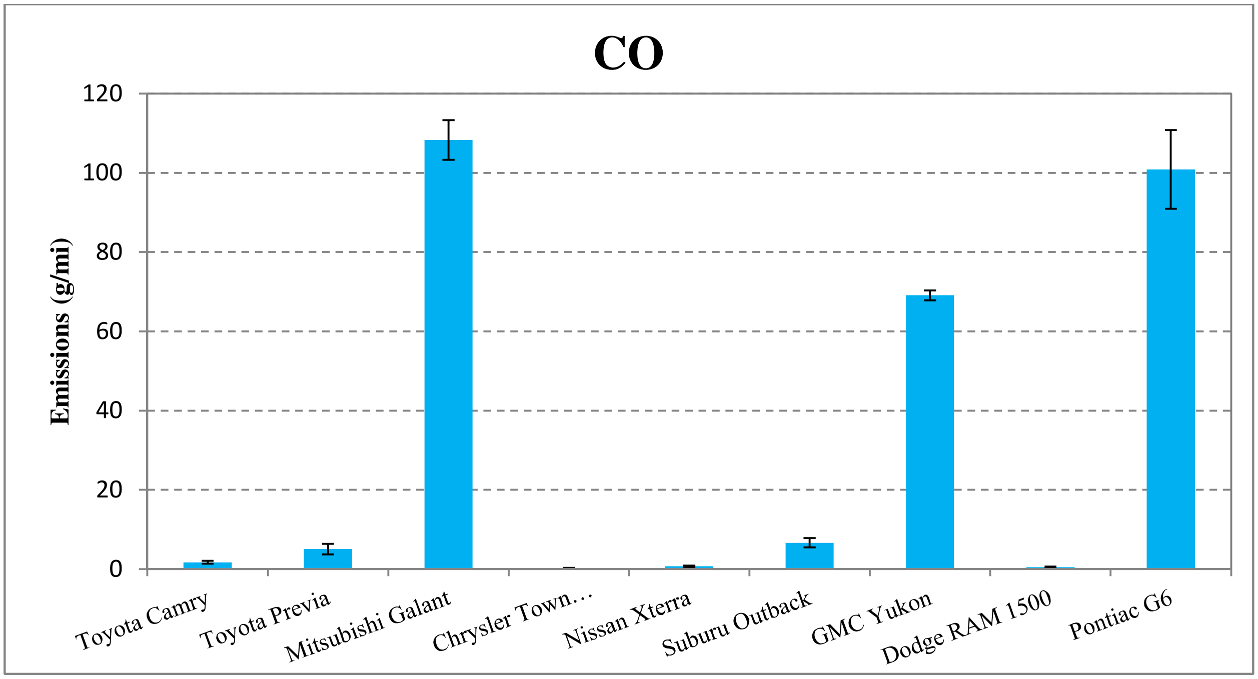

Figure 5. CO Personal vehicle comparison.

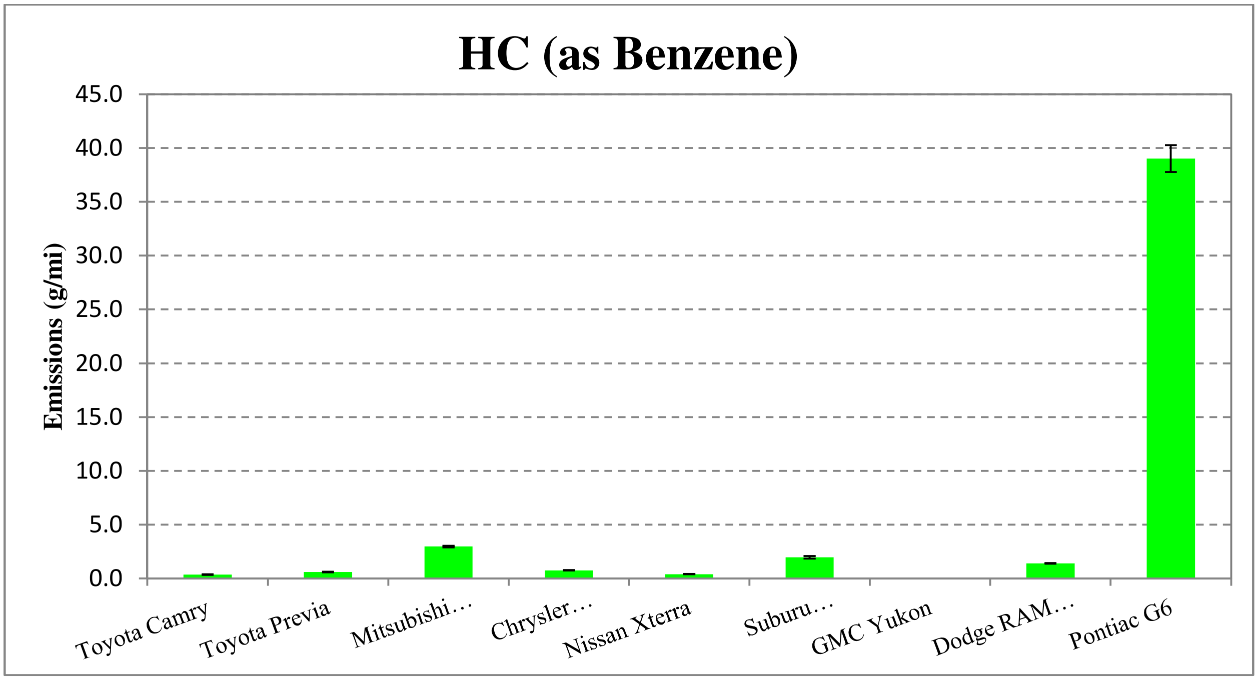

Figure 6. HC Personal vehicle comparison.

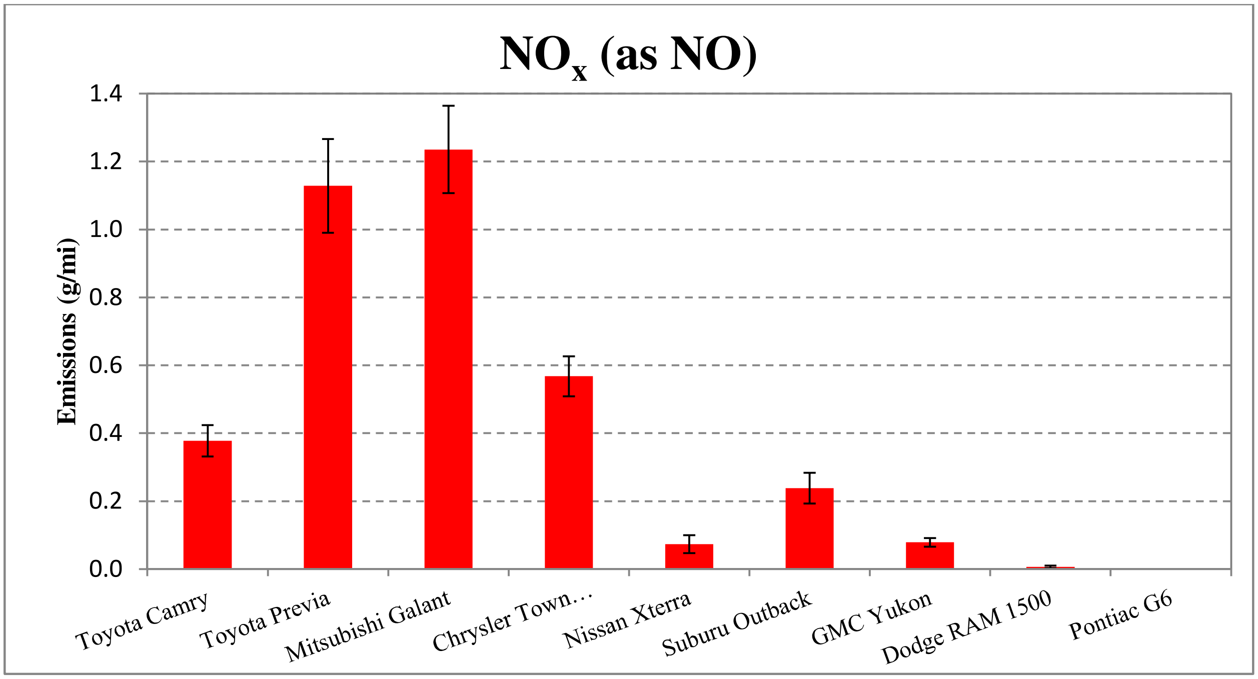

Figure 7. NO_X Personal vehicle comparison.

The following figures (Figures 8-11) display the data from all vehicle sources tested: the averaged personal vehicles (denoted as “SV” in the figures), the CNG (Aggie Shuttle) bus, and the two versions of the CVTD buses (diesel and hybrid). Also (4) indicates CVTD route #4 and (ID) indicates the CVTD Franklin County Connection route. The most immediate result which is apparent from Figures 8-11, is that, regardless of the monitored pollutant species, the measured personal vehicles showed the greatest average emission rates. Although, the “SV” NO_X emissions were nearly statistically indistinguishable from the hybrid diesel-electric bus operating on route #4. Due to many near-zero levels of emissions on many of the graphs, a table is provided, following the graphs, with all the numeric values.

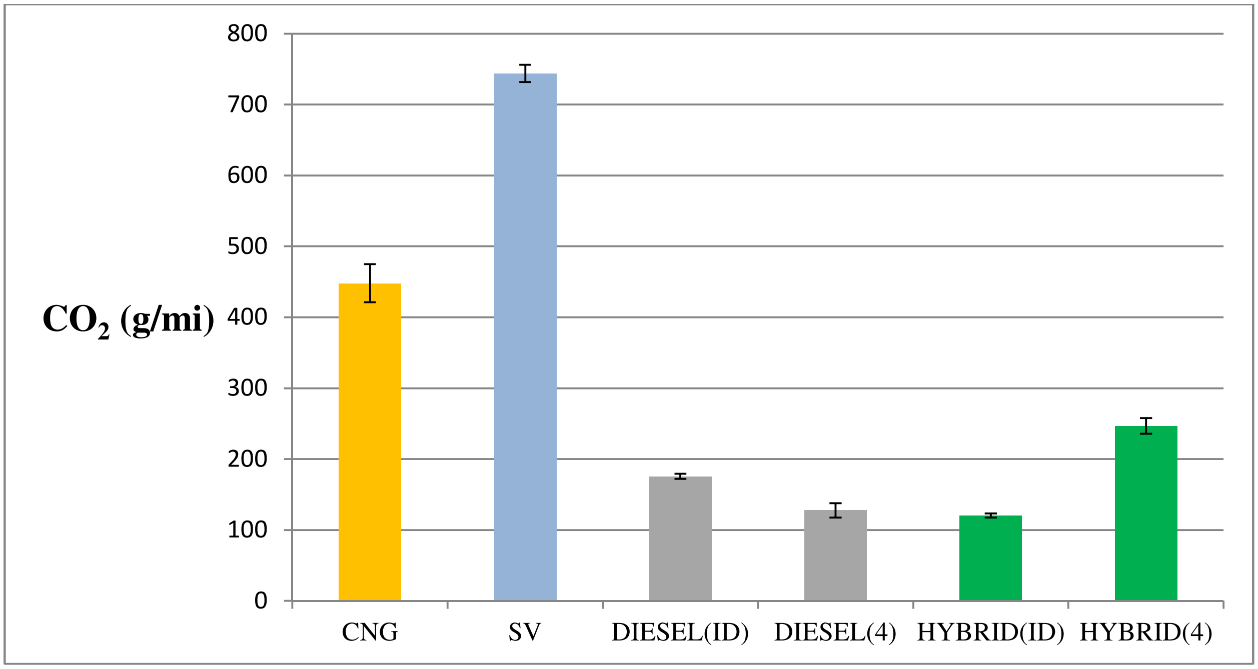

Figure 8. CO_2 Emissions Comparison.

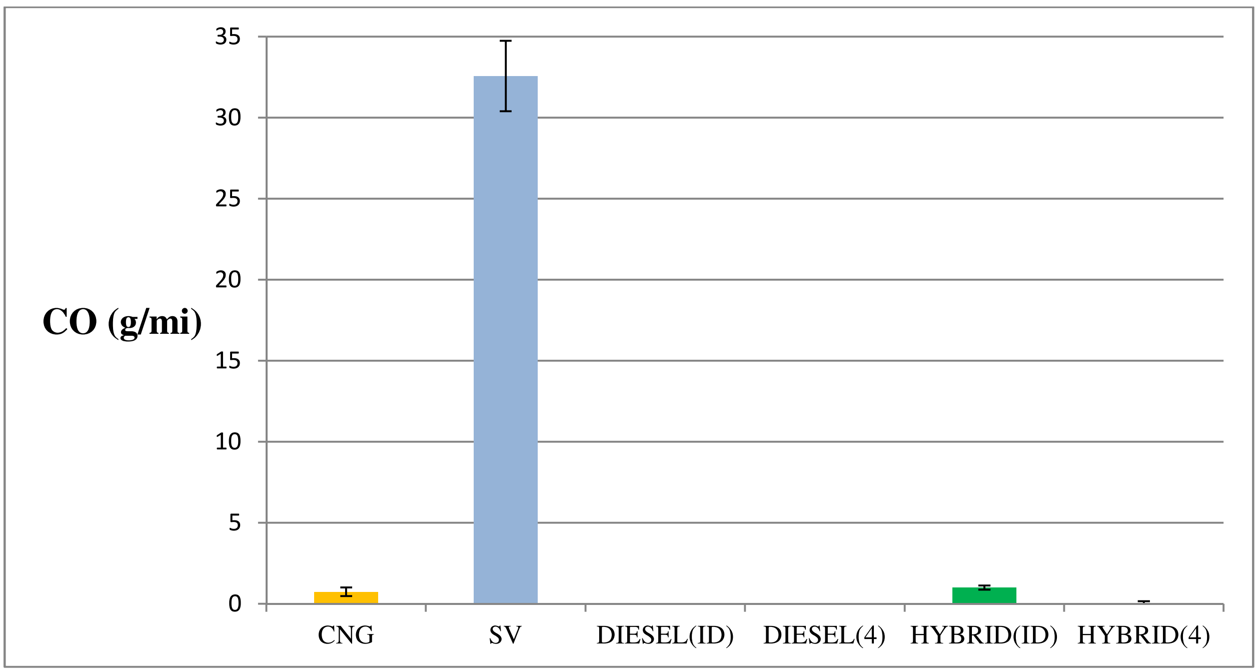

Figure 9. CO Emissions Comparison.

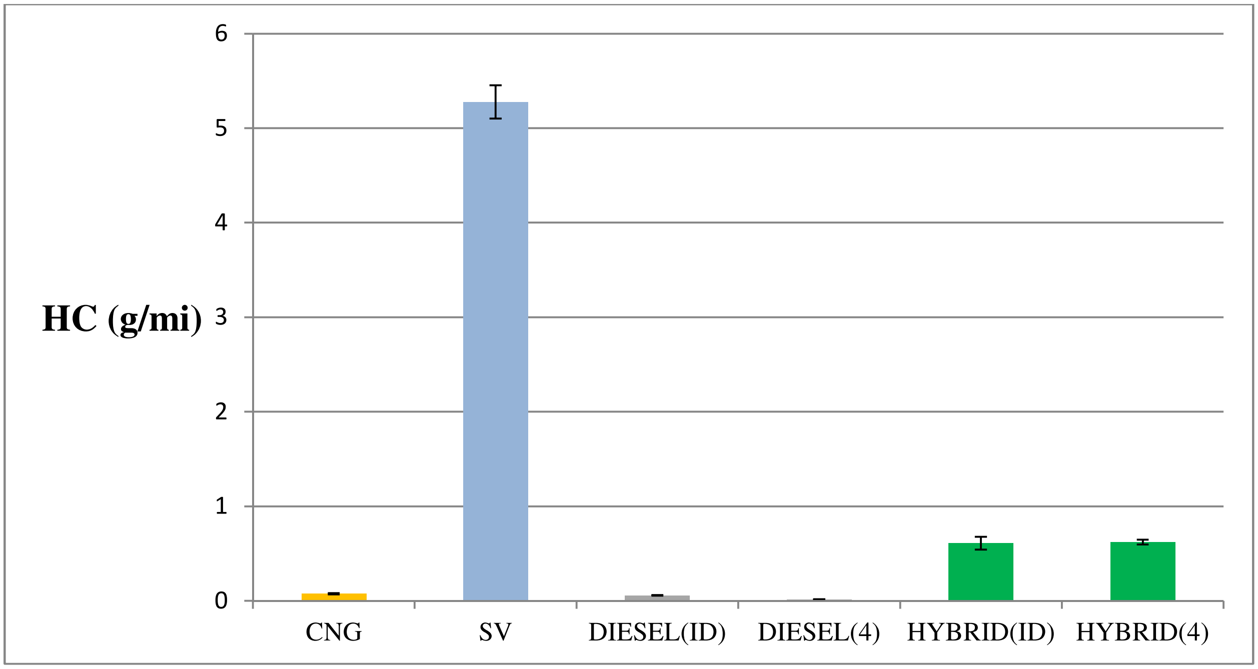

Figure 10. HC Emissions Comparison.

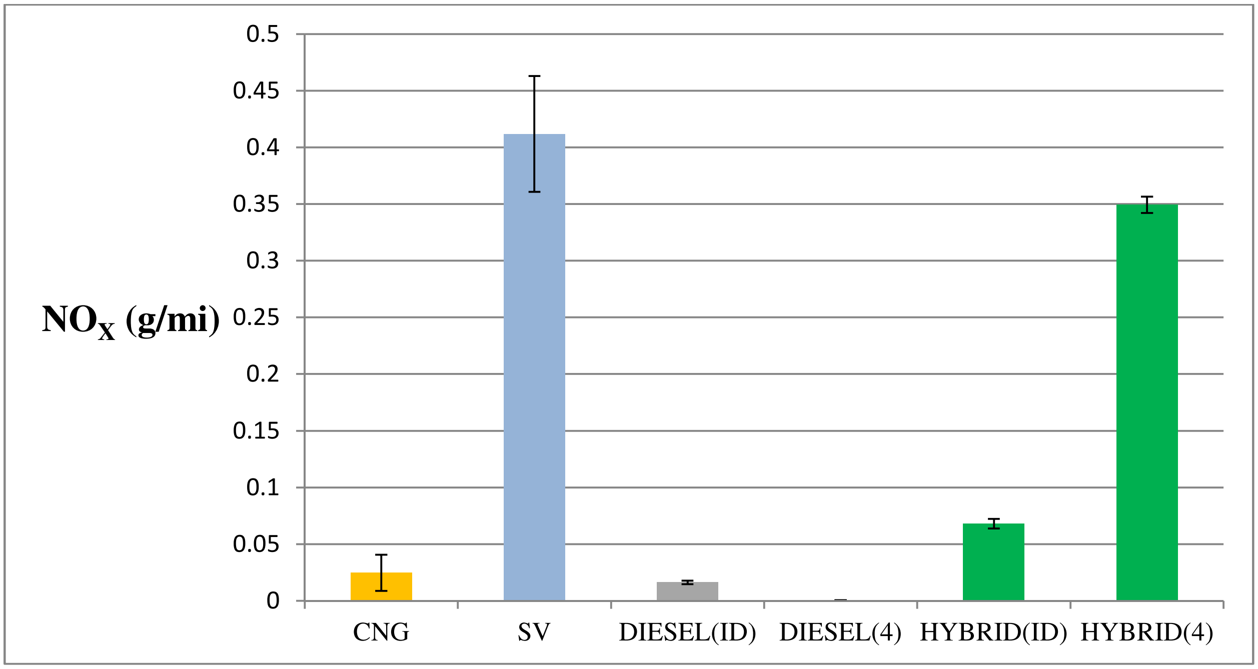

Figure 11. NO_X Emissions Comparison.

The following table (Table 3) displays the values from the previous four figures.

	CNG	Diesel (Rt. 4)	Diesel (ID)	Hybrid (Rt. 4)	Hybrid (ID)	SV
CO2 (g/mile)	447.9±26.9	127.6±10.2	175.8±3.55	246.6±11.1	120.6±2.96	743.9±12.3
CO (g/mile)	0.7321±0.268	0.0074±0.003	0.0035±0.001	0.0251±0.134	0.9986±0.132	32.56±2.17
HC (g/mile)	0.0752±0.007	0.0144±0.002	0.0583±0.004	0.6216±0.026	0.6010±0.068	5.277±0.175
NOX (g/mile)	0.0247±0.016	0.0004±0.000	0.0163±0.002	0.3494±0.007	0.0680±0.004	0.4118±0.051

Table 3. Comparison Data.

DISCUSSION

EXPECTED RESULTS

Although one of the main focuses in this study was an unbiased approach, there were some basic outcome projections and expectations. One being lower air-pollutant emissions from the hybrid diesel-electric buses compared to the other bus types, based on the essence of the hybrid concept and the research provided by the manufacturer(1). This hypothesis was not found to be supported by the results of this study.

One possible explanation for the former discrepancy comes from a comparative analysis of the engine and fuel consumption differences between the conventional diesel and the diesel hybrid. The conventional diesel bus tested has an 8.3L engine, whereas the hybrid has a smaller 6.7L engine. That is a 19% difference in displacement. However, the hybrid is only approximately 16%-18% more fuel efficient than the conventional diesel bus, indicating that it uses less fuel overall but more fuel per engine volume. This theory could indeed resolve the discrepancy between expectations and results.

Furthermore, a similar study performed by researchers at the University of Connecticut came to a corroborative conclusion(8). They examined the differences in particulate matter emissions between a diesel hybrid and a conventional diesel bus with regard to fuel and aftertreatment methods. They found that the hybrid buses emitted more particulate matter into the air than the conventional diesel buses. They stated the following about their results:

> "This surprising result contradicts the benefits typically attributed to hybrid-electric vehicle design and suggests that the Allison Transmission parallel hybrid drive control systems on the buses used in this study were optimized for performance rather than significant emission reductions."

AN INTERESTING FIND

One of the findings from the results that deserves some attention is the apparent incidence of a DPF regeneration process that occurred during one of the hybrid bus test runs. The CVTD diesel and hybrid diesel-electric buses are both equipped with DPFs to remove particulate matter from the exhaust gas. While some DPFs feature a one-time-use disposable filter, these buses use a burn-off method, called regeneration, to clean out the filter by burning out the collected debris. According to Ron Carver, head of maintenance at CVTD, this process occurs automatically and approximately every two weeks for about 15 to 20 minutes. This may explain the apparent spike in pollutant values from for a 20 minute period on the second hybrid run on the Franklin County Connection route. The logarithmic-scale graph below (Figure 12) shows the spike in HC during that period. Note: the abscissa values are chronological data points from the run.

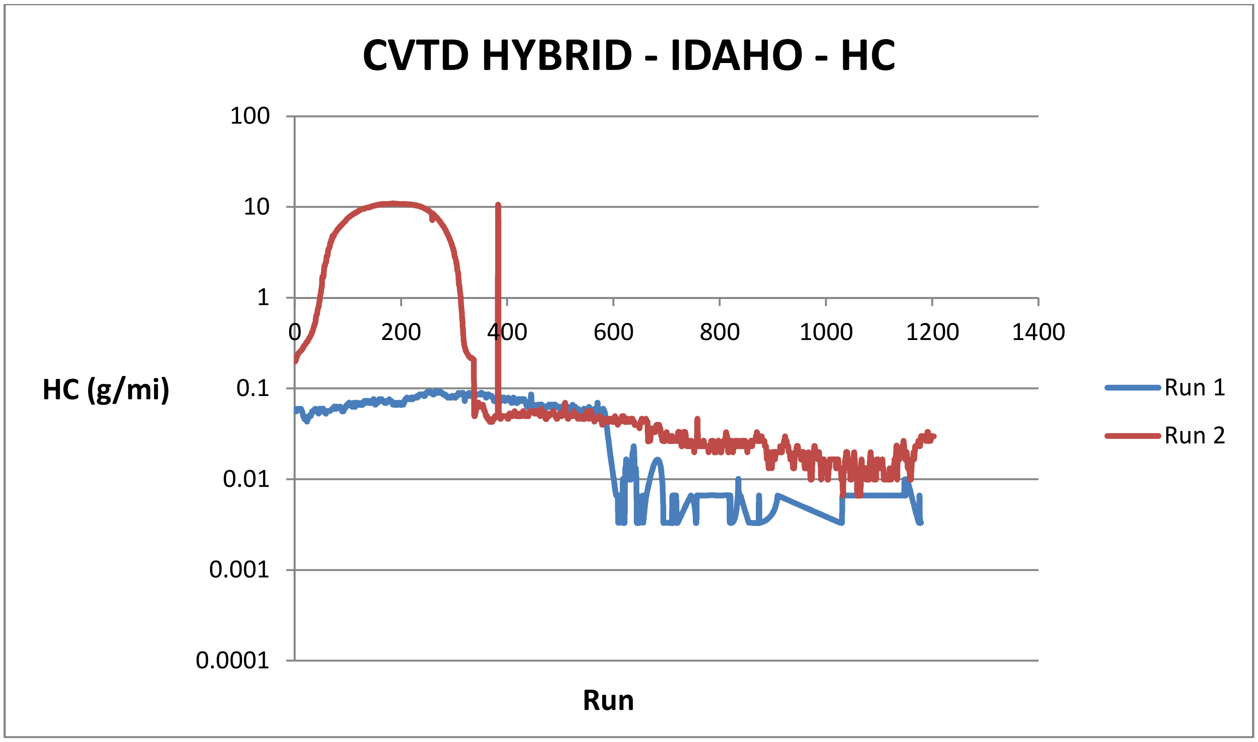

Figure 12. Suspected DPF regeneration spike.

The first figure below (Figure 13) shows the original comparison between the diesel bus results versus the hybrid diesel-electric bus results on the Franklin County Connection route. The second figure shows a modified comparison where the hybrid diesel-electric run with the suspected DPF regeneration has been removed from the data. Note that the ordinate values on the graphs between Figure 13 and Figure 14 different do to the significant decrease in values on the modified run (Figure 14.)

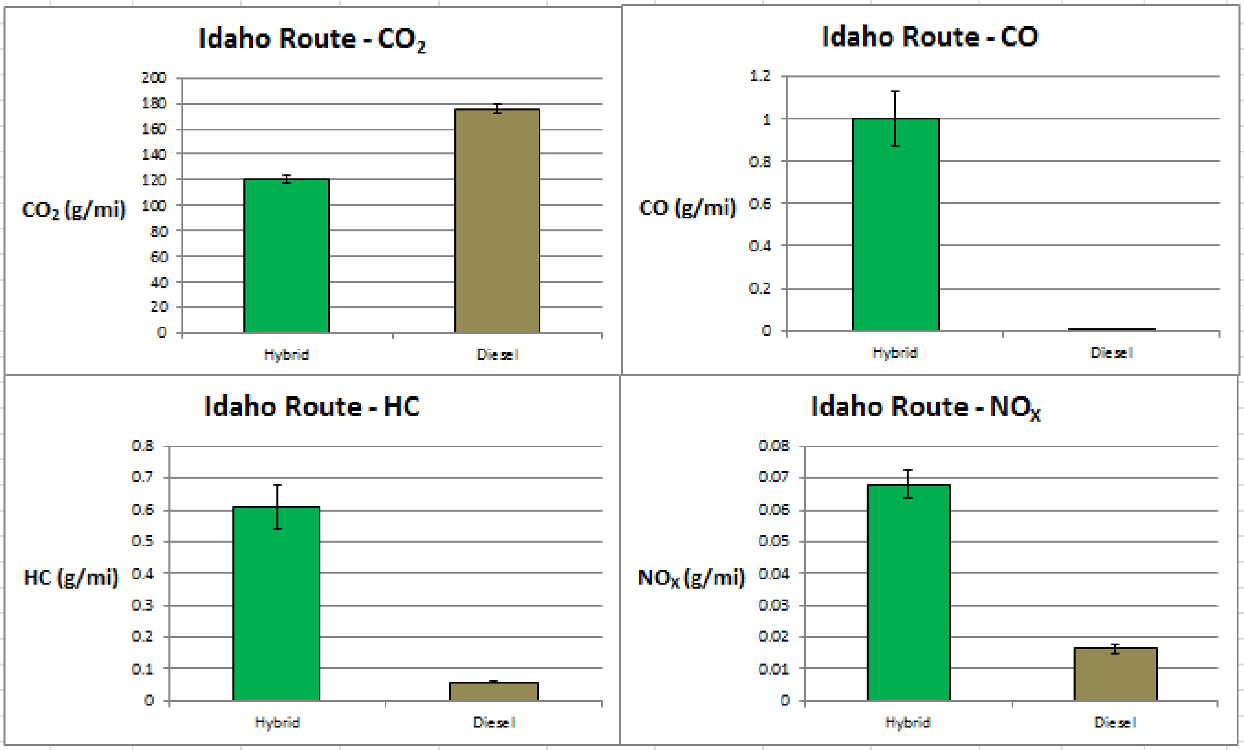

Figure 13. Diesel and hybrid diesel-electric bus emissions on the Franklin County Connection route.

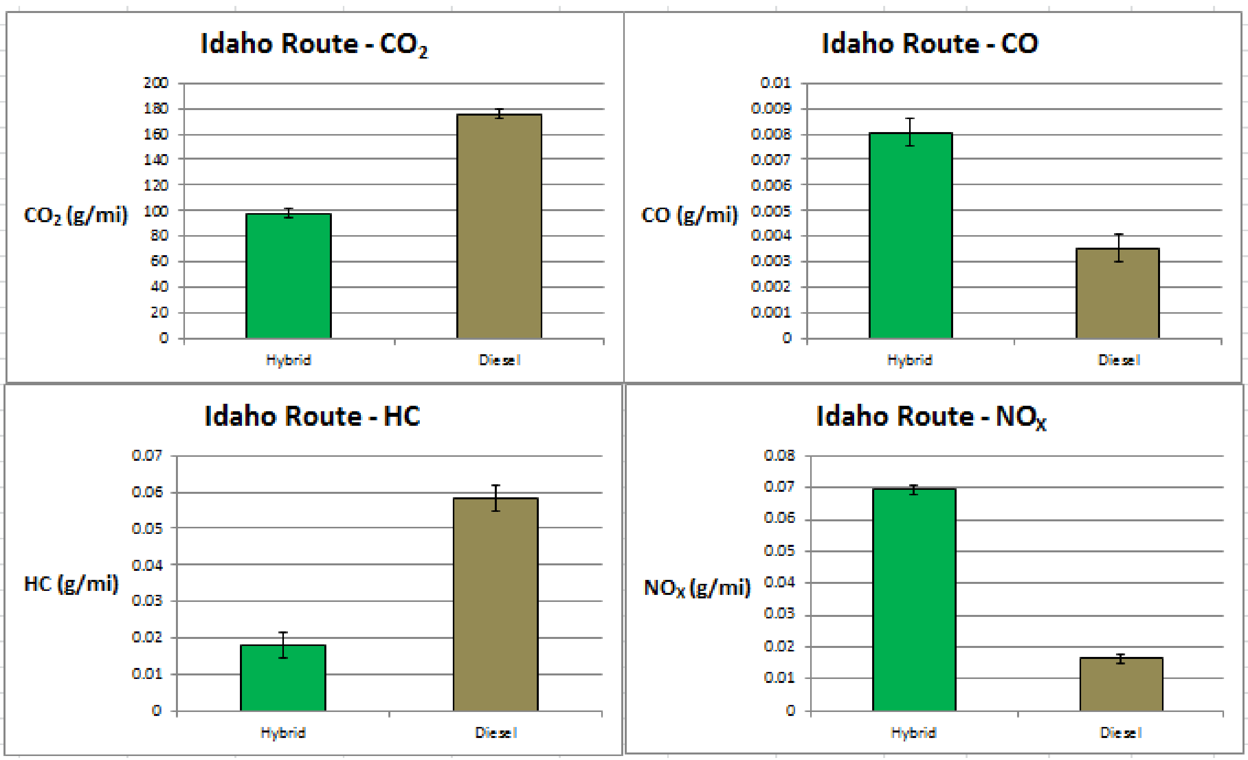

Figure 14. Diesel and modified hybrid diesel-electric bus emissions on the Franklin County Connection route.

Notice that while the NO_X and the CO_2 levels remain relatively unchanged, the CO levels begin to even out and the HC changes significantly.

There was only one test run on which a DPF regeneration was suspected to have occurred. Further study is needed to determine what effect DPF regenerations have on overall emissions performance.

STUDY-TO-STUDY COMPARISON

A similar study was performed here at Utah State University in 2007. In that study researchers measured air-pollutant emissions from conventional diesel buses with and without fuel additives and compared that with measured emissions from a CNG bus. Below is a table taken with permission from that report that shows a three-study comparison. The data from this current study has been added into the table for comparison. All values are in g/mile. "UofC" represents University of California and "WVU" represents West Virginia University. More details about those sources can be found through the 2001 USU study (9).

Study	Bus Type	NOx	HC	CO	CO2
USU Study 2007	Diesel (Rt 1)	7.3	0.11	3.4	2148
	Diesel (Rt 2)	2.5	0.03	0.46	737
	CNG	11.2	1.3	0.005	2366
UofC 2003	Diesel	30.2	0.05	0.5	2500
	CNG	15	7	4	2000
WVU 1999	Diesel	22	2	2	No Data
	CNG	10	6	0.5	No Data
Current Study 2011	Diesel	0.008	0.036	0.005	151
	CNG	0.025	0.075	0.73	447
	Hybrid	0.21	0.62	0.51	183

Table 4. Study Comparisons with previous USU (2007) study and literature studies.

The table above shows a positive trend in emissions reduction over time. The results from this current study which feature three bus types, all with the latest technology in emissions control (namely the Cummins Aftertreatment System), are substantially lower than the study done by USU four years ago and both of the other studies which were performed, one close to and one over, a decade ago. This table also shows that in the past CNG buses emitted less NO_X than diesel but over time this has changed. In the 2007 study and the current study alike the conventional diesel buses emitted less NO_X than the CNG. The hybrid diesel-electric bus, however, emitted more NO_X than the CNG in the current study.

CONCLUSION

RESEARCH QUESTIONS ANSWERED

Is the purchase of a hybrid diesel-electric bus over a conventional diesel bus an effective way to reduce air pollution in the Cache Valley region?

Based purely on the results of this study, the answer to this question is, no. The hybrid bus used in this study did not perform as well as a conventional diesel bus from an air quality perspective. This particular model of hybrid could have an underpowered engine that is required to work very hard and thus uses fuel less efficiently than its diesel counterpart. Or, like the conclusion the researchers from the University of Connecticut study, the bus' engine may be designed for power-output performance rather than emissions control and fuel efficiency. While the direct answer to the question is not in favor of the hybrid diesel-electric buses, there may be other hybrid buses on the market that would change that answer.

How do the emissions from a CNG bus compare to those from a conventional diesel and a diesel hybrid?

As presented in the figures of this report, the CNG bus outperformed the hybrid bus in lower emissions output, but was slightly outperformed by the conventional diesel bus. The CNG and the conventional diesel performed so similarly that any decision between the use of the two should take in to consideration other factors besides air-pollutant emission.

How do the emissions from newly acquired CVTD buses compare to EPA Emission Standards?

As displayed by the table below, the conventional diesel bus was well below the EPA standards in all three areas. The hybrid diesel-electric buses were well within the standards for CO and NO_X but slightly exceeded the NMHC standard. However, since an approximate conversion factor was used, there is an unknown margin of error in the EPA standard. Therefore the hybrid diesel-electric bus may in fact be under the EPA standard.

Pollutant	Standard (g/mile)	Diesel (high value)	Hybrid (high value)
CO	50.38	0.0074±0.003	0.9986±0.132
NO_X	0.650	0.0163±0.002	0.3494±0.007
NMHC	0.455	0.0583±0.004	0.6216±0.026

Table 5. CVTD buses compared to EPA emissions standards

Considering the results from the personal vehicle sample, how many bus passengers would be required to produce a net reduction in the overall emissions to the local air shed?

The answer to this question depends on which make and model of vehicle is being considered. As clearly displayed in the results section, there were large differences in emissions between the different personal vehicles examined. The answer may more importantly depend on which air-pollutant is the main concern. For example, the Pontiac G6 was found to produce the lowest levels of NO_X, but the highest levels of HC. However, considering the averages of all the vehicles combined, it would only take one person to choose to ride the bus over driving a car to reduce the net air pollution in Cache Valley.

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