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Emission Testing of Washington Metropolitan Area Transit Authority (WMATA) Natural Gas and Diesel Transit Buses

Technical Report
NREL/TP-540-36355
December 2005

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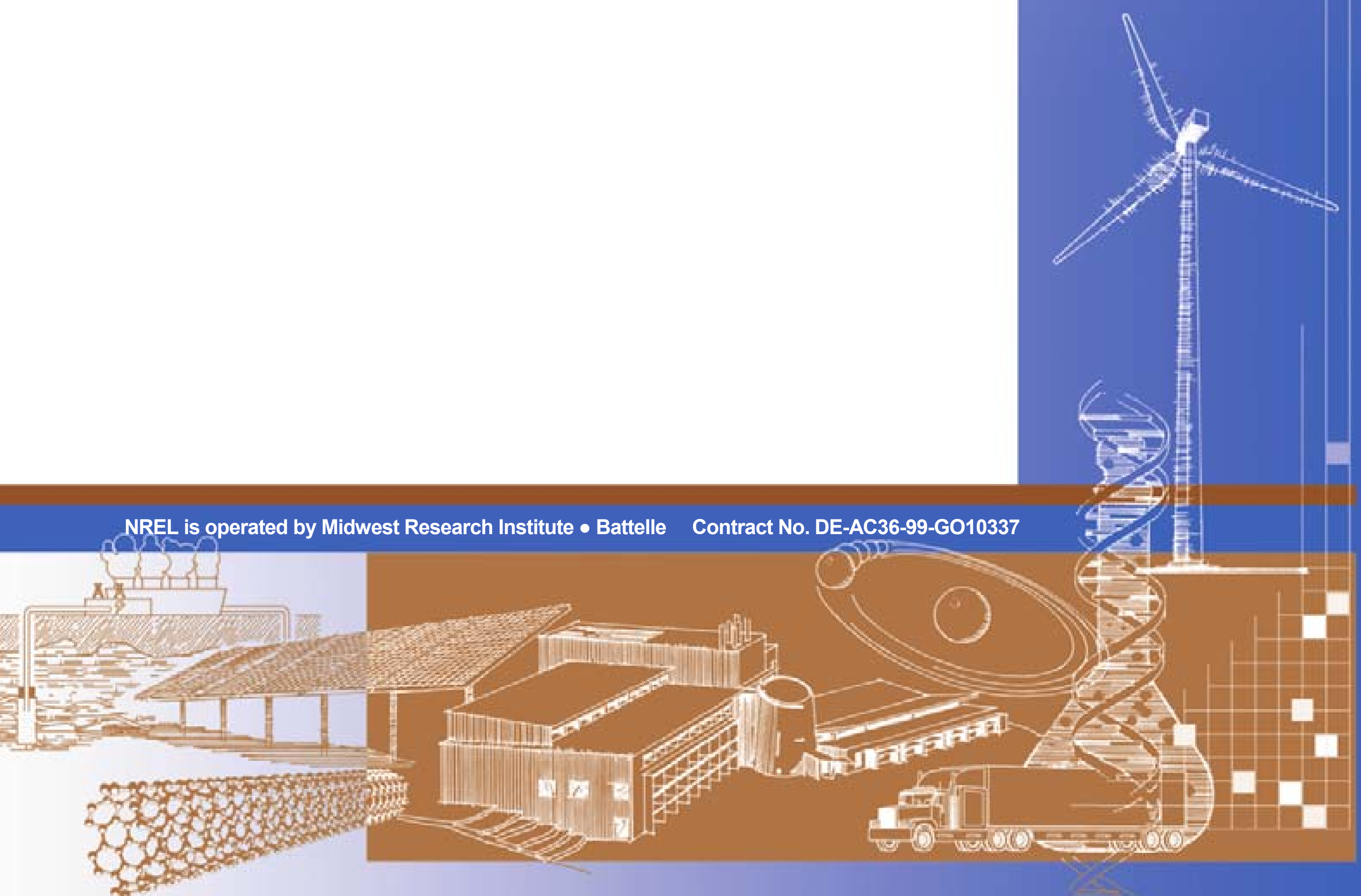

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Acronyms and Abbreviations

BDL	Below detection limit
BTEX	Benzene, toluene, ethylbenzene, and xylene isomers
CARB	California Air Resources Board
CBD	Central Business District (drive cycle)
CFR	Code of Federal Regulations
CH_4	Methane
CNG	Compressed natural gas
CO	Carbon monoxide
CO_2	Carbon dioxide
CWI	Cummins Westport Inc.
DDC	Detroit Diesel Corporation
DNPH	2,4-Dinitrophenylhydrazine
DPF	Diesel particulate filter
EGR	Exhaust gas recirculation
EPA	U.S. Environmental Protection Agency
FID	Flame ionization detection
g/bhp-hr	Grams per brake horsepower-hour
GC	Gas chromatograph
gC	Grams of carbon
GVWR	Gross vehicle weight rating
HC	Hydrocarbons
HEPA	High efficiency particulate air (filters)
HPLC	High-performance liquid chromatography
mi	Miles
mpeg	Miles per (diesel) equivalent gallon
MY	Model year
NDIR	Non-dispersive infrared analyzers
NMHC	Non-methane hydrocarbons
NO	Nitrogen oxide
NO_x	Oxides of nitrogen
NREL	National Renewable Energy Laboratory
PM	Particulate matter
ppmC	Parts per million carbon
PSI	Pounds per square inch
PSIA	Absolute PSI
ReFUEL	Renewable Fuels and Lubricants (Laboratory)
THC	Total hydrocarbons
TransLab	WVU Transportable Heavy-Duty Vehicle Emissions Testing Laboratory
ULS (ULSD)	Ultra low sulfur diesel
WMATA	Washington Metropolitan Area Transit Authority
WVU	West Virginia University

1.0 Executive Summary

Natural gas is a domestically available resource. The U.S. Department of Energy (DOE) supports natural gas vehicle research, development, deployment, and evaluation through its FreedomCAR and Vehicle Technologies Program to help the United States reduce its dependence on imported petroleum and to pave the way to a future transportation network based on hydrogen.

Historically, natural gas vehicles have exhibited lower emissions of regulated pollutants compared with vehicles powered by conventional fuels such as gasoline and diesel. However, this has come into question recently in light of increasingly stringent U.S. Environmental Protection Agency (EPA) regulations that all heavy-duty engines (including diesel engines) will have to meet. Cleaner diesel engine technologies are being introduced. The question is, "Are cleaner natural gas engine technologies being introduced that can still demonstrate emission reduction benefits by comparison?" This is of particular interest to transit fleets currently operating natural gas buses and, having already invested in natural gas refueling infrastructure, interested in expanding their fleet or buying new buses.

In 2004, DOE's National Renewable Energy Laboratory (NREL) led an evaluation of the emissions of transit buses operated by the Washington Metropolitan Area Transit Authority (WMATA). The goal of this project was to evaluate the emissions of natural gas transit buses and the improving baseline emissions of comparable diesel buses with advanced emission control technologies (both of which were operating in the regular WMATA fleet). The project was performed in cooperation with DOE's Clean Cities Program, which supports partnerships that reduce petroleum consumption through alternative fuels and vehicles, fuel blends, improved fuel economy, hybrid vehicles, and idle reduction.

The Washington Metropolitan Area Transit Authority serves the public transportation needs of metropolitan Washington, D.C., including Northern Virginia and Southern Maryland. Because the EPA has classified this area as a severe ozone non-attainment area, WMATA is continually working to reduce local air pollution while providing reliable, low-cost service to its customers. A variety of low-emission bus technologies can help WMATA, and other transit agencies, achieve these goals. Among these options are compressed natural gas (CNG) buses and low-sulfur diesel buses equipped with advanced emission control technologies.

A total of twelve 40-foot, low-floor WMATA buses were tested using West Virginia University's Transportable Heavy-Duty Vehicle Emission Testing Laboratory. These buses were of two types: CNG and low-sulfur diesel (approximately 17 ppm sulfur). All CNG buses had lean burn natural gas engines and oxidation catalysts. All diesel buses had catalyzed particulate filters, and one group of diesel buses had exhaust gas recirculation (EGR).

The buses were tested for numerous regulated and unregulated emissions, including hydrocarbons, carbon monoxide, oxides of nitrogen (NO_x), particulate matter (PM), and various toxic emissions. The increasingly strict EPA and California standards set for NO_x and PM, particularly NO_x, are considered to be the greatest challenge for heavy-duty engines. NO_x is also of particular concern to the Metropolitan Washington, D.C., area because this area's ozone problem is considered to be largely NO_x limited. As such, most of its air quality control measures are focused on an overall NO_x reduction strategy. All buses were tested over the WMATA cycle, a custom drive cycle designed to represent real-world operation of the WMATA buses.

The following are the four test bus configurations included in the study:

- CNG buses with model year (MY) 2004 John Deere 6081H engines, equipped with oxidation catalysts
- CNG buses with MY 2001 Cummins Westport, Inc. (CWI) C Gas Plus engines, equipped with oxidation catalysts
- Diesel buses with MY 2004 Detroit Diesel Corporation (DDC) Series 50 engines, equipped with catalyzed particulate filters and EGR
- Diesel buses with MY 2000 DDC Series 50 engines, equipped with catalyzed particulate filters.

The John Deere CNG buses produced 49% lower NO_x emissions and 84% lower PM emissions compared with the MY 2004 DDC diesel buses, and 63% lower NO_x emissions and 60% lower PM emissions compared with the MY 2000 DDC diesel buses. The CWI buses produced 6.1% higher NO_x emissions and 60% lower PM emissions compared with the MY 2004 DDC diesel buses, and 23% lower NO_x emissions and equal PM emissions compared with the MY 2000 DDC diesel buses.

In addition to showing the emissions advantage of CNG buses, this project showed promising fuel economy results for the CNG buses compared with the diesel buses. The following fuel economy comparisons are made on a diesel gallon equivalent basis. The John Deere CNG buses exhibited a 9.0% fuel economy improvement compared with the MY 2004 DDC diesel buses and a 2.9% improvement compared with the MY 2000 DDC diesel buses. The CWI CNG buses exhibited a fuel economy 4.2% higher than the MY 2004 DDC diesel buses and 1.6% lower than the MY 2000 DDC diesel buses. Both CNG engines use lean burn technology.

Formaldehyde and acetaldehyde emissions from the diesel buses and the John Deere CNG buses were very low, approaching ambient background levels. The CWI CNG buses produced formaldehyde and acetaldehyde emissions that were above ambient background levels and markedly higher than the other bus groups. This result may indicate a malfunction with the exhaust catalyst or a maintenance/durability issue, neither of which could be verified in time for inclusion in this report.

Other carbonyl emissions were not detected at levels that could be distinguished from ambient background, indicating that the levels are extremely low for these emissions from all vehicles tested. An attempt was made to characterize 1,3-butadiene and BTEX (benzene, toluene, ethylbenzene, and xylene isomers) emissions. However, the gas chromatography equipment available for this study did not have sufficient sensitivity to detect the low levels of 1,3-butadiene and BTEX in the vehicle exhaust.

2.0 Introduction

Because natural gas is a domestically available resource, the U.S. Department of Energy (DOE) supports natural gas vehicle research, development, deployment, and evaluation through its FreedomCAR and Vehicle Technologies Program. The main goal is to help the United States reduce its dependence on imported petroleum. Other goals include improving air quality in U.S. cities and advancing gaseous fuel technology to pave the way to a future transportation network based on hydrogen.

The goal of this project was to evaluate the emissions of natural gas transit buses and the emissions of diesel buses with advanced emission control technologies. The project was performed in cooperation with DOE's Clean Cities Program, which supports partnerships that reduce petroleum consumption through alternative fuels and vehicles, fuel blends, improved fuel economy, hybrid vehicles, and idle reduction.

The project was led by DOE's National Renewable Energy Laboratory (NREL) with the support of West Virginia University's National Research Center for Alternative Fuels, Engines, and Emissions (WVU). Since 1993, NREL has evaluated advanced technology alternative fuel and diesel trucks and buses nationwide. The resulting data are used to evaluate technologies and assist vehicle operators in selecting, purchasing, and maintaining their fleets. NREL has worked with WVU for many years in support of this purpose. Over the past 11 years, the WVU Transportable Heavy-Duty Vehicle Emissions Testing Laboratory (TransLab) has been used to measure exhaust emissions from more than 700 conventional and alternative fuel heavy-duty trucks and buses.

2.1 WMATA's Clean Bus Choices

Various vehicle choices are available to transit fleets that are balancing the goals of improving local air quality, achieving high customer satisfaction, and maintaining fiscal responsibility. The number of choices is increasing as heavy-duty engine manufacturers work toward meeting the stringent 2007/2010 U.S. Environmental Protection Agency (EPA) emission regulations. Choices include buses fueled with alternative fuels such as natural gas and biodiesel, buses equipped with advanced emission control devices and fueled with low-sulfur diesel, and hybrid electric buses fueled with conventional or alternative fuels.

These choices are critical for the Washington Metropolitan Area Transit Authority (WMATA), which serves 3.5 million people in the metropolitan Washington, D.C., area. More than 1.7 million commuters rely on WMATA's rail cars and transit buses daily, including 348 bus routes with more than 1,400 buses. The EPA has classified the Washington, D.C., metropolitan area as a severe ozone non-attainment area. Oxides of nitrogen (NO_x) emissions are of particular concern because the area's ozone problem is considered to be largely NO_x limited. As such, most of the area's air quality control measures are focused on an overall NO_x reduction strategy.

The air pollution in Washington, D.C., is primarily due to motor vehicle emissions. To reduce the area's vehicular emissions, WMATA is tasked with providing low-cost, reliable transportation in the cleanest way possible. Under the current operating plan, approximately 400 of WMATA's buses will be fueled with compressed natural gas (CNG), and the rest, roughly 1,400 vehicles, will be fueled with low-sulfur diesel (approximately 17 ppm sulfur).

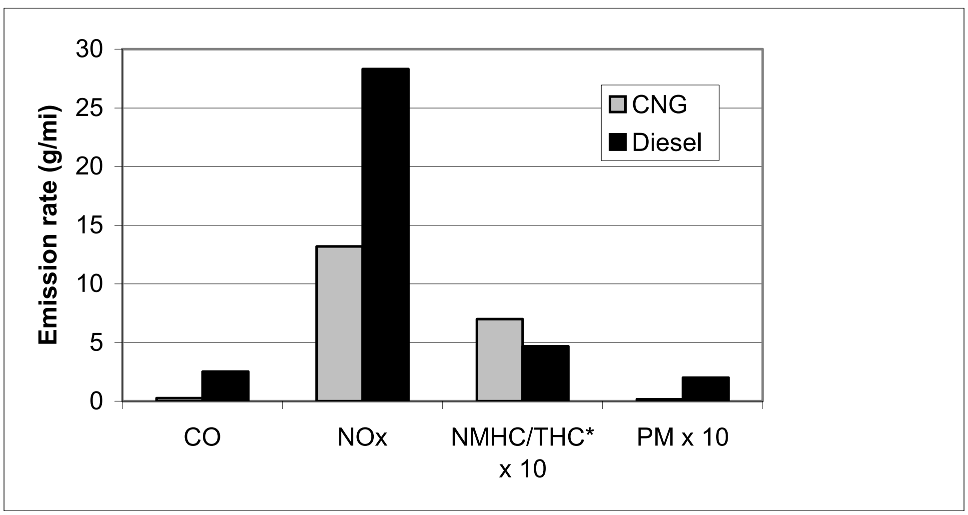
2.2 Emission Testing of WMATA's CNG and Diesel Buses

A two-phase emission test program was designed to evaluate the performance of WMATA's CNG and diesel buses. WMATA is using the test results to compare its CNG and diesel buses, which will aid in planning of future bus acquisitions. The results will help other transit agencies evaluate bus choices as well.

In 2001, NREL, WVU, and WMATA conducted the first phase, a short test program comparing the emissions of WMATA's Cummins Westport, Inc. (CWI) CNG buses and similar Detroit Diesel Corporation (DDC) diesel buses. Table 1 and Figure 1 summarize the vehicle specifications and results. For more information, see the NREL publication, *Evaluating the Emission Reduction Benefits of WMATA Natural Gas Buses* [1].*

Table 1: Vehicles Tested in Phase I of WMATA Emission Testing Program

	CNG Buses	Diesel Buses
Manufacturer	New Flyer	Orion
Model year	2001	2000
GVWR (lb)	40,600	42,540
Odometer (mi)	1,900 2,400 2,500 2,600 2,600	2,290 5,000 105,000 112,900
Engine	CWI C Gas Plus	DDC Series 50
Displacement (L)	8.3	8.5
Rated power (hp)	280	320



*NMHC for CNG buses, THC for diesel buses.

Figure 1: Results of WMATA Emission Testing Program, Phase I, Central Business District Drive Cycle

This report describes the second phase of the WMATA emission testing program. This phase, completed in 2004, represented a unique opportunity to compare emissions from WMATA's most recent technology CNG and "clean diesel" transit buses. It was designed to evaluate regulated emissions and selected toxic emissions from WMATA's CNG buses with CWI and John Deere engines, diesel buses with DDC engines and catalyzed particulate filters, and newly repowered diesel buses with DDC engines, catalyzed particulate filters, and exhaust gas recirculation (EGR). The following were the specific project objectives:

* To obtain this publication, visit the Alternative Fuels Data Center at www.eere.energy.gov/afdc/ or call the National Alternative Fuels Hotline at 1-800-423-1363.

- Demonstrate technologies and methods for controlling exhaust emissions from natural gas engines
- Quantify the levels of regulated and toxic emissions from advanced heavy-duty natural gas and clean diesel transit buses
- Evaluate the emission reduction benefits of recent generation heavy-duty natural gas engine technologies.

3.0 Test Vehicle Description

Table 2 describes the vehicles tested in this study. Buses were selected randomly from each category (CWI, John Deere, and DDC). WVU and WMATA coordinated the test schedule; when vehicles were next on the schedule, they were taken out of service and inspected by WMATA mechanics to ensure proper operation. In addition, all three engine manufacturers were given the opportunity to have technicians on site to inspect and prep their vehicles before testing (only John Deere chose to have staff on site for the testing). Table 2 lists the GVWR and curb weight; all buses were tested at a simulated inertia weight representing the empty vehicle curb weight plus one half of the maximum passenger load.

Table 2: Vehicles Tested in Phase II of WMATA Emission Testing Program

Diesel Buses					
	MY 2000 DDC Series 50		MY 2004 DDC Series 50 EGR		
Chassis	MY 2000 Orion Bus Industries Model 06.501		MY 1992 Orion Bus Industries Model 06.501		
Engine	MY 2000 DDC Series 50		MY 2004 DDC Series 50 EGR		
Engine Ratings	275 hp @ 2,100 rpm		275 hp @ 2,100 rpm		
EPA NO_x Certification	4.0 g/bhp-hr NO_x		2.5 g/bhp-hr NO_x + NMHC		
After-treatment	Engelhard DPX™ catalyzed particulate filter		DDC EGR Engelhard DPX™ catalyzed particulate filter		
Transmission	5-speed automatic		5-speed automatic		
GVWR/Curb Weight (lb)	42,540/27,800		39,375–40,600/27,325–29,025		
Bus Number	**2073**	**2074**	**9612**	**9633**	**9655**
Odometer Reading (mi)	159,855	145,804	395,917	568,846	482,874

CNG Buses							
	CWI C8.3G+ (C Gas Plus)				John Deere 6081H		
Chassis	MY 2001 New Flyer C40LF				MY 2002 New Flyer C40LF		
Engine	MY 2001 CWI C Gas Plus 280				MY 2004 John Deere 6081H		
Engine Ratings	280 hp @ 2,400 rpm				280 hp @ 2,200 rpm		
EPA NO_x Certification	1.8 g/bhp-hr NO_X + NMHC				1.8 g/bhp-hr NO_X + NMHC		
After-treatment	Fleetguard-Nelson oxidation catalyst				Johnson Matthey oxidation catalyst		
Transmission	5-speed automatic				5-speed automatic		
GVWR/Curb Weight (lb)	40,600/31,800				40,600/30,125–31,300		
Bus Number	**2302**	**2304**	**2307**	**2308**	**2460**	**2462**	**2463**
Odometer Reading (mi)	44,597	57,168	44,923	50,906	30,384	28,981	29,674

Two model year (MY) 2000 Orion Model 06.501 transit buses (Figure 2) were equipped with MY 2000 DDC Series 50 diesel engines and Engelhard DPX catalyzed diesel particulate filters canned by Nelson. The engines were certified to the 1998–2004 EPA standard of 4.0 g/bhp-hr NO_x. The buses were tested at a simulated inertia weight of 32,225 lb.

Figure 2: MY 2000 Orion Model 06.501 Bus with MY 2000 DDC Series 50 Diesel Engine

Three MY 1992 Orion Model 06.501 transit buses (Figure 3) were repowered with MY 2004 (post-October 2003) DDC Series 50 engines equipped with EGR and Engelhard DPX catalyzed particulate filters canned by Nelson. The repowers occurred in 2003: bus number 9612 completed 9/23/2003 at 490,847 mi; 9633 completed 4/15/2003 at 346,487 mi; and 9655 completed 8/14/2003 at 411,531 mi. The engines were certified to the 2004 EPA standard of 2.5 g/bhp-hr NO_x + NMHC (non-methane hydrocarbons). The buses were tested at simulated inertia weights of 34,125–34,700 lb.

Figure 3: MY 1992 Orion Model 06.501 Bus with MY 2004 DDC Series 50 Engine and EGR

Four MY 2001 New Flyer C40LF transit buses (Figure 4) were equipped with MY 2001 CWI C8.3G+ (C Gas Plus) CNG-fueled engines. These 8.3 L engines featured lean burn operation and oxidation catalysts to improve emission performance. They were certified to 1.8 g/bhp-hr NO_x + NMHC. The buses were tested at a simulated inertia weight of 36,450 lb. They have been in revenue service since the summer of 2001.

Figure 4: MY 2001 New Flyer C40LF Bus with MY 2001 CWI C Gas Plus CNG Engine

Three MY 2002 New Flyer C40LF transit buses (Figure 5) were equipped with MY 2004 John Deere 6081H CNG-fueled engines. These 8.1L engines were built in 2001–2002 and updated—software changes only—in 2004, immediately before the emission testing took place; John Deere considers the engines to be MY 2004 and in their field test confirmation stage of development. The engines feature lean burn operation and were equipped with new oxidation catalysts immediately before emission testing to update the engines to a 1.8 g/bhp-hr NO_x + NMHC standard. The oxidation catalysts from Johnson Matthey had been "de-greened" through bench operation of 90–120 hours prior to their installation and testing on the dynamometer for this test program. The buses were tested at simulated inertia weights of 34,700–35,875 lb.

Figure 5: MY 2001 New Flyer C40LF Bus with MY 2004 John Deere 6081H CNG Engine

4.0 Test Methodology

The equipment and methods used for this test program consisted of two parts: WVU's TransLab chassis dynamometer and sampling procedures and NREL's toxic emission equipment and sampling procedures.

4.1 WVU Laboratory Description and Analysis of Emissions

The WVU TransLab was used to conduct the emissions tests on location at the WMATA facility in Landover, Maryland. Detailed information pertaining to the design and operation of the TransLab can be found in technical papers [2,3,4]. The dynamometer unit consisted of power absorbers and a set of selectable flywheels, which allow simulation of tire rolling losses, aerodynamic drag, and inertial load equivalent to a gross vehicle weight of up to 60,000 lb. Torque cells and speed transducers continuously measured drive axle torque and speed. Road load drag on the vehicle was mimicked partially by the irreversible (frictional) losses in the laboratory and was adjusted to the correct value at each speed using eddy current power absorbers with closed-loop torque control. A human driver operated the vehicle according to a driving schedule selected to represent the typical duty cycle encountered by the WMATA buses during normal service. Figure 6 shows a bus undergoing emission testing on the dynamometer.

4.1.1 Analysis of EPA-Regulated Emissions and Fuel Economy

The emission measurement system used a full-scale dilution tunnel measuring 18 in (45 cm) in diameter and 20 ft (6.1 m) in length. The exhaust was mixed with HEPA-filtered ambient air, and the quantity of diluted exhaust was measured precisely by a critical flow venturi system. The diluted exhaust was analyzed using non-dispersive infrared analyzers (NDIR) for carbon monoxide (CO) and carbon dioxide (CO_2), and using chemiluminescent detection for NO_x. NO_x emissions were corrected for standard humidity per the Code of Federal Regulations. Hydrocarbons (HC) were analyzed using flame ionization detection (FID). Simultaneous pre-tunnel bag samples were taken during each test to establish ambient background gas concentrations. The gaseous emissions measurements were performed in accordance with the Code of Federal Regulations Title 40 (CFR40), Part 86, Subpart N [5] to the extent possible. A carbon balance using fuel properties and exhaust emissions data was used to determine fuel economy.

Particulate matter (PM) was collected using 70-mm fluorocarbon-coated glass fiber filter media, and PM emissions were measured gravimetrically. Dilution tunnel background samples were collected for establishing PM background levels. Even though the tunnel had HEPA-filtered dilution air, PM backgrounds were essential because the dilution tunnel walls may shed particles that are re-entrained into the sample stream or outgas heavy HC that condense onto the PM.

The PM emissions from the vehicles retrofitted with catalyzed particulate filters were expected to be far lower than the emissions from conventional diesel vehicles. To facilitate collection of sufficient PM mass for accurate microbalance measurement, these vehicles were exercised through two back-to-back test cycles such that emissions were collected over a test run that was twice the normal driving distance. The test cycle used for this program was the WMATA cycle. The double-length test cycle was designated as 2WMATA.

Triplicate runs were performed for each emissions test. Additional repeat runs were performed if the coefficient of variation for CO_2 and NO_x emissions exceeded 5%. A minimum of three test runs were averaged for each regulated emissions result reported.

4.1.2 Analysis of Methane Emissions

Methane emissions were measured using two identical sample bags collected during the test cycle. Total HC (THC) concentration was measured from one bag using the standard FID measurement and a methane response factor. The methane fraction of the HC was measured from the other bag using gas chromatography; this was achieved with a simplified analytical method and by determining the ratio of the area from the methane peak to the total area of the peaks in the sample. This ratio was multiplied by the THC concentration determined from the first bag, resulting in a value for methane concentration.

Figure 6: Bus under Test on the WVU TransLab Chassis Dynamometer

4.2 NREL Laboratory Description and Analysis of Unregulated Emissions

The NREL Renewable Fuels and Lubricants (ReFUEL) Laboratory's capabilities to measure unregulated toxic air contaminant emissions consist of a high-performance liquid chromatograph (HPLC). Samples were collected using 2,4-dinitrophenylhydrazine (DNPH) cartridges for subsequent analysis by NREL to determine the levels of carbonyl compounds in the exhaust. DNPH cartridges were acquired from Waters Corp. and stored in a refrigerator until they could be analyzed.

4.2.1 Analytical Method for Measuring Carbonyls

Carbonyl (aldehyde and ketone) samples were collected from two separate but identical sample streams, each containing two DNPH cartridges (primary and secondary) in series. The primary and secondary DNPH cartridges were extracted and analyzed separately to determine the concentration of the aldehyde and ketone emissions in the exhaust. Cartridges were eluted with approximately 3 mL of carbonyl-free HPLC-grade acetonitrile (Burdick and Jackson) to remove all unreacted and derivatized DNPH from the solid phase. The mass of eluent was measured for each cartridge using an analytical balance and was approximately 1.85 g. A volume of 1.5 mL eluent was transferred to an HPLC autosampler vial and loaded for analysis.

The HPLC analytical method was similar to that developed by the Coordinating Research Council and referred to as the Auto/Oil Method [6]. All analyses were performed in a Hewlett-Packard Model 1050 HPLC equipped with a quaternary pump and variable wavelength ultraviolet detector. Details of the analytical method are shown in Table 3.

Table 3: HPLC Analytical Method for Carbonyls (Aldehydes and Ketones)

Column	Deltabond AK, (5 µm, 150 mm x 4.6 mm)
Column temperature	40°C
Injection volume	10 µL
Flow rate	1.5 mL/min
Solvents	A: Pure acetonitrile B: 33% acetonitrile, 67% water
Gradient	0–10 min: Hold at 17% A, 83% B 10–15 min: Ramp to 25% A, 75% B 15–16 min: Hold at 25% A, 75% B 16–23 min: Ramp to 55% A, 45% B 23–27 min: Hold at 55% A, 45% B 27–29 min: Ramp to 17% A, 83% B 29–32 min: Hold at 17% A, 83% B
Detector	Variable wavelength set at 360 nm

The HPLC was calibrated with a prepared standard of 17 DNPH derivatized aldehydes and ketones. The standard was prepared by diluting the EPA TO-11 DNPH mixture (Supelco) from 15 µg/mL down to a final concentration of 240 ng/mL. Additionally, 2-butanone (methyl ethyl ketone) and methacrolein were added to the calibration standard at a concentration of 300 ng/mL. Sample output of the calibration standard from the HPLC using the method described above is shown in Figure 7. All peaks are resolved with the exception of meta- and paratolualdehyde, which coelute. Also, there is peak overlap between 2-butanone and methacrolein, which is not ideal but not problematic.

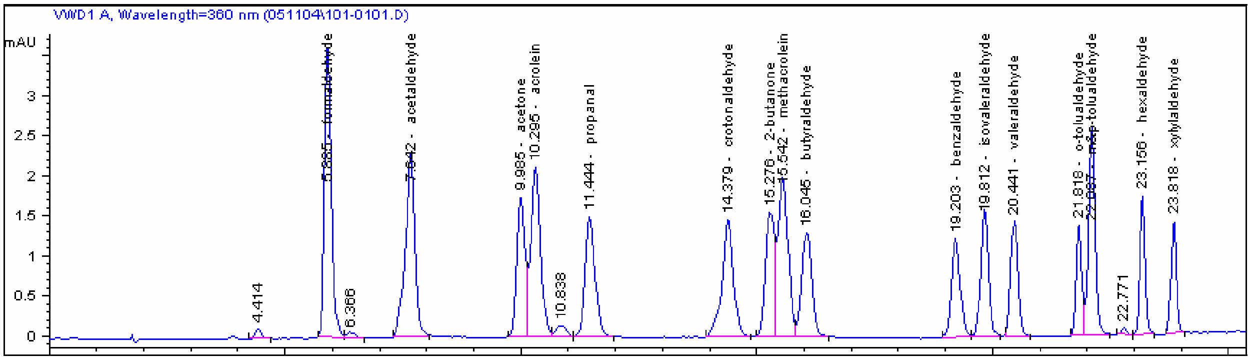


Figure 7: Sample Output from the HPLC for a Calibration Standard Using the Method Defined in Table 3

These concentrations were then converted to mass per unit distance units according to equations in CFR 40, Part 86, Subpart N [5]. The analysis included the following compounds:

- Formaldehyde
- Acetaldehyde
- Acetone
- Acrolein
- Propanal
- Crotonaldehyde
- 2-Butanone
- Methacrolein
- Butyraldehyde
- Benzaldehyde
- Isovaleraldehyde
- Valeraldehyde
- o-Tolualdehyde
- m&p-Tolualdehyde
- Hexaldehyde
- 2,5-Dimethylbenzaldehyde

4.2.2 Analytical Method for Hydrocarbons

Gaseous exhaust samples were also collected and analyzed on site by NREL for 1,3-butadiene and BTEX (benzene, toluene, ethylbenzene, and xylene isomers) using gas chromatography methods. Diluted exhaust samples were collected in 3.2 L canisters lined with fused silica (Entech Instruments, Part #29-10322G). The sample was collected from a 90-degree probe located along the center of the dilution tunnel at the sampling plane and conveyed through a non-heated Teflon sample line by an Air Dimensions Mini-Diavac diaphragm pump to the sample canister. A Sierra Sidetrack Model 840L-2-OV1-SV1-E-V1-S1 mass flow controller measured and controlled the sample rate. The sample was filtered through a glass microfiber filter element with a 95% efficient retention at 0.03 µm to remove PM from the sample before it entered the sample canister. After sample collection, the canisters were maintained at 100°C to prevent condensation until analysis could be performed. All samples were analyzed within 2 hours of collection.

A metal bellows pump was used to pump gas samples through the injection valve system for the gas chromatograph (GC). The injection valve system included a low-pressure gas regulator (Porter Instruments Co. Model 8310) upstream of an eight-way air-actuated Valco valve. Downstream of the Valco valve was a needle valve for back pressure and a gas flow meter. The sample was pumped at a pressure of 25 psig and a flow rate of approximately 25 mL/min. Two sample loops were connected to the Valco valve (in series when the valve was in "load" position) with volumes of 1 and 5 mL. Sample gas was pumped for approximately 2 minutes prior to injection for GC analysis. After injection, the sample loop was flushed thoroughly with hot helium gas.

The gas was analyzed using a Hewlett-Packard 5890 Series II GC equipped with cryogenic cooling and dual FID. Two identical DB-1 capillary columns (J&W Scientific, 60 m × 0.32 mm id × 1 µm film) were used for the analysis. The only difference in the two columns was the size of the sample injected. The column with the 1 mL sample was used to resolve C_1 to C_3 peaks, whereas the column with the 5 mL sample loop was used for C_4 to C_{12} compounds. Details of the analytical method are shown in Table 4.

Table 4: GC Analytical Method for Hydrocarbons

Inlet temperature	220°C
Carrier	UHP Helium at 1.5 mL/min
Oven program	0–3 min: Hold at -60°C 3–14 min: Ramp to 50°C at 10°C/min 14–56.5 min: Ramp to 220°C at 4°C/min 56.5–59 min: Hold at 220°C
Detectors	Dual FID at 280°C

The GC was calibrated using a 23-component mixture (Scott Specialty Gases, CRC Mix #4) of HC. The concentration of each compound varies but is approximately 5 ppmC for most compounds. The mixture was loaded into a gas sampling canister, and the same method of sample introduction was used. A sample of the calibration chromatogram from the column with the smaller sampling loop is shown in Figure 8.

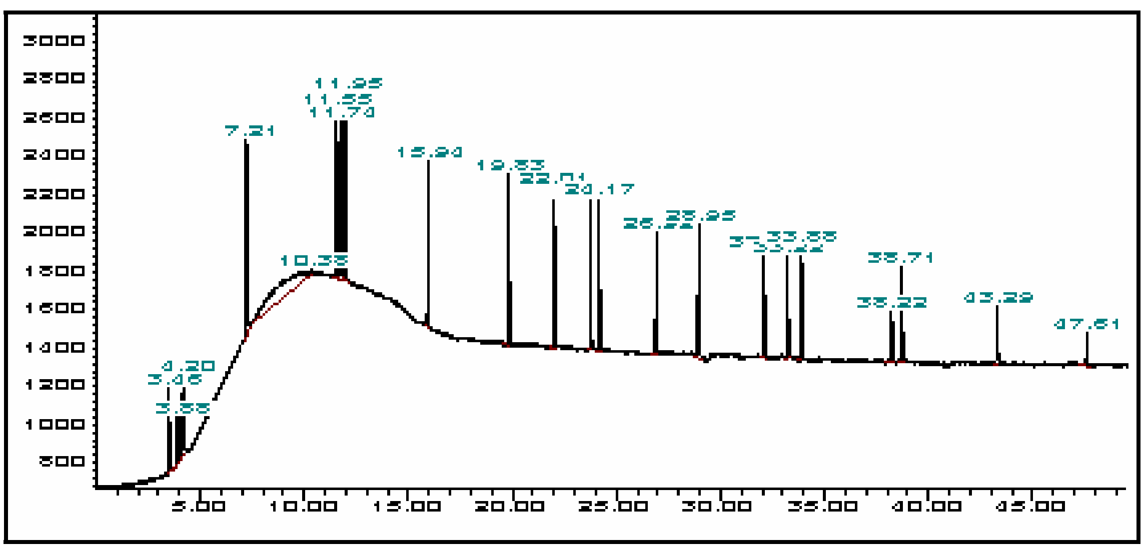


Figure 8: Sample Calibration Chromatogram

After each use, canisters were cleaned with an automated canister cleaning system (Entech Instruments). During the cleaning procedure, up to 6 canisters could be connected to a manifold that was in an oven maintained at 100°C. The cleaning procedure consisted of evacuating the canister to approximately 20 mtorr and holding it at vacuum for 10 min. The canister was then filled with humidified air to a pressure of 20 psig and held for another 10 min. This cycle was repeated three times, and then the canister was finally evacuated to 10 mtorr.

4.3 Test Cycle

Phase I of the WMATA emission testing used the Central Business District (CBD) driving cycle. For this program, it was determined that the WMATA cycle provided a more real-world duty cycle. The WMATA cycle is a fleet-specific dynamometer driving schedule derived from vehicle speed data logged from transit buses during normal operation in Washington, D.C., and surrounding areas. Vehicle speed data were recorded using a Global Positioning System for multiple routes within the WMATA system. These data constituted a database of vehicle activity, which was analyzed to characterize the duty cycle of a typical WMATA transit bus. The WMATA cycle is shown in Figure 9.

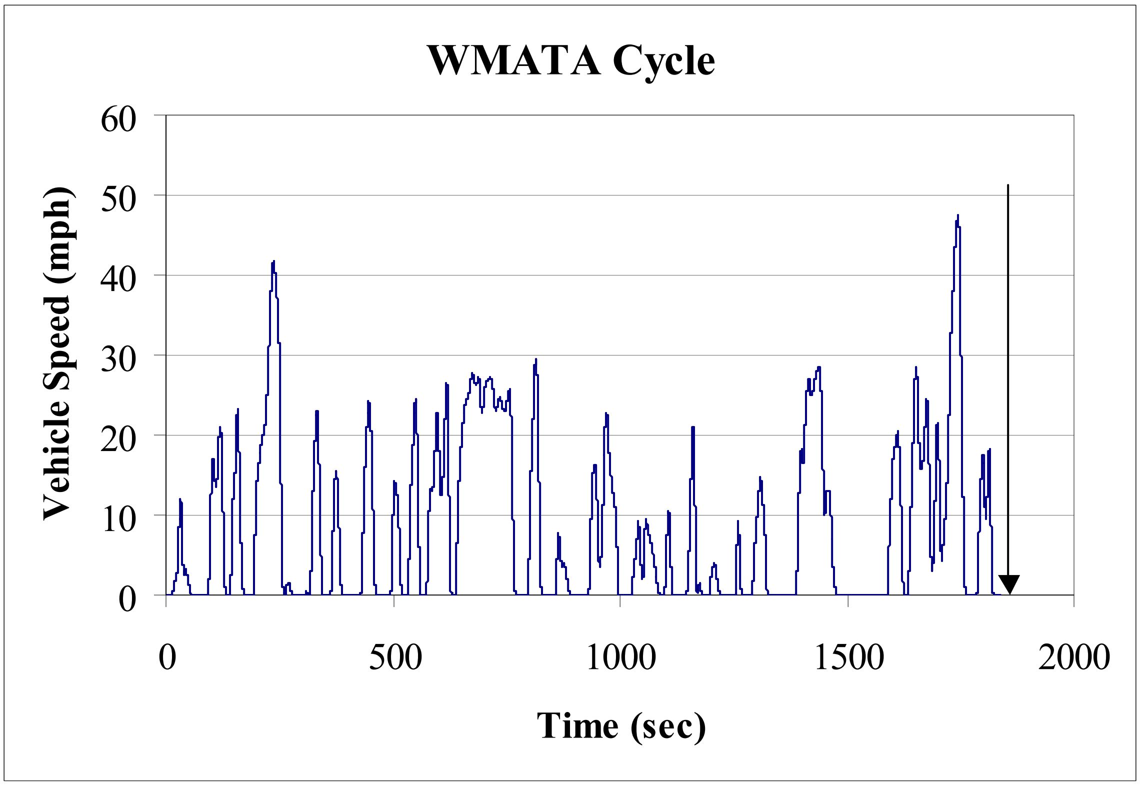


Figure 9: The WMATA Cycle

5.0 Test Fuels

At WMATA, natural gas is purchased from Washington Gas, and buses are fueled at WMATA's Bladensburg facility in northeast Washington, D.C. A fuel sample was taken from the first CNG bus as it was installed on the WVU dynamometer. Table 5 shows the results of the natural gas fuel analysis.

Table 5: WMATA Compressed Natural Gas Properties, April 2004

Gas Analytical Services, Inc.

P.O. Box 1028
Bridgeport, WV 26330-0461
Phone: (304) 623-0020
FAX: (304) 624-8065

FRACTIONAL ANALYSIS

Customer:	West Virginia University – MAE Department	**Sample Date:**	04/07/2004
Field:	Morgantown, WV	**Sample Time:**	00:00
Analysis #:	27091	**Collected By:**	B. Rapp
Station:	WMATA Bus 2302	**Effective Date:**	04/07/2004
Meter:		**Sample Pressure**	2200.00PSIG

Component	MOL %	GPM
Methane	94.291	
Ethane	3.624	0.97
Propane	0.627	0.17
I-Butane	0.101	0.03
N-Butane	0.112	0.04
I-Pentane	0.023	0.01
N-Pentane	0.018	0.01
Nitrogen	0.558	
CO2	0.564	
Oxygen	0.003	
Hexanes+	0.079	0.03
Total:	100.000	1.26

Analytical Results at Base Conditions	
BTU/SCF (Dry):	1049.599
BTU/SCF (Saturated):	1032.256
PSIA:	14.730
Temperature (°F):	60.000
Z Factor (Dry):	0.99777
Z Factor (Saturated):	0.99773

Analytical Results at Contract Conditions	
BTU/SCF (Dry):	1049.599
BTU/SCF (Saturated):	1032.256
PSIA:	14.730
Temperature (°F):	60.000
Z Factor (Dry):	0.99777
Z Factor (Saturated):	0.99773

Calculated Specific Gravities	
Ideal Gravity:	0.5913
Real Gravity:	0.5924

Gross Heating Values are Based on GPA 2145-91.
Compressibility is Calculated using AGA-8.

Diesel buses at WMATA are fueled with low-sulfur diesel fuel purchased from Tosco. There are several locations for refueling in the city, and all are supplied with the same contract fuel. A fuel sample was taken from the first diesel bus as it was installed on the WVU dynamometer. Table 6 shows the results of the diesel fuel analysis.

6.0 Results and Discussion

Emission data are summarized in Table 7. Bus number 2307 (CNG with CWI G Gas Plus engine) exhibited extremely high CO emissions compared with the other buses in the group. The anomalous CO result may indicate a malfunction or maintenance problem. Although results from bus 2307 are included in Table 7 and subsequent emissions results figures and tables, they are excluded from the average emissions results for this group discussed in the text.

Table 6: WMATA Diesel Properties, June 2004

Test Parameter	Test Method	WMATA BUS 9655
Density, g/mL API	ASTM D4052	0.8300 38.9
Kinematic Viscosity, 40°C, cSt	ASTM D445	1.773
Flash Point (°C)	ASTM D93	68.9
Pour Point (°C)	ASTM D97	-48
Sulfur (ppm)	ASTM D5453	17.9
Distillation (°C) IBP 10% 50% 90% FBP Recovery (vol%) Loss (vol%) Residue (vol%)	 ASTM D86	 179.1 202.8 225.9 254.0 275.0 99.1 0.5 0.5
Ash (mass %)	ASTM D482	< 0.001
Gross Heat of Combustion (BTU/lb) Net Heat of Combustion (BTU/lb)	ASTM D240	19675.4 18447.4
Carbon (mass %) Hydrogen (mass %) Oxygen (mass % by difference)	ASTM D5291	86.19 13.46 < 0.10
Cloud Point (°C)	ASTM D2500	-46
SFC Aromatics (mass %) Monoaromatics PNA Total Aromatics	ASTM D5186	 18.3 3.4 21.6
Hydrocarbon Types (vol %) Aromatics Olefins Saturates	ASTM D1319	 19.7 1.1 79.2
Gum Content (mg/100 mL)	ASTM D381	1.8
Cetane Number	ASTM D613	45
Water and Sediment	ASTM D2709	0.01
Copper Corrosion	ASTM D130	1A
Carbon Residue (mass %)	ASTM D524	0.05

API—American Petroleum Institute; cSt—centiStokes; FBP—final boiling point; IBP—initial boiling point; PNA—polynuclear aromatics; SFC—supercritical fluid chromatography.

6.1 Oxides of Nitrogen

Figure 10 shows NO_x emissions. The x-axis labels indicate engine model, fuel type, aftertreatment device, and vehicle ID number. Each NO_x result represents the average of three test runs. Each nitrogen oxide (NO) result is the average of two test runs. The error bars show the maximum and minimum individual test run values. The error bars do not indicate the standard deviation, confidence interval, or other statistically derived quantification of error. Chassis dynamometer emission results are given in units of g/mi; these results cannot be compared directly with emission standards (e.g., EPA standards) derived from engine dynamometer testing, which have units of g/bhp-hr.

Table 7: Summary of Emission Results

Vehicle Configuration	Vehicle Number	Test ID	Run ID	CO (g/mi)	NO_X (g/mi)	NO (g/mi)	CH_4 (g/mi)	NMHC* (g/mi)	PM (g/mi)	CO_2 (g/mi)	Miles	mpeg	BTU/mile
	Diesel Buses with MY 2000 DDC Series 50 Engines												
MY 2000 DDC Series 50 with DPX	2073	4166	1	0.27	26.1			BDL	0.016	3,266	4.25	2.96	43,267
			2	0.25	25.8	18.9		BDL	0.013	3,232	4.26	2.99	42,805
			3	0.18	24.9	17.6		BDL	0.011	3,229	4.24	2.99	42,765
		Average		**0.23**	**25.6**	**18.2**		**BDL**	**0.013**	**3,242**	**4.24**	**2.98**	**42,946**
	2074	4169	1	0.04	24.1			0.002	0.007	3,087	4.22	3.13	40,896
			2	0.33	23.9	18.1		BDL	0.005	3,067	4.22	3.15	40,632
			4	0.11	23.1	17.7		BDL	0.012	3,074	4.22	3.14	40,725
		Average		**0.16**	**23.7**	**17.9**		**0.002**	**0.008**	**3,076**	**4.22**	**3.14**	**40,751**
	2000 DDC S50 Average			**0.19**	**24.6**	**17.7**		**0.002**	**0.010**	**3,159**	**4.23**	**3.06**	**41,848**
	Diesel Buses with MY 2004 DDC Series 50 Engines												
MY 2004 DDC Series 50 with EGR & DPX	9612	4151	1	0.27	18.3			BDL	0.011	3,472	4.19	2.78	45,988
			3	0.44	17.9	13.1		BDL	0.007	3,430	4.25	2.82	45,432
			4	0.33	17.5	12.2		0.0028	0.013	3,424	4.23	2.82	45,354
		Average		**0.34**	**17.9**	**12.6**		**0.003**	**0.010**	**3,442**	**4.22**	**2.81**	**45,591**
	9633	4163	1	0.29	17.4			BDL	0.046	3,298	4.24	2.93	43,684
			2	0.23	16.9	8.7		BDL	0.042	3,278	4.26	2.95	43,427
			3	0.19	17.6	9.3		BDL	0.054	3,308	4.25	2.92	43,824
		Average		**0.24**	**17.3**	**9.0**		**BDL**	**0.047**	**3,295**	**4.25**	**2.93**	**43,645**
	9655	4148	1	0.34	18.3			BDL	0.020	3,299	4.22	2.93	43,703
			2	0.54	18.1	12.9		BDL	0.017	3,296	4.21	2.93	43,662
			3	0.41	18.7	13.5		BDL	0.021	3,312	4.22	2.92	43,872
		Average		**0.43**	**18.4**	**13.2**		**BDL**	**0.019**	**3,302**	**4.21**	**2.92**	**43,746**
	2004 DDC S50 Average			**0.34**	**17.9**	**11.6**		**0.003**	**0.025**	**3,346**	**4.23**	**2.89**	**44,327**
	CNG Buses with MY 2001 CWI C Gas Plus Engines												
MY 2001 CWI C8.3G+ CNG with oxidation catalyst	2302	4142	1	0.68	18.5		14.2	0.95	BDL	2,115	4.23	3.19	40,069
			2	0.49	17.5	14.7	13.9	0.94	BDL	2,063	4.28	3.27	39,079
			3	0.48	17.6	14.6	13.9	1.15	BDL	2,087	4.26	3.23	39,535
		Average		**0.55**	**17.9**	**14.6**	**14.0**	**1.01**	**BDL**	**2,088**	**4.26**	**3.23**	**39,561**
	2304	4139	2	0.26	17.0		15.6	1.11	0.011	1,209	4.26	3.19	40,033
			3	0.50	17.3	14.2	16.0	1.12	0.006	2,127	4.25	3.17	40,390
			4	0.37	17.8	14.4	16.1	1.13	0.005	2,092	4.24	3.22	39,749
		Average		**0.38**	**17.4**	**14.3**	**15.9**	**1.12**	**0.008**	**2,110**	**4.25**	**3.19**	**40,058**
	2307	4145	**1**	10.53	25.3		15.2	0.92	0.010	2,157	4.23	3.10	41,195
			2	8.61	24.5	21.8	16.9	1.05	0.009	2,145	4.23	3.12	41,004
			3	7.37	23.5	20.7	17.5	1.05	0.006	2,111	4.22	3.17	40,372
		Average		**8.84**	**24.4**	**21.2**	**16.5**	**1.01**	**0.008**	**2,138**	**4.22**	**3.13**	**40,857**
	2308	4198	1	0.77	21.7		21.8	1.18	0.025	2,585	4.22	2.60	49,207
			2	0.70	22.0	18.1	22.2	1.19	0.021	2,566	4.22	2.62	48,868
		Average		**0.73**	**21.8**	**18.1**	**22.0**	**1.18**	**0.023**	**2,575**	**4.22**	**2.61**	**49,038**
	CWI Average			**2.63**	**20.4**	**17.1**	**17.1**	**1.08**	**0.009**	**2,228**	**4.24**	**3.04**	**42,378**
	CWI Average w/out 2307			**0.55**	**19.0**	**15.7**	**17.3**	**1.10**	**0.010**	**2,258**	**4.24**	**3.01**	**42,886**

*THC for the diesel buses.

Table 7 (continued)

Vehicle Configuration	Vehicle Number	Test ID	Run ID	CO (g/mi)	NO_X (g/mi)	NO (g/mi)	CH_4 (g/mi)	NMHC* (g/mi)	PM (g/mi)	CO_2 (g/mi)	Miles	mpeg	BTU/mile
	CNG Buses with MY 2004 John Deere 6081H Engines												
MY 2004 John Deere 6081H CNG with oxidation catalyst	2460	4154	1	0.27	5.7		9.51	0.43	0.003	1,907	4.22	3.56	35,920
			2	0.06	5.7	4.7	N/A	**N/A**	0.004	1,914	4.23	3.55	36,052
			3	0.27	6.1	5.0	**9.51**	0.91	0.002	1,919	4.23	3.54	36,165
		Average		**0.20**	**5.82**	**4.8**	**9.51**	**0.67**	**0.003**	**1,913**	**4.23**	**3.55**	**36,046**
	2462	4160	1	BDL	**11.6**		10.2	0.48	0.003	2,375	4.23	2.87	44,626
			2	0.16	11.4	9.4	10.6	0.51	0.003	2,343	4.23	2.90	44,063
			3	0.12	11.5	**9.6**	10.6	0.42	0.006	2,357	4.22	2.89	44,330
		Average		**0.09**	**11.5**	**9.5**	**10.5**	**0.47**	**0.004**	**2,358**	**4.23**	**2.88**	**44,330**
	2463	4157	2	**0.14**	10.3	8.9	**11.0**	0.62	0.004	2,245	4.23	3.03	42,274
			3	0.14	10.1	8.6	12.7	N/A	0.006	2,233	4.24	3.04	42,087
			5	0.12	9.4		11,5	0.42	0.008	2,262	4.24	3.00	42,608
		Average		**0.13**	**9.92**	**8.7**	**11.8**	**0.52**	**0.006**	**2,247**	**4.24**	**3.02**	**42,323**
	John Deere Average			**0.14**	**9.08**	**7.7**	**10.6**	**0.55**	**0.004**	**2,173**	**4.23**	**3.15**	**40,899**

*THC for the diesel buses.

Two chemiluminescent NO_x analyzers were used to estimate the NO and NO_2 split. These analyzers shared a common probe in the dilution tunnel and could operate in either NO_x (NO + NO_2) or NO mode. During the first test run of each series, both analyzers were set in NO_x mode to verify satisfactory agreement between the two analyzers; therefore, there is not an NO result for the first run of each series. In subsequent runs, one analyzer was set in the NO_x mode, and the other was set to the NO mode. This approach made it simple and convenient to study emissions trends from diesel buses equipped with catalyzed particulate filters and natural gas buses equipped with oxidation catalysts. Emissions from vehicles equipped with catalyzed particulate filters and other aftertreatment devices may produce 30%–40% of the NO_x as NO_2. In these cases, it is possible to gather information on NO/NO_2 fractions from the NO_x and NO measurements with an expected accuracy of approximately plus or minus 10%.

The John Deere CNG buses averaged 9.08 g/mi NO_x, with a high of 11.5 g/mi and a low of 5.82 g/mi. NO constituted 82%–88% of total NO_x emissions.

The MY 2004 DDC diesel buses with EGR and DPX particulate filters averaged 17.9 g/mi NO_x, with a high of 18.4 g/mi and a low of 17.3 g/mi; NO_x emissions were highly consistent among the test buses. NO constituted 52%–72% of total NO_x emissions.

The CWI CNG buses averaged 19.0 g/mi NO_x, with a high of 21.8 g/mi and a low of 17.4 g/mi. NO constituted approximately 82% of total NO_x emissions.

The MY 2000 DDC diesel buses with DPX particulate filters averaged 24.6 g/mi NO_x, with a high of 25.6 g/mi and a low of 23.7 g/mi. NO constituted approximately 72% of total NO_x emissions.

6.2 Particulate Matter

Figure 11 shows PM emissions. Each PM result represents the average of three test runs. The error bars show the maximum and minimum individual test run values. PM emissions from all of the buses were very low—less than 0.05 g/mi.

The John Deere CNG buses averaged 0.004 g/mi PM, with a high of 0.006 g/mi and a low of 0.003 g/mi.

The MY 2004 DDC diesel buses with EGR and DPX particulate filters averaged 0.025 g/mi PM, with a low of 0.01 g/mi and a high of 0.047 g/mi.

The CWI CNG buses averaged 0.010 g/mi PM, with a high of 0.023 g/mi; PM emissions from bus number 2302 were below the detectable limit of the laboratory and measurement techniques employed.

The MY 2000 DDC diesel buses with DPX particulate filters averaged 0.010 g/mi PM, with a high of 0.013 g/mi and a low of 0.008 g/mi.

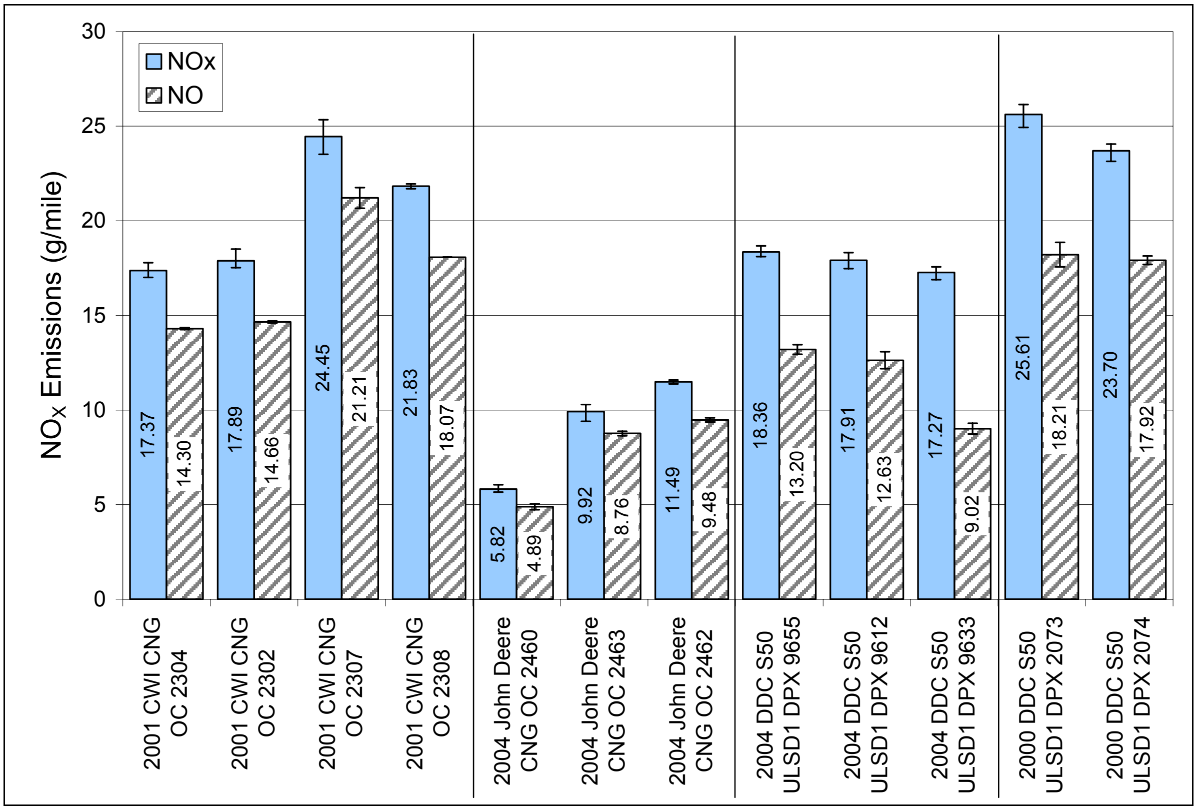


Figure 10: NO_x Emissions

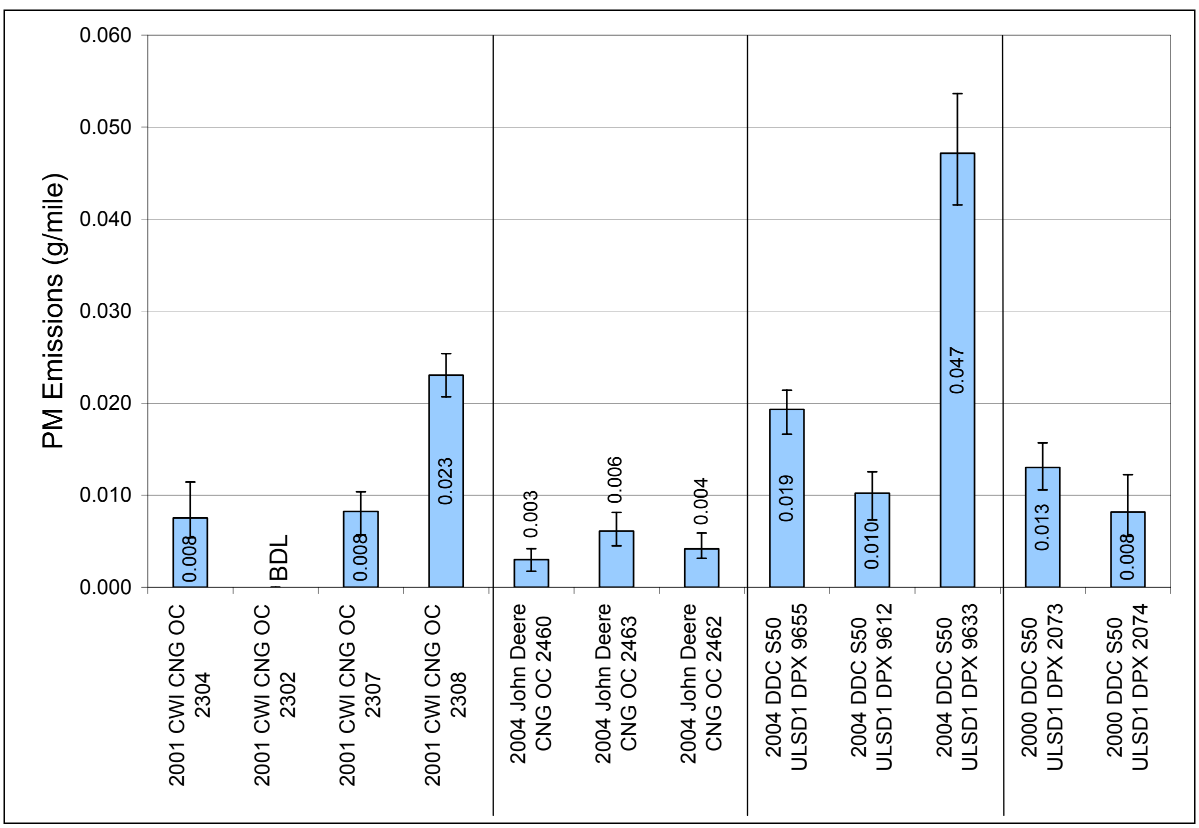


Figure 11: PM Emissions

6.3 Carbon Monoxide

Figure 12 shows CO emissions. CO emissions were extremely low for all vehicle technologies tested with the exception of one anomalously high result from CWI CNG bus 2307. Although CO emissions are not considered to be a great challenge in meeting future emission regulations, this result may prompt a closer look at the durability of specific oxidation catalysts. See Section 7.1 below for further discussion of CO results.

The John Deere CNG buses averaged 0.14 g/mi CO. The MY 2004 DDC diesel buses averaged 0.34 g/mi CO. The CWI CNG buses averaged 0.55 g/mi CO. The MY 2000 DDC diesel buses averaged 0.19 g/mi CO.

6.4 Hydrocarbons

Figure 13 shows HC emissions. THC emissions are shown for the diesel buses, whereas only NMHC are plotted for the CNG buses. For the diesel buses, THC emissions were below the detection limit for most test runs, most likely owing to the use of catalyzed particulate filters. The CWI CNG buses averaged 1.10 g/mi NMHC, and the John Deere CNG buses averaged 0.55 g/mi NMHC.

Figure 14 shows methane (CH_4) emissions for the CNG buses. Methane is not an ozone precursor and is, therefore, not regulated by the EPA or California Air Resources Board (CARB). For regulatory purposes, only the NMHC emissions from natural gas vehicles are considered. Figure 14 shows two methane values for each vehicle, one from WVU measurements and one from NREL measurements; the measurement methods are described in sections 4.1.2 (WVU) and 4.2.2 (NREL) above. Using the WVU method, methane emissions from the CWI CNG buses averaged 17.3 g/mi, with a high of 22.0 g/mi and a low of 14.0 g/mi. The John Deere CNG buses averaged 10.6 g/mi methane, with a high of 11.8 g/mi and a low of 9.51 g/mi.

6.5 Carbon Dioxide

Figure 15 shows CO_2 emissions. CO_2 is a greenhouse gas produced by complete combustion. Neither the EPA nor CARB currently regulate CO_2 emissions. However, with recently increased emphasis on the issue of global warming, there is increased focus on CO_2 emissions, and CO_2 emissions might be regulated in the future. In the short and medium term, voluntary incentives and increasing pressure for action by environmental groups may drive reductions in CO_2 emissions. CO_2 emissions averaged 3,159 g/mi from the MY 2000 DDC diesel buses and 3,346 g/mi from the MY 2004 DDC diesel buses. CO_2 emissions averaged 2,258 g/mi from the CWI CNG buses and 2,173 g/mi from the John Deere CNG buses.

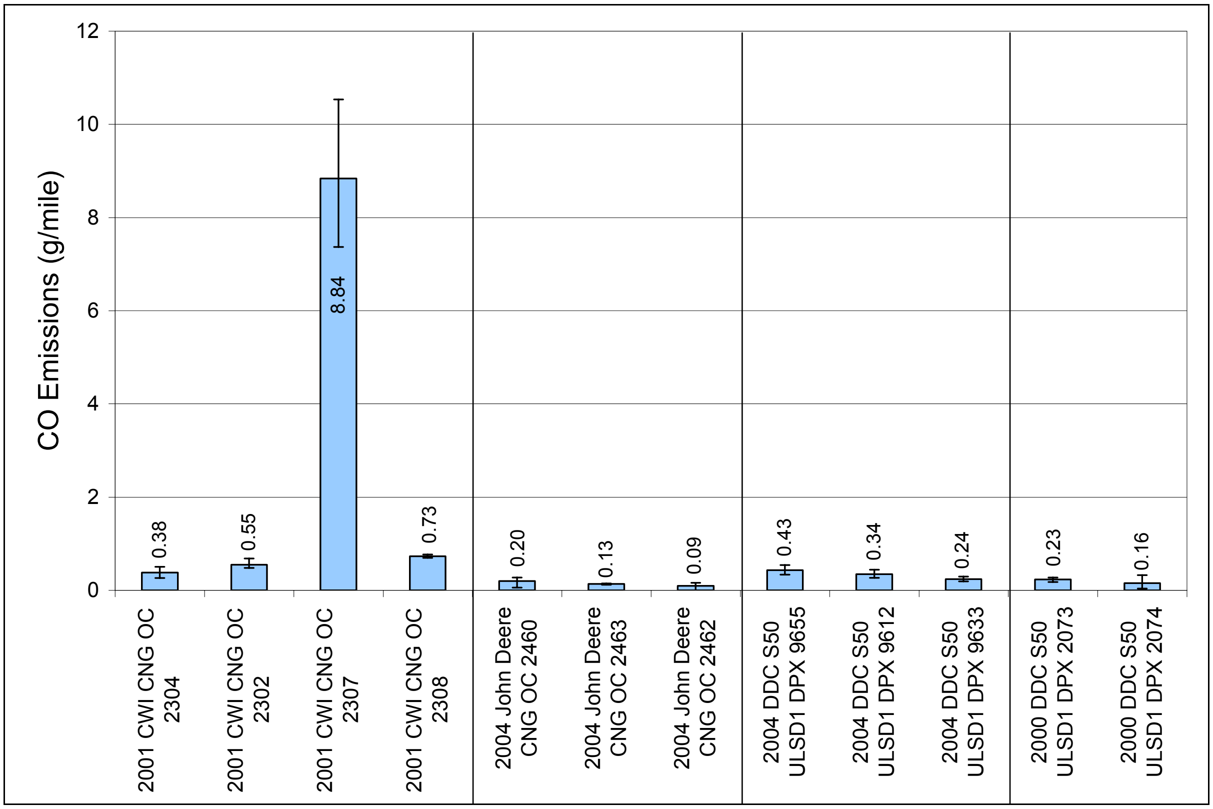


Figure 12: CO Emissions

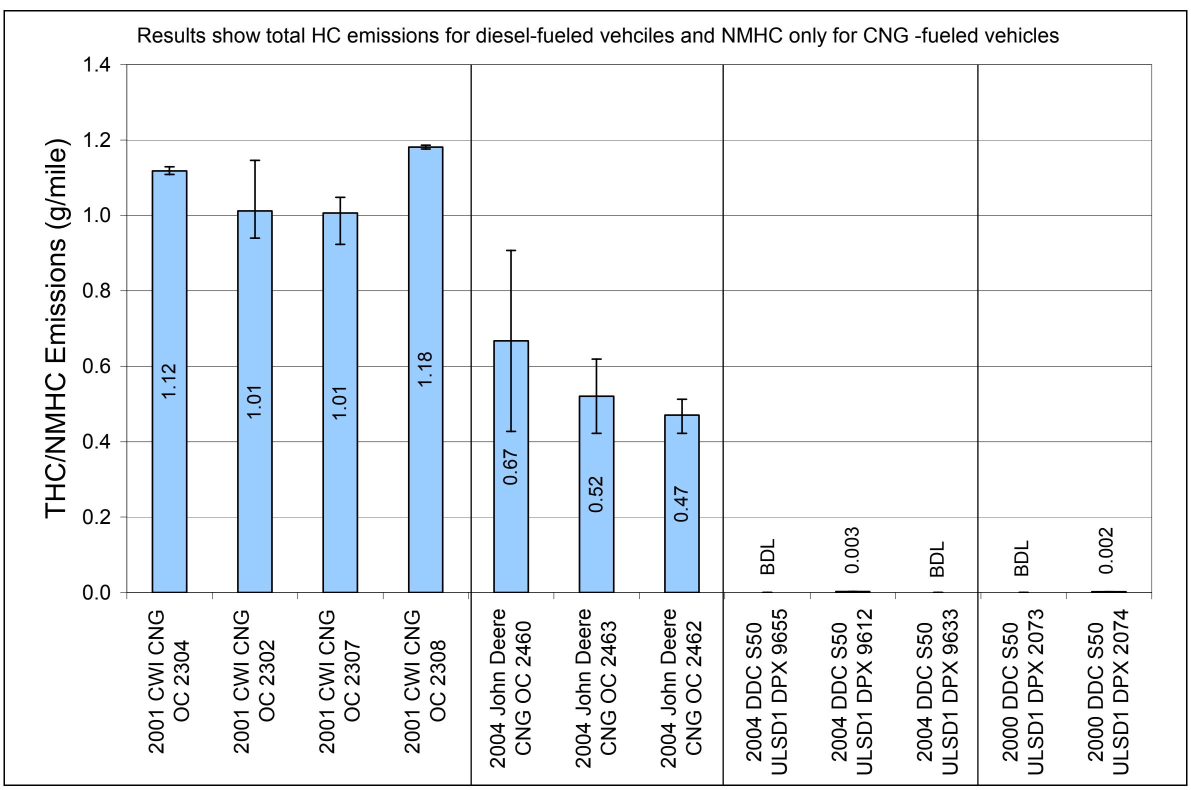


Figure 13: THC (Diesel Vehicles) and NMHC (CNG Vehicles) Emissions

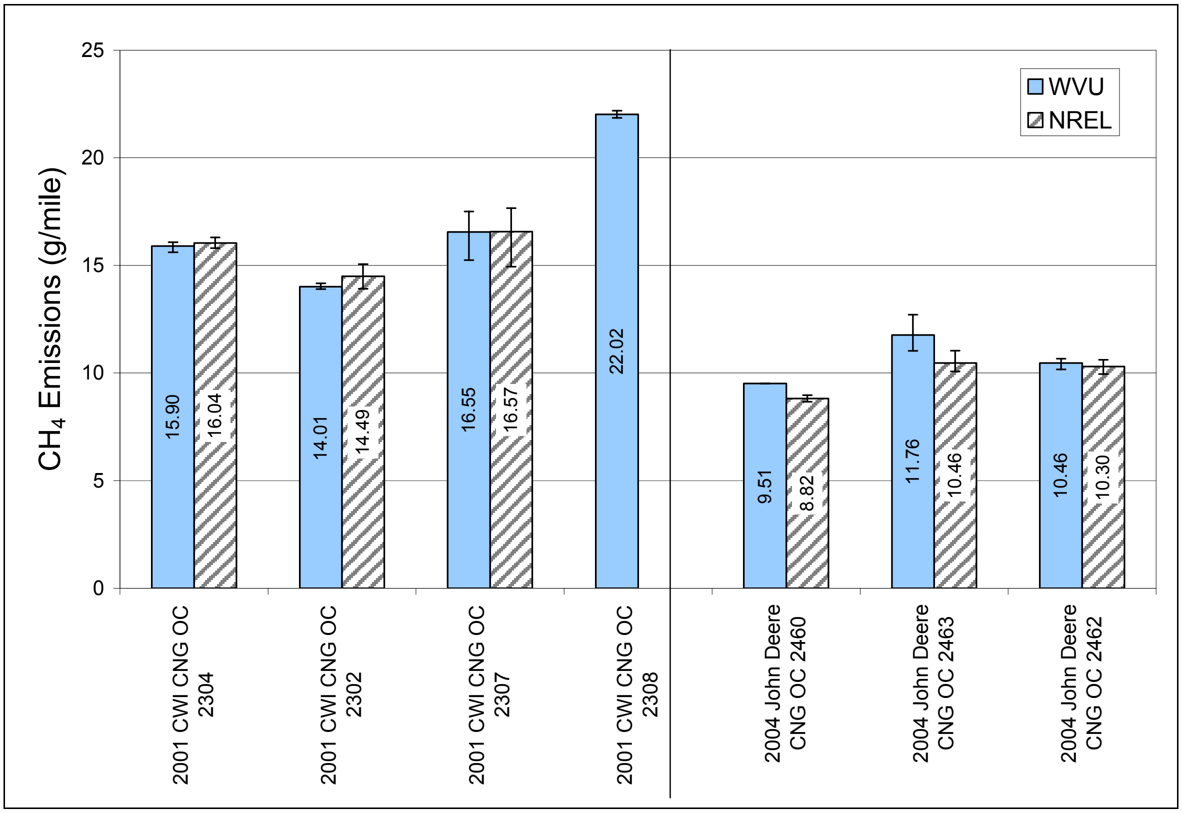


Figure 14: Methane Emissions (CNG vehicles only)

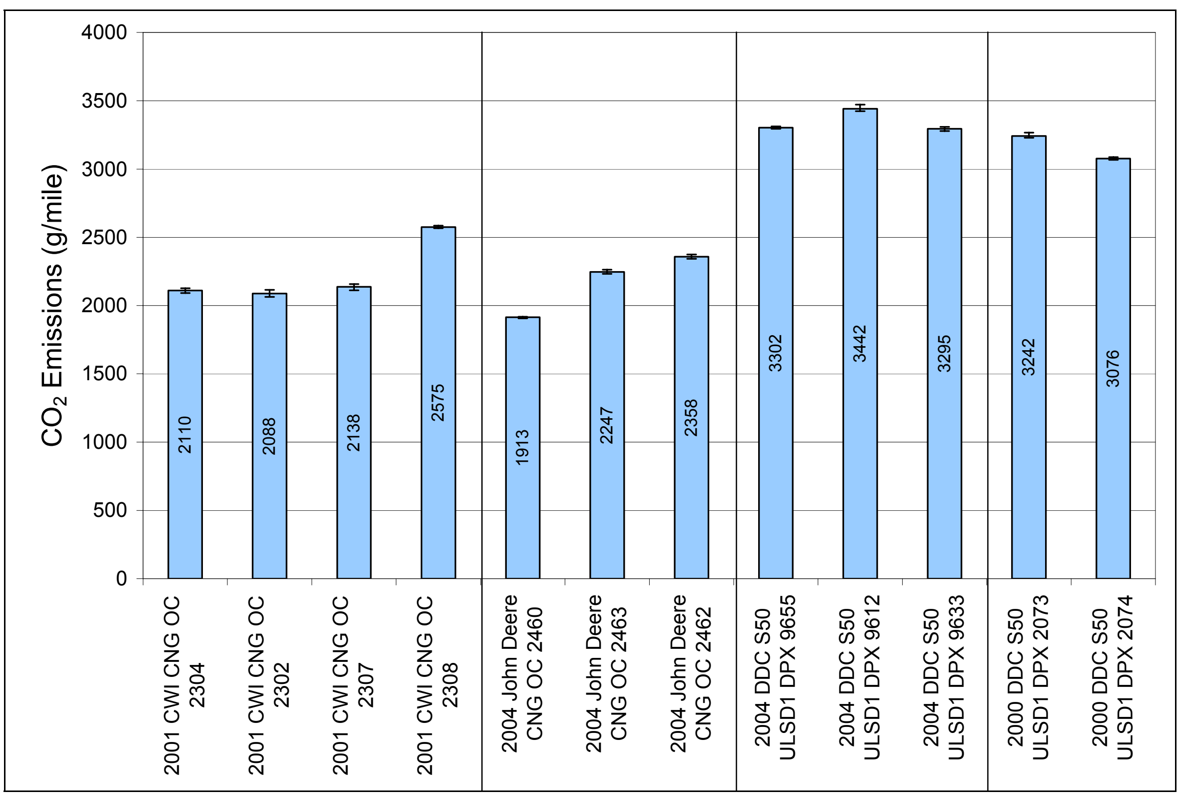


Figure 15: CO_2 Emissions

6.6 Fuel Economy

Fuel consumption and economy results were computed using a carbon balance, fuel properties, and measured emissions data. The carbon compounds (CO_2, CO, and HC) emitted in the exhaust were measured, and the fuel consumption was calculated using a carbon balance equation. Fuel economy was converted to miles per energy equivalent diesel gallon (mpeg) to facilitate comparison among the diesel and CNG buses. Fuel analysis results for the ultra-low sulfur diesel fuel and the CNG fuels are provided in Table 5 and Table 6.

The mass of carbon measured in the exhaust constituents during testing is calculated as follows:

$$G_S = R_{fuel} HC_{mass} + 0.429 CO_{mass} + 0.273 CO_{2mass} \quad \textbf{(Equation 1)}$$

Where G_S = grams of carbon in the exhaust, R_{fuel} = the ratio of carbon to hydrogen plus other constituents in the fuel (equals 0.75 for pure methane), HC_{mass} = HC emissions in grams (this assumes the HC in the exhaust have the same carbon mass fraction as the unburned fuel), CO_{mass} = CO emissions in grams, and CO_{2mass} = CO_2 emissions in grams. When a detailed fuel composition is known, R_{fuel} is calculated by determining the ratio of the mass of carbon in the fuel to the total mass of the fuel as shown in Table 8 for the CNG fuel. A similar calculation was performed for the diesel fuel.

Table 8: Calculation of the Carbon Weight Fraction (R_{fuel}) for CNG

	Mole %	Mass of Carbon (g)	Mass of Hydrogen & Others (g)
Methane CH_4	94.291	94.291*(1)*(12) = 1,131.492	94.291*(4)*(1) = 377.164
Ethane C_2H_6	3.624	3.624*(2)*(12) = 86.976	3.624*(6)*(1) = 21.744
Ethene C_2H_4	< 0.1	0*(2)*(12) = 0	0*(4)*(1) = 0
Propane C_3H_8	0.627	0.627*(3)*(12) = 22.572	0.627*(8)*(1) = 5.016
Propylene C_3H_6	< 0.1	0*(3)*(12) = 0	0*(6)*(1) = 0
Butanes C_4H_{10}	0.213	0.213*(4)*(12) = 10.224	0.213*(10)*(1) = 2.13
Butenes C_4H_8	< 0.1	0*(4)*(8) = 0	0*(8)*(1) = 0
Pentanes C_5H_{12}	0.041	0.041*(5)*(12) = 2.46	0.041*(10)*(1) = 0.492
Pentenes C_5H_{10}	< 0.1	0*(5)*(10) = 0	0*(10)*(1) = 0
Hexanes C_6H_{14}	0.079	0.079*(6)*(14) = 5.688	0.079*(14)*(1) = 1.106
C_6 +	< 0.1	0*(6)*(12) = 0	0*(14)*(1) = 0
CO_2	< 0.564	0.564*(1)*(12) = 6.768	0*(2)*(16) = 0
CO	< 0.1	0*(1)*(12) = 0	0*(1)*(16) = 0
O_2	0.003	0.003*(0)*(12) = 0	0.003*(2)*(16) = 0.096
N_2	0.558	0.558*(0)*(12) = 0	0.558*(2)*(14) = 15.624
H_2	< 0.1	+ 0*(0)*12) = 0	+ 0*(2)*(1) = 0
Sum		**1266.18**	**441.42**

$$R_{fuel} = \frac{1266}{(1266 + 441)} = 0.741 \quad \textbf{(Equation 2)}$$

The diesel energy equivalent fuel economy was calculated by computing the mass of carbon in a unit mass of CNG fuel having energy content equivalent to one gallon of CARB diesel fuel, as shown in Table 9. Relevant diesel fuel properties are included in Table 6. Fuel economy is then computed as follows:

$$MPG = \left[\frac{gC/equiv\,gal}{G_S}\right](\text{distance traveled}) \qquad \textbf{(Equation 3)}$$

Table 9: Calculation of Energy Equivalent Fuel Economy

	ULS Diesel #1	CNG
Density	3,142 g/gal	20.483 g/ft^3
Lower Heating Value	40.70 BTU/g	50.40 BTU/g
R_{fuel}	0.866 gC/g fuel	0.723 gC/g fuel
gC/equiv gal	2,636 gC/gal	1,881.7 gC/equiv gal

Figure 16 shows diesel energy equivalent fuel economy results. The John Deere CNG buses averaged 3.15 mpeg, with bus number 2460 performing somewhat better than the other two buses in the group. The MY 2004 DDC diesel buses averaged 2.89 mpg. The CWI CNG buses averaged 3.01 mpeg; the fuel economy of bus number 2308 was markedly lower than the other three buses in this group. The MY 2000 DDC diesel buses averaged 3.06 mpg. These are promising fuel economy results for the CNG buses; CNG buses typically suffer a fuel economy penalty compared with diesel buses. These results will be compared with in-use fuel economy results from WMATA.

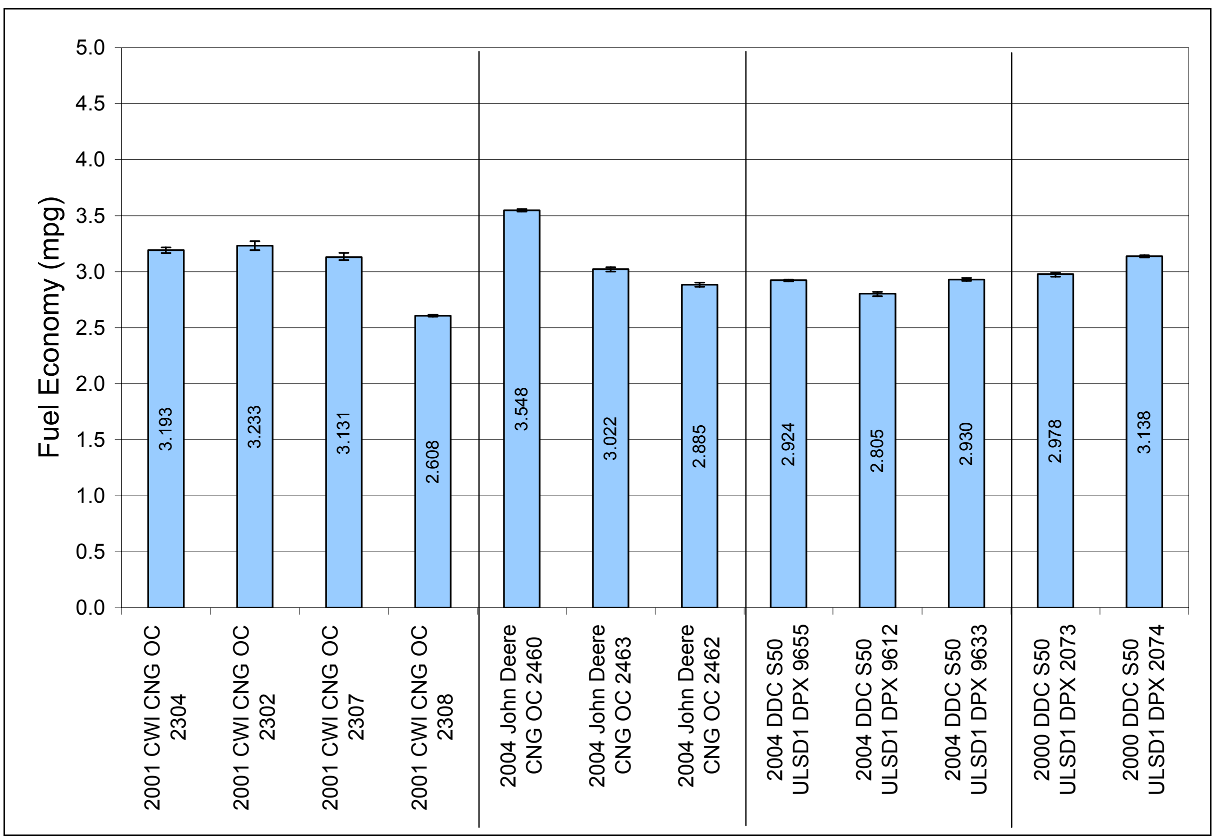


Figure 16: Diesel Energy Equivalent Fuel Economy

6.7 Carbonyl Emissions

Samples were collected and analyzed to determine the levels of carbonyl (aldehyde and ketone) compounds in the vehicle exhaust and ambient background air. Results are summarized in Table 10 and Table 11. Common practice dictates that the emissions values be background corrected according to equations specified in CFR40, Part 86, Subpart N [5] of the following form:

$$C_{mass} = (V_{mix} + V_{sf})x\left[\frac{C_f}{V_{sf}} - \left(\frac{C_{bg}}{V_{bg}}x\left[1-\left(\frac{1}{DF}\right)\right]\right)\right] \quad \textbf{(Equation 4)}$$

Where C_{mass} = mass of the carbonyl constituent emitted in the exhaust of the test vehicle, V_{mix} = total dilute exhaust volume corrected to standard conditions, V_{sf} = total volume of sample passed through the DNPH cartridge corrected to standard conditions, C_f = mass of the carbonyl constituent detected in the sample, C_{bg} = mass of the carbonyl constituent detect in the ambient background sample, V_{bg} = total volume of ambient air passed through the background sample cartridge, and DF is the dilution factor calculated as DF = 13.4/CO_{2e} for petroleum-fueled vehicles, where CO_{2e} is the CO_2 concentration in the diluted exhaust sample. This method is inaccurate when concentrations in the vehicle exhaust are very near the ambient background levels because DF is not an accurate representation of the dilution ratio (i.e., volume of exhaust/ volume of dilution air).

The results presented here have not been background corrected. Instead, the ambient background levels are reported along with the uncorrected foreground results. The ambient background levels are reported in units of mg/mi to facilitate comparison with the vehicle test results. The ambient background samples were collected over a period equal to the duration of the WMATA test cycle. The ambient background results were divided by 4.25 mi, the distance traveled during the WMATA cycle.

Figure 17 shows formaldehyde emissions. Each bar represents the average uncorrected emissions value from the three repeat test runs performed on each vehicle. The diamonds with error bars show the background emissions values associated with each vehicle. Table 10 and Table 11 show tabulated results. Anomalously high background emissions values are identified by footnotes in Table 10 and Table 11 but were omitted from the data plotted in Figure 17. Other anomalously high or low test results are also highlighted in the tabulated data, but these results were NOT omitted from the averaged results shown in Figure 17. Ambient background formaldehyde levels averaged 2.380 mg/mi. Formaldehyde emissions from the John Deere CNG buses averaged 8.84 mg/mi. Formaldehyde emissions from the MY 2004 DDC diesel buses averaged 3.147 mg/mi; these formaldehyde levels were of the same magnitude as the ambient background levels. The CWI CNG buses emitted substantially higher formaldehyde than the other bus groups, averaging 89.86 mg/mi with a low of 68.282 mg/mi and a high of 107.740 mg/mi. Formaldehyde emissions from the MY 2000 DDC diesel buses averaged 8.027 mg/mi.

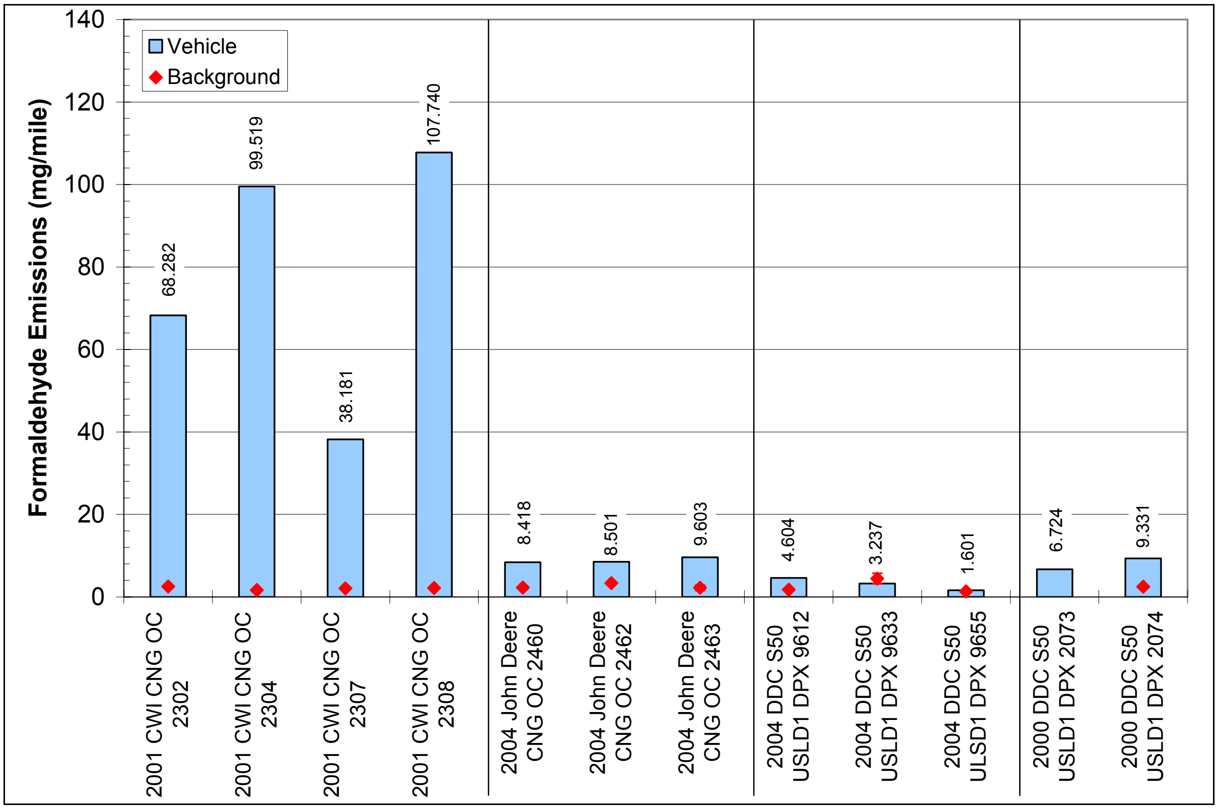


Figure 17: Formaldehyde Emissions

Figure 18 shows acetaldehyde emissions. The ambient background acetaldehyde level averaged over the test program was 2.419 mg/mi; however, the data exhibited more scatter than did the background formaldehyde data. The trend closely followed the formaldehyde results: the MY 2004 DDC diesel buses exhibited the lowest acetaldehyde emissions, followed by the John Deere CNG buses and the MY 2000 DDC diesel buses. The CWI CNG buses exhibited appreciably higher acetaldehyde emissions than the other buses—only these buses produced acetaldehyde emissions that were above ambient levels.

The formaldehyde and acetaldehyde emission results from the CWI CNG buses are unusual and might indicate a malfunction with the exhaust catalyst or a maintenance/durability issue, neither of which could be verified in time for inclusion in this report. See Section 7.2 below for further discussion of these results.

Figure 19 shows acetone emissions. The average ambient background acetone level was 4.098 mg/mi, but the data exhibited significant scatter. Acetone levels in the exhaust gases were very near ambient levels. Considering the very low acetone levels in the vehicle exhaust and the variability in the ambient background levels, no clear trends are apparent among the engine and bus technologies tested.

Results for other carbonyl compounds are listed in Table 10 and Table 11. Acrolein was detected in low concentrations in the exhaust from the CWI CNG buses. Acrolein was not detected in the ambient background samples. Propanal was detected in the exhaust and ambient background samples, but in nearly all instances the exhaust gas levels were at or below the ambient background levels. Crotonaldehyde was detected at low concentrations in samples from CWI CNG buses 2302 and 2304. The crotonaldehyde results from MY 2004 DDC diesel bus 9655 were anomalously high. Benzaldehyde, 2-butanone, and hexaldehyde were detected in a large number of samples, but exhaust gas levels were at or below ambient background levels.

Samples were collected and analyzed on site by NREL for 1,3-butadiene, BTEX, and other HC compounds using gas chromatography methods. However, the sensitivity of the GC equipment available for the analysis was not sufficient to detect the low levels of these compounds present in the exhaust gases. Results for compounds that were detected are presented in Appendix A.

7.0 Conclusions

7.1 Regulated Emissions and Fuel Economy

Reducing NO_x and PM emissions, particularly NO_x, represents the greatest challenge for heavy-duty engines being developed to meet increasingly strict EPA and California emission standards. This project compared numerous regulated and unregulated emissions of CNG and diesel transit buses, including NO_x and PM.

The John Deere CNG buses produced 49% lower NO_x emissions and 84% lower PM emissions compared with the MY 2004 DDC diesel buses, and 63% lower NO_x emissions and 60% lower PM emissions compared with the MY 2000 DDC diesel buses. The CWI CNG buses produced 6.1% higher NO_x emissions and 60% lower PM emissions compared with the MY 2004 DDC diesel buses, and 23% lower NO_x emissions and equal PM emissions compared with the MY 2000 DDC diesel buses.

Although CO emissions are not considered to be a great challenge in meeting future emission regulations, CO results from this project may prompt a closer look at the durability of specific oxidation catalysts. WMATA CWI CNG buses similar to those tested in this project were also tested 2 years ago (on a different drive cycle, the CBD cycle). CO emissions for one of the buses measured in the present project were almost double the CO emissions measured for similar buses in the past project. This might indicate that oxidation catalyst degradation or failure occurred during the 2 years of operation between the emission testing projects for this one bus. CO emissions from all the other buses tested were extremely low.

In addition to showing the emissions advantage of CNG buses, this project showed promising fuel economy results for the CNG buses compared with the benchmark diesel buses. The following fuel economy comparisons are made on a diesel gallon equivalent basis. The John Deere CNG buses exhibited a 9.0% fuel economy improvement compared with the MY 2004 DDC diesel buses and a 2.9% improvement compared with the MY 2000 DDC diesel buses. The CWI buses exhibited fuel economy that was 4.2% higher than the MY 2004 DDC diesel buses and 1.6% lower than the MY 2000 DDC diesel buses. Both CNG engines use lean burn technology.

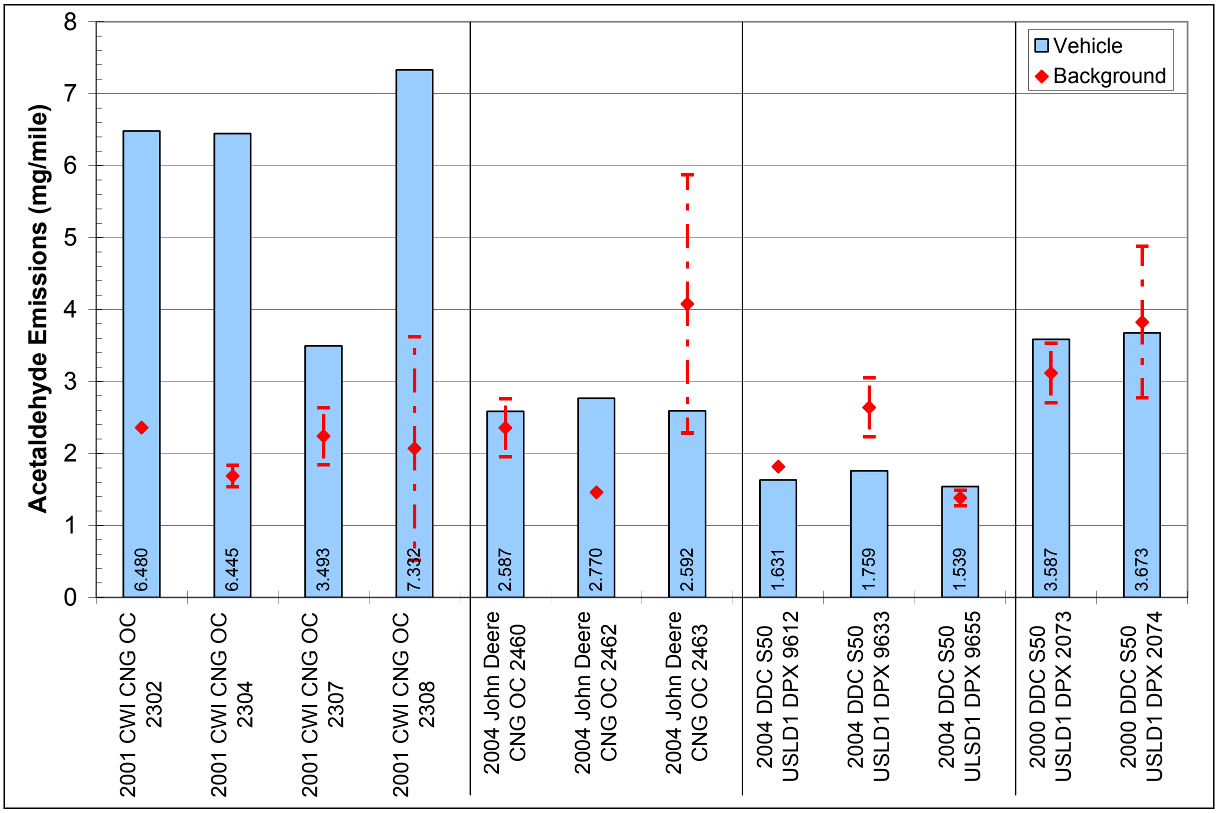


Figure 18: Acetaldehyde Emissions

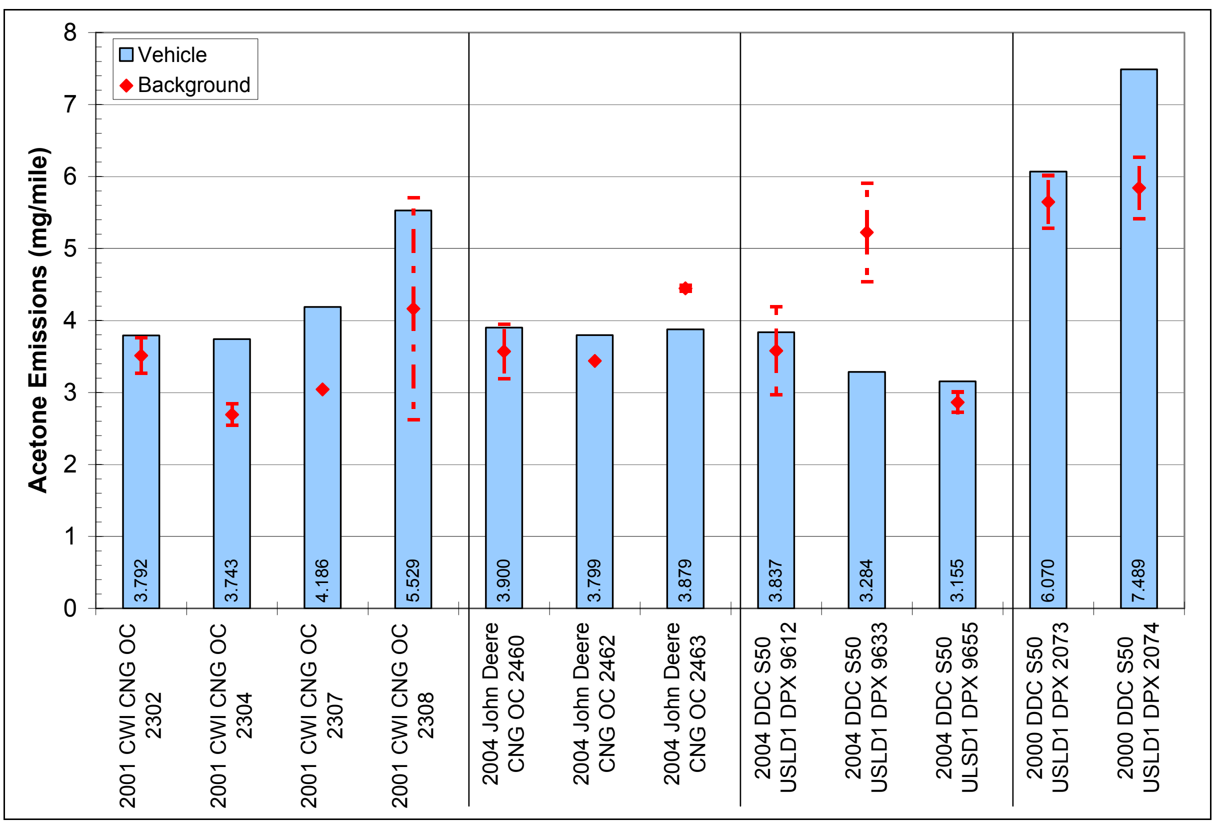


Figure 19: Acetone Emissions

Table 10: Diesel Vehicle Carbonyl Emissions (mg/mi)

Bus #	Run #	Formaldehyde	Acetaldehyde	Acetone	Acrolein	Propanal	Crotonaldehyde	2-Butanone	Methacrolein	Butyraldehyde	Benzaldehyde	Isovaleraldehyde	Valeraldehyde	o-Tolualdehyde	m&p-Tolualdehyde	Hexaldehyde	2,5-Dimethyl-benzaldehyde
Diesel Buses with MY 2000 DDC Series 50 Engines																	
2073	Backgnd	6.718 [1]	3.529	6.014		0.833		1.384			1.853						
	4166-1	8.227	1.785	3.355							0.558					0.768	
	4166-2	5.523	5.204	6.586		0.801		0.678								0.827	
	4166-3	6.423	3.771	8.268		0.727							0.669			0.923	
	Backgnd	5.674 [1]	2.705	5.282		0.520		1.238			1.742					1.080	0.514
2074	Backgnd	2.068	4.876	6.267		1.031		1.639		0.703	0.000					0.820	
	4169-1	9.620	3.062	7.623		0.636		1.077			1.128					1.121	
	4169-2	9.418	5.061	7.659		0.899		1.313			1.084					0.916	
	4169-4	8.955	2.897	7.185		0.633		1.142			0.763					0.858	
	Backgnd	2.853	2.772	5.418		1.179		1.191			0.934					1.060	
Diesel Buses with MY 2004 DDC Series 50 Engines																	
9612	Backgnd	1.597	1.816	2.966		0.414		0.627								0.594	0.385
	4151-1	3.827	1.166	3.411		0.377		0.506			0.771		0.801			0.480	
	4151-3	6.341	2.708	4.332		0.397		1.410		0.682	0.785		0.496			1.285	
	4151-4	3.645	1.019	3.768		0.397		0.662			1.123		0.512			0.524	
	Backgnd	1.940	4.369 [1]	4.193		0.633		1.049			1.067					0.737	0.348
9633	Backgnd	3.129	2.231	4.540		0.725		1.021								1.060	
	4163-1	3.934	0.520	0.812 [2]		0.214				0.564			1.191			0.734	
	4163-2	3.828	2.776	5.927		0.745		1.172			0.637		1.109			0.938	
	4163-3	1.951	1.981	3.113		0.644							0.878			0.728	
	Backgnd	5.712	3.050	5.909		0.818			0.818			2.029					
9655	Backgnd	0.934 [3]	1.278	3.007		0.530		1.032			1.534					0.837	
	4148-1	1.610	1.447	3.276			8.032 [4]				0.601		0.846			0.338	
	4148-2	1.587	1.320	3.119		0.335	8.869 [4]				0.264		0.847				
	4148-3	1.606	1.850	3.072		0.336	4.456 [4]		0.303		0.701						
	Backgnd	1.738	1.486	2.723		0.721		1.003			1.251	0.871			0.498	0.659	

[1] High ambient background
[2] Anomalously low result
[3] Low ambient background
[4] Anomalously high result
Blank cells indicate that the compound was not detected in the sample.

Table 11: CNG Vehicle Carbonyl Emissions (mg/mi)

Bus #	Run #	Formaldehyde	Acetaldehyde	Acetone	Acrolein	Propanal	Crotonaldehyde	2-Butanone	Methacrolein	Butyraldehyde	Benzaldehyde	Isovaleraldehyde	Valeraldehyde	o-Tolualdehyde	m&p-Tolualdehyde	Hexaldehyde	2,5-Dimethyl-benzaldehyde
CNG Buses with MY 2001 CWI C Gas Plus Engines																	
2302	Backgnd	4.598 [5]	5.139 [5]	3.759		0.813		1.543		0.590	1.925		0.246			1.081	
	4142-1	68.122	7.158	4.226	0.372	1.001		1.491		0.732	2.560		0.266		1.077	1.479	0.880
	4142-2	67.305	6.737	3.720	0.312	0.903	0.173	1.012		0.441	1.912				0.000	1.118	
	4142-3	69.418	5.545	3.431	0.283	0.687	0.442	0.917			1.816				0.325	0.879	
	Backgnd	2.527	2.360	3.267		0.525		0.946			2.268					0.810	
2304	Backgnd	1.474	1.838	2.839		0.585	0.191		0.848	0.289	0.933				0.287	1.028	
	4139-2	101.530	6.159	3.413	0.418	0.622		0.903			1.185					0.823	0.634
	4139-3	98.616	6.341	3.917	0.421	0.709	0.388		0.610		1.806	1.072				1.047	0.561
	4139-4	98.410	6.836	3.899	0.468	0.685	0.362	0.511	0.655		1.541					1.741	0.345
	Backgnd	1.794	1.536	2.545		0.592		0.637			1.062	0.759				0.576	
2307	Backgnd	1.908	1.845	3.043		0.386		0.830			0.440						
	4145-1	36.960	3.067	2.967	0.179	0.580		0.502	1.483							0.689	
	4145-2	39.255	3.861	5.561	0.334	0.697		0.984			0.843					0.763	
	4145-3	38.329	3.551	4.031		0.657		1.085			1.481					1.272	
	Backgnd	2.205	2.637	6.845 [5]		0.727		0.892			1.431					0.901	0.385
2308	Backgnd	8.454 [5]	3.622	5.705		0.966		1.079								1.527	
	4198-1	107.364	7.449	5.492	0.587	1.169		0.000	0.953		1.596						
	4198-2	108.115	7.215	5.566	0.607	0.939		1.558									
	Backgnd	2.171	0.516	2.625		0.359					0.830				1.133		
CNG Buses with MY 2004 John Deere 6081H Engines																	
2460	Backgnd	1.828	2.761	3.193		0.467		0.874								0.735	
	4154-1	8.058	2.871	4.159		0.924		1.023			0.546					0.939	0.369
	4154-2	8.587	2.563	4.281		0.610		1.134								0.849	
	4154-3	8.607	2.328	3.260		0.349		1.047								0.922	
	Backgnd	2.679	1.953	3.946		0.611		1.097			0.761				4.883	0.926	
2462	Backgnd	3.351	1.460	3.439				1.146								0.867	
	4160-1	8.557	3.353	3.673		0.573		0.979			1.222					0.918	
	4160-2	8.494	2.053	3.565				0.886			1.305					0.906	
	4160-3	8.452	2.903	4.158		0.622		1.027			2.119					0.905	
6463	Backgnd	1.573	5.870	4.405		1.231		1.801		0.781						1.031	
	4157-2	10.232	2.794	4.071		0.638		1.686			1.528					0.949	
	4157-3	8.049	2.222	3.405		0.672		0.852			1.731				0.651	0.785	
	4157-5	10.528	2.760	4.161		0.527		0.972			1.668					0.913	
	Backgnd	2.843	2.285	4.491		1.050		1.055		0.388	1.797					1.045	

[5] High Ambient Background
Blank cells indicate that the compound was not detected in the sample.

7.2 Carbonyl/Toxic Emissions

Formaldehyde and acetaldehyde emissions from the diesel buses and the John Deere CNG buses were very low, approaching ambient background levels. The CWI CNG buses produced formaldehyde and acetaldehyde emissions that were above ambient background levels and were markedly higher than the other bus groups. This result is unusual. It may indicate a malfunction with the exhaust catalyst or a maintenance/durability issue, neither of which could be verified in time for inclusion in this report.

Other carbonyl emissions were not detected at levels that could be distinguished from ambient levels, indicating that the levels are extremely low for these emissions from all the vehicles tested. An attempt was made to characterize 1,3-butadiene and BTEX emissions. However, the gas chromatography equipment available for this study did not have sufficient sensitivity to detect the low levels of 1,3-butadiene and BTEX in the vehicle exhaust. The NREL ReFUEL laboratory is examining options to acquire more sensitive equipment for future projects.

In general, the diesel and natural gas exhaust catalyst systems tested did well in reducing these toxic emissions to near ambient levels and, in some cases, to levels so low that the instruments could not detect them. However, enough anomalous readings occurred to suggest that the long-term durability of heavy-duty engine catalysts is uncertain and warrants further study.

7.3 Overall Conclusions

Overall, the CNG buses are showing significant improvements in fuel economy and show progress toward meeting the increasingly stringent EPA emission regulations that all heavy-duty engines will have to meet in 2006–2010 and beyond. In general, measured NO_x and PM emissions and fuel economy for the CNG vehicles in this study were comparable to or better than the benchmark diesel buses, indicating significant improvements in CNG engine technology and demonstrating that alternative fuels such as natural gas still offer valuable energy security and environmental benefits for transit fleets.

8.0 References

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Appendix A: Gas Chromatography Results

The following table gives gas chromatography results in units of g/mi. Blank cells indicate the compound was not detected in the sample.

Bus #	Run #	Methane	Ethene	Ethane + Acetylene	Propane	Isobutylene	Butane
MY 2000 DDC Series 50 Diesel with DPX							
2073	Background	0.4778				0.0287	
	4166-1	0.4416					
	4166-2	0.3992					
	4166-3	0.3955					
2074	Background	0.4704				0.0257	
	4169-1	0.4200					
	4169-2	0.4451					
	4169-4	0.4057					
MY 2004 DDC Series 50 Diesel with EGR and DPX							
9612	Background	0.3366					
	4151-1	0.3126					
	4151-3	0.3013					
	4151-4	0.2583					
	Background	0.3159					
9633	Background	0.6790				0.0186	
	4163-1	0.4767					
	4163-2	0.4628					
	4163-3	0.4501					
	Background	0.3290					
9655	4148-1	0.3112					
	4148-2	0.3093					
	4148-3	0.3055					
	Background	0.3209					
MY 2001 CWI C Gas Plus CNG with Oxidation Catalyst							
2302	Background	0.4148					
	4142-1	15.157	0.0841	0.7034	0.1123		0.0334
	4142-2	14.011	0.1506	0.6828	0.0971		0.0264
	4142-3	14.594	0.0268	0.7015	0.1057		0.0318
	Background	0.3625					
2304	Background	0.4263					
	4139-2	16.128	0.1719	0.7862	0.1823		0.0422
	4139-3	16.408	0.1745	0.7987	0.1586		0.0443
	4139-4	15.905	0.1371	0.8135	0.1662		0.0465
	Background	0.3833					
2307	Background	0.3605					
	4145-1	15.041	0.0841	0.6924	0.0796		0.0190
	4145-2	17.217	0.1506	0.8471	0.1053		0.0297
	4145-3	17.759	0.1268	0.8408	0.1002		0.0284
	Background	0.4280					
MY 2004 John Deere 6081H CNG with Oxidation Catalyst							
2460	Background	0.435					
	4154-1	8.560		0.2320			
	4154-2	8.817		0.3161			
	4154-3	9.125		0.2737			
	Background	0.4573					
2462	Background	0.5113					
	4160-1	10.511		0.2507			
	4160-2	10.127		0.3255			
	4160-3	10.79		0.3367			
2463	Background	0.4477					
	4157-2	10.238		0.3089			
	4157-3	10.443		0.3369			
	4157-5	11.202		0.2835			
	Background	0.5179					

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