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Update From The NREL Alternative Fuel Transit Bus Evaluation Program

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ABSTRACT

The objective of this project, which is supported by the U.S. Department of Energy (DOE) through the National Renewable Energy Laboratory (NREL), is to provide a comprehensive comparison of heavy-duty urban transit buses operating on alternative fuels and diesel fuel. Final reports from this project were produced in 1996 from data collection and evaluation of 111 transit buses from eight transit sites. With the publication of these final reports, three issues were raised that needed further investigation:

1) the natural gas engines studied were older, open-loop control engines;
2) propane was not included in the original study; and
3) liquefied natural gas (LNG) was found to be in the early stages of deployment in transit applications.

In response to these three issues, the project has continued by emissions testing newer natural gas engines (Detroit Diesel Corporation Series 50, Cummins Engine Company L10-280G and C8.3-250G) and adding two new data collection sites (GO Boulder in Boulder, CO and Dallas Area Rapid Transit in Dallas, TX) to study the newer natural gas technology and specifically to measure new technology LNG buses. Propane has not been included in this project because there are no original equipment manufacturer (OEM) heavy-duty engines powered by propane available to the transit market. This paper presents results to date on the continuation of the program.

INTRODUCTION

This program was developed in response to the requirements for the U.S. Department of Energy (DOE) to collect alternative fuel data on urban transit buses as part of the Alternative Motor Fuels Act of 1988 (AMFA). The National Renewable Energy Laboratory (NREL) is a DOE national laboratory. One of NREL's missions is to objectively evaluate the performance, emissions, and operating costs of alternative fuel vehicles so fleet managers can make informed decisions when purchasing them. Detailed data collection on a few carefully chosen heavy-duty urban transit buses was completed in 1996 at eight transit sites and tracking 111 buses. The data that Battelle collected were submitted to NREL for public access in NREL's Alternative Fuels Data Center (AFDC). In late 1996, Battelle and NREL produced final reports of the reliability and operating costs of the alternative fuel buses versus the diesel control buses at the sites (1, 2, 3, 4).

At the end of the data collection and evaluation in this program, three issues were raised from the results. Earlier versions of compressed natural gas (CNG) engines emissions tested in this program had open-loop engine control and had inconsistent emissions in some areas. Since the final reports were produced, newer closed-loop feedback engines have been emissions tested and compared to newer, matched diesel control buses. Engine technologies tested were Detroit Diesel Corporation (DDC) Series 50 diesel and natural gas, Cummins Engine Company L10-280G natural gas and M11-280 diesel, and Cummins Engine Company C8.3 natural gas and diesel. Results from emissions testing by West Virginia University (WVU) are presented.

Another issue from the final reports was that propane (LPG) fuel for transit buses was missing from the original study; however, to date, a heavy-duty, OEM propane engine has not been available to the transit industry. The third issue from the earlier study was that liquefied natural gas (LNG) needed more investigation because the technology was still in the early stages of development during the data collection and evaluation. In response to this need, a new LNG data collection site has been started at Dallas, TX for buses using Cummins L10-280G engines and LNG fuel. Another data collection site at Boulder, CO has been defined to look at newer CNG buses using Cummins B5.9G engines. Early results for these two sites are also presented.

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EMISSIONS TESTING OF NEWER ENGINE TECHNOLOGIES

All emissions testing for this program was performed by the West Virginia University (WVU). The U.S. Department of Energy funded WVU's Department of Mechanical and Aerospace Engineering to design and construct a transportable chassis dynamometer to test for emissions levels from heavy-duty vehicles. The purpose of the transportable chassis dynamometer is to allow for a large number of "real-world" emissions tests to be performed on heavy-duty vehicles, and in particular, alternative fuel heavy-duty vehicles around the country. The first transportable unit was built in 1991, and WVU has been traveling to transit agencies and other heavy-duty vehicle sites testing buses and trucks since early 1992 (5). A second unit was built in 1994 and began testing vehicles in 1995.

Typically for each emissions testing site, the transportable chassis dynamometer is set up on the grounds of the test fleet or local transit agency and the selected heavy-duty trucks or buses are tested using the fuel in the vehicle at the time of the test. The dynamometer may be set up to operate inside or outside depending on the space available at the site. The transit buses have been tested using the central business district (CBD) cycle shown in Figure 1. This cycle is a standard dynamometer test cycle that consists of a series of 14 speed-versus-time ramps in which the bus is driven from 0 to 20 miles per hour.

The continuation of this program started with choosing new emissions testing sites based on first looking for the newest technology natural gas engines as of 1997. The newest technology natural gas engines had closed-loop control, which promised better control of the emissions of the engines. After some review of available engines for the heavy-duty transit market, the new technology engines chosen were the Detroit Diesel Corporation (DDC) Series 50G and the Cummins Engine Company L10-280/300G and C8.3-250/275G. For the Cummins L10 natural gas engines, the control vehicle would have a Cummins M11 engine. Cummins discontinued the use of the L10 for diesel operations for heavy-duty trucks and buses. From discussions with Cummins, this comparison was considered appropriate.

In the earlier study (ending in 1996), the search for new data collection and evaluation sites was based on program criteria as follows:

1) target of 10 buses of each alternative fuel with 10 control buses split between two sites;
2) attempt to find the latest technology;
3) diesel control buses needed to be closely matched at the same site;
4) transit agency had to have excellent maintenance and fueling records and be willing to support the program.

These criteria were not sufficient for selecting emissions testing sites because of the lack of "matched" diesel control buses at the site which had the desired new

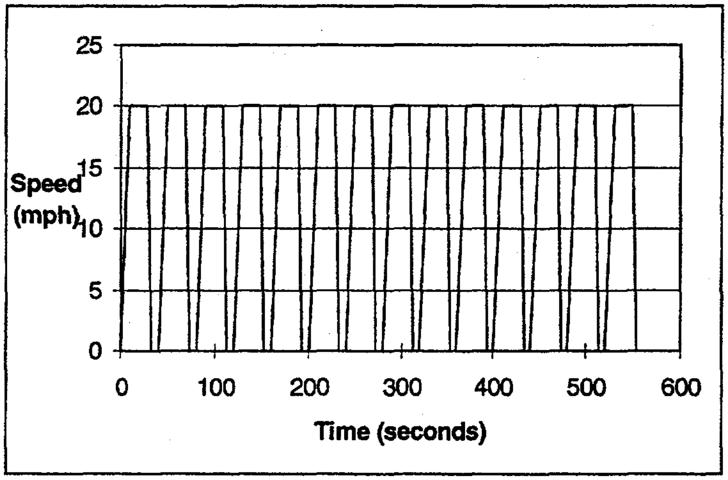

Figure 1. CBD Cycle

technology natural gas vehicles. Matched diesel control vehicles were defined as the same make and model of bus, same engine (except for fuel), same age and similar mileage, and both the alternative fuel and diesel fuel buses needed to be at the same location. The diesel control vehicles are used as a baseline to compare the alternative fuel bus results. The criteria used for selecting the emissions testing only sites (no data collection and evaluation) are given below in approximate decreasing order of importance:

1) The buses must be new with new engines, not repowered old buses
2) Both diesel and CNG engines must be model year 1994 or newer (i.e., 0.07 PM standard). Strong preference is for both to be 1996 model year or newer (0.05 g/bhp-hr. PM standard). Also, preference is for both to be certified to the same standard – 0.05 or 0.07. Series 50G's must be the ones recommended by DDC. Cummins L10G must be the 280 or 300 model.
3) Both diesel and CNG buses must have similar mileage on them, i.e., within approximately 50,000 miles
4) For the DDC Series 50 engines, the test and control buses should have the same or similar drivetrain, including transmission, axle ratio, and final drive ratio. For the Cummins L10/M11 match up, it will likely not be possible to get identical drivetrains since the axle ratio will be sized different for the different torque and power profiles. However, the transmission should at least be the same in terms of model and number of forward speeds. Axle/final drive ratio may be different between L10 and M11.
5) Ideally, the buses should be the same make and model, but this is not a major factor.

Using these criteria, locations were chosen for emissions testing for the DDC Series 50, Cummins L10/M11, and Cummins C8.3 diesel and natural gas engines. The natural gas buses for the Series 50G were those at MARTA (Metropolitan Atlanta Rapid Transit Authority) in Atlanta, Georgia. The matched Series 50 control buses were located in Flint, Michigan at the Mass Transportation Authority (MTA). For the Cummins L10 and M11, the natural gas buses were in Garden City, New York at Long Island Bus and the diesel control buses were in Cincinnati, Ohio at the Southwest Ohio Regional Transit Authority (SORTA). During the time period of the search for these sites, no transit sites were purchasing enough numbers of the Cummins C8.3 natural gas engine to do the emissions testing; however, the engine was being sold in large enough numbers in school buses. The natural gas school buses for the Cummins C8.3G engines tested were in LaQuinta, California at the Desert Sands Unified School District. The diesel control school buses were in Thermal, California at the Coachella Valley Unified School District. The emissions testing results and comparisons are shown in the following discussion. Table 1 shows the U.S. Environmental Protection Agency (EPA) certification standards and certification results for the engines presented here. The emissions certification data is different from the chassis dynamometer results both in the units used in the results and the cycles used to test the engines/vehicles. The engine certification data is presented here for information only.

Standard/ Certification	Non-Methane (Total) Hydrocarbons	Carbon Monoxide	Nitrigen Oxides	Paticulate Matter
	NMHC (HC)	CO	NOx	PM
Certification Standards				
1998 Bus	1.2 (1.3)	15.5	4.0	0.05
1996-1997 Bus	1.2 (1.3)	15.5	5.0	0.05
Certification Results				
Bus Series 50 With Catalyst – 1996	0.04	1.14	4.73	0.045
Bus L10-280G With Catalyst – 1996	0.47	0.62	2.44	0.026
Bus M11-280 With Catalyst – 1996	0.18	0.59	4.77	0.042
Bus C8.3-250G With Catalyst – 1996	0.12	0.12	2.56	0.009
Bus C8.3-250 With Catalyst – 1996	0.15	0.40	4.90	0.05

Table 1. Engine Certification Level and Data (Grams per Brake-Horsepower Hour)

Description	Diesel Control/Flint	CNG/Atlanta
Number of Buses	8	10
Chassis Manufacturer/Model	New Flyer, 40 foot	New Flyer, 40 foot
Chassis Model Year	1996	1996 and 1997
Engine Manufacturer/Model	Detroit Diesel, Series 50	Detroit Diesel, Series 50G
Engine Ratings Max. Horsepower Max. Torque	 275 hp @ 2100 rpm 890 lb-ft @ 1200 rpm	 275 hp @ 2100 rpm 890 lb-ft @ 1200 rpm
Fuel System Storage Capacity	125 gallons	6 CNG cylinders from Lincoln Composites, 18,120 scf
Transmission	Allison B400	Allison B400
Manufacturer/Model		
Catalytic Converter Used (Y/N)	No	No
Curb Weight (Lbs)	27,500	29,820
Gross Vehicle Weight (GVW)	37,920	38,140
Emissions Test Weight (Lbs)	32,825	35,145
EPA Engine Family Name	TDD8.5FJDABA	VDD8.5FZKARB

Table 2. Vehicle Descriptions for Atlanta and Flint

Site	Fuel	Odometer	PM	NOx	HC	NMHC	CO	CO2	MPG
Atlanta	CNG	36900	0.02	20.8	15.80	0.80	9.0	2631	2.80
Flint	Diesel #2	37200	0.28	30.2	0.13		4.9	2611	3.90
Difference (%)	AF/DC	-1	-93	-31	515*		84	1	-28

* Percent difference for hydrocarbons is based on NMHC for CNG and HC for diesel.

Table 3. Chassis Dynamometer Emissions Testing Results (Grams per Mile)

Emissions Results From Atlanta, GA and Flint, MI for DDC Series 50 Engine

Table 2 shows some specifications for the buses tested at Atlanta and Flint. Emissions testing average results for each group of buses are shown in Table 3 (6). The emissions testing at Atlanta occurred during February and March 1997, and for Flint, the testing occurred during May and June 1997. The average odometers for the two groups of buses are the same. The particulate matter (PM) and oxides of nitrogen (NOx) both show significant reductions for the natural gas engines at 93 percent lower on PM and 31 percent lower for NOx. For the hydrocarbons, the comparison shown is between non-methane hydrocarbons (NMHC) for the CNG buses and total hydrocarbons (HC) for the diesel buses. The CNG buses had much higher NMHC than the diesel HC. The carbon monoxide (CO) was much higher (84 percent) for the CNG buses and the carbon dioxide (CO2) was the same. Fuel economy is measured during the emissions testing on the same route. The CNG buses had a 28 percent lower fuel economy than the diesel buses on an energy equivalent basis.

Description	Diesel Control/Cincinnati	CNG/Long Island
Number of Buses	10	10
Chassis Manufacturer/Model	Gillig, 40 foot	Orion, 40 foot
Chassis Model Year	1996	1996
Engine Manufacturer/Model	Cummins M11-280	Cummins L10-280G
Engine Ratings Max. Horsepower Max. Torque	 280 hp @ 2000 rpm 280 hp @ 2100 rpm	 900 lb-ft @ 1200 rpm 900 lb-ft @ 1300 rpm
Fuel System Storage Capacity	125 gallons	12 CNG cylinders from SCI, 15,888 scf
Transmission Manufacturer/Model	Allison B400	Allison B400
Catalytic Converter Used (Y/N)	Yes	Yes
Curb Weight (Lbs)	29,020	31,320
Gross Vehicle Weight (GVW)	39,600	40,000
Emissions Test Weight (Lbs)	33,480	35,820
EPA Engine Family Name	TCE661FJDAAA	TCE661FBCABW

Table 4. Vehicle Descriptions for Long Island and Cincinnati

Site	Fuel	Odometer	PM	NOx	HC	NMHC	CO	CO2	MPG
Garden City	CNG	25600	0.03	23.5	18.9	0.86	2.5	2454	3.00
Cincinnati	Diesel #2	56600	0.69	28.4	1.89		4.2	2433	4.17
Difference (%)	AF/DC	-55	-96	-17	-54*		-40	1	-28

* Percent difference for hydrocarbons is based on NMHC for CNG and HC for diesel.

Table 5. Chassis Dynamometer Emissions Testing Results (Grams per Mile)

Emissions Results From Garden City, NY and Cincinnati, OH for Cummins L10-280G and M11-280

Table 4 shows some specifications for the buses tested in Garden City and Cincinnati. Emissions testing average results for each group of buses are shown in Table 5 (7). Emissions testing at Garden City occurred during September and October 1997, and for Cincinnati, the testing occurred during November 1997. The average odometers for the two groups of buses show that the diesel buses in Cincinnati on average had 31,000 more miles or about half to three-quarters of a year more service life. As with the Series 50, the L10G showed significantly lower PM (96 percent lower) and NOx (17 percent lower). Unlike the Atlanta and Flint busses, these buses at Garden City and Cincinnati were equipped with catalytic convertors. The comparison of NMHC for the CNG buses and HC for the diesel buses showed the CNG buses were 54 percent lower. The CO was 40 percent lower for the CNG buses and the CO2 was about the same. The energy equivalent fuel economy showed that the CNG buses were 28 percent lower.

Description	Diesel Control/Coachella Valley	CNG/Desert Sands
Number of Buses	3	11
Chassis Manufacturer/Model	Thomas Built, 40 foot	Thomas Built, 40 foot
Chassis Model Year	1996	1996
Engine Manufacturer/Model	Cummins C8.3-250	Cummins C8.3-250G
Engine Ratings Max. Horsepower Max. Torque	 250 hp @ 2000 rpm 800 lb-ft @ 1300 rpm	 250 hp @ 2400 rpm 750 lb-ft @ 1400 rpm
Fuel System Storage Capacity	100 gallons	6 CNG cylinders from Lincoln Composites, 50 gallons diesel equivalent
Transmission	Allison B400	Allison MD3060
Manufacturer/Model		
Catalytic Converter Used (Y/N)	Yes	Yes
Curb Weight (Lbs)	22,973	22,081
Gross Vehicle Weight (GVW)	37,600	37,400
Emissions Test Weight (Lbs)	28,531	28,531
EPA Engine Family Name	TCE505FGDABW	TCE505F1CAAW

Table 6. Vehicle Descriptions for Desert Sands and Coachella Valley USD

Site	Fuel	Odometer	PM	NOx	HC	NMHC	CO	CO2	MPG
Desert Sands	CNG	15500	0.06	17.9	22.1	1.05	10.9	2094	3.47
Desert Sands	CNG	25400	0.14	19.0	22.7	0.99	10.7	1949	3.71
Coachella Valley	Diesel #2	18200	0.26	21.0	0.49		1.5	2001	5.08
Difference (%) First Round	AF/DC	-15	-77	-15	114*		627	5	-32
Difference (%) Second Round	AF/DC	40	-46	-10	102*		613	-3	-27

* Percent difference for hydrocarbons is based on NMHC for CNG and HC for diesel.

Table 7. Chassis Dynamometer Emissions Testing Results (Grams per Mile)

Emissions Results from Desert Sands and Coachella Valley for Cummins C8.3

Table 6 shows some specifications for the school buses tested at Desert Sands and Coachella Valley. Emissions testing was performed twice at Desert Sands and only once at Coachella Valley. The diesel school buses at Coachella Valley were not ready for emissions testing during the first emissions testing at Desert Sands. Emissions testing average results for each group of buses are shown in Table 7 (8). Comparing the first round of emissions testing for Desert Sands with the results from Coachella Valley, the odometers showed that the CNG buses at Desert Sands had 15 percent lower average mileage than the diesel buses. The PM was 77 percent lower and the NOx was 15 percent lower. A comparison of the CNG bus NMHC and diesel bus HC showed the CNG buses had double the hydrocarbons (minus the methane). The CNG buses had much higher CO and nearly the same CO2. Both diesel and CNG buses were catalyst equipped. The energy equivalent fuel economy was 32 percent lower for the CNG buses.

Comparing the second round of emissions testing for Desert Sands with the results from Coachella Valley, the odometers for the CNG buses were 40 percent higher than the diesel buses. The PM results for the CNG buses were not as dramatic as the first round at 46 percent lower. The NOx results were 10 percent lower for the CNG buses. The NMHC for the CNG buses were double the HC for the diesel buses. Again, the CO was much higher and the CO2 results were nearly the same. The energy equivalent fuel economy was better at 27 percent lower for the CNG buses.

NEW DATA COLLECTION AND EVALUATION SITES

As part of the continuation of this program, a few more data collection and evaluation sites have been added to study new technology natural gas vehicles. There are two new data collection and evaluation sites currently under way. The first site is at GO Boulder in Boulder, Colorado. This transit agency is a part of the Regional Transportation District (RTD). Table 8 shows some specifications for the buses being studied at this site. The buses at this site represent the first medium-duty vehicles in this program. The buses are using the Cummins B5.9-195G engine operating on CNG. The CNG and diesel buses started service in August 1997. The data collection is planned to be complete in the Spring 1999 with a final report in the Summer.

The CNG buses had some issues with overheating, and some changes were made for the cooling system. These CNG buses were the first manufactured by World Trans so there were a few minor problems that were repaired during the first six months of operation. Through May 1998, the CNG buses showed a fuel economy of 5.5 miles per energy equivalent diesel gallon and the diesel buses showed a fuel economy of 7.0 miles per gallon. These fuel economies show a 21 percent decrease for the CNG buses on an energy equivalent basis.

Emissions testing average results for each group of buses are shown in Table 9 (9). The emissions testing at Boulder occurred during September 1998. The average odometers for the two groups of buses shows a 42 percent higher mileage

Description	Diesel Control	CNG
Number of Buses	3	3
Chassis Manufacturer/Model	World Trans, 26.5 foot	World Trans, 26.5 foot
Chassis Model Year	1997	1997
Engine Manufacturer/Model	Cummins ISB-175	Cummins B5.9-195G
Engine Ratings Max. Horsepower Max. Torque	 175 hp @ 2500 rpm 420 lb-ft @ 1600 rpm	 195 hp @ 2800 rpm 420 lb-ft @ 1600 rpm
Fuel System Storage Capacity	55 gallons	5 CNG cylinders from Lincoln Composites, 7,000 scf
Transmission	Allison AT545R	Allison AT545R
Manufacturer/Model		
Catalytic Converter Used (Y/N)	Yes	Yes
Curb Weight (Lbs)	14,525	14,525
Gross Vehicle Weight (GVW)	18,780	18,780
Emissions Test Weight (Lbs)	17,914	17,914
EPA Engine Family Name	VCE359DJDARA	VCE359DICAAA

Table 8. Vehicle Descriptions for Boulder

Site	Fuel	Odometer	PM	NOx	HC	NMHC	CO	CO2	MPG
Boulder	CNG	12400	0.01	8.89	12.6	0.54	0.39	1592	4.63
Boulder	Diesel #2	21500	0.38	21.1	0.25		2.38	1818	5.54
Difference (%)	AF/DC	-42	-96	-58	116*		-84	-12	-16

** Percent difference for hydrocarbons is based on NMHC for CNG and HC for diesel.*

Table 9. Chassis Dynamometer Emissions Testing Results (Grams per Mile)

Description	Diesel Control	LNG
Number of Buses	5	10
Chassis Manufacturer/Model	Nova Bus, 40 foot	Nova Bus, 40 foot
Chassis Model Year	1998	1998
Engine Manufacturer/Model	Cummins M11-280	Cummins L10-280G
Engine Ratings Max. Horsepower Max. Torque	 280 hp @ 2000 rpm 900 lb-ft @ 1200 rpm	 280 hp @ 2100 rpm 900 lb-ft @ 1300 rpm
Fuel System Storage Capacity	125 gallons	3 LNG MVE, Inc. tanks, 154 LNG gallons (92 diesel equivalent gallons)
Transmission	ZF 5HP590	ZF 5HP590
Manufacturer/Model		
Catalytic Converter Used (Y/N)	No, Particulate Trap	Yes
Curb Weight (Lbs)	28,740	29,540
Gross Vehicle Weight (GVW)	39,500	39,500

Table 10. Vehicle Descriptions for Dallas

for the diesel buses. The PM and NOx both show significant reductions for the natual gas engines at 97 percent lower on PM and 58 percent lower for NOx. For the hydrocarbons, the comparision shown is between NMHC for the CNG buses and HC for the diesel buses. The CNG buses had higher NMHC than the diesel HC. The CO was 84 percent lower for the CNG buses and the CO2 was the same. The CNG buses had a 16 percent lower fuel economy than the diesel buses on an energy equivalent basis.

The other data collection and evaluation site currently under way is the Dallas Area Rapid Transit (DART) LNG operations. Table 10 shows some specifications for the LNG and diesel buses in the study. Data collections at DART started in November 1998 and is planned to be complete by the end of 1999. The operation of the LNG buses has started with only the lower-than-expected range of the buses being an issue. DART is considering adding another LNG tank on-board the buses to extend this range. Emissions testing is planned to occur during February and March 1999.

FUTURE ACTIVITIES

The emissions testing has continued with the data collection and evaluation sites as well as a site to study the effects of Fischer-Tropsch fuels on emissions in older DDC 6V92TA engines. This testing has occurred in Pittsburgh at PATransit during December 1998 and January 1999 (10). The data collection and evaluation will continue with another site. New York City Transit (NYCT) has agreed to participate in this program with their diesel hybird buses from Orion with Lockheed Martin drive trains. Data collection is planned to begin in the late Spring 1999 with emissions testing planned in the May or June 1999 time frame.

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