January 2000 • NREL/SR-540-26758

Subcontractor Report

Demonstration of Caterpillar C-10 Dual-Fuel Engines in MCI 102DL3 Commuter Buses

California Energy Commission
Sacramento, California

Santa Barbara County Air Pollution Control District
Goleta, California

National Renewable Energy Laboratory

1617 Cole Boulevard
Golden, Colorado 80401-3393

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NREL Technical Monitor: Paul Norton

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Acronyms and Abbreviations

App.	appendix
Avg.	average
CARB	California Air Resources Board
CAVTC	Clean Air Vehicle Technology Center
CBD	central business district
CEC	California Energy Commission
CH_4	methane
CNG	compressed natural gas
CO	carbon monoxide
CO_2	carbon dioxide
D	diesel
DFNG	dual-fuel natural gas
DEG	diesel equivalent gallon (135,000 Btu)
DF	dual-fuel
EPA	Environmental Protection Agency
ERC	emission reduction credit
ft-lb	foot-pound (torque)
g/bhp-hr	grams per brake horsepower hour
gal	gallon
GVWR	gross vehicle weight rating
hp	horsepower
incr.	increase
LAMTA	Los Angeles Metropolitan Transportation Authority
MCI	Motor Coach Industries
mi	miles
MPH	miles per hour
NMHC	non-methane hydrocarbons
NO_x	oxides of nitrogen
OEM	original equipment manufacturer
PM	particulate matter
PSA	Power Systems Associates
psi	pounds per square inch (pressure)
red.	reduction
ROC	reactive organic compound
rpm	revolutions per minute
SBCAPCD	Santa Barbara County Air Pollution Control District
scfm	standard cubic feet per minute
THC	total hydrocarbons
UDDC	urban dynamometer drive cycle
WVU	West Virginia University
yr	year

Introduction

The purpose of this program was to demonstrate the Caterpillar C-10 Dual-Fuel Natural Gas (DFNG) engine in an over-the-road bus application. Four Motor Coach Industries (MCI) 102DL3 buses were operated side-by-side on similar fixed-route revenue service for a 12-month demonstration period from February 1998 through January 1999. Three of the buses were equipped with Caterpillar C-10 DFNG engines and the fourth was equipped with a C-10 diesel (D) engine. The buses were used as part of the Clean Air Express Commuter Bus Program in Santa Barbara County, California.

The buses were obtained by the City of Lompoc through a grant from the Federal Transportation Authority (through the Congestion Management and Air Quality Improvement Program). The Santa Barbara County Air Pollution Control District (SBCAPCD) provided a 20% cost-share toward the purchase of the buses. The base cost of the four buses was about $1,400,000 ($350,000 each). The conversion of the buses to compressed natural gas (CNG) operation was funded by the U.S. Department of Energy (DOE) through the National Renewable Energy Laboratory (NREL), the California Energy Commission (CEC), and the Southern California Gas Company. The buses were delivered from MCI with Caterpillar C-10 D engines. The cost to retrofit the buses to dual-fuel operation was $180,000 ($45,000 per bus).

Project Objective and Results Summary

Project Objective

The objective of the project was to determine the benefits and problems encountered in retrofitting and operating an over-the-road bus with the Caterpillar C-10 DFNG engine. Specifically, this demonstration evaluated the retrofit costs and process, performance, reliability, fuel economy, and emissions of the C-10 DFNG engine compared to a standard C-10 D engine.

Project Results Summary

All four buses performed well throughout the demonstration period. The dual-fuel buses accumulated a total of 94,228 miles, or an average of 31,400 miles each, during the 12-month operating period. The diesel bus accumulated 27,443 miles (this bus was removed from service after 11 months to be converted to dual-fuel operation). No significant obstacles were encountered in retrofitting the buses with the CNG components. Performance and reliability of the dual-fuel buses were comparable to that of the diesel bus. The performance and reliability of the C-10 DFNG engine was comparable to the C-10 D engine.

The C-10 DFNG engines averaged a 56% CNG-to-diesel substitution rate, on a total-energy-used basis, during the demonstration period. This means 56% of the energy used to operate the buses came from CNG. The remaining 44% was supplied by the diesel fuel. CNG use was primarily affected by electronic engine controls (i.e., termination of CNG injection because of engine operations outside allowable parameter ranges), failure of the bus operator to consistently refuel the buses with CNG, and breakdown of the CNG station. The C-10 DFNG engines have an electronic governor to reduce the available power when the engine is operated on diesel only. The intent of the "reduced power mode" is to dissuade the operator from routinely operating the engine in diesel-only mode, while still affording the opportunity to operate on diesel in an emergency. For this demonstration, the reduction in power in diesel-only mode was not severe enough to ensure consistent CNG use.

Although very few repairs were needed on either engine type during the demonstration period, the C-10 DNFG engine had higher initial capital, fuel, fueling labor, insurance, and maintenance costs than the C-10 D. On a 30,000 mile-per-year basis, the C-10 DFNG cost about $0.19 more per mile to operate than the C-10 D, based on the results of this demonstration. Cost differences between the C-10 DFNG and the C-10 D can vary greatly depending on the application. Fleet operators should assess the cost differences based on their specific application.

At the conclusion of the 12-month demonstration period, the C-10 DFNG and C-10 D engines were emissions tested on a chassis dynamometer using three drive cycles: the EPA Urban Dynamometer Drive Cycle Schedule D (UDDC), the Central Business District (CBD) Drive Cycle (West Virginia University [WVU] version), and a 55 Mile Per Hour (MPH) Steady State Drive Cycle. The emissions tests were performed by the Los Angeles Metropolitan Transportation Authority (LAMTA). The LAMTA test technician assured SBCAPCD that appropriate EPA and California Air Resources Board (CARB) test procedures were used, but no written documentation of the test methods, calibration procedures, or quality assurance procedures was provided. This report simply presents the emissions test results as they were provided by LAMTA. The C-10 DFNG engines in dual-fuel mode had lower emissions of the following pollutants as compared with the C-10 D engine (ranges represent lowest/highest value for all three drive cycles tested): NO_x (27%–60%), PM (54%–64%), and CO_2 (14%–19%), and increases of CO (634%–860%) and non-methane hydrocarbons (NMHC) (697%–1,718%). In the two variable load tests (EPA UDDC and the WVU CBD), the C-10 DFNG may have had higher combined NO_x and NMHC emissions. However, the smog-forming potential of these combined emissions compared to diesel combined NO_x and HC emissions cannot be quantified because specific hydrocarbons vary in their ozone reactivity. Because the HC emissions were not speciated in this study, the reactivity of the DFNG and diesel exhaust emissions cannot be compared. Even so, the simple addition of NO_x + NMHC emissions indicates a 17% increase compared with the C-10 D engine for the variable load cycles. In contrast, on the 55-MPH Steady State test, the C-10 DFNG engine had 42% lower NO_x + NMHC emissions compared with the C-10 D.

In comparing emissions from the C-10 DFNG engine in diesel mode with emissions from the C-10 D, differences in NO_x, CO_2, and CO were too small (generally less than 3%) to allow any meaningful conclusions. However, the C-10 DFNG engine in diesel mode had 25%–42% lower PM emissions and 14%–18% lower NMHC emissions (depending on the drive cycle) than the C-10 D diesel engine.

Project Description and Technical Concept

Vehicle Operations

The Clean Air Express Commuter Bus Service takes passengers from neighboring cities (e.g., Santa Maria, Lompoc, Ventura, Santa Ynez) to Santa Barbara/Goleta to and from work each day. The average one-way commute is about 60 miles. The purpose of the program is to reduce air pollution from long-distance single-occupancy commuter automobiles by getting as many as 55 people out of their cars and into one low-emissions bus.

The service currently uses 9 buses to serve approximately 350 commuters daily, 250 days per year. The four buses used as part of this demonstration project were placed into service in early 1998 on the City of Lompoc to Santa Barbara/Goleta route. The buses were operated by Melni Bus Company, which oversaw all aspects of vehicle operations, including maintenance, repairs, fueling, and passenger booking.

Description of Buses

The buses used in this demonstration were brand-new 1997 MCI 102DL3 over-the-road coaches. The buses were equipped by the original equipment manufacturer (OEM) with Caterpillar C-10 D engines. The buses are 45 feet long, about 11½ feet tall, and can carry 55 passengers. They are equipped with wheelchair lifts, but not with restrooms. The bus gross vehicle weight rating is 34,000 pounds.

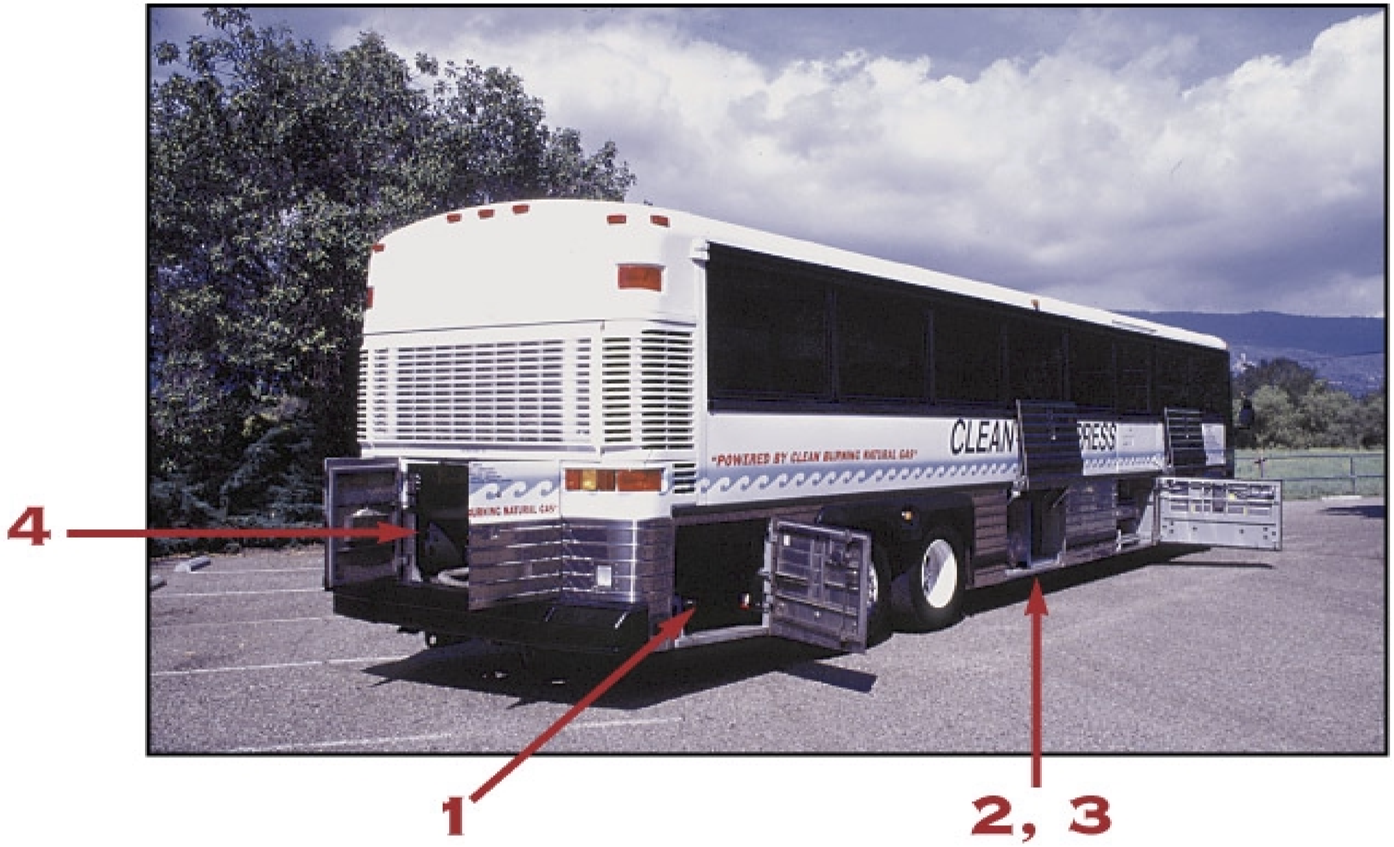
Three buses were retrofitted with Power Systems Associates' dual-fuel operating system. In the dual-fuel mode, the C-10 DFNG engine is rated at 350 hp and 1,075 ft-lb of torque. Each bus was fitted with 4 CNG cylinders for a total CNG capacity of 48 diesel equivalent gallons (DEGs) at 3,000 psi (58 DEGs at 3,600 psi). The buses had a range of approximately 460 miles in dual-fuel mode (based on the average 56% CNG substitution rate and 5.34 miles/DEG obtained during the demonstration period). Three cylinders were installed in the lower rear standard baggage compartment, and one in the lower forward baggage compartment. The cylinders were hooded to vent any leaks to the atmosphere, instead of into the baggage compartment. Also, pressure relief valves and associated plumbing were installed to vent over-pressurization to the rear roof area of the bus.

Figure 1 shows the Clean Air Express bus and the location of key CNG components. Figure 2 gives a detailed look at the various CNG components. Complete vehicle specifications are included as Appendix 1.

Dual-fuel Engine Operation

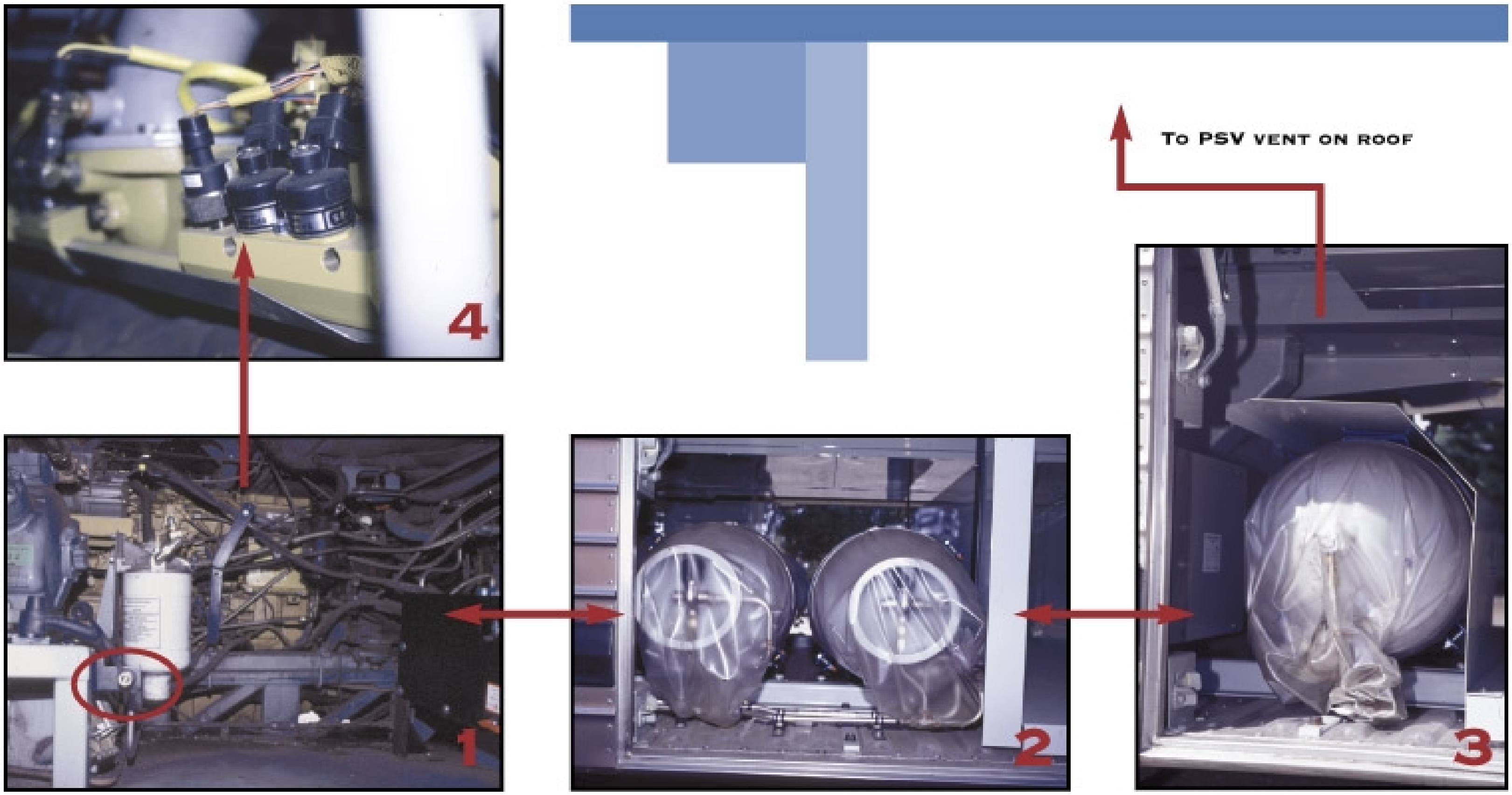
Dual-fuel engines operate by introducing a small charge of diesel fuel into the combustion chamber until the engine reaches idle. Beyond idle, natural gas is introduced as the engine load increases. Dual-fuel engines operate simultaneously on natural gas and diesel. Some dual-fuel engines operate on a mix of 80% CNG and 20% diesel fuel. The Caterpillar C-10 engine

Figure 1. Clean Air Express Bus



SIDEVIEW OF DUAL FUEL BUS SHOWING LOCATIONS OF KEY CNG COMPONENTS.
PLEASE SEE FOLLOWING PAGE FOR DETAILS ON THE ITEM NUMBERS.

Figure 2. CNG Bus Components



Passenger-side engine compartment (1) houses the CNG fill nozzle (circled), pressure gauge, pressure regulator, and shutoff valve. The same stainless steel tubing both transfers CNG to the storage tanks (2) in the luggage compartments from the fill nozzle, and from the tanks to the dual fuel engine (via the pressure regulator). Note the CNG fittings on and around the tanks are "bagged" and vented through the floor of the luggage compartment to prevent CNG buildup in the luggage area in the event of a leak. The driver-side of the storage tanks (3) incorporate a pressure relief valve to vent pressure relief events to the rear roof area of the bus. The CNG injectors (4) are located on the air intake manifold of the dual fuel engine. The arrows depict the flow of CNG.

demonstrated in this project is capable of operating on a mix of up to 85% CNG and 15% diesel fuel. However, if natural gas fuel is depleted, the dual-fuel engine will operate in a reduced power mode on diesel fuel until the vehicle is refueled with natural gas. Dual-fuel engines operating on CNG and diesel fuel reduce harmful pollutants such as oxides of nitrogen and particulates. The Caterpillar C-10 dual-fuel engine demonstrated in this project was certified to the California Air Resources Boards alternative low-NO_x standard of 2.5g/bhp-hr. This standard is 37.5% less than the applicable standard for diesel trucks.

Bus Route and Drive Cycles

The buses make one round trip from the City of Lompoc to Santa Barbara each day, and operate 250 days per year. After boarding, the buses leave the City of Lompoc at approximately 6:30 a.m. and travel about 60 miles to the Santa Barbara area. After delivering passengers to and around Santa Barbara, the buses are turned off, except for refueling and maintenance operations, until the return trip to Lompoc in the evening. More than 90% of the trip distance is on highways with posted speed limits of 65 mph. The entire route is characterized by gently rolling hills and one significant hill (approximately 2 miles long, 500 feet high [3%–7% grade]). The highway goes up then down this hill, so the buses must traverse this grade on each segment of the trip (i.e., twice per round trip). Aside from this grade, the entire route is less than 100 feet above mean sea level. The area is characterized by a temperate climate, with daytime temperatures of 50º–90°F. Nighttime temperatures occasionally reach freezing during the winter months.

Data Collection

Data collection was coordinated by SBCAPCD's Innovative Technologies Group. The bus operator maintained logs on routine maintenance, breakdowns, repairs, and fueling. Vendor receipts for both CNG and diesel were recorded to allow cross-checking of operator fuel logs. Once each month, the SBCAPCD downloaded engine operating data from each dual-fuel engine's computer, including total engine hours, engine hours in dual-fuel mode, amount of CNG used, and amount of diesel used in dual-fuel mode. The C-10 DFNG does not record total diesel use.

Fueling Facility Description

A public-access CNG fueling facility was used to fuel buses during the demonstration program. The facility was built and owned by the Southern California Gas Company; cost-share funding was provided by SBCAPCD. The facility is equipped with 400 gasoline-equivalent gallons of storage (at 3,000 psi), and a compressor rated at 170 scfm (approximately 1.3 DEGs per minute). Diesel fuel was obtained at county-owned fueling facilities; however, when necessary, diesel was obtained from commercial fueling sites.

Results and Discussion

Bus Operations

The buses were driven on similar routes in routine revenue service for 12 months. The three dual-fuel buses logged a total of 94,228 miles, or an average of about 31,400 miles each; the diesel bus logged 27,443 miles.[1] The dual-fuel buses logged 2,682 engine hours, or an average of 894 hours each. The diesel bus was not equipped with engine hour meter; however, because of the similarity in routes and miles driven, the diesel bus probably operated a comparable number of hours. A summary of the bus operations is presented in Table 1. Detailed monthly data for each bus are included in Appendix 2.

Table 1.
Summary of Bus Operating Data

		Operating Data					Calculations			
Bus No.	Engine Type	Engine Time (h)	DFNG Time (h)	Miles	CNG (DEGs)	Diesel (DEGs)	Average Miles/DEG	% CNG when in DF mode	% CNG of total fuel	% time in DF mode
Air 11	DFNG	909	492	31,704	3,191	3,085	5.05	86%	51%	54%
Air 13	DFNG	866	483	32,600	3,192	2,667	5.56	87%	54%	56%
Air 14	DFNG	907	567	29,924	3,437	2,094	5.41	86%	62%	63%
Avg. DF Bus :		894	514	31,409	3,273	2,615	5.34	86%	56%	57%
Air 12	**Diesel**	N/A	N/A	27,443	N/A	4,580	6.00	N/A	N/A	N/A

Discussion of Operating Data

Fuel Economy

The following discussion of fuel economy is based on actual operating data from the buses during the demonstration period. The amount of diesel fuel used was based on operator records, which were cross-checked by SBCAPCD staff against county fueling records. CNG use was based on the dual-fuel engine computer record and was cross-checked against Southern California Gas Company billing records. Overall, the fuel economy of the dual-fuel buses averaged 5.34 miles/DEG. The fuel economy of the diesel bus was 6.0 miles/DEG. Thus, the dual-fuel buses averaged about 11% fewer miles per DEG than the diesel bus. Because the C-10 DFNG engine's fuel efficiency is actually an *average* efficiency based on part dual-fuel operation and part straight-diesel operation, the fuel economy in dual-fuel mode is actually less than 5.3 miles per DEG. Assuming that the fuel economy of the dual-fuel bus, when being operated in "diesel mode" is equivalent to that of the diesel bus (6.0 miles/DEG), the fuel economy of the C-10 DFNG engine in dual-fuel mode is estimated to be

[1] One reason for the lower miles on the diesel bus was that it was taken out of service approximately 1 month before the end of the demonstration period for emissions testing and conversion to dual-fuel operation.

about 4.8 miles/ DEG,[2] or about 20% lower than that of the diesel engine. This estimated fuel economy of the dual-fuel engine is shown in Figure 3.

The fuel economy of the dual-fuel and diesel buses was also estimated during chassis dynamometer emissions testing (see Appendix 3). The fuel economy estimates made during emissions testing indicated that the dual-fuel engine had comparable, or better, fuel economy than the diesel engine. However, the estimated fuel economy during emissions testing was not based on actual measurement of fuel, but on a "carbon count" performed on the engine exhaust. The accuracy of this method depends on an accurate analysis of the fuel composition. There is considerable uncertainty associated with the fuel economy estimates obtained during the emissions testing for the dual-fuel engine, as neither the composition of the CNG nor the blend ratio of CNG at the time of testing was known.

Performance

Power output of the C-10 DFNG engines was comparable to that of the C-10 D diesel engine. Although the bus drivers reported a slight but noticeable reduction in power in dual-fuel mode, the C-10 DFNG engine's power was more than adequate to perform the required duty. The C-10 DFNG engine has lower horsepower and torque than the C-10 D at the lower half of the rpm operating range (see Appendix 4). For this demonstration, these differences were partially compensated by reprogramming the shift points in the electronically controlled automatic transmissions. Also, some drivers reported the C-10 DFNG engines had a slight delay in throttle response.

The dual-fuel buses were equipped with an electronic governor to reduce the available engine power when the buses were operated in diesel mode (see Appendix 4). This feature is designed to provide enough power to "limp home," yet reduce performance to such an extent that the driver is discouraged from routinely operating without CNG. The reduced power mode was most noticeable in hard accelerations and when traversing steep grades; otherwise, the C-10 DFNG engines performed similarly (including maintaining highway cruising speeds) in both dual-fuel and diesel-only modes. During this demonstration, the reduced power mode alone was not sufficient to ensure that the buses were consistently operated on CNG; the SBCAPCD had to play an active role in ensuring CNG use.

Reliability

For the three C-10 DFNG engines, only three mechanical breakdowns were experienced during the entire demonstration period. One consisted of water intrusion on two of the dual-fuel engine computers; the other was a broken charge air cooler belt. Once new engine computers were installed, the computers experienced no further water intrusion problems. The broken charge air cooler belt was not related to dual-fuel operation; the belt could just as likely have broken on the

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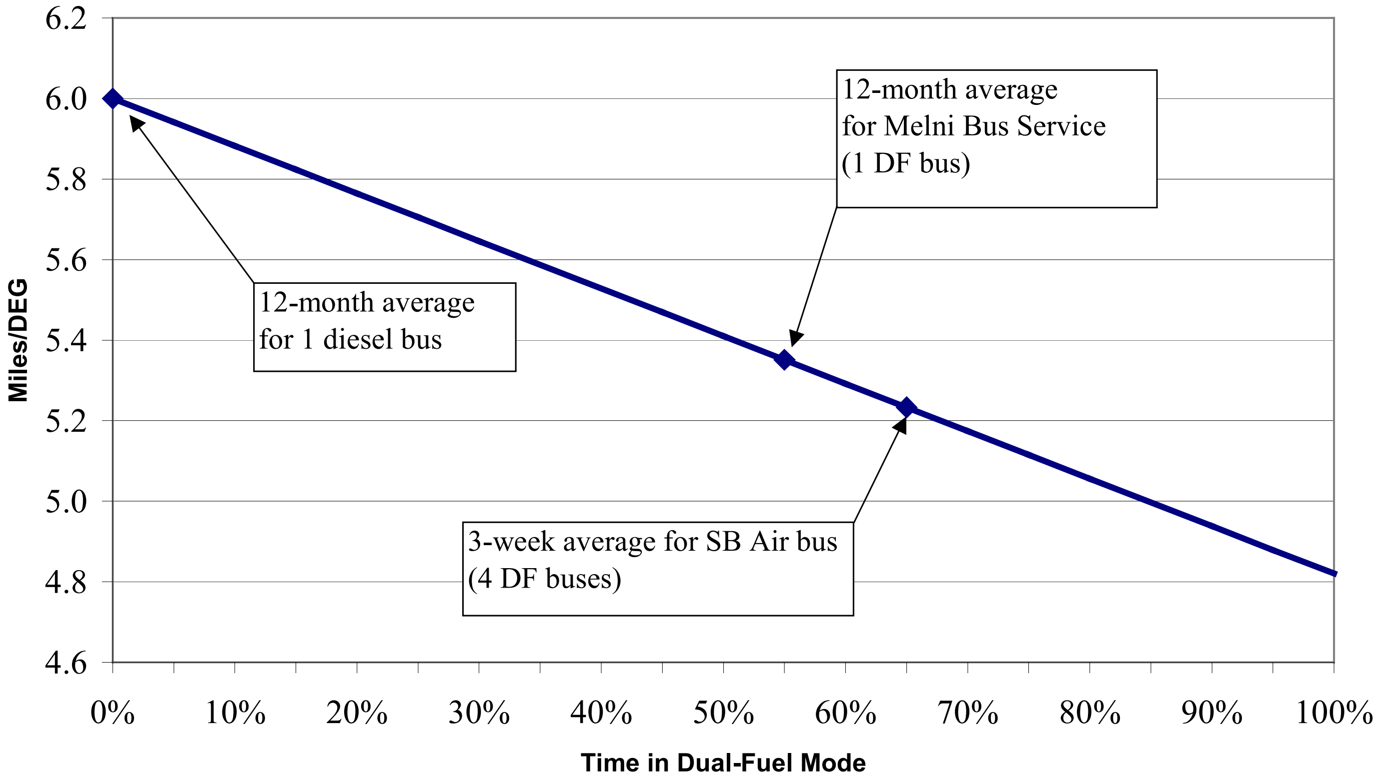
[2] Fuel Economy in DF-Mode
Average Fuel Economy = 5.34 miles/DEG =
= (Percent time DF) * miles/DEG (DF) + (Percent time diesel) * 6.0 miles/DEG (diesel)
= (56%) * "X" + 44% X 6.0 MPG
Then, X = Fuel Economy in dual fuel mode = 4.82 miles/DEG

diesel base-case bus. Overall, the mechanical reliability of the dual-fuel buses was excellent. There were no breakdowns on the diesel base-case engine.

Figure 3. C-10 DFNG Engine: Miles per Gallon versus Dual-Fuel Operating Time



CNG Fuel Substitution

Based on data retrieved from the C-10 DFNG engine computer, the CNG use averaged 86% when the engine was operating in the dual-fuel mode. However, during the demonstration period, the actual overall average CNG substitution rate was about 56% (on both a fuel-use and an operating-hour basis). Causes for the lower overall average CNG substitution rate were:

- Normal bus operations/"out of range" engine parameters;
- Bus CNG system downtime; and
- Failure to fuel the buses with CNG/breakdown of CNG station.

These issues are discussed more fully in the sections that follow.

The C-10 DFNG engines remained fully operational in the diesel mode, even when CNG was not in use. This has the effect of making the overall CNG substitution rate lower than the ideal rate. When comparing the fuel use of the C-10 DFNG engine to that of a dedicated CNG engine, consideration should be given to the amount of diesel used by replacement buses put into service when the dedicated CNG engine was inoperable.

Normal Engine Operations/"Out of Range" Engine Parameters

The C-10 DFNG engine is designed to operate in diesel-only mode under certain normal conditions. For example, the C-10 DFNG engine operates in diesel mode during idle and until the engine warms up (even under power). Applications for which the C-10 DFNG engine is idled for extended periods, driven in stop-and-go traffic, or used intermittently (when the engine is allowed to cool down between trips) will have lower overall CNG substitution rates than applications involving sustained highway driving.

According to Power Systems Associates (PSA), the C-10 DFNG engine computer is programmed to terminate dual-fuel operation (and operate in straight-diesel mode) any time one of numerous operating parameters strays outside an acceptable range. For example, if the CNG pressure drops too low or the engine becomes too hot, the computer reverts back to the diesel-only mode. C-10 DFNG engines regularly terminated dual-fuel operation because these "out of range" parameters were detected. Apparently, the "allowable" engine operating parameter ranges have been confined to a fairly narrow band to minimize the potential for damage to the engine. For increased CNG substitution rates to be realized in real-world driving applications, the C-10 DFNG engine computers need to be reprogrammed to allow wider ranges of allowable engine operating parameters.

Another factor affecting CNG use is that once the computer terminated CNG operation, the engine would typically not start using CNG again until the engine had been turned off, then on again. In over-the-road buses and trucks, it is impractical (and potentially unsafe) to pull over and turn the engine off and on to reset the computer. CNG use could be increased if the computer periodically reassessed the engine operating parameters and reinitiated CNG injection if the parameters had returned to within the allowable ranges.

Engine CNG System Downtime

CNG downtime can also be caused by mechanical failures of the CNG system. However, there were no such physical failures of the CNG system during the demonstration period. The C-10 DFNG computer failed on two of the buses because of moisture intrusion problems following heavy rains. This computer controls the injection of CNG to the engine. More often, CNG downtime occurred because of computer "glitches." Although these breakdowns were from relatively minor causes, the CNG downtime persisted for several days, and sometimes weeks, because of the logistics of having a qualified mechanic repair the bus.

Failure to Refuel Buses with CNG

To complete their routes without running out of CNG, the dual-fuel buses had to be refueled with CNG every other day. Sometimes the bus operator simply failed to fuel buses according to this schedule. Fueling a bus (including driving to and from the fueling station) took almost an hour. Consequently, this inconvenience served as a disincentive to consistently fill the buses with CNG.

In an effort to ensure consistent use of CNG, a system was implemented by which a special "fuel person" refueled each bus during the bus layover in Santa Barbara each day.

There were several periods when the CNG station was inoperable during the 12-month demonstration. Unfortunately, no convenient backup stations were available when the primary CNG station was down. To minimize the amount of time the buses operate on diesel fuel during CNG station downtime, a convenient backup facility should be available. For the Clean Air Express buses, use of small "time-fill" compressors to fuel the buses overnight would have been ideal. The public access CNG station could then have been used as the backup station when the time-fill compressor unit was down, or for quick fill-ups as needed.

Oil Consumption and Oil Change Intervals

There was very little oil consumption on all four buses. Oil in all buses was changed every 7,500 miles. The used oil was not sampled and analyzed.

Driver and Passenger Perspectives

Aside from the need to obtain CNG fuel, operation of the dual-fuel buses was essentially indistinguishable from that of the diesel bus. Engine noise and vibration were similar between the two engines. As mentioned previously, the drivers felt that the dual-fuel buses had slightly less power than the diesel bus, but the difference was very minor. Some drivers felt that the Caterpillar engines, both the dual-fuel and the diesel, were louder during idle, and had higher turbine whine at cruise than the Detroit Diesel 6V-92 DDEC engines that were familiar to them.

Emissions Testing

The CEC contracted with the Clean Air Vehicle Technology Center (CAVTC) to emissions test two of the C-10 DFNG buses and the C-10 D diesel bus. CAVTC, in turn, arranged to have the testing performed by and at LAMTA. The LAMTA test technician assured the SBCAPCD that appropriate EPA and CARB test procedures were used, but no written documentation of the test methods, calibration procedures, or quality assurance procedures was provided. This report simply presents the emissions test results as they were provided by LAMTA.

The C-10 DFNG engines were tested in both dual-fuel and diesel modes. The buses were tested on a chassis dynamometer using the following drive cycles: EPA Urban Dynamometer Drive Cycle Schedule D, the WVU CBD, 55 MPH Steady State, and Idle. These drive cycles are intended to provide a "snapshot" of the emissions from the buses under actual driving conditions.

A complete description of emission test results, including a description of test methods and drive cycles, is included in Appendix 3. Figures 4–6 and Tables 2–3 summarize the testing results for each loaded drive cycle.

C-10 DFNG Engine in Dual-Fuel Mode versus C-10 D Engine

When comparing the C-10 DFNG engines in dual-fuel mode to the base-case C-10 D engine, the emissions differences followed consistent trends between the three loaded drive cycles. The C-10 DFNG engines in dual-fuel mode had lower emissions of the following pollutants than the C-10 D engine (ranges represent lowest/highest value for all three drive cycles discussed in Section 4.3): NO_x (27%–60 %), PM (54%–64 %), and CO_2 (14%–19 %), and increases of CO (634%–860 %) and NMHC (697%–1,718 %). Refer to Figures 4–6 and Tables 2–3 for a summary of the emissions test results. NO_x reductions were most pronounced in the 55 MPH Steady State drive cycle. This may have been due to the C-10 D being equipped with a "defeat" device (see the discussion in the following paragraph). Although NMHC emissions from the C-10 DFNG engines in dual-fuel mode were expected to increase, the magnitude of the increase was surprising.

One interesting divergence in the emissions trends between the three tests was for NO_x and NMHC emissions combined (NO_x and non-methane/non-ethane hydrocarbon emissions are considered precursors to ground-level ozone). In the two variable load tests (EPA Urban Dynamometer Drive Cycle and the WVU CBD), the C-10 DFNG had about 18% greater NO_x and NMHC emissions (combined) than the C-10 D; on the 55 MPH Steady State test, the C-10 DFNG engine had 42% lower NO_x and NMHC emissions (combined) than the C-10 D. Based on discussions with PSA, the C-10 D engine computer is believed to operate the engine on one of two electronic "operating maps" depending on whether the engine is operating in a variable load or a steady-state mode. This type of system, commonly known as a "defeat device," effectively results in the engine being operated in a low-emissions mode when the engine is exposed to varying loads, as in city driving (or emissions certification tests), and a higher emissions (and fuel economy) mode when the engine is exposed to steady-state conditions, such as over-the-road highway driving. Although the C-10 DFNG engine has significantly lower NO_x/NMHC emissions when operated in steady-state mode than the C-10 D diesel engine (believed to be equipped with a defeat device), additional emissions testing is needed to determine whether the C-10 DFNG has lower NO_x/NMHC emissions than a modern diesel engine that is not equipped with a defeat device.

If the dual-fuel engine is intended for use in reducing ozone precursor emissions (NO_x and non-methane/non-ethane hydrocarbons), the engine should be source-tested initially before use and periodically over the life of the vehicle to verify assumptions made on ozone-precursor reductions. Such testing should emphasize the accurate determination of the engine's non-methane/non-ethane hydrocarbon emissions. Also, air districts should be aware that the C-10 DFNG engines produce significantly more CO emissions than the standard C-10 D diesel engine. Although high, the CO levels could be within the standard and can be corrected by the use of oxidation catalysts.

C-10 DFNG Engine in Diesel Mode versus C-10 D Engine

Emissions from the C-10 DFNG engine in diesel mode were compared with emissions from the C-10 D base-case engine. NO_x, CO, and CO_2 emissions were comparable (generally within 3%) between the two engine types when using diesel fuel. However, NMHC and PM emissions averaged about 17% and 33% lower, respectively, on the C-10 DFNG engine. Based on discussions with PSA, there are no inherent engine operating differences between the C-10 DFNG engine operating on diesel fuel and the C-10 D engine. No explanations for these emissions differences are offered in this report. Because of the toxicity concerns with PM in diesel engine exhaust, additional PM testing may be warranted to further explore whether the C-10 DFNG engine in diesel mode actually has lower emissions of PM than the C-10 D diesel engine.

Problems and Resolution

At the beginning of the demonstration period, there was some difficulty in coordinating the CNG fueling. The drivers were not used to fueling the buses every other day, as was necessary to ensure continuous dual-fuel operation. The buses were filled with diesel fuel in Lompoc in the evenings; however, because the CNG station was located in Santa Barbara, the buses had to be filled with CNG during the day when the buses were between trips. Because the bus drivers were commuters (i.e., they had other jobs during the day), the CNG fueling was difficult for them. One month into the demonstration period, this issue was resolved by having one person (not a bus driver) fuel all the buses with CNG during the day layover.

Because the C-10 DFNG engine had good power when used in diesel-only mode, there was little incentive for the drivers to ensure the buses were fueled with CNG. Close supervision by the SBCAPCD staff was necessary to ensure consistent use of CNG. Use of the dedicated fueling person helped to minimize this problem.

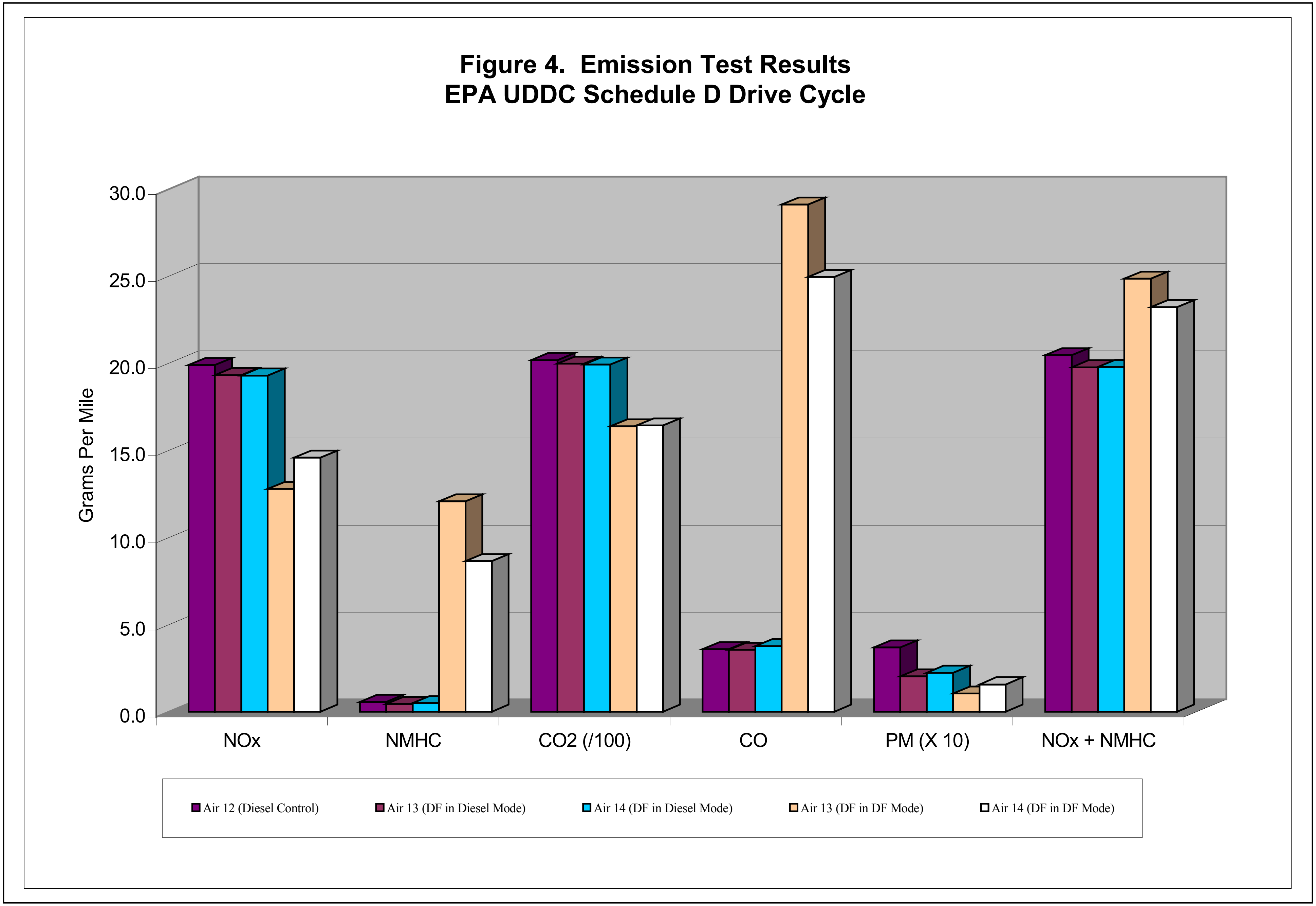


Figure 4. Emission Test Results
EPA UDDC Schedule D Drive Cycle
Grams Per Mile
30.0
25.0
20.0
15.0
10.0
5.0
0.0
NOx
NMHC
CO2 (/100)
CO
PM (X 10)
NOx + NMHC
Air 12 (Diesel Control)
Air 13 (DF in Diesel Mode)
Air 14 (DF in Diesel Mode)
Air 13 (DF in DF Mode)
Air 14 (DF in DF Mode)

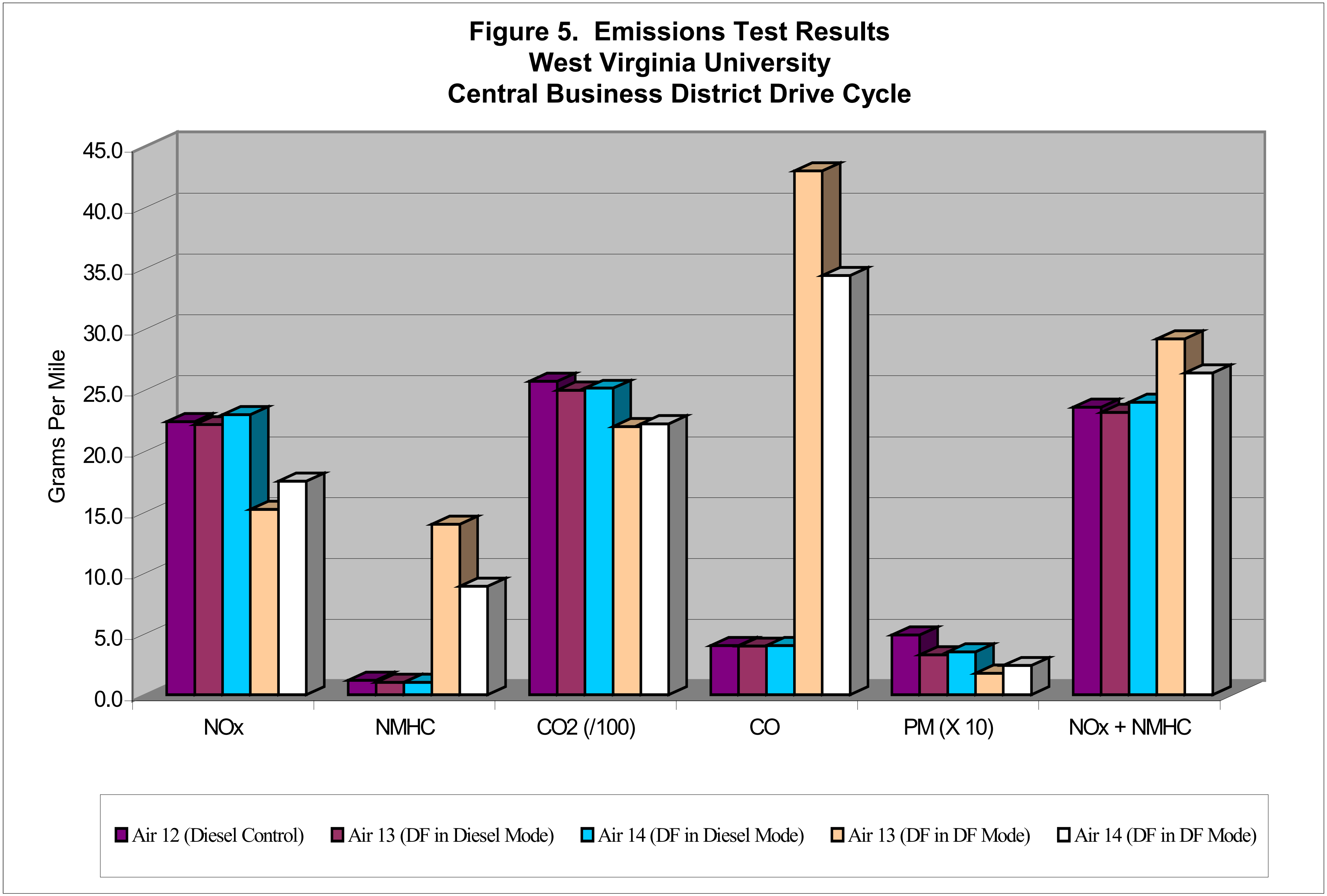


Figure 5. Emissions Test Results
West Virginia University
Central Business District Drive Cycle
Grams Per Mile
45.0
40.0
35.0
30.0
25.0
20.0
15.0
10.0
5.0
0.0
NOx
NMHC
CO2 (/100)
CO
PM (X 10)
NOx + NMHC
Air 12 (Diesel Control)
Air 13 (DF in Diesel Mode)
Air 14 (DF in Diesel Mode)
Air 13 (DF in DF Mode)
Air 14 (DF in DF Mode)

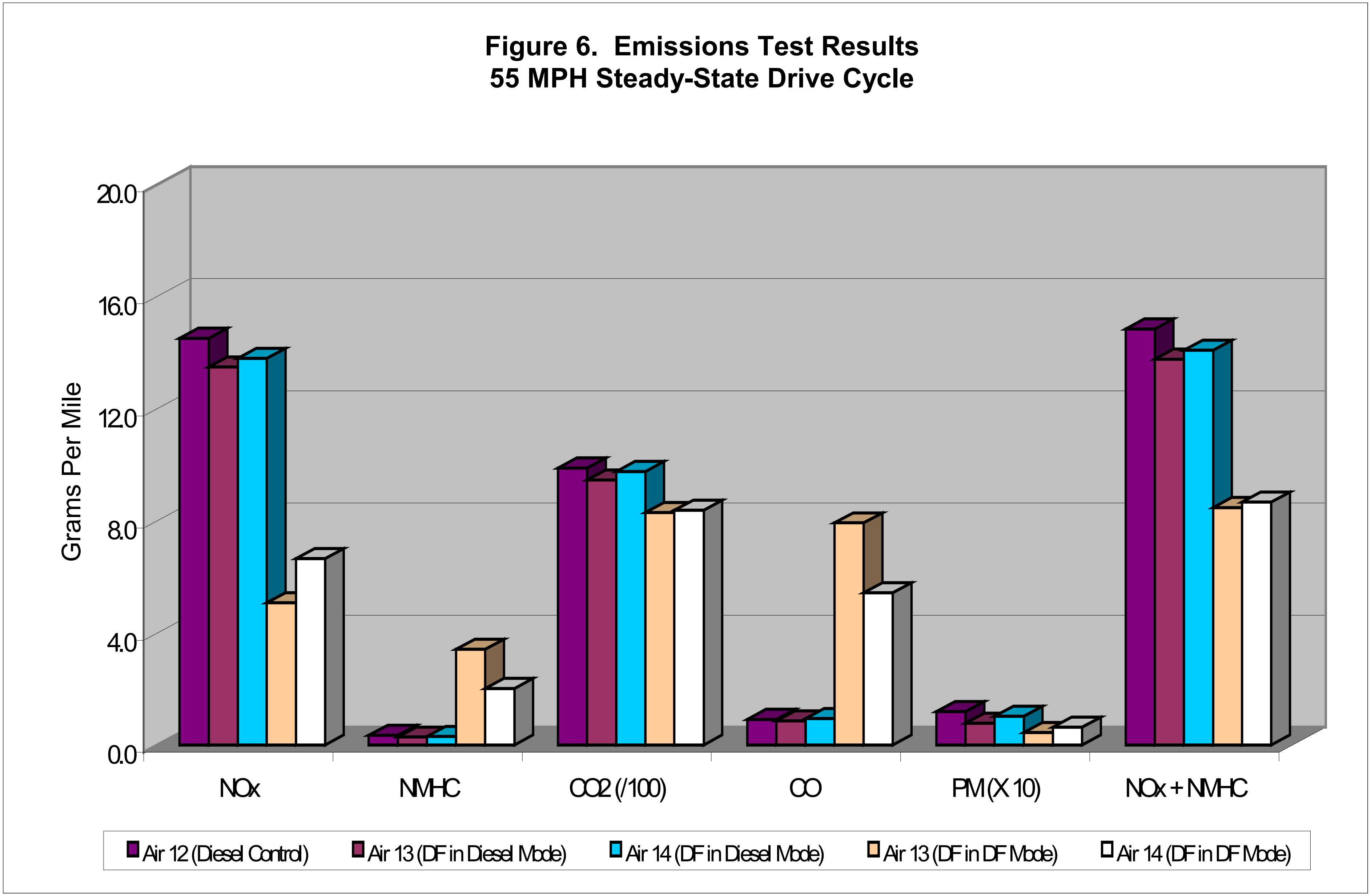


Figure 6. Emissions Test Results
55 MPH Steady-State Drive Cycle
Grams Per Mile
20.0
16.0
12.0
8.0
4.0
0.0
NOx
NMHC
CO2 (/100)
CO
PM (X 10)
NOx + NMHC
Air 12 (Diesel Control)
Air 13 (DF in Diesel Mode)
Air 14 (DF in Diesel Mode)
Air 13 (DF in DF Mode)
Air 14 (DF in DF Mode)

Table 2. Emissions Test Results:
Dual-Fuel Engine in Dual-Fuel Mode versus Diesel Engine

EPA UDDC Schedule D: Emissions units are grams/mile

Bus	Description	NO_x	NMHC	CO_2 (/100)[1]	CO	PM (x10)[1]	NO_x + NMHC
Air 12	Diesel Control	19.90	0.57	20.18	3.59	3.68	20.47
Air 13	DFNG in DF Mode	12.78	12.08	16.38	29.11	1.04	24.86
Air 14	DFNG in DF Mode	14.58	8.65	16.43	24.96	1.57	23.23
Avg. DFNG in DF Mode		13.68	10.36	16.40	27.04	1.31	24.04
Avg. % red. from DFNG engine		31%	N/A	19%	N/A	64%	N/A
Avg. % incr. from DFNG engine		N/A	1718%	N/A	653%	N/A	17%

WVU CBD: Emissions units are grams/mile

Bus	Description	NO_x	NMHC	CO_2 (/100)[1]	CO	PM (x10)[1]	NO_x + NMHC
Air 12	Diesel Control	22.41	1.19	25.71	4.03	4.90	23.60
Air 13	DFNG in DF Mode	15.21	13.99	21.99	42.99	1.76	29.2
Air 14	DFNG in DF Mode	17.51	8.90	22.23	34.40	2.39	26.41
Avg. DFNG in DF Mode		16.36	11.44	22.11	38.70	2.07	27.8
Avg. % red. From DFNG engine		27%	N/A	14%	N/A	58%	N/A
Avg. % incr. From DFNG engine		N/A	861%	N/A	860%	N/A	18%

55 MPH Steady State: Emissions units are grams/mile

Bus	Description	NO_x	NMHC	CO_2 (/100)[1]	CO	PM (x10)[1]	NO_x + NMHC
Air 12	Diesel Control	14.50	0.34	9.87	0.91	1.18	14.84
Air 13	DFNG in DF Mode[2]	5.06	3.41	8.28	7.92	0.44	8.47
Air 14	DFNG in DF Mode	6.64	2.02	8.38	5.43	0.64	8.66
Avg. DFNG in DF Mode		5.85	2.71	8.33	6.68	0.54	8.56
Avg. % red. From DFNG engine		60%	N/A	16%	N/A	54%	42%
Avg. % incr. From DFNG engine		N/A	697%	N/A	634%	N/A	N/A

1. CO_2 and PM values in the tables are 1/100 and 10 times actual values, respectively.
2. Air 13 NMHC estimated based on Air 13 THC times the ratio of NMHC/THC for Air 14.

Table 3. Emissions Test Results: Dual-Fuel Engine in Diesel Mode versus Diesel Engine

EPA UDDC Schedule D: Emissions units are grams/mile

Bus	Description	NO_x	NMHC	CO_2 (/100)[1]	CO	PM (x10)[1]	NO_x + NMHC
Air 12	Diesel Control	19.90	0.57	20.18	3.59	3.68	20.47
Air 13	DFNG in Diesel Mode	19.32	0.45	19.98	3.55	2.03	19.77
Air 14	DFNG in Diesel Mode	19.29	0.50	19.93	3.77	2.23	19.79
Avg. DFNG engine in Diesel Mode		19.31	0.47	19.95	3.66	2.13	19.78
Avg. % red. from DFNG engine		3%	18%	1%	N/A	42%	3%
Avg. % incr. from DFNG engine		N/A	N/A	N/A	2%	N/A	N/A

WVU CBD: Emissions units are grams/mile

Bus	Description	NO_x	NMHC	CO_2 (/100)[1]	CO	PM (x10)[1]	NO_x + NMHC
Air 12	Diesel Control	22.41	1.19	25.71	4.03	4.90	23.60
Air 13	DFNG in Diesel Mode	22.15	1.00	24.98	3.98	3.28	23.15
Air 14	DFNG in Diesel Mode	22.98	1.01	25.14	4.02	3.51	23.99
Avg. DFNG engine in Diesel Mode		22.57	1.00	25.06	4.00	3.39	23.57
Avg. % red. from DFNG engine		N/A	14%	3%	1%	31%	0%
Avg. % incr. from DFNG engine		1%	N/A	N/A	N/A	N/A	N/A

55 MPH Steady State: Emissions units are grams/mile

Bus	Description	NO_x	NMHC	CO_2 (/100)[1]	CO	PM (x10)[1]	NO_x + NMHC
Air 12	Diesel Control	14.50	0.34	9.87	0.91	1.18	14.84
Air 13	DFNG in Diesel Mode	13.48	0.28	9.45	0.85	0.77	13.76
Air 14	DFNG in Diesel Mode	13.79	0.29	9.75	0.93	1.02	14.08
Avg. DFNG engine in Diesel Mode		13.64	0.28	9.60	0.89	0.89	13.92
Avg. % red. from DFNG engine		6%	18%	3%	2%	25%	6%
Avg. % incr. from DFNG engine		N/A	N/A	N/A	N/A	N/A	N/A

1. CO_2 and PM values in the tables are 1/100 and 10 times actual values, respectively.

Project Economic Analysis

Fixed Cost Differences

The difference in fixed costs between the C-10 DFNG and the C-10 D was limited to the capital costs associated with the conversion of the C-10 D engines to dual-fuel operation ($45,000/bus). This price included all parts and labor to convert the base diesel engine to the dual-fuel configuration, and to install the CNG cylinders and plumbing. The Caterpillar engine was $1,300 per bus less than the original engine specified for the buses, a Cummins M11. However, for the purposes of this report, only the cost difference between the C-10 DFNG and the C-10 D engine is presented. If the buses had not already been equipped with the Caterpillar C-10 diesel engine, additional costs would have been incurred to remove the original engine and replace it with the Caterpillar engine, and from the need to modify any engine accessories (i.e., transmission, radiators, and charge air coolers).

Variable Cost Differences

Variable cost differences between the dual-fuel and diesel buses included fuel, maintenance, repairs, and insurance. Based on discussions with the insurance provider for the Clean Air Express buses, collision insurance was more for the dual-fuel buses because the buses cost more (because of the CNG hardware, not because of the use of CNG).

Cost for maintaining the dual-fuel buses was less for oil changes, because oil change intervals could be extended approximately 100% longer than for the diesel bus. The dual-fuel buses have an added cost in the maintenance of the CNG fueling system. All other maintenance costs are estimated to be the same.

Fuel costs were higher for the dual-fuel buses. Fuel costs are functions of the cost of the fuel and the efficiency of the engine (i.e., miles/DEG). During the demonstration period, the diesel was obtained at a wholesale rate averaging $0.80/DEG; the CNG was obtained at a retail rate averaging $0.90/DEG. Assuming a 56% CNG of the fuel used/total fuel blend in the C-10 DFNG engines, the cost of "blended" fuel averaged $0.856/DEG. These costs are based on actual invoices from fuel purchases during the course of the demonstration period. The dual-fuel buses also used more fuel, because they averaged only 5.34 miles/DEG; the diesel bus averaged 6.0 miles/DEG.

Labor charges associated with fueling were higher for the dual-fuel buses. Because the dual-fuel buses have less range than the diesel bus, they must be fueled more often. Also, the dual-fuel buses had to be driven to two separate stations to obtain CNG and diesel, thereby increasing the total time needed obtain fuel.

Based on reliability of the C-10 DFNG engine during the course of the demonstration period, the cost of repairing the C-10 DFNG engines was assumed to be the same as for the standard diesel engine. Because of the limited duration of this demonstration period, we could not determine whether the C-10 DFNG engines will require more or fewer repairs during the lives of the engines.

A summary of the differential costs of operating the C-10 DFNG engine compared to the C-10 D diesel engine is presented in a later section.

Potential Value of Emission Reduction Credits

The CEC requested that SBCAPCD evaluate the potential value of Emission Reduction Credits (ERCs) that could be generated through use of the C-10 DFNG engine. ERCs, once certified, can be sold on the open market to sources needing to "offset" their emissions increases. In 1998, the median purchase price for NO_x, reactive organic compounds (ROCs), PM_{10}, SO_x, and CO ERCs in California was $10,925/ton, $4,932/ton, $10,000/ton, $10,411/ton and $2,509/ton, respectively.[3] The potential value of ERCs generated from use of the C-10 DFNG engine was not determined because:

- Determining the overall value of ERCs from using the C-10 DFNG engine is complicated by the fact that the value of NO_x and PM reductions may be affected by the potentially significant increases in NMHC (a possible concern in ozone nonattainment areas) and CO (a concern in CO nonattainment areas) emissions.
- The quantity of ERCs generated can vary greatly depending on annual engine use, emissions test results (new versus replaced engine), remaining life of the replaced engine or vehicle, and the proximity of the source generating the ERCs to the source needing the ERCs.
- The cost to produce ERCs (and thus, the profit from selling the ERCs) can also vary greatly depending on repower costs, differences in new versus old engine operating costs, and air district compliance costs (permitting, emissions testing, reporting).

Summary of Costs during Demonstration Period

Based on the actual costs incurred during the demonstration period, the C-10 DFNG equipped buses cost $6,150 more per year, or about $0.20 more per mile, to operate than the C-10 D equipped bus. Table 4 summarizes the operating cost differential between the C-10 DFNG and C-10 D engines. Only cost differences between the two engines are listed: costs that were the same for both engine types are not listed. In this analysis, diesel was purchased at a wholesale rate; CNG was purchased at a retail rate.

Projected Costs Using Retail Diesel Prices and an On-Site CNG Station

The cost of operating the C-10 DFNG and C-10 D engines can vary greatly depending on the fleet application. The financial benefits of using CNG are optimized in cases where fleet operators obtain diesel fuel from commercial retailers, and CNG can be obtained at a "wholesale" rate by using an onsite CNG station owned by the fleet operator. An onsite CNG station can also be equipped with "time-fill" stations to fuel the vehicles overnight where they are

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[3] California Environmental Protection Agency, Air Resources Board, "*Emission Reduction Offset Transaction Cost Summary Report for 1998*," April 1999.

parked, thereby reducing, or even eliminating, the labor costs associated with CNG refueling. Table 5 summarizes the operating cost differential between the C-10 DFNG and C-10 D engine, assuming the operator pays retail rates for diesel fuel and obtains CNG via an onsite CNG station, and assuming an 80% CNG substitution rate. All other costs are assumed to be the same as for the actual demonstration period (see Fixed Cost Differences and Variable Cost Difference in this section). Based on this analysis, a C-10 DFNG engine is projected to cost approximately $0.40/mile to operate. This is about $0.12/mile more than the projected cost of operating a C-10 D engine in a similar application. If the vehicle operator did not have to pay for the capital costs to convert the vehicle ($0.15/mile) to dual-fuel operation, the C-10 DFNG engine could actually cost $0.03/mile less to operate than a diesel engine. Table 5 represents the presumed optimum cost scenario for CNG use. Presumably, actual cost differences will fall somewhere between the values presented in Tables 4 and 5. All fleet operators should assess the cost differences based on their own specific application.

Table 4.
Actual Annual Operating Cost Differences during Demonstration Period

Item Description	C-10 D	C-10 DFNG	Reference
Annualized Capital Cost	$ 0	$ 4,500	Appn 5: Section 1.1
Fuel	$ 4,000	$ 4,810	Appn 5: Section 1.2
Fueling Labor	$ 342	$ 814	Appn 5: Section 1.3
Insurance	$ 2,100	$ 2,370	Appn 5: Section 1.4
Maintenance—CNG System	$ 0	$ 298	Appn 5: Section 1.5
Repairs	$ 0	$ 0	Appn 5: Section 1.6
Maintenance—Oil Changes	$ 400	$ 200	Appn 5: Section 1.7
Emission Reduction Credits	$ 0	$ 0	Report Section 5.3
Total Cost per Year:	$ 6,842	$ 12,992	Basis: 30,000 mi/yr
Cost per Mile:	$ 0.23	$ 0.43	
Incremental Cost for DFNG:	$ 6,150/year or $ 0.20 mile		

Table 5.
Projected Annual Operating Cost Differences Using Retail Diesel and an On-Site CNG Station

Item Description	C-10 D	C-10 DFNG	Reference
Annualized Capital Cost	$ 0	$ 4,500	Appn. 5: Section 1.1
Fuel	$ 5,500	$ 4,494	Appn 5: Sec. 1.2/2.1
Fueling Labor	$ 342	$ 77	Appn 5: Sec. 1.3/2.2
Insurance	$ 2,100	$ 2,370	Appn 5: Section 1.4
Maintenance—CNG System	$ 0	$ 298	Appn 5: Section 1.5
Repairs	$ 0	$ 0	Appn 5: Section 1.6
Maintenance—Oil Changes	$ 400	$ 200	Appn 5: Section 1.7
Emission Reduction Credits	$ 0	$ 0	Report Section 5.3
Total Cost per Year:	$ 8,342	$ 11,939	Basis: 30,000 mi/yr
Cost per Mile:	$ 0.28	$ 0.40	
Incremental Cost for DFNG:	$ 3,597 or $ 0.12/mile		

Lessons Learned

Altoona Testing

Initially, the project team members tried to have MCI provide the buses equipped with the dual-fuel components as an OEM installation. We envisioned that this would minimize the number of purchase orders and contracts that would have to be issued to secure the buses. However, we soon discovered that the Federal Transit Administration requires that all new over-the-road chassis/engine combinations complete rigorous performance testing in Altoona, Maine. Having the OEM deliver the bus in the dual-fuel configuration would have certainly triggered the requirement for this testing. By having the buses delivered with the standard diesel engines, and then sending them to be converted to dual-fuel operation as used buses, the Altoona testing was not necessary.

Encouraging Bus Operators to Use CNG

Because the C-10 DFNG buses could operate satisfactorily on diesel fuel on the relatively flat terrain characteristic of the routes, some oversight was necessary to ensure that the bus operator consistently fueled the buses with CNG. If the buses had performed less satisfactorily in diesel-only mode, less oversight would have been necessary to ensure consistent CNG use (i.e., the process would have been self-regulating).

Conclusions and Recommendations

Conclusions

The following conclusions are based on the performance of the three C-10 DFNG and one C-10 D engines used in the Clean Air Express buses during the 12-month demonstration period.

Performance

- The performance and reliability of the C-10 DFNG engines were comparable to the C-10 D engine. This conclusion may need to be reassessed after more prolonged CNG use and higher mileage accumulation.

- When in dual-fuel mode, the C-10 DFNG engines used approximately 86% CNG and 14% diesel. At an 86% CNG substitution rate, the C-10 DFNG engines averaged about 4.8 miles/DEG, which is about 20% less than the C-10 D average of 6 miles/DEG.

- Averaged during the entire demonstration period, the C-10 DFNG engines operated about 57% of the time in dual fuel mode, and 43% of the time in diesel mode. The C-10 DFNG engines averaged 5.34 miles/DEG overall, which is about 11% less than the C-10 D average of 6.0 miles/DEG.

- When operating the C-10 DFNG engine in diesel mode, the reduced-power-mode feature provided only minimal incentive for drivers to refuel with CNG. The C-10 DFNG engines performed satisfactorily, even when fully loaded, in the reduced power mode.

- The lower-than-expected CNG substitution rate was the result of:
  - Occasional failure of the vehicle operator to fuel the buses with CNG.
  - Problems with the C-10 DFNG engine computer operating software.
  - Breakdowns of the CNG refueling station.

- The C-10 DFNG-engine-equipped buses cost about $0.20/mile more to operate than the C-10 D-engine-equipped bus.

Emissions

- Overall, the C-10 DFNG engine operating in the dual-fuel mode had lower NO_x, CO_2, and PM emissions and higher CO and NMHC emissions than the C-10 D engine.

- The C-10 DFNG engine had higher NO_x and NMHC emissions (combined) than the C-10 D for the both the EPA UDDC and WVU CBD drive cycles. The C-10 DFNG engine had lower NO_x and NMHC emissions (combined) than the C-10 D for the 55 MPH Steady State drive cycle.

- The C-10 DFNG engine demonstrated a greater percentage reduction in NO_x emissions than the C-10 D in the 55 MPH Steady-State drive cycle than in both the EPA UDDC and WVU CBD drive cycles. This may be due to the C-10 DFNG engine having relatively lower NO_x emissions, or to the C-10 D having relatively higher NO_x emissions (as would be expected if the C-10 D engine computer was equipped with a defeat device), when operated in the steady-state mode.

- When operated in the diesel mode, the C-10 DFNG engine had lower PM and NMHC emissions than the C-10 D engine. Emissions of NO_x, CO_2, and CO from the C-10 DFNG and C-10 D were similar when the engines were operated on diesel.

Recommendations

- Additional emissions testing may be warranted to:

  - Verify the differences in NMHC emissions between the C-10 DFNG and C-10 D.
  - Compare NO_x emissions from the C-10 DFNG with those of a C-10 D engine that is not equipped with a defeat device.
  - Verify that the C-10 DFNG, when operating in diesel mode, has lower NMHC and PM emissions than the C-10 D.

- Caterpillar should improve and refine the C-10 DFNG engine operating computer to increase the overall CNG substitution rate under typical driving conditions.

- Differences between the C-10 DFNG and C-10 D operating costs (e.g., costs for dual-fuel conversion, fuel, fueling labor, insurance, and engine repairs and maintenance) can vary greatly depending on the fleet application. Cost differences between the C-10 DFNG and C-10 D should be evaluated in detail for each specific application.

- Ongoing oversight of the vehicle operator may be needed if maximum CNG use is desired. Alternatively, the power available when the C-10 DFNG engine is used in diesel-only mode should be reduced to maximize the incentive for vehicle operators to consistently use CNG.

- A backup CNG station should be available to ensure maximum CNG use.

- If the C-10 DFNG engine is to be used for emissions mitigation purposes (e.g., to generate ERCs), air districts should consider requiring that the C-10 DFNG engines undergo regular emissions testing to verify any assumptions made on NO_x and PM reductions and NMHC and CO increases. Emissions testing should speciate hydrocarbon emissions to identify the non-methane/non-ethane portion of the exhaust.

Appendix A:

Detailed Bus Specifications

Bus Specifications

General Vehicle Data

Decal ID	A unique alphanumeric code for each vehicle	AIR 11	AIR 12	AIR 13	AIR 14
Vehicle ID Number (VIN)	Vehicle identification number	1M8PDMVA6-WP050429	1M8PDMVA6-WP050430	1M8PDMVA6-WP050431	1M8PDMVA6-WP050432
Fleet Veh ID	Vehicle Identification number used by fleet	1729	1730	1731	1732
Vehicle Make	Name of vehicle manufacturer	MCI			
Vehicle Model	Truck model number	102DL3			
Vehicle Year	Year vehicle was manufactured	1997			
Service Date	Date vehicle was put into service by fleet	1/19/98			
Start Mileage	Mileage on vehicle at the start of the fleet demonstration	2568	2490	2589	2563
Activity Code	Type of activity vehicle is used for (Code 1 from VMRSH)				
Equip. Category Code	Type of optional equipment installed on vehicle				
Body Mfgr Code	Name of body manufacturer	MCI			
Body Descr Code	Type of body attached to cab (Code 48 from VMRSH)				
Engine Serial	Serial number of the engine	2PN06582	2PN06563	2PN06580	2PN06570

Engine Data

OEM Retrofit	Is the engine OEM or a retrofit?	retrofit
Eng Mfgr Code	Name of engine manufacturer	Caterpiller
Eng Model	Engine model number	C10
Eng Config Code	Engine Configuration Code (Code 35 from VMRSH)	
Eng Cu In	Engine size in cubic Inches	629
Num Cylinders	Number of cylinders	6
Eng Year	Year engine was manufactured	1997
Cycle	Is the engine 2 cycle or 4 cycle?	4 cycle
Compr Ratio	Compression ratio	16
Ignition Aid Type	Type of Ignition aids used	none
EPA Certified (Y/N)	Is the engine configuration EPA certified?	no
Maximum bHp	Rated maximum brake horsepower of engine	350
Rpm of Max bHp	Rpm at rated maximum brake horsepower	1500 - 2100
Max. Torque (fl-lbs)	Rated maximum torque of engine	1050
Rpm of Max Torque	Rpm at rated maximum torque	1200 - 1500
Oil Capacity (qts)	Oil capacity In quarts	30
Blower? (Y/N)	Does the engine have a blower?	no
Turbocharger?	Does the engine have a turbocharger?	yes

Bus Specifications, continued

FUEL SYSTEMS Table

Alt Fuel Tank Model	Alternative fuel tank(s) model number	A15.08436
# of Alt Fuel Tanks	Number of alternative fuel tanks	4
# of Diesel Tanks	Number of diesel tanks	1
Amt of Useable AF	Total useful alternative fuel in tank(s)	48
Alt Fuel Units	Units used for diesel fuel diesel fuel tank(s) useful volume	U.S. gallons
Diesel Fuel Units	Units used for diesel fuel tank(s) useful volume	U.S. gallons
Fuel Type Code	What type of fuel is engine designed for?	CNG/Diesel
Diesel Additives	Type of additives used in diesel fuel	none
Alt Fuel Additives	Type of additives used in alternative fuel	none
Mech Elec	For liquid fuel engines, are the inj. mech. or electr. controlled	electronic
Amt of Useable Diesel	Total useful diesel fuel in tank(s)	182 gallons
AF Max Work Pres	Alternative fuel maximum working pressure in psi	3,600
AF-Tank Manufacturer	Name of alternative fuel tank(s) manufacturer	CNG Cylinder
Alt Fuel Empty Tank Wt	Alternative fuel tank(s) empty weight	1,384
Alt Fuel Tank WI Units	Units used for alternative fuel tank(s) empty weight	pounds
Injector Mfr	Name of liquid fuel injector manufacturer	Caterpillar
Inj Model	Liquid fuel injector model number	116-5414
Num of Injectors	Number of liquid fuel injectors	6
Liq-Fuel Filter Mfr	Name of liquid fuel filter manufacturer	Caterpillar
Liq-Fuel Filter Model	Liquid fuel filter model number	1Ro749
Fuel Induction	For gaseous fuel engines, Is it injection or fumigation?	Injection
Air Intake Throttle (Y/N)	Does the engine use an air intake throttle?	no
Diesel Tank Manu.	Name of diesel fuel tank(s) manufacturer	MCI
Diesel Tank Model	Diesel fuel tank(s) model number	9L-6-108
Diesel Empty Tank WI	Diesel fuel tank(s) empty weight	80
Diesel Tank WI Units	Units used for diesel fuel tank(s) empty weight	pounds
Gas Equip.	Is the gas fuel system OEM or retrofit?	retrofit

Bus Specifications, continued

TRANSMISSION Table

Transmission Mfr	Name of transmission manufacturer	Allison
Trans Model Number	Transmission model number	B-500 World
Trans Year of Mfr	Transmission year of manufacturer	1997
Trans Type Code	Type of Transmission (Code 7 from VMRSH)	
Forward Speeds	Number of forward speeds	6
Reverse Speeds	Number of reverse speeds	1

AXLE Table

Axle Type Code	Type of axle configuration (Code 3 from VMRSH)	
Axle Front Weight	Axle front weight	14,000
Front Tire Size	Size of front tire	12R22.5
Rear Tire Size	Size of rear tire	12R22.5
Axle Mfgr Code	Name of drive axle manufacturer (from VMRSH)	Rockwell
Axle Model	Drive axle model number	61143HX 205
Rear Axle Config Code	Rear axle configuration (Code 37 from VMRSH)	
Rear Axle Setup Code	Setup or rear axle configuration (Code 36 from VMRSH)	
Axle Ratio Low	Low axle ratio	none
Axle Ratio High	High axle ratio	4.56:1
Total GVW Wt (lb)	Total gross vehicle weight in pounds	46,000
Total Curb Wt (lb)	Total weight with the truck in curb weight configuration	48,000
Torque Converter Ratio	Torque converter ratio	NA
Wheelbase	Length of wheelbase	279 inches

EMISSION Table

Cat Conv	Does the vehicle have a catalytic converter? Y or N	N
Cat Conv Mfg	Name of catalytic converter manufacturer	-na-
Cat Conv Model	Model number of the catalytic converter	-na-
Dsl Prt Trap	Does the vehicle have a diesel particulate trap? Y or N	N
Trap Mfg	Name of the particulate trap manufacturer	-na-
Trap Model	Model number of the particulate trap	-na-
Trap Regen Type	Type of trap regeneration process	-na-
Trap Conf	Particulate trap configuration	-na-
Num Trap Ele	Number of particulate trap elements	-na-
Trap Sys WI	Weight of the particulate trap system	-na-

Appendix B:

Detailed Bus Operating Data

Bus No. AIR 11 (Dual Fuel)

Month	Reading Date	Total Engine Hours[1]	Total Dual-fuel Hours[1]	Miles Traveled	Dual Fuel Mode CNG (DEG)[1]	Dual Fuel Mode Diesel (DEG)[1]	Total Diesel (DEG)[2]
February	3/2/98	45.1	23.8	2792	149.7	37.0	281.1
March	4/1/98	82.8	55.7	2702	358.7	55.9	189.5
April	5/4/98	88.1	61.3	2853	404.1	61.4	209.8
May	6/1/98	74.0	50.2	2419	339.2	49.7	218.0
June	7/1/98	79.0	44.8	2596	286.2	44.7	231.6
July	7/31/98	74.1	45.6	2437	272.5	46.3	178.4
August	9/2/98	83.1	4.7	2533	21.4	4.6	400.4
September	10/1/98	71.6	28.3	2494	192.6	29.6	415.5
October	11/2/98	79.5	58.2	2757	398.1	61.6	182.5
November	12/2/98	72.0	34.6	2272	215.0	34.6	325.8
December	12/31/98	93.0	41.1	3018	273.6	44.4	274.3
January	1/29/99	66.8	44.1	2831	279.9	46.0	178.5
Total		909.1	492.4	31704	3191.0	515.8	3085.4

Bus No. AIR 12 (Diesel)

Month	Reading Date	Total Engine Hours	Total Dual-Fuel Hours	Miles Traveled	CNG Used (DEG)	Diesel (DEG)	Total Diesel (DEG)[2]
February	3/2/98	NA	NA	2059	NA	NA	442.0
March	4/1/98	NA	NA	2622	NA	NA	374.6
April	5/1/98	NA	NA	2534	NA	NA	499.0
May	6/1/98	NA	NA	2179	NA	NA	349.6
June	7/1/98	NA	NA	2506	NA	NA	445.0
July	7/31/98	NA	NA	2374	NA	NA	430.3
August	9/1/98	NA	NA	2805	NA	NA	438.6
September	10/1/98	NA	NA	2273	NA	NA	377.9
October	11/2/98	NA	NA	2679	NA	NA	379.5
November	12/2/98	NA	NA	2335	NA	NA	295.0
December	12/31/98	NA	NA	2503	NA	NA	448.8
January (*)	1/29/99	NA	NA	574	NA	NA	99.7
Total				27443			4580

* This bus was taken out of service of January 11 for emissions testing and DF conversion.

1. This information was downloaded directly from the C-10 DFNG engine computer.
2. This information is based on operator fueling logs.

Bus No. AIR 13 (Dual Fuel)

Month	Reading Date	Total Engine Hours[1]	Total Dual-Fuel Hours[1]	Miles Traveled	Dual-Fuel Mode CNG (DEG)[1]	Dual-Fuel Mode Diesel (DEG)[1]	Total Diesel (DEG)[2]
February	3/2/98	41.5	29.3	2364	170.6	41.3	345.0
March	4/1/98	79.8	58.7	2995	393.8	58.0	99.3
April	5/4/98	77.7	55.9	2775	407.1	56.3	198.2
May	6/1/98	68.9	47.1	2525	342.8	48.1	99.0
June *	7/1/98	53.8	6.0	2864	20.8	5.5	310.5
July	7/31/98	79.2	19.0	2753	126.2	18.8	423.9
August	9/2/98	83.6	44.4	3021	311.4	44.1	222.5
September	10/1/98	75.5	36.2	2632	262.2	38.9	260.8
October	11/2/98	86.9	65.2	2975	469.5	69.1	90.8
November	12/1/98	72.0	32.1	2208	211.0	30.6	240.0
December	12/31/98	78.1	49.9	3250	214.0	33.4	200.8
January	1/1/99	69.4	39.2	2238	262.1	41.4	176.1
Total		866.4	483.0	32600	3191.5	485.5	2666.9

* The engine computer was reset during CNG repairs, some of the month's data were lost.

Bus No. AIR 14 (Dual Fuel)

Month	Reading Date	Total Engine Hours[1]	Total Dual-Fuel Hours[1]	Miles Traveled	Dual-Fuel Mode CNG (DEG)[1]	Dual-Fuel Mode Diesel (DEG)[1]	Total Diesel (DEG)[2]
February	3/1/98	45.1	13.5	2267	77.5	21	391
March	4/1/98	80.8	43.6	2696	278.0	39.7	111.0
April	5/4/98	81.5	59.2	2690	377.9	60.0	89.7
May	6/1/98	70.0	49.7	2273	302.1	48.4	219.0
June	7/1/98	83.3	47.7	2642	306.0	46.2	207.1
July	7/31/98	77.4	44.8	2521	281.6	42.4	193.5
August	9/2/98	84.0	64.1	2739	398.4	60.3	112.0
September	10/1/98	73.5	49.6	2390	309.9	48.2	159.0
October	11/2/98	84.3	63.4	2727	381.1	62.0	164.4
November (*)	12/1/98						182.0
December	12/31/98	153.7	85.0	4988	487.5	81.6	191.0
January	1/29/99	73.3	46.4	1991	236.5	42.9	73.9
Total		906.9	567.0	29924	3436.6	552.7	2093.6

* Unable to download data due to faulty connection. November data included with December's.

1. This information was downloaded directly from the C-10 DFNG engine computer.
2. This information is based on operator fueling logs.

Appendix C:

Emissions Test Results

SUMMARY
EMISSIONS TESTING FACILITY

LOS ANGELES COUNTY METROPOLITAN TRANSPORTATION AUTHORITY

TEST BACKGROUND

Dynamometer	**:- Chassis (Road Load Model#57)**
Vehicle I.D.	**:- Clean Air Express "Air 12"**
Fuel	**:- Diesel (dedicated)**
Engine Type	**:- Caterpillar C10 D**
Vehicle Type	**:- MCI 45 ft., 55 passenger**
Test Date	**:- 1/13/99**
Test Inertia	**:- 38,555 lbs. (34,280 tare + 1/2 pass. load)**
Eng. Mileage	**:- 030,276 miles**
Project Description	**:- California Energy Commission**

TEST DATA EPA UDDC SCHEDULE "D"

Test I.D.	THC (gm/mile)	CO (gm/mile)	NO_x (gm/mile)	CO_2 (gm/mile)	PM (gm/mile)	Economy (mpg)	CH_4 gm/mile	
T01955	0.565	3.59	19.90	2018.46	0.3684	5.02	nm	

TEST DATA CYCLE:WEST VIRGINIA UNIV. CBD

Test I.D.	THC (gm/mile)	CO (gm/mile)	NO_x (gm/mile)	CO_2 (gm/mile)	PM (gm/mile)	Economy (mpg)	CH_4 gm/mile	
T01957	1.145	3.96	22.30	2559.99	0.4702	3.96	nm	
T01958	1.181	4.05	22.59	2587.98	0.4904	3.92	nm	
T01959	1.241	4.09	22.34	2565.63	0.5083	3.95	nm	
Mean	1.189	4.03	22.41	2571.20	0.4896	3.94		
Std. Dev.	0.05	0.07	0.16	14.80	0.02	0.02		

TEST DATA CYCLE STEADY STATE:

Test I.D.	THC	CO	NO_x	CO_2	PM	Economy	CH_4	
T01960	0.0014	0.0044	0.041	2.05	0.00018	na	nm	
T01961	0.336	0.91	14.50	987.04	0.1181	10.28	nm	

Comments: T01960 - Idle test, emissions data reported in grams/second.
T01961 – 55 MPH test, emissions data reported in grams/mile, economy in miles/gallon.

Legend: na = not applicable nm = not measured

SUMMARY
EMISSIONS TESTING FACILITY

LOS ANGELES COUNTY METROPOLITAN TRANSPORTATION AUTHORITY

TEST BACKGROUND

Dynamometer	**:- Chassis (Road Load Model #57)**
Vehicle I.D.	**:- Clean Air Express Bus "Air 13"**
Fuel	**:- CNG mode**
Engine Type	**:- Caterpillar C10 DNFG**
Vehicle Type	**:- MCI 45 ft., 55 passenger**
Test Date	**:- 1/20/99**
Test Inertia	**:- 38,555 lbs. (34,280 tare + 1/2 pass. load)**
Eng. Mileage	**:- 034,556 miles**
Project Description	**:- California Energy Commission**

TEST DATA CYCLE: EPA UDDC SCHEDULE "D"

Test I.D.	THC (gm/mile)	CO (gm/mile)	NO_x (gm/mile)	CO_2 (gm/mile)	PM (gm/mile)	Economy (mpg)	CH_4 gm/mile	NMHC gm/mile
T01964	63.552	29.11	12.78	1638.02	0.1042	5.40	57.374	12.075

TEST DATA CYCLE: WEST VIRGINIA UNIV. CBD

Test I.D.	THC (gm/mile)	CO (gm/mile)	NO_x (gm/mile)	CO_2 (gm/mile)	PM (gm/mile)	Economy (mpg)	CH_4 gm/mile	NMHC gm/mile
T01966	91.940	44.15	15.25	2222.16	0.1761	3.94	67.276	14.325
T01967	84.206	41.67	15.21	2192.14	0.1777	4.03	62.709	13.327
T01968	89.346	43.14	15.16	2183.59	0.1728	4.01	67.512	14.322
Mean	88.497	42.99	15.21	2199.30	0.1755	3.99	65.83	13.99
Std. Dev.	3.94	1.25	0.05	20.26	0.00	0.05	2.71	0.58

TEST DATA CYCLE:STEADY STATE

Test I.D.	THC	CO	NO_x	CO_2	PM	Economy	CH_4	NMHC
T01969	0.0013	0.0059	0.026	1.96	0.00016	na	nm	nm
T01970	17.128	7.92	5.06	828.26	0.0442	11.37	nm	nm

Comments: T01969 - Idle test, emissions data reported in grams/second.
T01970 - 55mph cruise test, emissions data reported in grams/mile, economy in miles/gallon.

Legend: na = not applicable nm = not measured

SUMMARY
EMISSIONS TESTING FACILITY

LOS ANGELES COUNTY METROPOLITAN TRANSPORTATION AUTHORITY

TEST BACKGROUND

Dynamometer	**:- Chassis (Road Load Model #57)**
Vehicle I.D.	**:- Clean Air Express Bus "Air 13"**
Fuel	**:- Diesel mode**
Engine Type	**:- Caterpillar C10 DFNG**
Vehicle Type	**:- MCI 45 ft., 55 passenger**
Test Date	**:- 1/21/99**
Test Inertia	**:- 38,555 lbs. (34,280 tare + 1/2 pass. load)**
Eng. Mileage	**:- 034,556 miles**
Project	**:- California Energy Commission**

TEST DATA CYCLE: EPA UDDC SCHEDULE "D"

Test I.D.	THC (gm/mile)	CO (gm/mile)	NO_x (gm/mile)	CO_2 (gm/mile)	PM (gm/mile)	Economy (mpg)	CH_4 gm/mile	NMHC gm/mile
T01972	0.449	3.55	19.32	1997.84	0.2034	5.07	nm	nm

TEST DATA CYCLE: WEST VIRGINIA UNIV. CBD

Test I.D.	THC (gm/mile)	CO (gm/mile)	NO_x (gm/mile)	CO_2 (gm/mile)	PM (gm/mile)	Economy (mpg)	CH_4 gm/mile	NMHC gm/mile
T01974	0.979	4.02	22.31	2518.64	0.3193	4.02	nm	nm
T01975	0.994	3.93	21.98	2488.14	0.3310	4.07	nm	nm
T01976	1.013	3.98	22.15	2487.75	0.3326	4.07	nm	nm
Mean	0.995	3.98	22.15	2498.18	0.3276	4.05		
Std. Dev.	0.02	0.05	0.17	17.72	0.01	0.03		

TEST DATA CYCLE: STEADY STATE

Test I.D.	THC	CO	NO_x	CO_2	PM	Economy	CH_4	NMHC
T01977	0.0013	0.0044	0.040	2.02	0.00024	na	nm	nm
T01978	0.277	0.85	13.48	945.16	0.0774	10.74	nm	nm

Comments: T01977 - Idle test, emissions data reported in grams/second.
T01978 - 55 MPH test, emissions data reported in grams/mile, economy is miles/gallon.

Legend: na = not applicable, nm = not measured

SUMMARY
EMISSIONS TESTING FACILITY

LOS ANGELES COUNTY METROPOLITAN TRANSPORTATION AUTHORITY

TEST BACKGROUND

Dynamometer :- Chassis (Road Load Model #57)
Vehicle I.D. :- Clean Air Express Bus "Air 14"
Fuel :- CNG mode
Engine Type :- Caterpillar C10 DFNG
Vehicle Type :- MCI 45 ft., 55 passenger
Test Date :- 1/27/99
Test Inertia :- 38,555 lbs. (34,280 tare + 1/2 pass. load)
Eng. Mileage :- 032,598 miles
Project :- California Energy Commission

TEST DATA CYCLE: EPA UDDC SCHEDULE "D"

Test I.D.	THC (gm/mile)	CO (gm/mile)	NO_x (gm/mile)	CO_2 (gm/mile)	PM (gm/mile)	Economy (mpg)	CH_4 gm/mile	NMHC gm/mile
T01990	43.906	24.96	14.58	1642.59	0.1568	5.59	40.588	8.646

TEST DATA CYCLE: WEST VIRGINIA UNIV. CBD

Test I.D.	THC (gm/mile)	CO (gm/mile)	NO_x (gm/mile)	CO_2 (gm/mile)	PM (gm/mile)	Economy (mpg)	CH_4 gm/mile	NMHC gm/mile
T01994	63.213	36.08	17.33	2226.56	0.2389	4.10	43.422	9.296
T01995	54.994	34.32	17.63	2224.82	0.2394	4.15	41.976	9.033
T01996	52.173	32.79	17.58	2218.65	0.2372	4.18	38.493	8.357
Mean	56.793	34.40	17.51	2223.34	0.2385	4.14	41.30	8.90
Std. Dev.	5.74	1.65	0.16	4.16	0.00	0.04	2.53	0.48

TEST DATA CYCLE: STEADY STATE

Test I.D.	THC	CO	NO_x	CO_2	PM	Economy	CH_4	NMHC
T01991	0.0021	0.0058	0.026	1.93	0.00031	na	0.0013	0.00078
T01992	10.128	5.43	6.64	837.56	0.0635	11.58	9.171	2.017

Comments: T01991 - Idle test, emissions data reported in grams/second.
T01992 - 55 MPH test, emissions data reported in grams/mile, economy in miles/gallon.

Legend: na = not applicable nm = not measured

SUMMARY
EMISSIONS TESTING FACILITY

LOS ANGELES COUNTY METROPOLITAN TRANSPORTATION AUTHORITY

TEST BACKGROUND

Dynamometer	**:- Chassis (Road Load Model #57)**
Vehicle I.D.	**:- Clean Air Express Bus "Air 14"**
Fuel	**:- Diesel mode**
Engine Type	**:- Caterpillar C10 DFNG**
Vehicle Type	**:- MCI 45 ft., 55 passenger**
Test Date	**:- 1/26/99**
Test Inertia	**:- 38,555 lbs. (34,280 tare + 1/2 pass. load)**
Eng. Mileage	**:- 032,598 miles**
Project	**:- California Energy Commission**

TEST DATA CYCLE: EPA UDDC SCHEDULE "D"

Test I.D.	THC (gm/mile)	CO (gm/mile)	NO_x (gm/mile)	CO_2 (gm/mile)	PM (gm/mile)	Economy (mpg)	CH_4 gm/mile	NMHC gm/mile
T01981	0.498	3.77	19.29	1992.51	0.2233	5.09	nm	nm

TEST DATA CYCLE: WEST VIRGINIA UNIV. CBD

Test I.D.	THC (gm/mile)	CO (gm/mile)	NO_x (gm/mile)	CO_2 (gm/mile)	PM (gm/mile)	Economy (mpg)	CH_4 gm/mile	NMHC gm/mile
T01983	0.994	4.05	22.74	2503.11	0.3494	4.05	nm	nm
T01984	1.023	4.03	23.13	2525.59	0.3428	4.01	nm	nm
T01985	1.015	3.97	23.07	2514.02	0.3599	4.03	nm	nm
Mean	1.011	4.02	22.98	2514.24	0.3507	4.03		
Std. Dev.	0.01	0.04	0.21	11.24	0.01	0.02		

TEST DATA CYCLE: STEADY STATE

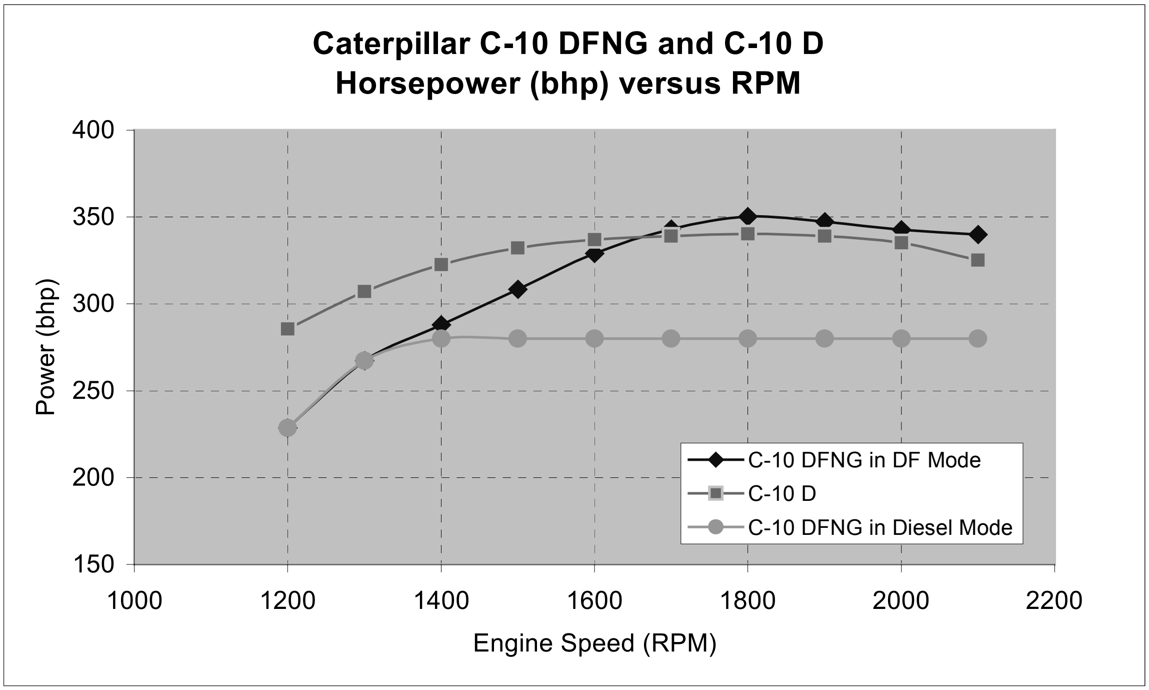
Test I.D.	THC	CO	NO_x	CO_2	PM	Economy	CH_4	NMHC
T01986	0.0013	0.0046	0.041	2.33	0.00021	na	nm	nm
T01987	0.292	0.93	13.79	974.61	0.1015	10.41	nm	nm

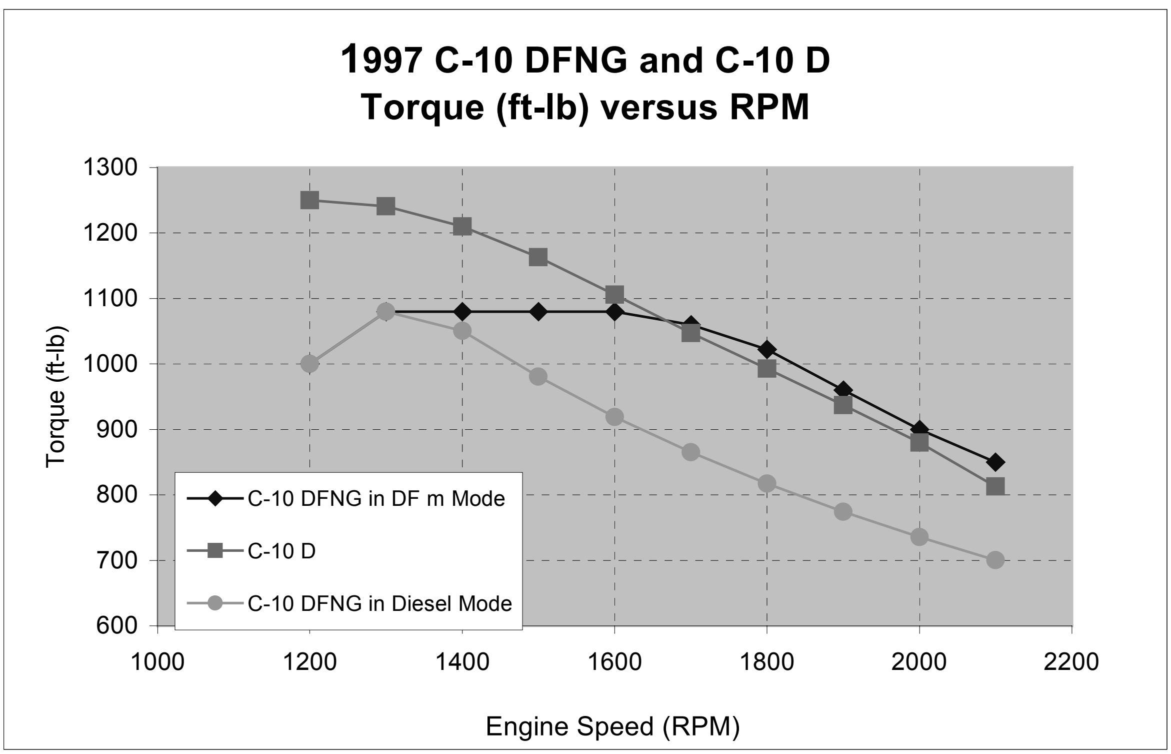
Comment T01977 - Idle test, emissions data reported in grams/second.
T01978 – 55 MPH test, emissions data reported in grams/mile, economy in miles/gallon.

Legend: na = not applicable, nm = not measured

Appendix D:

Caterpillar C-10 DFNG and D
Performance Ratings


Caterpillar C-10 DFNG and C-10 D
Horsepower (bhp) versus RPM
Power (bhp)
400
350
300
250
200
150
1000
1200
1400
1600
1800
2000
2200
Engine Speed (RPM)
C-10 DFNG in DF Mode
C-10 D
C-10 DFNG in Diesel Mode


1997 C-10 DFNG and C-10 D
Torque (ft-lb) versus RPM
Torque (ft-lb)
1300
1200
1100
1000
900
800
700
600
1000
1200
1400
1600
1800
2000
2200
Engine Speed (RPM)
C-10 DFNG in DF m Mode
C-10 D
C-10 DFNG in Diesel Mode

Appendix E:

Differential Cost Analysis References

Actual Costs During Demonstration Period

Annualized Capital Costs

The dual-fuel conversion costs were amortized over the expected life of the engines (12 years). These conversion costs are representative of retrofitting a C-10 D equipped vehicle to dual-fuel operation: if the engine has to be removed and replaced with a C-10 D engine before conversion, total conversion costs would be considerably higher. The amortization formula uses a capital recovery factor that reflects the time value of the funds used for the conversion. This methodology is consistent with that recommended by CARB for the Carl Moyer Program.

C-10 DFNG Annualized Capital Cost (ACC) ($/yr) = CC * CRF

Where:	CC	=	Conversion Costs	=	$45,000/bus
	CRF	=	Capital Recovery Costs	=	$[(1 + i)^n * i] / [(1 + i)^n - 1]$
	i	=	Interest Rate	=	3%
	n	=	Project Life	=	12
Then:	ACC	=	$45,000 * 0.10	=	$4,500
			C-10 D ACC	=	$0

Fuel Costs

The average cost of CNG fuel during the 12-month demonstration was $0.90/DEG (retail price); the cost for diesel was $0.80/DEG (wholesale price). Using the 56% average CNG use actually achieved in this demonstration, the "mixed" cost of CNG and diesel used in the C-10 DFNG engine is $0.856/DEG.

C-10 DFNG fuel costs	=	30,000 miles/yr/5.34 miles/DEG * $0.856/DEG
	=	$4,810
C-10 D fuel costs	=	30,000 miles/yr/6.00 miles/DEG * $0.80/DEG
	=	$4,000

Fueling Labor Costs

Assumptions

- A dual-fuel bus requires 30 minutes (at a driver cost of $20/h) to fuel the bus with both diesel and CNG fuel ($10/fillup). This includes driving time to/from the diesel and CNG stations. Although the dual-fuel buses obtain less fuel per fillup than the diesel bus, the time per fillup was assumed to be the same because the dual-fuel buses had to obtain both diesel and CNG, and the CNG station was further away than the diesel station.
- For the dual fuel bus, the CNG and diesel tanks are fueled when the CNG tanks are 80% empty, and the CNG-to-diesel substitution rate is 56% (max. CNG capacity 48 DEG: each dual-fuel fillup obtains 38 DEG (80% of 48) and 31 DEGs of diesel).

- The driver needs 30 minutes at a rate of $20/h to fill a diesel bus ($10/fillup). This includes driving time to/from the diesel station.
- The diesel tank is filled when the tank is 80% empty (maximum capacity 182 DEG: 80% of 182 = 146 DEG).

C-10 DFNG fueling labor costs = (DFL/CNG-D/fill-up) * (miles/yr/MPG_{DF})

Where:
DFL = dual fuel labor cost = $10/fillup
CNG-D/fillup = DEG/fill-up for DF engine = 38 DEG CNG + 31 DEG diesel (56% CNG ratio) = 69 DEG total
mi/yr = 30,000 miles/year
MPG_{DF} = miles/DEG for dual fuel engine = 5.34 miles/DEG

Then:
C-10 DFNG fueling labor costs = ($10/fill-up/69 DEG/fillup) * (30,000 miles/yr/ 5.34 mi/DEG) = $814

C-10 D Fueling labor costs = (DL/D/fill-up) * (miles/yr/MPG_D)

Where:
DL = diesel fuel labor cost = $10/fill-up
D/fillup = DEG/fillup for diesel engine = 182 * 0.8 = 146 DEG
mi/yr = 30,000 miles/year
MPG_D = miles/DEG for diesel engine = 6.0 mi/DEG

Then:
C-10 D Fueling Labor Costs = ($10/fill-up/146 DEG/fill-up) / (30,000 miles/yr/ 6.0 miles/DEG = $342

Insurance Costs

The following insurance quotes were obtained from Lancer Insurance Company:

Deductible	Cost
$10,000	0.006 * insured value
$ 5,000	0.012 * insured value
$ 1,000	0.015 * insured value

Using the value quoted for a $10,000 deductible:

C-10 DFNG Bus Insurance Cost = $395,000 * 0.06 = $2,370
C-10 D Bus Insurance Costs = $350,000 * 0.06 = $2,100

Maintenance – CNG System

Costs for maintaining the CNG were provided by Caterpillar and are included in this appendix. Costs were estimated for a 150,000-mile cycle to include all recurring maintenance costs.

Bus Miles	Service Description		Charge
15,000	15,000-mile service		$110
30,000	15,000-mile service		$110
45,000	45,000-mile service		$155
60,000	15,000-mile service		$110
75,000	15,000-mile service		$110
90,000	45,000-mile service		$155
105,000	15,000-mile service		$110
120,000	15,000-mile service		$110
135,000	45,000-mile service		$155
150,000	150,000-mile service		$165
	Total cost per 150,000 miles	=	$1,490
	Prorated cost for 30,000 miles	=	$298

There are no such costs for the C-10 D engine.

Repair Costs

Repairs on the C-10 DFNG engine were estimated to be the same as that of the C-10 D engine.

Maintenance Costs – Oil Changes

Oil changes for the C-10 DFNG engine were assumed to be needed every 15,000 miles, versus 7,500 miles for the C-10 D. The cost of each oil change was estimated by the Clean Air Express operator to be about $100. Thus:

C-10 DFNG Oil Change Costs = 30,000 miles/yr/15,000 miles/change * $100/change
= $200

C-10 DFNG Oil Change Costs = 30,000 miles/yr / 7,500 miles/change * $100/change
= $400

Projected Costs using Retail Diesel Rates and an Onsite CNG Station

Fuel Costs

The average retail cost per gallon of diesel fuel for the West Coast Region was estimated at $1.10.[1] Based on discussions with Mr. Ron Smith (Southern California Gas Company), a "ballpark" reasonable cost estimate for producing CNG at a fleet owner-owned onsite CNG station was estimated at about $0.75/DEG. This price includes capital costs for the equipment, electrical costs for compressor operation, pipeline natural gas costs, and maintenance station costs. Actual costs can be higher or lower than this estimate depending on the CNG throughput, utility costs, and type of station purchased. Assuming the Caterpillar technology can be refined to achieved an 80% average CNG substitution rate, the "mixed" cost of CNG and diesel for the C-10DFNG engine would be $0.80/DEG (0.2 *$1.10/DEG + 0.8 *$0.74/DEG).

C-10 DFNG fuel costs	=	30,000 miles/yr/5.34 miles/DEG * $0.80/DEG
	=	$4,494
C-10 D fuel costs	=	30,000 miles/yr / 6 miles/ DEG * $1.10/DEG
	=	$5,500

Fueling Labor Costs

Assumptions

- For a dual-fuel bus, CNG fueling takes place overnight ("time-filled") where the vehicles are parked overnight (i.e., there is no labor cost associated with CNG fueling). Diesel fueling for the dual-fuel bus takes 30 minutes at a rate of $20/h (i.e., $10/fillup). This includes driving time to and from the diesel station.
- Diesel has to be obtained less often for the dual-fuel bus because the bus runs on a combination of CNG and diesel. The CNG-to-diesel substitution rate is 80%.
- The driver needs 30 minutes at a rate of $20/h to fill a diesel bus ($10/fillup). This includes driving time to and from the diesel station.
- The diesel tanks on diesel and dual-fuel buses are fueled to completely full whenever they are 80% empty (max. capacity 182 DEG; 80% of 182 DEG = 146 DEG).

[1] National Energy Information Center, "On-Highway Diesel Fuel Price Survey," for period from 4/13/98–4/5/99.

C-10 DFNG fueling labor costs = (DFL / D/fill-up) * (miles/yr/MPG_{DF})

Where:

DFL	=	dual fuel labor cost = $10/fill-up
D/fill-up	=	effective DEG per diesel-fill-up for DF engine = 146 DEG diesel + 584 DEG CNG
	=	730 DEG (80% CNG ratio)
mi/yr	=	30,000 miles/yr
MPG_D	=	miles/DEG for dual-fuel engine = 5.34 miles/DEG

Then:
C-10 DFNG fueling labor costs = ($10/fill-up / 730 DEG/fill-up) * (30,000 mi/yr / 5.34 mi/DEG = $77

C-10 D fueling labor costs = (DL / D/fill-up) * (miles/yr / MPG_D)

Where:

DL	=	diesel fuel labor cost = $10/fill-up
D/fillup	=	DEG/fill-up for diesel engine = 182 * 0.8 = 146 DEG
mi/yr	=	30,000 miles/year
MPG_D	=	miles/DEG for diesel engine = 6.0 miles/DEG

Then:
C-10 D fueling labor costs = ($10/fill-up / 146 DEG/fill-up) / (30,000 miles/yr/6.0 miles/ DEG = $342

Dual-Fuel Engine – C-10 Engine (CNG Only)

(Earlier Model Fuel Management Module)

Maintenance Intervals/Customer Pricing

Recommended Service Interval	*Suggested List Price*
Every 10,000 miles Drain Coalescing Filter	 By Customer
Every 15,000 miles Replace Coalescing Filter Clean Last-hance Filter Inspect Natural Gas Connections for Leaks	$110 Part # 3000072 Requires 1 hour labor ($70/h)
Every 45,000 miles Replace Coalescing Filter Replace Last-hance Filter Inspect Natural Gas Connections for Leaks	$155 Part # 3000072 Part # 902112-1 (1/2" line size) Requires 1 hour labor ($70/h)
Every 150,000 miles Clean Natural Gas Injectors Replace Injector Seals Replace Coalescing Filter Clean Last-hance Filter Inspect Natural Gas Connections for Leaks	$365 Part # 3000072 Requires 4 hours labor ($70/h)

Parts Pricing

Part Number	Description	Customer List Price
3000072	Coalescing Filter	$40.00
902112-1	Last-Chance Filter	$45.00

Please verify the Fuel Management Module type with your Caterpillar Dealer prior to placing filter order.

(pricing effective October 1998)

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13. ABSTRACT *(Maximum 200 words)*
The purpose of this program was to demonstrate the Caterpillar C-10 Dual-Fuel Natural Gas (DFNG) engine in an over-the-road bus application. Three new Motor Coach Industries (MCI) 102DL3 buses, equipped with Caterpillar C-10 DFNG engines, and one bus, equipped with a Caterpillar C-10 diesel engine, were operated side by side on similar fixed-route revenue service for a 12-month demonstration period (February 1998 to January 1999). The buses were used as part of the Clean Air Express Commuter Bus Program in Santa Barbara County, California. The performance and reliability of the DFNG engines were similar to that of the diesel engine, but the emissions results were mixed.

14. SUBJECT TERMS
Dual-fuel natural gas engines, Caterpillar engines, Clean Air Express Commuter Bus Program, alternative fuel vehicles, alternative fuel vehicle emissions

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