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CNG and Diesel Transit Bus Emissions in Review

Alberto Ayala[a], Norman Kado[a,b], Robert Okamoto[a], Michael Gebel[a], Paul Rieger[a], Reiko Kobayashi[b], and Paul Kuzmicky[b]

[a]California Environmental Protection Agency, Air Resources Board
Sacramento and El Monte, California

[b]Department of Environmental Toxicology, University of California, Davis

ABSTRACT

Over the past three years, the California Air Resources Board (CARB), in collaboration with the University of California and other entities, has investigated the tailpipe emissions from three different late-model, in-use heavy-duty transit buses in five different configurations. The study has focused on the measurement of regulated emissions (NO_X, HC, CO, total PM), other gaseous emissions (CO_2, NO_2, CH_4, NMHC), a number of pollutants of toxic risk significance (aromatics, carbonyls, PAHs, elements), composition (elemental and organic carbon), and the physical characterization (size-segregated number count and mass) of the particles in the exhaust aerosol. Emission samples are also tested in a modified Ames assay. The impact of oxidation catalyst control for both diesel and compressed natural gas (CNG) buses and a passive diesel particulate filter (DPF) were evaluated over multiple driving cycles (idle, 55 mph cruise, CBD, UDDS, NYBC) using a chassis dynamometer. For brevity, only CBD results are discussed in this paper and particle sizing results are omitted. The database of results is large and some findings have been reported already at various forums including last year's DEER conference. The goal of this paper is to offer an overview of the lessons learned and attempt to draw overall conclusions and interpretations based on key findings to date.

INTRODUCTION

The objective of the project is to compare heavy-duty engine technology options for transit buses. Specifically, the study considers the available after-treatment options for CNG and diesel heavy-duty transit buses. Emissions testing is conducted over multiple driving schedules to assess cycle effects. A primary driver for the project is the characterization of the emission rates for several exhaust components of toxic risk significance. This information is intended to support the assessment of toxicity equivalency for CNG and diesel buses. Finally, the study includes investigation of PM and ultrafine (<100nm) particle emissions [1].

BACKGROUND

Table 1 shows a description of the test buses. All three buses are 40 passenger, New Flyer chassis vehicles. The diesel and CNG-1 buses came from the Los Angeles County Metropolitan Transit Authority (LACMTA) fleet while CNG-2 came from San Bernardino. The diesel bus is a 1998 model year bus powered by a DDC-S50 engine. This bus is equipped with a diesel oxidation catalyst (a catalyzed muffler) and a catalyst-based DPF. CNG-1 is a 2000 model year bus powered by a DDC S-50G engine. This bus is tested in two configurations, without after-treatment and with an oxidation catalyst (OC). The second CNG bus (CNG-2) is a 2001 model year vehicle powered by a Cummins Westport C Gas Plus engine. This bus is equipped with an OC by the OEM. All emissions tests were conducted at CARB's heavy-duty emission laboratory located on the grounds of the LACMTA as described by Ayala et al. [1]. Chronologically, the diesel and CNG-1 buses were tested first as illustrated in Table 2. This is referred to as Phase 1.A of the emissions study. The effect of OC for CNG applications was studied during Phase 1.B [2]. Phase 1.A included five duty cycles: 1) idle, 2) steady-state (SS) operation at 55 mph, 3) CBD, 4)

UDDS, and 5) NYBC. Phase 1.B included two cycles: SS (55mph) and CBD. In all instances, bus after-treatment was degreened prior to testing. This was accomplished by a combination of vehicle operation in revenue service and operation on the dynamometer for mileage accumulation. Lubricating oil and fuel samples (for both diesel and CNG) were collected and analyzed by commercial laboratories. The CNG fuel came from a LACMTA refueling station. The diesel fuel was ECD-1 donated by BP.

Table 1. Description of test buses.

	Model Year	Engine Make	After-treatment	Fuel
Diesel	1998	DDC-S50	DOC CB-DPF	ULSD
CNG-1	2000	DDC-S50G	none OC	CNG
CNG-2	2001	Cummins-Westport C-Gas Plus	OC	CNG

Table 2. Chronology of emissions testing.

	Test Bus Configuration	Test Date
	CNG-1	March 2001
	Diesel (DOC)	April 2001
Phase 1.A	**Diesel (DPF)**	May 2001
	CNG-1	June 2001
	CNG-2 (OC)	May 2002
Phase 1.B	**CNG-1 (OC)**	May 2002
	CNG-1	May 2002

All testing was conducted at ambient conditions in Los Angeles following the test procedures specified in the CFR for heavy-duty engine certification [3]. Criteria gas emission measurements included total HC based on heated FID, NO_X based on chemiluminescence, and CO using a NDIR analyzer. NO_2 emissions, assumed as the difference between NO_X and NO, were determined with a second NO_X analyzer. CH_4, NMHC, and aromatic hydrocarbons were determined from Tedllar bag samples and GC-FID analysis. Carbonyl emissions were determined from DNPH cartridge samples analyzed using HPLC. Emission sample collected using filters followed by vapor traps were extracted with organic solvents for PAH and mutagenicity analysis. PM-bound inorganic elements were determined from filter samples via XRF analysis. Elemental and organic carbon emissions were determined from filter samples and TOR. During Phase 1.A, size-resolved mass emissions were collected using a MOUDI. Particle number concentrations were determined using an ELPI and two SMPSs, but these results are not included here for brevity.

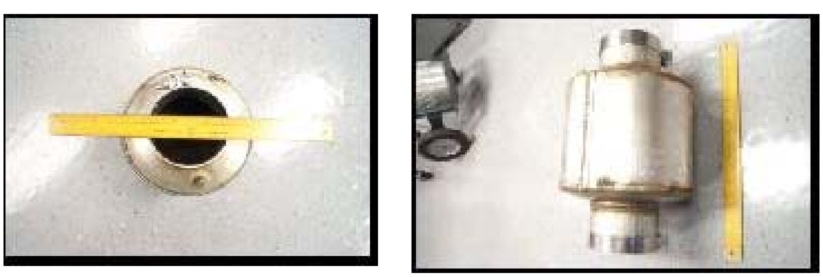

Figure 1. Catalyst for 2000 DDC S50G transit bus (CNG-1).

Figure 1 shows two views of the OC procured and installed by the OEM on the DDC-powered CNG bus (CNG-1). Figure 2 illustrates the CB-DPF used on the diesel bus. The DPF is made by Johnson Matthey, Inc. and was recently verified by CARB as a “Level 3” (i.e., 85% or better reduction in PM) diesel emission control technology for use in California [4].

Figure 2. DPF for 1998 DDC S50 transit bus (Diesel (DPF)).

DISCUSSION OF RESULTS OVER CBD CYCLE

Figure 3 shows the average emissions for PM, EC, OC, and elements over the CBD cycle for the five different bus configurations included in this study. Total PM emissions from the Diesel (DPF) were lowered than the CNG bus with and without after-treatment. The composition of PM from the Diesel (DOC) is largely EC (2/3) and 1/3 OC. In contrast, the emissions from Diesel (DPF) and CNG are dominated by OC. For all buses, the emission of PM-bound inorganic elements is dwarfed by the carbon emissions. Figure 4 illustrates the average NO_X results over the same cycle. On average, the NO_X emission from a CNG bus are approximately half of the NO_X emission from a diesel bus. In addition, the NO_X from the Diesel (DPF) is approximately half NO_2. Except for the uncontrolled CNG bus (CNG-1), CO emissions from the test vehicles were low. CO_2 from the CNG buses were slightly lower than for the diesel bus (See Figure 5).

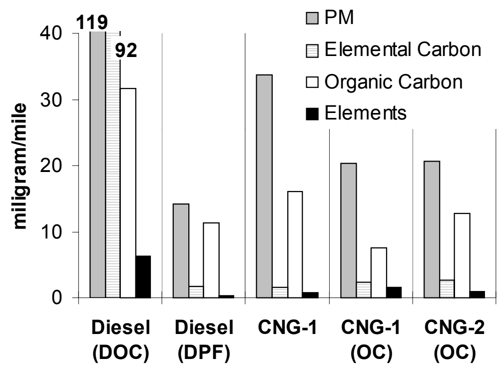

Figure 3. Average emissions over CBD cycle.

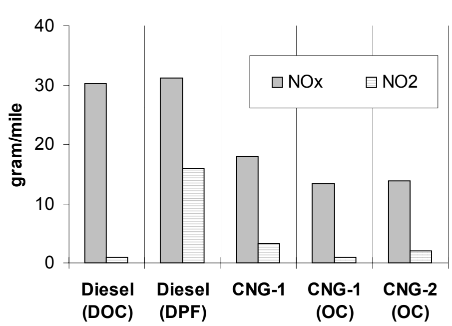

Figure 4. Average NOX emissions over CBD cycle.

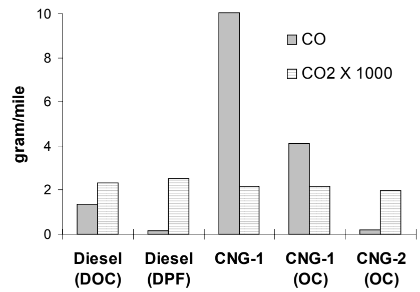

Figure 5. Average CO and CO_2 emissions over CBD cycle.

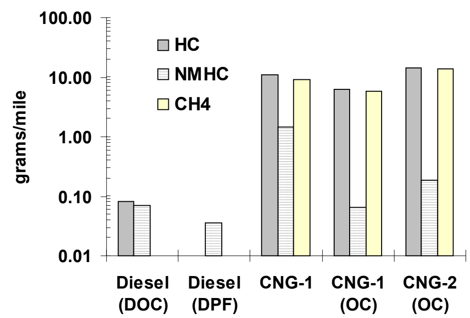

Figure 6. Average HC emissions over CBD cycle. *Note*: CH_4 not measured for diesel tests.

Because of after-treatment, HC emissions from the diesel bus were low. In the case of the Diesel (DPF), HC were measured at zero. As expected, HC from the CNG were primarily CH_4. As shown in Figure 6, the OC for CNG applications yielded reductions in NMHC. In contrast, the CNG OC was not very active in the control of CH_4. Carbonyl emissions from the uncontrolled CNG bus were highest among all five test bus configurations. These emissions were dominated by HCHO. The CNG OC was able to reduced HCHO significantly. The lowest carbonyl emissions came from the Diesel (DPF) as illustrated in Figure 7. VOC emissions were also measured and speciated. The lowest emission of benzene corresponded to the Diesel (DPF) and the CNG (OC) configurations. Although not shown, these measurements exhibited high variability. 1,3-butadiene was only detected in the exhaust from the uncontrolled CNG bus (See Figure 8).

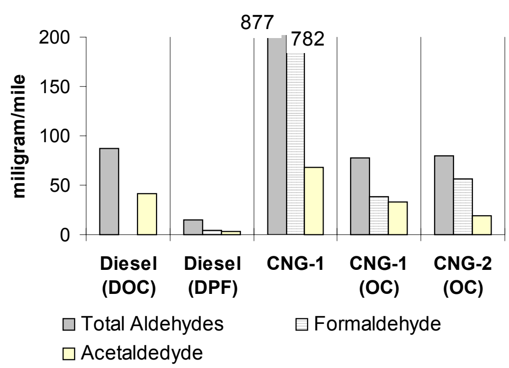

Figure 7. Average carbonyl emissions over CBD cycle.

The last two sets of results correspond to PAH and mutagen emissions. Figure 9 shows the results for the phase distribution of emissions of PAHs. PM-bound PAHs emissions are dwarfed by the emissions of volatile and semivolatile PAHs. The most abundant volatile PAH is napthalene. The Diesel (DPF) and the CNG (OC) configurations had the lowest emission of heavy PAHs. The CNG (OC) configuration had the lowest emission of light PAHs. Thus, the CNG OC appeared better able for controlling the semivolatile PAH fraction. Finally, mutagen emissions are shown in Figure 10. Sample extracts were tested in a modified Ames assay in strains TA98 and TA100 with and without S9. Only TA98 with S9 results are discussed here for brevity. Only the Diesel (DOC) and the uncontrolled CNG samples had activity in the volatile phase. The lowest activity corresponded to the Diesel (DPF). The CNG OC appears to be able to reduce some of the activity in both the volatile and PM phase.

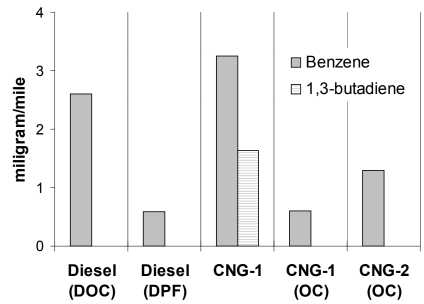

Figure 8. Average VOC emissions over CBD cycle.

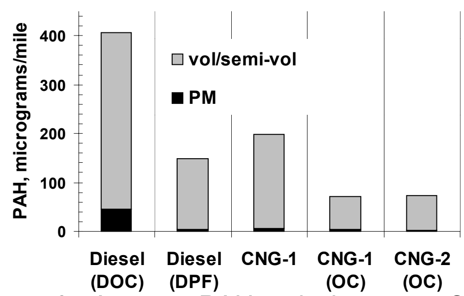

Figure 9. Average PAH emissions over CBD cycle.

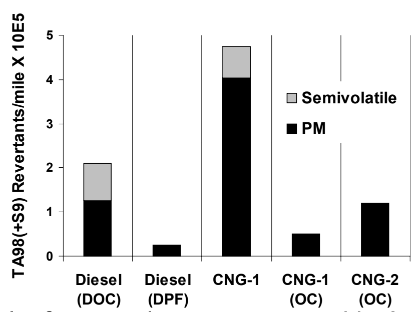

Figure 10. Average results for sample extracts tested in Ames assay (for CBD cycle).

CONCLUSIONS

After-treatment shows potential for significant emission reductions for both CNG and diesel heavy-duty engine applications. The magnitude of these reductions differs by pollutant and duty cycle. The CB-DPF yielded reductions of total PM, EC, OC, elements, CO, HC, NMHC, carbonyls, VOCs, PM-bound and volatile PAHs, and PM-bound and volatile mutagen emissions relative to the Diesel (DOC). The CNG catalyst (CNG-1 (OC)) yielded reductions of total PM, OC, CO, HC, NMHC, CH_4, carbonyls, VOCs, semivolatile PAHs, and PM-bound and volatile mutagen emissions relative to the uncontrolled configuration (CNG-1). The NO_X emissions from the CNG buses were approximately half of those from the diesel bus. In addition, the NO_X from the DPF-equipped bus were approximately 50% NO_2. Comparing results for the Diesel (DPF) to the uncontrolled CNG (CNG-1) suggests that the DPF yielded lower emissions of all pollutants measured in this study, with the exception of NO_X (and NO_2), EC, and CO_2. Furthermore, speciation of emission profiles suggests that, at least, the CNG with catalyst and the DPF-equipped bus are equivalent. Aside from NO_X, average gram per average gram of emissions, the trap-equipped diesel still appears to have a slight advantage over the OC-equipped CNG. However, the comparison of toxicity equivalency on an average gram per average gram basis is difficult because while diesel PM is considered a toxic air contaminant by the State of California, CNG PM has no such designation at present.

Finally, the results are a snap-shot of three buses only. While it is believed that the emissions from the buses typify the expected difference between the tested technologies, results cannot be used to infer differences for the fleet as a whole. After-treatment durability, deterioration, and vehicle maintenance were not considered.

DISCLAIMER

The statements and opinions expressed in this document are solely the authors' and do not represent the official position of the California Air Resources Board or the University of California. The mention of trade names, products, and organizations does not constitute endorsement or recommendation for use.

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