

Briefing Paper on Interim Results and Tentative Conclusions

For

ARB's Study of Emissions from "Late-model" Diesel and CNG Heavy-duty Transit Buses

April 2002

Preface

This document discusses the available results from the Air Resources Board's (ARB) study of emissions from two late-model transit buses, which utilize three distinctly different emission reduction configurations. This report provides a synopsis of the test results from a study for which additional data reduction and analysis is still in progress. Therefore, interpretations are not definitive or exhaustive. This analysis is based on a partial set of results that has not been subject to full external and/or peer review and as such is subject to revision and change. The data is being presented at this time because of the high interest expressed by numerous parties. The report is intended to facilitate further review and discussion of the available information.

Project Summary

The ARB led a multi-agency research effort and gathered tail-pipe emissions data from two late-model public transit buses in operation in Los Angeles. The objective of this study was to compare emissions from diesel and compressed natural gas (CNG) transit buses. Chassis dynamometer testing was conducted at ARB's Heavy-duty Emissions Testing Laboratory (HDETL) to: 1) assess driving cycle effects, 2) evaluate toxicity between new and "clean" heavy duty engine in-use technologies popular in California, and 3) to investigate ultrafine (<100 nm) particle emissions. Since the goal was to obtain in-depth emissions profiles from current buses using different fuels and control systems, rather than a true fleet average, only three individual vehicle configurations were investigated. These were:

- 1) A CNG 40-passenger New Flyer bus equipped with a 2000 DDC Series 50G engine.
- 2) A "baseline" diesel 40-passenger New Flyer bus equipped with a 1998 DDC Series 50 engine, a Nelson's catalyzed muffler, and running on low-sulfur ECD-1 diesel fuel.
- 3) The same diesel vehicle retrofitted with a Johnson Matthey Continuously Regenerating Technology (CRT™) diesel particulate filter (DPF) in place of the muffler and running on ECD-1 fuel.

The CNG bus was not equipped with any aftertreatment devices. Although a particle trap for the CNG was explored as an option, this is currently not available. At present, a follow-up study is being planned for a catalyst-equipped OEM conversion of the same CNG bus. The CRT was installed new and de-greened prior to testing. The diesel vehicle was fueled by BP ARCO ECD-1 with a measured sulfur content of 11 ppm. The duty cycles were:

- 1) Idle operation.
- 2) A 55 mph steady-state (SS) "loaded" cruise condition.

- 3) The Central Business District (CBD) cycle.
- 4) The Urban Dynamometer Driving Schedule (UDDS).
- 5) The New York City Bus Cycle (NYBC).

Collection of total particulate matter (PM) over multiple cycles was performed for subsequent chemical analyses. Regulated (nitrogen oxides [NO_x], total hydrocarbons, total PM, and carbon monoxide [CO]) and unregulated (carbon dioxide [CO₂], nitrogen dioxide [NO₂], nonmethane hydrocarbons, toxic hydrocarbons, carbonyl compounds, polycyclic aromatic hydrocarbons [PAHs], elements, elemental carbon, and organic carbon) emissions were determined. Extracts from diesel and CNG samples were tested in a modified Ames mutagenicity bioassay (salmonella/microsuspension procedure). A Micro-Orifice Uniform Deposit Impactor (MOUDI) and an Electrical Low Pressure Impactor (ELPI) were used to collect size-selective measurements. Two Scanning Mobility Particle Sizers (SMPS) were used to characterize ultrafine particle emissions in the range of 6 to 230 nm.

Project Status

Dynamometer testing was completed in June 2001. Most chemical analyses were completed by December 2001. PAH and bioassay analyses were completed recently. Staff are currently involved in interpretation of results. All of the data reported to date passed internal quality control protocols. Inquiries about data availability may be directed to the contact listed at the end of this document.

Interpretations

This report provides an analysis of available results and identifies possible conclusions that may emerge from this study. Plausible interpretations of the data in terms of a comparison between the emission profiles of the different vehicles are offered with the following caveats.

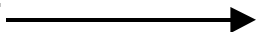
- Caveats**
- 1) Work is in progress to generate technical documents for external peer review. It is possible that peer review may offer a different interpretation of results.
 - 2) The study was limited to extensive testing of only two buses and three configurations. While we believe the emissions from these vehicles typify, in a qualitative and semi-quantitative manner, the emissions differences between the tested technologies, it may eventually be determined that results are not quantitatively representative for some pollutants for the fleet as a whole.
 - 3) Interpretation of the data and comparisons of the properties of the vehicle emissions are still a work in progress and additional and/or different conclusions may emerge later.
 - 4) The vehicles' degree of control technology for each configuration tested was not the same. The CNG bus was not equipped with a catalyst or any other aftertreatment device. The DPF was relatively new and had no significant mileage accumulation. The baseline diesel bus used ECD-1 fuel and an oxidation catalyst. This configuration is relatively clean in comparison to conventional on-road diesel vehicles.

6) The mutagenicity results are only an indication of the presence of potentially carcinogenic compounds in the samples analyzed. Although significant differences are an indication of relative toxicity potential of the samples analyzed, these results cannot be used to quantify cancer risk.

7) Testing of the CNG and CRT technologies challenged the sampling and analytical methodologies to the limits of detection. Further analysis and evaluation of the conventional sampling protocols may be required before final conclusions can be reached. For example, the Constant Volume Sample (CVS) dilution tunnel background effects have not been rigorously quantified. These can have a significant impact on results and will be extensively evaluated.

Summary of Results

Cumulatively, the available results from this study indicate that the relative emissions impact from the vehicle configurations investigated is as follows. Specifically, while the emissions profiles for all vehicle configurations showed some duty cycle dependence, the emissions data reported on a per mile basis suggests broadly the hierarchy given below.

Most Significant Emissions		HIGHEST  LOWEST
1	NO _x	Diesel baseline ~ Diesel/CRT > CNG
2	Total PM Mass	Diesel baseline >> CNG > Diesel/CRT
3	Total Ultrafine Particle Number*	Diesel baseline > CNG ~ Diesel/CRT
4	Aldehydes**	CNG > Diesel/CRT
5	Mutagenicity	CNG >> Diesel baseline ~ Diesel/CRT
6	PAH Species***	Diesel baseline > CNG > Diesel/CRT
7	NO ₂ /NO _x	Diesel/CRT >> Diesel baseline ~ CNG
8	CO ₂	Diesel/CRT ≥ Diesel baseline > CNG
Other Measured Emissions		
9	Nonmethane Hydrocarbons	CNG >> Diesel baseline > Diesel/CRT
10	Other Toxic Hydrocarbons	CNG > Diesel baseline > Diesel/CRT
11	CO	CNG > Diesel baseline > Diesel/CRT

* The ultrafine particles measured for the CNG bus appear to be smaller relative to the diesel particles.

** Diesel baseline samples invalidated.

*** Excluding naphthalene, due to contamination of sampling media.

Perspective

Qualitatively and in general, the regulated emissions from the three tested vehicle configurations are lower relative to a “conventional” heavy-duty diesel vehicle fueled by CA reformulated diesel and not equipped with an aftertreatment device. With regards to the toxic emissions, they also appear to be emitted at lower rates. However, quantification of the magnitude of these differences would require further study since a direct parallel comparison with such a “conventional” vehicle was not conducted in this study.

In terms of total PM mass, this study shows that CNG and trap-equipped diesel buses are significantly superior to the current and conventional diesel bus, even when that vehicle is fueled with very low sulfur diesel fuel and equipped with a catalyst. This alone represents a clear advantage. Both technologies are proven and offer a verified benefit for reduction of total PM mass emissions. However, no single technology is clearly superior to the others for every pollutant or pollutant indicator measured. Results suggest that, in their current configuration, neither the CNG nor the trap-equipped option is clearly superior in all aspects to the other and both may need additional improvement. The current mutagenicity findings suggest that CNG PM is not inert and may pose a toxic risk. The CNG bus also exhibited relatively high aldehyde and nonmethane hydrocarbon emissions; and the use of an oxidation catalyst may be advisable since it would be expected to greatly reduce these emissions. Furthermore, although the total count of ultrafine particles measured for the CNG bus is lower compared to the diesel baseline bus, the population of the CNG bus particles appears to be shifted towards smaller diameters relative to both diesel and CRT particles. Therefore, a PM trap for CNG applications may be desirable to offer further PM reduction benefits relative to controlled diesel technology options. For the DPF retrofit, optimization of catalysis appears essential to minimize tailpipe-out NO₂ emissions. In both scenarios, additional testing may be necessary to determine the impact on other emissions.

In terms of the mutagenicity results, the bioassay procedure is used only as a biological detector of mutagenic compounds in the emissions samples collected. These results are only indicators of potentially toxic compounds being emitted. The mutagenic activity numbers cannot be used directly to determine cancer risk by inhalation, but are only part of a process to evaluate the toxicity of emissions. However, the present results need to be taken into consideration to direct future research and development efforts to optimize the benefits offered by CNG and DPFs.

In conclusion, these results and interpretations are presented to inform interested parties of the study findings to date and to facilitate further review and discussion. In addition, input is being sought on the potential areas where additional research for technology improvement may be focused. Additional information is provided in Attachment A. For comments or questions, please contact Mr. Bart E. Croes, P.E., Chief, Research Division at (916) 445-0753 or bcroes@arb.ca.gov.

ATTACHMENT A

Preliminary Responses to Questions Concerning the Study

1. How do regulated emissions compare between vehicles?

Both CNG and CRT buses offered a clear advantage over the baseline diesel bus in terms of total PM emissions. Both nonmethane hydrocarbons and CO emissions for the CRT were near detection limits. CNG NO_x emissions were approximately a third lower than the diesel vehicle emissions.

2. Is there duty cycle dependence in the emissions from the test vehicles?

Yes. In general, emissions results showed some degree of dependence on duty cycle. For both criteria and toxic hydrocarbon emissions (e.g., benzene), the NYBC resulted in the highest gram/mile emissions for all three vehicle configurations.

3. Were significant NO₂ emissions observed from all vehicles?

No. As expected, only the CRT showed NO₂/NO_x ratios around 40 to 50%. The NO₂, but not the NO emissions, from the CNG were negligible. For the diesel baseline bus, NO₂/NO_x ratios were approximately single digit percentages.

4. Is there an atmospheric impact of the NO₂ increase?

Atmospheric modeling results suggest that an increase in tailpipe-out NO₂ emissions from trap-equipped vehicles observed in this study could have a negative air quality impact on the ambient ozone, nitric acid, and NO₂ levels in California. However, the same analysis showed that, because of PM and nonmethane hydrocarbon reductions achieved by DPFs, a modest increase in tailpipe-out NO₂ emissions offers more benefits than disbenefits. In all scenarios, ambient PM_{2.5} was reduced. Modeling results were presented by ARB staff at the February 2002 meeting of ARB's International Diesel Retrofit Advisory Committee.

5. Did the vehicles exhibit high oil consumption?

No. While there was not rigorous measurement of oil consumption rate, oil use was monitored and a qualitative observation was made that the vehicles exhibited normal oil use.

6. Were the buses well maintained?

The vehicles met the operational and maintenance requirements for normal use. While the maintenance records for each vehicle were not considered prior to testing, the vehicles were recruited directly from the in-use fleet. They were taken out of service to participate in this study and then sent back into service.

7. How do ultrafine particle emissions compare between the vehicle configurations investigated?

While it is known that ultrafine particle emissions are strongly influenced by both engine operation and sampling conditions, some general and relative observations can be made based on the present study. In comparison to the diesel baseline, the CRT showed significant reduction of ultrafine particle concentrations in the measured size range (6 to 230 nm). Total ultrafine particle counts for the CNG and CRT were roughly equivalent and lower than the counts for the baseline diesel. However, in most cases, the CNG produced particles that were smaller in size than those from the diesel vehicle.

8. How do toxic hydrocarbon and aldehyde emissions compare between vehicles?

Detectable 1,3-butadiene emissions were only observed for the CNG bus. Benzene emissions were slightly higher for the CNG bus relative to the baseline diesel bus. The CRT resulted in significant reduction of these toxic emissions. Formaldehyde and acetaldehyde were the primary carbonyl components in CNG bus exhaust. Over the CBD and SS cycles, these CNG formaldehyde emissions were significantly higher than the CRT emissions.

9. What is the composition of PM for the test vehicles?

Organic carbon dominates the PM composition of both CNG and CRT exhaust. This composition does not vary as a function of duty cycle. In contrast, the elemental carbon (EC) to organic carbon (OC) fraction in diesel baseline PM shows strong duty cycle dependence. The NYBC showed 80% EC fraction, while at idle EC accounts for only approximately 25% of the EC/OC split. Calcium, chlorine, phosphorus, zinc, and sulfur are oil components that were identified in the exhaust. Iron from engine wear was also evident.

10. How do tunnel blank measurements compare?

Tunnel blank measurements corresponding to every sample collected were taken in series before or after the sample. The composition of the tunnel blanks was primarily OC for all vehicles. In terms of total PM, the tunnel blank samples were of the same order as the actual emission samples for the CRT bus.

11. What was the phase distribution of PAHs?

Generally, the PAH emissions from the diesel baseline were higher than the CNG and the CNG were generally higher than the CRT. PAHs from the diesel baseline were found in all phases: particle-bound, semi-volatile, and volatile. In contrast, the PAHs in CNG and CRT exhaust were distributed primarily in the semi-volatile and volatile

phases. For all three configurations, the highest concentrations of PAHs were found in the volatile phase.

12. How does mutagenicity compare between vehicles?

While bioassay results showed cycle dependence for the diesel baseline and CRT results, the activity in the CNG sample extracts were three to four times more mutagenic than the diesel extracts for the TA98 strain without metabolic enzyme activation. The CNG PM extracts were approximately two to three times more mutagenic compared to the diesel for the same strain with metabolic enzyme activation. The bioassay procedure is used as a biological detector of mutagenic compounds in the emissions samples collected. These results are only indicators of potentially toxic compounds being emitted. The mutagenic emission numbers cannot be used directly to determine cancer risk by inhalation, but are only part of a process to evaluate the toxicity of emissions.

13. Will there be additional testing?

Yes. A follow up study is currently in the planning stages. The study will expand on the emission control technologies evaluated previously and will include two buses: 1) the same CNG bus tested, but equipped with an OEM oxidation catalyst, and 2) a state-of-the-art ultra-low emissions new CNG transit bus equipped with an oxidation catalyst. Also, additional biological effects testing will include in-vitro exposure analyses.