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# On-Road, In-Use Gaseous Emission Measurements by Remote Sensing of School Buses Equipped with Diesel Oxidation Catalysts and Diesel Particulate Filters

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## ABSTRACT

A remote sensing device was used to obtain on-road and in-use gaseous emission measurements from three fleets of schools buses at two locations in Washington State. This paper reports each fleet's carbon monoxide (CO), hydrocarbon (HC), nitric oxide (NO), and nitrogen dioxide (NO<sub>2</sub>) mean data. The fleets represent current emission retrofit technologies, such as diesel particulate filters and diesel oxidation catalysts, and a control fleet. This study shows that CO and HC emissions decrease with the use of either retrofit technology when compared with control buses of the same initial emission standards. The CO and HC emission reductions are consistent with published U.S. Environmental Protection Agency verified values. The total oxides of nitrogen (NO<sub>x</sub>), NO, and the NO<sub>2</sub>/NO<sub>x</sub> ratio all increase with each retrofit technology when compared with control buses. As was expected, the diesel particulate filters emitted significantly higher levels of NO<sub>2</sub> than the control fleet because of the intentional conversion of NO to NO<sub>2</sub> by these systems. Most prior research suggests that NO<sub>x</sub> emissions are unaffected by the retrofits; however, these previous studies have not included measurements from retrofit devices on-road and after nearly 5 yr of use. Two 2006 model-year buses were also measured. These vehicles did not have retrofit devices but were built to more stringent new engine standards. Reductions in HCs and NO<sub>x</sub> were observed for these 2006 vehicles in comparison to other non-retrofit earlier model-year vehicles.

## INTRODUCTION

Particulate matter (PM) emitted from diesel engines is of major concern in urban areas. Findings from the Puget

### IMPLICATIONS

New diesel vehicles are required to meet the stringent particulate matter standards enacted in 2007 and will soon have to meet the new 2010 NO<sub>x</sub> standards. To clean up pre-2007 model-year vehicles, many public and private entities are installing diesel oxidation catalysts or diesel particulate filters. This on-road study measures the gaseous emissions from these retrofit devices used on school buses after 5 yr of use. Reductions of CO and HCs are apparent, but a significant increase in NO<sub>x</sub> emissions is seen for the driving modes associated with bus traffic near the entrance and exit of schools.

Sound Clean Air Agency (PSCAA) estimate that 78% of the potential cancer risk from exposure to outdoor air toxics comes from diesel exhaust in the Seattle and Puget Sound region.<sup>1</sup> This issue is not contained to the Pacific Northwest. The U.S. Environmental Protection Agency (EPA) has been aggressively working to reduce emissions from on-road diesel vehicles across the country. In December of 2000, EPA enacted stringent standards for new diesel engines. These stringent PM standards for heavy-duty diesel engines, such as those on semi trucks and buses, were put into effect on 2007 model-year vehicles with major oxides of nitrogen (NO<sub>x</sub>) reductions coming in 2010.<sup>2</sup> Because these regulations are only for new vehicles, national and local programs exist to retrofit existing vehicles that still have a usable lifespan. The EPA's National Clean Diesel Campaign and PSCAA's Diesel Solutions are such programs.<sup>3,4</sup>

Thus far, the best solutions for reducing PM from these diesel vehicles are soot-reducing technologies such as diesel oxidation catalysts (DOCs) and diesel particulate filters (DPFs).<sup>3</sup> The DOCs oxidize PM, carbon monoxide (CO), and hydrocarbons (HCs) in the emission stream into nontoxic substances such as carbon dioxide (CO<sub>2</sub>) by using a metal catalyst. Typical EPA-certified reductions for these devices are 20% for PM, 40% for CO, and 50% for HCs.<sup>5</sup> Many DPFs, including the ones used in this study and in the comparative studies, are a two-chambered device that remove the PM via physical filtration after passing through an oxidation catalyst that oxidizes engine-out gases. The catalyst, in addition to reducing CO and HC emissions through oxidation, has another purpose, which is to oxidize nitric oxide (NO) to nitrogen dioxide (NO<sub>2</sub>). This production of NO<sub>2</sub> is necessary for the filter to be self-cleaning. Combustion of the trapped soot happens at a lower temperature with NO<sub>2</sub> than combustion with O<sub>2</sub>. These devices tend to be more effective than a DOC, with reductions in PM, HCs, and CO ranging from 60 to 90%.<sup>5</sup> However, the chemistry that occurs on a DPF filter, which converts a larger percentage of NO<sub>x</sub> toward NO<sub>2</sub>, has the potential to affect atmospheric chemistry because this ratio is important in the production of ground-level ozone.<sup>6</sup> Realizing this, the California Air Resources Board (CARB) established regulations that limit the increase in NO<sub>2</sub> from these devices to be no more than 30% of the baseline engine-out levels starting in January of 2007 and no more than 20% starting in 2009.<sup>7,8</sup> EPA has developed and verified a list of all soot-reducing technologies that comply with their own standards for PM reductions and the CARB NO<sub>2</sub> regulations.<sup>5</sup>

### School Buses

A comprehensive study conducted by the Universities of California Riverside and Los Angeles in April of 2004 concerning the exposure of children to school bus exhaust found that most student exposure comes from the commute and not in the loading and unloading process.<sup>9</sup> One of the major recommendations at the end of the study was to replace conventional (buses without retrofits) diesel buses with buses that have particle traps. If this suggestion was implemented nationally, this cleanup would potentially reduce a tremendous amount of toxic emissions because school buses drive over 4 billion mi every year in the United States, servicing more than 24 million children.<sup>10</sup> Because children are believed to be at a greater risk for health effects from exposure to PM,<sup>9</sup> EPA and PSCAA have created sub-programs from their more general diesel emission reduction programs directed at school buses. In Washington State alone, over \$25 million has been spent installing various retrofit devices on school buses to date.<sup>4</sup>

There has been extensive evaluation of these retrofit devices, including durability testing on chassis dynamometers.<sup>11-13</sup> These studies have been, understandably, focused more on the reductions of PM and to a lesser extent CO and HCs; however, there has been little on-road, in-use evaluation of their use. One on-road study tested DPF and DOC retrofits on school buses on a controlled track with a simulated driving mode and loads.<sup>14</sup> Other studies have followed retrofit urban buses with a chase vehicle equipped with emission monitoring systems.<sup>15</sup> These studies have produced valuable on-road data but suffer from a limited sample size. Remote sensing technology has proven to be an effective means for measuring on-road, in-use emissions from many different vehicles.<sup>16-19</sup> One study has measured school buses using a remote sensing device (RSD), but that instrument could only measure CO and HCs and it was performed before the introduction of retrofit technologies.<sup>20</sup> The two goals of this study were (1) to use an RSD to increase the number of on-road, in-use measurements of school buses with retrofit devices, and (2) to focus on the effects these retrofit devices have on the gaseous emissions, particularly NO<sub>x</sub> and the NO<sub>2</sub>/NO<sub>x</sub> ratio. Measurements were also made on a control fleet without retrofits to establish a baseline on-road, in-use emission factor.

## EXPERIMENTAL METHODS

### Apparatus

The RSD used in this study was the Fuel Efficiency Automobile Test (FEAT), which has been discussed previously for light-<sup>18,21,22</sup> and heavy-duty vehicles.<sup>17,23</sup> For light-duty vehicle measurements, the system rests directly on the ground or on the roadway. Heavy-duty vehicle measurements elevate the instrument on scaffolding. For this bus application, the source and detector units were set on 0.3 m tall wooden risers to raise the sampling beam closer to the straight-out tail pipe of the school buses. This system has recently been expanded to measure NO<sub>2</sub> in addition to NO to produce a total NO<sub>x</sub> picture.<sup>24</sup> This original expansion of the NO<sub>x</sub> system included two FEAT units positioned such that the light beams formed an "X" in the roadway. This involved two instruments being set up, one measuring CO<sub>2</sub>, CO, HCs, and NO, whereas the other measured NO<sub>2</sub> and CO<sub>2</sub>. The system has since been further modified and now uses only

one light source and one FEAT detector unit that directs light to two separate spectrometers via a bifurcated optical fiber. The instrument was calibrated twice daily with the use of two certified gas mixtures (Praxair) containing 6.01% CO<sub>2</sub>, 6.06% CO, 6190 parts per million (ppm) propane, and 3016 ppm NO in nitrogen; and 520 ppm NO<sub>2</sub> and 14.87% CO<sub>2</sub> in air. The calibrations were performed just before the morning and afternoon school bus traffic corresponding to each of the local school days. The FEAT RSD measures ratios of pollutants to CO<sub>2</sub>, from which grams of pollutant per kilogram of fuel burned can be calculated.<sup>25</sup> Accuracy is achieved by calibration using certified cylinders of gas mixtures that have reported uncertainties of ±5% or better.

### Field Measurements

The emissions from in-use school buses were measured at two different sites in Washington State. The system was manned during all measurements and the bus identification numbers were recorded. The PSCAA helped determine the most appropriate fleets to measure. The Bainbridge Island school district was chosen as the retrofit fleet of school buses. This was the first fleet to obtain retrofits in Washington (2003) and had DOC- and DPF-equipped buses. The retrofits used on this fleet were either the DPF from Johnson Matthey (continuously regenerating technology [CRT]) or a Purimuffler DOC. For comparison purposes, a second fleet on Vashon Island was also studied. This fleet was chosen because it has the most comparable engines to the Bainbridge Island fleet and has yet to be retrofit with soot-reducing devices. Table 1 shows the vehicle makeup of these two fleets. Most buses were measured in the morning, loaded with students before entering the school drive, and then empty pulling out after dropping off students. In the afternoon, most buses were first measured empty pulling into the school and then loaded with children when leaving.

*Retrofit Fleet.* The FEAT remote sensor was set up on school grounds just inside of the entrance/exit gate to the school parking lot. This location allowed for data to be collected for buses entering and exiting the parking lot; however, traffic was only in one direction during measurements. All buses entering the parking lot were under load because of the nearly universal need to stop before turning and accelerating into or out of the parking lot.

*Control Fleet.* The FEAT remote sensor was set up on the two lane road that serviced the entrance and exit of the control group's school. There was minimal traffic heading in the opposite direction from the buses in the second lane. However, to alleviate any plume confusion, the bus drivers were instructed to slow down before the instrument if a vehicle was coming in the opposite direction and then to gently accelerate after the other vehicle had passed by the instrument.

Measurements for this study spanned from May 21 to October 9, 2007. Initial measurements of the retrofit fleet were made from May 21 to May 25 and for the control fleet from May 29 through June 1. These field measurements yielded successful data for CO, HCs, and NO; however, because of a software malfunction the NO<sub>2</sub> spectrometer did not transfer data properly to the main

**Table 1.** Information about engine make, model, and retrofit used from Bainbridge and Vashon Islands.

NO <sub>x</sub> Emission Standard (g/bhp · hr)	Bainbridge Island				Vashon Island		
	Body Model Year	Engine Manufacturer	Engine Size (L)	Retrofit Type	Body Model Year	Engine Manufacturer	Engine Size (L)
4.0	2000	INT	7.6	DPF	2002	NAV	7.3
	2000	INT	7.6	DPF	2002	NAV	7.3
	2000	INT	7.6	DPF	2002	NAV	7.3
	2000	INT	7.6	DPF	1999	INT	7.3
	2000	INT	7.6	DPF	1999	INT	7.3
	2000	INT	7.6	DPF	1999	INT	7.3
	2000	INT	7.6	DPF	1999	INT	7.3
	2000	INT	7.6	DPF	1999	INT	7.3
	2000	INT	7.6	DPF	1999	INT	7.3
	2000	INT	7.6	DPF	1999	INT	7.3
5.0	1995	CUM	6.9	DOC	1997	INT	7.3
	1995	CUM	6.9	DOC	1997	INT	7.3
	1995	CUM	8.3	DOC	1997	INT	7.3
	1995	CUM	8.3	DOC	1997	INT	7.3
	1994	INT	7.3	DOC	1995	INT	7.6
	1993	FORD	7.3	DOC			

Notes: Engine manufacturers are International (INT), Cummins (CUM), and Navistar (NAV). All buses had the engine located in the rear.

computer and the NO<sub>2</sub> measurements were lost. To obtain a more complete NO<sub>x</sub> picture, the retrofit fleet was revisited on October 5 and 8 and the control fleet on July 15 and October 9. Note that the July 15 data from the control fleet were obtained without students on the buses; however, emission factors in grams of pollutant per kilogram fuel consumed measured on this day did not statistically differ from those of loaded school buses on October 9 and were therefore averaged together.

## RESULTS

The measure of ratios of pollutants to CO<sub>2</sub> allows for the reporting of emissions in grams of pollutant per kilogram of fuel.<sup>25</sup> The reported NO values are grams per kilogram of NO, whereas NO<sub>x</sub> is reported in NO<sub>2</sub> equivalents and is the sum of NO and NO<sub>2</sub>. Reported NO, NO<sub>2</sub>, and NO<sub>x</sub> data have not been adjusted for humidity.<sup>26</sup> Table 2 summarizes the average emissions from the three bus fleets. The Vashon Island control fleet includes data from those

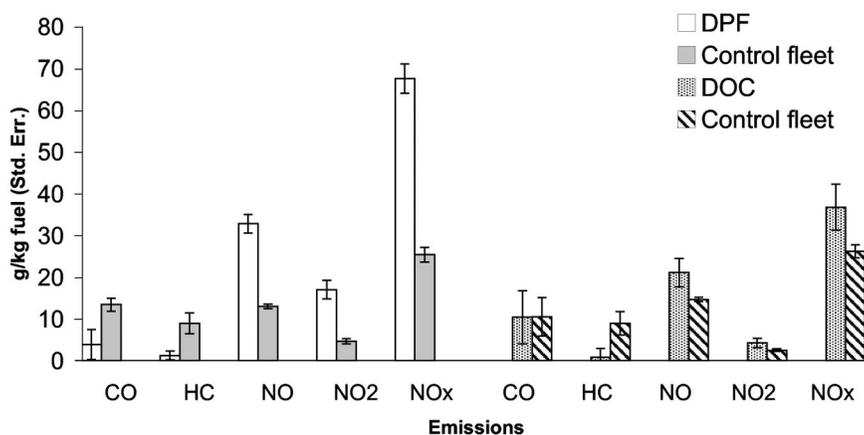
days that the NO<sub>2</sub> measurements were unavailable, as mentioned in the previous section. However, the NO<sub>x</sub> emissions and the NO<sub>2</sub>/NO<sub>x</sub> ratio are calculated only from vehicles with valid NO and NO<sub>2</sub> data. The data from both retrofit devices in comparison to the control fleet show lower levels of CO and HCs and higher levels of NO, NO<sub>2</sub>, and total NO<sub>x</sub>. The DPF buses also show higher NO<sub>2</sub> to total NO<sub>x</sub> ratios. These higher NO<sub>2</sub> concentrations are expected from a DPF-equipped vehicle because of the purposeful conversion from NO for trap regeneration.

Table 1 shows that the DOC, DPF, and control fleets are composed of buses spanning many model years. These model years were built to different emissions standards, which makes comparisons between the DOC and DPF fleets difficult. However, the retrofit fleets can be compared with vehicles from the control fleet, which were manufactured to meet similar standards. The major difference in emissions standards between the DPF and DOC fleets is that beginning with 1998 model-year vehicles,

**Table 2.** Results for the Vashon Island control fleet and the Bainbridge Island retrofit fleet with uncertainties at 95% confidence interval and *n* values.

	Bainbridge Island Average (g/kg)		Vashon Island Average (g/kg)
	DPF (74)	DOC (53)	All Buses (162)
CO	4.0 ± 7.2	10.6 ± 6.4	12.0 ± 5.1
HC	1.4 ± 2.0	1.0 ± 2.1	9.1 ± 3.7
NO	33.0 ± 4.5	21.2 ± 3.4	14.0 ± 0.7
NO <sub>2</sub> <sup>a</sup>	17.2 ± 4.5	4.4 ± 1.1	3.8 ± 0.8
Total NO <sub>x</sub> <sup>a</sup>	67.7 ± 7.1	37.0 ± 5.5	25.9 ± 2.3
NO <sub>2</sub> /NO <sub>x</sub> (%) <sup>a</sup>	26.5 ± 5.4	12.7 ± 3.8	14.2 ± 2.4
Model Year	2000	1993–1995	1995–2002

Notes: <sup>a</sup>There were 37 NO<sub>2</sub> measurements for the Vashon dataset.



**Figure 1.** Gaseous emission comparisons between the retrofit DPF and control fleet and the retrofit DOC and control fleet. The comparisons are between vehicles of the same new vehicle emission standards. Uncertainties represent the standard errors of the mean.

the EPA  $\text{NO}_x$  standards were lowered by 20% from previous levels (5 g/bhp · hr to 4 g/bhp · hr).<sup>2</sup> Figure 1 shows a comparison of the retrofit data to the data from the control group of the same initial model-year emission standards. The DOC-equipped vehicles represented in Figure 1 are the model years 1993–1995 and the DPF-equipped vehicles were all model-year 2000. The DOC vehicles are compared with 1997 buses from the control fleet and the DPF are compared with 1999–2002. Although there were no statistical differences at either site in CO, HCs, and NO from the two measurement campaigns, only the control fleet included measurements missing accompanying  $\text{NO}_2$  data. These data were included to help increase the statistical certainty of the CO, HC, and NO mean values because of the paring down of the control fleet when separated into model-year categories. This figure illustrates that the increase in total  $\text{NO}_x$  still exists even when model-year emission standards are taken into account.

Further comparisons to actual initial certification standards in g/bhp · hr are not possible with the data obtained from a RSD instrument that reports emissions on a fuel consumption basis. Although engine model year and type were known, the specific engine speeds at which these buses were operating are unknown and the speeds were approximated at 5–20 mph based on driver reported values. Vehicle-specific power was not possible to calculate because many of the buses would stop briefly in the path of the speed/acceleration detector before exiting the school grounds and entering onto the roadway, thus invalidating these data. However, comparisons can be made on a percent reduction basis. Table 3 shows the calculated percent difference in concentrations from the control fleet to the buses treated with a Johnson Matthey CRT and a Purimuffler DOC. These values are then further compared with the EPA-certified reductions

in HCs and CO; however, the CO difference for the DOC is not statistically significant. The on-road reductions that were found for HCs and CO are comparable to the values certified by the EPA.  $\text{NO}_x$  values are not published with the EPA-certified reduction data, and thus no comparisons can be made.

As mentioned in the introduction, on-road data from these retrofit devices are scarce in the literature. However, one such on-road study conducted by Toback et al.<sup>14</sup> at Rowan University is summarized and compared in Table 4. This study used a portable emissions monitoring system on-board the vehicles to measure emissions. The study installed and tested three retrofit devices each for a 20-min test cycle on three different buses. One of the DPFs that was used in the Rowan study was the Johnson Matthey CRT. Table 4 shows that the two studies have good agreement for CO and HC reductions using the same brand of DPF retrofits. However, a 165% increase in  $\text{NO}_x$  was found with the use of this device, whereas the Toback et al. study found a 9% decrease. The other DPF that was tested by Toback et al. was a Lubrizol Purifilter DPF, which did see a slight increase in  $\text{NO}_x$  production. The two studies were both on-road but differ in that the Rowan study was performed on a test track under a mobile test cycle, simulated student loads, new retrofit devices, and average emissions over this cycle. The measurements in the study presented here were collected from in-use, relatively consistent driving modes and retrofit devices that had been in use for 5 yr.

Unrelated to the retrofit comparison, there were two 2006 model-year buses measured at the control site that were not used in the above comparisons. Figure 2 shows how these newer model-year buses with more stringent emission standards compare on-road to the other technologies. There are significant reductions in HCs as well as

**Table 3.** Percent change between retrofit and control fleets from this study compared to EPA-certified values.

Gas	Johnson Matthey CRT DPF	EPA-Verified Retrofit Technologies <sup>5</sup>	Engine Control System Purimufflers DOC	EPA-Verified Retrofit Technologies <sup>5</sup>
CO	-71	-85	-1	-40
HC	-85	-95	-89	-70
$\text{NO}_x$	+165	NA	+40	NA

**Table 4.** Comparison of our results with New Jersey results and EPA values.

Gas	Johnson Matthey CRT DPF			Other Technologies <sup>b</sup>	
	Washington <sup>a</sup>	New Jersey <sup>b</sup>	EPA <sup>c</sup>	Lubrizol Purifilter DPF	Nett Technologies DOC
CO	-71	-79	-85	-75	-64
HC	-85	-88	-95	-95	-74
NO <sub>x</sub>	+165	-9	NA	+2	-7

Notes: <sup>a</sup>This study; <sup>b</sup>ref 14; <sup>c</sup>ref 5.

NO and NO<sub>2</sub> and thus total NO<sub>x</sub>. These on-road reductions reflect the EPA standards implemented starting with 2004 model-year vehicles that mandated a reduction in nonmethane HCs + NO<sub>x</sub> to nearly half of the previous standard.<sup>2</sup> Figure 2 shows the benefit (or penalty) of retrofitting older vehicles versus lowering new vehicle emission standards.

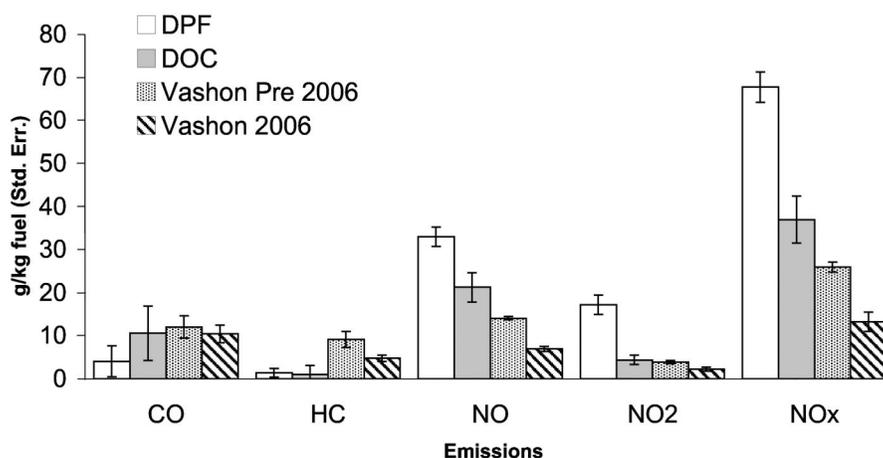
## DISCUSSION

The data from Table 2 and Figure 1 show a statistically significant decrease in emitted HCs for both retrofit technologies and a decrease in CO for the DPF. However, a statistically significant increase in emitted NO and NO<sub>x</sub> from the DPF- and DOC-equipped buses is also seen when compared with the control fleet of similar model year. The increased level of NO<sub>2</sub> to regenerate the trap appears to be in excess because there is an increase in emitted NO<sub>2</sub> for the DPF-equipped buses when compared with the control fleet. The results from this study suggest that in this driving mode these DPFs oxidize and produce more NO<sub>2</sub> than is necessary to regenerate the trap or the trap was not being regenerated when measured. None of these buses were measured after a cold start but some of the devices may not have been hot enough for regeneration to occur at the moment the vehicle was measured. The remote sensor is not able to measure the temperature of the catalyst and there were no temperature probes recording data on the devices.

It is curious to find such a large increase in total NO<sub>x</sub> from the retrofit devices. Studies and EPA verifications of new devices show that they reduce CO, HCs, and PM, but NO<sub>x</sub> emissions are not reported or reported as negligible. A durability study of transit buses retrofit with the same

DPF devices as were installed in the study presented here showed no NO<sub>x</sub> increase but only conducted follow-up tests after a 9- to 12-month period.<sup>12</sup> The longest durability study to date, 3.5 yr, tested the CRT devices and reported a 13% increase in NO<sub>x</sub> emissions during that time period.<sup>11</sup> However, the authors conclude that this increase is not statistically significant because of the variability that was present in the yearly variability of each subsequent test. The devices tested in the study presented here have been in-use for nearly 5 yr.

The increase in NO<sub>x</sub> emissions for DPF-equipped buses seen in this study could be attributed to dissimilar driving modes between the two sites as NO<sub>x</sub> levels increase at lower power requirements.<sup>27</sup> Actual power requirements are not known; however, the two sites both involved similar bus power requirements of acceleration and creep modes near the entrance/exit of a school. Vehicle-specific power could not be calculated because the buses often stopped within the span of the speed/acceleration measuring device, giving invalid speed data. Differences in road grade between the two sites were as great as within the road at each site but were considered flat. However, site-specific reasons are not the probable reason for the increase in total NO<sub>x</sub> and the NO<sub>2</sub>/NO<sub>x</sub> ratio because these emissions do not uniformly increase for the DOC and DPF retrofit buses at the Bainbridge Island location. Buses at this same site are presumably operating under the same driving conditions but exhibit different emission trends with different retrofit technologies. The DOC-equipped buses do not statistically differ from the control fleet in the NO<sub>2</sub> or NO<sub>x</sub> ratio emission categories,



**Figure 2.** Gaseous emission comparison of the retrofit technologies to the control fleet pre- and post-2004 EPA new vehicle standards. Uncertainties represent the standard errors of the mean.

thus suggesting that the increases seen from the DPF buses are real and not due to the measurement location. In addition, the NO<sub>2</sub>/NO<sub>x</sub> ratio for the DPF fleet of 26.5% as seen in Table 2 is in agreement with the results of "about one-third" that were found by the chase vehicle following New York City Transit buses equipped with particulate filters.<sup>15</sup> Day-to-day variability has also been excluded as a reason for this NO<sub>x</sub> increase because there is no significant difference between NO emissions from the early tests when the NO<sub>2</sub> was not reported and later when the NO<sub>2</sub> channel was recording measurements.

Because the Washington State retrofit program has only been successful installing and maintaining the DPF systems on the Bainbridge Island fleet, it is possible that the specific installation at this site may have led to increased NO<sub>x</sub>. Increased NO<sub>x</sub> could be explained if the engine parameters had been adjusted so as to increase engine-out NO<sub>x</sub>, which would ensure more NO<sub>2</sub> and thus favor trap regeneration. However, when the installation contractor was contacted they assured us that the devices were installed in the normal manner with representatives from the manufacturer present and that no other adjustments were made to increase NO<sub>x</sub>.

## CONCLUSIONS

Results from this study are consistent with EPA-verified CO and HC emissions for the Johnson Matthey CRT; however, they indicate that further measurements should be made for NO<sub>x</sub> emissions with long-term emissions in mind. Previous durability tests have not included 5-yr-old devices such as those in this study. It is also important to note that although nearly 300 valid bus measurements were collected among the three different fleets at different sites, this is not a direct comparison of the identical vehicle with and without retrofit. Comparisons do not account for driving mode or other site-specific variables; however, the sites are quite similar and both involve low speeds and typical driving conditions at the entrance and exits of a school parking lot with virtually no incline. A more direct comparison could be collected after the Vashon Island control fleet receives its intended DOC retrofits; however, this scheduled implementation is not yet known.

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