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Evaluation of retrofit crankcase ventilation controls and diesel oxidation catalysts for reducing air pollution in school buses

Kim Trenbath [a], Michael P. Hannigan [b], Jana B. Milford [b,*]

[a] Department of Atmospheric and Oceanic Sciences, 311 UCB, University of Colorado, Boulder, CO 80309, USA
[b] Department of Mechanical Engineering, 427 UCB, University of Colorado, Boulder, CO 80309-0427, USA

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ABSTRACT

This study evaluates the effect of retrofit closed crankcase ventilation filters (CCFs) and diesel oxidation catalysts (DOCs) on the in-cabin air quality in transit-style diesel school buses. In-cabin pollution levels were measured on three buses from the Pueblo, CO District 70 fleet. Monitoring was conducted while buses were driven along their regular routes, with each bus tested three times before and three times after installation of control devices. Ultrafine number concentrations in the school bus cabins were 33–41% lower, on average, after the control devices were installed. Mean mass concentrations of particulate matter less than 2.5 μm in diameter (PM2.5) were 56% lower, organic carbon (OC) 41% lower, elemental carbon (EC) 85% lower, and formaldehyde 32% lower after control devices were installed. While carbon monoxide concentrations were low in all tests, mean concentrations were higher after control devices were installed than in pre-retrofit tests. Reductions in number, OC, and formaldehyde concentrations were statistically significant, but reductions in PM2.5 mass were not. Even with control devices installed, during some runs PM2.5 and OC concentrations in the bus cabins were elevated compared to ambient concentrations observed in the area. OC concentrations inside the bus cabins ranged from 22 to 58 $\mu g\ m^{-3}$ before and 13 to 33 $\mu g\ m^{-3}$ after control devices were installed. OC concentrations were correlated with particle-bound organic tracers for lubricating oil emissions (hopanes) and diesel fuel and tailpipe emissions (polycyclic aromatic hydrocarbons (PAH) and aliphatic hydrocarbons). Mean concentrations of hopanes, PAH, and aliphatic hydrocarbons were lower by 37, 50, and 43%, respectively, after the control devices were installed, suggesting that both CCFs and DOCs were effective at reducing in-cabin OC concentrations.

1. Introduction

Time spent in school buses can contribute substantially to children's exposure to diesel emissions (Marshall and Behrentz, 2005). Levels of pollutants associated with diesel exhaust may be elevated inside of diesel-fueled school buses, compared to the ambient environment (e.g., Hill et al., 2005; Sabin et al., 2005). Excess pollution inside school buses may result from self-pollution from the vehicle's tailpipe or crankcase vent, pollution from other vehicles in the vicinity, and ambient outdoor pollution (Behrentz et al., 2004; Sabin et al., 2005; Hill et al., 2005; Adar et al., 2008).

To reduce children's exposure, school buses in Pueblo, CO have been retrofit with Racor 4500 closed crankcase ventilation filter systems and Donaldson Series 6100 diesel oxidation catalysts. This study evaluates the effectiveness of these devices for reducing bus cabin exposures by testing a sample of three buses from the Pueblo District 70 fleet before and after installation of the control devices. We tested each bus as it was driven along its regular route three times prior to and three times after control device installation. The study measured in-cabin concentrations of particle number, PM2.5 mass, EC, OC, particle-bound hopanes (a tracer for lubricating oil; Riddle et al., 2007), P-PAH and particle-bound aliphatic hydrocarbons (tracers for diesel fuel and exhaust emissions; Riddle et al., 2007), and carbonyls including formaldehyde and acetaldehyde.

As part of its Emissions Technology Verification program, the U.S. Environmental Protection Agency tested the Donaldson 6100 Series DOC on a 1998 Detroit Diesel Heavy Duty Engine operated over the Federal Test Procedure Heavy Duty Cycle with ultralow sulfur diesel fuel, and reported tailpipe emissions reductions averaging 22% for PM, 66% for hydrocarbons, and 41% for CO (RTI, 2003). Although to our knowledge emissions reductions from Racor 4500 closed crankcase ventilation filter systems have not been verified, these devices are designed to substantially reduce crankcase emissions by capturing and filtering blowby gases and directing them into the engine air intake.

* Corresponding author. Tel.: +1 303 492 5542; fax: +1 303 492 3498.
E-mail addresses: kim.trenbath@colorado.edu (K. Trenbath), michael.hannigan@colorado.edu (M.P. Hannigan), jana.milford@colorado.edu (J.B. Milford).

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Tailpipe and crankcase emissions reductions may not translate proportionately to bus cabin pollution concentrations, since the in-cabin concentrations are also influenced by emissions from other sources. A few previous studies have examined in-cabin pollution concentrations in buses with and without DOC and/or CCF retrofits. Hill et al. (2005) tested a school bus in Ann Arbor, MI before and after the bus was retrofit with a DOC and then with a DOC–CCF combination. PM2.5 concentrations were reduced by about half after the DOC–CCF combination was installed compared to levels observed without controls or with the DOC alone. Ultrafine PM concentrations did not change significantly after the retrofits were installed. Rim et al. (2008) measured concentrations in three school buses in Round Rock, TX, with each bus tested once before and once after being retrofit with DOC and CCF. Post-retrofit PM2.5 mass concentrations ranged from about 10% to 50% lower than the pre-retrofit concentrations. Post-retrofit number concentrations ranged from about 7% higher to 60% lower than the pre-retrofit levels. Over 15 tests, mean and median in-cabin concentrations of PM2.5 and particle number were comparable to concentrations measured out the bus windows. Based on measurements on conventional buses and on a different set of buses retrofit with DOCs, Hammond et al. (2007) estimated that DOCs reduced in-cabin particle number concentrations by about 25%. Through multivariate regression of data from 46 bus trips in Seattle and Tacoma, WA, Adar et al. (2008) estimated that new buses (2005 or later) equipped with DOCs reduced in-cabin PM2.5 concentrations by 13 $\mu g\ m^{-3}$. Their study could not distinguish the effect of the DOC from other attributes of the newer buses on which they came installed.

This study supplements the previous studies by measuring levels of a relatively broad set of pollutants in three buses tested before and after installation of the same control equipment. The study design allowed us to assess the statistical significance of the changes we observed and to account for variations across different buses. The study also measured organic tracers for lubricating oil and diesel emissions, enabling us to distinguish pollution reductions likely due to crankcase versus exhaust control devices.

2. Methods

2.1. Bus and route selection

Three AmTran Genesis model buses, model years 1996 or 1997, were selected to represent buses in the Pueblo District 70 fleet that were targeted for retrofits. All three were transit-style buses, with the engine mounted beside the driver's seat. The buses had each been driven about 100,000 miles prior to the study. For testing, each bus was paired with a distinct route, selected from the district's regular routes and spanning the variety of road conditions in the district. Each route included some travel on unpaved roads. Traffic volumes along the mostly residential routes were light. The route on which one bus (Bus 86) was driven for its first post-retrofit test (Run 12) inadvertently deviated slightly from the route driven on its other runs; we judged the deviation small enough to retain the results in our analysis. The route was corrected for the two remaining runs with this bus.

Because spare buses were not available, testing was conducted on weekends or school holidays during November and December 2007 (pre-retrofit) and March 2008 (post-retrofit). Buses were driven by district bus drivers, with no passengers except two research team members. All sampling equipment was placed in the back of the buses, because preliminary sampling using particle counters showed that the counts were highest there (Trenbath, 2008). Passenger windows were always closed to the extent possible; windows that would not close completely were left cracked open. Bus vents were closed for all tests. On some days, the bus drivers opened their windows for comfort. On cold days, they turned on the bus heaters. While previous studies have indicated in-cabin concentrations are highest with all windows closed (Sabin et al., 2005; Hill et al., 2005), the conditions in our study represent a more realistic high exposure scenario than a tightly closed cabin. Average ambient temperatures during the pre-retrofit runs ranged from −3 °C (Runs 8 and 9) to 27 °C (Run 3). Temperatures during the post-retrofit runs ranged from 11 °C (Run 19) to 24 °C (Run 17). Road conditions were wet or snowy on November 14 and 21, and December 8, but otherwise were dry.

For each test, the bus was started and allowed to idle for 5–10 min before sampling began. Once sampling began, the bus was driven from the depot towards school, simulating all stops where students were picked up, stopping at the school for a few minutes, then driving the return route towards the students' homes simulating all stops where students were dropped off, and ultimately arriving back at the depot. We simulated bus stops by stopping the bus, opening the doors and waiting a length of time that would allow students to board (or exit) the bus. All sampling devices were shut off as soon as the bus was stopped back at the depot. With the exception of Runs 1 and 19, multiple runs were completed during each sampling day. No individual bus was tested more than once during a day in order to sample each bus in a wider variety of ambient conditions. Travel times for the tests varied from about 1.5 to 2 h. Average bus speeds ranged from 10.0 to 15.2 $m\ s^{-1}$ for the pre-retrofit runs and from 9.9 to 15.8 $m\ s^{-1}$ for the post-retrofit runs.

2.2. In-cabin sampling

The filter sampler used for this study is described in detail by Dutton et al. (2009a) with modifications as described below. The sampler drew air into three channels through (1) a 90 mm quartz filter (VWR Pallflex Tissuequartz) to measure EC, OC, hopanes, and P-PAH; (2) a 47 mm Teflon filter (VWR Pall Teflon 47 mm diameter, 2 μm pore diameter) for gravimetric analysis; and (3) a DNPH-impregnated carbonyl cartridge. We constructed the sampler to sustain a high flow rate (92 $L\ min^{-1}$) for approximately 7 h and to fit in a bus aisle. The sampler used a ¼ HP pump, powered by three dry cell batteries connected in parallel to an inverter. The sampler is equipped with a cyclone inlet (University Research Glassware #URG-2000-30ENB, Chapel Hill, NC) that provided a 2.5 μm size cutoff at a 92 $L\ min^{-1}$ flow rate. After passing through the cyclone, the flow was split with 67 $L\ min^{-1}$ of the air directed into the quartz filter channel, 24 $L\ min^{-1}$ into the Teflon filter channel, and 1.1 $L\ min^{-1}$ into the carbonyl sampling cartridges (Supelco LpDNPH S10). The flow was regulated by critical orifices below each channel. Air in the quartz channel flowed through a flow totalizer, which recorded the total volume. The filter sampler was cleaned prior to the pre- and post-retrofit campaigns. During sampling, the sampler was placed in the aisle at the back of the bus. Its inlet was 1.27 m above the floor.

Filters and carbonyl cartridges were loaded immediately prior to sampling and unloaded immediately afterwards. During the field campaigns, filters and carbonyl cartridges were stored with ice in a portable cooler. Prior to sampling, quartz filters were baked at 500 °C for 12 h. Teflon filters were individually stored in their own Teflon tape-sealed container. Carbonyl cartridges were stored unopened until immediately before sampling. Used cartridges were placed in an amber jar immediately after sampling; this jar was kept in the cooler during the field campaign and then stored in the lab refrigerator until extraction. Quartz filter, Teflon filter, and carbonyl cartridge blanks were taken to the sampling site and handled in the same manner as sample filters and cartridges, except that they were not loaded into the filter sampler but rather were briefly exposed to air at the sampling site. Filter and cartridge blanks were processed on four out of the five days on which pre-retrofit sampling was conducted and all four post-retrofit sampling