Office of Science
Research Project Summary
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School Bus In-Cabin Particulate Matter Quantification and Reduction Strategies and Associated Risk Assessment

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Abstract

Public Law 2005, c.219 was signed on Sept 7, 2005. This law was intended to reduce fine particle emissions from diesel mobile sources in New Jersey. The law required the New Jersey Department of Environmental Protection (NJDEP) to conduct a project to (1) evaluate the relative contribution of emissions from both the crankcase and the tailpipe to in-cabin levels of fine particles in school buses; and (2) evaluate the feasibility of requiring, and the environmental and health benefits of, the reduction of fine particle levels from school bus tailpipe emissions through the use of additional retrofit devices. The monitoring study was carried out by Rowan University (Martinez-Morett D., et al., 2009) and overseen by the NJDEP Division of Science, Research and Technology (DSRT).

Two size ranges of particulate matter (PM) were measured, $PM_{2.5}$ (fine particles) and UFPC (ultrafine particulate count). Examples of the adverse health effects from breathing diesel exhaust $PM_{2.5}$ are exacerbations of asthma and lung cancer. The adverse health effects from breathing ultrafine particles are less well established, however, recent studies suggest respiratory as well as cardiovascular effects.

During simulated school bus runs using ultralow sulfur diesel fuel, in-cabin levels of particles were measured in the front of the bus, the back of the bus and in ambient air. Three measurements were conducted for each of the following conditions:

1. No retrofits (baseline)
2. Crankcase retrofit (crankcase ventilation system or CCVS).
3. Tailpipe Flow Through filter (FTF)
4. Tailpipe Diesel Particulate Filter (DPF)
5. CCVS + FTF
6. CCVS + DPF

The results from this study indicate that properly sealed front/back doors, engine compartment and exhaust system in addition to the use of a CCVS, substantially reduce in-cabin $PM_{2.5}$ and UFPC levels. The use of a tailpipe retrofit, either FTF or DPF alone or in conjunction with the CCVS, appear to marginally improve in-cabin $PM_{2.5}$ levels relative to when the CCVS was used alone. For UFPC, compared to CCVS alone, the combination of CCVS and DPF may provide a small additional reduction, however there is greater uncertainty associated with those measurements because the use of a DPF alone appears to increase UFPC (see Figure 2). The combination of CCVS and FTF, however, does not appear to provide a significant improvement over CCVS alone.

There are significant uncertainties involved in applying standard risk assessment approaches to the relatively short term exposures that occur on a school bus. However, even when taking these uncertainties into account, it is estimated that the installation of the CCVS will result in a significant reduction in asthma attacks for children riding on the buses based on the risk estimates from the Abt Associates model. The cancer risk without any retrofit device(s) is slightly above the target of 1×10^{-6} used for permitting of individual sources in the NJDEP air program. The risk becomes negligible with the use of a CCVS.

Please note that the initial 69 runs of this study were not considered when assessing results of the data because NJDEP identified problems with the bus and testing equipment which impacted the results from those runs to the extent that they had to be discarded in the final assessment of the retrofit technology(ies). The problems were resolved, and another 19 runs were completed (1 was discarded due to improperly installed FTF) and the final conclusions were based on the data from the final runs. The initial 69 runs demonstrated the need for proper seals on the doors (front and back) engine compartment (fire wall) and exhaust system to prohibit the intrusion of particles into the cabin of the bus.

Introduction

There will be an estimated 18,000 buses transporting children to and from school in 2009 (Personal communication, NJDEP Diesel Reduction Program, 1/2008). It is estimated that approximately 800,000+ New Jersey children will be on those buses, the majority of which have diesel engines. It is estimated that, on average, each of these children spends 1 ½ hours per school day on a school bus.

The intent of Public Law 2005, c.219 (http://www.njleg.state.nj.us), signed on Sept 7, 2005, was to reduce diesel emissions in New Jersey. As part of that legislation, the NJDEP was charged with conducting research to (1) evaluate the relative contribution of emissions from both the crankcase and the tailpipe to in-cabin levels of fine particles in school buses; and (2) evaluate the feasibility, and the environmental and health benefits of, the reduction of fine particle levels from school bus tailpipe emissions through the use of additional retrofit devices. This study was undertaken in response to that charge. The study was carried out by Rowan University (Martinez-Morett D., et al., 2009) in collaboration with the NJDEP Division of Science, Research, and Technology (DSRT) now known as Office of Science.

Methods

The study was conducted using a 1998 school bus with a 190 hp International DT466E engine with approximately 50,000 accumulated miles at the start of the project. Water-filled containers were placed in seats to simulate a bus half filled with children. The bus was driven on an isolated testing track in Aberdeen Testing Center, Aberdeen Md. The drive cycle was constructed to simulate typical pick ups/drop offs of school children. Details of the methodology can be found in the technical report by Rowan University (Martinez-Morett D., et al., 2009).

In-cabin levels of $PM_{2.5}$ (0.08-2.5 mm diameter particles) and UFPC (0.02-1.0 ìm diameter particles) were measured in the front and the back of the school bus while the bus was driven on the track. Ambient air $PM_{2.5}$ and UFPC were also measured during the runs at a site intended to be beyond the influence of the bus's emissions. Measurements were made under the following conditions:

1. No retrofits (baseline)
2. Crankcase enclosure retrofit (crankcase ventilation system, CCVS).
3. Tailpipe flow through filter (FTF) designed to reduce fine particles by at least 50% as a level 2 verified technology (http://www.arb.ca.gov/diesel/verdev/level2/level2.htm).
4. Tailpipe diesel particulate filter (DPF) designed to reduce fine particles by at least 85% as a level 3 verified technology (http://www.arb.ca.gov/diesel/verdev/level3/level3.htm)
5. CCVS + FTF
6. CCVS + DPF

$PM_{2.5}$ concentration is measured as mass of particulates per volume of air (i.e., ìg/m^3). UFPC concentration is measured as particle count per volume of air (i.e., pt#/cm^3) because of its large particle count relative to its small mass. $PM_{2.5}$ and UFPC were measured in the breathing zone of a seated child in both the front and back of the bus and in ambient air with ThermoFisher Scientific DataRAM4s, which measured $PM_{2.5}$ mass concentration, and TSI P-TRAKS, which measured UFPC concentration.

Gaseous emissions from the tailpipe of the bus, as well as pertinent engine parameters, were measured with a Sensors, Inc., Semtech-D tailpipe emissions analyzer in order to verify that the bus was operating under normal conditions during each run.

Results

There was an initial series of 69 runs. After those runs were completed, NJDEP staff discovered that the back door to the bus had been damaged and was not sealed in compliance with NJMVC inspection requirements. In addition, the test track was found to be inundated with other sources of PM. This initiated a series of inspections of the equipment used in this study. The NJMVC inspection indentified faulty seals in the front/back doors, fire wall (engine compartment) and exhaust system. This resulted in significant intrusion of tailpipe emissions into the cabin of the bus. An inspection by the manufacturer of the CCVS revealed that the installation of the CCVS was not in compliance with manufacturer's requirements. All deficiencies were remedied, an isolated track with few other sources of PM was found and another 19 runs were completed (1 run was discarded due to improper installation of FTF). The results below reflect the second series of runs with a bus that was now representative of the fleet in New Jersey. While the results from the first series of runs are not quantitatively evaluated here, they make a strong case that proper sealing of the doors, engine compartment and exhaust system are major factors in reducing exposure and risk inside school buses.

Figure 1 displays the $PM_{2.5}$ concentrations in the front and the back of the cabin of the school bus for each of the second series of runs that was completed after remediating the problems identified during the first series of runs. These data represent the in-cabin concentrations minus the contribution measured in the ambient air. Each group of 3 runs was done on the same day during the afternoon in the summertime. For runs 1-3 there was no retrofit technology (the baseline). Runs 4-6 are with the FTF installed. Runs 7-9 are with the DPF installed. Runs 10-12 are with the CCVS plus DPF installed. Runs 14-16 are with the CCVS alone. Runs 17, 18 and 19 are with the CVS plus FTF. Run 13 is not reported because it was found that the FTF was not installed properly.

It is observed from Figure 1 that the CCVS does a good job of reducing $PM_{2.5}$ in the cabin of the bus. Figure 1 indicates that the addition of tailpipe retrofits appears to provide marginal improvement (~1-2 μg/m^3) to in-cabin $PM_{2.5}$ concentration versus the CCVS alone.

Figure 1: In-Cabin $PM_{2.5}$ Concentrations in the Front and Back of the Bus, With and Without Various Retrofit Technology Configuration(s).

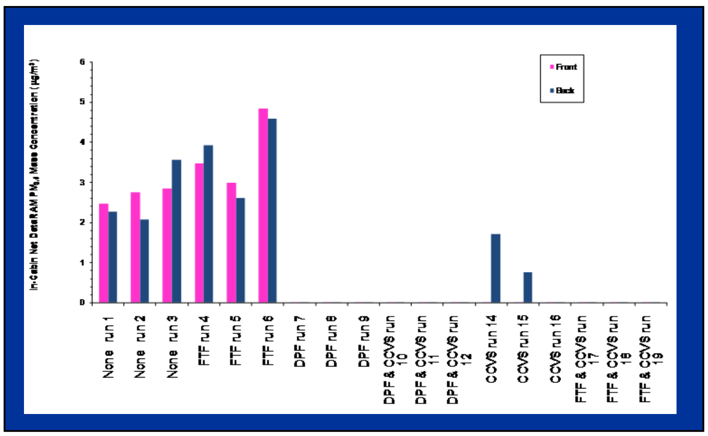

Table 1 presents the average concentrations of $PM_{2.5}$ for the three runs for each type of retrofit configuration(s). The CCVS is able to reduce $PM_{2.5}$ by 100% in the front of the bus and 70% in the back of the bus. When averaged together, the CCVS provides 85% reduction of $PM_{2.5}$ in the cabin of the school bus. The FTF alone provides no benefit to concentrations of $PM_{2.5}$. The CCVS+FTF, the DPF, and the combination of the CCVS and DPF provided approximately 100% reduction of $PM_{2.5}$ in the cabin of the school bus.

Retrofit Technology	Front run with ambient subtracted (µg/m3)	Back with ambient subtracted (µg/m3)	% Reduction from Baseline Front/Back	Average overall reduction
None	2.7	2.7		
CCVS	~0	0.8	100 / 70	85
FTF	3.8	3.7	0 / 0	0
CCVS & FTF	~0	~0	100 / 100	100
DPF	~0	~0	100 / 100	100
CCVS & DPF	~0	~0	100 / 100	100

It can be observed from Figure 2 that the influence of the retrofit technologies on UFPC levels follows a similar pattern to that obtained for $PM_{2.5}$: the CCVS provides a good reduction of UFPC and the addition of a DPF marginally improves the reduction of UFPC inside the cabin of the bus. The combination of CCVS and FTF does not provide any additional reduction versus the CCVS alone. When the tailpipe retrofit devices are used by themselves, they do not provide any reduction in UFPC inside the cabin of the bus. There appears to be significant variability in the UFPC across each of the three runs conducted on the same day. It is not clear whether this reflects actual changes or is an artifact of sampling.

Figure 2: In-Cabin UFPC Concentrations in the Front and Back of the Bus, With and Without Various Retrofit Technology Configuration(s).

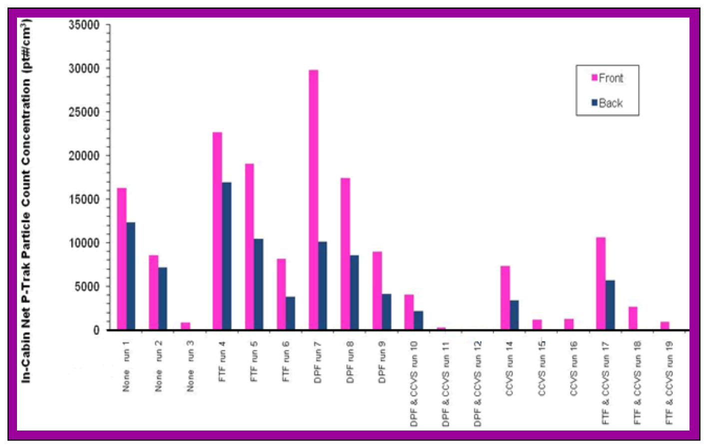

Table 2: Average of Three Runs per Retrofit Configuration(s) for Ultrafine Particle Count.

Retrofit Technology	Front with ambient subtracted (pt#/cm3)	Back with ambient subtracted (pt#/cm3)	% Reduction from Baseline Front/Back	Average overall reduction
None	8597	6221		
CCVS	3299	373	62 / 94	78
FTF	16686	10413	0 / 0	0
CCVS & FTF	4777	1215	44 / 80	62
DPF	18764	7654	0 / 0	0
CCVS & DPF	1272	126	85 / 98	92

Taking into consideration the reduction of $PM_{2.5}$ and UFPC, the CCVS does a very good job of reducing both particle size fractions in the cabin of a properly sealed school bus. The additional reductions obtained by adding in a DPF are marginal. There is also some uncertainty in the data from the runs with the DPE since the DPF alone may increase UFPC, or at the very least, did not provide any reduction of UFPC.

Discussions and Conclusions

The recommendation from this study is to retrofit all school buses with CCVS and continue the NJMVC rigorous inspection and retirement requirements for all New Jersey school buses.

Based on the available data in the scientific and engineering literature and on the results obtained from this study, it appears that a crankcase ventilation system (CCVS) provides good overall reduction in the potential for exposure to both $PM_{2.5}$ and UFPC inside school buses. Tailpipe retrofit devices either alone or in combination with CCVS provide little additional improvement for in-cabin air quality.

Consistency With Other Studies

There are recently published studies showing that the majority of self-pollution is from the crankcase (Phuleria HC., et al. 4/2009, Zielinska B., et al., 8/2008). This supports the results observed in this study.

There are many reports on the web which have measured the impact of retrofit control devices on in-cabin levels of PM. Although differences in methodology, instrumentation, retrofit devices, bus age, engine type and operational parameters occurred, the one common conclusion was that ultra low sulfur diesel fuel (ULSDF) and crankcase ventilation systems are an easy and cost effective way to reduce in-cabin levels of PM (Clean Air Task Force, 2005; Southern Alliance for Clean Energy/Carolina Clean Air Coaliton, 2006; Ontario Public Health Association, 2005). This is consistent with NJDEP's recommendation.

In addition to the use of ULSDF and the CCVS, the studies cited above also recommend the addition of a DPF to further reduce self pollution inside the cabin. These studies did not report on whether the school buses were inspected for leaks, but did report that increased levels of PM inside the cabin of the bus occurred when idling in queue, when other diesel vehicles were operating in the vicinity, and with older buses. In NJ, idling is restricted to 3 minutes and nearly all school buses must be retired in 12 years (as further explained below). In addition, those reports were completed before the tracer studies which indicate that the majority of self-pollution is from the crankcase. Therefore, the recommendation of the installation of the DPF is not applicable to New Jersey.

NJ School Bus Fleet

New Jersey requires inspections twice a year for school buses. These inspections, conducted by the NJ Motor Vehicle Commission, include making sure that the seals on the front and back door, engine compartment and exhaust system are working. Therefore, the well-sealed bus that was used in this study is representative of the overall school bus fleet in NJ. In addition, New Jersey retires conventional chassis style buses from transporting children to and from school after 12 years of service (N.J.S.A. 39:3B-5.139:3B-5.1) (Note that transit style school buses are on a 20 year service N.J.S.A. 39:B-5.2, but they are less than 5% of the school bus population.) and prohibits idling of all vehicles for more than three minutes (N.J.A.C. 7:27-14, N.J.A.C. 7:27-15). Therefore, using a CCVS on a bus which passes the rigorous NJMVC inspection process substantially reduces the infiltration of PM into the cabin of the bus.

Risk Assessment
Health Benefits to Students From Reducing Fine Particulate Levels in the Cabin of a School Bus

PM2.5

There are several ways to assess the health risk to students who ride school buses and the decrease in risk that would result from installation of retrofit devices. For the purposes of this assessment, the crankcase enclosure (CCVS) alone will be the only retrofit technology that is compared to the no-retrofit (baseline) condition. The risks arising from the other retrofit scenarios will be either larger or approximately equal to those estimated for the CCVS case. In addition, this approach is consistent with the charge of the legislation. For the baseline (no-retrofit) condition the attributable $PM_{2.5}$ average concentration is taken to be 2.7 $\mu g/m^3$. For the CCVS condition, the attributable $PM_{2.5}$ concentration is taken to be 0.4 $\mu g/m^3$. In both cases, the values are the average across runs of the front and back of the bus.

All metrics available to assess the health risk from exposure to particulates inside the cabin of a school bus share the significant limitation that they are based on relatively long-term exposure (24 hr - >1 year). In contrast, exposure on a school bus is assumed to occur approximately 1.5 hours a day, 5 days per week, during 180 days per year, for 14 years. This exposure would generally not be considered to be long-term. The estimates of risk that are generated under assumptions of long-term exposure would, therefore, likely overestimate the risk from exposure in the school bus even with adjustment (where feasible) for the reduced exposure period.

Cancer risk

Cancer risk is estimated based on the California EPA –OEHHA potency for diesel exhaust particulate of 3×10^{-4} $(\mu g/m^3)^{-1}$ (CalEPA, 2005). This potency value is adjusted from the original assumption of full-time 70 year exposure to school bus-specific exposure as follows:

Equation 1

$$3\times10^{-4}/(\mu g/m^3)\,(1.5\ \text{hr/day}/24\ \text{hr/day})\,(180\ \text{days/yr}/365\ \text{days/yr})\,(14\ \text{yr}/70\ \text{yr}) = 2\times10^{-6}/(\mu g/m^3).$$

Where:

1.5 is the # of hours per day a child spends on the bus

180 days is the # of days of a child rides a school bus

14 years is the # of years a child rides a school bus

Based on this adjusted potency, the cancer risk from the baseline (no retrofit) condition is estimated to be $2\times10^{-6}/(\mu g/m^3) \times 2.7\ \mu g/m^3 = 5.4 \times 10^{-6}$ which is slightly above the target of 1×10^{-6} used for permitting of individual sources in the NJDEP air program. For the CCVS retrofit condition, the risk is estimated to be $2\times10^{-6}/(\mu g/m^3) \times 0.4\ \mu g/m^3 = 8.0 \times 10^{-7}$, which is considered negligible by the NJDEP air program. The CCVS provides a reduction in cancer risk over the baseline condition.

Non-cancer risk (RfC)

The Reference Concentration (RfC) is the concentration that is not anticipated to result in adverse effects in the population including sensitive subgroups over a lifetime of exposure. The USEPA has set the RfC for diesel engine exhaust at 5 mg/m^3 based on prevention of pulmonary inflammation and histopathology (USEPA, 2009). Any concentration below the RfC is estimated not to result in any adverse health effects. The RfC is a single criterion and does not provide a continuous scale of risk. However, the extent to which an exposure approaches or exceeds the RfC can be expressed as the Hazard Index (HI), the ratio of the exposure concentration to the RfC concentration. Values £1.0 are considered to pose no significant risk. For the baseline condition, the HI = $2.7 \mu g/m^3 / 5\ \mu g/m^3 = 0.54$. For the CCVS retrofit, the HI = $0.4\ \mu g/m^3/5\ \mu g/m^3 = 0.08$. Thus, neither the baseline condition, nor the CCVS condition appears to pose a significant risk with respect to the RfC.

Specific Respiratory Health Effects from $PM_{2.5}$ Exposure

Based on a number of epidemiological studies, Abt Assoc. derived for the USEPA (2000) a series of empirical equations that describe the relationship between ambient particulate (PM) exposures and the annual incidence or prevalence of a variety of respiratory symptoms. These relationships do not distinguish the nature or origin of the PM and implicitly treat the measured PM concentration as a homogeneous entity. While ambient PM contains diesel exhaust particulates, it also contains particulates from many other sources. Diesel exhaust particulates may be more or less potent than ambient PM in their association with these respiratory symptoms. Some of these relationships are based on measured PM_{10} while the in-cabin measurements in this study are $PM_{2.5}$. In such cases, two estimates of health outcomes are calculated. The lower estimate assumes that the PM_{10} and $PM_{2.5}$ are equally potent and therefore applies the $PM_{2.5}$ measurements to the PM_{10} –based equations. The upper estimate assumes that the bulk of the potency in the PM_{10} resides in the $PM_{2.5}$ and that the $PM_{2.5}$ constitutes half of the PM_{10} mass. Therefore, in the upper estimate it is assumed that the reported PM_{10} potency is doubled for measured $PM_{2.5}$. The results of these equations are presented in Table 3.

Table 3: Estimated number of yearly cases of specific respiratory health outcomes attributable to in-cabin exposure in school buses

	Estimated number of yearly attributable cases among NJ students riding school buses		Estimated number of cases prevented by use of CCVS
Health Outcome	**Baseline (no retrofit)**	CCVS installed	
Chronic bronchitis	84-165	13-25	71-140
Hospital admission for asthma	7	1	6
Emergency room admission for asthma	20-40	3-6	17-34
Acute bronchitis	765	117	648
Upper respiratory symptoms	11,026	1,636	9,390
Lower respiratory symptoms	8,613	1,303	7,310
Asthma attacks	2,402-4,796	356-713	2,046-4,083

Based on these empirical relationships, it appears that installation of the CCVS retrofit can result in a significant reduction in several adverse respiratory health outcomes. Of particular note is the estimated reduction of approximately 3,000 acute asthma incidents statewide.

Ultrafine Particle Count (UFPC) also known as Ultrafine Particulate Matter (UFPM)

Compared to $PM_{2.5}$, a larger proportion of UFPC penetrates into the alveolar portion of the lungs. Unlike $PM_{2.5}$, UFPC can cross the alveolar membrane into the blood, and be transported to other parts of the body including circulating blood and liver (Obderdörster et al. 2000, 2002). There is evidence linking both moderate length exposure (0-5 days) and long-term exposure to UFPC and increased risk of premature mortality (Wichman et al., 2000). There is also some evidence suggesting that UFPC can increase the risk of stroke (Kettunen et al. 2006). There is, as yet, no direct evidence linking UFPC with asthma incidence. However, there is some evidence implicating UFPC in respiratory effects in asthmatics that are associated with the onset of clinical asthma symptoms. ((Peters et al.,1997). There is evidence for at least mild, acute (same day) effects on respiratory function in asthmatics after 2 hours of exposure (McCreanor et al., 2007). Evidence for acute respiratory effects of UFPC similar to those that might occur in asthmatics also comes from animal studies, albeit at relatively high doses. (Hahn et al. 2005, Obderdörster et al. 2000). However, not all studies show adverse effects, even at high levels of exposure. This may point to the importance of the specific nature of the UFPC.

Despite these qualitative observations, there are currently no exposure guidelines (e.g., NAAQS, RfC, cancer potency/URF) for UFPC. Nor is there a clear basis for deriving a dose-response relationship to support quantitative risk assessment. Therefore, it is not currently possible to assess the risk or health-outcomes implications of the UFPC levels measured in this study. However, the significant reduction in UFPC achieved with CCVS (and CCVS + DPF) are, at the least, health protective, and may provide significant health benefits.

<u>Risk Assessment Conclusions</u>
Given the significant uncertainties inherent in applying long-term risk metrics to the relatively short-duration exposures experienced on a school bus, the above estimates should be considered to be only semi-quantitative. From that standpoint, it appears that in-cabin particulate exposure may be responsible for a moderate amount of asthma attacks and transient lower and upper respiratory symptoms (e.g., cough and nasal irritation) based on the risk estimates from the Abt Associates model. Installation of CCVS retrofits is anticipated to largely, but not completely, eliminate these adverse health effects. Cancer risk from in-cabin particulate exposure is considered negligible with the installation of a CCVS.

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RESEARCH PROJECT SUMMARY

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