CLEAN AIR TASK FORCE

A Multi-City Investigation of the Effectiveness of Retrofit Emissions Controls in Reducing Exposures to Particulate Matter in School Buses

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ABSTRACT/EXECUTIVE SUMMARY

Diesel exhaust is a major source of combustion particles that contribute to poor air quality nationwide. Since almost all school buses are operated with diesel engines, diesel engine exhaust can thus also be a source of concern, specifically with regard to exposure to children. Diesel particulate matter (DPM) is a complex and unhealthy mixture of inorganic and organic carbon particles with adhered toxic substances and metals. The purpose of the study was to investigate the causes of school bus self-pollution and to document in-cabin diesel particulate matter exposures in buses retrofit with a variety of available particulate matter emissions control combinations. [1] This is one of the first studies to report on the in-cabin benefits of retrofit technology.[2] To date, our testing has been conducted on school bus fleets in three U.S. cities—Chicago, IL and Atlanta, GA in 2003 and in Ann Arbor, MI in 2004. Retrofit combinations tested included:

- Conventional buses on conventional fuel
- Conventional bus with ultra-low sulfur diesel fuel (ULSD)
- Bus with diesel oxidation catalyst (DOC) and conventional fuel
- Bus with Spiracle and ULSD fuel
- Bus with diesel particulate filter (DPF) and ULSD fuel
- Bus with DPF, Spiracle and ULSD fuel
- Bus with DOC, Spiracle and ULSD fuel
- Bus with DPF, ULSD and Enviroguard
- Compressed natural gas (CNG) bus

During all bus runs, a lead car with identical instrumentation was used as a control to characterize ambient air in the roadway in front of the bus. Actual school bus routes were followed in largely quiet residential neighborhoods with few nearby diesel sources thereby minimizing the confounding influence of sources of diesel emissions other than the bus itself. Measured parameters included: 1) fine particulate matter (particles 2.5 microns[3] and less), 2) ultrafine particles (extremely small particles smaller than 0.1 microns) and 3) black carbon (elemental carbon soot) and particle-bound polycyclic aromatic hydrocarbon (PAH).

Tests conducted on conventional buses (common yellow school buses with the engine in the front and without emissions controls devices) along actual bus routes found that diesel exhaust routinely penetrated the school bus cabins from the tailpipe and the engine compartment through the front door of the bus. Over the course of the bus routes, particulate matter built up to levels multiple times that of outdoor ambient conditions above the daily and annual particulate matter ($PM_{2.5}$) NAAQS. Particle emissions rarely were found to seep into conventional school buses through other pathways such as closed windows, the back door or from the engine compartment. During queuing—where buses are parked closely end-to-end with front doors open--we observed rapid build up of particulate matter within the bus cabin.

Ultrafine particles, black carbon and particle-bound PAH measured in the cabins of the buses during bus routes, idling, and queuing were traced directly to the tailpipe of the buses. In contrast, however, fine mass ($PM_{2.5}$) concentrations were dominated by particulate matter emissions from the crankcase vented under the hood of the bus through the "road draft tube." Crankcase emissions proved to be an extremely strong source of $PM_{2.5}$ in the school bus.

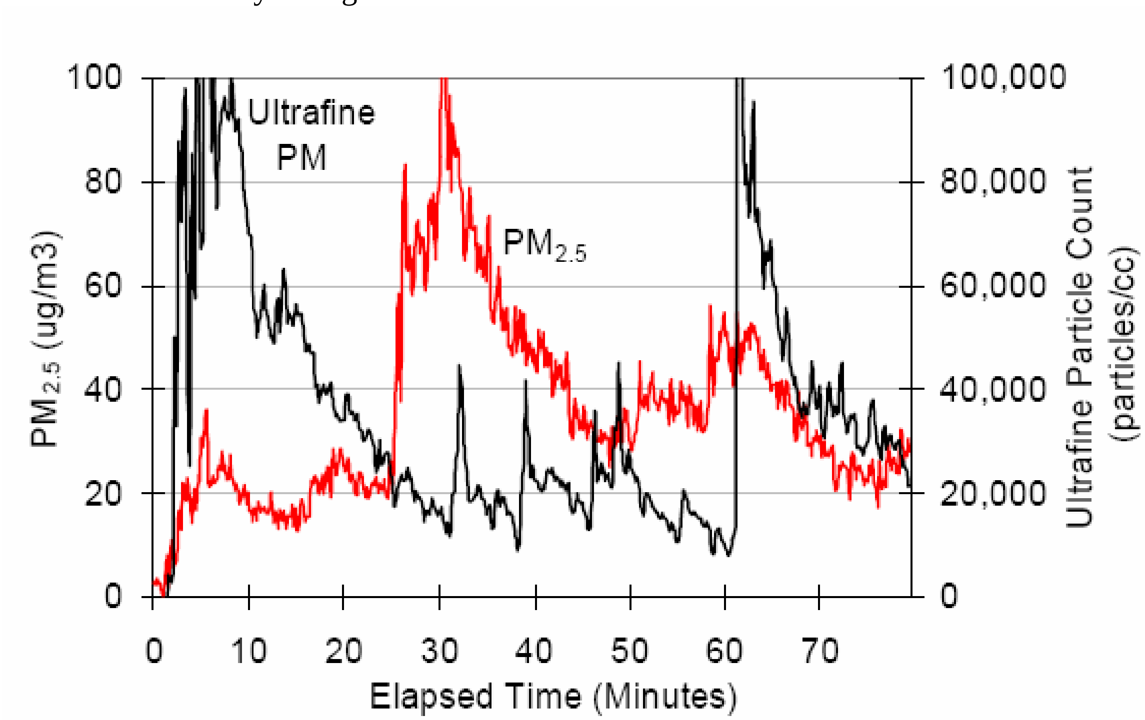

Figure 1: Conventional buses tested showed significant $PM_{2.5}$, ultrafine particle, black cabin and PAH self-pollution. (Ambient concentrations have been subtracted.)

A number of emissions controls combinations were tested following the assessment of cabin air quality on the conventional buses. The application of a diesel particulate filter Clean Air Task Force 4 1/6/2005 (DPF) and ultraflow sulfur diesel fuel (ULSD) virtually eliminated ultrafine particles, black carbon, and PAH pollutants in the cabin. Surprisingly, the DPFs did not measurably reduce fine particle mass ($PM_{2.5}$) in the cabin—not due to a lack of particle removal efficiency--but instead as a result of the strong crankcase $PM_{2.5}$ source under the hood of the bus. To control the strong $PM_{2.5}$ concentrations remaining after application of DPF-ULSD retrofit, several experiments were performed including: 1) adding extension tubing to the road draft tube shunting emissions toward the back of the bus away from the door, 2) installation of a Fleetguard Enviroguard filter, and 3) installation of a Donaldson Spiracle, a closed-crankcase filtration device. In the first experiment, the extension tubing had showed a limited $PM_{2.5}$ reduction in the cabin. In the second experiment, the Enviroguard demonstrated no measurable $PM_{2.5}$ benefit. The device designed to reduce oil spillage in the roadway from the crankcase--releases strong post filtration $PM_{2.5}$ emissions in the engine area close to the bus doorway where they enter the bus cabin. In the third attempt to abate the crankcase emissions, we found that the Spiracle eliminated the $PM_{2.5}$ self-pollution in the cabin but did not result in improvements in ultrafine particles, black carbon or PAH. The Spiracle reroutes the crankcase emissions back into the intake manifold of the engine, ultimately directing them through the exhaust system and away from the engine compartment, where they can be removed by tailpipe filtration devices.

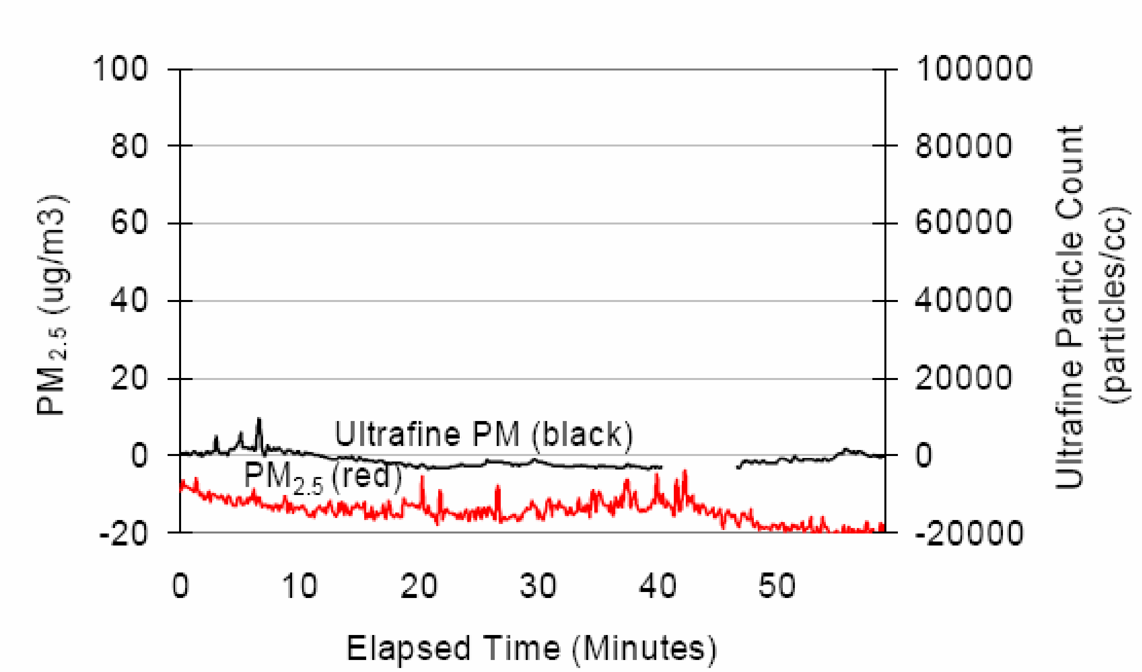

Figure 2: The DPF-ULSD-Spiracle combination eliminated $PM_{2.5}$, ultrafine particles, black carbon, and PAH self pollution from the bus cabin. Ambient concentrations have been subtracted resulting in slightly negative apparent net concentrations. Concentrations below zero should be taken as zero net $PM_{2.5}$ contribution to the bus.

A bus equipped with a diesel oxidation catalyst (DOC) showed cabin levels of ultrafine particles, black carbon and PAH that were similar in magnitude to those observed in conventional buses. Thus, we found it difficult to ascertain whether a DOC provided any in-cabin benefit. This may be for a variety of reasons including: 1) inability of the methodology to determine small changes, 2) confounding by variable wind directions relative to the two emissions sources and the cabin door, 3) potential ineffectiveness of DOC under idle conditions. Our testing did not examine benefits that may occur for other pollutants with the DOC such as hydrocarbons, CO and nitrogen oxides (NOx). Furthermore, how particulate matter levels outside the bus (e.g. in a schoolyard during idling, drop off, or pick up) are affected by the DOC were not fully investigated warrants further research.

A compressed natural gas (CNG) bus –with a rear engine--showed little build up of $PM_{2.5}$ in the cabin and mean levels were largely the same as outdoor ambient. However, the CNG bus showed evidence of limited *ultrafine* particle self-pollution at a few bus stops but at much lower levels compared to the conventional bus.

Combinations of both tailpipe and crankcase emissions control devices were also tested including the DPF-ULSD-Spiracle, and DOC-Spiracle. The DOC-Spiracle combination eliminated only one parameter—$PM_{2.5}$ mass, presumably due to the Spiracle alone. *The DPF-ULSD-Spiracle combination resulted in elimination of all measure parameters on the bus—ultrafine particles, black carbon, PAH and $PM_{2.5}$.*

In addition to cabin air quality, air quality outside school buses is also a factor in children's exposure to diesel exhaust. In a Connecticut test, ambient air quality measurements were measured adjacent to a New Haven elementary school yard to gauge the impact of buses during student drop off and pick up. Significant increases in $PM_{2.5}$ and ultrafine particulate matter levels were observed

adjacent to the school yard when uncontrolled conventional buses left the school after dropping off children leaving a cloud of diesel smoke in their wake. Because retrofit buses were unavailable for comparison at the time in New Haven, we simulated school bus drop off scenario with retrofit buses in tests conducted in all three cities. These tests show that the DPF-ULSD combination eliminated all $PM_{2.5}$ and ultrafine particulate matter at the curbside outside of the bus. CATF has prepared video clips graphically superimposing changing pollutant levels over a digital video image of the bus at drop off. These videos vividly demonstrate the benefits of the retrofits
(see www.catf.us/diesel/videos.)

In conclusion, this research suggests that the combination of DPF, Spiracle and ULSD results in a comprehensive elimination of all particle species measured and is the most effective solution for addressing school bus cabin air quality as well as improving conditions outside of schools. In addition, the closed crankcase filtration device proved to be an extremely cost-effective *initial* step to improve *cabin air quality* in school buses we tested.

INTRODUCTION

While school buses are generally considered to be the safest way to transport children to and from school—statistically safer, for example than riding in a personal car[4], recent U.S. studies (e.g. CARB, 2003[5]; EHHI 2001[6]) suggest that diesel exhaust builds up in school bus cabins as a result of self-pollution and may expose children to elevated levels of particulate matter and related pollutants. In 2003 the Clean Air Task Force and Clean Air Task Force 6 1/6/2005 partners began a multi-year, multi-city study of cabin air quality in conventional and an array of retrofit school buses in Chicago, IL, Atlanta GA, and Ann Arbor MI. The purpose of the study was to investigate the causes of school bus self-pollution and to test the effectiveness of emissions reduction devices in mitigating diesel particulate matter exposures in the cabins of school buses. The present research demonstrates that cost effective emissions control devices can virtually eliminate exposures to diesel exhaust particles resulting from school bus self-pollution and ensure that children arrive at school healthy and ready to learn.[7]

Particulate Matter and Children's Health

While no direct studies of the health effects of short-term exposures have been undertaken on children riding school buses, it is well known that children are a population that is particularly susceptible to air pollution. In fact, children may be at even higher risk for particulate matter exposure than adults.[8] One factor contributing to higher childhood risk is that their exposures to fine particulate matter may be much higher than adults.[9] Health researchers believe that children are more susceptible than adults to the adverse health effects of air pollution for a variety of reasons.[10,11] For example, children are more active than adults and therefore breathe more rapidly. Children have more lung surface area compared to their body weight and therefore inhale more air pound-for-pound than adults. Furthermore, children typically spend more time outdoors, for example in or near schoolyards where air pollution levels may be higher. Finally, children's essential defense mechanisms have not yet fully developed, which also increases their susceptibility to the harmful effects of pollution.

Brief exposures to diesel exhaust commonly result in upper and lower respiratory symptoms such as a cough or wheeze, as well as burning eyes, nose or throat, especially during prolonged exposures. However, in many other studies particulate matter exposures have also been associated with more serious impacts in children such as triggering asthma attacks. For example, emergency room visits by asthmatic children increase when particulate matter levels rise just slightly above the national air quality standards.[12, 13] One study found that emergency room visits by asthmatic children increased even at fine particulate levels *below* EPA's air quality standard.[14] Even worse, the California Children's Health Study suggests that particulate matter (PM_{10}) may slow lung function growth in children. Children examined in a dozen communities near Los Angeles experienced a three to five percent relative reduction in lung function *growth* between the most polluted and least polluted cities as a result of exposure to particulate matter.[15]

When children moved to communities with higher particulate matter, a decreased growth in lung function was observed.[16] Conversely, for those children who moved to communities with cleaner air, lung function growth rates increased. This suggests serious permanent harm may befall children living in areas chronically polluted with particulate matter.

In adults, long-term exposure to particulate matter is associated with health risks.[17] A 2003 HEI report cites "modest concentrations of diesel exhaust have clear-cut inflammatory effects on the airways of nonasthmatic (or control) subjects." [18] Long term cohort studies and short-term time series studies of particulate matter (PM10 and $PM_{2.5}$) suggest elevated risk of heart attacks and stroke as well as elevated risk of premature Clean Air Task Force 7 1/6/2005 mortality in adults including both respiratory and cardiovascular diseases.[19, 20] Lifetime exposure to diesel exhaust by railroad workers is associated with lung cancer mortality.[21]

Similarly, one of the most prevalent and important components of diesel exhaust, *ultrafine particles* (the smallest particles, 0.1 microns[22] or less) are suspected to cause adverse health effects in individuals, including premature death.[23] Medical researchers believe that ultrafine particles are sufficiently small that they may invade the deepest part of the lung and enter the bloodstream, triggering a host of systemic impacts beginning with lung inflammation and leading to adverse cardiac effects in adults.[24,25] One 2003 study suggests that deposition of ultrafine particles increases 4.5 times with exercise in adults, a finding that also could have an important bearing on exposure to children.[26] Another 2003 experimental study, where diesel particles were instilled in the lungs of hamsters, supports the biological plausibility of cardiovascular mortality from inhaled diesel particulate matter in humans.[27] In its draft criteria document for particulate matter, EPA reports that in four European studies, changes in peak expiratory flow (lung function) has been more closely associated with ultrafine particles (particle number) than mass.[28]

Diesel exhaust is also a major source of hazardous air pollutants. One such family of pollutants, particle-bound polycyclic aromatic hydrocarbons (PAH) include potent carcinogens and mutagens.

Roadway proximity studies have shed light on the impact of traffic-related emissions on health. For example, recent studies suggest significantly elevated mortality rates for people living in residential areas within 50 meters of a major roadway. [29] A recent New England Journal of Medicine study suggests that exposure to traffic significantly increases risk of heart attacks.[30] Thus, uncontrolled school buses engines are not only a source of roadway pollution but can contribute to long term exposures in school children living in proximity to already high pollutant levels adjacent to roadways.

Research suggests that emissions controls on existing diesel engines can lead to important health benefits. A 2004 comparative study of the toxicity of emissions from a conventional diesel engine relative to an engine with low sulfur fuel and a catalyzed particle trap concluded that relative to the uncontrolled diesel engine exhaust: "*the use of low sulfur fuel and a catalyzed particle trap markedly reduce the diesel engine exhaust health hazard associated with resistance to infection, inflammation and oxidative stress*"[31] As a part of the chamber study which was conducted on mice, testing of the DPF-ULSD retrofit combination reduced total particle number to below limits of detection, black carbon by 100%, organic carbon by 90%, particle mass by 99%, particulate PAH by 100%. CO by 90% and NOx by 10% and reduced a class of air toxics known as carbonyls, such as formaldehyde and acetaldehyde, between 17-45 percent.

In sum, although the acute (short-term) effects of diesel particulate matter exposures in children are not fully known, diesel particulate matter emissions could be a factor in asthma respiratory illness. Furthermore, long-term exposures to these pollutants are associated with serious adverse health impacts in adults and school buses could contribute significantly to lifetime exposures of diesel exhaust in some individuals, especially those dependent on school bus transportation.

Previous School Bus Studies

A number of studies of cabin air quality in school buses have documented the influx of diesel exhaust into the cabin of school buses (e.g., Natural Resources Defense Council (NRDC) (2001)[32], Environment and Human Health Inc. (EHHI) (2002) [33], California Air Resources Board (CARB) (2003)[34]. Most importantly, based on our review of the available literature, none of the previous studies we are aware of have investigated sources of emissions in the cabins of buses. Results of the conventional bus tests in these studies are well within the range of results in our study. However none of these studies specifically identified the sources of particulate matter measured on the buses. Only one study (CARB) examined a single retrofit bus.

The NRDC study concluded that $PM_{2.5}$ levels measured in a 1986 school bus contributed, an average additional 14 ug/m^3 above the exposures experienced while walking or riding in a car on the same streets. The EHHI study similarly found that the highest levels recorded in buses exceeded 100 ug/m^3, a reported 5-10 times ambient outdoor levels. The CARB study, used both continuous and integrated (filter-based measurements) including a tracer test. CARB reported average $PM_{2.5}$ conditions of 56 ug/m^3 during bus routes, with diesel related pollutant levels 2.5 times greater with windows closed than when windows were open. A high variability in concentrations was found throughout the study. Compared to residential neighborhoods, CARB's study found roadways with high traffic density resulted in levels inside the buses that were even higher.

A tracer study, undertaken by the Southwest Research Institute, International Truck and Engine Corporation, ConocoPhillips and Lapin and Associates (2003), used iridium tracer and filter-based sampling.[35] The study concluded *"A reliable tracer test shows that the exhaust from a diesel school bus's engine adds virtually no diesel particulates to the air inside the bus.* The study found: "*that the bus' engine contributed less than 1 per cent of the fine particulate matter inside the bus.*"[36] Furthermore the study reported that $PM_{2.5}$ concentrations inside the bus were not correlated to tailpipe emissions.[37] This second result is consistent with our study which suggests that the crankcase is the principal source of cabin $PM_{2.5}$ pollution. However, our testing demonstrates that the strong build up of diesel exhaust is indeed attributable to self –pollution but from two sources—the tailpipe and the engine crankcase--especially in residential settings.

Another study in Fairfax County VA in 2001, was undertaken because "officials were concerned by media reports about research findings on the possible negative health effects of diesel exhaust from older school buses."[38] In this study, air samples were "undertaken in accordance with standardized methods prescribed by OSHA (for respirable particles), NIOSH ((for carbon particles). The study concluded that the particle levels on the school buses were below the limits of detection. However, this methodology of this study –appropriate for an occupational study--appears to have been inadequately sensitive to PM2.5 and the short term changes in particle concentration on a school bus.

A brief discussion of these results of these studies in the context of the present study can be found later in the report.

For full report, go to:
http://www.catf.us/publications/reports/CATF-Purdue_Multi_City_Bus_Study.pdf