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

CLEAN AIR TASK FORCE

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In memory of Mary Beth Doyle--
Michigan environmental leader and partner in this project.

Cover Image:
Ultrafine particle data overlay on video of bus during simulated school bus drop off scenario.

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.

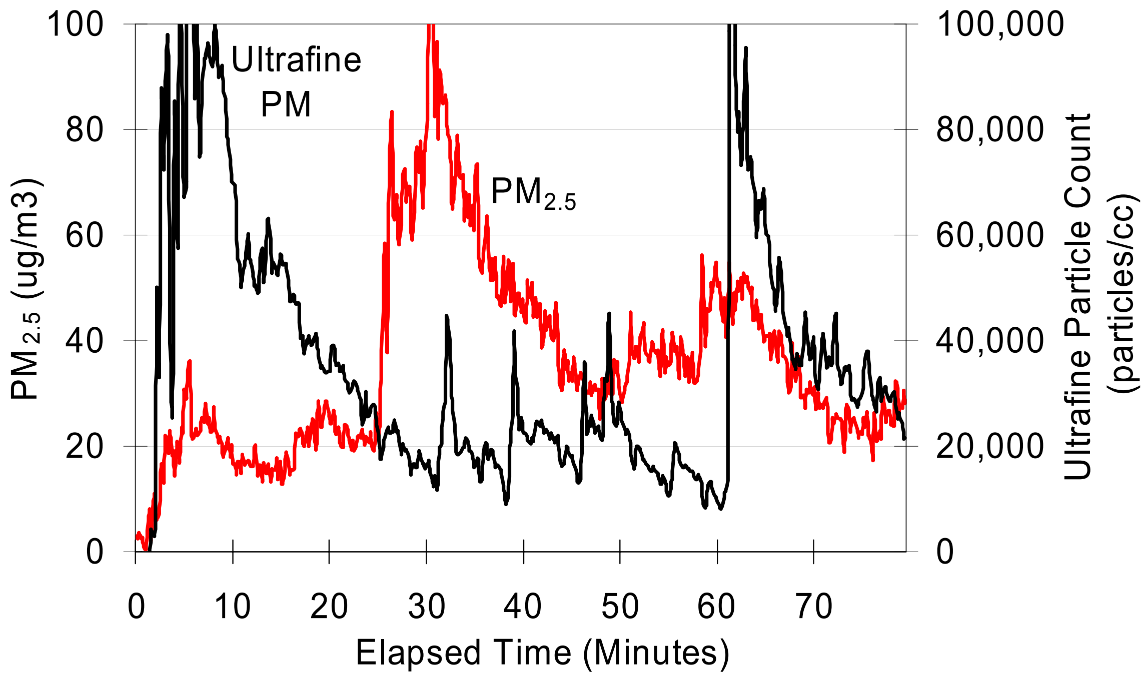

Figure 1: Conventional buses tested showed significant $PM_{2.5}$, ultrafine particle, black cabin and PAH self-pollution. (Ambient concentrations have been subtracted.)

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

(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.

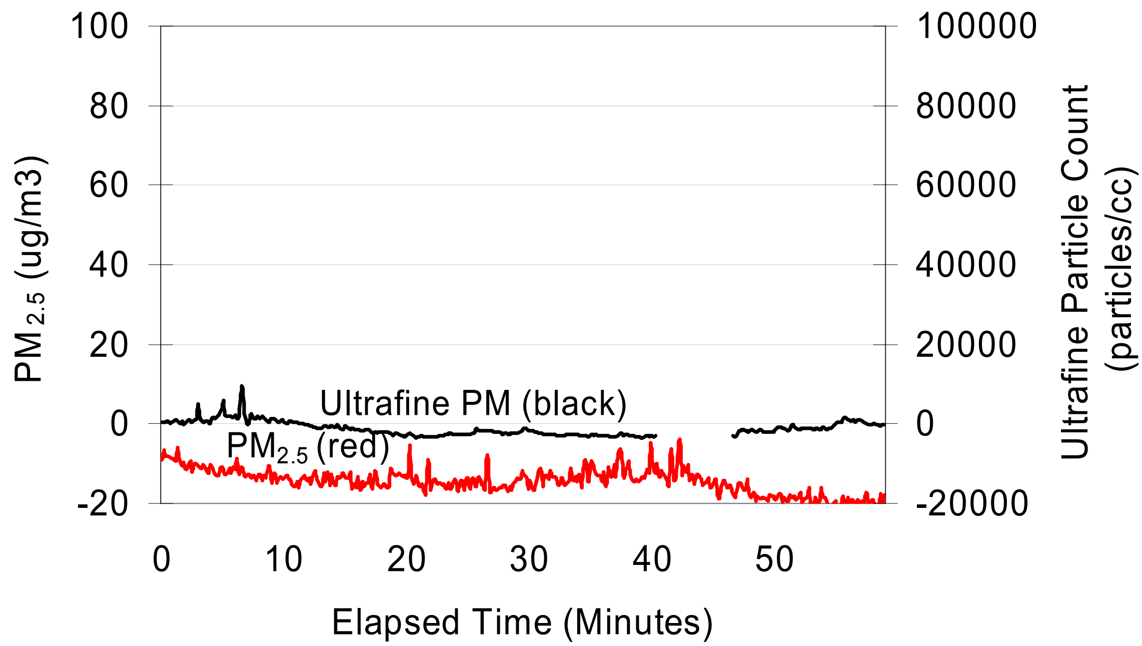

Figure 2: The DPF-ULSD-Spiracle combination eliminated $PM_{2.5}$, ultrafine particles, black carbon, and PAH self pollution from the bus cabin. Ambient concentrations have been subtracted resulting in slightly negative apparent net concentrations. Concentrations below zero should be taken as zero net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

METHODOLOGY

Study Goals

The goals of the study were to: 1) investigate the sources and pathways for exhaust penetrating the cabins of conventional, retrofit conventional and compressed natural gas (CNG) buses school buses, 2) identify specific sources of particulate matter emissions on the bus, and 3) investigate the effectiveness of a variety of available particulate matter retrofit solutions. In this paper we organize the results by the four pollutants measured.

General Methodology

In order to test the hypothesis that a conventional school bus pollutes its own cabin, we designed a comparative study to test conventional and retrofit buses and compare those results with air quality conditions in a car leading the bus.[39] To do this, we used continuous monitoring techniques to measure 3 particulate matter parameters, fine particulate matter ($PM_{2.5}$), ultrafine particle count, black carbon and particle-bound PAH inside the bus cabins before and after the buses were retrofit with emissions controls devices. Tests were conducted in 3 cities (Table 1).

Previous investigators have reported that particulate matter in the cabins of school buses may be a result of external sources in the roadway in front of the bus. Thus, to determine the extent of school bus self-pollution, bus cabin air quality levels were compared to a levels measured by a lead car ahead of the bus equipped with identical instrumentation. In contrast to the bus, the car windows remained rolled down at all times in order to most effectively sample ambient air in front of the bus. This method allowed us to distinguish impacts of bus self-pollution from any emissions from diesel vehicles in front of the bus.

Fleet managers in the three cities provided us with what they considered to be 'typical' age, mid-mileage, relatively recent conventional buses (1998-2001). We avoided testing buses that were obvious super-emitters with visible smoke plumes. Buses were also inspected to ensure that they were typical and well maintained, including ensuring that rear doors were adequately sealed and that windows shut tightly.

City	Conventional	DPF	DOC	Spiracle	ULSD	CNG	Enviroguard
Ann Arbor	X						
Ann Arbor					X		
Ann Arbor				X			
Ann Arbor			X				
Ann Arbor		X					
Ann Arbor		X			X		
Ann Arbor		X		X	X		
Ann Arbor			X	X			
Ann Arbor						X	
Ann Arbor		X			X		X
Atlanta	X						
Atlanta		X			X		
Chicago	X						
Chicago		X			X		

Table 1: School bus conventional and retrofit combinations tested.

Cabin air quality conditions were monitored under the following three scenarios:

1. One bus idling, separated from external diesel sources;
2. The middle bus of a 3-conventional bus queue;
3. A typical bus route, approximately one hour in duration.

All research was conducted without school district students on the buses in order to avoid exposure to students. Duplicate runs were undertaken to assess and confirm relationships and variability from one ride to the next.[40] Bus routes selected in each city were mainly residential, and roads used for routes were also largely free of diesel traffic. Thus, confounding of the data was minimized by a general absence of external source influences and any particulate matter build up on the bus was a result of the buses own emissions. Buses were shut off and fully ventilated at the start of every bus route, by opening the windows and doors with the bus shut off, to return the bus cabin to outdoor ambient levels. At the start of each route, following ventilation, each bus was typically idled in place for 10 minutes with the door open, and then 10 minutes with the door shut to simulate bus warm up.

Figure 3: Installation of diesel particulate filter on DeKalb bus prior to testing.

City	Bus Number	Model	Age	Mileage	Test(s)
Chicago School Transit	517 conventional	Thomas – International	2001	69,000	idle, queue, route 2X
Chicago/Naperville IL	662 retrofit	International 444E –DPF Retrofit/ULSD	1998	50,260	idle, queue, route 2X
Atlanta/DeKalb GA	1450 conventional	International 446 (rebuilt from 444E)	1999	70,637	idle, queue, route 2X
Atlanta/DeKalb GA	1481 conventional (alternate)	International 446(?)	1999	46,723	Route 1X
Atlanta/DeKalb GA	1450 retrofit	International 446 (rebuilt from 444E)	1999	70,637	idle, queue, rout 2Xe
Ann Arbor, MI April 2004	56 conventional	International	2000	46,723	idle, queue, route 2X
Ann Arbor, MI April 2004	24 CNG	CNG transit style, Thomas-Cummins	2000	48,000	Idle, route 2X
Ann Arbor, MI April 2004	56 retrofit- DPF DPF-Enviroguard	International	2000	46,723	idle, queue, route 2X
Ann Arbor MI October 2004	56 retrofit combinations: Spiracle-DPF Spiracle-DOC, ULSD	International	2000	46.723	idle, queue, route 2X

Table 2: Buses Tested in the three cities.

Instrumentation

The instruments utilized in this study are summarized in Table 3. The principal sets of monitors were situated at the middle of the bus with sample inlets at a height approximately level with the top of the seat (Figure 4). Standard measurements were made with windows tightly closed in the bus in all bus runs and idle tests. In Chicago and Ann Arbor, a duplicate set of PTrak and Dust Trak instruments were situated by the front door in addition to the instruments at mid-bus.

Pollutant	Instrument Used	Instrument Manufacturer
$PM_{2.5}$ mass (ug/m^3)	DustTrak with $PM_{2.5}$ impactor & Nafion tube dryer	TSI Inc.
Ultrafine particles (particles/cc)	PTrak	TSI Inc.
Black Carbon mass (ug/m^3)	Aethalometer With BGI $PM_{2.5}$ cyclone	Magee Scientific
Particle-bound PAH (ng/m^3)	PAS 2000 ce Personal PAH monitor	Ecochem Analytics
T, RH wind speed	Pocket Weather Meter	Kestrel 3000

Table 3: Monitoring Instruments

Figure 4: Bus instrumentation in Chicago. Dust Trak and Aethalometer on bus #662. The Dust Trak was operated with a Nafion Tube dryer-pump assembly. Not shown: PTrak ultrafine particle counter and PAS 2000 (PAH.)

<u>$PM_{2.5}$ Measurements</u>

Particulate matter mass was measured using the TSI Dust Trak.[41] Instruments were located in the middle and the front of the bus as well as in the lead car.[42] Unless noted otherwise, data reported in the charts below are from the middle monitor in the bus. A lightly greased $PM_{2.5}$ impactor plate was installed for all measurements. The Dust Traks were zeroed daily prior to conducting measurements. For instrument response stability, the time constant was set to 10 seconds, but the data was collected in one second intervals for most tests.[43] During data processing we smoothed the data using rolling 10 second averages for plotting.

Because the Dust Trak measurements are based on light scattering, a Nafion Tube diffusion dryer was attached to the inlet to mitigate the effects of humidity, based on the method of Chang et al (2001).[44] However, the Purdue Dust Trak, located in the front of the bus, was operated *without* the Nafion tube dryer. Despite our field calibration results that show that the Nafion tube dryer reduced the response of the Dust Trak on ambient aerosols (described below), when run in parallel with the CATF units in the same location, we observed no systematic difference in response between the CATF Dust Traks and the Purdue Dust Trak (we did not, however, undertake a rigorous parallel test.) Therefore we believe that relative humidity (RH) levels on the bus had little apparent effect on the $PM_{2.5}$ levels measured in the bus as measured in the front and middle locations. It is also important to note that measurements taken in the lead car were made with the Nafion Tube dryer. This was done to eliminate possible RH-related concentration differences between the car and the bus, as the car was operated with windows open and the bus with windows closed, setting up potential differences in RH between the bus and car.

VALIDATING THE DUST TRAK MEASUREMENTS. $PM_{2.5}$ data reported in this paper are raw measurements, uncorrected for the reported high-bias of the instrument. The Dust Trak is calibrated to Arizona road dust which has very different light scattering characteristics than combustion aerosol resulting in a different response. Therefore, calibrating the response of the Dust Trak relative to the federal reference method was necessary in order to understand its response relative to federal air quality benchmarks and methods. We first reviewed the literature and then undertook a two-week field study comparing the Dust Trak to a Tapered Element Oscillating Mass Balance monitor (TEOM). Chang et al (2001) reported that the response of the Dust Trak (with the Nafion Tube diffusion dryer) was linear with respect to a range of 12-hour "Personal Exposure Monitor" (PEM) measurements. The PEM is a filter-based, integrated personal PM exposure monitor.[45] The slope of the line relating the PEM and the Dust Trak was 2.07 in the study. Similarly, McIntosh (2002)[46] co-located the Dust Trak indoors (without diffusion dryer) with a BGI PQ 2000, an EPA Federal Reference Method (FRM) sampler, for twenty 24-hour simultaneous samples. The 24 hour FRM samples correlated well with the Dust Trak. According to the paper, the Dust Trak provided precise measurements compared to the FRM but noted that the accuracy could be improved through statistical adjustment (using the slope of the line). The slope of the line relating the two methods was 2.57 (+/- 0.57) and the intercept -1.73, the Dust Trak again overestimating $PM_{2.5}$ by an approximate factor of 2. In yet another study, (Chung et al (2001)[47] the Dust Trak was found to overestimate airborne particle concentrations in Bakersfield CA by a factor of 3. Levy et al (2001) suggest concentrations measured by the Dust Trak approximately twice as high as concentrations from mass-based methods.[48] Further, Levy et al found a "strong correlation but a consistent factor of 2-3 difference between the methods." Another study suggests, however, that the relationship between the Dust Trak and integrated (filter) samples may actually be closer to 1:1 when measuring fresh welding fume aerosols rather than aged ambient PM aerosol. However it is not clear whether the 1:1 relationship is valid for fresh diesel particulate matter. [49]

In order to calibrate our specific instruments, we deployed the two Dust Traks at an accessible rural USFS/New Hampshire DES IMPROVE monitoring site in Gorham, NH for 13 days in late August and early September 2004. The monitor is located in an airshed dominated by sulfates on the haziest days and to a lesser extent, organic carbon, elemental carbon and nitrate, an aerosol mixture quite different from diesel exhaust aerosol.[50] For comparison, we ran two Dust Traks, one with a Nafion tube diffusion dryer assembly and one without the dryer. There were three particulate matter devices at the monitoring site to compare with the Dust Traks: 1) TEOM 1400A 50 degree C continuous PM monitor, 2) IMPROVE cyclone-based particle monitor (run every three days--data yet unavailable) and 3) a Harvard Impactor (HI) particle monitor (also run every 3 days, with only 2 days available during the period for comparison) (Figure 5.)

Table 4, below, lists results for the two days where there were filter based measurements for comparison. August 28 was characterized by high relative humidity (RH) and September 3 low RH. For August 28th, with high RH, the Nafion tube dryer showed a substantial benefit in reducing the Dust Trak's tendency to yield high PM2.5 concentrations relative to the filter measurements, in comparison to the Dust Trak without the dryer tube. However, on the day with lower RH, the two Dust Traks largely agreed. This suggests that the Nafion dryer tube is particularly valuable in conditions of high RH. Based on the results of the Dust Trak with the diffusion dryer, the Dust Trak appears to yield concentrations relative to the filter method high by a factor of about 2.

We also compared the Dust Traks to the TEOM (Figure 6). A linear regression of TEOM and Dust Trak data for hourly measurements over the course of a day (Figure 7) suggests a predictable relationship between the TEOM and Dust Trak (Pearson's R^2=0.96.) Relative to the TEOM, the Dust Trak with the Nafion tube dryer yielded concentrations that were higher by about 2-3 times. It should be noted, however, that the TEOM itself yielded lower measurements than the filter-based HI measurements. This is supported by a more comprehensive study that also suggests that the TEOM may yield low $PM_{2.5}$ values.[51] In conclusion, the results of our comparison are largely consistent with the literature. Our comparison suggests that raw Dust Trak measurements and TEOM show similar temporal responses. However, the Dust Trak appears to over-predict $PM_{2.5}$ concentrations in a rural airshed by a factor of approximately two, and as much as three under humid conditions. Further testing of the Dust Trak's response relative to fresh diesel emissions is needed to more carefully calibrate the Dust Trak to federal reference measurements.

Figure 5: Camp Dodge Monitoring site where Dust Traks were co-located with TEOM, IMPROVE and Harvard Impactors for 13 days.

Date	Harvard Impactor	NH DES	CATF-1	CATF-2
	AMC	TEOM	Dust Trak w/ dryer	Dust Trak w/o dryer
	24-hr (ug/m^3)	24 hr $PM_{2.5}$ (ug/m^3)	24 hr $PM_{2.5}$ (ug/m^3)	24 hr $PM_{2.5}$ (ug/m^3)
28-Aug-04	19.0	13.1	37.2	86.1
3-Sep-04	8.2	5.7	15.0	15.8

Table 4. Comparison of Dust Trak measurements with TEOM and Harvard Impactor during two 24-hr periods at CAMP Dodge (data courtesy Appalachian Mountain Club and NH Department of Environmental Services.

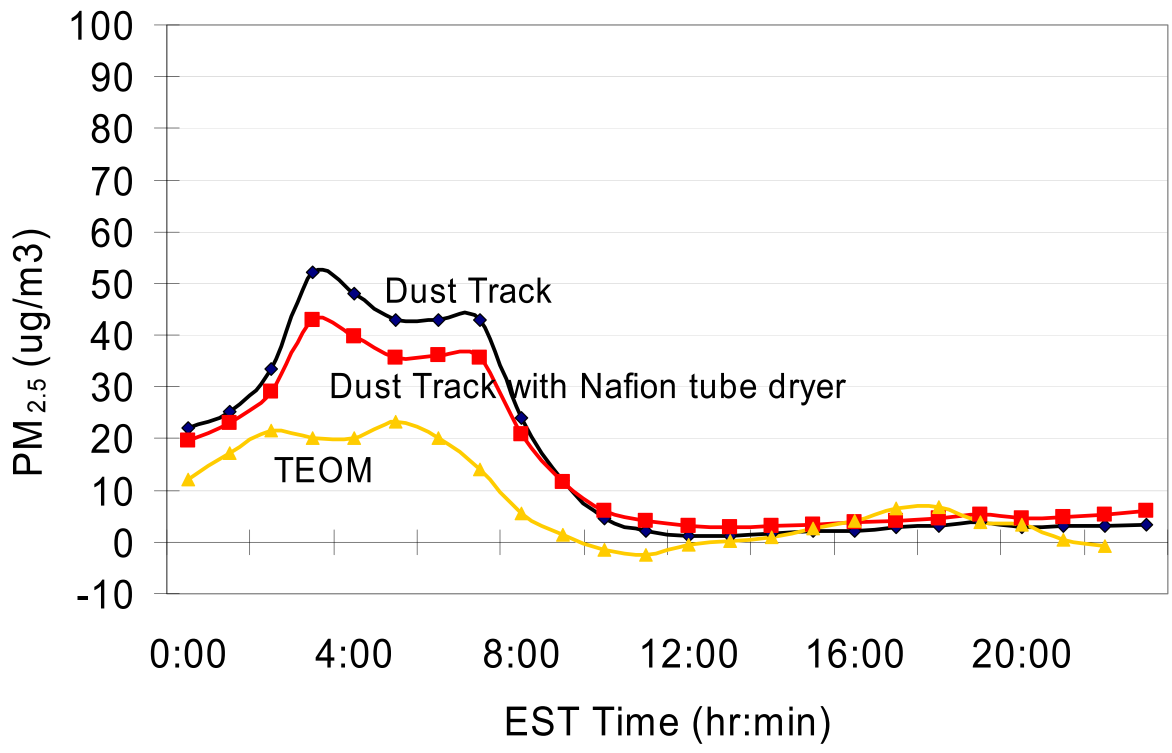

Figure 6: Comparison of Dust Trak to TEOM in Gorham NH. Note site is rural and dominated by sulfates. Suggests Dust Trak with Nafion tube dryer overpredicts $PM_{2.5}$ levels roughly by a factor of 2 when the Nafion Tube dryer is used.

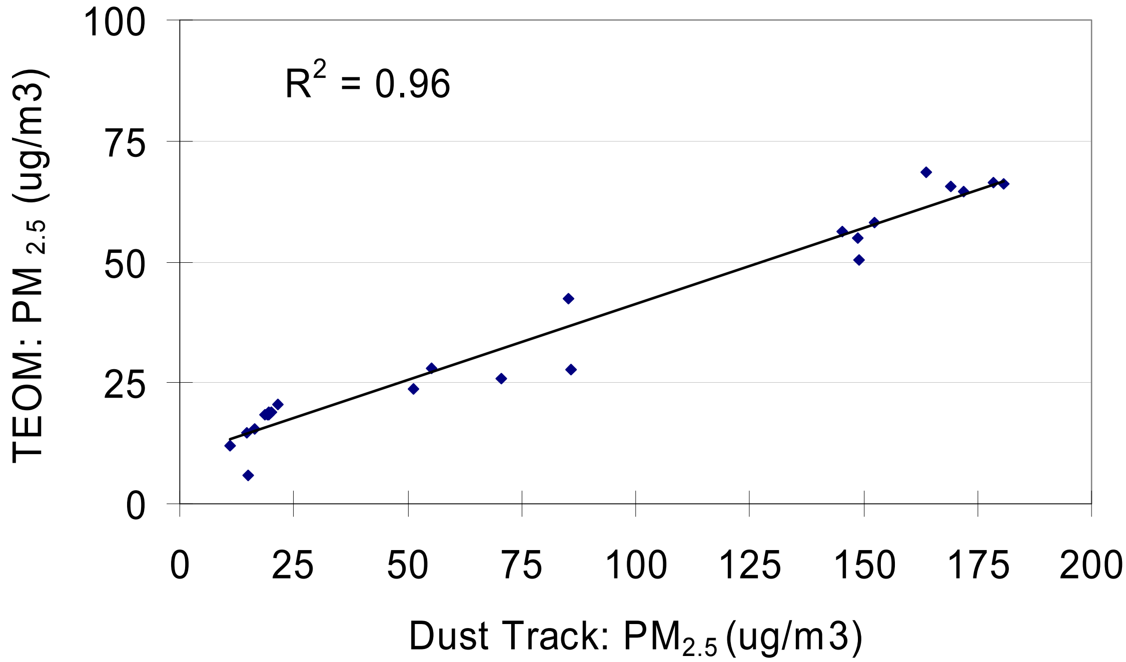

Figure 7: Linear regression of Dust Trak vs TEOM response on August 30, 2004.

Ultrafine Particle Measurements
Ultrafine particles were measured using a TSI PTrak, a continuous monitoring device which measures the number of ultrafine particles per cubic centimeter of ambient air.[52] PTraks were located in the middle and front of the buses, as well as in the lead car. The PTrak is a condensation particle counter that measures particles in the range of 0.01 to 1.0 microns aerodynamic diameter. PTrak data was collected in 1.0 second intervals for most tests, while a few runs experimented with collecting 10.0 second data. The instrument was zeroed daily using a HEPA filter. Unless noted otherwise, data reported in the charts below are from the middle monitor in the bus.

Black Carbon Measurements
Continuous black carbon was measured using two single channel Magee Scientific Aethalometers set up for maximum sensitivity.[53] A BGI Inc $PM_{2.5}$ cyclone was attached to the inlet in each instrument. In Chicago and Atlanta, a rack-mounted single-channel aethalometer on loan from Magee Scientific was used in the lead car. However the resulting data in Chicago and Atlanta was generally unreliable due to a loose internal circuit board disrupted during shipping. As a result, black carbon data from the lead car was largely invalidated in Chicago and Atlanta tests. However, Clean Air Task Force purchased a second aethalometer which performed reliably in Ann Arbor, MI testing. The aethalometer were portable single channel units set up for collecting data at maximum sensitivity and flow rates of 5 liters per minute. After some experimentation with logging intervals, a 60 second interval was generally used to ensure stability of response. We found that below 15 second response, the aethalometer was exceedingly noisy. Despite the problems, criticisms leveled at the aethalometer (e.g. Borak, 2003[54] and Cohen, et al (2002)[55] appear unfounded as we found the portable units—when set up properly-- to

provide stable measurements and the units were not sensitive to vibrations experienced on school bus routes we traveled as reported in those studies.

Particle Bound PAH Measurements

Particle-bound PAH measurements were collected only during the second phase of Ann Arbor testing, using a portable Ecochem analytics PAS 2000CE loaned by the Harvard School of Public Health. Data was recorded in 10 second intervals using a 5 second time constant.

Weather

A hand-held Kestrel 2000® weather measurement device was used to measure basic meteorological parameters for each bus run (T, RH, wind speed). Wind direction was also determined outside of the bus relative to the bus to document the movement of the plumes from both the tailpipe and the crankcase.

Videotaping During Bus Runs

A Sony DV-Cam digital video camera documented cabin pollution events, traffic conditions in front of the bus and other key observations such as the path of visible smoke from the engine's crankcase into the door of the bus. The camera also was used to log interior and exterior video clips synchronously with emission monitoring at selected bus stops. During data processing, the video clips ware combined with a continuous data stream graphic to generate a 'real time' illustration of cabin and curbside impacts from bus emissions. CATF combined video-data clips can be viewed as at the Clean Air Task Force's web: http://catf.us/diesel/videos.php.

BUS ROUTE TESTING RESULTS AND DISCUSSION

General Observations: Conventional Buses on Conventional Fuel

During the initial monitoring in Chicago, we explored all potential emissions sources and pathways affecting cabin air quality including 1) leaky rear doors, 2) leaky engine compartments, 3) leaky windows, 4) front door. DPM pollution in the cabin of the bus was not typically influenced by steady leakage from the rear door, windows or the engine compartment nor diesels in the roadway but instead through opening and closing of the bus door during bus stops.[56] In all tests we found the influx of diesel smoke through the front door to strongly dominate all other pathways, especially with windows shut tightly.

Diesel particulate matter systematically entered the bus cabins through the front doorway. Supporting this observation, the highest concentrations for both $PM_{2.5}$ and ultrafine PM were systematically recorded by monitors situated on the front seat relative to concentrations recorded simultaneously at the mid-bus monitors (Figures 8-10).

Influx of diesel exhaust particles into the cabin typically depended upon the direction of wind relative to two identified sources of school bus emissions (tailpipe and engine crankcase) and the door of the bus. Conditions in conventional school buses lacking particulate matter controls were highly variable and dependant on the wind direction relative to the bus which dictated how much of the tailpipe or engine plume entered the cabin door.

A clear gradient was observed from the front of the bus to the middle of the bus as the plume from the tailpipe entered the bus door and migrated toward the back of the bus, particularly as the bus pulls away mildly forcing the air to the rear. Furthermore, school bus-lead car comparative data suggests diesel particulate matter inside the cabin of school buses is consistently higher than in the lead car, which generally remained near ambient in residential neighborhoods.

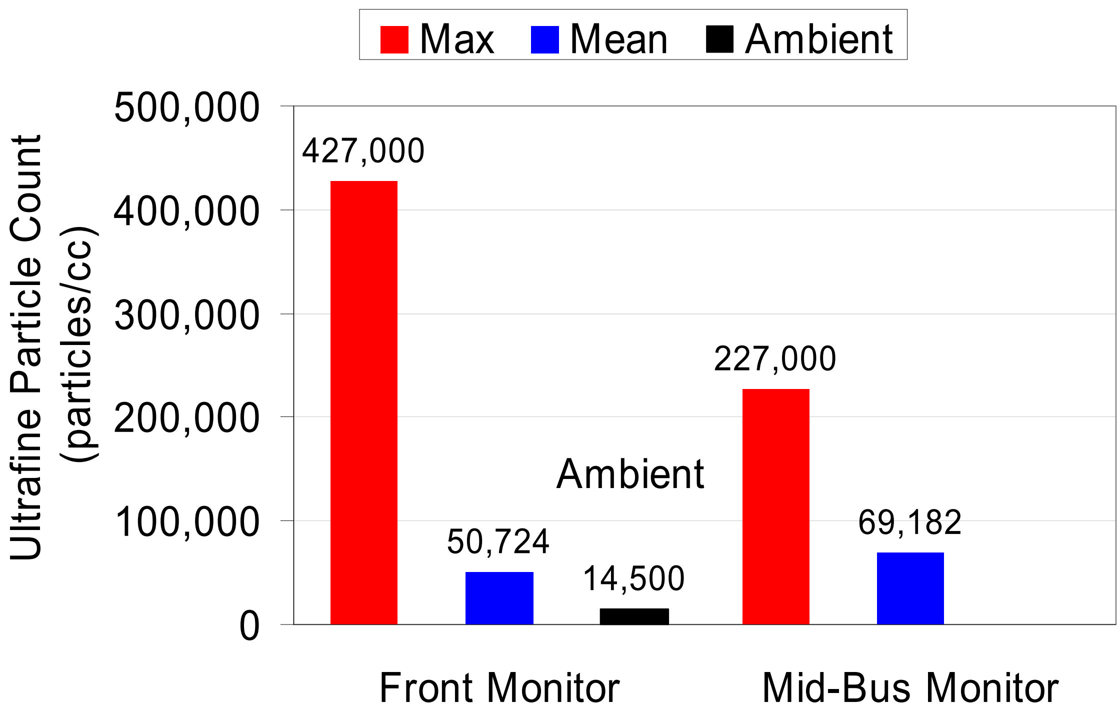

Figure 8: Comparison of ultrafine PM levels between front and mid bus monitors. In all three cities, tailpipe exhaust was documented entering bus through door, thus levels were typically higher in the front of the bus than mid bus.

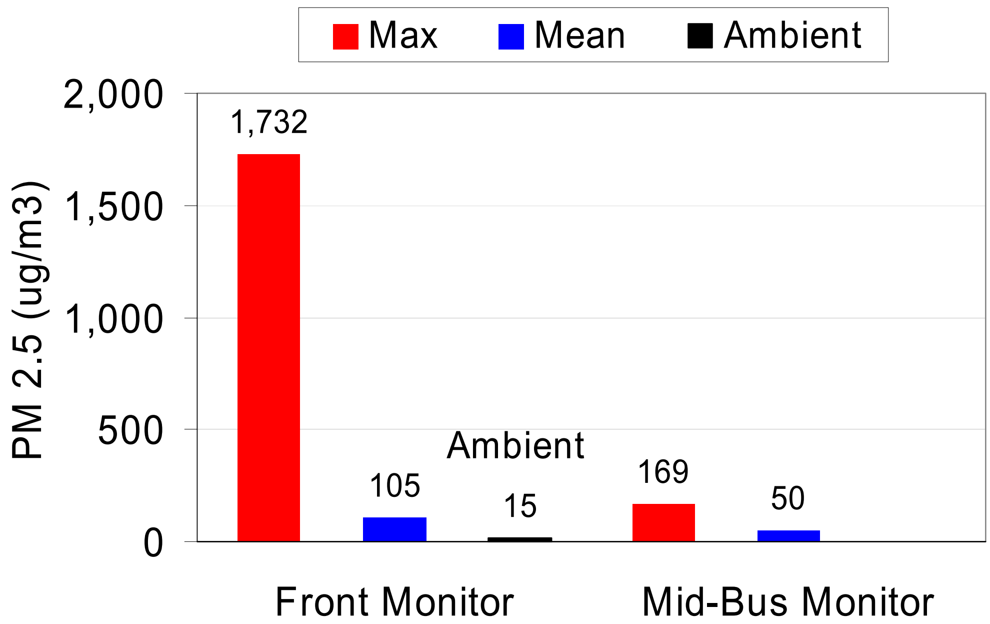

Figure 9: Comparison of $PM_{2.5}$ levels between front and mid bus monitors. In all three cities, crankcase exhaust was documented entering bus through door, thus levels are systematically higher in the front of the bus than mid bus.

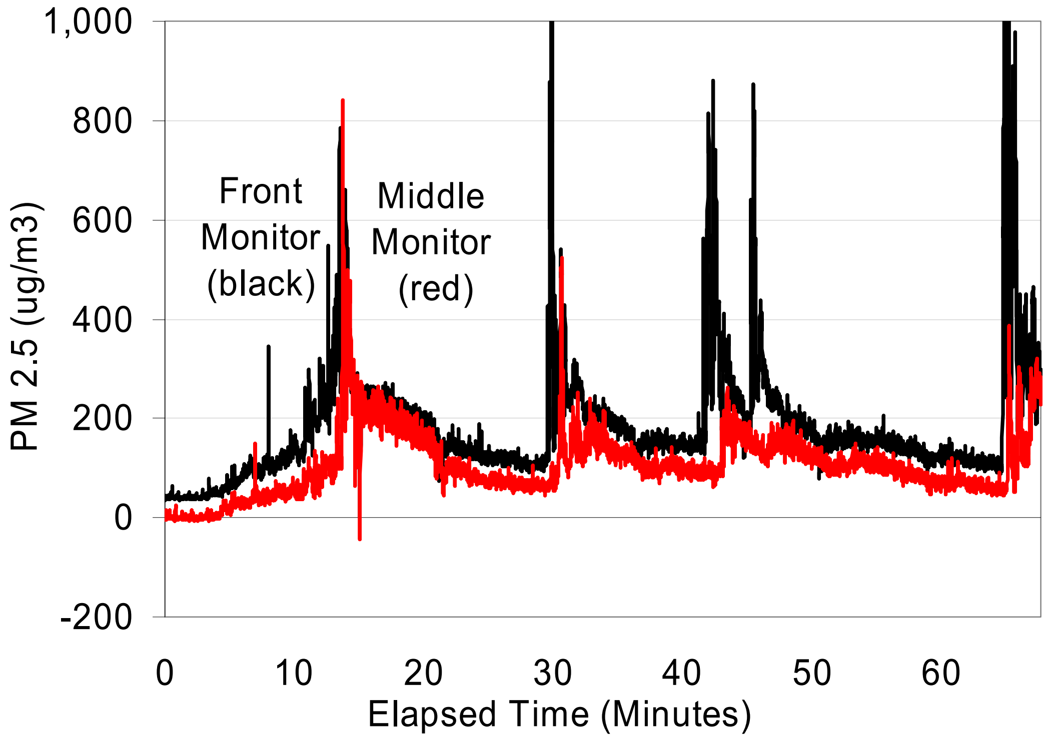

Figure 10: Comparison of $PM_{2.5}$ concentrations between front and middle of bus in Chicago. Note the parallel signatures with levels exceeding 1,000 ug/m^3 in the front of the bus. Levels in the middle of the bus are lower and slightly lagging. This supports

the emissions pathways through the front door into the bus. Source of these emissions is the crankcase vent. Ambient concentration has been subtracted.

Effect of Window Position

As documented in earlier studies, particulate matter build-up on buses is dependent on window position. With windows closed, diesel particulate matter levels rose only at bus stops with the door open and then decayed between stops (Figures 10, 24 provide a good illustration of this.) Otherwise, PM in the roadway in front of the bus was very slow to penetrate into the cabin with windows up. In a bus with windows open on a busy street (with diesel sources in front of the bus) particulate matter concentrations would rapidly increase but would then ventilate rapidly once the source influence was gone. With windows down in a quiet residential area, our observations demonstrated that any emissions on the bus would rapidly dilute as the bus ventilated to ambient conditions.

External Sources of Exhaust and Effect on Cabin Particulate Matter

Figures 11 and 12 illustrate $PM_{2.5}$ and ultrafine PM conditions on the bus, respectively, relative to synchronous conditions in the lead car during a bus route in Atlanta. While the bus shows a strong influx of both pollutants ($PM_{2.5}$ and ultrafine PM), the lead car data shows that there is little in the way of diesel in the roadway to account for the changes seen in the bus. This particulate matter build up in the presence of no external PM sources confirms the bus self-pollution mechanism. Linear regressions were performed to compare changes in bus air quality due to diesel exhaust sources in the roadway in front of the bus (Figure 13). Regressions were calculated, adjusting the data curves with both zero and 10 second lags—the 10 second lag to account for the time required for outside emission to penetrate the bus. Both approaches yielded Pearson's R^2 of close to zero suggesting no apparent relationship. In summary, buses tested showed higher levels of PM than the lead car while at the same time they were rarely affected by other emissions, especially in residential areas. However, in instances where diesels ahead of the bus did affect cabin air quality, peaks were also seen in the lead car and easy to identify.

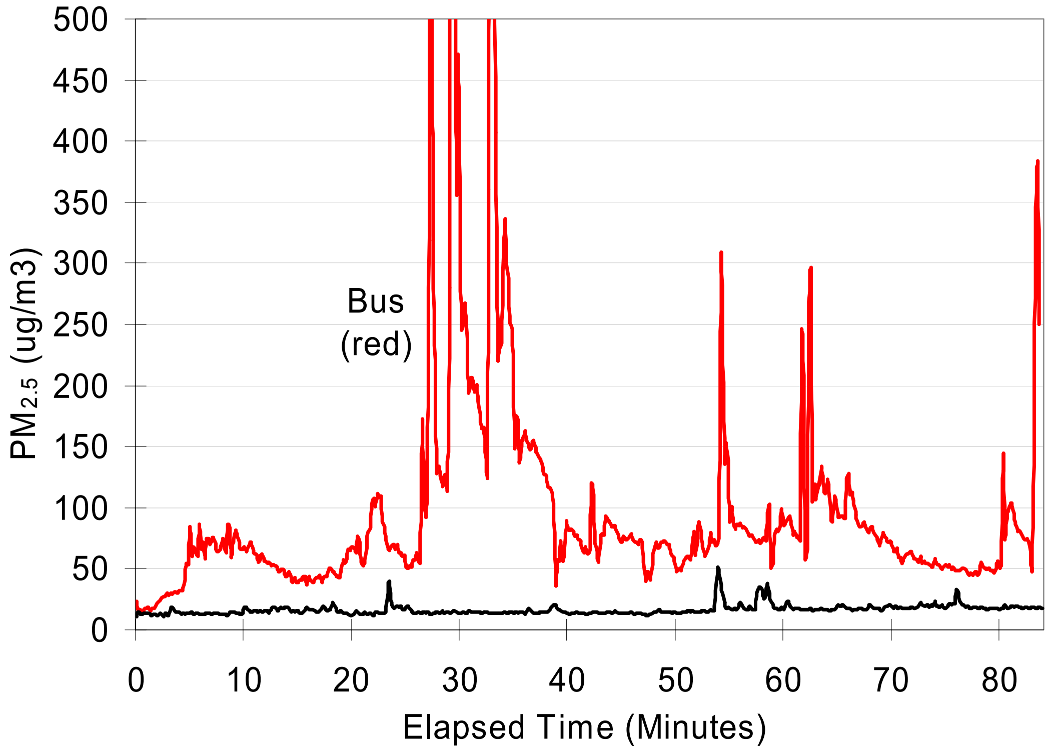

Figure 11: $PM_{2.5}$ in the bus cabin is not from the roadway but instead result from bus self pollution-- as indicated by the low concentrations in the lead car relative to the bus.

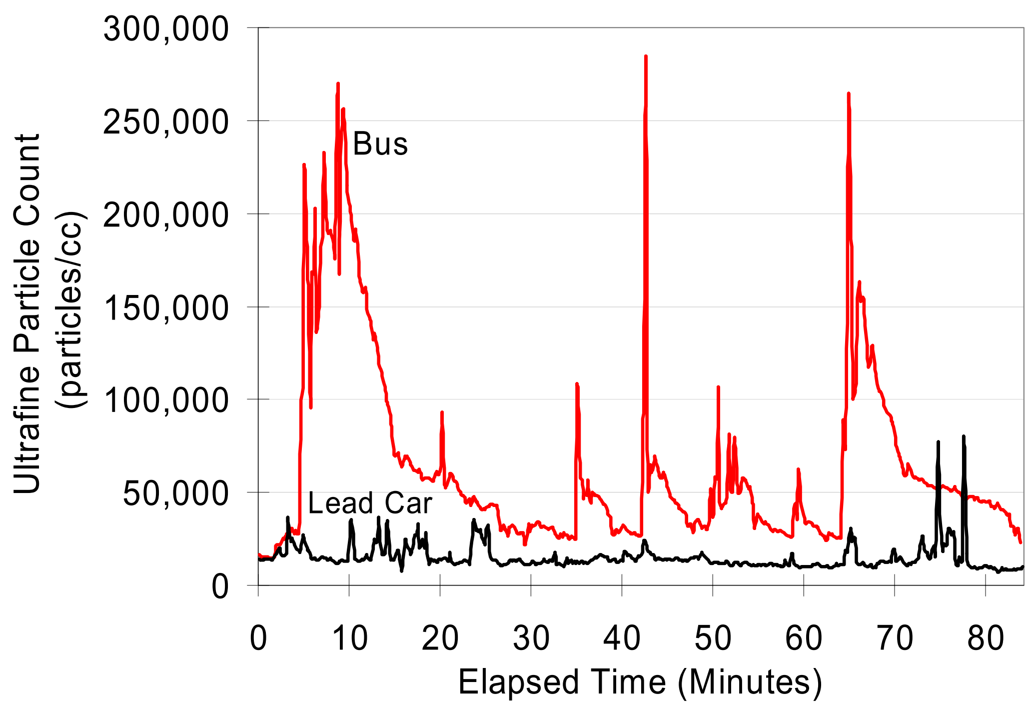

Figure 12: Ultrafine particles in the bus cabin are not from the roadway but instead result from bus self pollution-- as indicated by the low concentrations in the lead car relative to the bus.

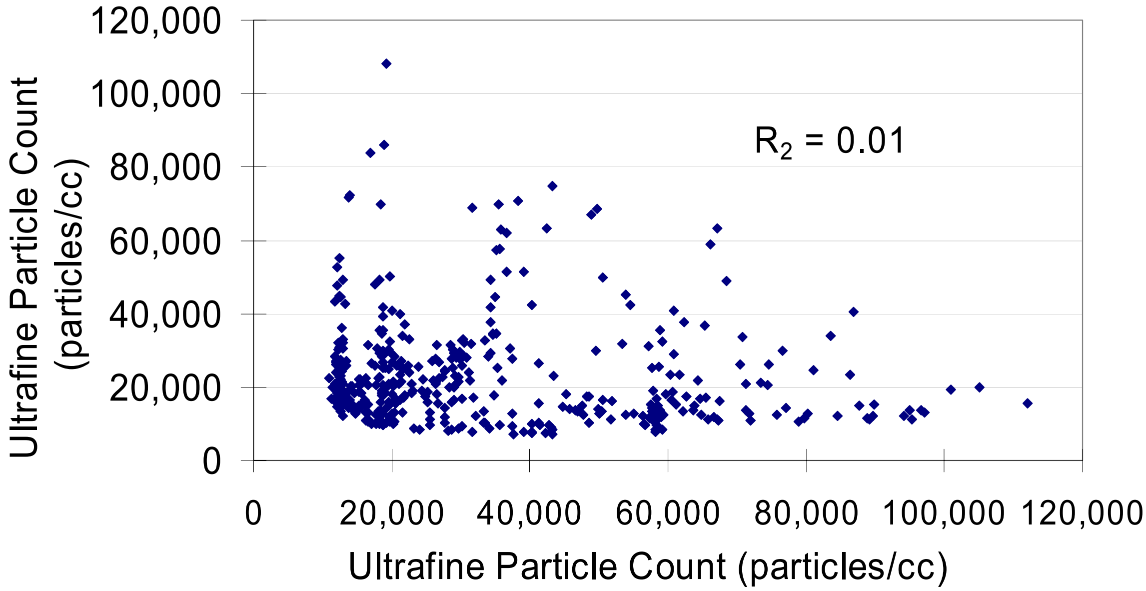

Figure 13: Linear regression of ultrafine PM levels in bus with a 10 second lag (to compensate for time for emissions to penetrate bus) with ultrafine PM in lead car. Suggests no predictable relationship between roadway exhaust and cabin exhaust.

Influence of Weather

Weather conditions during testing in all three cities were generally cool, as the tests were conducted in late fall and early spring. Conditions varied widely during testing-- from sunny and breezy to rainy. Rain-related particle deposition did not measurably reduce exhaust impacting the cabin of the buses although it did affect ambient conditions outside the bus—rain tended to reduce PM in the ambient air. We found that the strength of the emissions plume entering the cabin was highly dependent upon the wind direction relative to the two principal sources of emissions-- engine crankcase and tailpipe. Winds from the rear typically brought tailpipe emissions to the front door of the bus, and winds from the front or driver's side carried smoke from the engine toward and through the cabin door.

Figure 14: Schematic of bus tailpipe plume entrained from rear toward bus door..

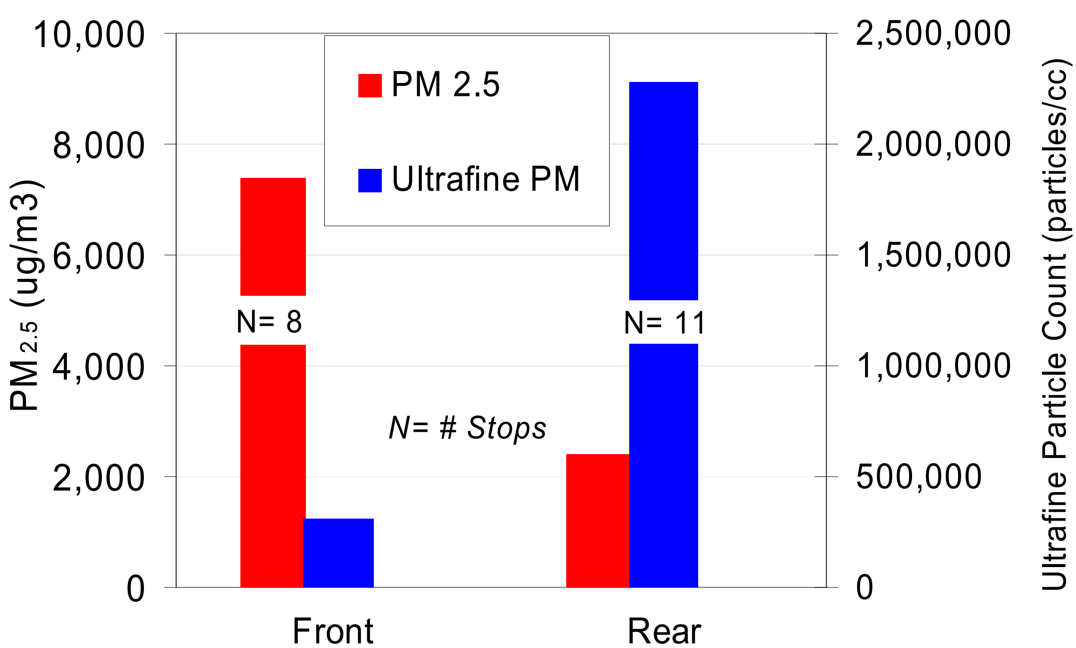

Figure 15: Graph shows relationship between wind direction and build-up (cumulative peaks) of ultrafine PM and $PM_{2.5}$ on the conventional bus with conventional fuel. $PM_{2.5}$ is highest when wind blows from the front of the bus (crankcase emissions) and

ultrafine PM is highest when wind blows from the rear (tailpipe emissions.) Ann Arbor data.

ULTRAFINE PARTICULATE MATTER RESULTS

Conventional Bus on Conventional Fuel
Ultrafine particles are a significant and potentially toxic component of diesel exhaust. Table 5 summarizes ambient, maximum and mean concentrations of ultrafine PM for buses in each city. Cabin levels of measured pollutants build up substantially on bus runs but varied considerably from run to run in the conventional buses. For all bus runs, ultrafine PM levels on the bus were well above—and many multiples of-- ambient conditions. Clearly, based on the variability of our data, it would be risky to generalize about exposure levels in the cabins of school buses in general. Because ambient conditions varied widely from run to run and city to city, we typically subtracted the ambient from cabin levels measured on data plots so as not to show comparative relationships biased by ambient conditions. In our data summary tables, however, we report raw values along side approximate ambient conditions.

Ultrafine PM (particles/cc)	Ambient	Maximum	Mean
Ann Arbor			
Conventional Bus 56 Run 1	14,000	227,000	50,724
Conventional Bus 56 Run 2	11,000	76,500	28,145
ULSD Bus 56 Run 1	10,000	158,000	53,040
CNG Bus 24 Run 1	23,000	78,400	26,621
CNG Bus 24 Run 2	7,000	57,000	9,570
DOC Bus 56 Run 1	18,000	131,000	38,091
DOC Bus 56 Run 2	22,000	129,000	40,782
DOC-Spiracle Bus 56 Run 1	22,000	70,700	30,969
DOC-Spiracle Bus 56 Run 2	21,000	78,500	38,139
Spiracle Bus 56 Run 1	9,000	65,500	26,927
DPF-ULSD Bus 56 Run 1	11,000	43,600	15,445
DPF-ULSD Bus 56 Run 2	5,000	26,000	9,859
DPF-ULSD-Spiracle Bus 56 Run 1	9,000	34,100	13,029
DPF-ULSD-Spiracle Bus 56 Run 2	11,000	21,200	9,823
DPF-ULSD-Enviroguard Bus 56 Run 1	11,000	68,800	18,810
Chicago			
Conventional Bus 517 Run 1	23,000	136,000	72,462
Conventional Bus 517 Run 2	19,000	195,000	68,565
Conventional Bus 662 Run 1	26,000	209,000	74,466
Conventional Bus 662 Run 2	19,000	152,000	65,839
DPF-ULSD Bus 128 Run 1	25,000	38,600	30,808
DPF-ULSD Bus 128 Run 2	24,000	37,200	29,868

Atlanta			
Conventional Bus 1450 Run 1	28,000	110,000	50,230
Conventional Bus 1450 Run 2	22,000	94,600	47,994
Conventional Bus 1481 Run 1	13,000	112,000	35,114
DPF-ULSD-Vent Tube Extension Bus 1450 Run 1	9,000	23,000	10,735
DPF-ULSD-Vent Tube Extension Bus 1450 Run 2	17,000	38,300	19,388
DPF-ULSD-Vent Tube Extension Bus 1450 Run 3	11,000	16,200	7,381

Table 5: Ultrafine PM Summary Data.

	$PM_{2.5}$	*Ultrafine Particles*	*PPAH*
	ug/m^3	**particles/cc**	**ng/m^3**
Conventional			
1 m from tailpipe			n/a
Engine compartment			n/a
CNG			
1 m from tailpipe	100	30,000-500,000	n/a
Engine compartment	n/a	n/a	n/a
DOC+ Spiracle			
1 m from tailpipe	1,500	500,000	2,500
Engine compartment	9	25,000	6
DOC-only (Bus 56)			
1 m from tailpipe	2,400	500,000	2,650
Engine compartment	2,000	20,000	7
DOC-only (Bus 60)			
1 m from tailpipe	6,000	500,000	2,600
Engine compartment	1,400	13,000	5
ULSD alone			
1 m from tailpipe	3,000	500,000	1,300
Engine compartment	2,100	36,000	7
Spiracle-only			
1 m from tailpipe	2,400	500,000	2,450
Engine compartment	41	9,000	6
DPF + Spiracle			
1 m from tailpipe	19	8,000	33
Engine compartment	28	9,000	7

Table 6: Peak concentrations measured adjacent to engine crankcase and tailpipe. In order to get a sense of the relative strengths of 3 measured pollutants ($PM_{2.5}$, ultrafine particles and particle-bound PAH) emitted from the engine and tailpipe sources, we measured air quality conditions 1 meter behind the tailpipe and under the engine hood. While these numbers do not represent rigorous tailpipe testing, they are useful in understanding the approximate source strengths (emissions fro the bus available to pollute the cabin) for the three pollutants from the tailpipe and engine compartment under different retrofit scenarios. Note that the DPF + Spiracle +ULSD combination brings PM measurements down to ambient. 500,000 particles / cc is the maximum range of the PTrak ultrafine particle counter.

Bus Equipped with DPF and ULSD Fuel

In all cities, we tested a conventional bus retrofit with a diesel particulate filter (trap) and ultralow sulfur diesel fuel. In Chicago, we tested an identical bus to the conventional bus, but in Atlanta and Ann Arbor we retrofit the same conventional bus we had initially tested.

Ultrafine particle self-pollution was effectively eliminated in the cabin by the DPF-ULSD fuel retrofit. Ultrafine particle spikes observed at conventional bus stops were eliminated in the DPF-ULSD bus, regardless of wind direction Furthermore, ultrafine particle concentrations 1.0 meter behind the tailpipe of the DPF-ULSD retrofit buses were at or near ambient levels--compared to off scale (>500,000 particles per cc) conditions recorded on the conventional buses (See Table 6).

While the DPF virtually eliminated the ultrafine particles from the tailpipe in the school bus cabin, the Dust Trak continued to indicate intrusion of $PM_{2.5}$ smoke into the cabin when the wind was from the front of the bus. However, this was not due to any failing of the DPF-ULSD retrofit (note the simple tailpipe demonstration showed zero PM2.5 for the DPF-ULSD combination) but instead a result of engine crankcase $PM_{2.5}$ as described in the $PM_{2.5}$ discussion below. Thus, while the retrofit of the tailpipe resulted in virtual elimination of ultrafine PM (self-pollution) build-up in the cabin, the crankcase continued to pollute the bus cabin with high concentrations of $PM_{2.5}$.

Figure 16: A simple tailpipe demonstration of the effectiveness of the DPF-ULSD combination in reducing ultrafine PM to ambient conditions . Conventional bus (on left) reads 500,000 ultrafine particles/cc, the upper limit of detection for the PTrak. The retrofit bus (on right) reads 9,570 ultrafine particles/cc—levels that were actually below ambient that day.

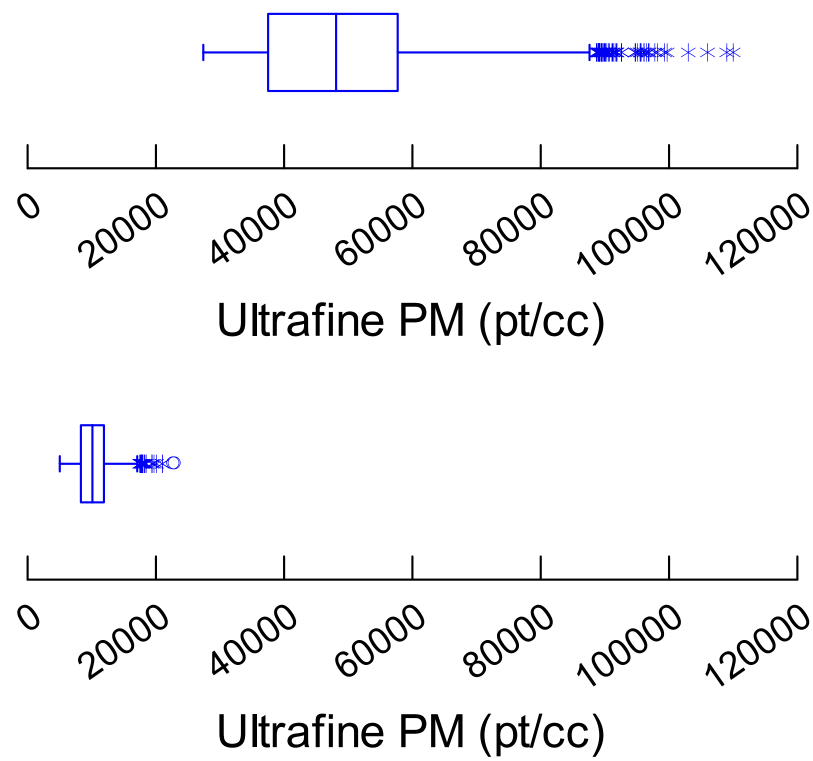

Figure 17: Box plots display the range of ultrafine particulate matter concentrations measured in a conventional school bus (top plot) and later equipped with DPF-ULSD in Atlanta (lower plot). Note there is little or no overlap between ultrafine particle ranges in conventional buses and buses equipped with DPF – ULSD retrofit. Measured levels on the bus are near ambient levels (17,000 pt/cc that day).

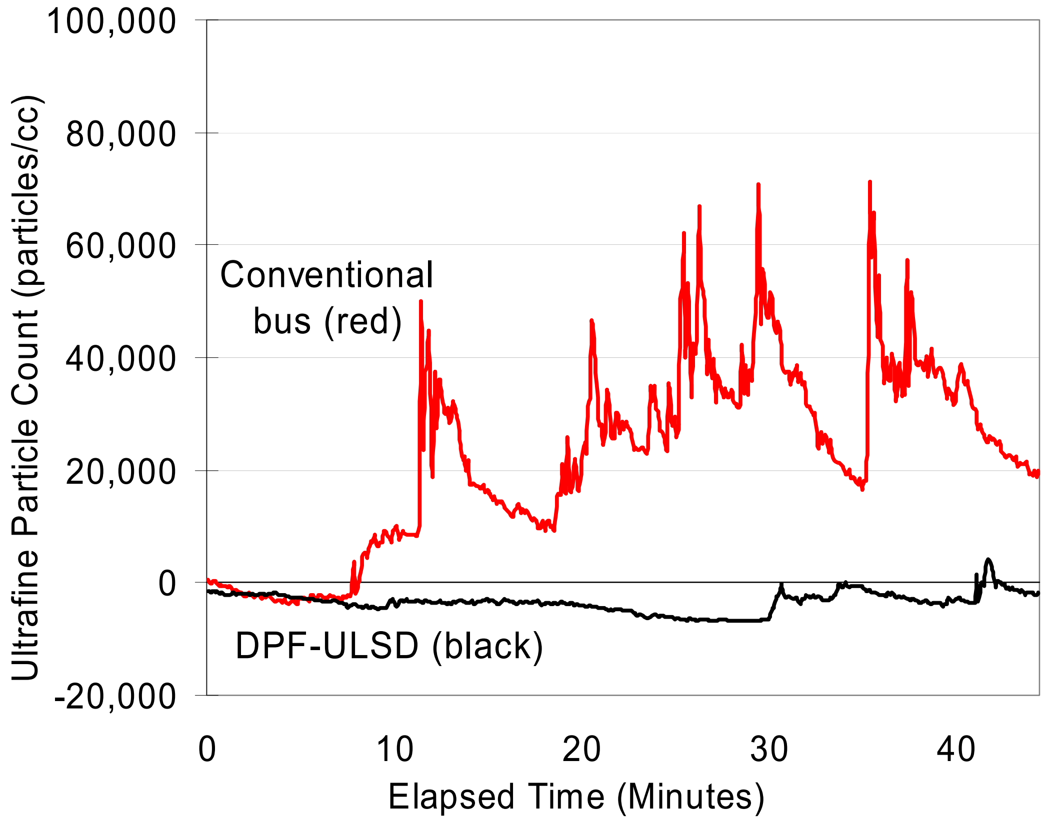

Figure 18: Comparison of cabin air quality before and after retrofit. Spikes in the conventional bus curve occurred at bus stops when exhaust from the tailpipe entered front door. These spikes were eliminated by the DPF-ULSD retrofit. (Atlanta data). Ambient concentrations have been subtracted from the data resulting in the slightly negative concentration range.

Bus Equipped with Diesel Oxidation Catalyst

In another testing configuration, Ann Arbor Bus 56 was equipped with a diesel oxidation catalyst (DOC) and conventional fuel. In the cabin of the DOC-equipped bus we documented substantial influx of all measured pollutants. Levels were apparently somewhat lower than, but not substantially different from the range of concentration in conventional bus runs. Given the uncertainty created by alternating wind directions and magnitudes which varied from run to run, it is difficult to ascertain whether the DOC provided any in-cabin reduction in PM relative to the conventional bus. In addition to cabin testing, we documented emissions 1.0 meters behind the tailpipe during idling which were also within the range of measurements from conventional buses. The high levels recorded behind the bus equipped with the DOC -- levels exceeding the upper limit of the PTrak monitor (Table 6) --suggests that there is little difference between a DOC and a conventional bus. The strong concentrations of ultrafine PM behind the bus, exceeding the limits of detection are consistent with the high levels of ultrafine PM entrained into the bus cabin in the DOC-equipped bus, especially compared to the DPF-ULSD combination that cut emissions of ultrafine PM to ambient concentrations.

Thus, we found it difficult to ascertain whether a DOC provided any in-cabin benefit. The poor apparent performance of the DOC may be due to the ineffectiveness of DOC under idle conditions. EPA verification testing suggests an approximate 10-30% benefit from DOCs under loaded conditions. However, it is unclear whether this emissions reduction is maintained under idle conditions at bus stops when the emissions typically enter the bus. Thus, the effectiveness of the DOC in reducing in-cabin ultrafine PM should be investigated further. 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. Also note that these results also do not reflect benefits in reducing other pollutants such as NOx not measured in the study. In sum, the results of the DPF-ULSD retrofit stand in stark contrast to the DOC results, suggest that the DOC has, at best, limited usefulness as a device to remedy in-cabin ultrafine particulate matter air quality.

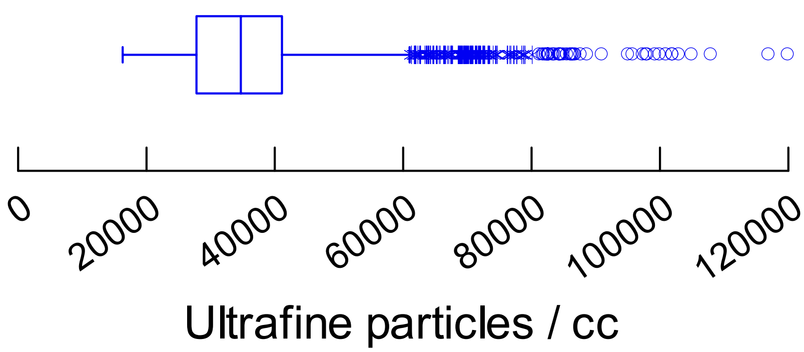

Figure 19: Distribution of in-cabin ultrafine particulate matter levels in the bus equipped with a DOC. Compared to Figure 13, the ultrafine PM remains elevated at levels similar to the conventional bus, but with the DPF-ULSD combination, cabin levels are cut to ambient. This suggests that the DOC has limited usefulness as a device to improve in-cabin ultrafine PM.

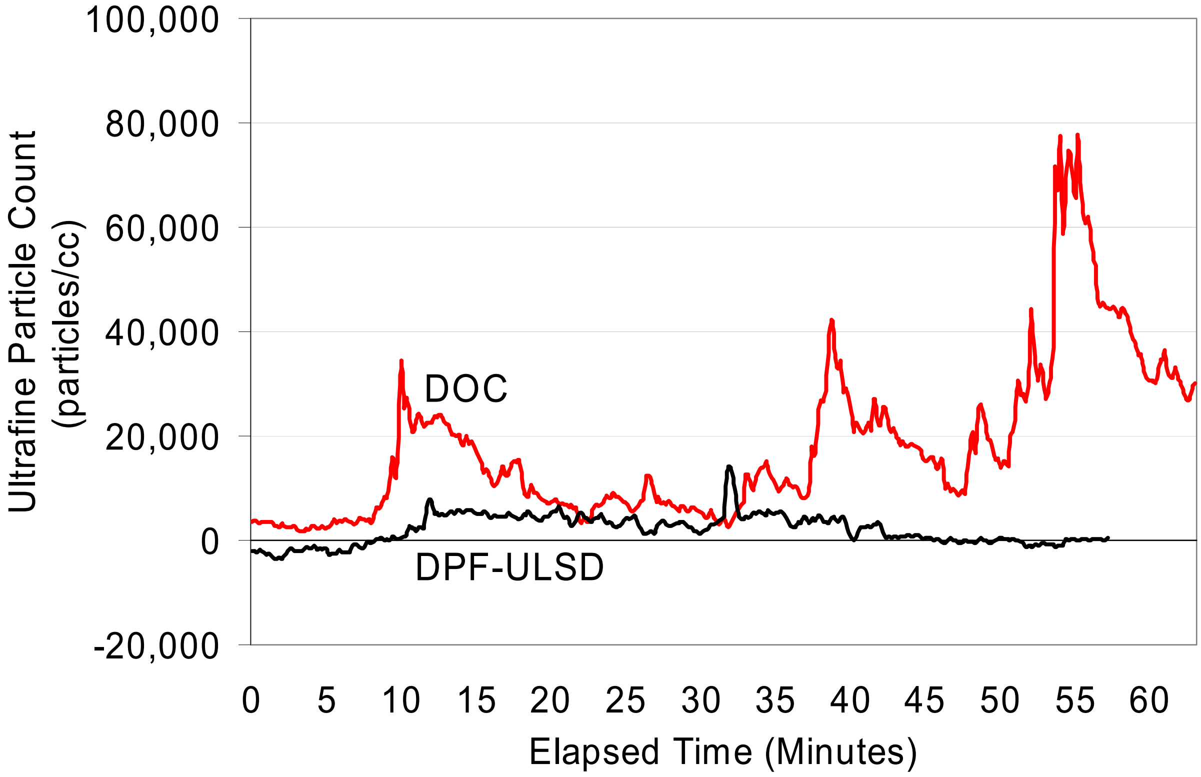

Figure 20: Net cabin ultrafine pollution, comparing DPF vs DOC in reducing ultrafine particles. Ambient concentration has been subtracted. The DPF remains near ambient the entire bus route.

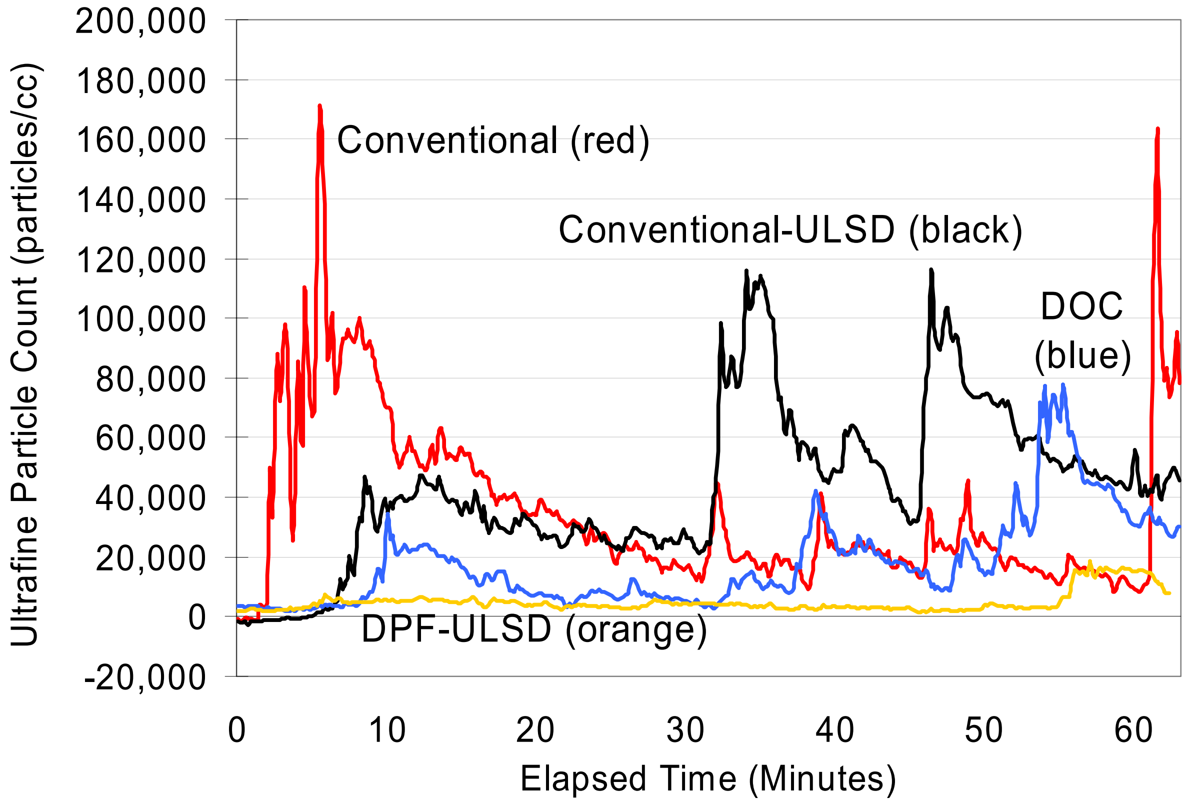

Figure 21: Comparison of ultrafine particles on the conventional, ULSD-only, DOC and DPF-equipped buses. The DPF-ULSD combination (flat orange line) is the only device that eliminates the in-cabin ultrafine particles. Ambient concentration has been subtracted.

Compressed Natural Gas Bus

Ann Arbor compressed natural gas (CNG) bus #24 is a transit style bus with the engine and tailpipe in the rear. Testing directly behind the tailpipe documented elevated ultrafine particle emissions, but at levels considerably lower than for a conventional bus (Table 6). Testing along the bus route indicated occasional intrusion of the ultrafines into the bus depending on wind direction (Figure 22.) However, the source strength (concentration behind tailpipe) is much lower than for the conventional bus and the conventional bus with ULSD or with a DOC.

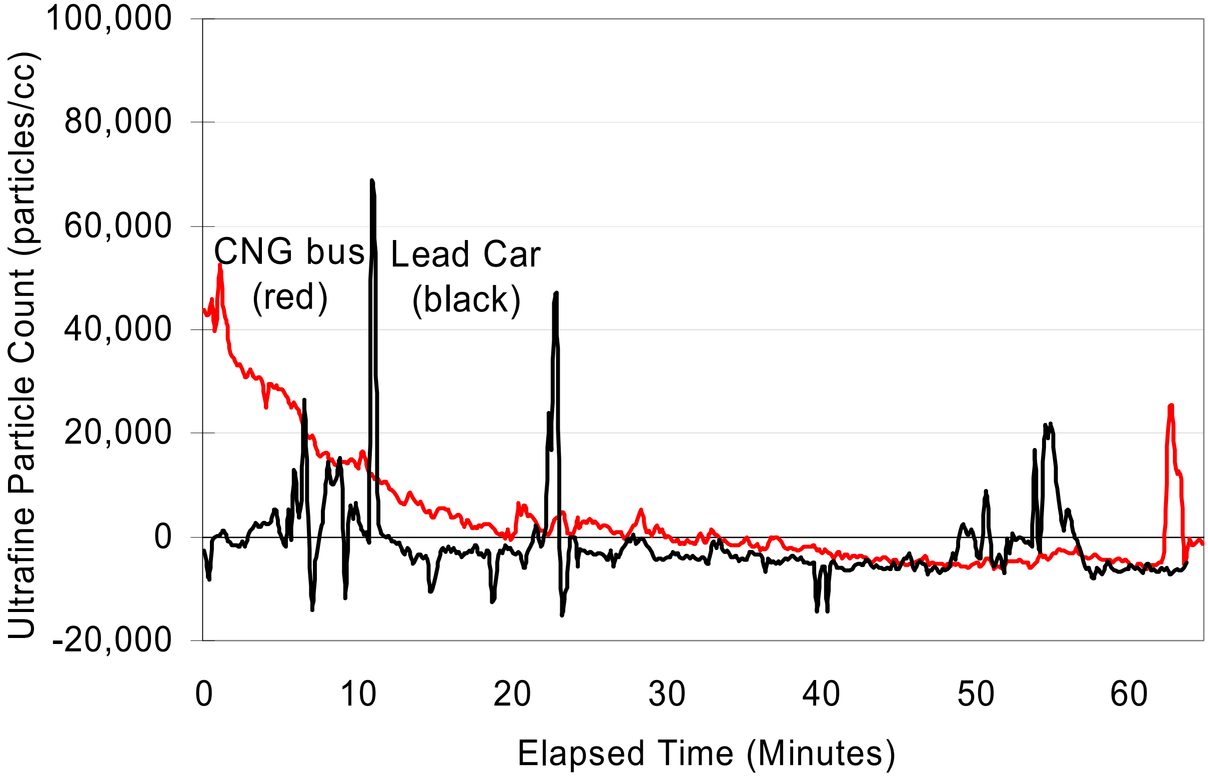

Figure 22: Ultrafine PM in Ann Arbor transit-style compressed natural gas (CNG) bus #24 compared to lead car. Ultrafine PM was detected in the cabin of the CNG bus from the bus and traced to its tailpipe which was on the driver's side, farthest from the cab. The initial particle concentration build up on the graph occurred during idling. Ambient concentration has been subtracted.

FINE PARTICULATE MATTER ($PM_{2.5}$) RESULTS

Conventional Bus and Conventional Fuel.

Fine particulate matter ($PM_{2.5}$) levels on conventional buses were highly variable during bus routes with raw maximum $PM_{2.5}$ levels recorded in the middle of the bus ranging from 90 to 336 ug/m^3 in the three cities. As described below, PM mass was traced to emissions from the engine crankcase.

$PM_{2.5}$ (ug/m^3)	Ambient	Maximum	Mean
Ann Arbor			
Conventional Bus 56 Run 1	12	169	50
Conventional Bus 56 Run 2	21	199	47
ULSD Bus 56 Run 1	40	207	76
CNG Bus 24 Run 1	36	104	36
CNG Bus 24 Run 2	21	157	21
DOC Bus 56 Run 1	13	184	52
DOC Bus 56 Run 2	17	212	65
DOC-Spiracle Bus 56 Run 1	16	73	22
DOC-Spiracle Bus 56 Run 2	25	74	25
Spiracle –ULSD Bus 56 Run 1	43	108	36
DPF-ULSD Bus 56 Run 1	33	329	45
DPF-ULSD Bus 56 Run 2	22	189	47
DPF-ULSD-Spiracle Bus 56 Run 1	50	193	43
DPF-ULSD-Spiracle Bus 56 Run 2	45	113	31
DPF-ULSD-Enviroguard Bus 56 Run 1	11	647	32
Chicago			
Conventional Bus 517 Run 1	51	336	50
Conventional Bus 517 Run 2	39	90	40
Conventional Bus 662 Run 1	39	302	92
Conventional Bus 662 Run 2	53	311	85
DPF-ULSD Bus 128 Run 1	58	242	77
DPF-ULSD Bus 128 Run 2	44	564	163
Atlanta			
Conventional Bus 1450 Run 1	65	185	75
Conventional Bus 1450 Run 2	63	135	77
Conventional Bus 1481 Run 1	43	131	54
DPF-ULSD-Vent Tube Extension Bus 1450 Run 1	23	188	23
DPF-ULSD-Vent Tube Extension Bus 1450 Run 2	13	130	35
DPF-ULSD-Vent Tube Extension Bus 1450 Run 3	34	73	37

Table 7: A summary of raw fine particulate matter ($PM_{2.5}$) mass (unadjusted) for bus routes in three cities.

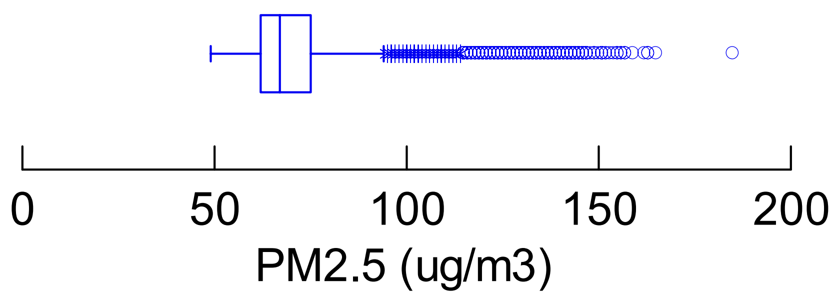

Figure 23: Fine particulate matter ($PM_{2.5}$) in DPF-ULSD retrofit bus remain high following retrofit. $PM_{2.5}$ was found to be a result of direct engine emissions rather than tailpipe emissions.

Two Sources of Bus Self-Pollution: Tailpipe and Engine Crankcase.

During initial testing in Chicago it became clear that ultrafine particles and $PM_{2.5}$ were displaying peak concentrations at alternating bus stops (Figure 24) suggesting more than one source of emissions entering the cabin. Indeed, we inspected the bus exterior for all potential sources of emissions and found there to be a second source--a tube protruding downwards from the engine crankcase emitting visible smoke—the road draft tube. When the bus stopped and the door opened, the smoke from the tube—a few meters away from the door—blew into the cabin when the wind was from the driver's side front of the bus (Figure 15). Further investigation demonstrated extreme concentrations of PM, over 10,000 ug/m^3 as far as a meter away from the road draft tube (Figure 25), indicating that the crankcase is a very strong source of $PM_{2.5}$ mass.

Wind measurements supported two emissions sources as well: when the wind was from the rear of the bus, ultrafine particles peaked; when the wind was from the front the $PM_{2.5}$ peaked.

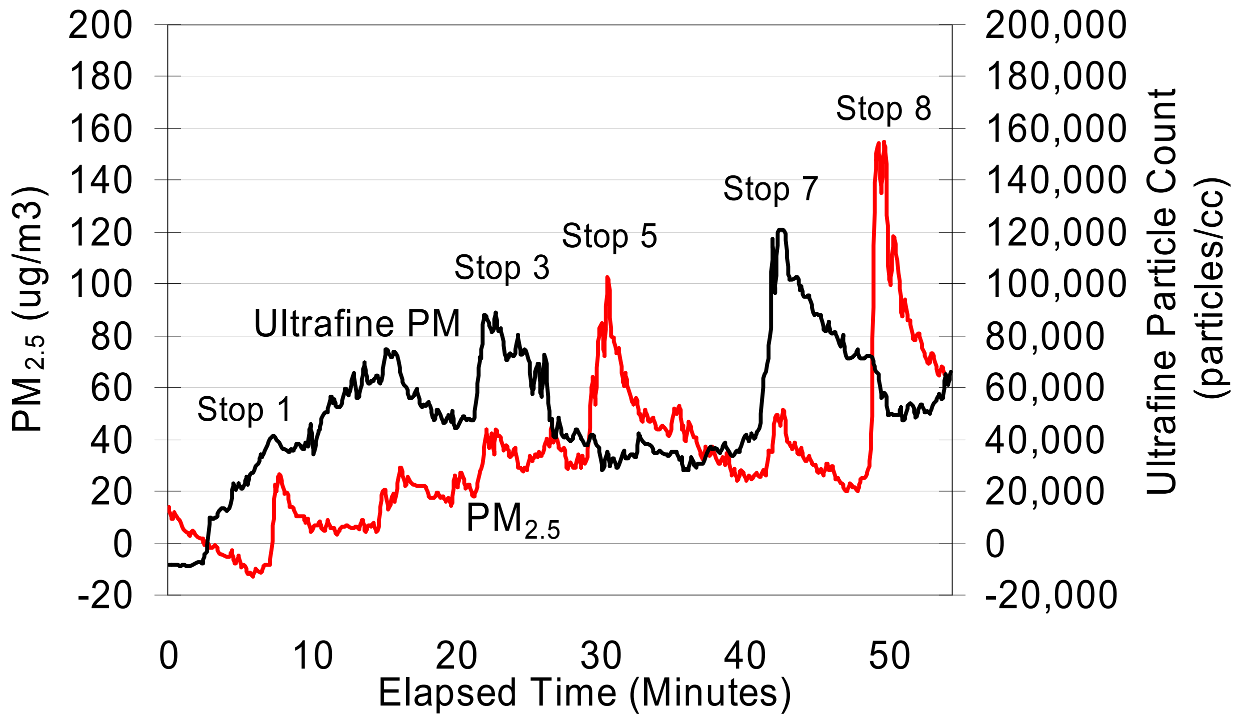

Figure 24: Cabin air quality on a conventional school bus. Spikes in particle levels occur only at stops when door is opened. The alternating ultrafine- $PM_{2.5}$ peaks are indicative of 2 different sources for $PM_{2.5}$ on the bus. $PM_{2.5}$ increases were associated with crankcase emissions, whereas ultrafine PM increases were associated with tailpipe emissions. This explains why $PM_{2.5}$ levels remained high in DPF-ULSD bus cabin despite the retrofit and attendant reduction in ultrafine PM. Ambient concentrations have been subtracted. (Chicago data.)

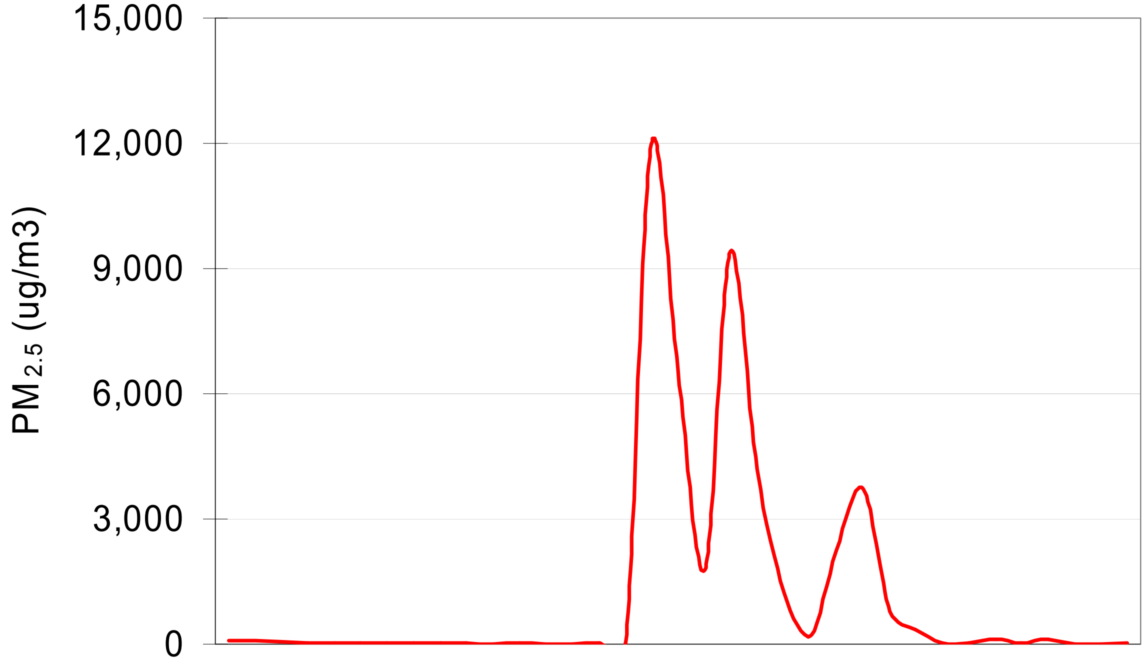

Figure 25: Raw $PM_{2.5}$ concentrations approximately one meter from tubing connected to the road draft tube on the retrofit bus. These extreme $PM_{2.5}$ levels (exceeding 10,000 ug/m^3) explain why this source –which vents very near the front door of the bus--so strongly impacts in-cabin air quality.

Figure 26: In a simple experiment, the Dust Trak (rectangular instrument) responded strongly to $PM_{2.5}$ from engine crankcase smoke from the road draft tube (left photo). The PTrak (instrument with handle) responded strongly to tailpipe emissions (right photo).

The strong $PM_{2.5}$ signature and attendant low ultrafine measured from the crankcase are consistent with the size mode of oil mist particles during idle conditions (Figure 27).[57] Particles emitted from the crankcase fall well within in the typical $PM_{2.5}$ distribution with a peak at approximately 1.0 microns or " PM 1.0" but little mass from the ultrafine fraction; ultrafine particles constitute a small fraction of the particulate matter mass.

The composition of engine crankcase emissions has not been well documented. Crankcase emissions are result from engine exhaust "blowing by" the piston rings into the crankcase which are then, in turn, vented to avoid high pressures building up in the crankcase.[58] Crankcase emissions are comprised of hydrocarbons, NOx and PM, and according to EPA can emit over 100 lbs. of these pollutants over and engines lifetime.[59,60] Crankcase PM may also contain a significant fraction of organic particulate matter (soluble organic fraction). There are few devices designed to control blow-by emissions. Some simply filter emissions. One such device is the Fleetguard Enviroguard which we tested in Atlanta. Another technology, one that we tested in Ann Arbor, is a closed crankcase filtration system, the Donaldson Spiracle. The Spiracle filters and reroutes the crankcase blow-by back into the engine (similar conceptually to positive crankcase ventilation (PCV) valves installed in cars beginning decades ago). The Spiracle reroutes blow-by away from the front door of the bus back into the engine and out through the exhaust system and any post combustion emissions controls.[61]

EPA in its final regulatory impact analysis for both the highway diesel and the non-road diesel rules describe requirements to reduce crankcase emissions in new diesel engines.[62,63] Although the rules for newly manufactured engines require reductions in emissions equivalent to the crankcase emissions, both rules stop short of requiring rerouting all crankcase emissions back into the engine and allow manufacturers to treat the crankcase emissions as a part of the total emissions from the engine.[64] Therefore, this source of cabin pollution may remain a problem in some vehicles indefinitely. Furthermore, in-use testing does not specifically require quantification of emissions from the crankcase.

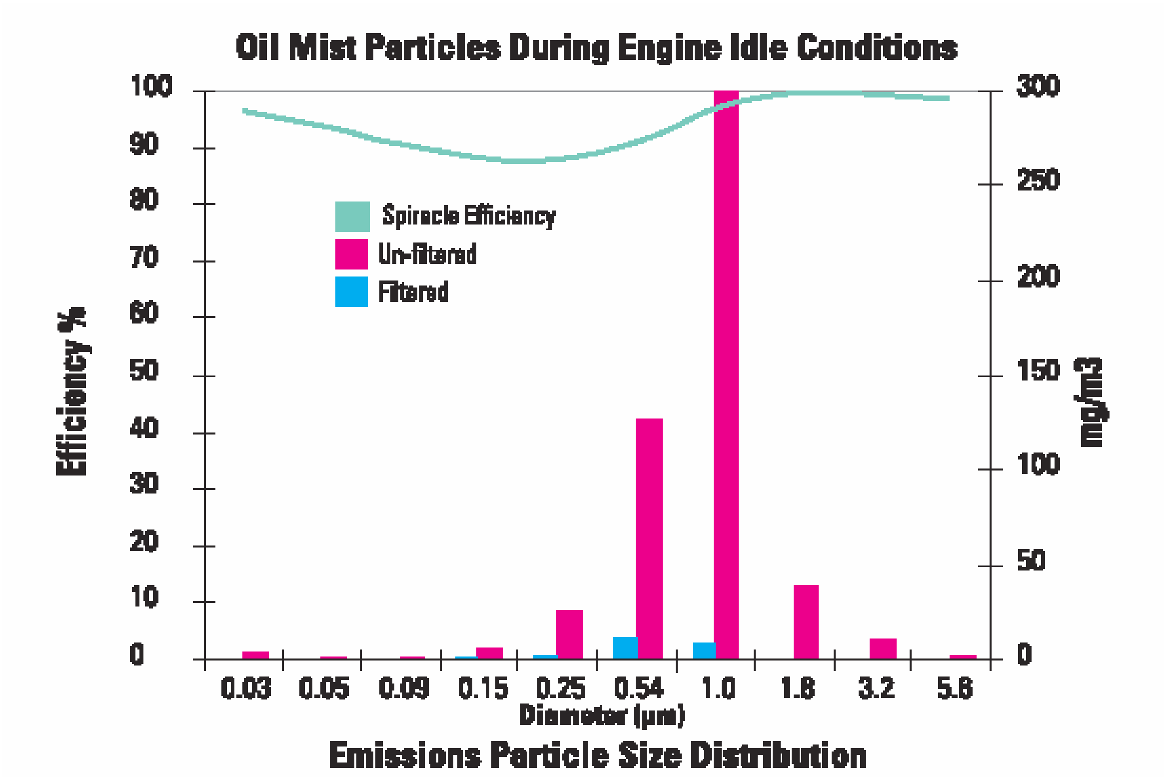

***Figure 27: Size distribution of particles from crankcase blow-by. (Source: Donaldson.)*[65]**

Bus Equipped with Diesel Particulate Filter and ULSD.
In tests of buses retrofit with the DPF-ULSD combination we found that $PM_{2.5}$ remained high. Maximum raw $PM_{2.5}$ levels ranged from 189 to 564 ug/m^3 in the middle of the bus, with peak raw front of the bus levels over 900 ug/m^3. During bus stops we observed that when wind from the front of the bus caused smoke from the road draft tube to blow toward the bus door, significant peaks in $PM_{2.5}$ were observed (Figure 28). [66] This relationship explains why cabin $PM_{2.5}$ levels were not mitigated by the DPF installed on the tailpipe.

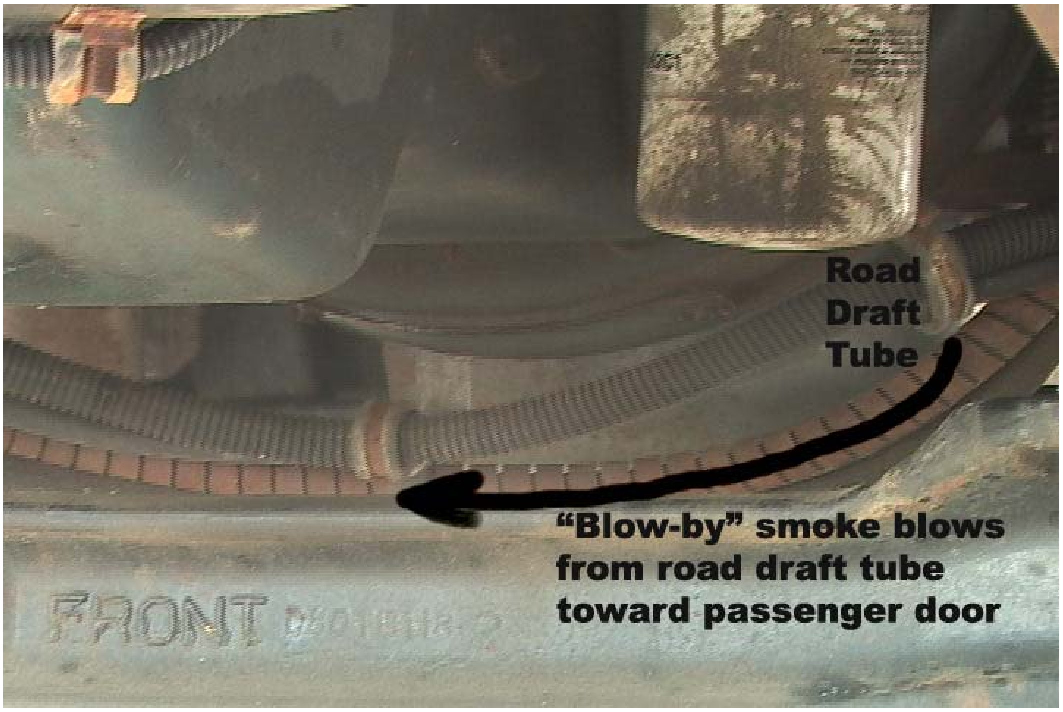

Figure 28: Single frame from video from under front end of bus showing diffused smoke emitted by the engine crankcase road draft tube. When wind blew from the driver's side of the bus toward the open cabin door, a plume of "blow-by" smoke entered into the cabin, dramatically increasing particulate matter levels inside the bus.

Crankcase Emissions Controls Experiments

We explored options for reducing or eliminating the particulate matter blow-by emissions from the crankcase road draft tube in order to confirm that the $PM_{2.5}$ emissions recorded inside the cabin were indeed from the engine rather than the tailpipe. Three modifications were tested. First, in Atlanta, we used simple plastic tubing to redirect the smoke toward the back of the bus (Figure 29a). Indeed, this strategy resulted in some reduction in $PM_{2.5}$, but was still highly dependant upon the wind direction and the ability of the emissions plume from the tube to impinge upon the cabin door (Table 7). Next, in Ann Arbor, we tested the Fleetguard Enviroguard, a filter device directly attached to the road draft tube (Figure 29b). The Enviroguard is a filtration device designed to reduce oil droplets and related oil spillage from the crankcase onto the road—rather than to eliminate emissions. In our tests of the device we found that the crankcase still emitted high levels of $PM_{2.5}$ thereby polluting the cabin because the post-filtration emissions were still released under the hood of the bus in close proximity to the cabin door despite the device (Table 7.)

The third device we tested was a closed crankcase filtration device, the Donaldson Spiracle. Testing of Ann Arbor Bus 56 retrofitted with a Donaldson Spiracle (Figures 31 and 32) showed successful reduction of cabin $PM_{2.5}$ with no influx of $PM_{2.5}$ mass into the bus at bus stops regardless of the tailpipe configuration (DPF, DOC or conventional bus with no tailpipe retrofits.) This observation demonstrates that the $PM_{2.5}$ mass in the bus cabin is coming entirely from the engine crankcase. As a result the Spiracle alone eliminated $PM_{2.5}$ *mass* self-pollution in the cabin (Note ultrafine PM, black carbon and PAH were not reduced by the Spiracle). It is unclear why $PM_{2.5}$ mass from the tailpipe does not reach the cabin but may suggest that it is not effectively transported between the tailpipe and the cabin. We do not presently offer an explanation for this observation, but speculate that it may be a result of dilution. Further investigation of this phenomenon with more sophisticated equipment would be useful.

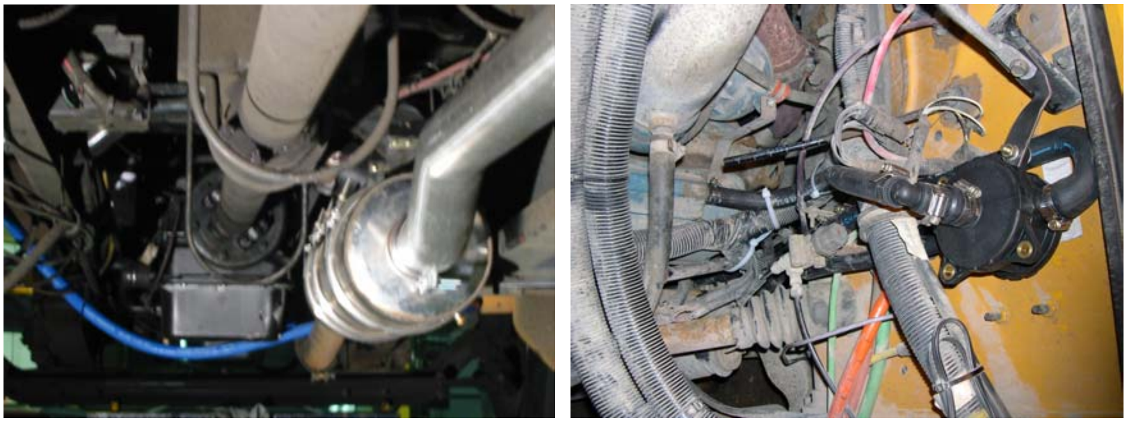

Figure 29: Experiments to mitigate smoke from road draft tube. (a) Left: Simple blue plastic extension of road draft tube (Atlanta). (b) Right: Enviroguard "blow-by" filter (black) attached to road draft tube (Ann Arbor.)

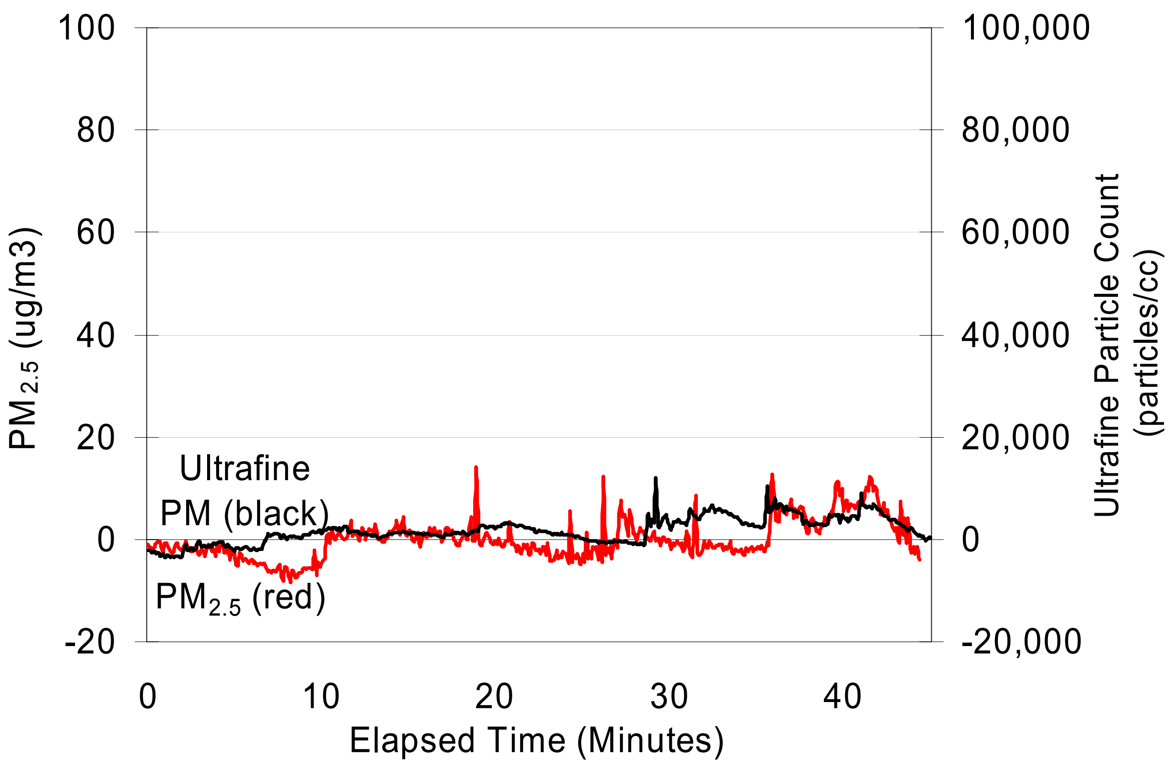

Figure 30: Fine particulate matter ($PM_{2.5}$) levels on retrofit DeKalb GA bus #1450 following retrofit and addition of a simple extension of the road draft tube). In this run, the extension tube effectively redirected the crankcase emissions so they did not enter the bus. However two other runs with the extension tube exhibited significant $PM_{2.5}$ influx (Table 7). Ambient concentrations have been subtracted.

Figure 31: Donaldson's closed crankcase filtration device, the Spiracle was installed in combination with a conventional bus, a DPF-ULSD retrofit bus, and a bus with a DOC. The Spiracle eliminated the $PM_{2.5}$ self-pollution in the cabin of the bus.

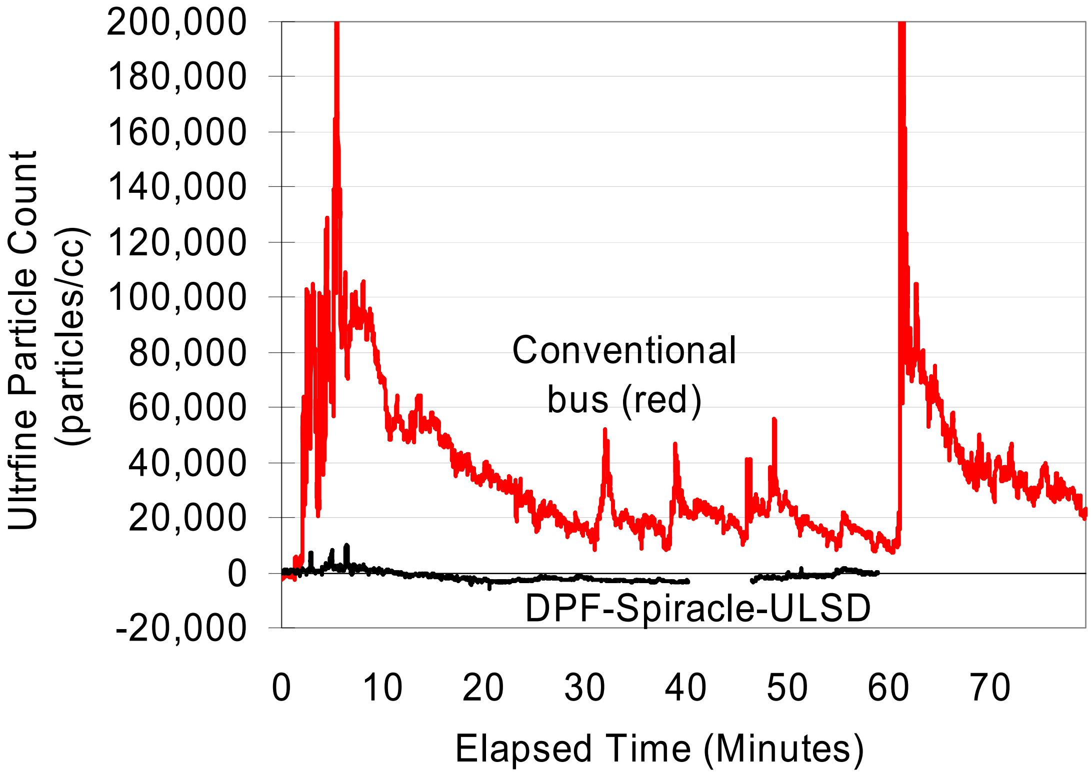

Figure 32: Comparison of ultrafine particle levels on a conventional bus and bus equipped with the DPF –ULSD – Spiracle combination. Ambient concentrations have been subtracted which may result in a false negative net ultrafine count. Ambient concentration has been subtracted.

Bus equipped with DPF-ULSD-Spiracle
The bus equipped with the DPF, Spiracle and ULSD proved to be the most effective retrofit solution for reducing all measured particulate matter species. It was the only combination of devices that completely elimnated particulate matter self-pollution. During bus runs with this combination, levels of $PM_{2.5}$, ultrafine particles, black carbon and particle-bound PAH remained at ambient outdoor levels.

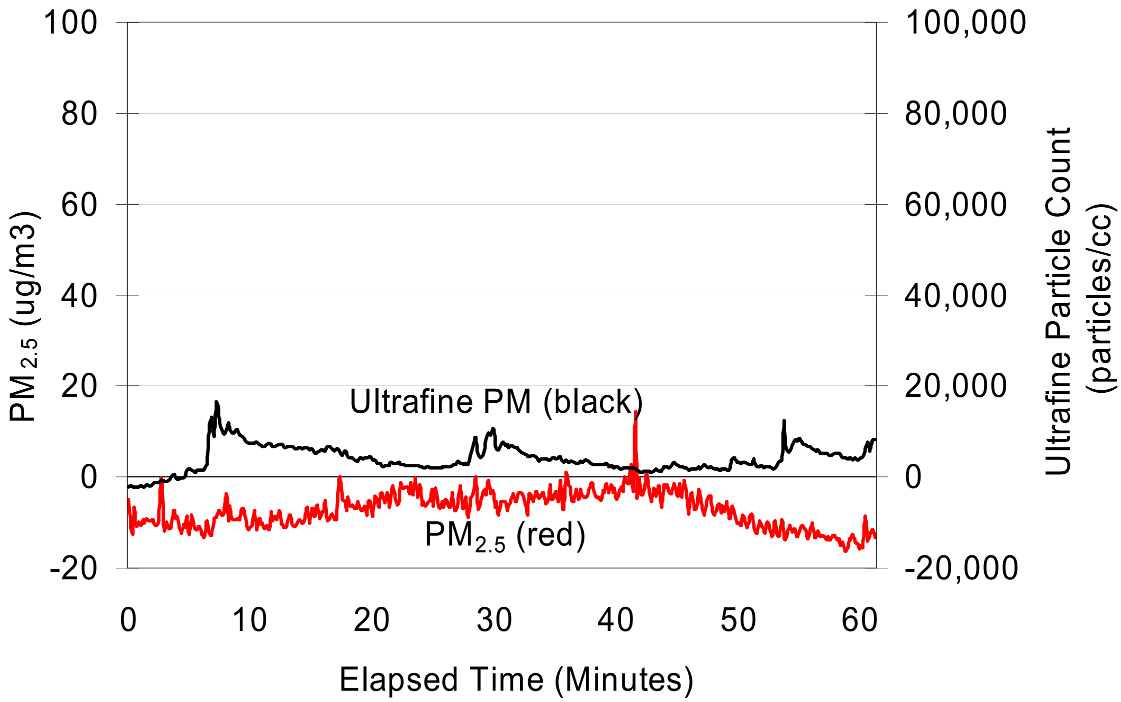

Figure 33: Net ultrafine particles and $PM_{2.5}$ concentrations on bus equipped with a DPF-ULSD-Spiracle. The DPF-ULSD-Spiracle combination eliminated all monitored particulate matter self pollution ($PM_{2.5}$, ultrafine particles, black carbon and particle-bound PAH.) on the bus. Ambient concentrations have been subtracted.

Bus equipped with DOC and Conventional Fuel
Testing directly behind the tailpipe of the DOC-equipped bus suggested that $PM_{2.5}$ levels in a range comparable to the conventional bus (Table 6, Figure 34). However, the lack of $PM_{2.5}$ benefit in the cabin, similar to the DPF-ULSD combination, once again, is not due to the performance of the DOC; cabin fine particulate matter mass ($PM_{2.5}$) is due to the engine crankcase source rather than the tailpipe.

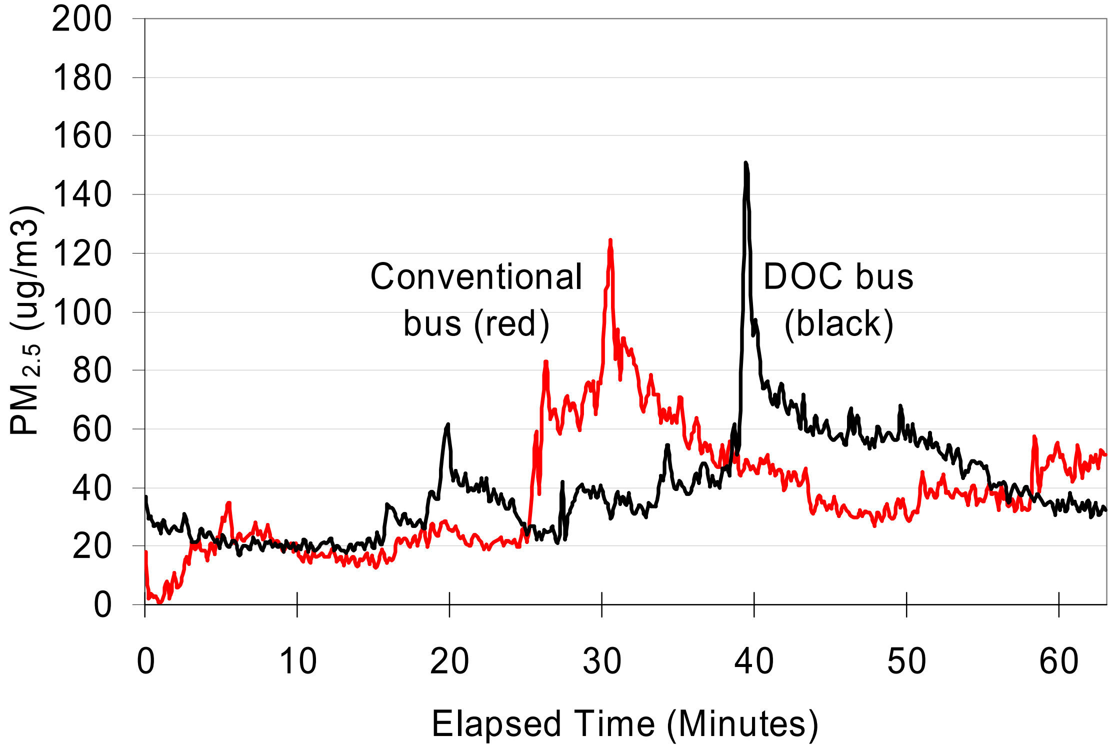

Figure 34: $PM_{2.5}$ on bus equipped with a DOC compared to conventional bus in Ann Arbor, MI. Cabin $PM_{2.5}$ remains elevated with DOC. Ambient concentration has been subtracted.

Bus equipped with DOC and Spiracle

When the Spiracle was added to Ann Arbor Bus # 56 already equipped with a DOC, the cabin $PM_{2.5}$ concentration dropped to near ambient levels, consistent with our observation that cabin $PM_{2.5}$ is dominated by engine rather than tailpipe emissions. This supports the conclusion that the Spiracle is an effective device for reducing cabin $PM_{2.5}$ in combination with the DOC, the DPF, or without tailpipe emissions controls.

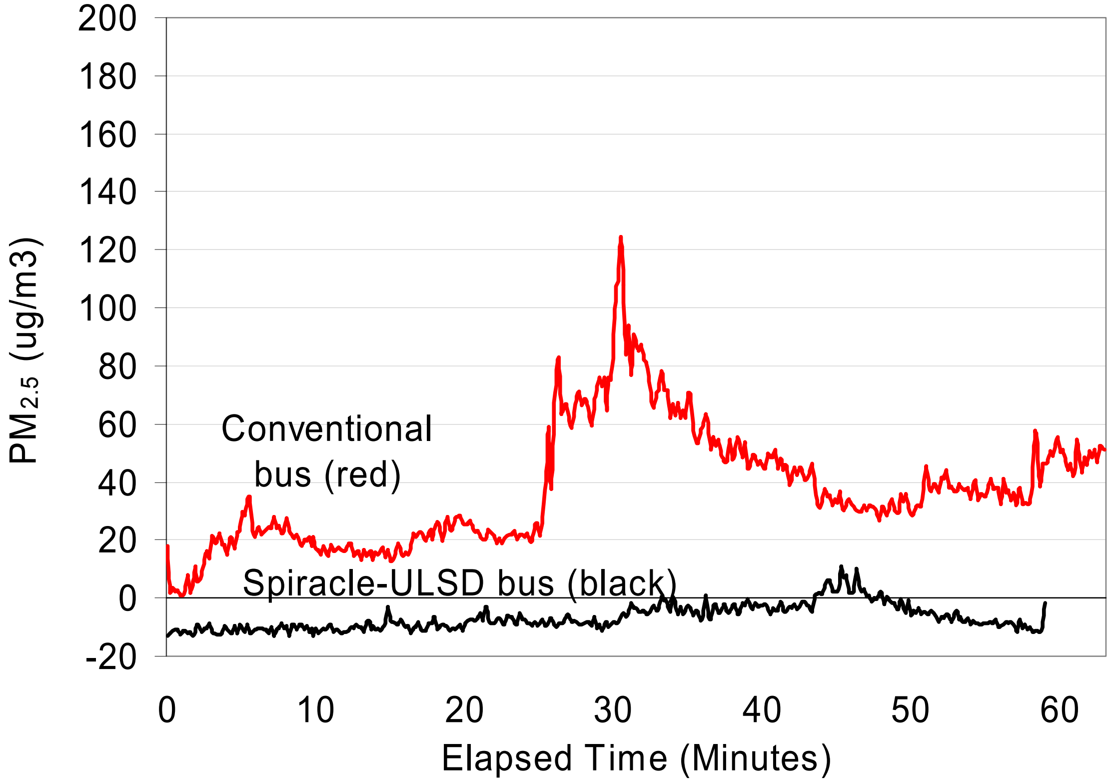

Figure 35: Comparison of $PM_{2.5}$ levels in conventional bus vs Spiracle-retrofit bus. Ambient concentration has been subtracted. (Ann Arbor, MI.)

Compressed Natural Gas Bus

As described above, the Ann Arbor compressed natural gas bus #24 is a transit style bus with the engine and tailpipe in the rear. Testing directly behind the tailpipe demonstrated low $PM_{2.5}$ emissions. Testing along the bus route indicated no intrusion of $PM_{2.5}$ into the cabin from the bus. The transit style CNG bus did not have a crankcase vent and therefore lacks the problems identified in the diesel buses tested.

BLACK CARBON and PAH

Black carbon and particle-bound PAH closely tracked changes in ultrafine particles based on tests conducted in Ann Arbor. When ultrafine PM increased, black carbon and PAH did as well. As indicated in Table 8, black carbon levels were low relative to total $PM_{2.5}$ during all bus runs –generally ranging from a few ug/m^3 to 8-9 ug/m^3. This relationship suggests that elemental (black) carbon (EC) may be a small fraction of the overall $PM_{2.5}$ mass on the school buses. Consequently, a substantial portion of the PM on school buses may be organic carbon (OC). This hypothesis is consistent with our observation suggesting that most of the $PM_{2.5}$ mass in the cabin comes from the engine crankcase. Crankcase emissions (otherwise known as "blow-by") emissions leak by the piston rings and combine with volatilized engine oil which is then vented as smoke from the "road draft tube" under the hood of the bus. Furthermore, laboratory research suggests that PM emissions from heavy duty diesel engines at idle are dominated by OC and conversely by

EC under a load.[67] Thus, when a bus comes to a full stop and the door is opened, any tailpipe emissions entering the cabin may be dominated by OC while the engine is idling.

Results summarized below in tables 8 and 9 and Figures 36-41 suggest that black carbon and particulate polycyclic aromatic hydrocarbons tracked each other closely. The bus equipped with the Spiracle showed no apparent benefit for black carbon and PAH, similar to the ultrafine PM. However, the DPF and ULSD combination reduced both black carbon and PAH to near background concentrations.

BLACK CARBON (ug/m^3)	Max	Mean
ANN ARBOR		
Conventional Bus 56 Run 1	11.5	2.0
Conventional Bus 56 Run 2	3.7	0.4
ULSD Bus 56 Run 1	5.5	2.5
CNG Bus 24 Run 1	1.8	0.4
CNG Bus 24 Run 2	1.3	0.3
DOC Bus 56 Run 1	8.1	2.8
DOC Bus 56 Run 2	9.0	3.1
DOC-Spiracle Bus 56 Run 1	9.1	2.8
DOC-Spiracle Bus 56 Run 2	5.2	2.6
Spiracle-ULSD Bus 56 Run 1	7.0	2.6
DPF-ULSD Bus 56 Run 1	2.9	0.7
DPF-ULSD-Spiracle Bus 56 Run 1	1.6	1.1
DPF-ULSD-Spiracle Bus 56 Run 2	1.1	0.7
DPF-ULSD-Enviroguard Bus 56 Run 1	7.4	0.4
CHICAGO		
Conventional Bus 517 Run 1	1.9	0.9
Conventional Bus 517 Run 2	2.2	0.9
Conventional Bus 662 Run 1	2.8	1.8
Conventional Bus 662 Run 2	2.3	1.5
DPF-ULSD Bus 128 Run 1	4.0	1.3
DPF-ULSD Bus 128 Run 2	1.7	1.2
ATLANTA		
Conventional Bus #1450 Run 1	2.8	1.5
Conventional Bus #1450 Run 2	8.1	2.6
Conventional Bus #1481	0.0	0.0
Retrofit Bus #1450 Run 1	1.6	0.8
Retrofit Bus #1450 Run 2	2.2	1.0
Retrofit Bus #1450 Run 3	1.0	0.5

Table 8: Data Summary Table: Black Carbon

PPAH (ng/m3)	Ambient	Max	Mean
ULSD Bus 56 Run 2	5	62	25
DOC Bus 56 Run 1	8	158	41
DOC Bus 56 Run 2	15	115	37
DOC-Spiracle Bus 56 Run 1	12	199	56
DOC-Spiracle Bus 56 Run 2	22	93	41
Spiracle Bus 56 Run 1	10	108	34
DPF-ULSD-Spiracle Bus 56 Run 1	4	45	19
DPF-ULSD-Spiracle Bus 56 Run 2	7	40	13

Table 9: PAH Data Summary. Maximum and mean 10.0 second average levels of particulate polycyclic aromatic hydrocarbons (PAH) levels recorded on Ann Arbor school buses during bus routes.

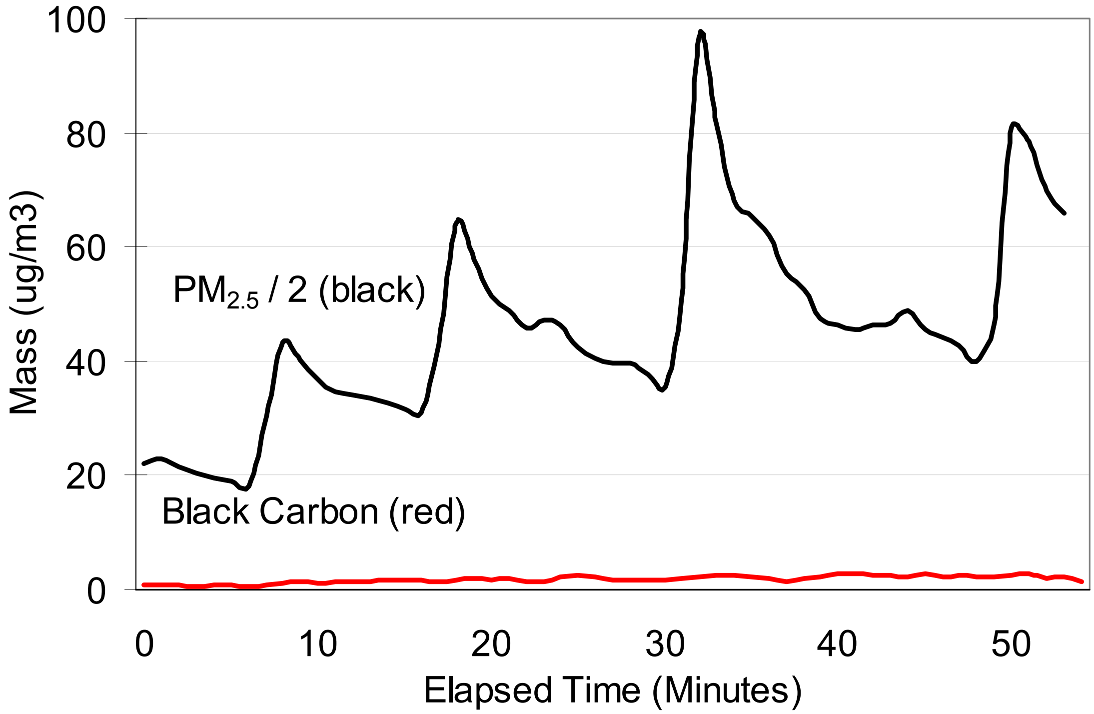

Figure 36: A comparison of $PM_{2.5}$ (divided by 2.0 to account for Dust Trak overestimate of $PM_{2.5}$) suggests that black carbon accounts for a very small fraction of in-cabin $PM_{2.5}$ mass in conventional diesel school buses. Chicago data.

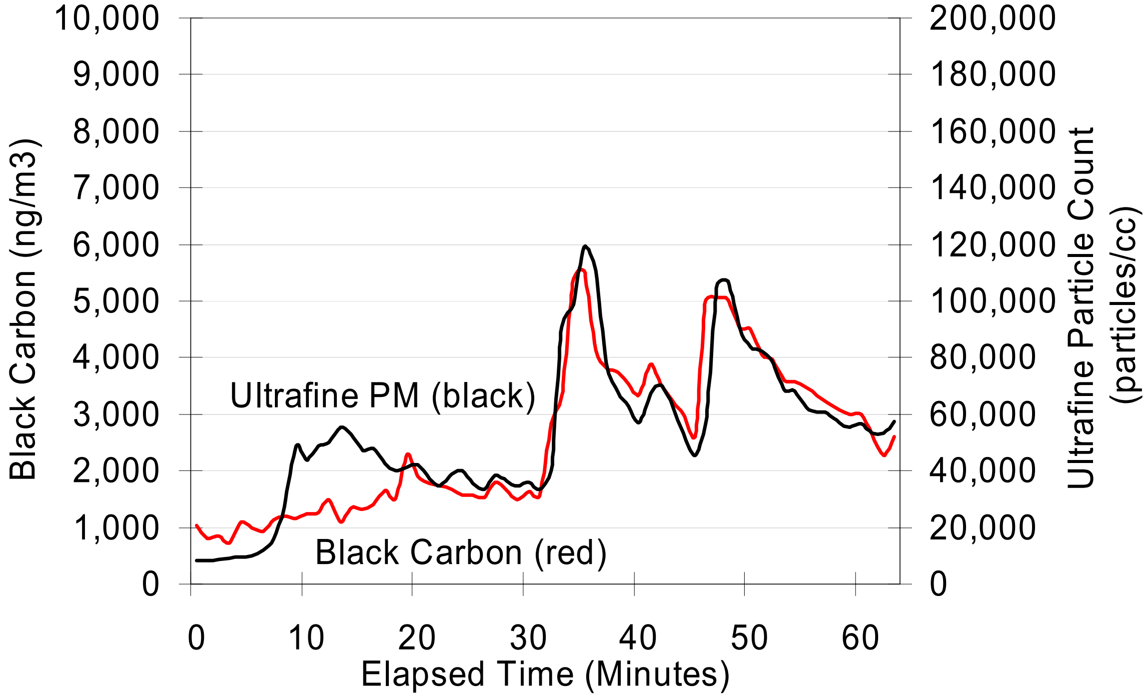

Figure 37: Conventional bus with ULSD fuel showed persistent BC and Ultrafine PM in the bus cabin.

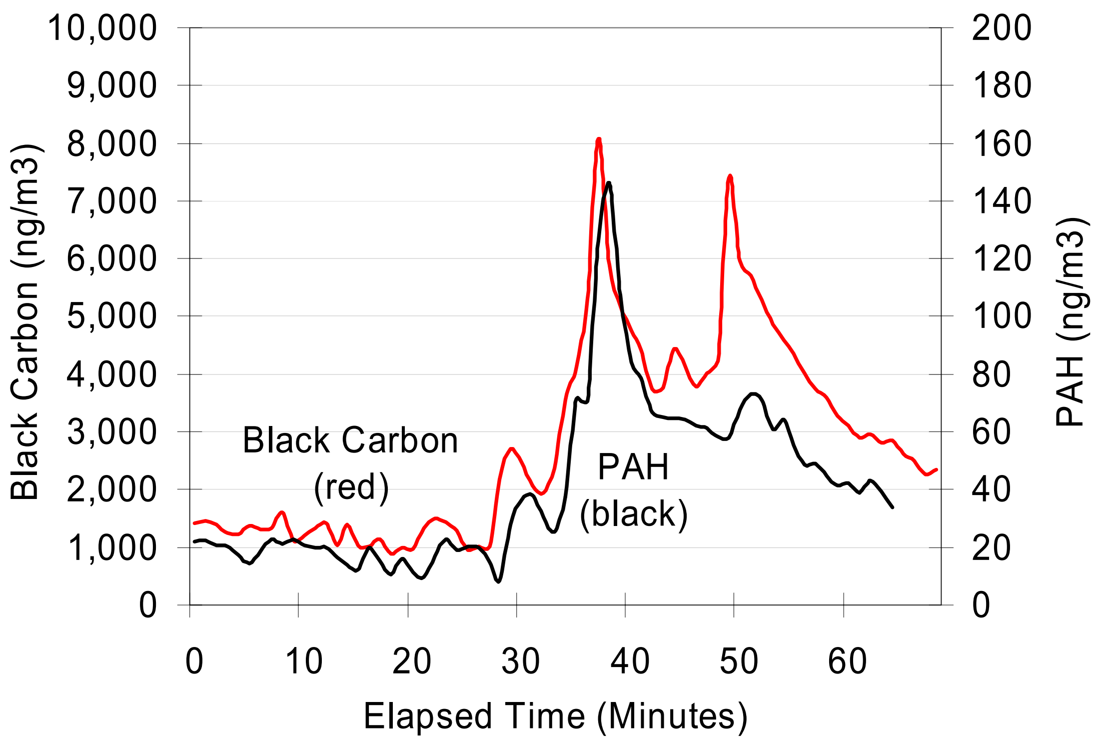

Figure 38: PAH and Black Carbon levels remain elevated on the DOC-equipped bus in Ann Arbor, MI.

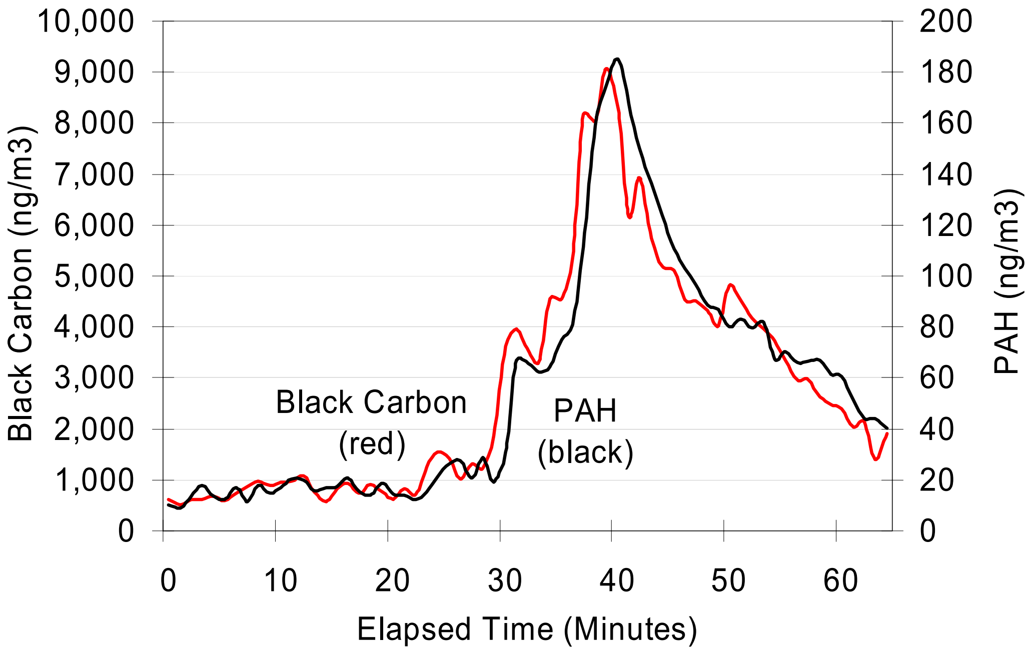

Figure 39: PAH and black carbon levels are unimproved with the DOC-Spiracle combination in Ann Arbor, MI.

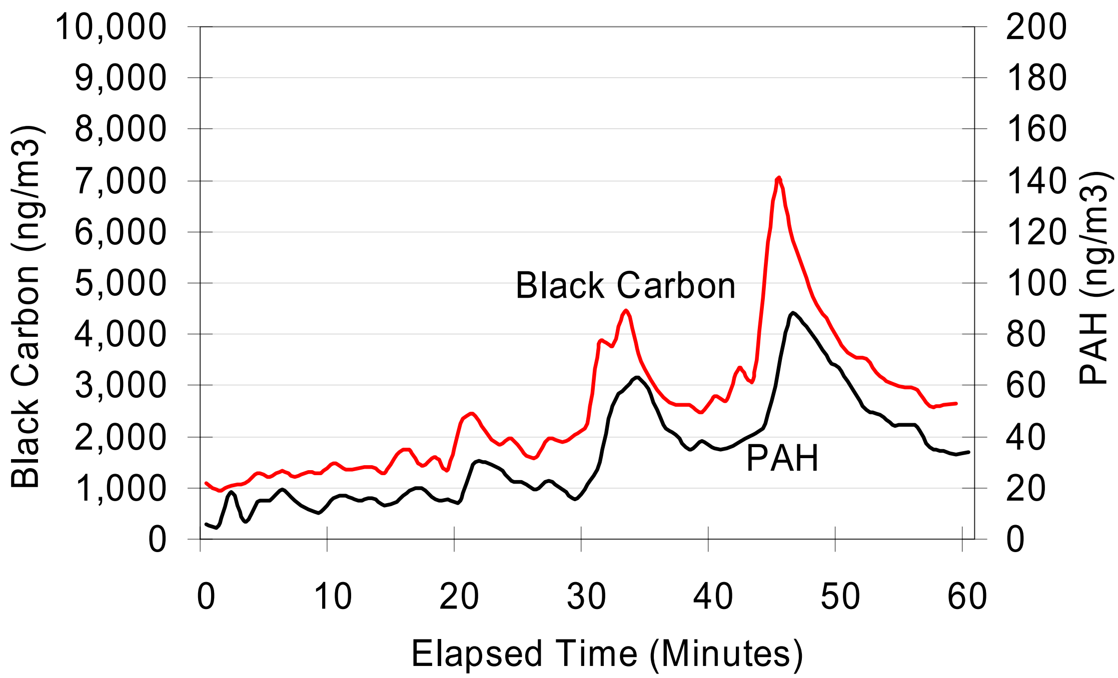

Figure 40: The Spiracle alone showed no apparent benefit in reducing black carbon and PAH levels.

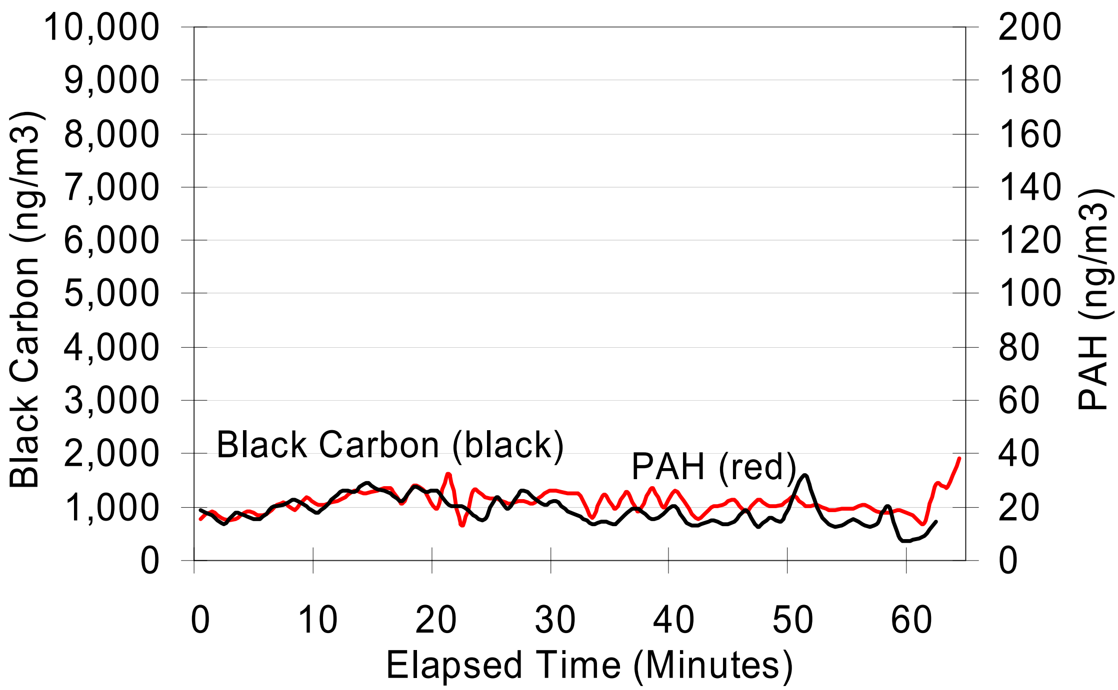

Figure 41: PAH and black carbon self-pollution is reduced to ambient levels by the DPF in the ULSD-DPF-Spiracle combination. (Ann Arbor data.)

IDLING AND QUEUING TESTS

IDLING: Fleet operators are steadily becoming more aware of the benefits of anti-idling policies—it saves fuel and reduced exposure to diesel fumes. As an integral part of this study we separately examined the impacts of idling on cabin air quality and the attendant benefits of emissions controls. In addition, as a part of our bus route tests we idled each bus for 10 minutes prior to leaving (5 minutes with door open, and 5 minutes with doors closed.) Buses were parked away from other diesel sources, and fully ventilated to ambient conditions prior to testing. In the separate 20-minute idle tests, doors were closed, the bus started and idled for 10 minutes with the door open and then 10 minutes with the door closed.

For buses that had tight window and door seals, we found that very little particulate matter exhaust penetrated into the vehicle. However, once doors were opened, particulate matter exhaust levels rose rapidly and steadily (Figure 44.) The magnitude of the effect was heavily dependent upon wind direction. In general, conventional (non-retrofit) buses parked into the wind, saw increases in $PM_{2.5}$ (from the engine crankcase), while buses parked in a tailwind saw increases in ultrafine PM, black carbon (from the tailpipe.) Limited evidence also suggested that PAH rose with wind from the rear of the bus.

For comparison, we idle-tested the same buses retrofitted with DPFs and ultralow sulfur diesel fuel in all three cities. In these tests, the ultrafine PM levels remained low at ambient levels—there was no impact from the tailpipe (Figure 45) compared to the conventional bus. However $PM_{2.5}$ rose substantially–under headwind conditions--due to the strong influence of the crankcase ventilation. With the DPF-ULSD-Spiracle combination, cabin levels remained entirely at ambient (Figure 46.)

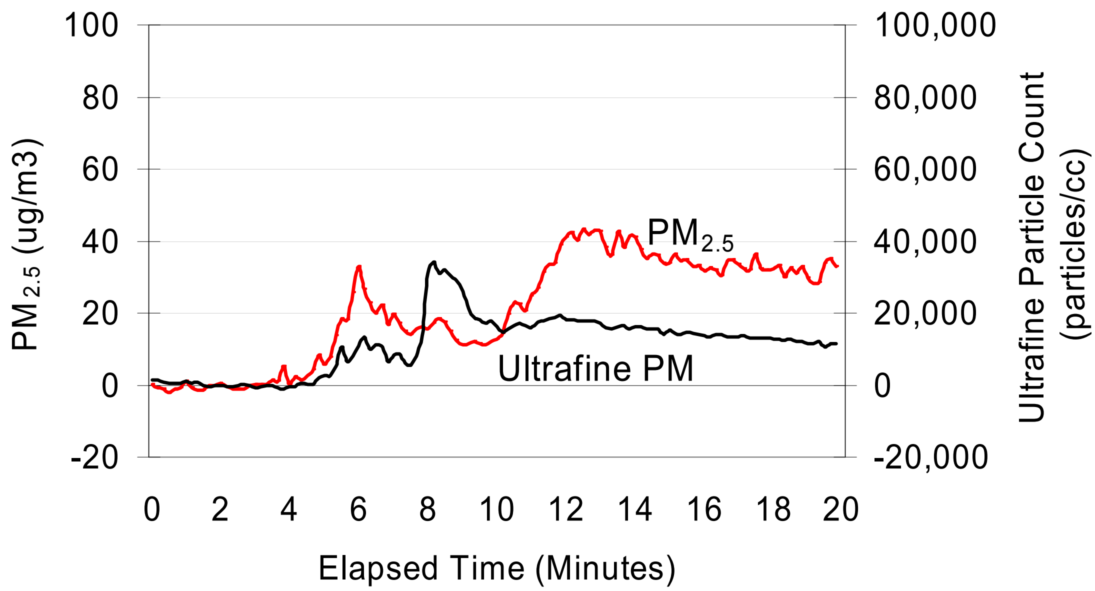

Figure 42: Idle test of DOC-equipped bus. Ambient concentrations have been subtracted. (Ann Arbor data.)

QUEUING: In a set of separate tests, buses were also idled in a 3-bus queue, with monitors located in the middle bus of the three. However, we did not have access to enough retrofit buses to test a retrofit queue. Therefore we only performed tests on conventional buses. Similar to the idle testing, doors were closed for a period (typically 10 minutes) and then opened (Figure 44). When bus doors were closed and windows tight, very little change was observed in cabin air. But within seconds of the door opening, all particulate matter measurements rose dramatically. For example, in Figure 45, $PM_{2.5}$ levels exceeded 200 ug/m^3 and at the same time ultrafine PM levels exceeded the limits of detection on the instrument. Black carbon levels hit 65 micrograms per cubic meter of air—levels equivalent to the daily $PM_{2.5}$ standard, and some of the highest levels we recorded in all of the three cities.

We conclude from this series of idle and queuing tests that the both tailpipe and crankcase emissions contribute to poor air quality on idling buses. While we do not have data for queued retrofit buses, idle tests suggest that DPF-ULSD-Spiracle combination would virtually eliminate particulate matter pollution in school bus cabins. Moreover, these results demonstrate that management of idling as well as closing doors and windows prior to start-up is extremely important in protecting cabin air in conventional buses and provides a cost-effective way to reduce particulate matter exposures while at the same time saving fuel which has become a major cost to fleets with fuel hovering around $2.00 per gallon.

Figure 43: Bus queue in Chicago. Here, three transit-style buses were lined up in a common safety protocol allowing no walking space between buses (so that children cannot walk between buses.) This puts the tailpipe of one bus near the door of the one behind it and accounts for the dramatic increases in particulate matter levels when the doors are open and the buses at idle.

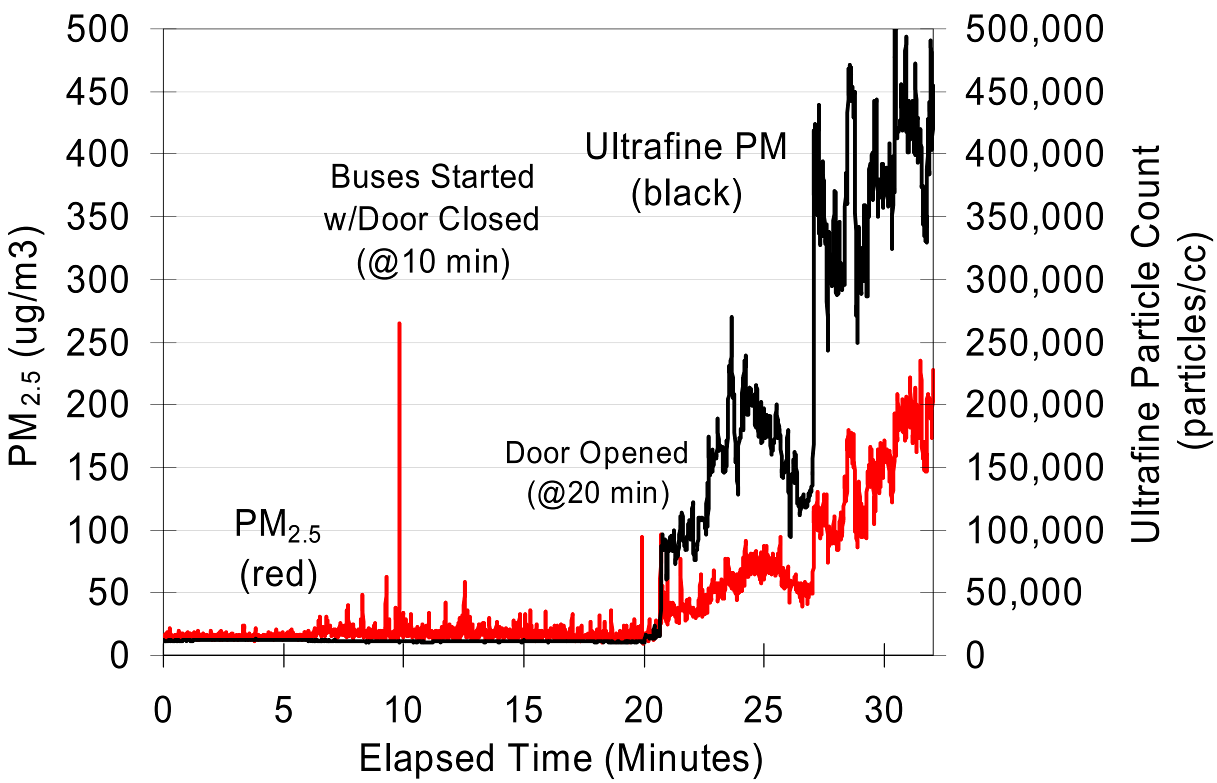

Figure 44: Results of Ann Arbor bus queue. Concentrations of both $PM_{2.5}$ and ultrafine $PM_{2.5}$ remain near ambient with doors initially closed. When doors were opened levels rise very rapidly to levels three times the federal daily $PM_{2.5}$ standard and 15 times the federal annual standard in ten minutes. Ultrafine PM levels exceeded 500,000 particles/cc limit of detection.

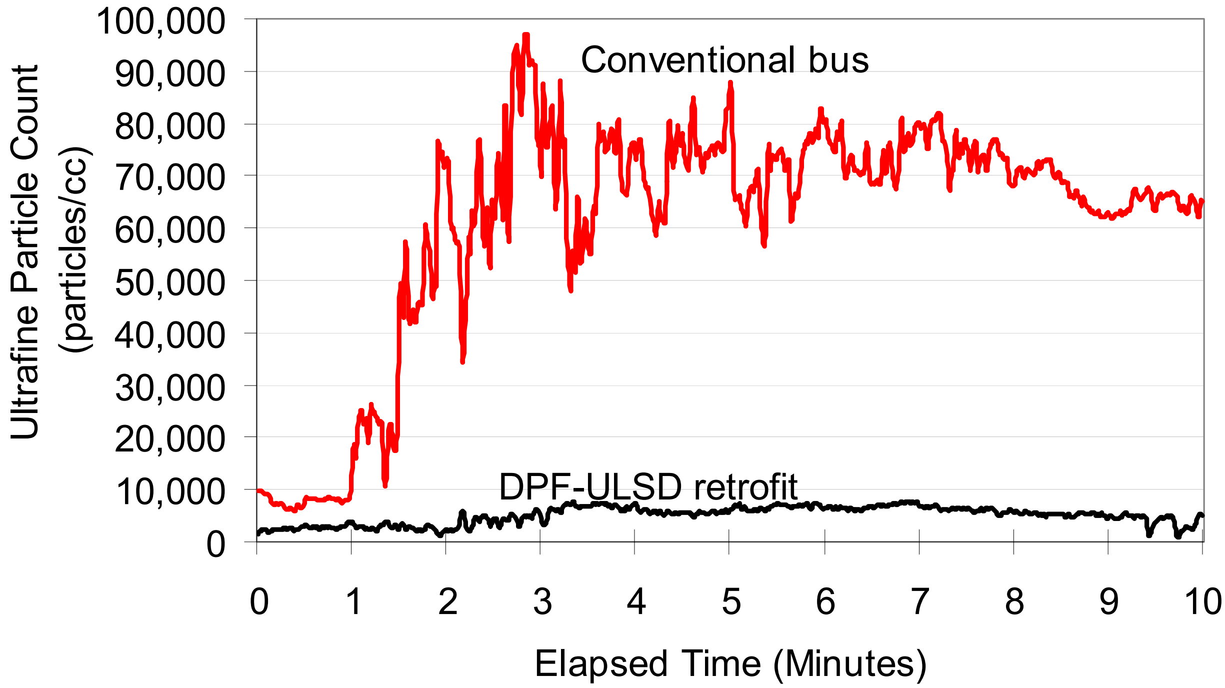

Figure 45: In this 15 minute idle test of a Chicago bus, ultrafine particle levels rose rapidly. In contrast a Naperville, IL bus (ULSD-DPF) remained at ambient conditions. Ambient ultrafine concentrations have been subtracted from both curves.

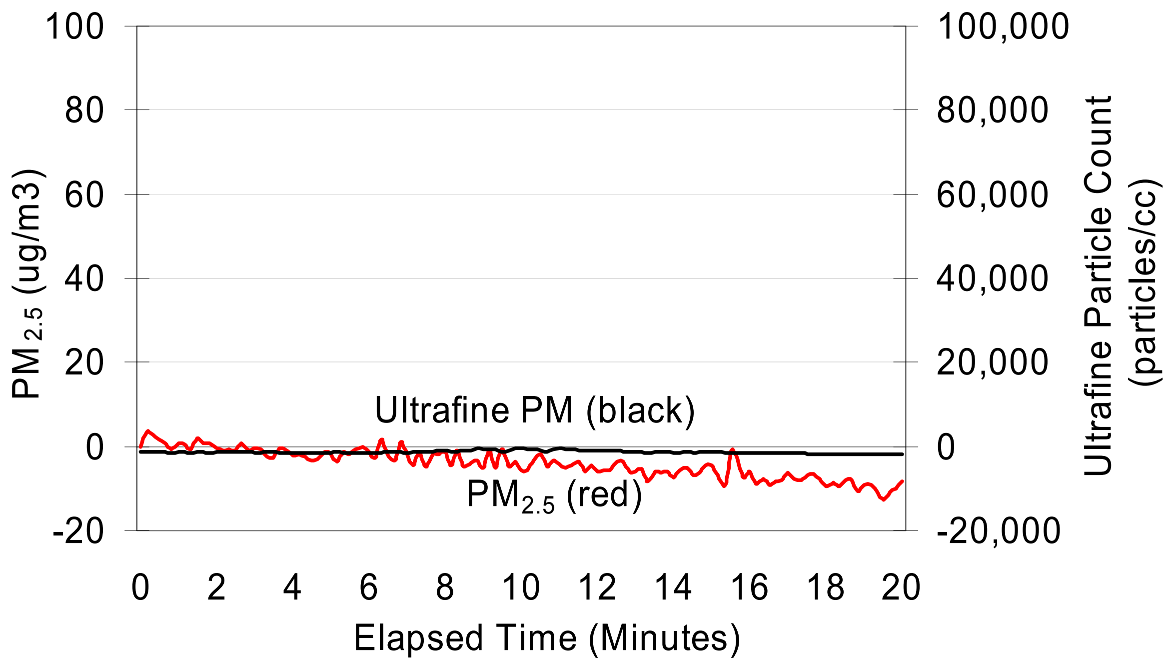

Figure 46: Idle test of bus retrofit with DPF-ULSD-Spiracle combination showing elimination of self-pollution. Ambient concentrations have been subtracted.

IMPACT OF DIESEL BUSES ON PARTICULATE MATTER CONDITIONS IN A SCHOOL YARD DURING MORNING SCHOOL BUS DROP OFF

While this project largely focused on cabin air quality, we undertook a preliminary assessment of the potential impact of diesel school buses in and around schools and neighborhood bus stops. First we set up air quality monitoring outside a Connecticut elementary school where approximately a dozen buses drop off and pick up children. Secondly, we followed up the CT schoolyard testing by testing curbside air quality conditions in simulated school bus drop off and pick up situations in Chicago, Atlanta, and Ann Arbor in order to compare the impacts of conventional versus retrofit school buses.

Levels of particulate matter adjacent to a CT elementary school were measured as approximately a dozen school buses dropped off children between 7:30 and 8:00 AM. A monitoring vehicle equipped with the same instruments utilized in the cabin air quality study was stationed directly across from the school on a narrow residential street in the zone where busses stopped to let the students off. In Figure 52, visible $PM_{2.5}$ peaks occurred as each bus dropped off its students and pulled away from the school. (Note that the levels were initially elevated as our monitoring was not fully set up when the first buses arrived.) Particulate matter levels tapered off as the buses finish delivering children to the school. Note at 08:01 AM the final bus left the school leaving behind a significant burst of diesel exhaust.

As a follow up, we monitored the particulate matter condition in a school bus fleet parking lot in Atlanta located near a residential neighborhood as the buses warmed up in the morning. With tens of buses idling, the air quality rapidly deteriorated as shown in Figure 47.

Simulated drop off tests showed high levels of $PM_{2.5}$ and ultrafine particles as the bus arrived and pulled away from the curb. Furthermore, we followed a conventional bus and a DPF-ULSD bus to observe the impacts in the vehicle behind (which in many cases may be another school bus.) Pollutants behind the conventional bus rapidly reached high levels suggesting that when queued buses leave a school they may strongly influence the air quality in the bus behind them (Figure 48).

Simulated drop-off tests suggest that the ULSD-DPF combination (with or without the Spiracle) would eliminate measurable ultrafine particle and $PM_{2.5}$ pollution at drop-off time. Furthermore this retrofit combination would also protect cabin air quality when buses are following each other upon leaving a school or bus lot (Figures 49, 52, 53.) For illustrative purposes, videos with a graphic stream of data digitally overlaid on the video image were created for the simulated drop-off scenarios in Chicago, Atlanta and Ann Arbor on both conventional and retrofit buses and can be viewed at: http://www.catf.us/diesel/videos.php.

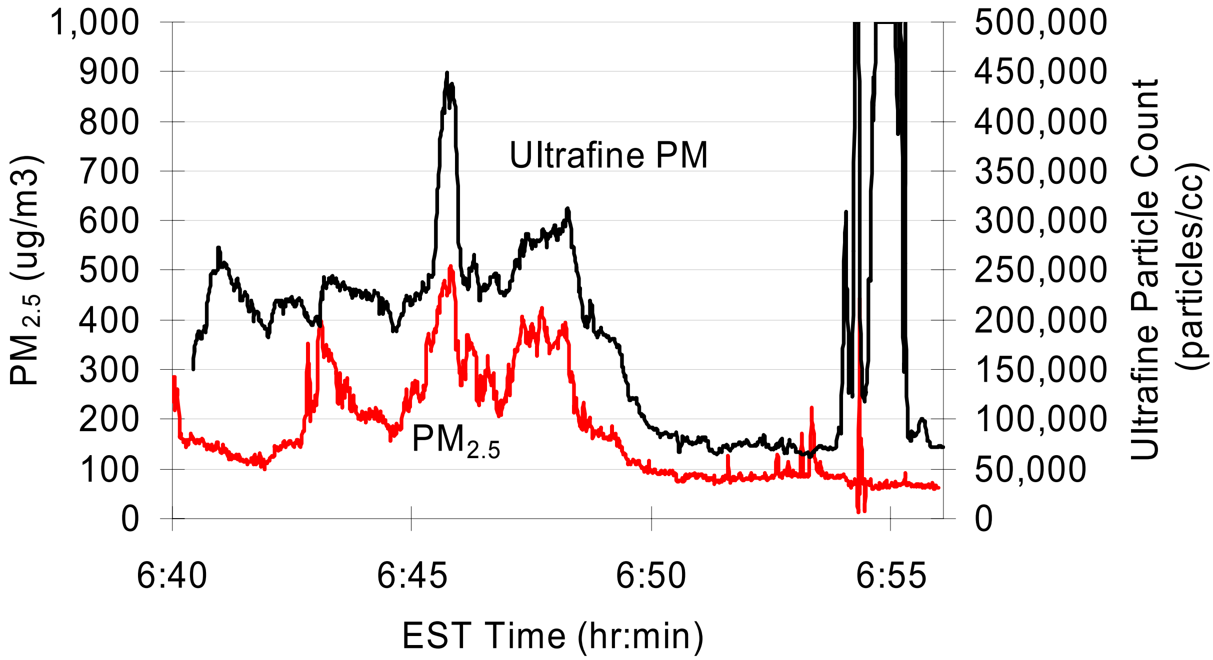

Figure 47: Particulate matter levels rise to high levels in fleet bus lot in Atlanta as buses warm up prior to morning bus routes. The idling emissions strongly affected the cabin air of all buses in lot and the smoke diffused into the adjacent residential area.

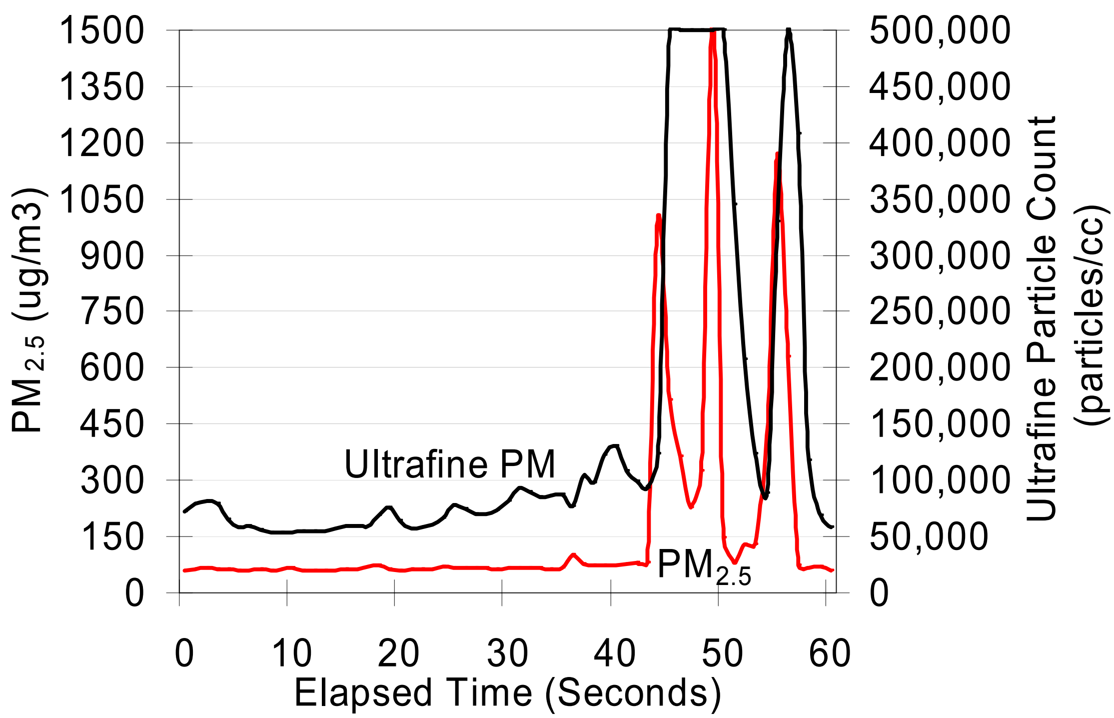

Figure 48: Simulation of school bus drop-off scenario on conventional bus shows large spikes in PM2.5 as bus pulls up and then pulls away from the curb.

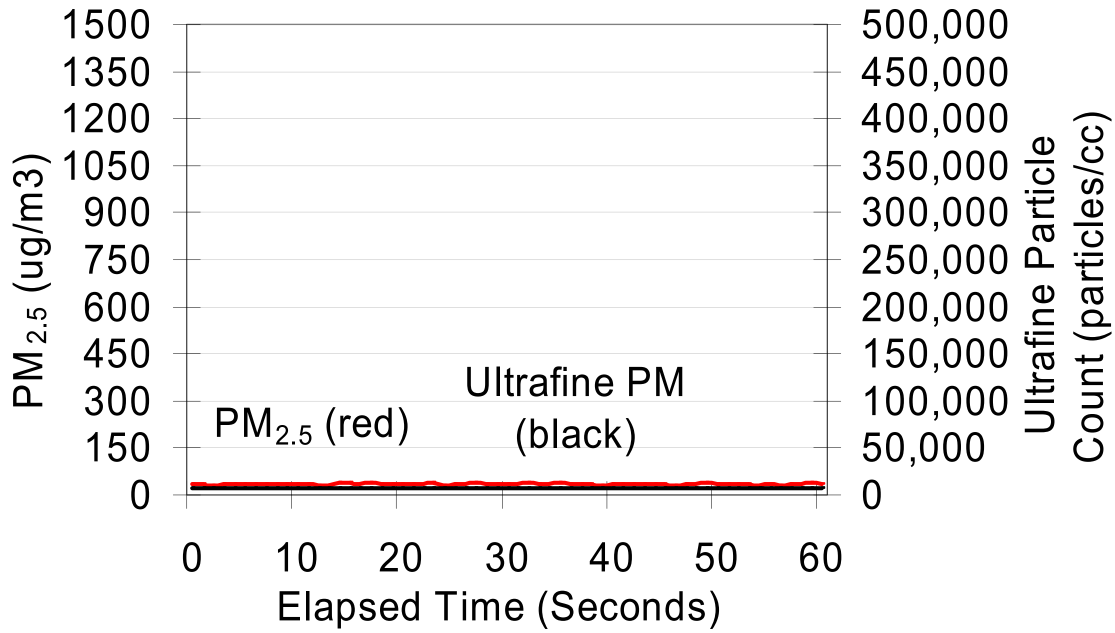

Figure 49: Simulation of drop-off scenario on retrofit bus demonstrates elimination of curbside pollution from the bus. DPF-ULSD-Spiracle retrofit.

Figure 50: Monitoring set up outside elementary school in CT during morning school bus drop off.

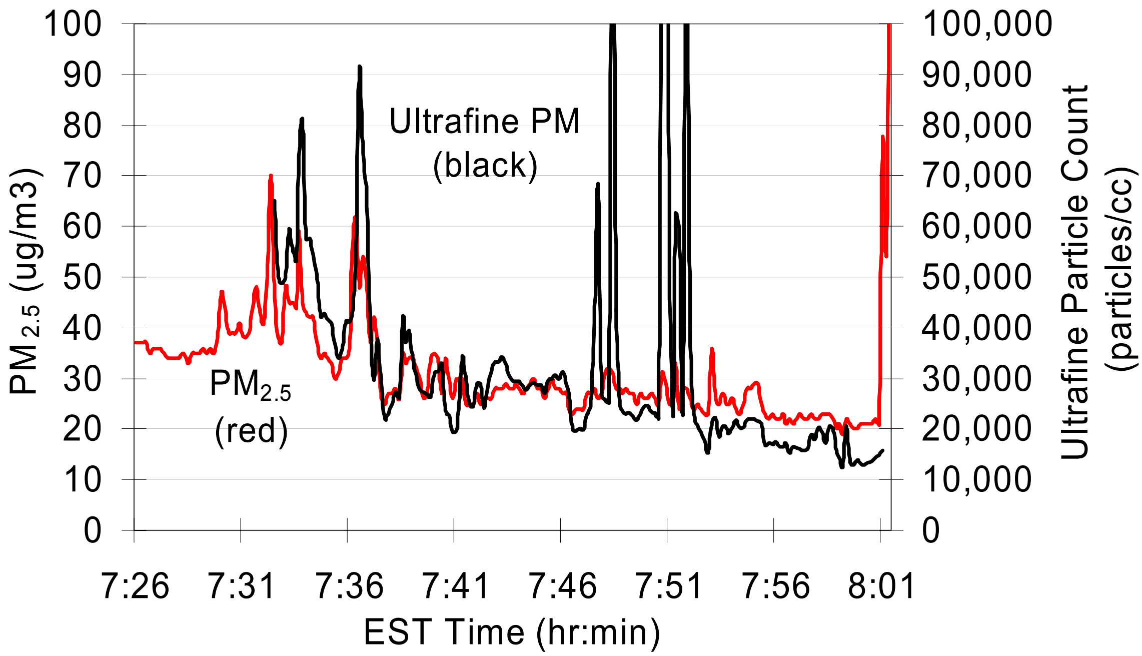

Figure 51: $PM_{2.5}$ and ultrafine PM levels during morning school bus drop off at CT elementary school. Spikes in particulate matter occurred when buses left the school after dropping off children, leaving a cloud of diesel smoke in their wake.

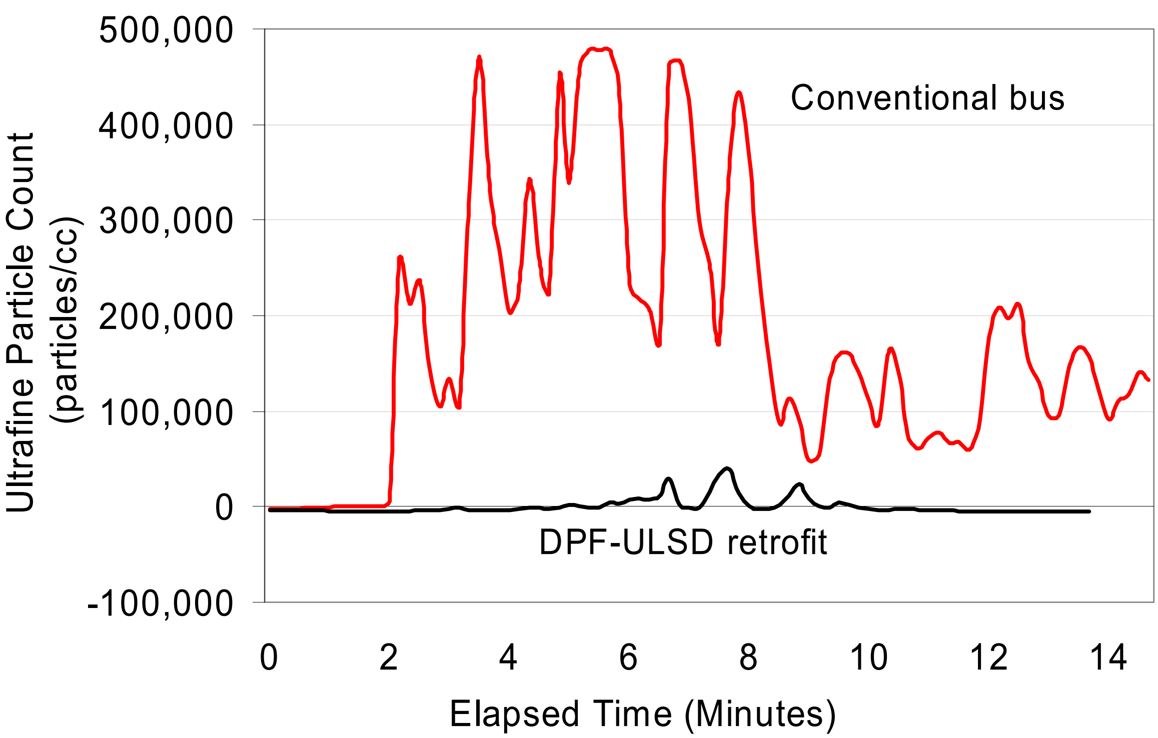

Figure 52: Ultrafine particulate matter behind the school bus are strongly impacted by emissions from an unmodified conventional bus. In contrast, the bus retrofit with the DPF-ULSD shows little or no impact on the trailing car. This demonstrates the effectiveness of the DPF-ULSD combination in reducing ultrafine particulate matter in

schoolyards and roadways and for queued buses leaving schoolyard and fleet lots. Ambient concentration has been subtracted.

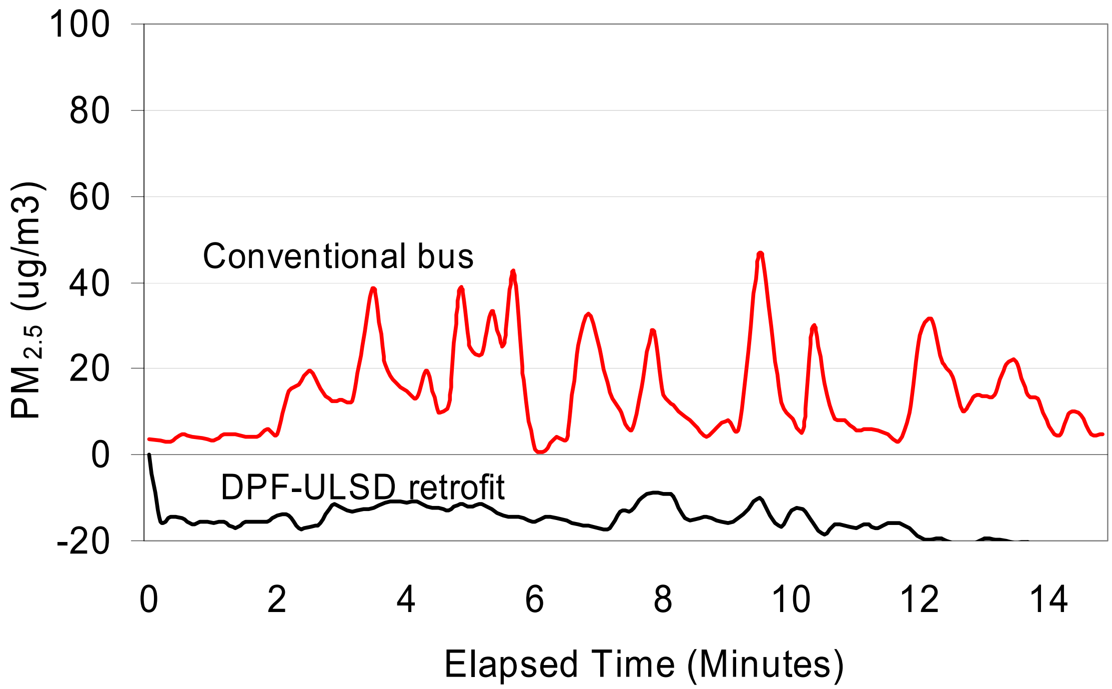

Figure 53: $PM_{2.5}$ levels behind the school bus are strongly impacted by emissions from an unmodified conventional bus. In contrast, the bus retrofit with the DPF-ULSD shows little or no impact on the trailing car. This demonstrates the effectiveness of the DPF-ULSD combination in reducing ultrafine particulate matter in schoolyards and roadways and for queued buses leaving schoolyard and fleet lots. Ambient concentration has been subtracted.

SUMMARY AND DISCUSSION OF RESULTS

General Observations

Tailpipes and crankcase emissions were the dominant sources affecting cabin air quality on school buses tested in this study. Clearly, both emissions sources need to be addressed in order to provide clean air for riders of conventional school buses.

On residential bus routes in suburban Atlanta, urban Chicago and suburban Ann Arbor there were few external diesel sources contributing to particulate matter levels on the bus. Instead build up occurred at bus stops. Emissions were found to typically enter the tested school buses through the front door causing attendant increases in cabin particulate matter levels. Whether particulate matter built up or decayed during a bus route was dictated by: 1) the strength of three potential sources (tailpipe, crankcase of engine, other diesels in roadway), and 2) outdoor wind conditions relative to the bus doorway at bus stops. Wind direction and magnitude relative to the buses front door largely determined the strength of the plume entering the bus and the PM species that affect cabin air.

Our observations demonstrate that tailpipe emissions are responsible for the buildup of ultrafine PM, black carbon and PAH in the bus cabin—when wind is from the rear. The engine crankcase contributes most of the $PM_{2.5}$ mass to the cabin and affects cabin air quality when the wind is from the front. Furthermore we have observed that although school bus tailpipes emit substantial direct $PM_{2.5}$ mass, the particulate matter mass apparently is not transported effectively between the tailpipe and the cabin (unlike ultrafine PM). Our results do not provide adequate information to support an explanation for this observation; an undocumented dilution, deposition, or chemical mechanism may be active between the tailpipe and the doorway.

This study also presents some of the first data showing that a DPF retrofit combined with a closed crankcase filtration device (Spiracle) *effectively eliminates all detectable particulate matter self-pollution in the cabin of school buses--including $PM_{2.5}$, ultrafine particulate matter, black carbon and PAH.* The Spiracle used alone was very effective at lowering $PM_{2.5}$ exposures on the bus, but did not reduce ultrafine PM, black carbon or PAH.

In a test of a diesel oxidation catalyst we found it difficult to ascertain whether a DOC provided any in-cabin benefit. This may be for a variety of reasons including: 1) insensitivity of methodology, 2) confounding by variable wind directions relative to the two emissions sources and the cabin door, 3) potential ineffectiveness of DOC under idle conditions. Relative to the latter point, verification testing suggests an approximate 10-30% benefit from DOCs under loaded conditions. However, it is unclear whether this emissions reduction is maintained under idle conditions at bus stops when the emissions typically enter the bus.[68] Regardless of the reasons, the results of the DOC retrofit stand in stark contrast to the DPF-ULSD results, suggesting that the DOC has, at best, limited usefulness as a device to remedy in-cabin ultrafine particulate matter air quality. 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. The close crankcase filtration device-the Donaldson Spiracle, was comparable in cost and effectively eliminated in-cabin $PM_{2.5}$. Note however, that this is because it is rerouted, not necessarily filtered out.

The compressed natural gas bus demonstrated the second lowest exposures after the bus with the DPF-ULSD-Spiracle retrofit. Mechanically, the CNG bus lacks the crankcase emissions source and thus the $PM_{2.5}$ levels were much lower than for the conventional bus.

In order to investigate relationships between pollutants, we calculated linear regressions between $PM_{2.5}$, ultrafine particles, black carbon and PAH for the conventional bus with ULSD Ann Arbor (Figure 54, Table 10). (The ULSD bus run was utilized in this analysis because it was the only conventional bus test that included a full suite of pollutants—PAH was not measured on any of the conventional bus-conventional fuel runs.) Results of this analysis are consistent with our empirical observations that there is a predictable relationship between ultrafine particulate matter, black carbon and PAH emissions. Conversely, the low Pearson's R^2 between $PM_{2.5}$ and the three other pollutants shows a much lower probability of association.

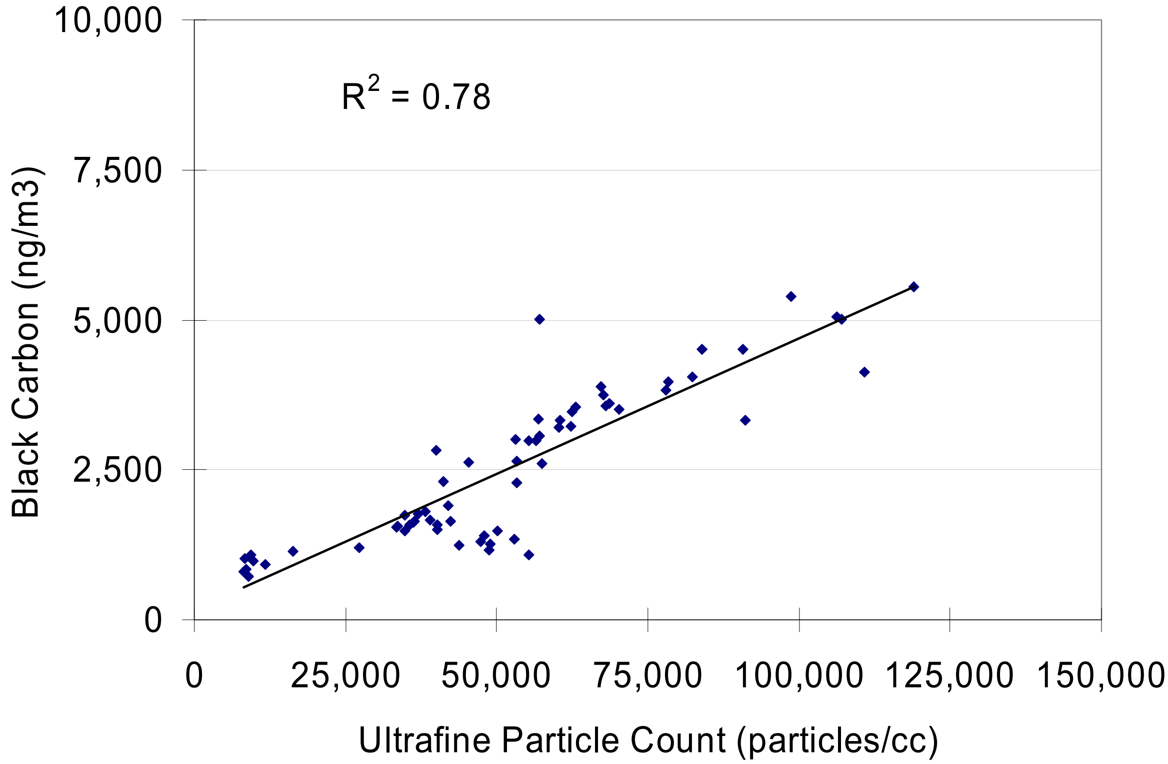

Figure 54: Linear regression illustrating the close relationship between black carbon and ultrafine particles. Similarly the Pearson's R^2 in Table 10 suggests a predictable relationship between black carbon and PAH particle emissions (Ann Arbor Conventional bus on ULSD fuel.)

R^2	$PM_{2.5}$	UF	BC	PPAH
$PM_{2.5}$		0.16	0.25	0.11
UF			0.78	0.61
BC				0.73
PPAH				

Table 10: Pearson's R^2 for pollutants monitored during a conventional bus run (with ULSD fuel) in Ann Arbor, MI. Black Carbon and PAH particles are most closely related to ultrafine particle emissions.

Summary Graphs.

The following series of five graphs and captions concisely summarize the results of this study. The bus runs represented in these graphs followed the same route. Ambient concentrations have been subtracted in order to normalize for background concentrations which varied day-to-day. Black carbon and PPAH results are found in the previous section, but were closely tied to relationships with ultrafine particle concentrations as noted in the captions below.

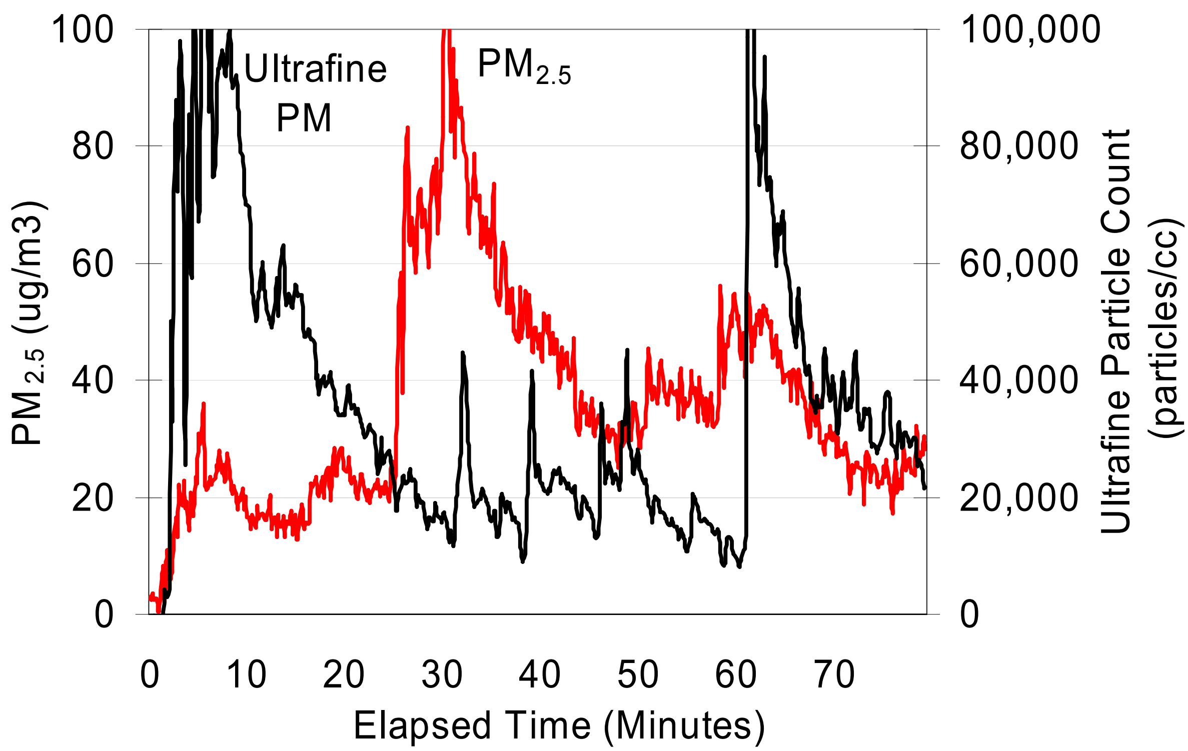

Figure 55: High $PM_{2.5}$ and ultrafine particle concentrations in a conventional bus indicate significant cabin self-pollution. Black carbon and PPAH were elevated as well (see previous section.) Ambient concentrations have been subtracted. (Ann Arbor data.)

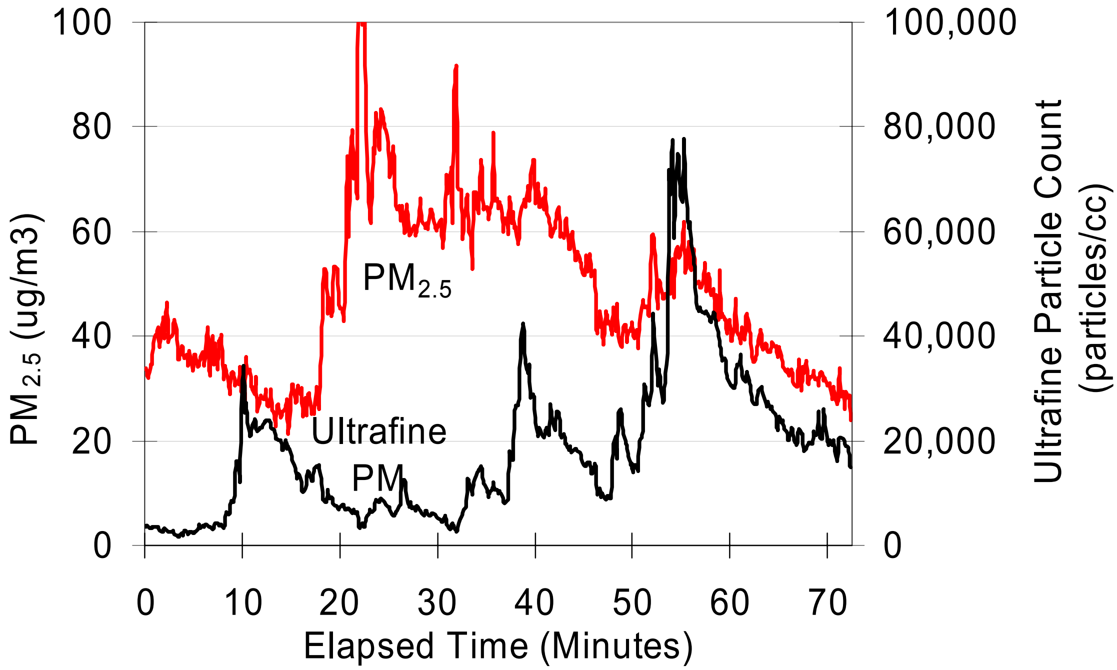

Figure 56: $PM_{2.5}$ and ultrafine particle concentrations remain substantially elevated on bus retrofit with DOC. Black carbon and PPAH were also elevated. Ambient concentrations have been subtracted. (Ann Arbor data.)

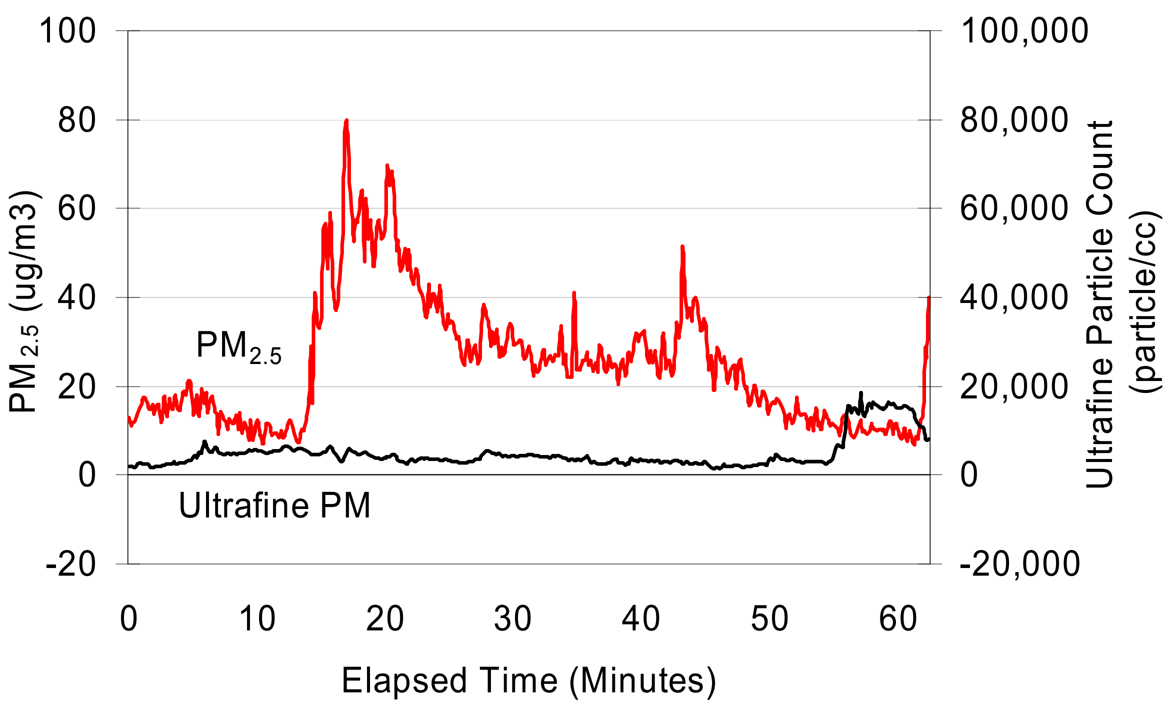

Figure 57: $PM_{2.5}$ and ultrafine particle concentrations on bus retrofit with DPF-ULSD shows reduction in cabin ultrafine particles approximately to ambient. $PM_{2.5}$ remains elevated, however. Source of cabin $PM_{2.5}$ is engine crankcase, not tailpipe,

thereby explaining why DPF did not reduce $PM_{2.5}$. Ambient concentrations have been subtracted. (Ann Arbor data.)

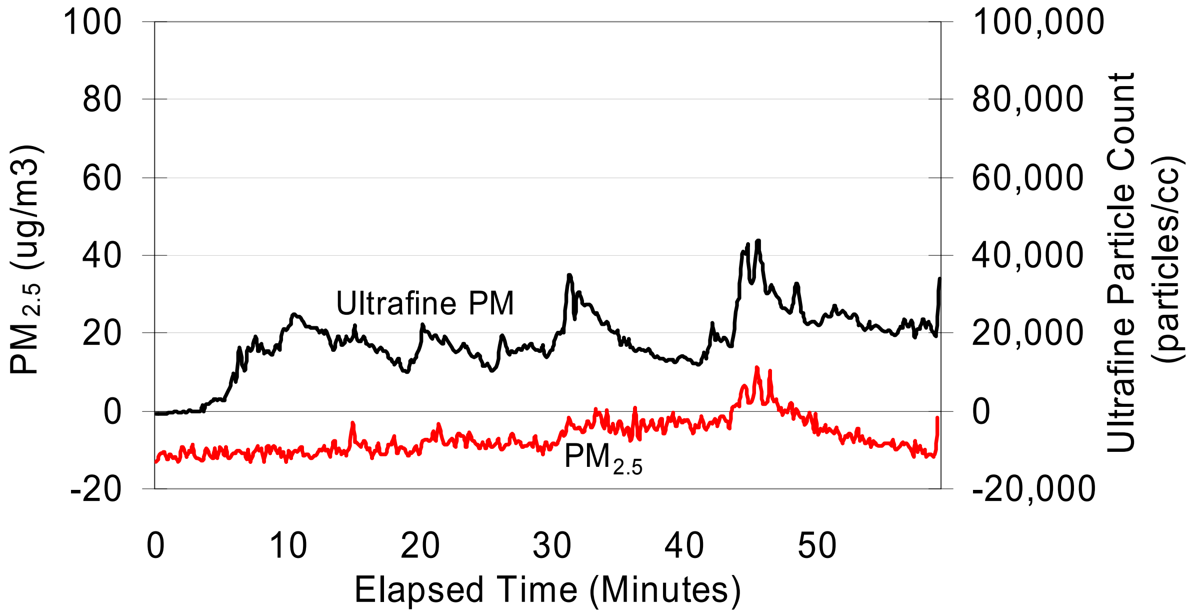

Figure 58: $PM_{2.5}$ and ultrafine particle concentrations on bus retrofit with Spiracle-- ULSD shows reduction in cabin $PM_{2.5}$ approximately to ambient or slightly below. Ultrafine particles remain elevated. Suggests source of cabin $PM_{2.5}$ is engine crankcase. Ambient concentrations have been subtracted. (Ann Arbor data.)

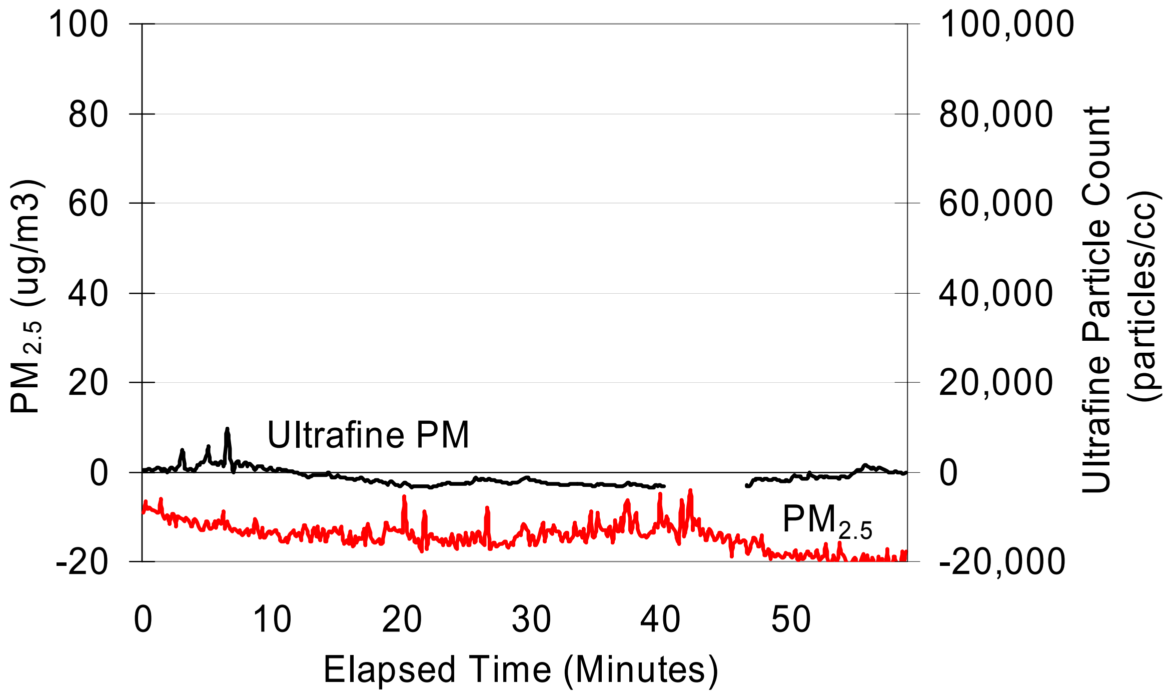

Figure 59: $PM_{2.5}$ and ultrafine particle concentrations on bus #56 retrofit with DPF-ULSD-Spiracle shows reduction in all cabin particulate matter parameters measured approximately to ambient or slightly below. Ambient concentrations have been subtracted. (Ann Arbor data.)

Discussion and Technical Recommendations for Future Work

The present study, unlike previous studies, sought to:

1) Characterize school bus cabin air quality conditions during typical bus routes, idling and queuing as well as external impacts during bus drop off;

2) Document the sources of emissions in school bus.

3) Investigate the benefits of a variety of particulate matter emissions control devices.

Our approach used continuous monitors in the front and middle of each bus combined with a control vehicle in the road ahead of the bus. The buses were tested in residential neighborhoods without concentrated nearby diesel emissions sources that would confound results. Systematic wind measurements were also documented as well as measurements of pollutants adjacent to the engine crankcase and tailpipes to investigate the sources of emissions. The testing of emissions control devices allowed us to virtually "shut off" emissions from the crankcase (Spiracle) and tailpipes (DPF), yielding an effective process of elimination. In addition, the study results are robust because we were able to repeat tests in 3 cities with different fleets and buses. In sum, this methodology had the advantage of allowing us to investigate sources of pollution and solutions without the use of a tracer and integrated filter-based monitoring-- that yields no information on spatial and temporal changes in pollutants onboard.

As a result of this approach we were able to investigate the effectiveness of emissions controls devices on cabin air quality. With the exception of one CARB test, retrofits had not been examined in prior studies. Our method was able to detect and identify multiple sources of emissions affecting the cabin air quality. Unlike previous studies, crankcase "blow-by" was identified as the principal source of $PM_{2.5}$ in the cabin, thereby casting doubt on results of prior work that assumed all cabin emissions originated at the tailpipe. In fact, International's finding that a small fraction of cabin diesel $PM_{2.5}$ was originating at the tailpipe is consistent with the present study's findings that $PM_{2.5}$ in the cabin of the bus is from the engine crankcase rather than the tailpipe. In that study, we suspect that the $PM_{2.5}$ measured in the cabin may have been composed of volatilized engine oil rather than tailpipe PM. If this is indeed the case, the iridium tracer would have underestimated the contribution of the bus emissions to its own cabin as the emissions from the crankcase vent tube is likely a mixture of blow—by and volatilized engine oil. Furthermore, International's finding of minimal entrained particulate matter in the cabin from the bus tailpipe is not supported by our testing which shows substantial ultrafine particulate matter self-pollution, a parameter that was not measured during their study. As such, it would be useful to conduct a study combining tracer work and continuous methods with expanded parameters in a residential setting, particularly in light of International's finding of the high $PM_{2.5}$ levels (72 ug/m^3) in the bus.

We find that the use of the CARB lung cancer unit risk in conjunction with raw measurements of cabin $PM_{2.5}$ is ill-advised for two reasons: 1) $PM_{2.5}$ mass self-pollution measured in the cabin of buses in residential areas is comprised of a complex, poorly understood combination of volatilized engine oil and unburned fuel, 2) wind direction plays a key role in affecting in-cabin particulate matter conditions making exposure generalizations difficult.

Recommendations for Future Work

The results of this study leave a number of unanswered questions that warrant future investigation. Based on the importance of temporal and spatial relationships observed in this study, future school bus cabin air quality studies must be designed so as to be sensitive to acute short term changes in exposure.

- Future studies should be designed such that they are sensitive to multiple emissions sources, in particular engine crankcase emissions.

- A combined study incorporating continuous measurements and integrated particle measurements would help better quantify cabin exposures. Tracer work may or may not help determine the relative contributions of tailpipe and crankcase sources, depending on the contribution of piston blow-by to the emissions from the road draft tube;

- A future study should examine exposures to other diesel pollutants onboard school buses relative to the two emissions sources and the attendant benefits from emissions controls devices;

- Closer examination of the diesel oxidation catalyst is needed to determine whether the device provides quantifiable improvements in cabin air quality under idling conditions;

- A study is needed to investigate the dynamics and chemistry of emissions between the tailpipe and the door of the bus to determine why tailpipe $PM_{2.5}$ does not reach the cabin door.

References

[1] California refers to pollution on a school bus resulting from the same bus "self pollution." http://www.arb.ca.gov/research/schoolbus/schoolbus.htm

[2] All prior studies we are aware of have documented particulate matter self pollution on conventional school buses (with uncontrolled emissions.) Only in one study, conducted by CARB, was a (single) bus equipped with a particulate filter and ultralow diesel fuel tested. Moreover, to determine if *all* DPM emission sources that cause self-pollution can be eliminated (including both tailpipe and direct engine emissions), CATF and partners are testing several devices designed to reduce or eliminate emissions from the engine compartment /crankcase.

[3] A micron is one millionth of a meter. Fine particles fall in a wide range, generally smaller than 1/100th of a human hair and smaller.

[4] California Air Resources Board suggests that fatality risk due to switching to passenger cars from buses would overshadow decreased cancer risk due to decreased exposures to diesel particulate matter. See: California Air Resources Board (2003). Characterizing the range of children's pollutant exposure during school bus commutes. Available at: http://www.arb.ca.gov/research/schoolbus/schoolbus.htm

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