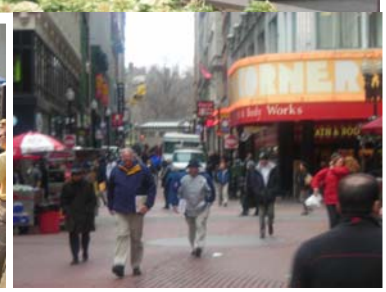
CATF Special Report 2007-1

A Multi-City Investigation of Exposure to Diesel Exhaust in Multiple Commuting Modes

Columbus OH, Austin TX, Boston MA, New York City, NY







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CLEAN AIR TASK FORCE

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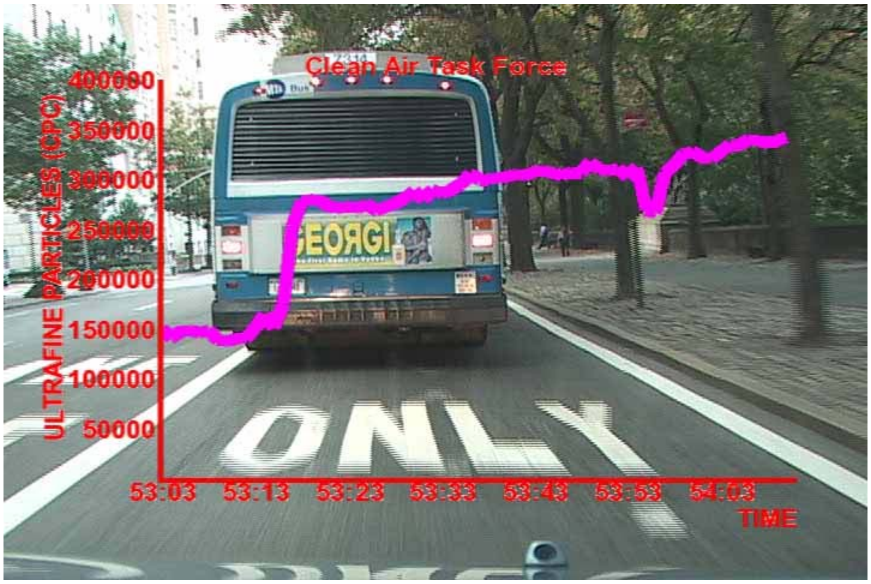

Acknowledgements--

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A Note on Report Versions:

CATF considers this white paper a *work in progress* which may be updated as new data become available or as data analysis is further refined. Report versions and dates will be noted on the cover of the report starting with the initial version 1.0 released February 28, 2007. Only the most recent version will be posted to the CATF web so please check at www.catf.us/goto/noescape for updates.

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ABSTRACT AND BRIEF FINDINGS

Routine exposure to diesel exhaust is not just an occupational hazard for truckers, railroad or construction workers—most of us breathe it every day in traffic and near major thoroughfares. In fact, diesel exhaust shortens the lives of an estimated 21,000 people per year in the U.S. and many more suffer the effects of diesel-related respiratory and cardiovascular disease. Both long-term and short term exposures to the particles that characterize diesel exhaust have been shown to result in serious health damage. Moreover, health researchers have long associated traffic with maladies.

If not at work, when are the rest of us exposed to diesel? According to a University of California study, highway commuters may receive approximately half of their daily exposure to ultrafine particles and black carbon soot from diesels while commuting—in only about 4-6 percent of the day. CATF's investigations in Columbus OH support this estimate. According to the Transportation Research Board, half of us--one hundred and fifty million people --go work in the U.S. daily. Worse, our commutes-and therefore our exposures--are lengthening.

While most people drive to their place of employment, many others take commuter trains or city buses. Some walk and in some cities a few travel on ferries. Few existing U.S. studies have examined commuter and in-vehicle exposure to air pollution. But now new monitoring instruments now make it possible to investigate real time changes in particles and health impacts. A few of the most recent studies that suggest harm from acute exposures to these pollutants. One such study of healthy highway patrolmen documented heart rhythm irregularities using strap-on heart monitors

Seeking to investigate commuter exposures further, Clean Air Task Force researchers set out to investigate commuter exposures to diesel exhaust in three cities in different modes of transit. Results confirm that diesel soot dominates roadway particulate matter and that people commuting regularly to and from work along truck routes are exposed to high levels of diesel soot. Our study documents diesel particle exposures cars, in older buses, trains, ferries and on foot on sidewalks along city streets.

Clean Air Task Force began its exposure investigations in 2005 and 2006 .Representative cities were selected for investigating commuter exposure to diesel exhaust (Austin, TX; Boston, MA, Columbus, OH and New York City) using methodologies developed at major universities. Four key constituents of diesel exhaust were tracked with continuous monitors: fine particles ($PM_{2.5}$), ultrafine particles (PM<0.1um), black carbon, and particulate polycyclic aromatic hydrocarbons (PAHs). Because CATF's monitoring suggests ultrafine particles may be the best marker of fresh diesel exhaust across all modes of transit, those results are highlighted in this report. Graphics were selected to illustrate key findings. Pollutant exposure data was normalized by subtracting daily ambient background concentrations. For in-depth results and methodological details see companion white paper at www.catf.us/goto/noescape/ . The focus of the effort has been on highway commute runs, where the most robust data is based on over100 car commute runs. However, the data that CATF has collected for other modes of transit is also revealing.

- Car Commutes: In Boston, Austin and Columbus typical commute routes were run in a 2006 minivan equipped with four monitors for a total of 107 runs over 79 hours. CATF investigated the effects of window position, air conditioning, and recirculation of cabin air. The results from "windows open" runs are reported here.
- Transit Buses: Researchers boarded buses in Boston and Columbus using monitors housed in backpacks and roll-around bags.
- Commuter Rail: Researchers boarded trains in Boston and New York City with monitors housed in backpacks and roll-around bags for inbound (locomotive push) and outbound (locomotive pull) runs.
- Ferries: Researchers boarded Boston commuter ferries with monitors housed in a backpack.
- Walking Commutes: With monitors in backpacks, researchers walked from residential to commercial areas in Boston and Columbus.
- Chase Studies: CATF monitored comparative particle levels behind conventional and DPF retrofit buses in New York City and Boston and behind garbage trucks in New York City. As a controlled experiment, CATF retrofitted a Class-5 box truck with a DPF, testing air behind the truck before and after.

Brief Findings
Note: for the findings below, data represent net particle exposures (ambient outdoor air concentration subtracted to normalize data between days with different regional background.)

CARS:

- <u>Car commuters experience their highest daily exposures to diesel particles on the way to work</u> ($PM_{2.5}$, ultrafine particles, black carbon soot, and particulate polycyclic aromatic hydrocarbons (PAH))
- <u>Mean exposures to ultrafine particles—found to be the most sensitive indicator of diesel exhaust, ranged from 4-8 times the ambient outdoor particle levels</u> averaged across all runs and all modes of transit.
- <u>Averaged peak UFP levels ranged from 19-38 times the ambient outdoor air concentrations.</u>
- <u>Trucks are the principal source of the four primary particulate matter pollutants measured</u>, Highways banning large trucks are characterized by lower exposures to all four particle pollutants. Increases in particulate matter pollutants were not observed following gasoline vehicles (with the exception of several super emitters with visible smoke.)
- <u>Pollutant levels inside commuter cars are significantly higher than the ambient air in downtown areas.</u>
- <u>In-vehicle exposures were greatest with windows open</u>, Levels were systematically reduced for all measured pollutants when the air conditioning or heat was on with the windows closed, and lowest when heat or air conditioning is on and cabin air is set to re-circulate.
- <u>Exposure is much higher in highway tunnels.</u>

TRAINS:

- Diesel exhaust pollutes passenger trains. Mean net $PM_{2.5}$ exposures averaged across all runs were 1-5 times the concentrations in the outdoor air (locomotive being in rear or front, respectively) and mean peak concentrations ranged from 28-46 times outdoor air. Mean UFP exposures across all runs range from 3-20 times the concentrations found in the outdoor air; factors of 6-17 times outdoor air for black carbon; 2-15 times for particulate PAH.
- The exhaust plume from the locomotive penetrates the cabins of commuter coaches particularly when the locomotive is located in front (pulling the train / "engine out")
- Diesel exhaust pollutes the coach when the doors open on a platform polluted by the engine exhaust if downwind of locomotive or where the platform is partly enclosed.
- Underground rail stations serviced by diesel locomotives exhibit dangerously high air pollution where diesel fumes are trapped underground. Opening of cabin doors results in the influx of these pollutants into the passenger car.

TRANSIT BUSES:

- Transit buses are polluted by their own tailpipe exhaust. Field tests suggest that soot emissions may enter the cabin through front and side doors at bus stops when the door is downwind of the tailpipe. When windows are shut, those emissions are trapped inside the bus for extended periods, only slowly ventilating.
- CONVENTIONAL BUSES. CATF's investigations in Boston's older spare conventional buses found $PM_{2.5}$ exposures averaged across all conventional runs to be about 2 times the concentrations in the outdoor air; mean peak $PM_{2.5}$ concentrations were about 11 times the outdoor air. UFP exposures across all runs were 4 times the outdoor air with mean peak levels a factor of 11 higher than outdoor air. Particulate PAH exposures averaged a factor of 12 higher than outdoor air and peak levels a factor of 22 times higher than outdoor air. Black carbon measurements were not captured for conventional transit buses.
- DPF-EQUIPPED BUSES*:* CATF's investigations of Boston's newer and retrofit buses found mean $PM_{2.5}$ exposures averaged across all conventional runs to be 3 times the concentrations in the outdoor air. Mean peak $PM_{2.5}$ concentrations were 14 times those in the outdoor air. *(NOTE: The higher $PM_{2.5}$ levels on a few of the DPF runs were a result of open windows on 2 runs where the transit buses followed heavy duty diesel sources or encountered suspended road dust.)*
- UFP exposures in DPF-equipped buses across all runs were the *same as* (1 x) the levels in the outdoor air with peak levels a factor of 3 higher than outdoor air. The UFP result is consistent with CATF chase studies demonstrating the effectiveness of the DPF. This result is significant since UFPs may be the best indicator of fresh diesel exhaust. Particulate PAH exposures were a factor of 7 times the levels in the outdoor air and peak levels a factor of 30 times higher than in the outdoor air. Black carbon measurements suggested a factor of 3 higher than outdoor levels and average peaks 7 times outdoor air.
- One Boston run suggests that DPF-equipped buses may be cleaner than outdoor air. Mean UFP levels for one DPF bus on a polluted day averaged lower than levels measured in the outdoor ambient air.

- CNG –FUELED BUSES: Buses running on compressed natural gas were characterized by clean cabin air, in some cases cleaner than the outdoor air. Average $PM_{2.5}$ levels were about the same as ambient outdoor air, UFPs a low 2 times the levels in the outdoor air, PAH averaging 5 times the ambient outdoor air and black carbon 2 times outdoor air. Mean short-term peak exposures were, 5, 5, 19 and 5 times the outdoor ambient air for $PM_{2.5}$, UFP, PAH and black carbon respectively. These runs were affected by outside sources.
- When bus windows are open, changes in pollutants in the bus appear more volatile, rising sharply when behind other diesels or when affected by self pollution and ventilating to ambient concentrations when not following other sources.
- Cars following conventional transit buses are polluted by the bus exhaust plume. CATF chase studies document that transit buses in Boston and New York and New York sanitation trucks not equipped with DPFs leave concentrated trails of diesel soot behind them that permeate the cars behind those vehicles and reduces air quality along community sidewalks.
- Diesel particulate filters work.. When installed on Boston and New York transit buses and New York sanitation trucks, chase studies confirm that the DPFs eliminate the diesel soot plume behind the bus, making the air quality in the roadway less hazardous to breathe.
- Preliminary chase studies behind Columbus OH transit buses fueled with 90% biodiesel appear to exhibit elevated levels of ultrafine particles.

FERRIES:

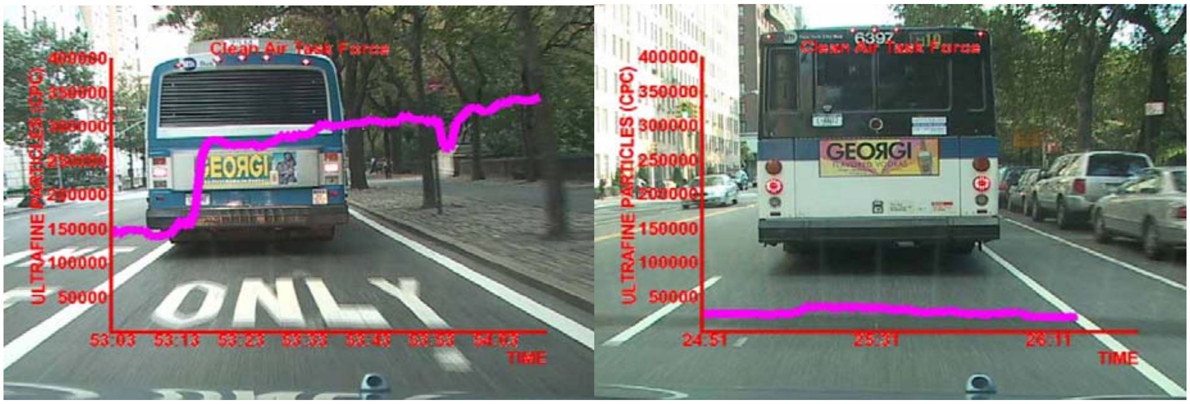
- CATF researchers documented very high short term levels of diesel smoke and related particulate matter swirling in and around the passenger cabins of Boston commuter ferries. Average $PM_{2.5}$ and UFP levels were about 3 times simultaneous levels the ambient outdoor air, PAH averaging 17 times the ambient outdoor air and black carbon 6 times outdoor air. Mean short-term peak exposures were much higher, 14, 21, 117 and 50 times the outdoor ambient air for $PM_{2.5}$, UFP, PAH and black carbon respectively.

PEDESTRIANS

- People walking to work are subject to breathing elevated fresh diesel exhaust on city sidewalks. Levels of all four pollutant spiked as diesel vehicles passed, However, due to rapid ventilation, exhaust did not typically lingers as seen inside cabins of other modes of transit. Mean exposures ranged from 1.5, 2-3, 2-8, and 2 times the levels in the outdoor ambient air for $PM_{2.5}$, UFP, PAH and black carbon, respectively. Average peak exposures ranged from 12-16, 19-29, 34-43 and 15 times the levels in the outdoor ambient air for $PM_{2.5}$, UFP, PAH and black carbon, respectively.

SUBWAY:

- CATF researchers found low levels of combustion-related pollution on electrified subway and light rail especially where underground, with no confounding external combustion particle sources. However CATF recorded suspended fine particles (likely non combustion) entrained along the underground track as well as pollution from other sources when the electrified rail was above ground and near busy streets.



New York City bus chase proves DPFs Work. *Left:* Real-time measurements documents tailpipe plume polluting chase vehicle following a New York MTA bus without a diesel particulate filter (DPF). *Right:* A NYC Transit bus equipped with a DPF eliminates the soot plume behind the bus. (For video see www.catf/us/goto/noescape/)

PART I: THE MEDICAL CASE FOR REDUCING DIESEL EXHAUST

Particles Cause > 45,000 premature Deaths a Year in the U.S., 21,000 from Diesel.

Diesel exhaust is unhealthy to breathe; the adverse health effects of breathing diesel pollution have been known by the scientific community for decades. Diesel exhaust is a toxic combination of carbon, sulfur and nitrogen particulate matter compounds and related gases created from combustion of diesel fuel, burning lubricating oil commonly containing minute metallic engine particles. Initial research, based on occupational studies conducted in the U.S. and Canada, raised concern linking exposure to cancer.[1] Recent investigations of health damages resulting from exposure to pollutants found in diesel exhaust encompass long-term, short-term and laboratory studies. But workers are not the only people exposed to diesel exhaust—we all breathe it every day whether we drive regularly on a country road or a city street.[2,3] We are surrounded by America's 13 million diesel engines—America's industrial workhorses-- powering tractor trailer trucks, transit and school buses, trains, ferries, generators, construction and agricultural equipment. As our study suggests, high levels of diesel exposure may be experienced by anyone who commutes. In fact, commuters may be the ones whom are most exposed.

Particulate matter soot may be the most carcinogenic and harmful component in whole diesel exhaust. The International Agency for Research on Cancer (IARC) states that there is sufficient animal experimental evidence for the carcinogenicity of diesel engine exhaust particles, but inadequate evidence for the carcinogenicity of gas-phase diesel engine exhaust.[4] However, coronary artery constriction has been documented in animal studies resulting from exposure to non-particulate diesel compounds.[5]

Diesel particles are not only toxic but they are the tiniest of combustion particles. In general, diesels emit two types of particles—*fine particles*, less than 1 micron (a millionth of a meter) in diameter, and 'nucleation mode" particles, otherwise known as *ultrafine particles*, under 10-100 nm (billionths of a meter.) Under U.S. law the Environmental Protection Agency has set daily and annual health standards for fine particles (35 ug/m3 and 15 ug/m3 respectively). Health standards have not been established for ultrafine particles but recent medical community investigations suggest that their extremely small size may allow them to pass easily into the bloodstream where they can cause oxidative stress and inflammation.[6]

The U.S. Environmental Protection Agency's most recent National Air Toxics Assessment estimated that the average concentration of diesel particles in the air in the U.S. is about 1.2 ug/m3.[7] This translates to about 363 lung cancers per million, well above EPA's acceptable level of 1 cancer per million. Moreover, the cancer risk from diesel exhaust in the U.S. exceeds the combined total of all the other 132 air toxics tracked by EPA. However, in many areas, diesel particles may be even more concentrated in 'hot spots' such as areas of concentrated traffic, heavy machinery use or construction.

Particulate matter soot is a potent pollutant. In fact, prominent medical researchers have suggested that particulate matter pollution in the air is responsible for at least 70,000 deaths a year.[8,9] Two analyses by Abt Associates for the Clean Air Task Force, following EPA Scientific Advisory Board methodologies, have estimated that approximately 45,000 American lives are lost prematurely each year from exposure to particulate matter pollution from two sources of particles, 21,000 from diesel soot and 24,000 from power plants.[10] This is roughly equivalent to the 44,000 motor vehicle deaths per year in the U.S. in 2002 and 2003 (the latest years of available data.)[11]

For the average risk from diesel soot in your community go to the CATF web at: http://www.catf.us/projects/diesel/dieselhealth/. Your risk may be considerably higher if you are exposed to diesel exhaust while commuting.

Short and Long Term Exposure to Diesel Can Cause Cancer, Cardiopulmonary Disease, Slow Lung Growth in Children, Trigger Asthma Attacks.

While the link between lung cancer and breathing fumes over many years has been known for decades, recent research links diesel exhaust exposure to cardiovascular and respiratory harms over much shorter time frames such as a single day. The following is a summary of selected findings:

Years of Breathing Diesel Soot May Lead to…

- Lung Cancer. Diesel exhaust is a probable carcinogen based on occupational health studies of truckers and railroad workers.[12] Diesel soot is known to U.S. EPA, the State of California and the International Agency for Research on Cancer (IARC).[13, 14, 15] Gaseous and particulate compounds in diesel exhaust are also known carcinogens such as polycyclic aromatic hydrocarbons, and formaldehyde.
- Cardiovascular death. Two of the largest long term air pollution studies ever conducted (one tracking 1 million people in 150 cities over 16 years) strongly associated exposure to

fine particles—a major component of diesel exhaust—with an elevated risk of premature cardiac death.[16] A link between exposure to particles and vascular inflammation/atherosclerosis is suggested by animal studies and could explain how particles are linked to heart attacks.[17]

- Elevated cardiac risk for women. A 2007 study of particles and cardiovascular health published in the New England Journal of Medicine tracked the medical records of 65,000 women across 36 metropolitan areas from 1994-1998.[18] Researchers documented a 24% increase in risk of women having a cardiovascular event and an overall 76% increase in risk of death from cardiovascular disease for each 10 ug/m^3 in $PM_{2.5.}$ The study also found a 35% increased risk in cerebrovascular events (e.g. stroke.) Within-city risks were found to be greater than the risk between cities suggesting the importance of local sources of particles.[19]
- Stroke. Diesel exhaust particles may raise the risk of stroke.[20]
- Asthma, respiratory infections and allergic symptoms. Multiple studies link asthma and allergic sensitization and diesel particles.[21, 22] A study from the Netherlands links asthma diagnosed before 1 year of age to traffic.[23] An East Bronx NY study suggests children exposed to higher levels of truck exhaust have higher incidences of asthma.[24] In a California study, asthma and bronchitis was found to be 7 percent higher among children attending school in high-traffic areas, compared with schools along quieter streets.[25]
- Slowed lung growth in children.[26]
- Slowed fetal growth as a result of maternal exposure during pregnancy[27]
- Infant mortality[28, 29]
- DNA damage. [30]

A Day of Breathing Diesel Soot May Lead to….

- Cardiovascular illness. In a 2004 study, University of North Carolina researchers tracked particle exposures and cardiac response in young (ages 23-30), healthy and physically fit highway patrolmen on their daily shift.[31] Using the same or similar portable monitoring devices as CATF, particulate matter concentrations—well within the same ranges as CATF observed-- were linked to significant changes in heart rate variability, ectopic (out of place) heart beats and increases in blood inflammatory markers within hours of exposure. [32]
- Asthma symptoms and asthma attacks in children[33,34,35]
- Increased susceptibility to allergy[36, 37]
- Premature death, based on the 90-city National Morbidity and Mortality Air Pollution Study associating daily exposures of particles with premature death.[38]
- Highest circulatory and cardiovascular risk for diabetics based in 24 hour exposures to particles.[39]
- Nervous system impairment based on a study of railroad workers exposed to diesel exhaust. Concludes: “crews may be unable to operate trains safely.”[40]
- Increased allergies, with increased sensitization caused by diesel exhaust exposures.[41]
- Infant mortality.[42]

A Few Hours of Breathing Diesel Soot May Lead to…

- Irritation of nose and eyes, respiratory/lung function changes, cough headache, fatigue and nausea.
- Pulmonary inflammation found after 1 hour of exposure to diesel exhaust (in humans.)[43]
- Higher risk of pulmonary inflammation to asthmatics after 2-hours of exposure.[44]
- Adverse cardiovascular effects. Changes in heart rate variability, heartbeat and blood indices were recorded in California Highway troopers exposed to elevated in-vehicle particulate matter (average 24 ug/m3) during midnight to 9 AM shifts.
- Doubled risk of death due to stroke. Risk increased by a factor of over two within 2 hours of exposure to high levels of fine particles in a Japanese study.[45]
- Suppressed defense mechanisms and increased susceptibility to lung bacterial infection for a week after exposure. Observed in rats after exposure to diesel exhaust for 4 hours per day for 5 days by prolonging the growth of bacteria in the lung for a sustained period exposure.[46]

Proximity to traffic is associated with adverse health risk.

Traffic studies have consistently and overwhelmingly defined an adverse relationship between proximity to highly trafficked areas and a variety of illnesses. Epidemiology studies generally suggest that living within approximately 50-100 meters of a busy road may result in mild to acute respiratory symptoms or worse. A New York City study underway links asthma to truck traffic.[47] An assessment of the health impacts of traffic related air pollution estimated approximately 40,000 premature deaths annually in the Austria, France and Switzerland, a whopping 6% of total mortality.[48]

Importantly, studies find that truck traffic volume is most strongly related to health risks rather than car volume[49,50,51] This is consistent with our findings that particle levels on freeways are directly associated with volume of truck traffic.

Medical studies have linked proximity to traffic to:

- Heart attacks (myocardial infarction) [52,53,54] For example, a study of 700 heart attack survivors shows that they were most likely to have been in heavy traffic the hour before they suffered the heart attack than any other hour of the day.
- Increased risk of mortality.[55]
- Reduced lung function growth. In a cohort of 3677 children tracked for 8 years, those living within 500 meters of a California freeway had deficits in lung volume growth.[56]
- Chronic respiratory symptoms in children and adults such as cough, persistent wheeze and bronchitis[57, 58,59,60,61]
- Asthma in children with larger effects in girls, and children's hospital admissions for asthma[62, 63,64,65]
- School absence.[66]
- Aging affect ("mortality rate advancement"), similar in magnitude to chronic respiratory and pulmonary diseases and diabetes.[67]
- DNA damage.[68]

Ultrafine Particles—an Indicator of Fresh Diesel Exhaust-- Pose Independent Health Risks.

In addition to the impacts of fine particle soot, even tinier “ultrafine” particles found in fresh diesel exhaust may have their own suite of risks. Diesel exhaust particles consist of two important size fractions: fine and ultrafine particles. *Fine particles* (0.1 to 1 micron in aerodynamic diameter) comprise the dominant diesel soot mass and contribute to adverse $PM_{2.5}$ conditions in the air. *Ultrafine particles* (also known as “nanoparticles” or “nucleation mode” particles) are particles 5 to 100 nanometers (0.05 to 0.1 microns). Ultrafine particles are characteristic of fresh diesel exhaust but rapidly coalesce to form fine particles. Ultrafine particles by themselves contribute little to the mass of fine particle soot in the air but their small size means they are very high in number. Moreover, their tiny size allows them to carry toxins deeper into the lung and into the bloodstream. Because geographic dispersion and distribution of ultrafine particles is very different than fine particles, ultrafine particles cannot be called on as the sole ‘smoking gun” responsible for fine particle effects. Some medical studies also suggest that health impacts of ultrafine particles may, in fact, be independent of fine particles.[69,70] Recent medical studies have found:

- Systemic acute inflammation from exposure to ultrafine particles that could lead to exacerbation of cardiovascular disease.[71, 72]
- Penetration of ultrafine particles from the lung into the bloodstream.[73]
- Formation of blood clots (thromboses), in laboratory animals[74]
- DNA damage.[75,76]
- Premature mortality, with effect independent of fine particles[77]
- Acute respiratory effects in asthmatics.[78,79] Greater ultrafine particle deposition in the lungs is observed for asthmatics, suggesting greater health risk.[80]
- Increased particle deposition with exercise suggesting a potentially greater risk to children and athletes.[81]

The Carcinogenicity of Diesel Exhaust: Enhanced by Particulate Polycyclic Aromatic Hydrocarbons (PAH)

Diesel is an important source of the air toxic Polycyclic aromatic hydrocarbons or PAH. While gasoline combustion releases some PAH, the strongest mobile sources of PAH are from diesels. The following are some findings relative to exposures to PAHs in the air:
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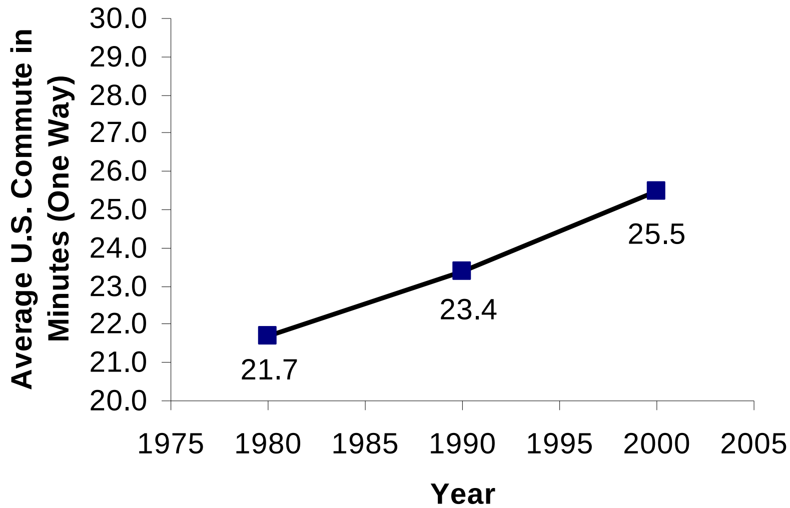
- Mutagenic and carcinogenic properties of diesel exhausts may be attributable to polycyclic aromatic hydrocarbons[82]
- Results from the commuter and mobile laboratory studies show that high exposures to PAHs are not limited to drivers of diesel trucks but can in fact be experiences by any driver or passenger.[83]
- On a per-vehicle basis buses and trucks emit greater amounts of PPAH[84]
- Excess relative risk were found for the PAH benzo[a]pyrene, as documented within 0.3 km of diesel hotspots bus stations, rail stations, heavy transport centers; diesel engine exhausts were particularly incriminated.[85]
- Environmental PAH at levels in New York City air may adversely affect children’s cognitive development at age 3, with implications for school performance.[86]

PART II: COMMUTING AND EXPOSURE TO DIESEL EXHAUST

The Changing Face of Commuting in the U.S.: Increasing Risk to the Broader Public?

Commutes are getting longer, more of us our commuting. And while commuting has been previously thought of as a drive from the suburbs to work in the city, many commuters are traveling from suburb to suburb. Corporations have located work campuses outside of cities along beltways, and with that change means more suburban freight warehouses and accompanying truck traffic. As a result more of us may be being exposed to diesel exhaust. The following are a few transportation Research Board (TRB) commuter survey statistics that reflect these changes.[87]

- One-way commutes have increased to 25.5 minutes nationally, a three minute increase over 1990.
- 41 million people travel suburb to suburb, now the dominant flow of traffic.
- Nearly 113 million people commuted by car in 2000, as compared to approximately 100 million in 1990
- Approximately 6 million people took mass transit to work in 2000, 4 million walked, 5 million worked at home
- 73% of transit usage occurs in metro areas with 5000 or more people. So for most of us, its exposure in our cars



Above: Commute Times are increasing in the U.S.

Previous Commuter Exposure Studies

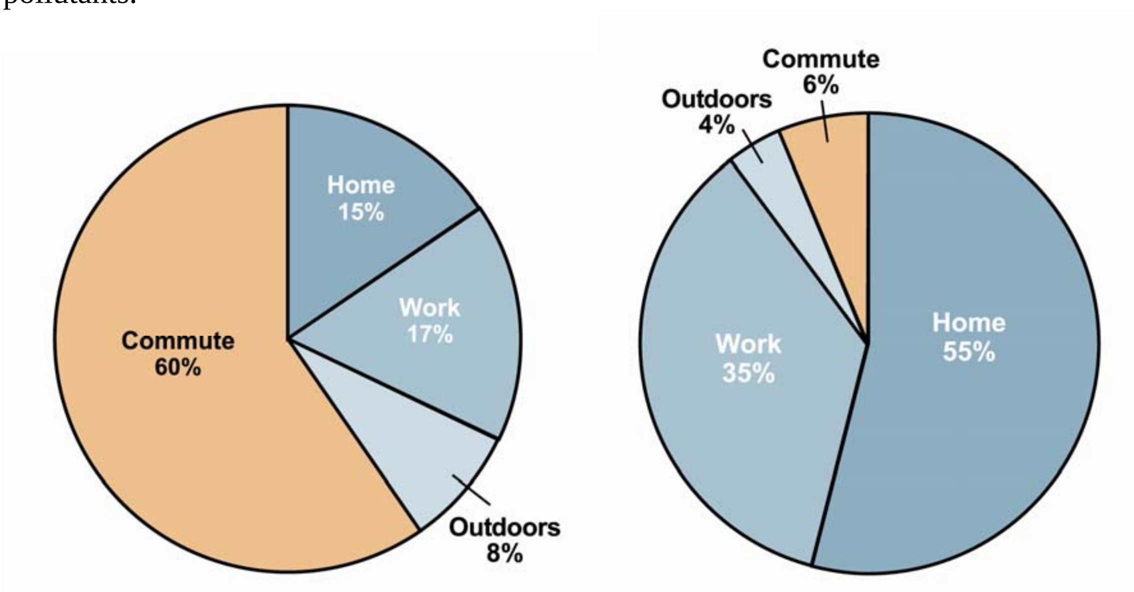
With an estimated 21,000 Americans dying from exposure to diesel particles each year, clearly it's not just occupational exposures that are responsible—research suggests that diesel exhaust exposure is a much more widespread public health problem that affects all of us. According to U.S. EPA modeling Americans are exposed to diesel soot disseminated in hazy air throughout the United States.[88] But that is not all. Commuter and exposure studies suggest we can be exposed to much higher levels of soot when we are commuting. Worse, we are used to it; we hardly notice.

Numerous exposure studies confirm that diesel soot is concentrate in areas of high traffic. Methods have been developed to quantify commuter pollutant exposures in a variety of cities around the world. Many of the methods are similar to the approach and instruments used in this study. The following summarized examples of studies using similar approaches and equipment as the present study.

- A 2003 California study points to commuting as the principal route of human diesel exposure accounting for one third to one half of total exposure.[89] Total California statewide in-vehicle concentrations were seven times that associated with the national average cancer risk. Exposures on L.A. freeways were similar to the findings of the present study.[90]
- In the same California study, on- road emissions were three times as effective at producing exposures as off-road emissions. Six percent of the time spent following a diesel vehicle during a commute, was responsible for one quarter of the black carbon exposure in the vehicle.
- In a Los Angeles study, exposures are typically elevated within 100 meters of a freeway (about the length of one large-city block).[91]
- A 2004 NESCAUM Boston diesel commuter rail exposure study documented high levels of black carbon particles in-coach and on-platform.[92]
- A London investigated ultrafine particle exposures while commuting on foot, by bicycle in a car and by taxi in London.[93] Like the present study, elevated exposures were documented in every mode of transit. Personal exposures on sidewalks were multiple times higher than fixed urban background monitoring sites.[94]
- In a Copenhagen study, traffic was found to be responsible for the majority of ultrafine particles in the air.[95]
- In Amsterdam, black carbon soot levels increased near highways by a factor of three times.[96]
- Elevated black carbon exposures on Harlem New York sidewalks are associated with increased truck/bus counts. Exposure increased in proximity to a bus depot. Black carbon varied 4-fold.[97] Researchers conclude that adolescents in Harlem are exposed to elevated diesel exhaust.[98]
- A personal exposure study in Mexico City study found elevated fine particle exposures in a variety of microenvironments, including cars, public transportation, relative to ambient conditions.[99]

Commuting May be the Most Common Pathway for Diesel Exposure.

Scores of studies throughout the world show that people that live or work around diesel traffic are at highest risk.[100,101,102,103,104,105,106] But commuters may also be exposed to high levels of diesel exhaust as well. The 2001 National Human Activity Pattern Study (NHAPS) suggests that we spend 6% of our day in an enclosed vehicle and most of the rest of it indoors at home or at work.[107] A smaller amount of time (1 hr or 4%) is spent outdoors in the outdoor air. A 2004 study conducted by researchers at the University of California School of Public Health estimates that during the small fraction of the day when we are in our vehicles (about 1.5 hours) we experience *half* of our exposures to diesel soot and ultrafine particles, up significantly in the 2000 U.S. census, and every year since. This means commuters, already at higher risk than average, are experiencing steadily increasing exposures to roadway pollutants.



A California study suggests that over half a commuter's exposure to ultrafine particles or black carbon may occur during 6% of the time. <u>Left pie</u>: More than half of an average person's exposure to ultrafine particles (typically an indicator of fresh diesel exhaust) may result from commuting on freeways and city streets.[108] <u>Right pie</u>: daily average time spent by Americans in vehicles is only approximately 6 percent (about 1.5 hours).[109]

California (Adapted from Fruin 2006)	Hours	Time %	Mean UFP	Conc-Hrs	Exposure %
Home	13	55%	3,000	39,000	15%
Office	8.5	35%	5,000	42,500	17%
Outdoor	1	4%	20,000	20,000	8%
Commute	1.5	6%	100,000	150,000	60%

PART III: CATF RESEARCH FINDINGS

Clean Air Task Force began its exposure investigations in 2006 with a focus on car commutes in 3 cities, Austin TX, Boston, MA and Columbus OH, supplemented by pilot investigations into rail , transit bus, marine and pedestrian particle exposures (where each mode of transit is available) supplemented by rail and chase studies in New York City. In total, CATF researchers accumulated approximately 80 hours of monitoring data commuting in cars, 12 hours commuting in commuter trains, 14 hours riding in transit buses, 5 hours on foot, 3 hours in electric subways and 3 hours in ferries. Results, highlighted below, support previous work in the literature documenting the impact of diesel engines on air quality and indicate that significant particle pollutant exposures may be routinely experienced in all commuting venues.

METHODOLOGIES AND INSTRUMENTATION

Three primary cities were selected for investigating commuter exposure to diesel exhaust, Austin TX, Boston MA, and Columbus OH. These cities were identified so as to be representative of typical Eastern and Midwestern cities across the U.S. In addition to these three cities, data was collected on New York City commuter trains, supplementing the Boston commuter train dataset. **Car commutes** were the cornerstone of the investigation and undertaken exhaustively in all three of the primary cities. **Commuter rail commutes** were investigated in Boston and New York City. **Transit bus commutes** were investigated in Boston and Columbus. Exposure to marine diesel was investigated in Boston on Boston **Harbor ferry commutes**. Downtown **pedestrian commutes** were preliminarily investigated in Boston and Columbus. In addition to investigation of these multimodal commutes, truck and bus chase studies (following vehicles) were conducted in New York City and Boston in order to examine the effectiveness of diesel particulate filters in reducing exposures behind moving garbage trucks and transit buses.

For all modes of transit, combinations of four particulate matter parameters were measured using state-of-the-art portable monitoring devices. Pollutants measured were: 1) $PM_{2.5}$, 2) ultrafine particles (nanoparticles), 3) black carbon, and 4) Particle-bound PAH. Monitoring equipment utilized in this study has been used in numerous peer-reviewed studies by Harvard University researchers and researchers abroad (e.g. U.K. taxi study described elsewhere in this report.) The following is a description of the equipment utilized.

Fine Particles (PM2.5)

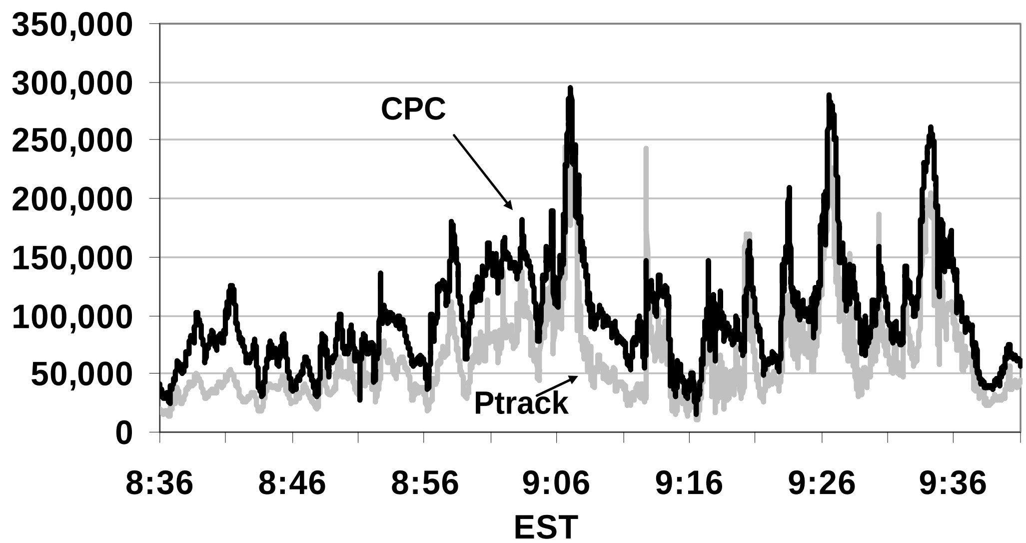
Fine particulate matter mass was measured using the TSI Dust Trak.[110] The $PM_{2.5}$ impactor plate was maintained and cleaned with a light grease for all measurements. The Dust Traks were zeroed daily prior to conducting measurements. For instrument response stability, the time constant was set to 10 seconds, but the data was collected in one second intervals for most tests. During data processing we further smoothed the 10 second data using rolling 10 second means for plotting. In data tables, concentration are also reported a 1 second mean concentrations.

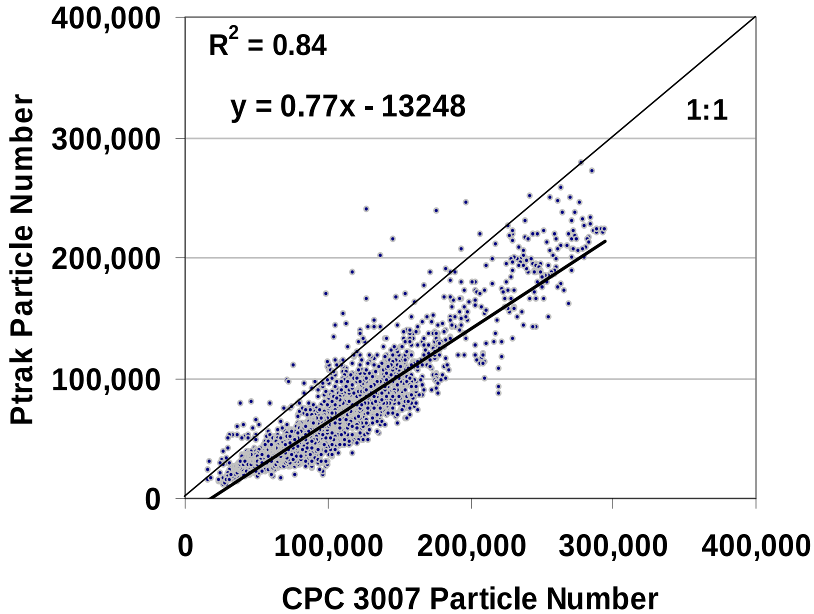
$PM_{2.5}$ data reported in this paper are raw measurements, uncorrected for the reported high-bias of the instrument. The Dust Trak is calibrated to Arizona road dust which has very different light scattering characteristics than combustion aerosol resulting in a different response. Chang et al (2001) 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.[111] The slope of the line relating the PEM and the Dust Trak was 2.07 in the study. Similarly, McIntosh (2002)[112] 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)[113] 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.[114] Further, Levy et al found a "strong correlation but a consistent factor of 2-3 difference between the methods." A Harvard 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.[115]

Ultrafine Particles (Nanoparticles)
Ultrafine particles were measured using two instruments: 1) the TSI Incorporated PTrak, a continuous monitoring device which measures the number of ultrafine particles per cubic centimeter of ambient air[116], and 2) the TSI Condensation Particle Counter (CPC 3007.)[117] Both instruments are condensation particle counters that count nanoparticles. TSI Inc reports the effective range of measurement for the PTrak to be 0.02 microns (20 nm) to 1.0 microns aerodynamic diameter. Another study suggests an approximate range of 0.025-0.030 microns (25-30 nm).[118] Use of the TSI CPC supplemented the dataset when greater sensitivity in the smaller size range was required. The CPC 3007 counts nanoparticles down to 0.01 microns (10 nm.) Because of some laboratory studies suggesting DPFs to be ineffective at reducing nanoparticles (particularly where LSD (500 ppm was in use), the CPC 3007 was acquired for the chase studies to ensure that the full range of particle sizes were measured. PTrak data was collected in 1.0 second intervals in order to synchronize data output with videotape. The instrument was zeroed using a HEPA filter.

Our study results suggest that the while CPC is more sensitive to changes in particle numbers, the PTrak responded in a predictable way to the CPC. A time series plot and a linear regression of raw (uncorrected) CPC 3007 data vs PTrak data for three Boston highway commute runs exhibiting a wide range of concentrations (below) largely validates the use of the PTrak as a lower cost , albeit less quantitative surrogate for the more sensitive CPC 3007 for our general commuter study purposes.

Pearson's r^2 suggest that the PTrak response is predictable relative to the CPC (0.79-0.84.) In the equation shown in the regression plot below, Y= PTrak response and X=CPC response. The slope of the responses (also seen in the time series plot below) suggests that the PTrak underestimates particle number significantly (slopes = 0.77, 0.46, 0.60). Also noted was a consistent negative Y intercept. It should be noted that there is some evidence that CPC may incorrectly estimate particle number above 100,000 pt/cc and requires correction.[119] The CPC 3007 data in this report was only used for chase studies; all other UFP data presented is PTrak data which can be assumed from the above relationship to represent *conservative* estimates of exposures.





Above: one of three linear regressions comparing *uncorrected* CPC 3007 to PTrak response. Note that the PTrak underestimates particle count and therefore data in this paper likely represent conservative estimates of ultrafine particle/nanoparticle exposure

Black Carbon

Continuous black carbon was measured using two single channel Magee Scientific Aethalometers set up for maximum sensitivity.[120] A BGI Inc PM2.5 cyclone was attached to the inlet in each instrument. The aethalometers are portable single channel units set up for collecting data at maximum sensitivity and flow rates of 5 liters per minute. A 60 second interval was generally used to ensure stability of response. Criticisms leveled at the aethalometer (e.g. Borak, 2003[121] and Cohen, et al (2002)[122] appear unfounded as we found the portable units—when set up properly-- to provide stable measurements and the units were not sensitive to vibrations as reported in those studies.

Particle Bound PAH

Particle-bound PAH measurements were collected only during the second phase of Ann Arbor testing, using a portable Ecochem analytics PAS 2000CE[123] loaned by the Harvard School of Public Health. Data was recorded in 10 second intervals using a 5 second time constant.

Data Reporting

<u>All data presented in this paper are reported as 'net' concentrations after calculated ambient conditions have been subtracted</u>. CATF developed this simple approach to normalize each data set in an attempt to remove the effect of outdoor air quality. In this way we compare pollutant exposure contribution (rather than total exposure) from the commuting environment across different days, commuting modes and multiple cities.

As an example of how we handled the data, on hypothetical day 1 the commuter takes the train and the ambient outdoor $PM_{2.5}$ is 50 ug/m^3 and the total concentration on the train is 100 ug/m^3. On day 2, the same commuter *drives* to work and the outdoor $PM_{2.5}$ concentration is a much lower 10 ug/m^3 but in the car it's the same 100 ug/m^3. On day 1 in the train the net exposure is:100–50 = 50 ug/m^3 and on day 2 the car exposure is 100-10 = 90 ug/m^3. The net data tells us that the contribution from the commuting environment was higher in the car (90 ug/m^3) than in the train (50 ug/m^3). (Again this data is not real but is hypothetical for illustrative purposes)

CATF used a very simple methodology to estimate ambient conditions. Monitors were run—where possible—prior to the commute to acquire at least 5 minutes of ambient data in advance. Where this initial ambient data was successfully acquired, the mean of these 5 minutes was used as the ambient concentration and then simply subtracted from the entire run. In some instances acquisition of a stable ambient value was not possible where the starting environment was already polluted by local sources (e.g the monitors are started by necessity near a busy street, a parking garage, an indoor rail or bus station.) In these instances, the best estimate of ambient is made from inspection of the data set and ideally a mean 2 minute segment was used. This simplistic approach can yield net negative concentrations if the ambient conditions are changing during course of the run (e.g. from suburbs to city on car or rail). As a result, net negative concentration reported here simply represent an approximate zero contribution from the commuting environment. While this is not ideal, capturing a stable ambient is virtually impossible along the course of what may be a 10-30 mile commute. Thus, believe our method, with its inherent flaws, is still the best way to normalize data for outdoor ambient condition such that exposures can be compared across different days in different cities and across different commute modes. In general, data was collected at the maximum resolution possible depending upon instrument. For example for the Dust Trak, PTrak and CPC 3007 concentrations were acquired by the instruments using a 10-second time constants (smoothing) but data were recorded in 1-second intervals. PAH data was recorded in 10-second intervals, the lowest allowable setting for the instrument. For the aethalometer we set the instrument to record in 1-minute intervals due to a noisy signal at shorter collection interval settings experienced in our school bus exposure study. During data processing we further smoothed the 10-second Dust Trak, PTrak and CPC data using rolling 10-second means for plotting. In data tables, concentrations are also reported a 1-minute mean concentrations for all four measure pollutants as a more stable metric of exposure. Unless otherwise noted, data plotted in this report is in the following intervals:

- $PM_{2.5}$: 1 second intervals, 10 second averages
- Ultrafine particles: 1 second intervals, 10 second averages
- Black Carbon : 1 minute averages, 1 minute intervals
- PAH : 10 second intervals, 10 second averages

Videotaping Runs

A Sony model DSR-PDX-10 digital video camera was used to film most car commutes and vehicle chases. The DSR-PDX10 records a time signature in 30th of a second intervals on mini-dv format tape that can be used to synchronize with one second data from the TSI PTrak or Dust Trak instruments. Data is graphed in one second intervals using proprietary software written specifically for this purpose for CATF and merged with the videotape using Adobe Premier Pro software.

Videotaped Chase Studies: For comparative purposes, CATF undertook a series of chase studies investigations to document the benefits of diesel particulate filter technology for city transit buses in New York and Boston and New York City waste trucks. In a related investigation, CATF retrofit a box truck with a CRT, flushed the tank and ran ultralow sulfur diesel fuel. As noted above, a condensation particle counter TSI CPC 3007 was utilized to ensure sensitivity to the smallest ultrafine particles (nanoparticles) were measured (10 nm) given some research suggesting that DPFs might create sulfate nanoparticles in this size range under some conditions.[124]

Dashboard videotaping during chase studies.

Monitoring Scenarios

HIGHWAY/CAR COMMUTES. For car commutes, instruments were typically located inside a recent vintage (2005+) research vehicle (e.g. 2006 Dodge minivans in most Austin and Columbus tests) that showed no evidence of tailpipe influence or self-pollution. Car commutes consisted of a typical 30-45 minute suburb to downtown commute and reverse. In Austin Texas, the primary commute was along I-35 from Roundrock, TX to downtown Austin at the offices of Texas Public Citizen on West Avenue. The reverse commute was also a busy commute route (Austin to Roundrock the home of Dell computer, and its many thousands of employees.) In the case of Boston, most typically we followed a longer commute route (more representative of the large metropolitan area) from the suburbs to the southwest of the city from I-495 to highway 24, to to I-95 (128), then along the Southeast Expressway (I-93) into a downtown Boston parking garage. Several commutes were undertaken from the north of Boston as well. In Columbus, the commute route was into the city from the north along I-71 into the downtown on High Street by the Civic Center.

The following scenarios were examined in car commutes utilizing CATF’s two sets of monitoring equipment:

- Runs with windows open and runs with windows closed;

- Simultaneous interior and exterior exposures;
- Synchronous comparisons of car commuting conditions relative to a stationary outdoor location in a downtown area away from a main roadway;

COMMUTER RAIL: For rail (as well as bus and ferry commutes) a roll-round suitcase or backpack were used to investigate exposures not only as a convenience, but so as not to alarm commuters. For portability in some instances the back pack was used with a subset of the monitors (usually $PM_{2.5}$ and UFP) due to the unwieldy size of the black carbon monitor (aethalometer). Data-logging was started and carried via backpack or roll-around on to the platform and the train. Researcher followed round-trip routes into the city and back (or vice-versa) such that the commuter cars were pushed by the locomotive (commonly referred to as a "push-train") inbound and pushed back to the suburbs but the locomotive (commonly referred to as a"pull train").

TRANSIT BUS: Interior air quality was monitored inside Boston and Columbus OH transit buses using both the roll-around and backpack setups. Transit buses in Boston were run on ultralow sulfur diesel fuel and were largely equipped with diesel particle filters (or run on compressed natural gas). A small number of conventional buses remain in the fleet and CATF was able to ride a few of these for the purposes of the project. In contrast, Columbus OH's fleet consisted of conventional transit buses run on a conventional fuel–biodiesel fuel mix. During the October 2006 runs, the fuel mix was B-90 or 90% biodiesel, 10% conventional fuel.

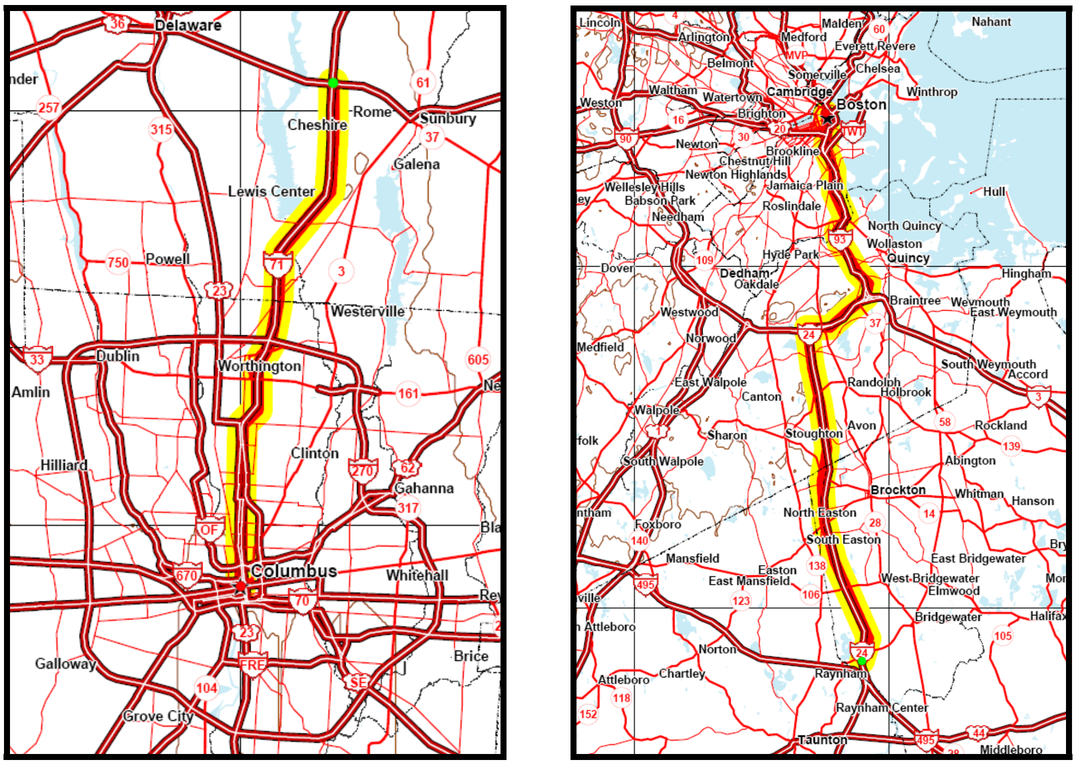
MARINE FERRY. CATF investigated air quality on a half dozen rides on Boston harbor commuter ferries in July 2006 including the Boston to Hingham commuter ferry and the F4 ferry from Long Wharf to Charlestown. Similar to rail and transit bus investigations, backpack monitoring was used to measure diesel particulate matter exposures.

PEDESTRIAN: CATF's investigations on foot in Boston and Columbus, utilized similar equipment as the London taxi study, including the Dust Trak and the PTrak monitors loaded in a backpack with air inlet hoses extending outside of the pack. Researchers followed a typical route within the downtown areas from residential to commercial locations, separated by approximate 20-30 minute walking times.

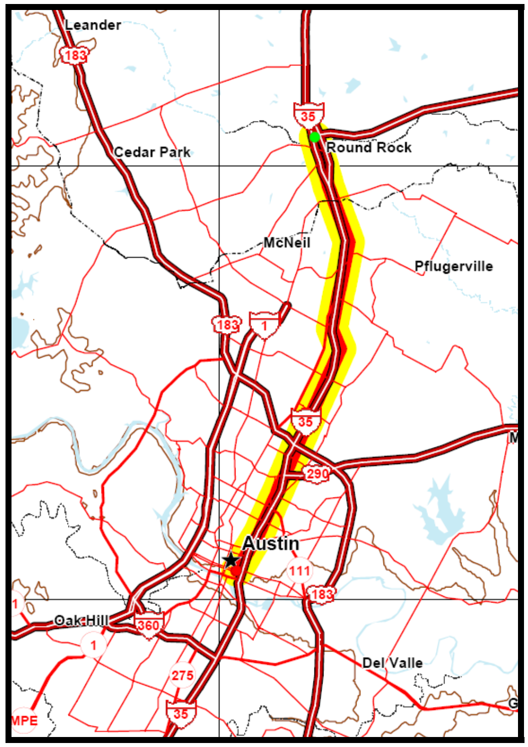


Left: roll-around monitoring in portable luggage. Center: CATF researcher setting up particle monitoring equipment to monitor both cabin and outdoor air simultaneously with 2 sets of equipment. Right: Backpack monitoring.

Highway Commute Routes



Standard highway commute routes for Columbus, OH (left), Boston, MA (right).



Above: Standard highway commute route in Austin TX between Austin and Round Rock

Field Data Observations--by Pollutant

Four tables below, organized by pollutant, summarize mean and peak pollutant concentrations averaged across all runs. The following is a brief discussion of observations by pollutant taken from the study as a whole. Raw concentrations and net concentrations (with ambient background concentration for each run subtracted) are shown.

Fine Particles ($PM_{2.5}$)

In general, fine particle exposure factors (mean net pollutant concentration divided by the outdoor ambient air concentration) were much lower for $PM_{2.5}$ than for other three pollutants. Fine particle concentrations in cars open to outdoor air and to pedestrians, averaged about one-and-a half times levels measured in the ambient air (i.e. 40 % higher), 2-3 times higher in transit buses trains and ferries. $PM_{2.5}$ levels in electrified subways were elevated presumably by re-suspended (non-combustion) rail dust given the lack of combustion sources. None of the other 3 pollutants were elevated in electrified underground subways in New York and Boston.

Bus results measured in the summer and fall were affected by fine particle pollutants from other vehicles and road dust entering thorough open windows, explaining why for some runs, levels were high in vehicles equipped with particle filters. Commuter rail exposures were affected by incursion of particles when doors were opened at the platform, especially where the platform is partially (Porter Square Station Boston MBTA Rail) or fully enclosed (Back Bay Station, Boston MBTA Commuter Rail.) This explains pollutant build up on “push” train runs (locomotive in rear—see discussion below.)

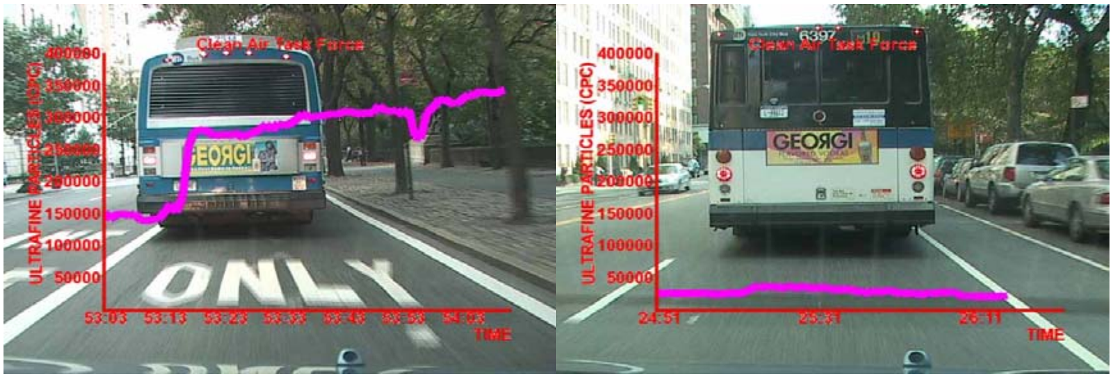
The relatively high regional levels of ambient $PM_{2.5}$ pollution may help explain why $PM_{2.5}$ factors are low relative to the other three pollutants which appear to be local rather than regional in nature. However, chase studies also suggest that temporal changes in $PM_{2.5}$ are subdued relative to ultrafine particles and tend to be related to accelerations and load rather than steady state operation. Moreover, in the box truck investigation (where CATF chased a box truck before and after DPF retrofit) levels as measured close to the tailpipe before being retrofit with a DPF were extremely high (~5000 ug/m3) compared levels following the retrofit (~25 ug/m3.)—suggesting a greater than 99% removal efficiency (note these monitors are not designed for in-use testing to quantitatively measure concentrated tailpipe emissions.) We hypothesize from this observation that $PM_{2.5}$ mass may be rapidly diluted after release from the tailpipe. This is consistent with observations from the CATF school bus retrofit study which showed that, unlike for ultrafine particles, $PM_{2.5}$ was rarely observed in the bus cabin from the tailpipe despite high levels near the tailpipe itself.

In summary, these data suggest that $PM_{2.5}$ is not the sensitive marker of near-field diesel exhaust that ultrafine particles are.

Ultrafine particles (nanoparticles)
As noted in methodology section, ultrafine particles (UFPs) were measured using both the Ptrak (down to 20 nm) and CPC 3007 (down to 10 nm). Both instruments were sensitive to changes in UFPs in all commute modes. Average UFP factors across all highway commutes were consistent across cities with mean concentrations 4 times the ambient outdoor air and average peak concentrations roughly 30 times the outdoor air. For commuter trains, pull trains (locomotive in front) average mean UFPs were 15-17 times the outdoor air, and average peak levels 49-60 times the outdoor air. For push trains, mean average UFP levels ranged from 4-5 times the outdoor air-- much lower but still strongly affected by influx of pollution in enclosed rail stations. For conventional transit buses average mean exposures were 4 times the outdoor ambient air, and *for DPF-equipped buses the same as outdoor air*. However average peak levels were 11 times outdoor air for conventional buses and 3 times outdoor air for DPF –equipped buses, the later being influenced by sources in the road in front of the bus. The pilot marine ferry runs suggest UFP levels averaging 3 times the outdoor air and for pedestrian/walking commutes 2-3 times the outdoor air substantially away from the sidewalk.

Thus, large fluctuations in ultrafine particles were observed across all mode of commuting; of the four pollutants measured UFPs were perhaps the most sensitive indicator of diesel exhaust from changes in truck traffic, upon acceleration in commuter trains, when buses or trucks passed walking commuters, or when conventional buses stopped and doors opened. In cars and pull trains. Our observations suggest, therefore, UFPs to be an excellent indicator of fresh diesel exhaust.

CATF UFP INVESTIGATION RELATIVE TO DPFs. Recent investigations have documented creation of sulfate nanoparticles, particularly where low sulfur diesel fuel (500 ppm) was utilized or when using first generation DPFs (CRTs). CATF undertook four chase studies comparing retrofit vehicles to conventional vehicles. In order to ensure maximum sensitivity, CATF used a TSI CPC 3007, sensitive to 10 nm—a levels that should be capable of sensing nanoparticles in the lowest potential size distribution bracketing 10 nm. Chases of DPF-equipped transit buses in New York and Boston and waste trucks in New York City found them to be “clean” with no higher than the outdoor ambient air (see videos with data overlays at www.catf.us/goto/noescape.



Illustrating the ultrafine particle reduction benefit in DPF-equipped New York City transit buses. Left: ultrafine particle (nanoparticle) buildup in chase car from conventional bus exhaust in New York City MTA bus (for videos see www.catf.us/goto/noescape/). Right: No detectable ultrafine particle plume in chase car behind New York City buses equipped with DPFs. Results were similar for Boston transit buses and New York City waste trucks but conflicting evidence was found for a CATF box truck retrofit (see text).

However, in CATF’s box truck retrofit experiment, after installing a used 2000 vintage Johnston-Matthey CRT transit bus DPF on a class-5 5.2 liter Caterpillar engine-equipped delivery truck with a 23 foot box, high levels ultrafine particles remained detectable in the chase car. Informed by the owner of the vehicle that the fuel was a cold-weather combination fuel (ULSD with kerosene additive) CATF flushed the fuel tank to ensure 100% 15 ppm ultralow sulfur diesel fuel. However, this failed to eliminate the UFPs. Taking apart the DPF prior to the runs revealed no cracks in the honeycomb filter but significant sulfate buildup in the outlet portion of the DPF. The sulfate was wiped out and subsequently no sulfate was seen in the outlet after CATF’s 2 hours of runs. Possible explanations for the UFPs measured behind the DPF-equipped box truck include: 1) the DOC portion of the CRT was worn out, 2) the cold temperatures (0-23 degrees F) were cold enough to create condensation nuclei not present in warmer temperatures, 3) the previously used honeycomb mechanical filter failed, 4) the DPF was a CRT, not a CCRT and therefore had inadequate catalyst. CATF plans to continue investigations into this issue in the future.

Black Carbon

Changes in black carbon levels were less sensitive than for the other three pollutants since the data recording interval and averaging times were 1 minute. Moreover, the aethalometer is a cumbersome instrument and was not carried on all bus routes. Black carbon levels were elevated relative to outdoor ambient concentrations for all modes of commuting. Mean levels ranged from a factor of 6 higher than outdoor air in highway commutes and marine ferries, a factor of 3 in DPF-equipped buses (with windows open and affected by outdoor sources—no BC data for conventionals), a factor ranging from 6-17 in commuter trains, and a factor of 2 in one pedestrian commute. Black carbon built up in pull trains and was particularly concentrated at Boston’s underground and poorly ventilated Back Bay Station which affected push and pull trains alike. Black carbon levels were not investigated during chase studies.

Particulate PAH

Harvard’s studies in Boston (referenced elsewhere in this paper) have suggested PAH to be a sensitive indicator of diesel exhaust. Our data suggest same conclusion. However, under hard acceleration, some PAH increases also come from cars, especially super emitters. PAH levels were elevated relative to outdoor ambient concentrations for all modes of commuting. Mean levels ranged from a factor of 5 higher than outdoor air in highway commutes. Factors ranging from 2-15 were found in commuter trains, and a factor of 12 in conventional buses and 7 in DPF-equipped buses. PAH concentrations were elevated by an average factor of 2 relative to outdoor air in one pedestrian commute and a factor of 17 in two ferry commutes. PAH exposure levels were not investigated during chase studies

Summary Data Tables

Fine Particles($PM_{2.5}$)	#		Mean	Mean		Max 10 sec	Max 10 sec
(ug/m3)	Runs		RAW	NET		RAW	NET
All-Run Means							
Car Commutes							
Austin-windows open	15		55	19		331	295
Austin-windows closed-recirc with AC	13		66	14		137	85
Austin--MOPAC-windows open (no trucks)	7		30	5		173	149
Boston--windows open	16		35	10		221	209
Boston-windows closed - recirc w/ & w/o AC	12		34	5		94	64
Boston-windows up vent	2		65	20		186	141
Columbus-windows open	34		48	7		146	134
Columbus --windows closed recirc with AC	8		58	-50		260	152
Rail Commutes							
Boston--locomotive in front (pull)	6		70	13		359	302
Boston--locomotive in rear (push)	6		56	7		268	223
NYC--locomotive in front (pull)	3		13	4		207	197
NYC--locomotive in rear (push)	2		5	-3		287	279
Bus Commutes							
Boston- Conventional	5		26	15		111	100
Boston- CNG	10		24	-3		87	60
Boston- DPF	9		55	38		307	202
Columbus- B90 biodiesel	15		36	7		85	56
Boston Bus Stations	7		23	5		217	198
Ferry Commutes							
Boston	3		214	122		1,294	1,202
Pedestrian Commutes							
Boston- Pedestrian Commute	6		14	4		118	108
Columbus-Pedestrian Commute	3		21	4		167	150
Tunnels							
Boston Tunnels Recirc	4		21	1		48	18
Boston Tunnels windows open	7		83	32		179	128
Boston Back Bay Station Underground Track	2		576	503		1,297	1,225
Subway Electric Rail							
Boston Subway	3		47	2		111	67
NY Subway	3		55	46		729	721

Ultrafine Particle Number	#		Mean	Mean		Max 1 sec	Max 1 sec
(particles/cc)	Runs		RAW	NET		RAW	NET
All-Run Means							
Car Commutes							
Austin-windows open	15		25,928	18,747		192,171	185,399
Austin-windows closed-recirc with AC	13		21,248	15,932		57,204	51,888
Austin--MOPAC-windows open (no trucks)	7		8,671	8,216		119,881	114,669
Boston--windows open	16		29,401	20,003		237,813	217,838
Boston-windows closed - recirc w/ & w/o AC	12		17,429	10,815		67,233	60,620
Boston-windows up vent	2		28,981	20,131		129,500	120,650
Columbus-windows open	34		43,337	22,372		195,879	150,612
Columbus --windows closed recirc with AC	8		14,328	1,905		20,282	7,859
Rail Commutes							
Boston--locomotive in front (pull)	6		118,218	99,073		383,500	376,304
Boston--locomotive in rear (push)	6		13,607	13,640		109,395	175,571
NYC--locomotive in front (pull)	3		137,366	124,465		398,053	385,152
NYC--locomotive in rear (push)	2		51,591	31,281		221,800	201,600
Bus Commutes							
Boston- Conventional	5		83,227	65,177		155,400	137,350
Boston- CNG	10		23,452	12,410		51,714	39,368
Boston- DPF	9		29,788	6,854		69,040	43,524
Columbus- B90 biodiesel	15		17,196	5,339		50,571	38,715
Boston Bus Stations	7		37,169	21,520		131,810	126,864
Ferry Commutes							
Boston	3		63,032	50,588		409,250	396,856
Pedestrian Commutes							
Boston- Pedestrian Commute	6		30,273	14,755		205,500	189,982
Columbus-Pedestrian Commute	3		22,502	16,665		235,333	227,787
Tunnels							
Boston Tunnels Recirc	4		33,671	4,115		58,163	16,862
Boston Tunnels windows open	7		48,043	34,740		257,533	175,091
Boston Back Bay Station Underground Track	2		173,513	166,123		454,000	446,611
Subway Electric Rail							
Boston Subway	3		11,909	2,667		19,833	10,591
NY Subway	3		49,045	33,583		239,200	223,738

Black Carbon (ng/m³)	**#**		**Mean**	**Mean**		**Max 1 min**	**Max 1 min**
	Runs		**RAW**	**NET**		**RAW**	**NET**
All-Run Means							
Car Commutes							
Austin-windows open	15		4,049	3,540		18,416	17,856
Austin-windows closed-recirc with AC	13		4,288	3,511		12,377	11,534
Austin--MOPAC-windows open (no trucks)	7		1,733	1,022		8,677	7,966
Boston--windows open	16		3,104	2,187		16,768	15,094
Boston-windows closed - recirc w/ & w/o AC	12		2,292	1,539		8,344	7,577
Boston-windows up vent	2		11,952	11,237		29,604	28,889
Columbus-windows open	34		3,732	2,840		10,721	11,238
Columbus --windows closed recirc with AC	8		2,485	1,211		4,091	2,816
Rail Commutes							
Boston--locomotive in front (pull)	6		8,264	7,684		26,204	25,624
Boston--locomotive in rear (push)	6		2,996	2,227		12,283	11,515
NYC--locomotive in front (pull)	3		-	-		-	-
NYC--locomotive in rear (push)	2		-	-		-	-
Bus Commutes							
Boston- Conventional	5		-	-		-	-
Boston- CNG	10		1,092	524		2,731	2,163
Boston- DPF	9		1,642	1,090		3,159	2,606
Columbus- B90 biodiesel	15		1,919	1,262		4,320	3,734
Boston Bus Stations	7		-	-		-	-
Ferry Commutes							
Boston	3		6,014	4,847		47,642	46,682
Pedestrian Commutes							
Boston- Pedestrian Commute	6		765	382		5,839	5,456
Columbus-Pedestrian Commute	3			-			-
Tunnels							
Boston Tunnels Recirc	4		2,117	4,376		4,549	13,721
Boston Tunnels windows open	7		8,146	4,373		24,105	14,951
Boston Back Bay Station Underground Track	2		46,599	46,265		158,376	157,931
Subway Electric Rail							
Boston Subway	3		-	-		-	-
NY Subway	3		-	-		-	-

PAH (ng/m^3)	#		Mean	Mean		Max 10 sec	Max 10 sec
	Runs		RAW	NET		RAW	NET
All-Run Means							
Car Commutes							
Austin-windows open	15		117	105		947	934
Austin-windows closed-recirc with AC	13		178	147		683	651
Austin--MOPAC-windows open (no trucks)	7		17	8		156	147
Boston--windows open	16		79	65		540	526
Boston-windows closed - recirc w/ & w/o AC	12		74	51		303	281
Boston-windows up vent	2		92	92		290	290
Columbus-windows open	34		108	85		430	408
Columbus --windows closed recirc with AC	8		69	33		189	158
Rail Commutes							
Boston--locomotive in front (pull)	6		183	170		685	673
Boston--locomotive in rear (push)	6		40	30		494	483
NYC--locomotive in front (pull)	3		58	39		226	207
NYC--locomotive in rear (push)	2		20	-2		155	131
Bus Commutes							
Boston- Conventional	5		48	43		89	97
Boston- CNG	10		44	34		194	208
Boston- DPF	9		63	53		284	316
Columbus- B90 biodiesel	15		36	19		181	165
Boston Bus Stations	7		37	30		164	290
Ferry Commutes							
Boston	3		132	124		982	974
Pedestrian Commutes							
Boston- Pedestrian Commute	6		51	42		297	285
Columbus-Pedestrian Commute	3		14	9		188	183
Tunnels							
Boston Tunnels Recirc	4		125	162		883	810
Boston Tunnels windows open	7		-	-		-	-
Boston Back Bay Station Underground Track	2		429	418		1,677	1,666
Subway Electric Rail							
Boston Subway	3		23	2		143	121
NY Subway	3		-	-		-	-

Exposure Factors Table

POLLUTANT		PM2.5			Ultrafine Particles			PAH			Black Carbon		
		# runs	Peak	Average	# runs	Peak	Average	# runs	Peak	Average	#runs	Peak	Average
CAR													
Austin	I-35	15	8	1.4	15	35	4	4	22	3	15	33	7
Boston	I-93	15	14	1.7	15	38	4	6	60	9	14	35	6
Columbus	I-71	31	5	1.2	34	19	4	17	14	4	25	12	5
all-city mean			*9*	*1.4*		*30*	*4*		*32*	*5*		*27*	*6*
BUS													
Boston	Conventional	5	11	2.4	5	11	4	1	22	12	n/a	n/a	n/a
	CNG	11	5	1.1	8	5	2	7	19	5	2	5	2
	DPF	9	14	3.4	5	3	1	6	30	7	4	7	3
RAIL													
Boston	Push	6	30	3.4	6	22	3	4	54	4	4	22	6
	Pull	6	46	4.5	6	61	20	5	69	15	4	45	17
New York	Push	2	28	1.0	2	19	5	2	11	2	n/a	n/a	n/a
	Pull	3	29	1.7	3	49	15	3	12	3	n/a	n/a	n/a
FERRY													
Boston		2	14	2.6	3	21	3	2	117	17	1	50	6
PEDESTRIAN													
Boston		6	12	1.5	5	19	2	1	43	8	1	15	2
Columbus		3	16	1.4	3	29	2.8	1	34	2.5	n/a	n/a	n/a

The data shown in the table represent exposure factors—the number of times the raw exposure concentration exceeds the outdoor air ambient outdoor concentration for each pollutant. Data were averaged across all runs for each mode of transit (For cars commutes windows open runs.) The table also gives number of runs the data was averaged across to arrive at the factor. (Note this is the most recent revision of this table, February 28, 2007, updating the table in the No Escape report.)

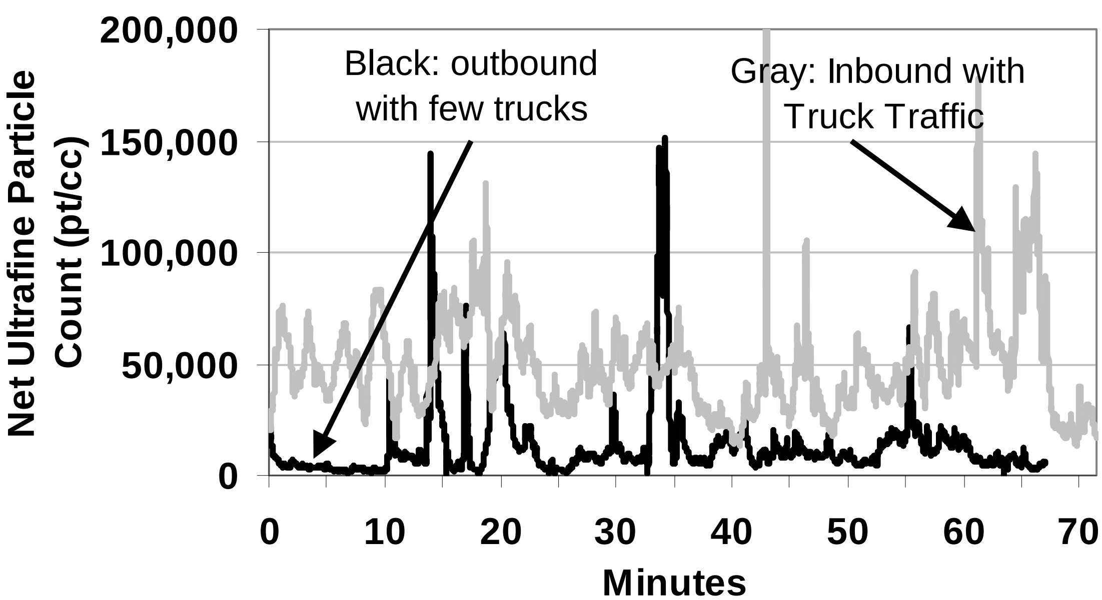
--DISCUSSION BY COMMUTE MODE--

HIGHWAY COMMUTES

Highway commute investigations were undertaken in Austin TX, Boston, MA and Columbus OH. In the three cities, 79 hours of data were recorded over 107 runs. CATF researchers assessed exposures to particulate exhaust in 2006 model year rental minivans on a typical inbound commute in the three cities. The monitoring vehicle was equipped with continuous (real time) particle monitors to assess exposures to PM $_{2.5}$ (fine particles), ultrafine particles (nanoparticles), black carbon soot and particulate polycyclic aromatic hydrocarbons (PAH), a carcinogenic air toxic. A second set of equipment allowed for comparative experiments such as: 1) cabin air vs. outdoor roadway air, 2) interstate commute vs. roads banning trucks, 3) roadway air vs. downtown air at a fixed location. Measurements were made in several tunnels as well. The test vehicle drivers were instruct to drive “normally” at ambient roadway speed, typically 55-65 mph and predominantly in the middle lane, except when passing, without regard to truck and bus traffic in an attempt to avoid bias from tracking air behind trucks directly. Our work supports existing research suggesting that drivers are exposed to substantially higher levels of diesel particles on the roadway than in other situations. In the car commute runs we found (See data tables. Unless otherwise noted, car commute data is reported is for windows open):

- Highest cabin levels were typically generated during hard accelerations, such as in moderate stop and go accordion-like traffic, or at high speeds under intense load, especially climbing hills.
- Exposures were approximately proportional to truck volume. Under conditions in all 3 cities with very heavy car traffic and few or no trucks, measured pollutants were low, suggesting that the diesel vehicles were by far the largest contributors to particles, with the exception of a few super-emitter cars with visible smoke plumes. For example, low levels of pollutants were observed on Boston’s I-93 Southeast Expressway when trucks were minimal (see plot below.) An Austin roadway (MoPac) banning heavy duty trucks were measurably less polluted.
- Car commuters on I-35 were exposed to higher exposures than in the downtown area with roughly 6 times the black carbon and PAH levels in downtown Austin and 4 times ambient outdoor levels for UFPs , averaged over the approximate 45 minutes of the commute.
- In general, car commutes averaged across all cities resulted in mean net exposures that ranged from multiples of 4 times the outdoor ambient conditions for ultrafine particles (UFP), 5 times for PAH particles and 6 times for black carbon. Averaged peaks during these commutes were much higher, multiples of approximately 27-32 times ambient for these three pollutants.
- $PM_{2.5}$ levels do not appear to vary as dramatically as UFP, BC and PAH. Across all runs, mean $PM_{2.5}$ levels were 1.4 times higher than the outdoor air and 9 times ambient for average peaks. $PM_{2.5}$ exposures averaged 7-19 ug/m^3 above ambient.
- Where the short-term regional background $PM_{2.5}$ was high (e.g. a few >60-125 ug/m^3 days in Columbus and Boston) the $PM_{2.5}$ signal in traffic appeared to be drowned out.

- UFP levels were very sensitive to the presence of diesel vehicles. For the 65 highway runs UFP exposures averaged approximately 20,000 particles / cc above ambient across the three cities; peak UFP exposures averaged 114,000-185,000 pt/cc above ambient across all cities.
- Black carbon particles averaged 2- 3.5 ug/m^3 above ambient background. PAH exposures were 65-105 ng/m^3 above ambient.
- For 2 runs with windows closed, but with ventilation open, levels penetrated and appeared to persist in the vehicle. UFP, $PM_{2.5}$, black carbon, PAH levels averaged across all cites were respectively: 20,000 pt/cc, 20 ug/m^3, 1.5 ug/m^3, and 92 ng/m^3, similar to window-open values.
- Diesel particles penetrated the test vehicle cabin with windows closed and air conditioning on (without recirculate).
- Air recirculation appears effective a reducing exposure to particles. For car commutes with air recirculate on, Cabin $PM_{2.5}$ was well below ambient under very high ambient $PM_{2.5}$ conditions in Columbus at ~ 125 ug/m^3. UFP exposures averaged across all runs were 1000 particles/cc (20 X less than for windows open); Black carbon exposures were 1-3.5 ug/m^3. PAH exposures ranged from 8-51 ng/m^3. $PM_{2.5}$ exposures were 14 – 50 ug/m^3.



Example of ultrafine particle numbers in 2 contrasting Boston commutes: inbound on 93 with steady heavy duty diesel traffic and outbound on 93 with only a few diesel peaks.

Low ultrafine particle exposures along the Southeast Expressway in Boston during a southbound afternoon commute with very low truck volume. (Data shown for 1 minute video overlay segment.)

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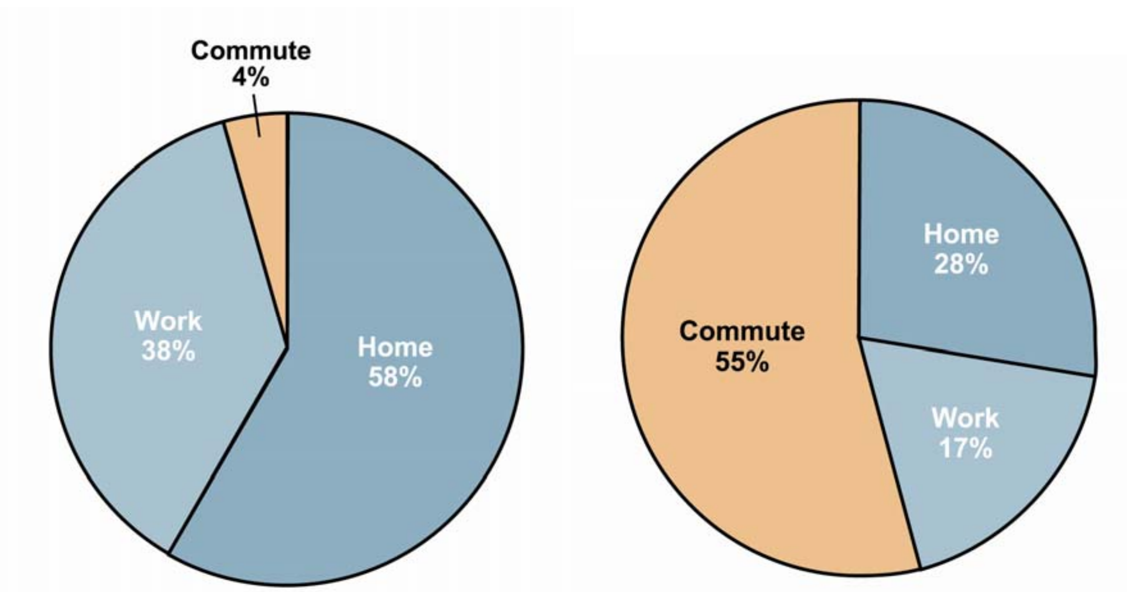
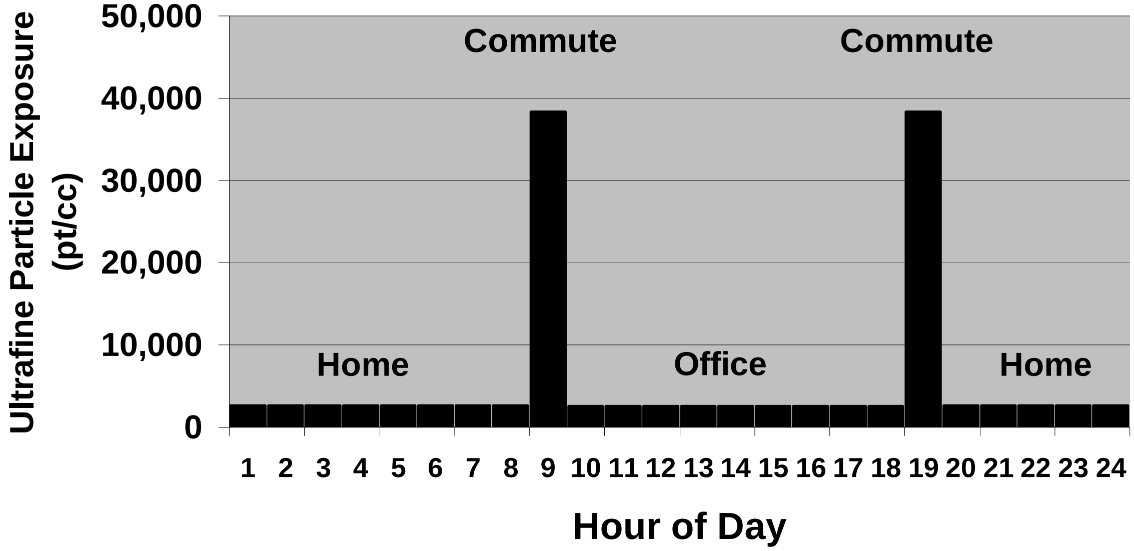


Above: Columbus pie charts based on CATF field data show that during 4% percent of the time spent commuting to Columbus along I-71 resulted in more than half of the exposure to ultrafine particles.



Above: Columbus commuter exposure model summarizing 24 hour ultrafine particle exposure.

	Hours	Time %	Mean UFP	Conc-Hrs	Exposure %
Home	14	58%	2,669	37,370	28%
Office	9	38%	2,528	22,748	17%
Commute	1	4%	74,217	74,217	55%

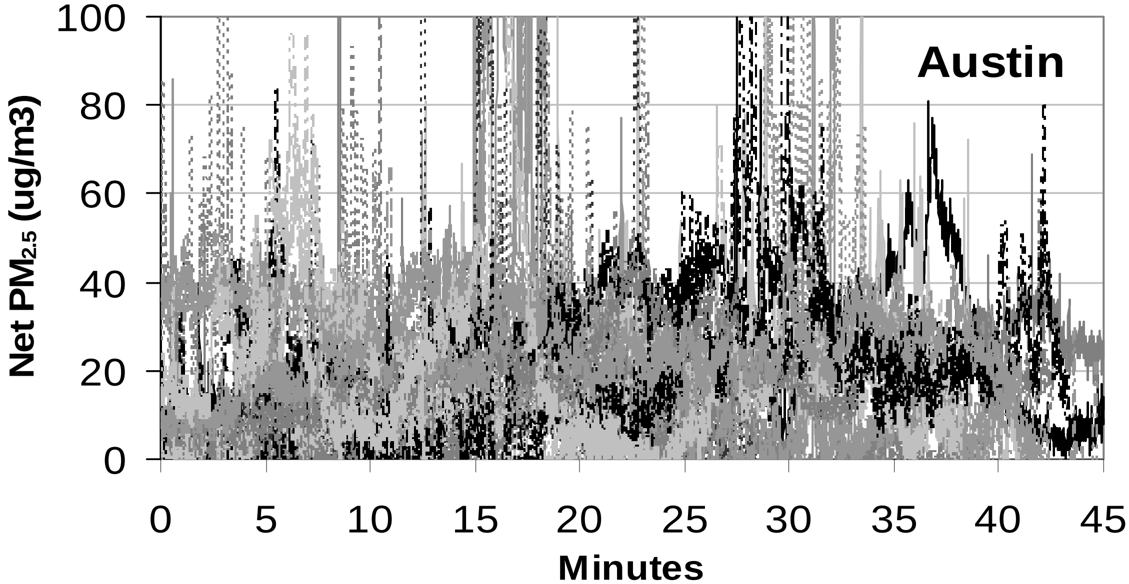
Above: Columbus pie chart data table. Mean data from 9 CATF highway commute runs. Assumes 14 hours spent at a Columbus home, 9 hours in a downtown Columbus office and 1 hour commuting (30 min each way).

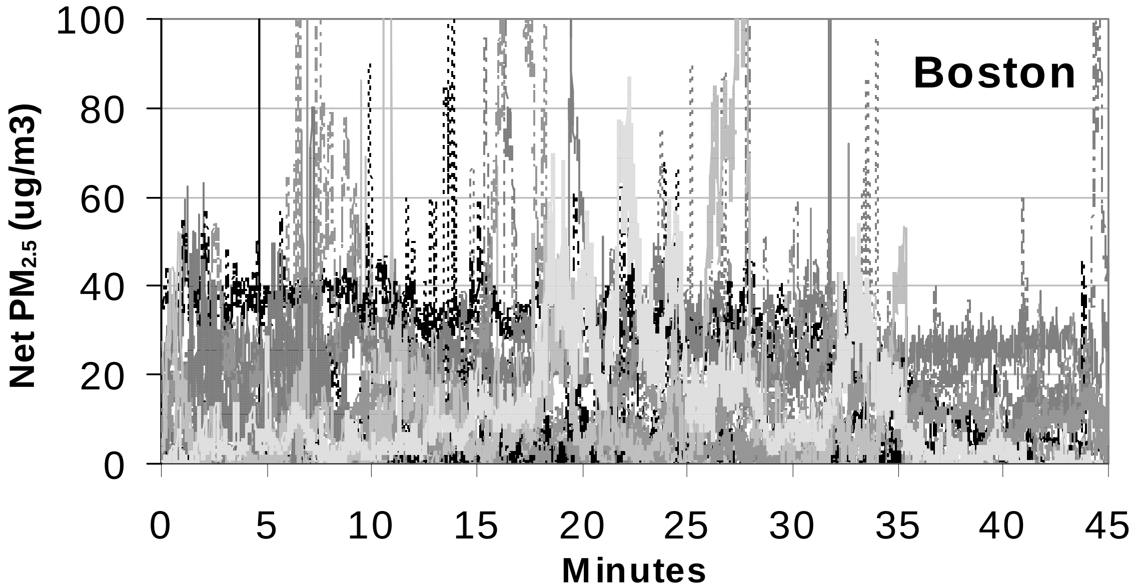
COMPOSITE CAR COMMUTE TIME SERIES PLOTS BY CITY

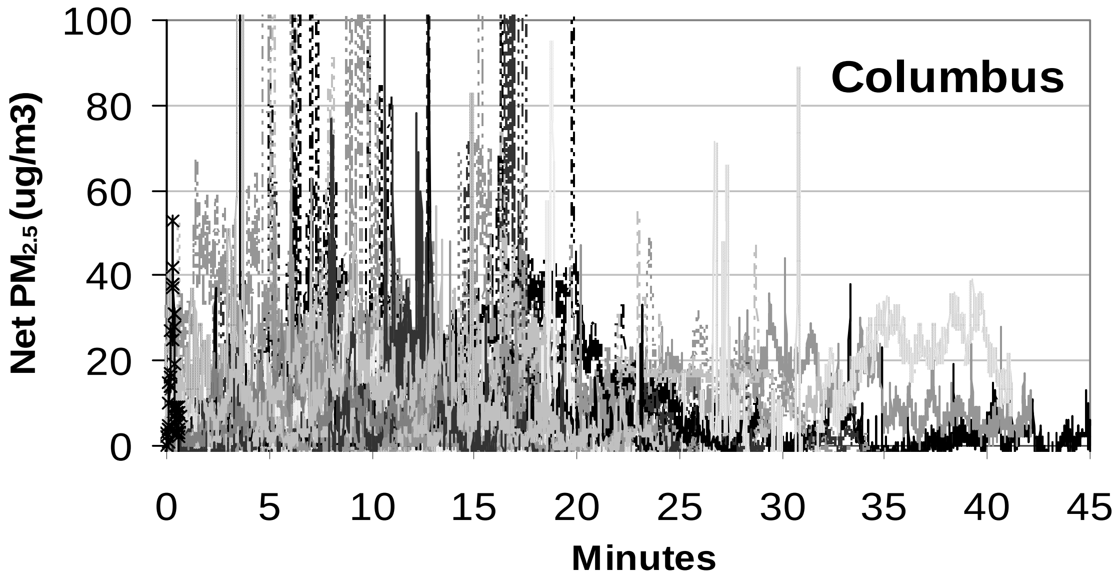
The following plots are intended to indicate the range and weight of data and are not intended for tracking individual runs or for ranking cities. Data is for runs where outdoor air is allowed in cabin (e.g. windows open.)

FINE PARTICLES-HIGHWAY COMMUTES ($PM_{2.5}$)

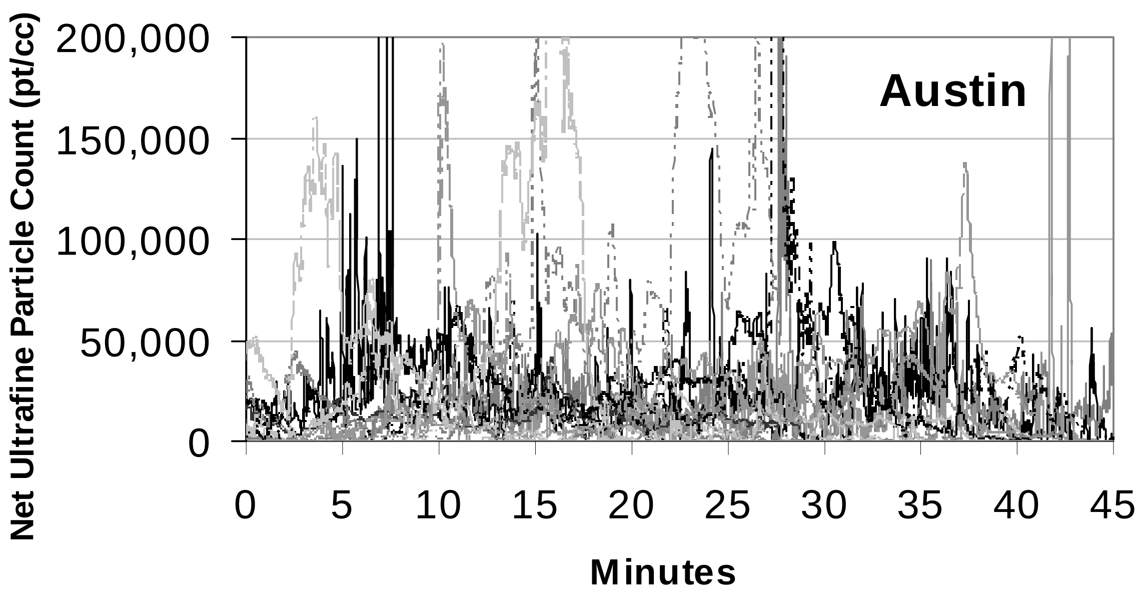
Number of runs plotted: Austin: 16, Boston: 18, Columbus: 32.

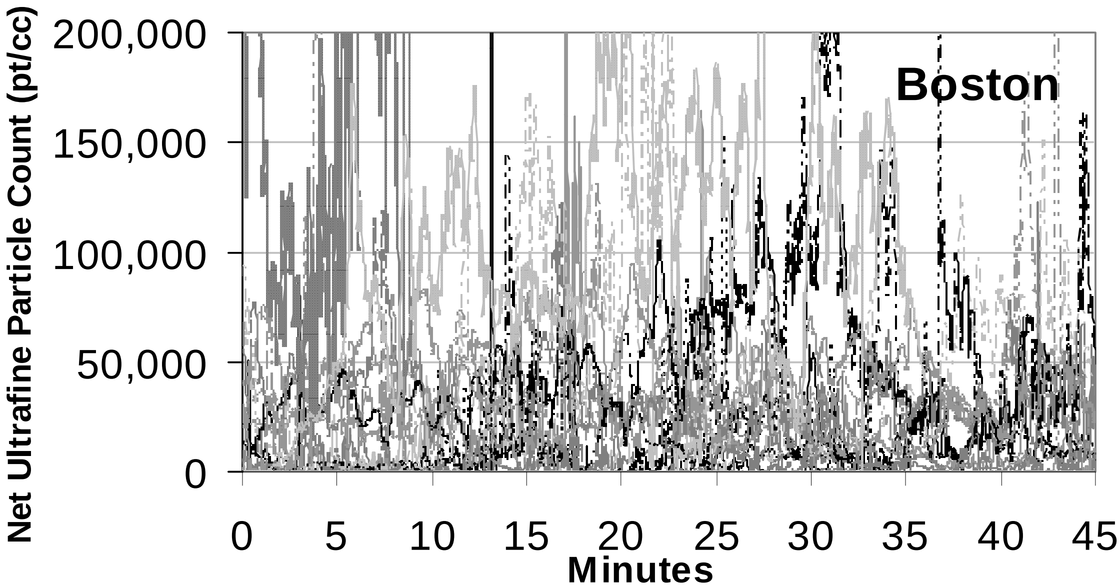




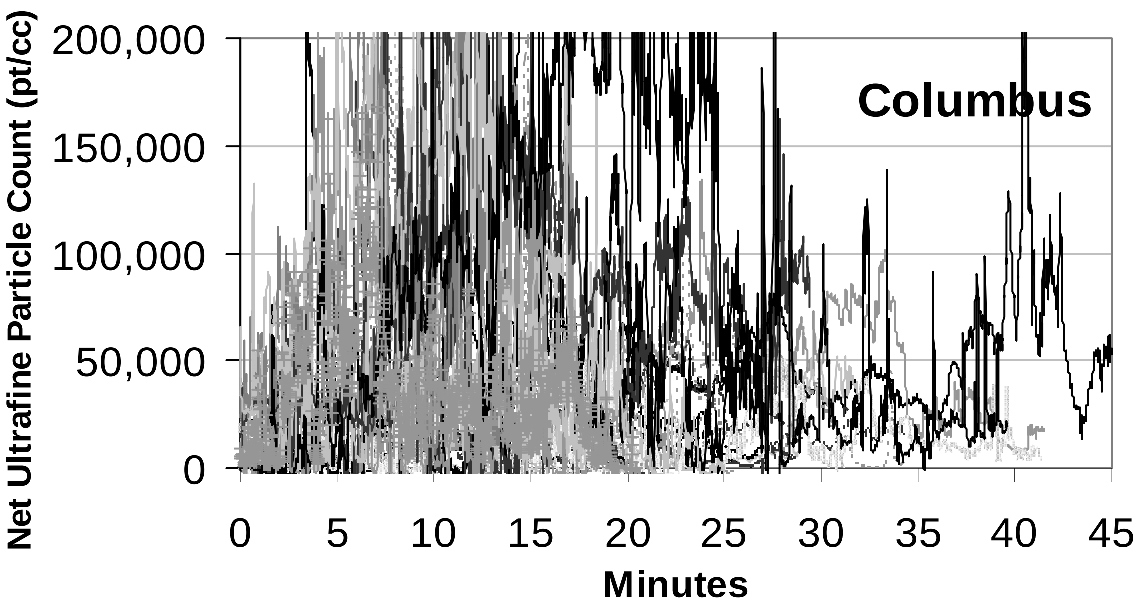


<u>ULTRAFINE PARTICLES/NANOPARTICLES-HIGHWAY COMMUTES</u>.
Number of runs plotted: Austin: 16, Boston: 17, Columbus: 32





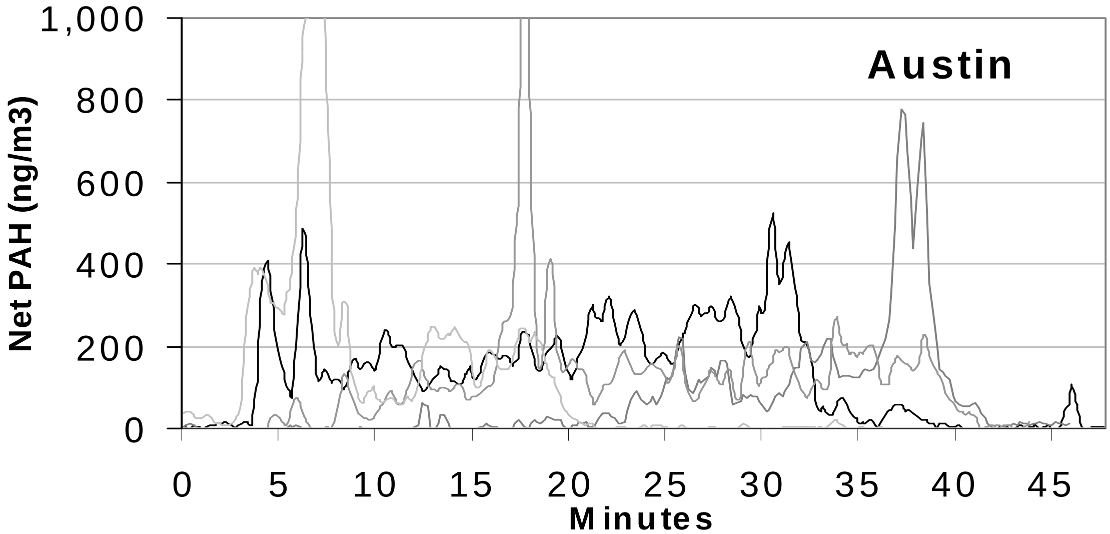
Boston
Net Ultrafine Particle Count (pt/cc)
200,000
150,000
100,000
50,000
0
0
5
10
15
20
25
30
35
40
45
Minutes

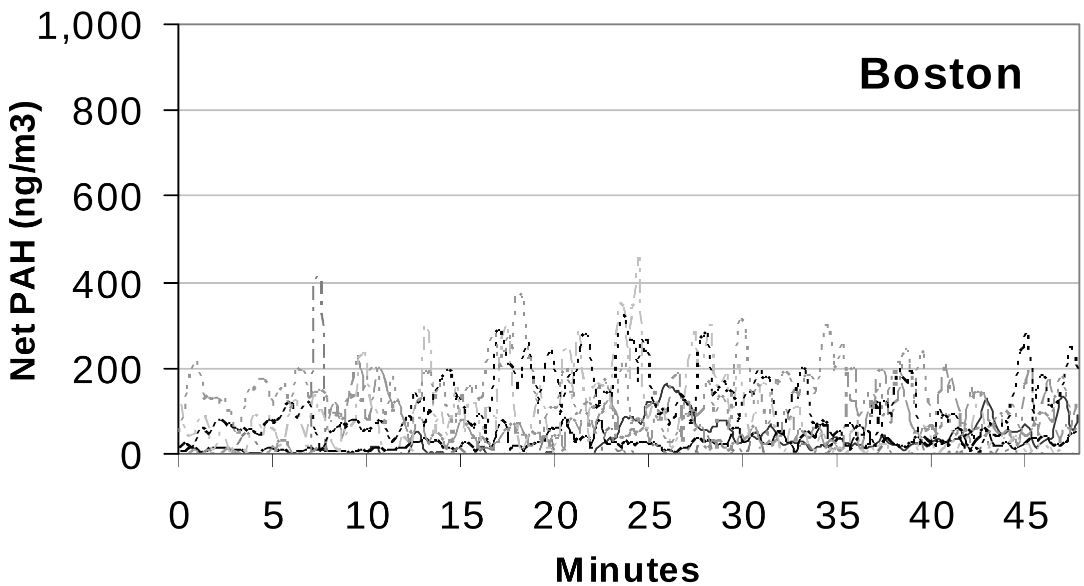


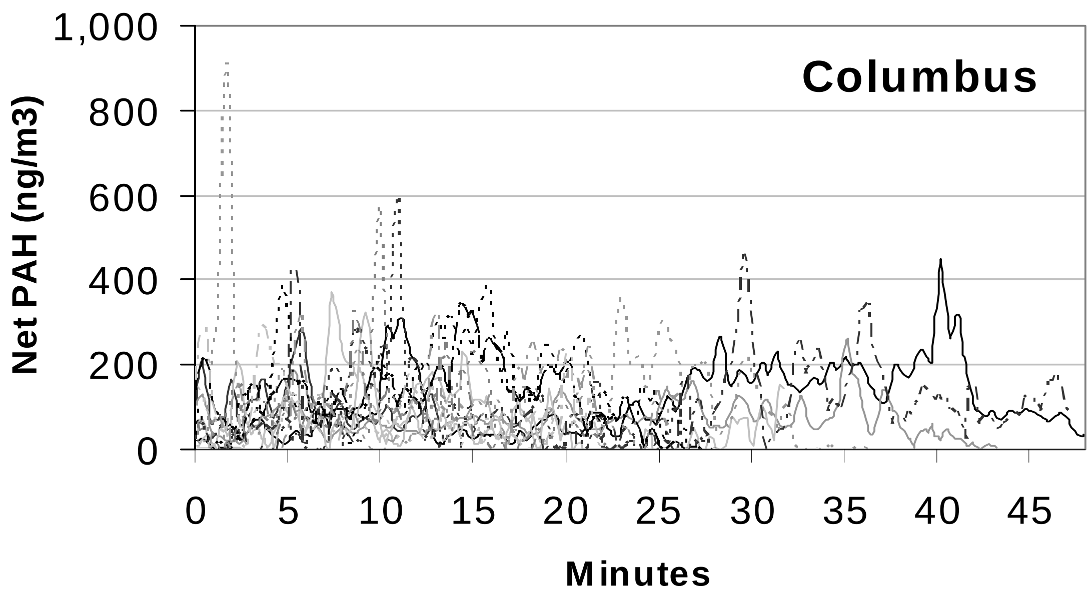
Columbus
Net Ultrafine Particle Count (pt/cc)
200,000
150,000
100,000
50,000
0
0
5
10
15
20
25
30
35
40
45
Minutes

PARTICULATE PAH HIGHWAY COMMUTES

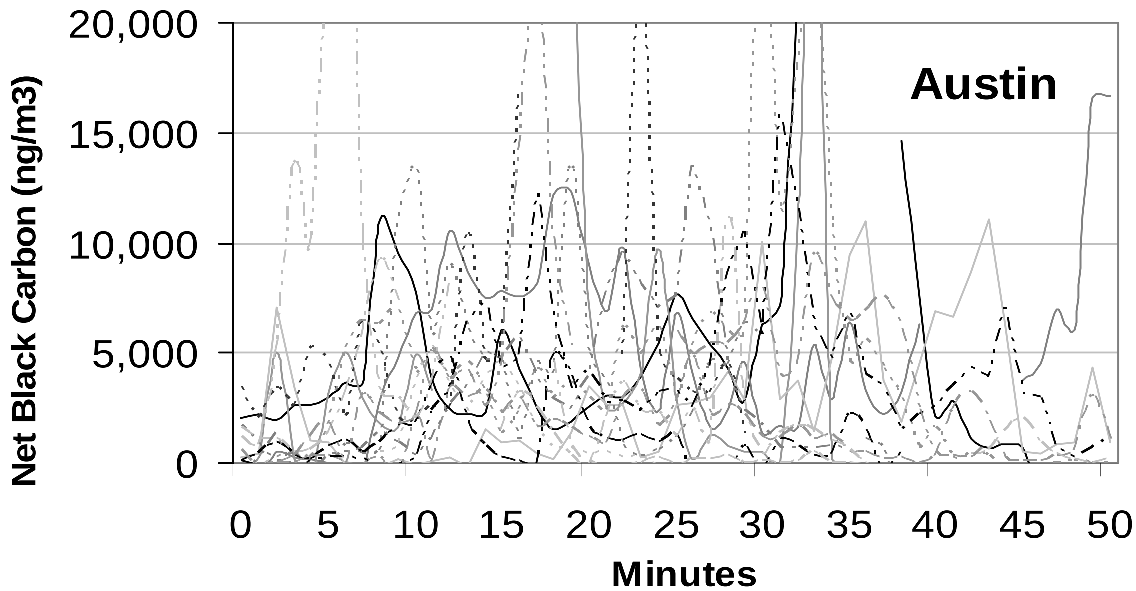
Number of runs plotted: Austin: 4, Boston: 6, Columbus: 14.

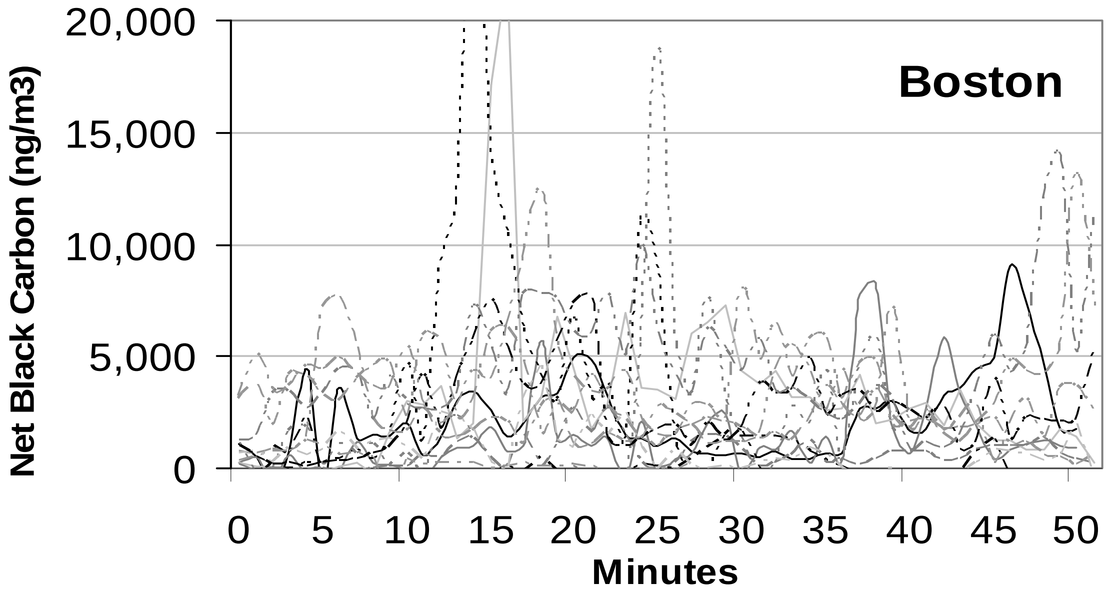


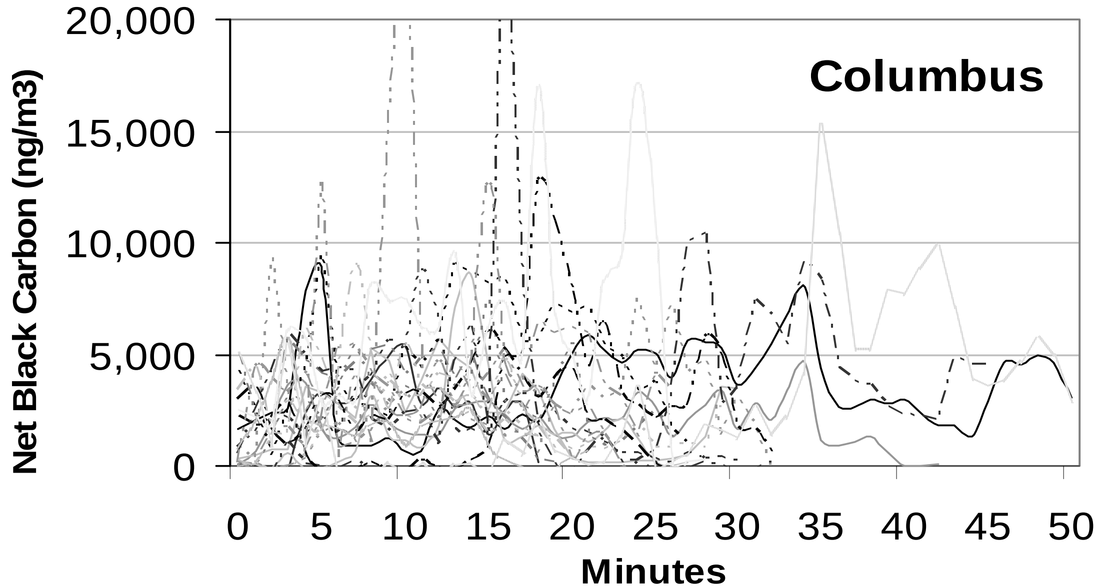




<u>BLACK CARBON—HIGHWAY C0MMUTES</u>
Number of runs plotted: Austin: 15, Boston: 14, Columbus: 23

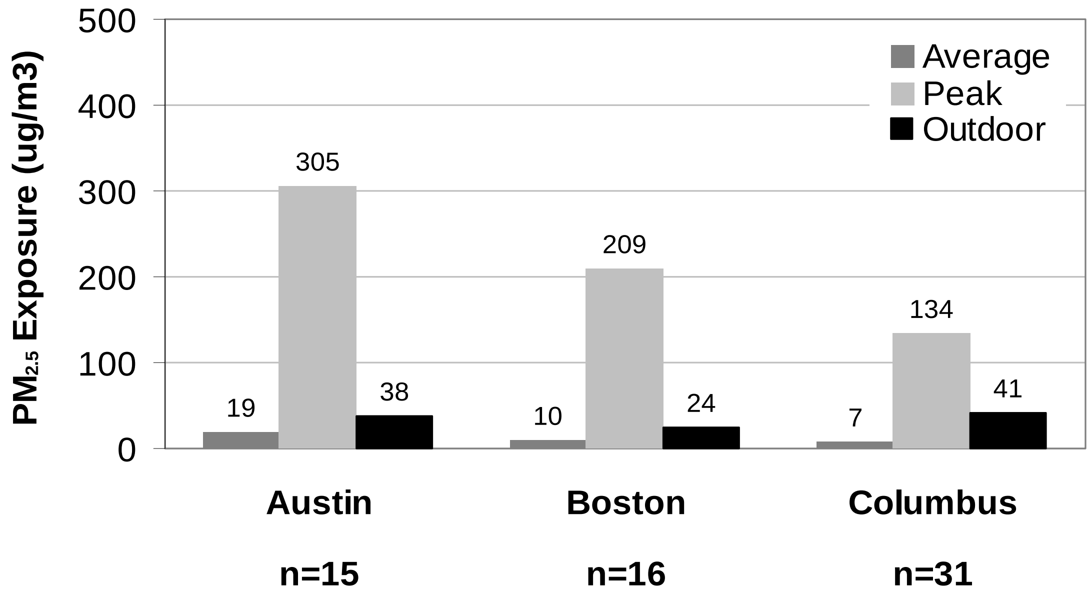


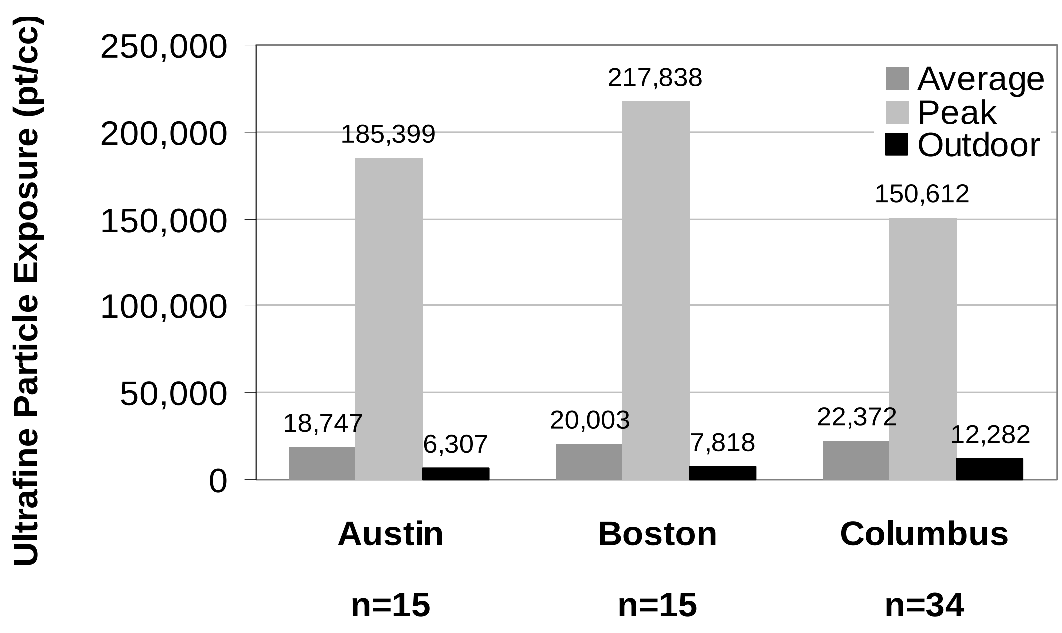

Boston
Net Black Carbon (ng/m3)
20,000
15,000
10,000
5,000
0
0 5 10 15 20 25 30 35 40 45 50
Minutes

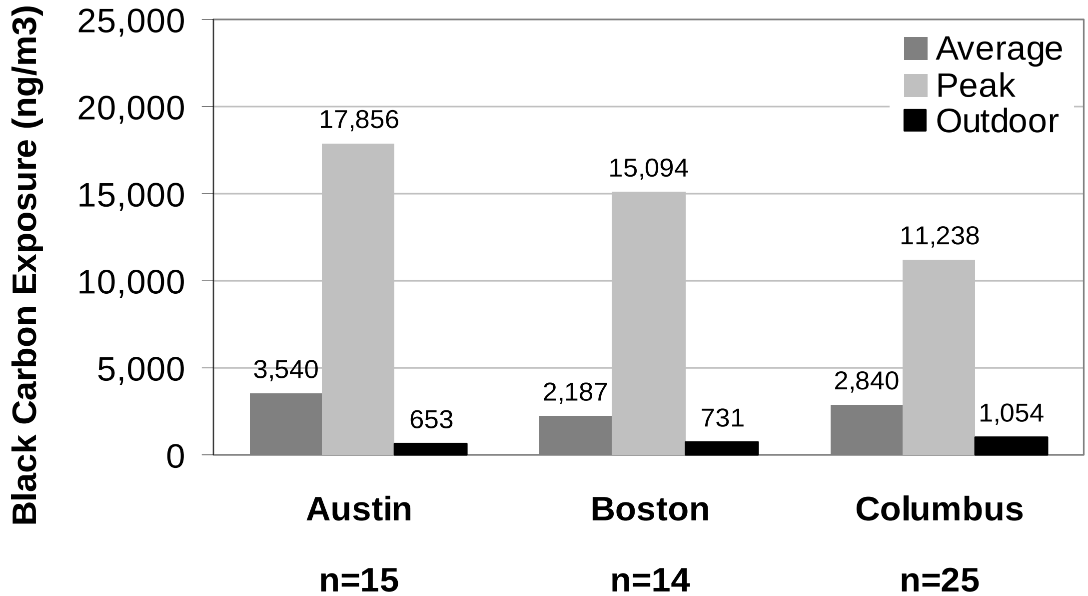

Columbus
Net Black Carbon (ng/m3)
20,000
15,000
10,000
5,000
0
0 5 10 15 20 25 30 35 40 45 50
Minutes

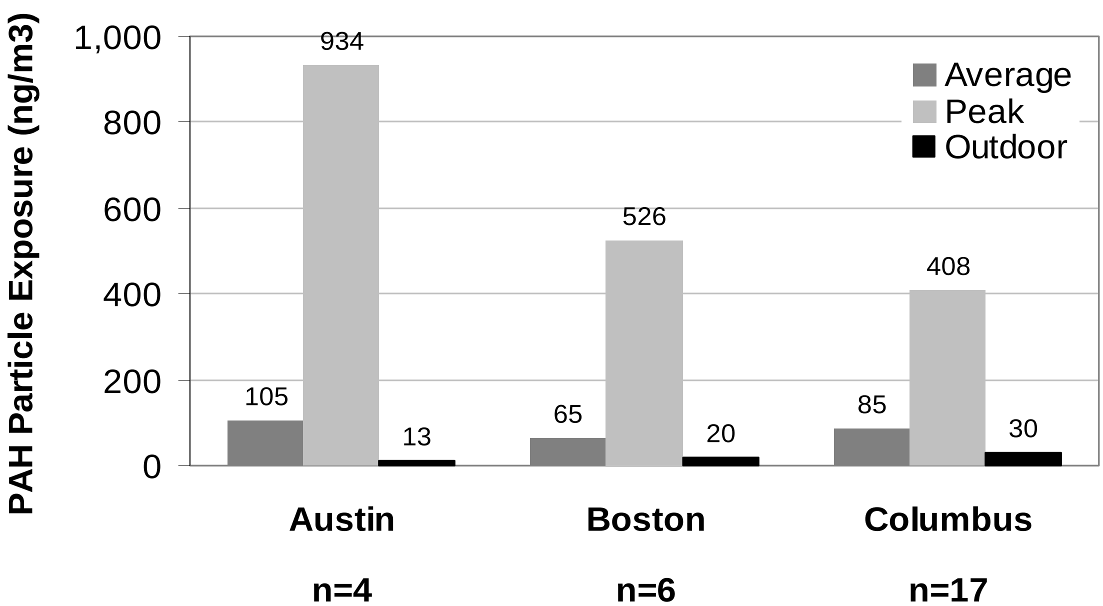
Summary Histograms—Highway/Car Commutes

Bar charts below summarize mean average and maximum net (outdoor ambient subtracted) exposures across all car commutes (windows open) and average ambient outdoor conditions.





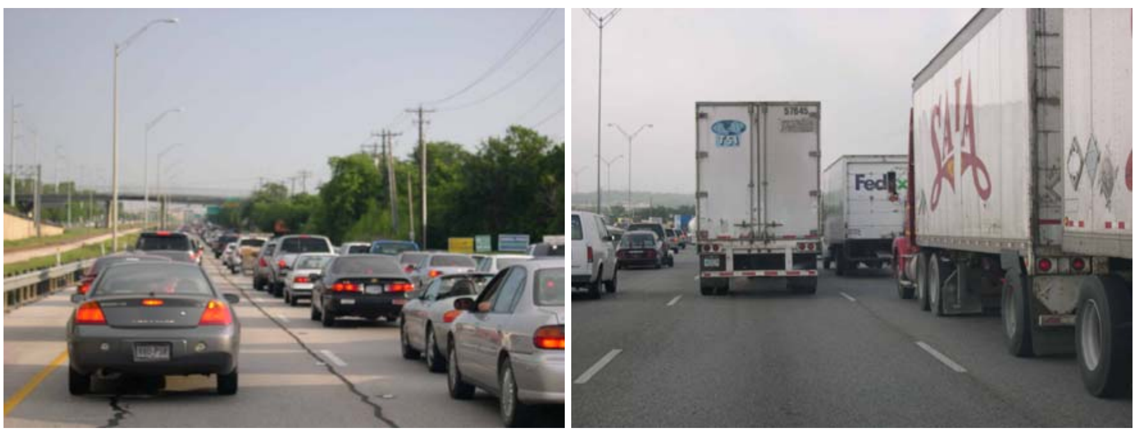

Black Carbon Exposure (ng/m3)
25,000
20,000
15,000
10,000
5,000
0
Average
Peak
Outdoor
17,856
15,094
11,238
3,540
653
2,187
731
2,840
1,054
Austin
Boston
Columbus
n=15
n=14
n=25


PAH Particle Exposure (ng/m3)
1,000
800
600
400
200
0
Average
Peak
Outdoor
934
526
408
105
13
65
20
85
30
Austin
Boston
Columbus
n=4
n=6
n=17

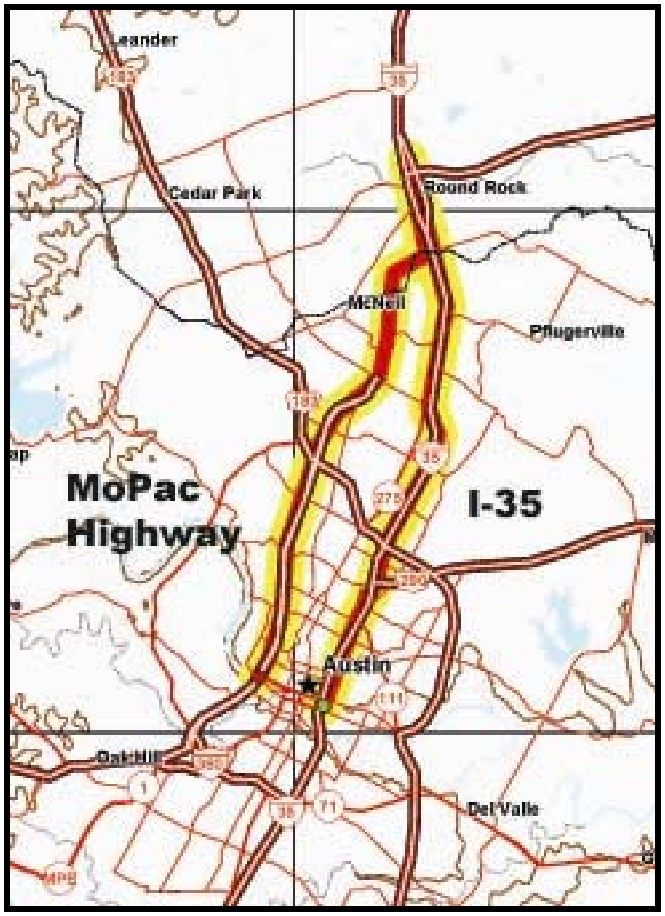
Observations of Busy Truck Routes vs Highways with Few Diesels

The most potent sources of fine and ultrafine particles, black carbon and PAH in traffic are diesel trucks and buses. For example, in a 2006 study, few passenger vehicles were found to have measurable black carbon or PAH emissions.[125] Black carbon soot and fine particles near a school in the Netherlands significantly increased with increasing truck traffic density and decreased with distance from the highway.[126] Elevated black carbon exposures on Harlem New York sidewalks are associated with higher bus and truck counts and proximity to a bus depot.[127] In Boston, MA, a GIS-based study concludes that fine particles and particulate PAH concentrations (an air toxic in diesel exhaust) were significantly higher close to bus stations and along bus routes.[128] Our Austin's observations and results support this conclusion where highways with less diesel traffic had lower particle exposures.

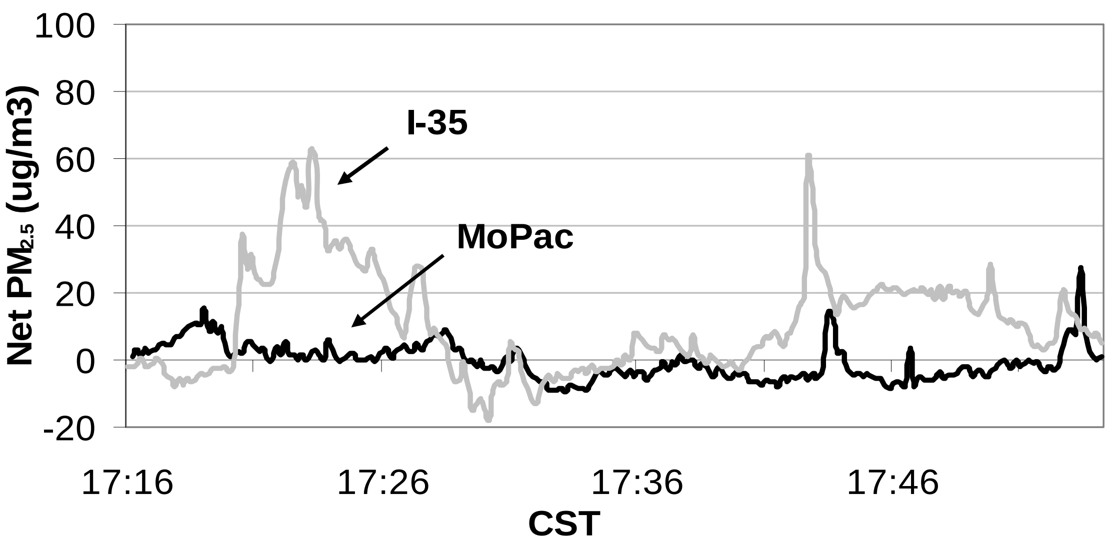
Our own investigations in all three cities support these conclusions as illustrated in the following graphics.



CATF undertook simultaneous commuter monitoring runs on Interstate 35 (right photo), the principal commuter artery into Austin) and the MOPAC highway (left photo) where only small diesel delivery and pickup trucks are allowed. Exposures were lower on the MoPac as illustrated in chart below.



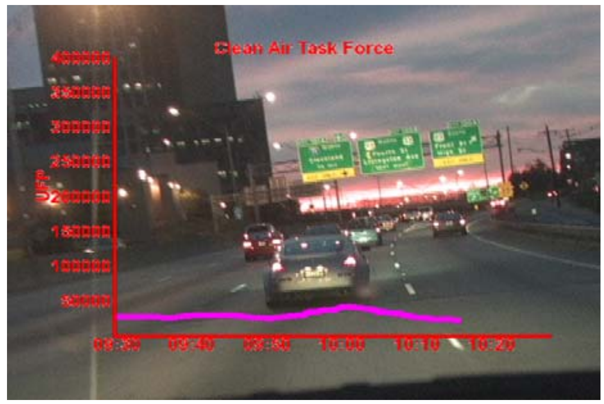
Above: Map of simultaneously monitored commutes along truck filled I-35 (right) and the no-HDD MoPac highway (left) starting in downtown Austin and ending in Round Rock Texas.



Above: Fine particles and other pollutants were elevated on I-35 relative to the MoPac.

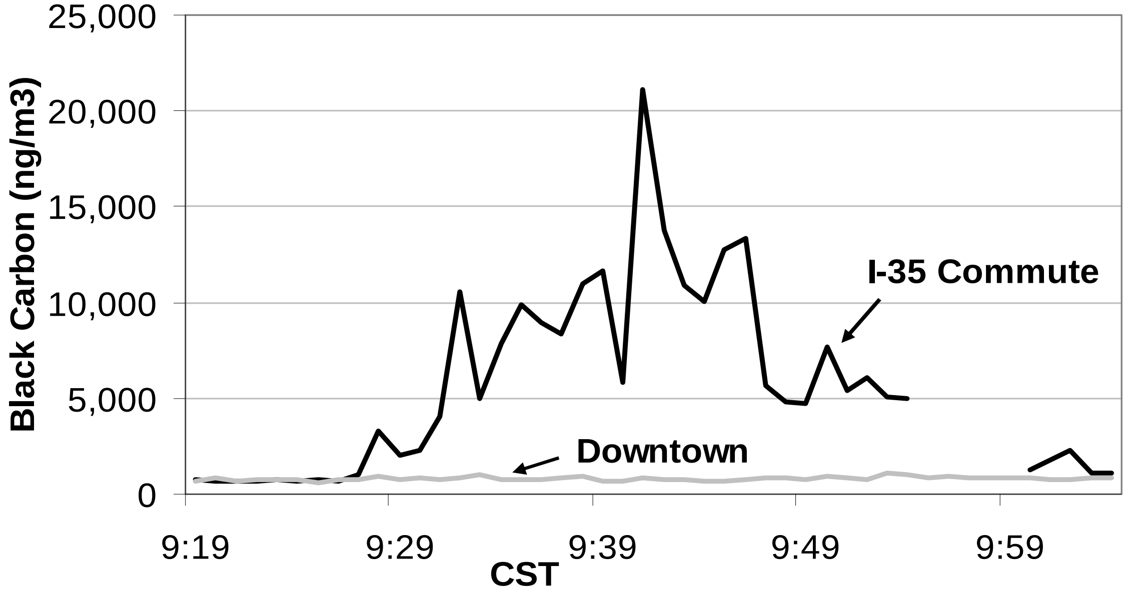
Diesels observed to be responsible for elevated particle levels in roadway.

Images captured from video below illustrate that diesels were responsible for the majority of the particulate matter detected in CATF's highway commute runs. Ultrafine particles (nanoparticles) were a sensitive marker for the presence of diesel vehicles. UFPs remained low in the absence of diesels (with the exception of old super-emitter cars.)



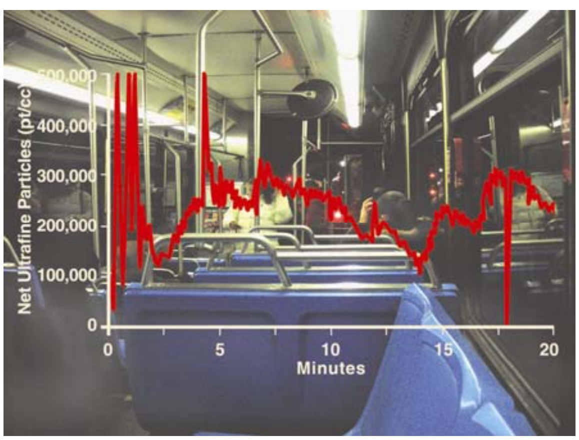
Columbus OH video footage with real-time data supports finding that truck filled roads are characterized by elevated soot exposures relative to roads lacking the heavy duty diesels. See http://www.catf.us/goto/noescape/ to view these videos.

Comparative one-minute Boston video footage with real-time data, as for Columbus, supports finding that truck filled roads are also characterized by elevated exposures relative to commutes lacking heavy duty diesels. See http://www.catf.us/goto/noescape/ to view these videos.



Black carbon in the commuter vehicle is concentrated during an urban-to suburban commute on I- 35 in Austin Texas (black), a heavy truck route, relative to outdoor air in downtown Austin.

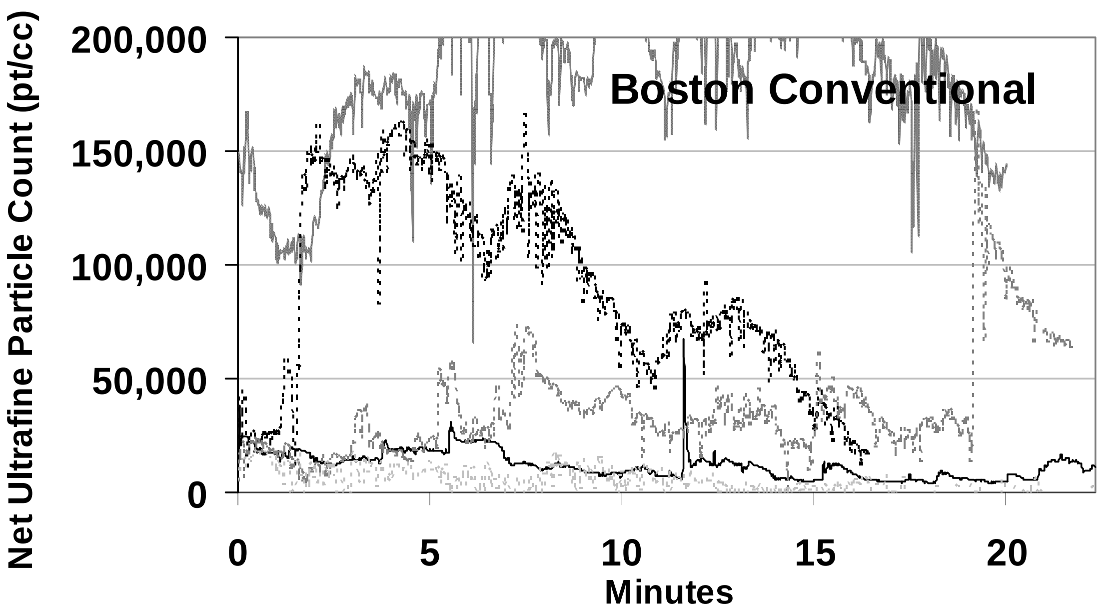
COMMUTING BY CITY BUS



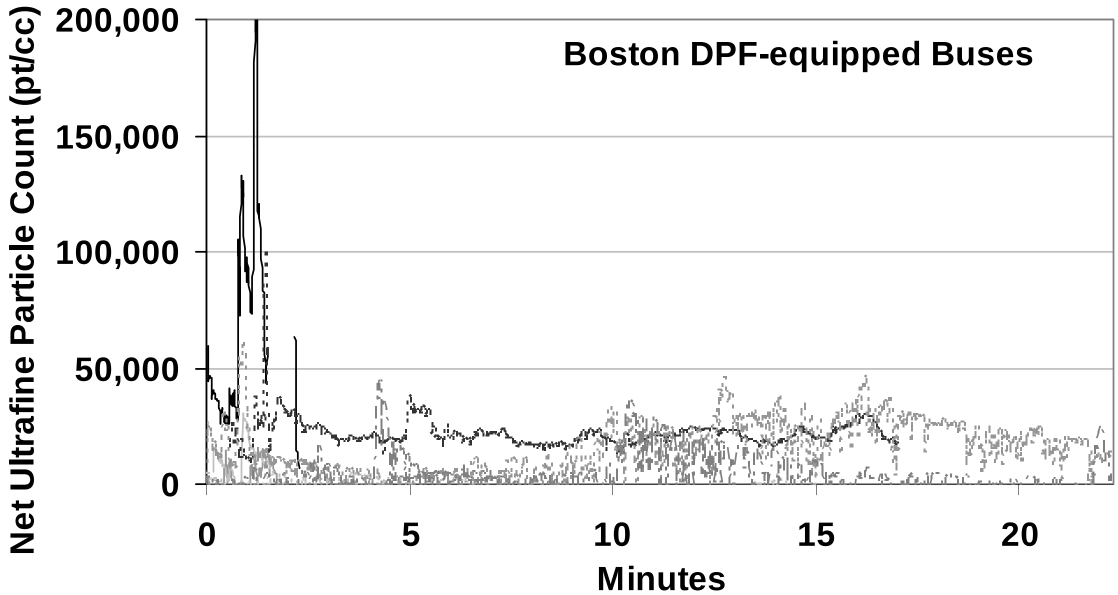
CATF researchers boarded conventional, DPF-retrofit and biodiesel fueled transit buses with the roll around monitor (see inset.) Findings suggest that as CATF found for school buses (see http://www.catf.us/publications/view/82), exhaust may enter the bus from its own tailpipe. CATF investigations into cabin air quality inside transit buses should be considered preliminary given the confounding influence of traffic in the results. More data is needed to ensure robust interpretation. Ideally cabin air quality should be tested in areas devoid of other diesel sources in order to investigate self-pollution.

For the conventional buses in both Boston and New York City CATF observed tailpipes located near ground level. However, the cleanest runs, with the lowest exposures were on buses equipped with a diesel particulate filter (DPF), and in *at least one bus run cabin air was cleaner than the outdoor air*. Moreover, chase studies (following the bus) clearly showed the benefit on the DPF-equipped buses, with extremely high ultrafine particle concentrations—indicative of a fresh diesel exhaust plume—behind conventional buses but with no plume documented behind the clean buses. Chase studies behind urban transit buses in Los Angeles documented similarly high $PM_{2.5}$ levels (130 ug/m^3).[129]

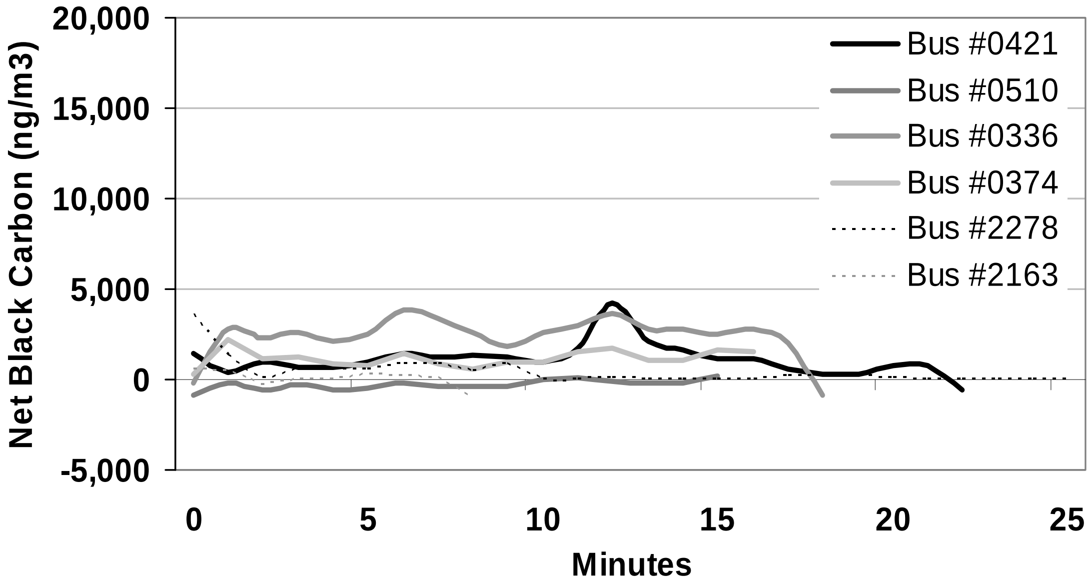
Boston is a leader in clean bus technology with about 90% of its approximate 1000 buses DPF-equipped or compressed natural gas. Boston's ~100 older conventional buses are kept as "spares." $PM_{2.5}$ exposures inside Boston conventional buses were approximately 15 ug/m^3 above outdoor ambient concentrations, 65,000 pt/cc for UFPs, and 43 ng/m^3 for PAH particles. For DPF-equipped buses, $PM_{2.5}$, UFP, PAH and black carbon were 38 ug/m^3 , 6,000 pt/cc, 53 ng/m^3 , 1,000 ng/m^3 above outdoor ambient. CNG buses were also clean, with mean $PM_{2.5}$, UFP, PAH and black carbon 0 ug/m^3 , 12,000 pt/cc, 34 ng/m^3 , 500 ng/m^3 above outdoor ambient. Where exposures for DPF –equipped and CNG buses are apparently higher field observations suggest confounding by external sources.



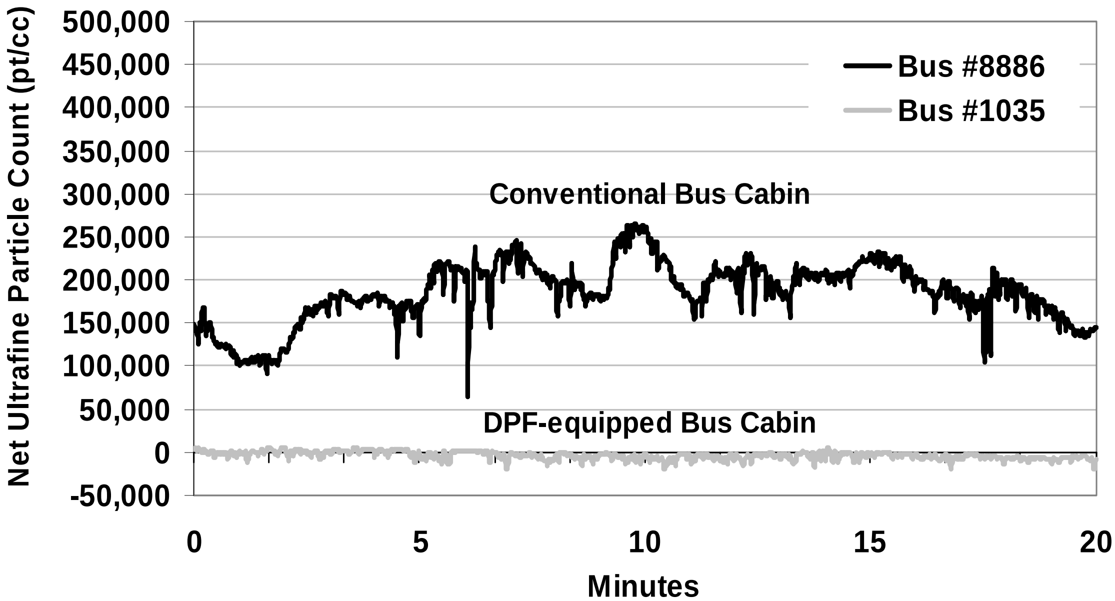
Above: Elevated UPFs in cabin air on conventional transit buses during rides in Boston.



Above: Comparative net ultrafine particle exposures in conventional and DPF-equipped transit buses in Boston. Exposures were found to be lower on DPF equipped buses. This finding is consistent with CATF's school bus study results (http://www.catf.us/publications/view/82)

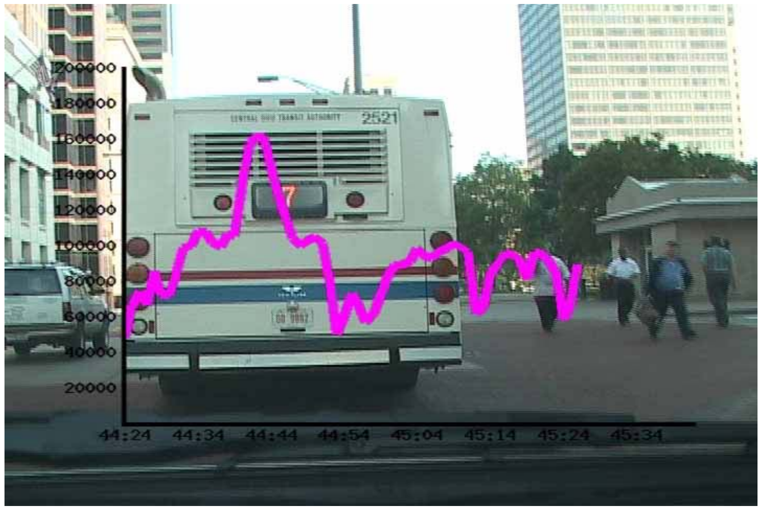


Above: Boston's DPF-Equipped and CNG buses (that are not influenced by other diesels in the roadway) were characterized by low in-cabin black carbon levels.



Above: Comparison of cabin air in conventional Boston transit bus (black line) with a retrofit bus (blue line). (Note this represents the most polluted conventional bus we rode vs the cleanest DPF equipped bus.)

Columbus Biodiesel Buses and Chase: As a part of this study CATF investigated interior and exterior exposures from transit buses in Columbus OH running on B90 biodiesel--90% biodiesel fuel mixed with 10% conventional fuel. Researchers rode transit buses with back pack and roll-around monitoring along Columbus's High Street and related nearby routes in the downtown area. Buses were also chased in the monitoring vehicle to document the magnitude of the exhaust plume behind the bus affecting a following car. Cabin air quality measurements were confounded by diesel sources in front of the bus which complicate the interpretation of the data. Nevertheless, our data suggest elevated ultrafine/nanoparticle levels. Little information is available on UFP/ nanoparticle in-use emissions from biodiesel buses, but our investigations suggest they remain elevated similar to other diesel fuels used without diesel particulate filter controls. Further investigation is warranted before robust conclusions can be made relative to any benefits from biodiesel fuels used alone without emissions controls. Biodiesel, a naturally low-sulfur fuel, in combination with ultralow sulfur diesel fuel *and a diesel particulate filter* is effective in reducing fine particles.[130] Preliminary data collected inside Columbus biodiesel buses resulted in some of the lowest average exposures with 7 ug/m^3, 5,000 pt/cc, 19 ng/m^3, and 1200 ng/m^3 for $PM_{2.5}$, UFPs, PAH and black carbon, respectively. However the low internal UFP concentrations do not square with chase study results suggesting a substantially elevated UFP plume behind the bus.



Above: **Columbus biodiesel bus leaves ultrafine particle pollution in its wake as detected in CATF chase vehicle.**

COMMUTING BY RAIL

CATF researchers boarded commuter trains in New York City in 2005 and Boston in 2006 in a pilot assessment of cabin particulate matter conditions in coaches. Backpack and roll-around monitoring was used (see methodology) with $PM_{2.5}$ and ultrafine particle (nanoparticle) monitors in both cities and additionally for Boston, black carbon and PAH.

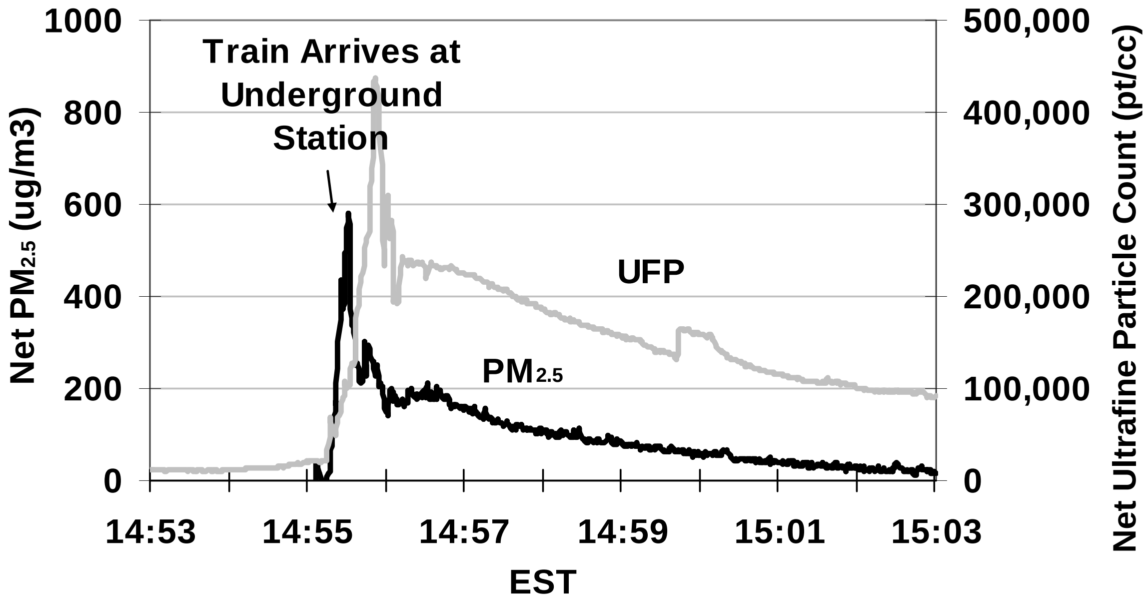
Elevated exposures to diesel exhaust in the passenger coaches were documented, particularly when the locomotive pulls the train (a "*pull*" train) relative to when the train is pushed by the locomotive (a "push" train") after reversing direction at a final stop in a rail line. Locomotives were in typical "engine out" configuration, with the engine furthest from the terminal of partly enclosed South Station in Boston. Elevated levels of all four pollutants were documented inside passenger coaches, however the most dramatic changes in concentrations were observed in ultrafine particles during train accelerations and in Boston's underground and poorly ventilated Back Bay station. The following are key observations from the commuter rail investigations:

- Ultrafine particles appeared to be the most sensitive indicator of changes in coach air quality. Generally as trains accelerated, UFPs were observed to systematically increase with apparent speed but dropped as the train slowed. This evidence supports CATF's observation that UFPs appear to be a strong indicator of fresh diesel exhaust entering the train cabin.
- Net UFP levels averaged approximately 100,000-125,000 pt /cc inside pull-trains as compared to 14,000-31,000 pt/cc in push-trains. Ultrafine particles (UFPs) were 15-20 times the concentration of the outdoor air in pull-trains and 3-5 times outdoor exposures in push trains (Note: coach exposures are elevated in all Boston trains when they enter and load passengers in enclosed or partly enclosed stations)

- Net $PM_{2.5}$ exposures averaged 4-13 ug/m^3 with push-train factors relative to ambient outdoor air ranging from 1 (NYC) to 3 (Boston) and pull-train factors ranging from 2 to 5.
- Net black carbon exposures over 6 runs in Boston averaged 8 ug/m^3 (i.e., 7,684 ng/m3) for pull trains and 2 ug/m^3 for push-trains, with peak1-minute levels averaging 26 ug/m^3 in pull trains and 12 ug/m^3 in pull-trains..
- Net PAH exposures averaged across all Boston and New York runs ranged from 39-170 ng/m^3 in pull trains and 0-30 ng/m^3 in push-trains.
- Black carbon and PAH levels were 17 and 15 times higher in pull-trains than for the outdoor air, respectively.
- Sensitivity to car position was not investigated systematically, however exposures were observed in all coaches including those that were closest and those that were furthest from the locomotive.

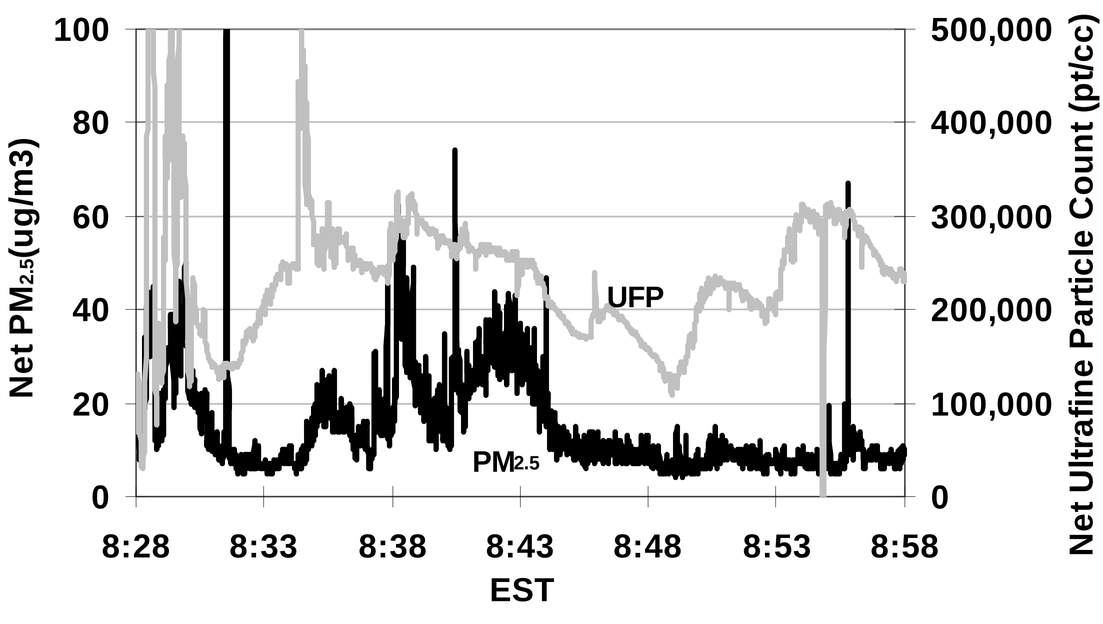



BOSTON PUSH and PULL TRAINS: The following data plots contrast exposures in Boston and New York City commuter trains when the locomotive is in the rear ("push train") vs when the train changes direction and the locomotive is in front ("pull train.") The higher exposures result from the exhaust plume from the locomotive in front (in "pull" position) blowing down and entering the ventilation system in the commuter cars that follow. Spikes in concentrations appeared to be greatest where the train is confined on either side or all sides, as air pressure rises forcing air into the cabin when train is accelerating to higher speeds. For the push train, the plume is apparently left behind the train so that the commuter cabin remains at ambient. Replicating findings of NESCAUM (see Special Studies: Motor Vehicle and Rail Tunnels below) coaches were systematically polluted in Back Bay station whether in "push" or "pull" configuration (see graphic below)

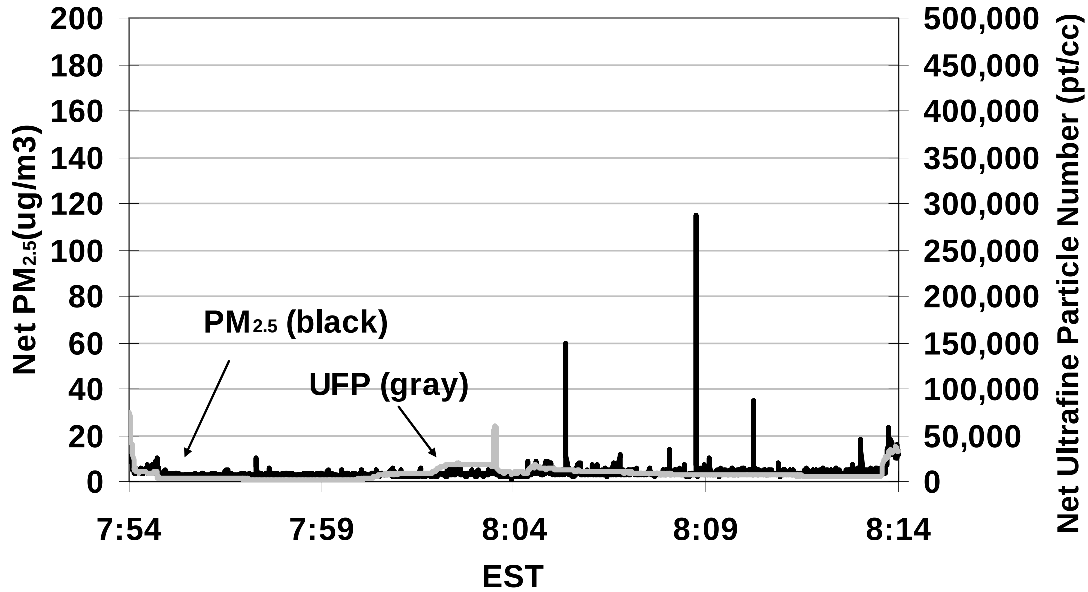


Above: Plot shows impact of underground station on coach air quality on "push" train. Exposures from the underground station decay but generally persist through much of the rest of the train ride

Round trip on Boston commuter rail: contrasting the same train in "Push" and "Pull" configurations:



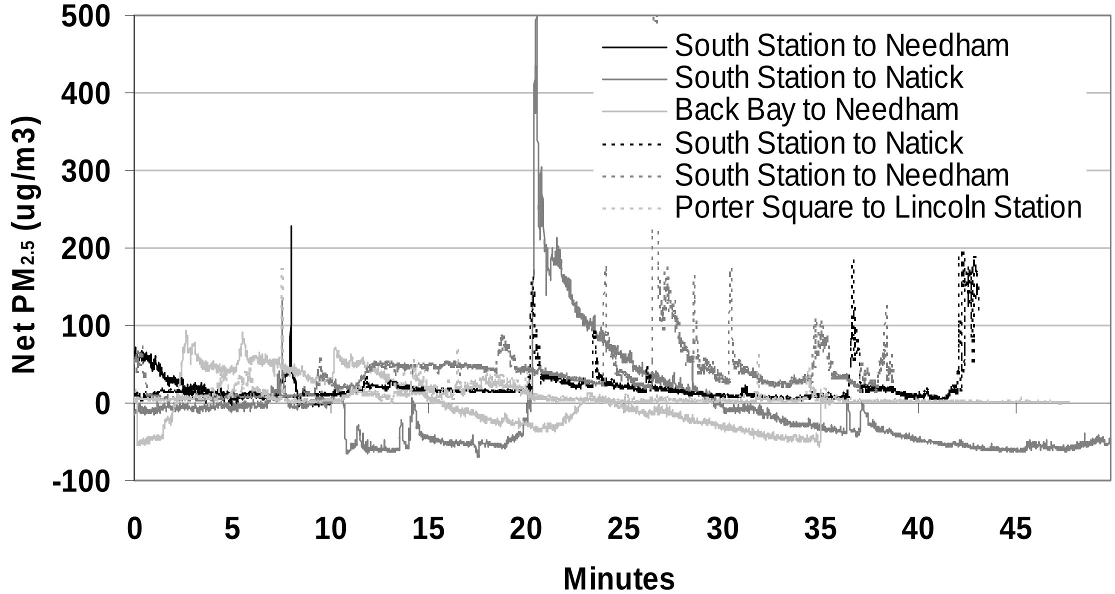
Above: Pull train returning from Porter Square to Lincoln in Boston MBTA shows substantial buildup of UFPs and $PM_{2.5}$.



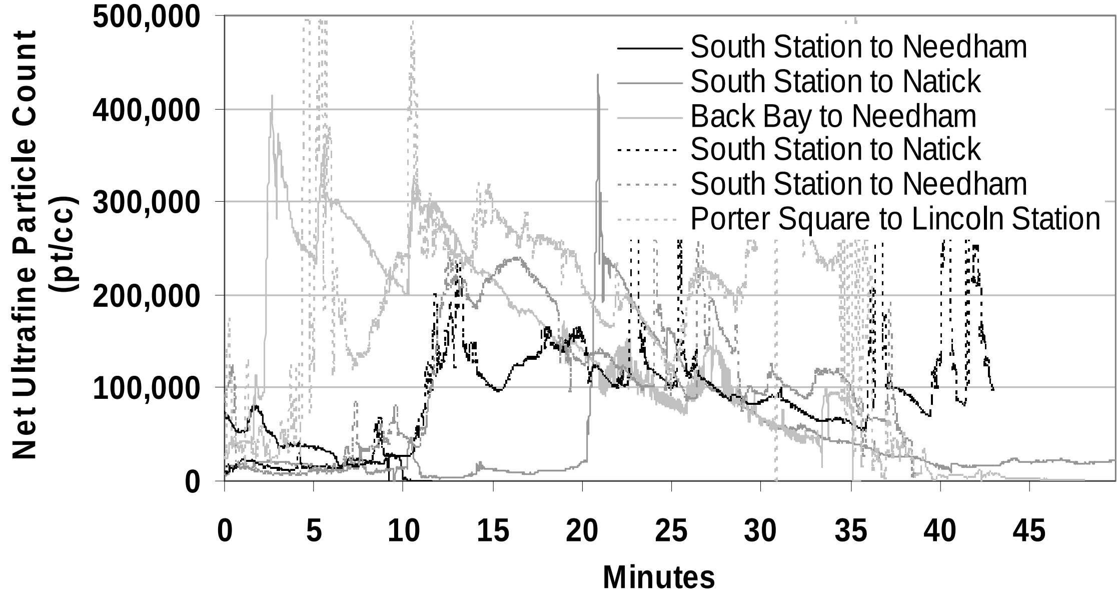
Above: Push train from Lincoln to Porter Square in Boston MBTA in contrast to pull train shows little to no buildup of UFPs and $PM_{2.5}$.

Boston Pull Train Compilation Plots

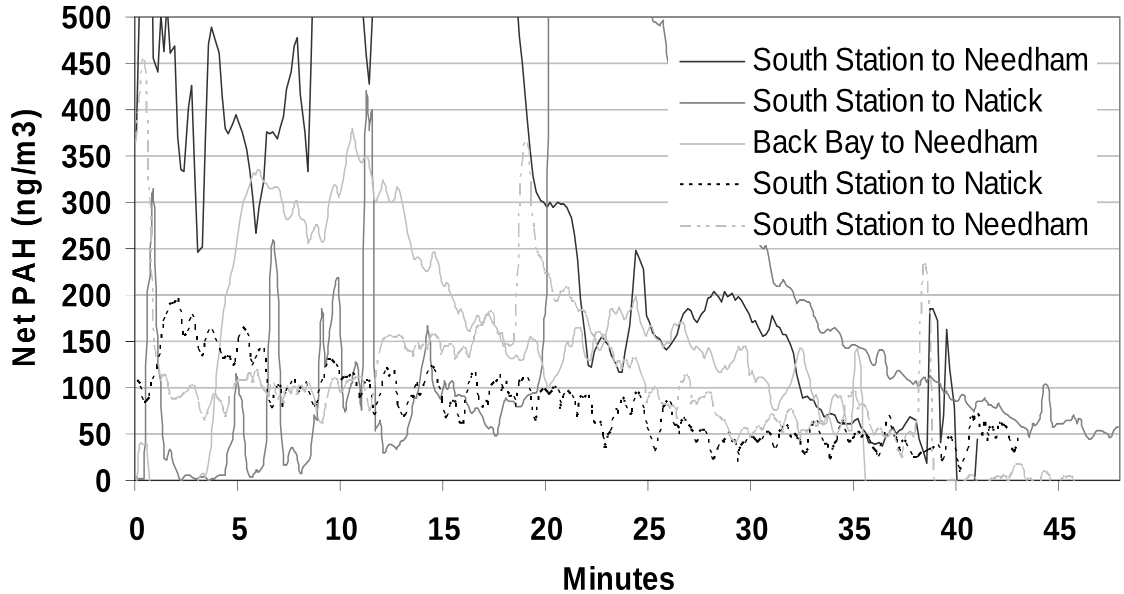
$PM_{2.5}$ (pull)



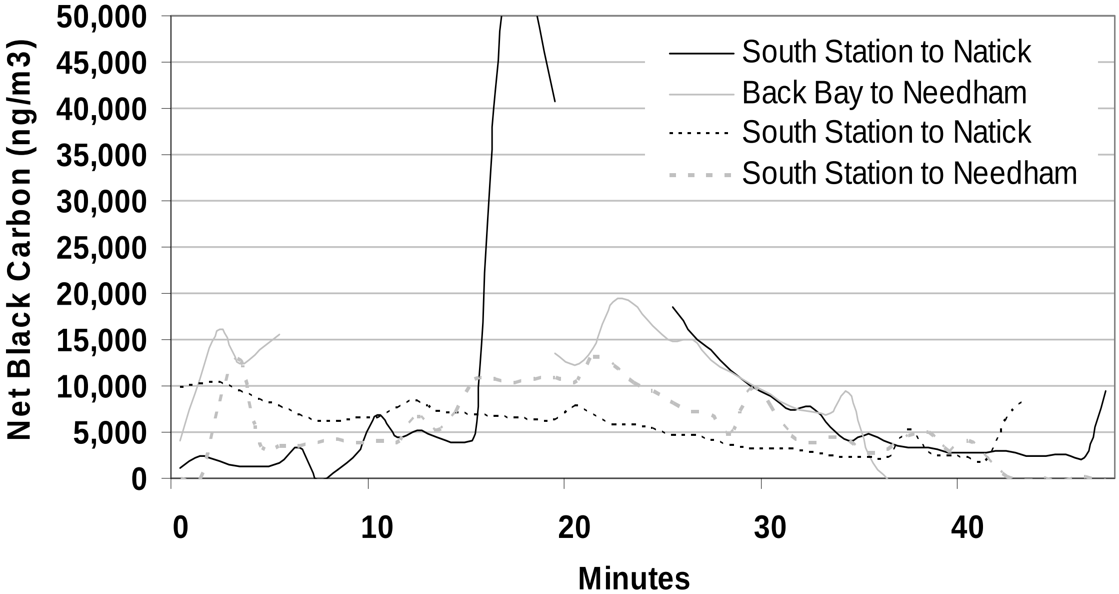
Ultrafine Particles (pull)



Particulate PAH (pull)

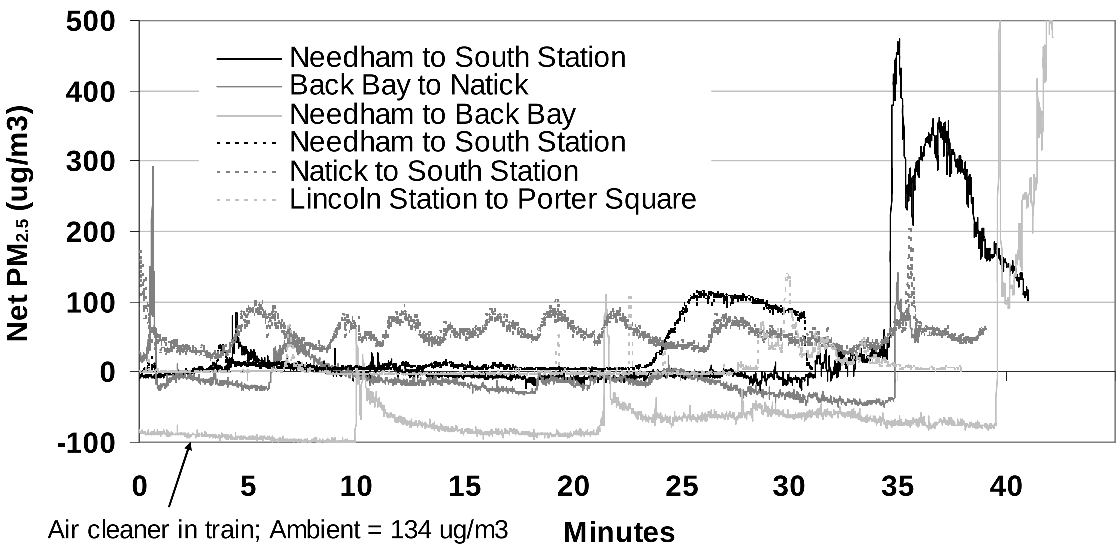


Black Carbon (pull)

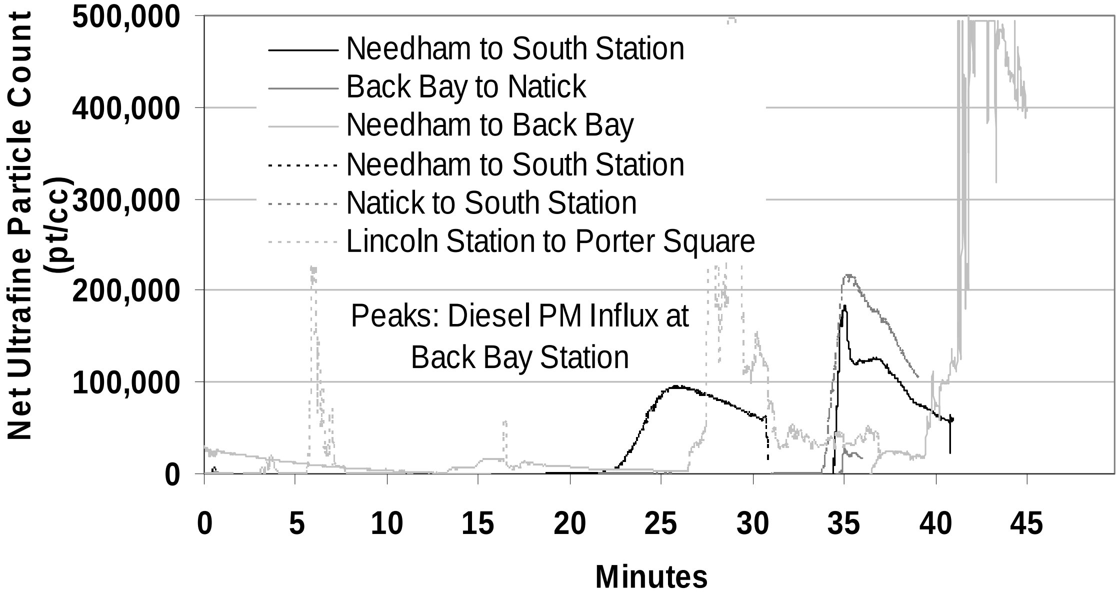


Boston Push Train Compilation Plots

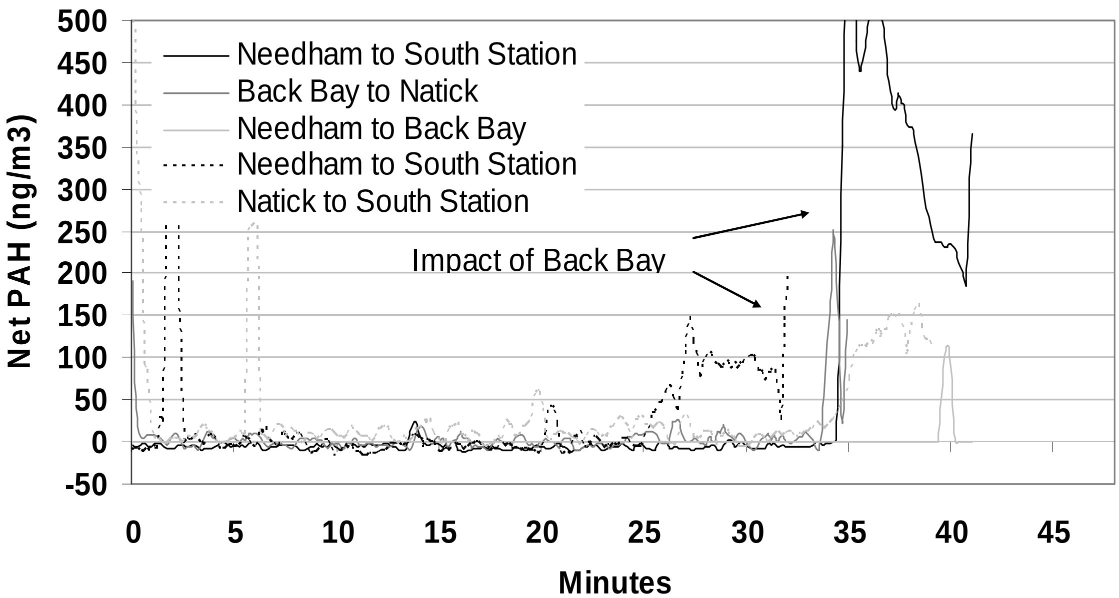
PM 2.5 (push)



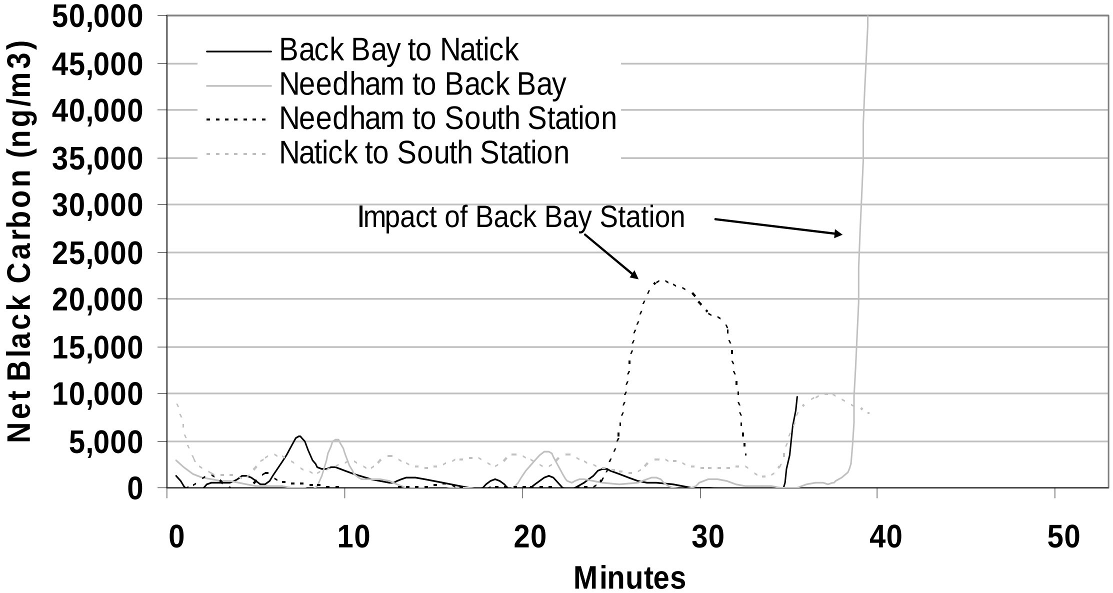
Ultrafine Particles (push)



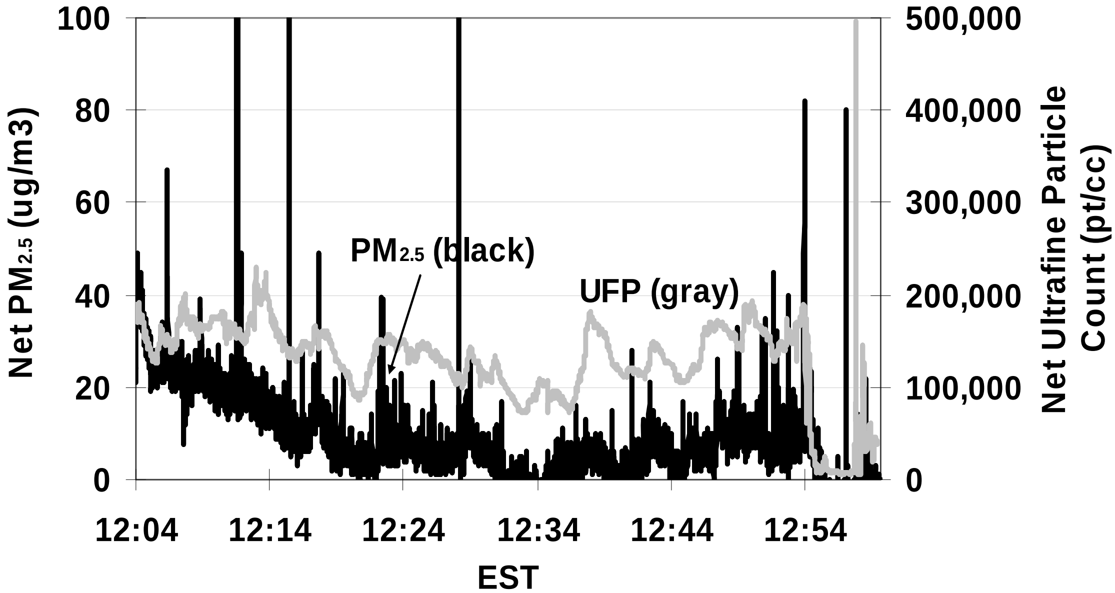
Particulate PAH (push)



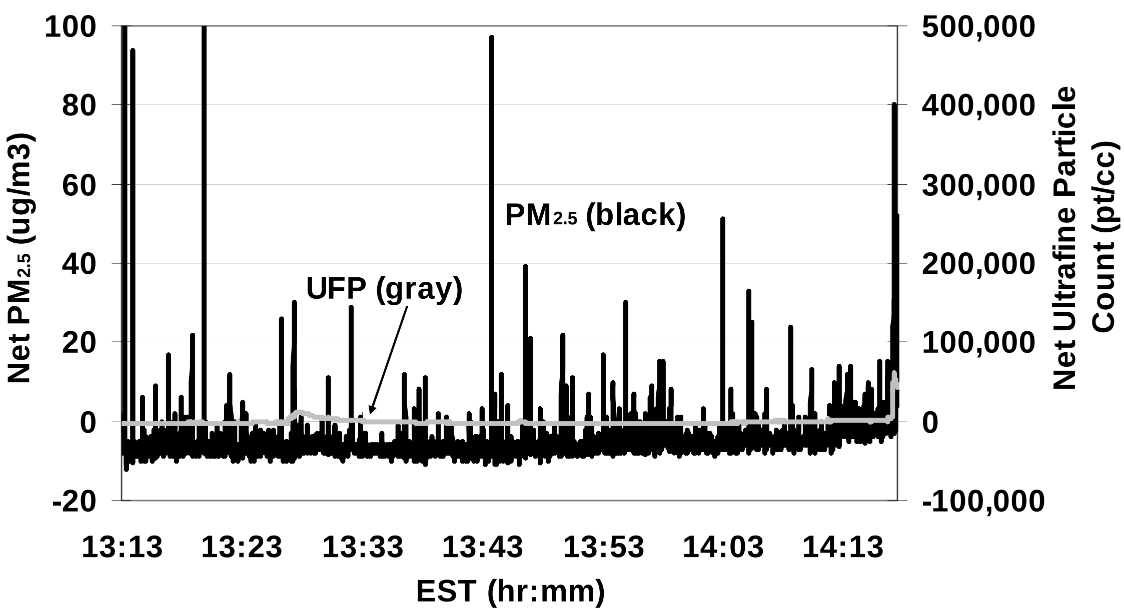
Black Carbon (push)



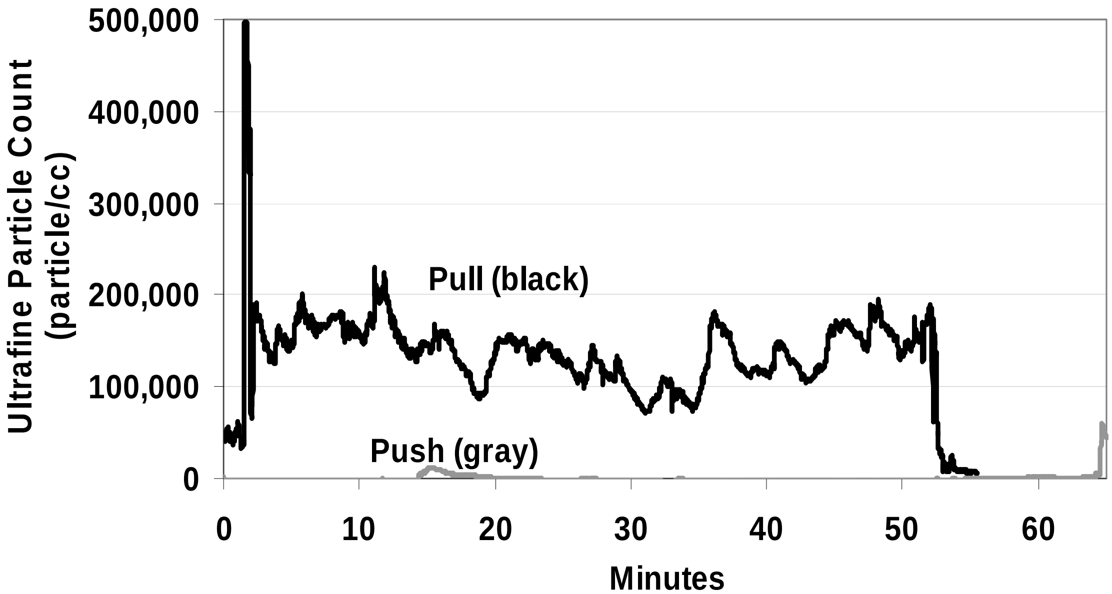
NEW YORK PUSH AND PULL TRAINS A preliminary effort to investigate air quality on New York City commuter rail coaches was undertaken in 2005 in New York City. Researchers boarded outbound pull-trains and returned on push-trains. Results are similar for Boston and document the adverse impact of the locomotive's plume on cabin air quality in the coach for the pull-trains.



Above: New York City Commuter "pull" train showing elevated ultrafine particle concentrations and slightly elevated $PM_{2.5}$. Ultrafine particle exposures are a strong indicator of fresh diesel exhaust from the train.



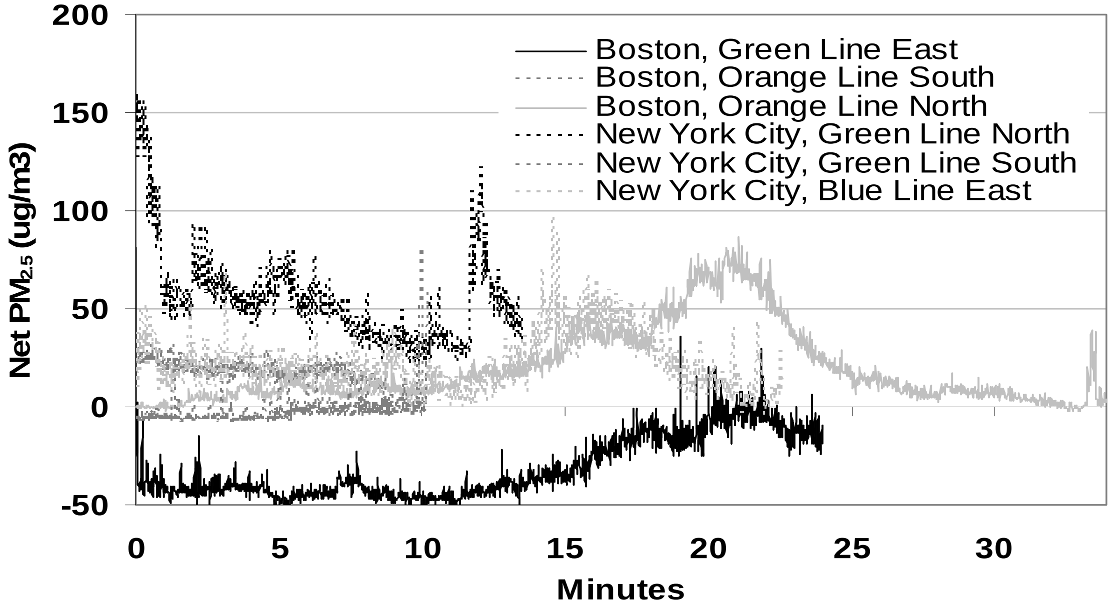
Above: "Push" train exposure signature in New York City commuter rail run with very low net exposures to ultrafine particles and $PM_{2.5}$.



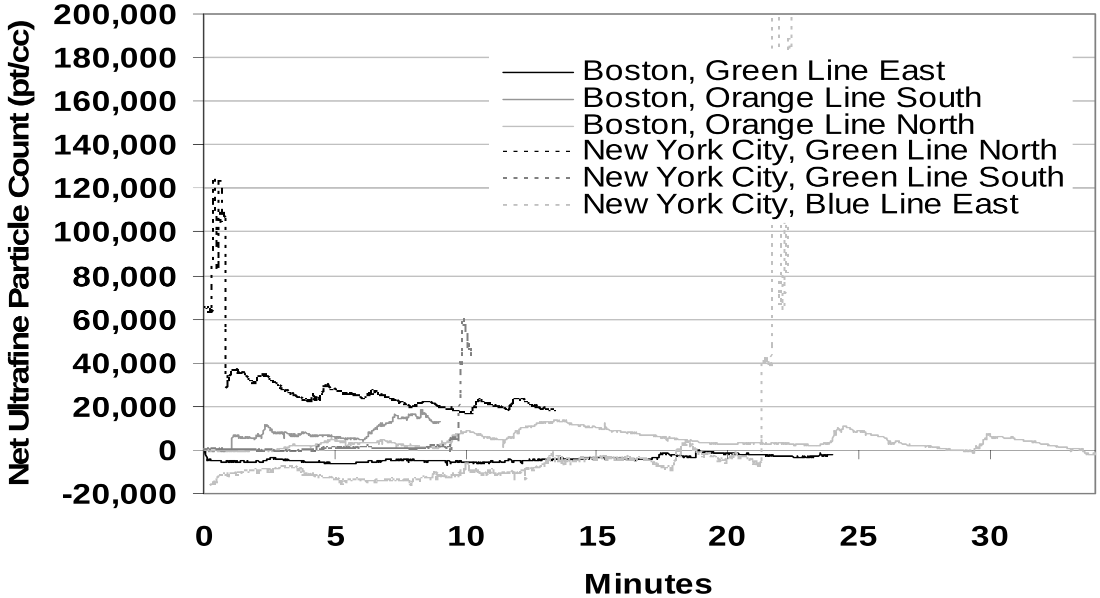
Above: Net UFPs in New York City commuter trains pulled (black) and pushed (gray) by the locomotive.

COMMUTING BY SUBWAY

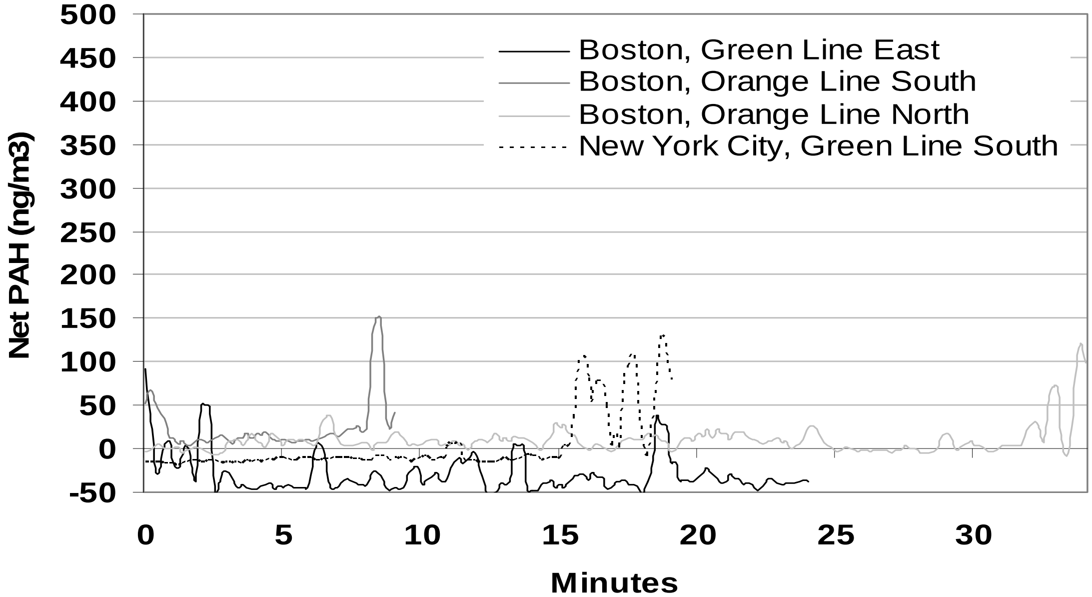
A limited number of backpack commuter runs inside the Boston "T" and NYC subway system were undertaken for comparative purposes. These lines run on electricity and do not create combustion –related particles. In general, conditions inside the subway and electrified rail, especially where underground, were equivalent to or lower than for the outdoor background air with the exception of $PM_{2.5}$. Net $PM_{2.5}$ concentrations averaged over 3 runs on Boston averaged 2 ug/m^3 but higher for New York (46 ug/m^3), likely due to entrained dust. Previous studies suggest that elevated fine particles ($PM_{2.5}$) due to entrained railway dust. Researchers have investigated the composition of the dust and found it to be a combination of crustal dust and metals derived from rail decomposition. Net UFPs in Boston averaged a low 2,700 pt/cc. Average PAH concentrations (A good indicator of combustion) for 3 runs averaged 2 ng/m^3 —at or below the instrument's limit of detection. No black carbon data was collected on any of the runs.



Above: Net $PM_{2.5}$ concentrations in Boston and New York Subway. Some segments of subway were above ground. Net negative concentrations represent levels in the subway below ambient outdoor concentrations.



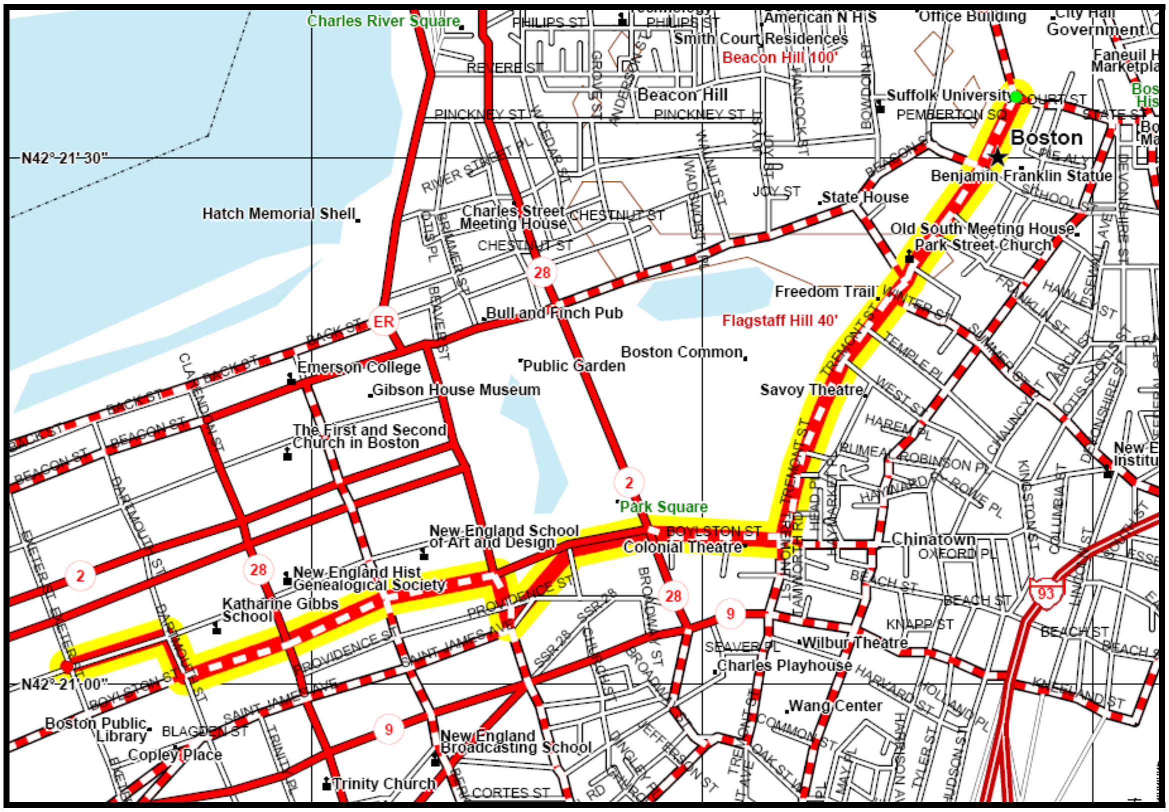
Above: Net UFP concentrations. Subways were generally low (influenced by urban background) and free of local sources of UFPs. Any changes in UFPs were a result of external sources, e.g. nearby diesels or cigarette smokers. (Net negative numbers mean that UFPs in the subway were lower than the outdoor air.)



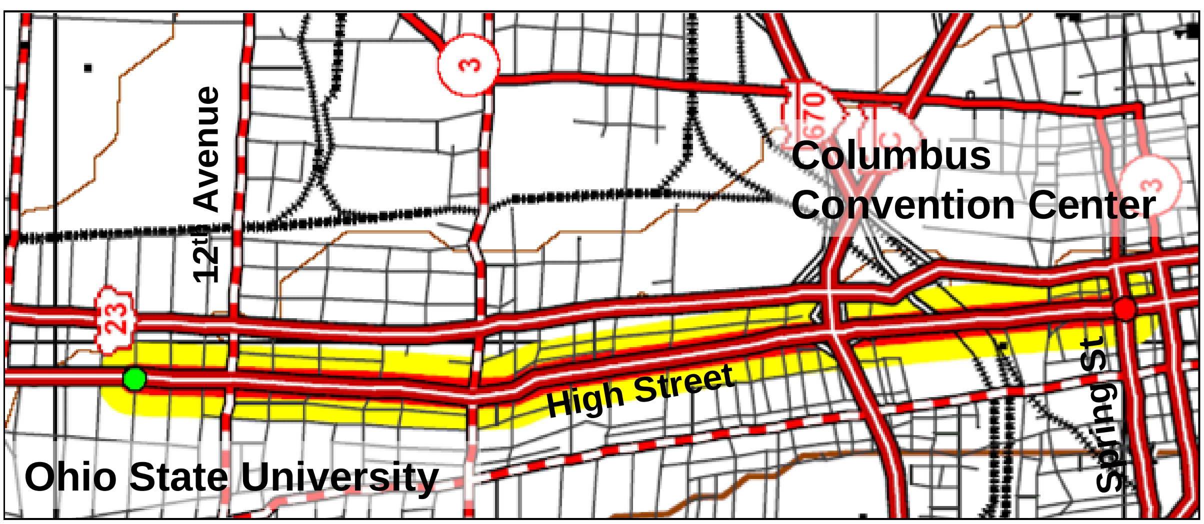
Above: Low net particulate PAH concentrations in electrified Boston and New York subways.. PAH is a combustion-related air toxic and therefore changes in concentration are related to local sources—such as cigarettes. (Net negative concentrations mean levels in the subway are lower than the outdoor air.)

WALKING: PEDESTRIAN EXPOSURE

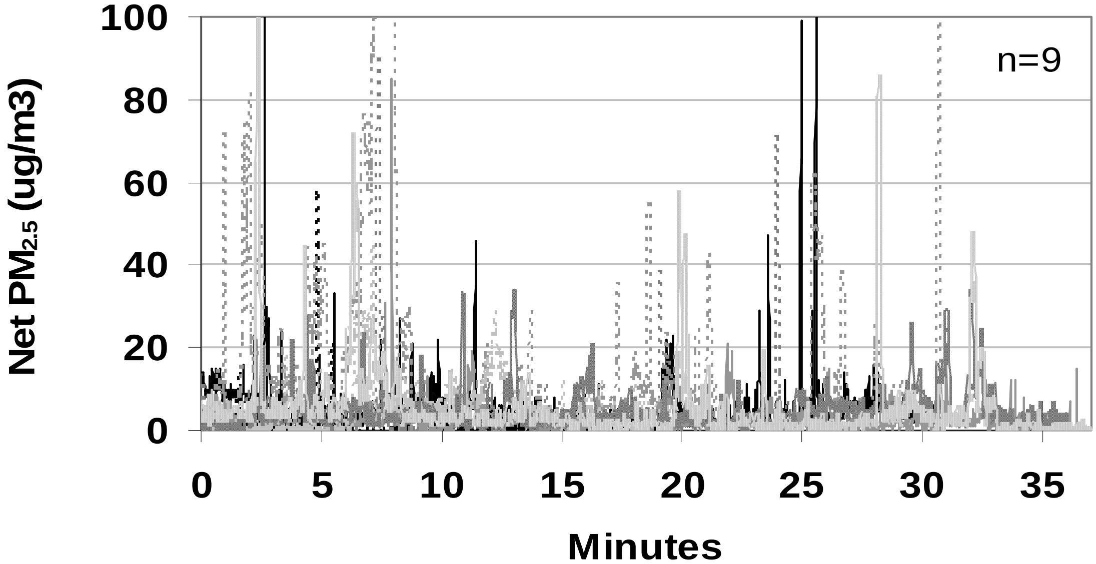
CATF's efforts to document pedestrian exposures were preliminary; researchers walked city streets in Boston and Columbus in order to collect pilot data on exposure while walking on sidewalks. These data include a number of different routes although systematic routes were identified for study. For example in Boston , CATF researchers walked from Newbury St. (urban residential area) to Tremont Street (CATF's office). In Columbus researchers walked from the 12th St./ Ohio State University campus to the convention center along High Street. Other walks are included in this data set, for example travel on foot from Boston's South Station (commuter rail) to CATF's downtown office. Exposures changed rapidly, concentrations being transient as a function of nearby parked or passing sources and wind conditions. Mean $PM_{2.5}$ concentrations while city walking averaged 4 ug/m^3 higher than ambient outdoor conditions, with UFPs ranging from 14,000--17,000 pt/cc above ambient, PAH 9-42 ng/m^3 above outdoor ambient, and black carbon 400 ng/m^3 above ambient. This translated into exposures that were an approximate factor 2 X above outdoor ambient conditions (in absence of traffic) for $PM_{2.5}$ UFP and black carbon, with PAH a factor of 8 higher. Further, more systematic investigation is needed to better understand exposures to pedestrians.



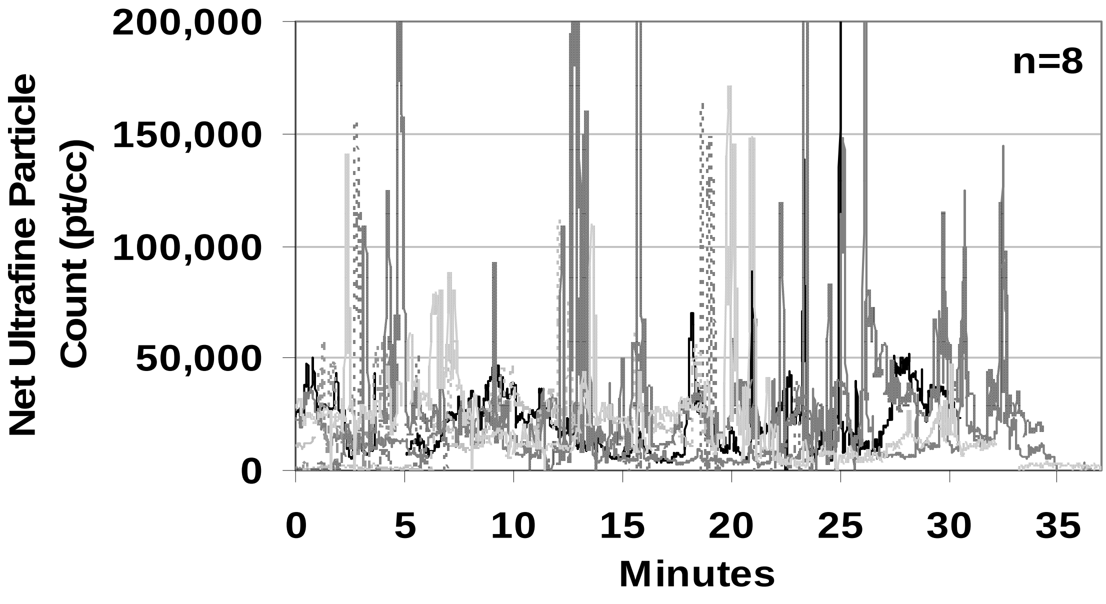
Map of 20 minute walking commute in Boston from the residential neighborhood on Newbury Street to the Business district on Tremont Street where CATF's offices are located.



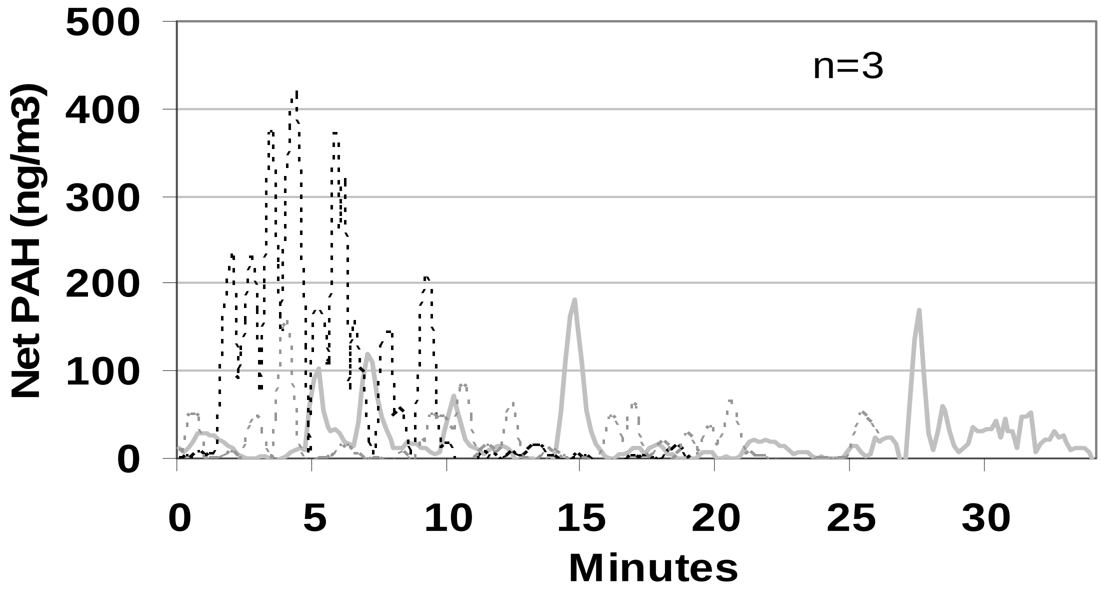
Above: Map of walking commute in Columbus south from 12th Street near OH State to the convention center at Spring Street.



Above: Net PM $_{2.5}$ exposures walking in Boston and Columbus. In general net PM $_{2.5}$ exposures were only moderate. Spikes resulted from passing of diesel trucks and buses.



Above: Significantly elevated net ultrafine particle exposures (PTrak data) walking in Boston and Columbus. UFP spikes are a marker for passing diesel vehicles. Cars did not trigger increases.

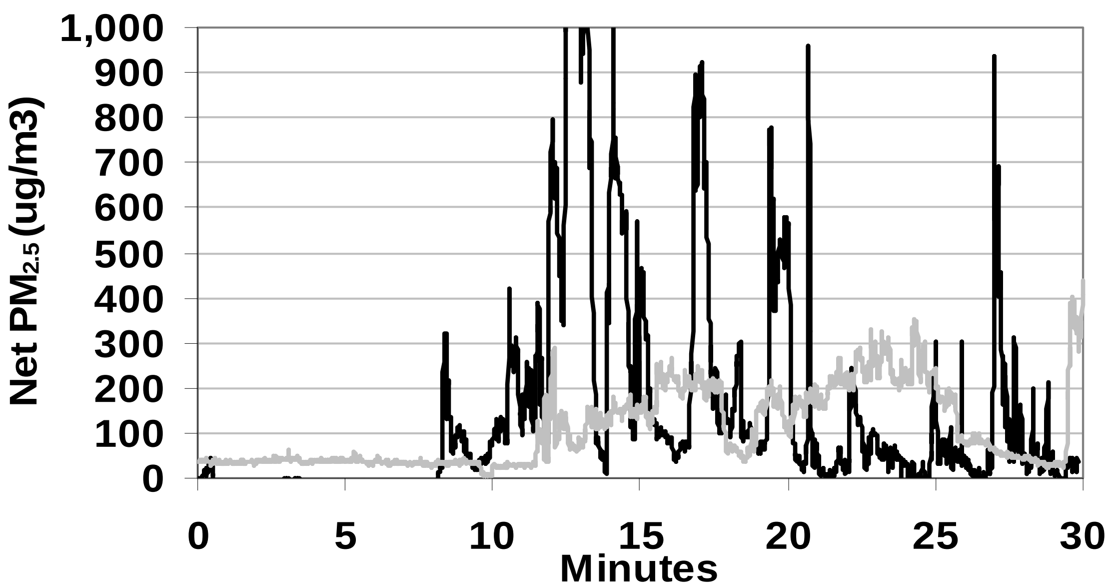


Above: Net particulate PAH exposures for walking commutes in Boston and Columbus. PAH appears to be a sensitive marker for fresh diesel exhaust.

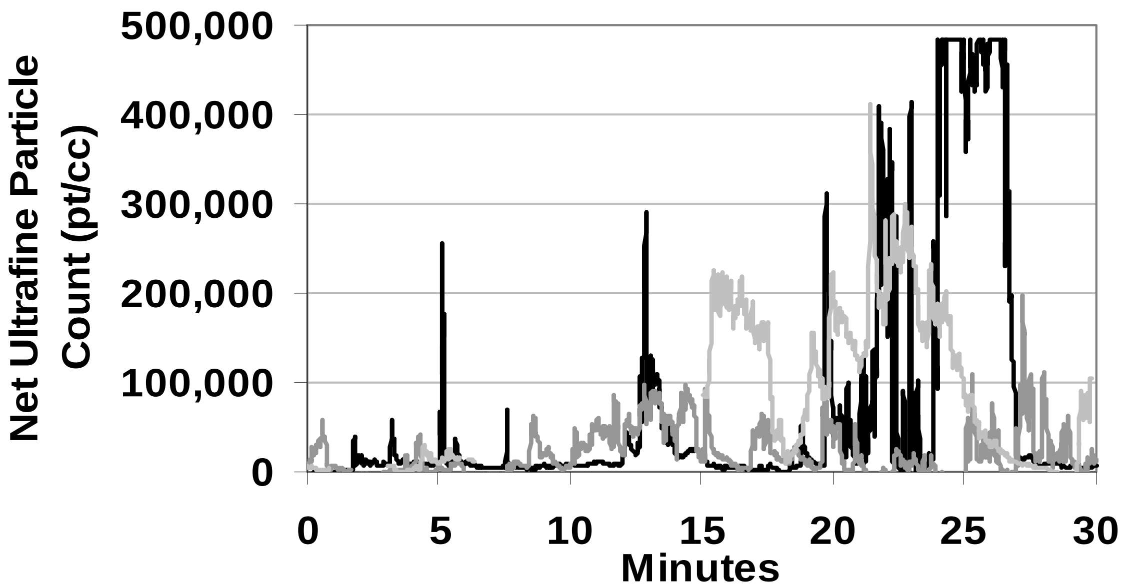
Above: walking commute in downtown Boston.

COMMUTING BY FERRY

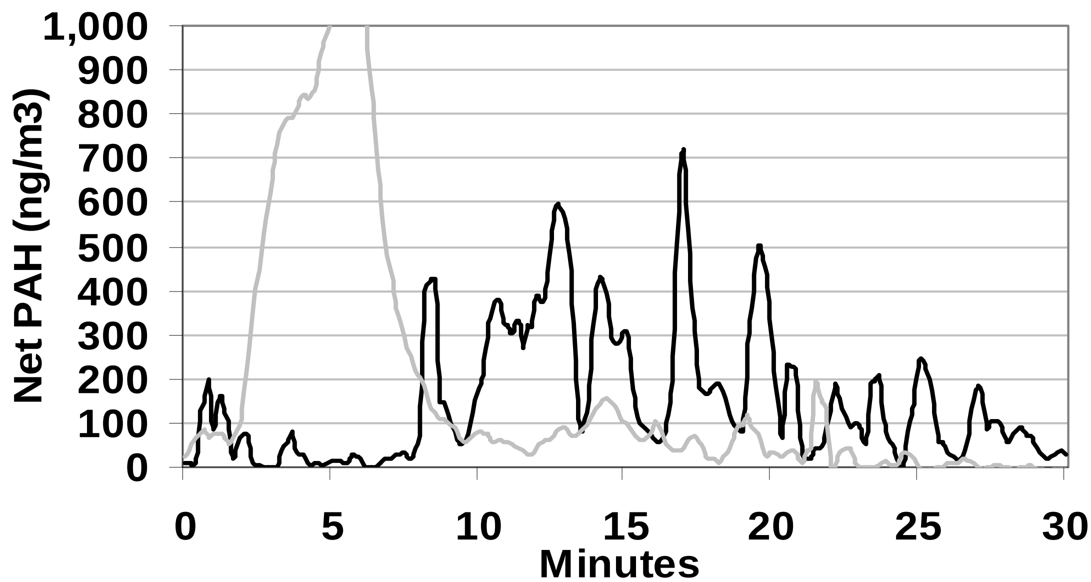
In communities around Boston Harbor, some commuters are able to get to work via ferry. Probably the most utilized ferry service is the 45 minute ferry service from Hingham MA to Long Wharf. CATF researcher boarded several Boston ferries with back pack and roll around monitoring setups to preliminarily investigate exposures to marine diesel exhaust. Findings, illustrated in the data plots below, suggest that exhaust can enter ferry cabins and form swirling eddies behind the harborcraft resulting in extremely high levels of particulate pollutants including very high $PM_{2.5}$ and ultrafine particles. While these data suggest exposures may be problematic on ferries, more work is needed to adequately define those exposures.



High Net $PM_{2.5}$ exposures on 2 Boston Harbor ferry runs. Exhaust smoke eddies behind the boat and enters through the rear door.



High Net ultrafine particle exposures on Boston Harbor ferry runs.



Elevated Net PAH particle exposures on 2 Boston Harbor ferry runs.

SPECIAL PILOT STUDIES: BOSTON'S RAIL AND MOTOR VEHICLE TUNNELS

It may come as no surprise that air quality in vehicular and rail tunnels is exceptionally poor, but how poor? The Northeast States for Coordinated Air Use Management undertook preliminary studies in Boston's Back Bay underground commuter rail station and documented alarmingly high levels of black carbon.[131] Informed by the NESCAUM data and as a part of the present study, CATF researchers planned its own pilot assessment of particulate matter conditions at Back Bay Station as part of a larger effort to understand pollution to rail commuters in Boston.

Findings confirm high to extreme particle levels in the Back Bay underground rail station. Moreover, the polluted station is a strong source of cabin pollution for coaches loading and unloading on the platform. CATF data documented substantial pollution of "push" trains that would otherwise be largely unaffected by diesel locomotive exhaust (thus the factor above ambient of 4 for UPFs in Boston push trains). CATF observations suggest that the strong pollution spikes from open doors on the Back Bay Station platform could take 10-20 minutes to decay in the coach in the absence of other pollution increases.

Researchers found it difficult to wait on the platform with the equipment—experiencing mild respiratory effects such as coughing, runny nose and watery eyes. We suspect that exposures in the underground diesel train station environment could prove hazardous for some sensitive individuals—at peak concentrations that were documented at perhaps 100 times outdoor concentrations of black carbon and ultrafine particles.

Seven passes through Boston's highway tunnels documented the following average net exposures above outdoor ambient background across the runs: For $PM_{2.5}$: 32 ug/m^3, for UFPs 35,000 pt/cc, for black carbon 4 ug/m^3. But average maximum levels were much higher: For $PM_{2.5}$: 128 ug/m^3, UFPs: 175,000 pt/cc, black carbon 15 ug/m^3. For individual runs some pollutant levels were extreme.

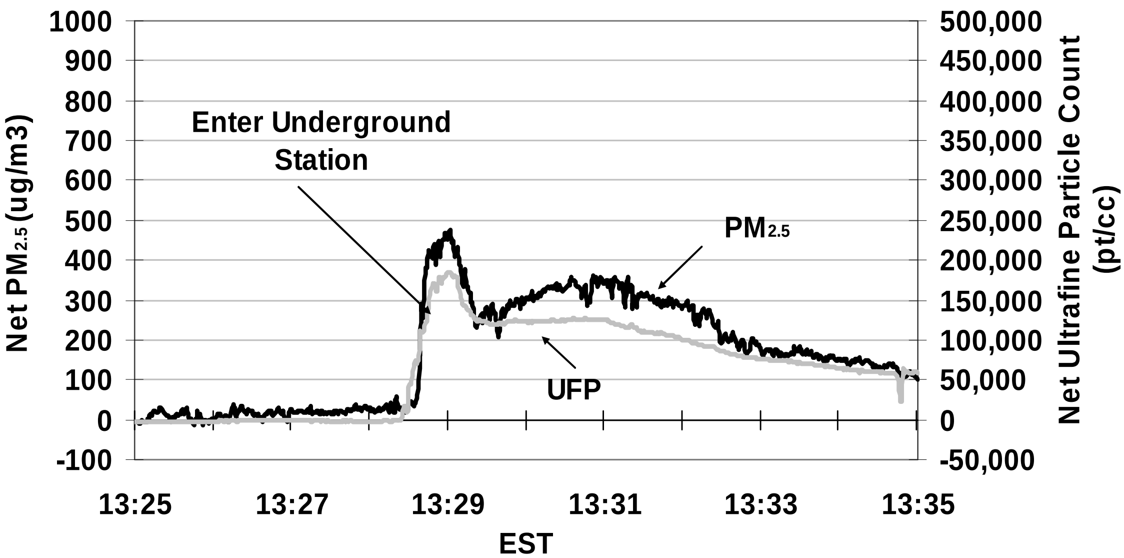
Two investigations at Boston's Back Bay commuter rail station resulted in the following extreme *average* exposures: For $PM_{2.5}$: 503 ug/m^3, for UFPs: 166,000 pt/cc, for black carbon: 46 ug/m^3 and for PAH 418 ng/m^3. Peak levels reached averages of: for $PM_{2.5}$: 1,225 ug/m3, for UFPs: 446,000 pt/cc, for black carbon, 157 ug/m^3, and for PAH, 1,666 ng/m^3.

Prior work documents pollutant exposures in highway tunnels. A variety of tunnel studies have been undertaken in California.[132] One study documented:

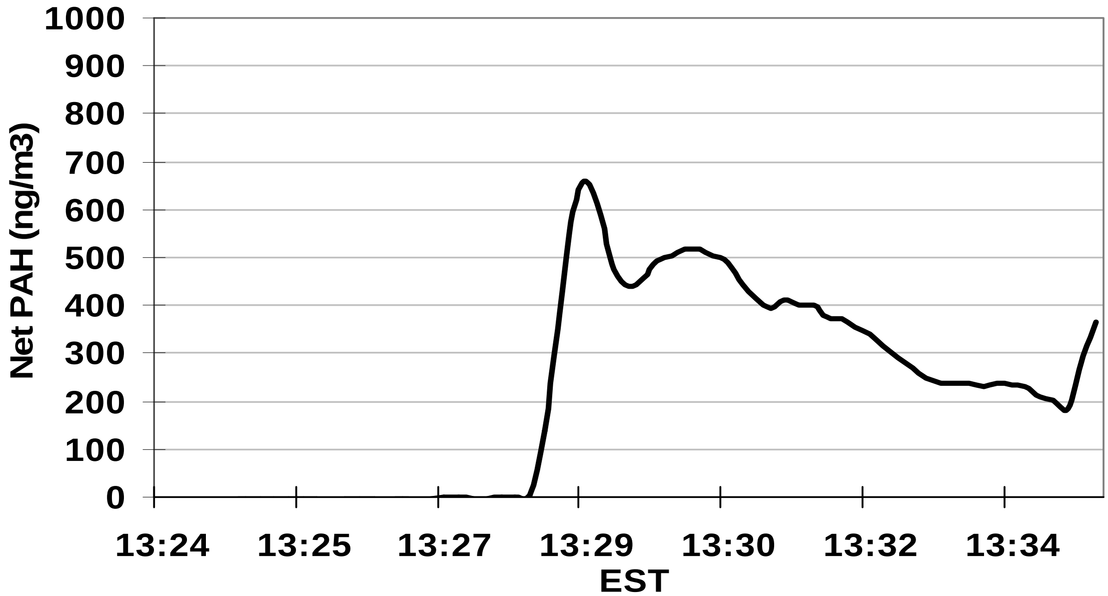
- Diesel-derived particle phase PAH found dominantly in ultrafine(<12 um) and fine (12-2 um) modes
- Black carbon levels in the truck-influenced bore were 5X the car-only bore
- Chemical mass balance calculations suggesting that HDD trucks were responsible for 93% of the black carbon emissions in the truck-influenced bore.

I. Boston's Underground Back Bay Rail Station

Standing on the platform in Boston's underground Back Bay Stations next to a diesel engine. In Back Bay station, diesel locomotives operate in a potentially dangerously confined indoor environment. The commuter rail platform in Porter Square in Cambridge MA is also of concern as it is partially confined and characterized by elevated diesel pollutant exposures



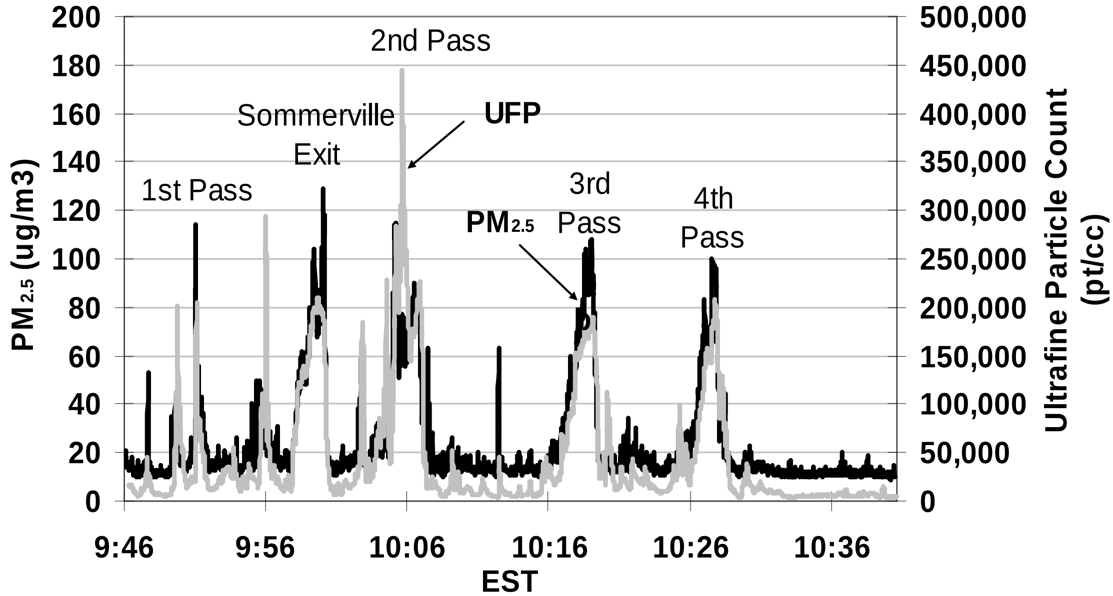
Above: Major spike in cabin pollution observed in train after stopping to pick up passengers at Boston's Back Bay Station.



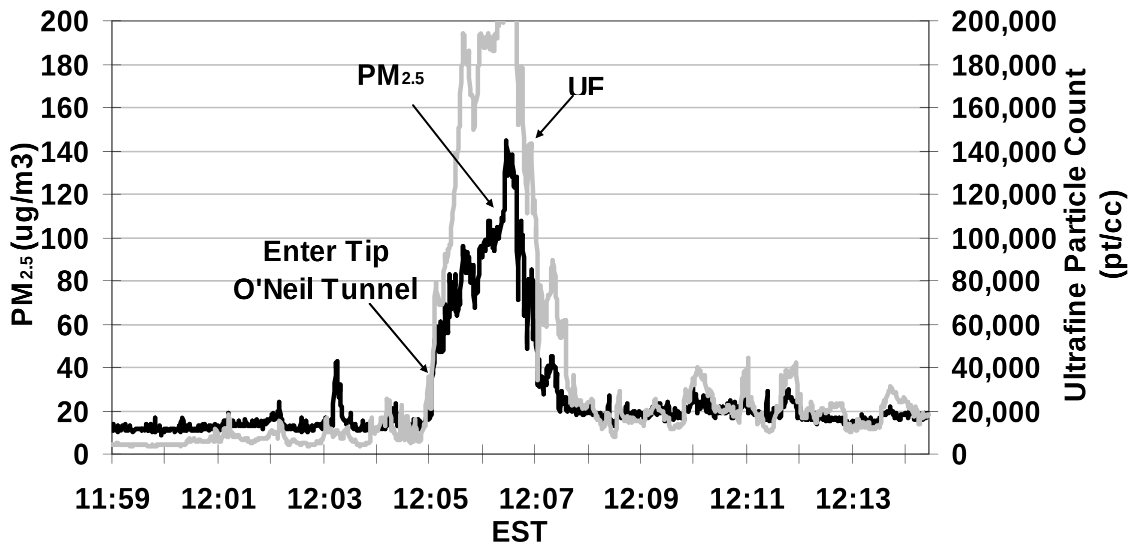
Boston train with locomotive in rear is polluted by particulate PAH when entering the underground Back Bay station at 13:28. Note parallel curve to UFP and $PM_{2.5}$ plots above.

II. Boston's Thomas' P. O'Neill Jr. Highway Tunnel

Entering Boston's 2 mile "Big Dig" Thomas P O'Neill tunnel.



Above: Multiple passes through Boston's "Big Dig" Thomas P. O'Neill tunnel document high levels of all four measured pollutants inside the tunnels. Exposures were reduced somewhat with windows closed, but substantially reduced when internal recirculation was used in the monitoring vehicle as determined in a 2 car parallel / simultaneous run experiment in the tunnels.



Above: Single pass through Boston motor vehicle tunnel demonstrates dramatic increases in fine and ultrafine particles in the monitoring vehicle (window partially open.)

PART IV: SOLUTIONS.

Today's Clean Air Retrofit Technology Means Cleaner Commutes

Starting this year (2007), highway engine emissions standards for newly manufactured diesels will ensure that *new and future* vehicles will never leave that telltale plume of black smoke. Similar rules require non-road vehicles such as diesel locomotives and marine vehicles such as commuter ferries, to begin to meet tougher emissions standards in the next decade through cleaner fuels and technologies. EPA's benefits analyses demonstrate that the technologies required by these rules will indeed provide important public health benefits. For example, EPA estimates that the 2007 highway rule, phasing in through 2010, will, once fully implemented in 2030, prevent 8,300 premature deaths and 1.5 million lost work days.[133] The federal non road diesel rule, rolling out in 2010, is estimated to prevent 12,000 premature deaths, 15,000 non-fatal heart attacks, and a million lost work days per year.[134] But that's in 2030—an entire generation away. What about today? The 13 millions diesels in use today will continue to pollute for many years to come. And as our studies suggest, there is no technological reason to wait to relieve commuters of the inescapable exposures they face.

Tackling this serious public health problem now— for the health of today's generations--depends on aggressive efforts to retrofit existing engines beyond waiting around for decades for fleet turnover as the cleaner engines replace the older ones. The technology required for the new vehicles is in use today and works. To improve public health, today's engines need to be retrofit the same technology as mandated for tomorrow's new engines.

Retrofitting buses and trucks to reduce diesel soot by 90% means the simple replacement of a muffler with a diesel particulate filter (DPF). In fact every 1994 and newer vintage truck can be retrofit with a DPF, a widely available and thoroughly tested technology. New York City and Boston have taken a lead in this arena, equipping much of their bus fleets with diesel particulate filters. New York City has also retrofit a large portion of its fleet of sanitation trucks. Other cities are experimenting with other marginally effective emissions controls strategies such as biodiesel fuel use in Columbus OH, or purchasing hybrid diesel-electric buses as in New York City and Seattle.

Box Truck Retrofit

CATF retrofit a class 5 box truck with a diesel particulate filter and undertook chase studies before and after. The DPF was extremely effective at reducing $PM_{2.5}$, with near-tailpipe levels dropping from 5000 ug/m3 to 25 ug/m3. thereby improving the air quality in the chase car behind it.

Above: Left: Box truck tested. Right: Monitoring vehicle videotaping while chasing the class 5 truck with monitoring equipment

Above: the box truck was retrofitted in short order. Note the internal DPF's honeycomb trap facing the viewer.

Above: A catalyzed diesel particulate filter (DPF) is nearly as simple as replacing the muffler. Verification tests by EPA and CARB suggest that DPFs are extremely effective and remove over 85 percent of diesel exhaust particles. Our results confirm that they work in traffic. These filters can typically be installed on vehicles 1994 and newer that have electronic engine systems. Some newer DPFs may be able to be used on all engines.

The DPF is as effective as it is easy to install. Left: before installation, right: reduced particles following DPF installation.

Progressive cities New York and Boston operate large fleets of new or retrofit diesel particulate filter-equipped transit buses and are in the process of retrofitting or replacing their entire fleets.

Above: Boston is one city leading the way with cleaner buses. Side-by-side images of videotaped Boston chase study shows that conventional transit bus (left) leaves a diesel exhaust plume behind, in comparison to the transit bus (right) with a diesel particulate filter, leaving no measurable plume in its wake. DPFs mean healthier air quality in and alongside the roadway and in adjacent neighborhoods. (See: www.catf.us/goto/noescape for the real time movie)

EPA estimates that the cost of the technology in new highway vehicles to be between $1200 and $1900 per vehicle. The current cost of retrofitting a highway diesel engine with a diesel particulate filter is still higher (typically greater than $5,000 per unit). However it is likely that EPA's manufacturing rules may result in a better economy of scale for diesel particulate filters and thus reduce cost of retrofitting, making retrofits more affordable for even the smallest fleets.

New York Sanitation Department has retrofit many of its trucks with DPFs. This overlay demonstrates the benefits in reducing ultrafine particles behind the truck. (CPC 3007 data.) Left: conventional truck without DPF. Right: retrofit truck. See video at www.catf.us/goto/noescape .

Retrofitting non-road vehicles is also an important part of the solution. Only about one fifth (varies by region) of the distillate fuel sold for use in diesel engines is delivered to operators of off-road diesel engines such as agricultural and construction equipment, locomotive and marine vessels. While the gallons of diesel fuel delivered to these types of equipment is far lower than that delivered to on-road trucks, off-road diesel engines can be up to ten times as dirty from an emission perspective on a per gallon basis. This means what while less fuel is consumed the actual pollution from off-road equipment is substantially higher representing in many areas of the country nearly 75% of the diesel engine PM inventory.

While a small part of the physical inventory, domestic marine vessels and locomotives currently represent about 25% of the diesel PM inventory. While new technology forcing emission standards have been developed for on-road and off-road construction engines, new emission standards for marine and locomotive engines are only now being developed. The emission control technologies themselves are expected to be similar to that used in on-road vehicles but the durability requirements will need to be substantially enhanced as marine and locomotive engines remain in service far longer than engines used in trucks.

Technologies to clean up locomotives and marine vessels are still largely under development with the most recent progress being the successful proof-of-concept for implementing oxidation catalyst technology on two-stroke diesel engines. For all marine and locomotive engines, the best practice first includes re-building with new internal components or re-powering and starting with the newer engines (e.g Tier 2/ 40%) and then followed by retrofit with diesel emission control technology such as an oxidation catalyst. The new Tier 3 and

Tier 4 standards are due in late 2007 and these new technology forcing standards are expected to drive the implementation of diesel particulate filter (DPF) technology, exhaust gas recirculation (EGR) as well as selective catalytic reduction (SCR) technology (for NOx removal). This is substantially similar to the technology paths for on-road and off-road diesel engines, but the timelines for marine and rail lag the other sectors to give manufacturers the needed time to harden the technologies for use in these demanding applications. Emission control technologies also need ULSD fuel (<15-ppm sulfur) to perform at their best and for marine and locomotive this fuel will not be required until 2012.

For locomotive and marine auxiliary engines, retrofit with DPF is possible subject to clean fuel availability as these are essentially off-road engines. Retrofit with passive DPFs must await 15 ppm ULSD fuel although many of the actively regenerated DPFs (i.e. those that use fuel injection to burn off carbon soot) have been successfully deployed with 500-ppm fuels that are now required for all locomotives . For existing road locomotives, the current recommendation/best practice is to rebuild the engine and consider DOC technology as it becomes available. In switching applications, repowering is recommended utilizing smaller off-road certified diesel engines that can more easily be equipped with DOC, DPF, EGR and SCR technology. These re-powered “gen-set” locomotives (can also be hybrid) can also net a substantial fuel economy improvement over conventional switch locomotives, essentially paying for themselves over the life of the locomotive. Results of this study also suggest improvement of ventilation or banning use in underground areas

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