In-Cabin Particulate Matter Quantification and Reduction Strategies

Final Report

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1. EXECUTIVE SUMMARY

This study evaluated the actual contributions from both the crankcase and the tailpipe emissions to in-cabin levels of fine and ultrafine particulate matter, and determined the effectiveness of commercially available retrofit technologies towards reducing levels of particulate matter inside the school bus passenger compartment. Previous studies have reported elevated concentrations of diesel particulate matter inside the cabin of the school bus. The elevated particulate concentrations have been attributed to the self-pollution from the school bus tailpipe and/or crankcase vent. Although there are uncertainties in the source of the particulate matter, the issue has gained national attention because children are a particularly sensitive subpopulation to the adverse health effects from diesel particulate matter. The objectives of this study are to measure the concentrations of fine and ultrafine particles within the cabin of a school bus with and without retrofit technologies.

To satisfy these objectives, mobile tests were conducted with a school bus powered by an International DT466E engine on an outdoor test track at the Aberdeen Test Center in Aberdeen, MD. The tests utilized a drive cycle developed using Global Positioning System data from actual school bus routes. Particulate matter concentrations were measured using three Thermo Electron DataRAM-4 units, and three TSI P-Trak ultrafine particle counters. Gaseous emissions (CO, CO_2, HC, NO_x), as well as pertinent engine parameters such as engine speed, fuel flow rate, engine oil temperature, and percent engine load were measured using the Sensors SEMTECH-D portable emission measurement system. Tests were conducted using the original school bus configuration without installed retrofit technology, a single retrofit technology and combinations of a closed crankcase ventilation system from Donaldson Company and a tailpipe retrofit. The two tailpipe retrofits that were tested were a Diesel Particulate Filter (DPF) using the Johnson Matthey-continuous regenerating technology[(1)] and a Flow Through Filter (FTF) using an Environmental Solutions Worldwide-particulate reactor[(2)]. All the tests were performed using ultra-low sulfur diesel fuel. At minimum of three runs were completed for each device combination for the windows closed position.

[1]Verified BART Level 3 by CA ARB and by VERT Filter List.

[2]Verified Level 2 by CA ARB (use only when Level 3 is not available)

This report is presents the results of two studies. The initial study was conducted using a bus that had several leaks through faulty seals in the bus. A total of 69 runs were conducted in this initial study. In the final study 19 runs were conducted with the same bus after sealing the leaks and establishing a new testing protocol. This new testing protocol was designed to minimize all extraneous sources of particulate matter except for that produced by the bus under normal operation. In this final study the bus was driven on an isolated test track that had no vehicles in operation while testing was in progress. Additionally the track was power washed to eliminate entrainment of particles from the road surface. Furthermore, a bus cabin cleaning procedure was employed for each run to eliminate re-entrainment of particulate matter from previous runs. Finally, for the final set of runs the bus was inspected following NJDMV protocols to insure that the condition of the bus with respect to emissions and in-cabin air quality met the rigorous state of New Jersey school bus standards.

From the analysis of the data from initial study, it was found that operating the bus with the windows open resulted in low concentrations of particulate matter in the cabin of the bus. Operating the bus with the windows closed resulted in higher particulate matter concentrations in the cabin of the bus compared to the particulate matter concentrations in the ambient air outside of the bus. This final study found that the average in-cabin particulate mass concentration with the ambient value subtracted for a bus driving without using any emission control technology on a school bus route with windows closed was 2.7$\mu g/m^3$. This value of 2.7 $\mu g/m^3$ was measured by DataRAM4 instruments located in the front and back of the bus. Based on the feasibility study data presented in the section, "Feasibility Study for Particulate Instrumentation ," this value is 1.3 to 1.8 times higher than the Federal Reference Method (FRM) standards. This in-cabin baseline value is substantially lower than those found from previous school bus studies. In addition this value is much lower than the national ambient air quality standard for $PM_{2.5}$ of 15$\mu g/m^3$. It is believed that this low $PM_{2.5}$ value resulted from operating a well-maintained and well-sealed school bus in an environment free of other point or moving sources of particulate matter. The initial study performed the experimentation with a leak in the back door of the school bus caused by a bent upper section of the door. The baseline values obtained for the initial study (with ambient subtracted and no retrofit technology) were 12$\mu g/m^3$ and 35$\mu g/m^3$ measured at the front and back of the bus respectively. The final study did not have these leaks and lower concentrations of particulate matter were measured in the bus cabin. This finding shows the significance of rigorous school bus inspections for passenger cabin leaks that are designed in part to minimize the influx of air containing pollutants into the school bus.

While this study did not directly measure tailpipe or crankcase PM, this study confirmed that the use of tailpipe retrofit technologies resulted in large emission reductions of gaseous pollutants normally emitted from the tailpipe. For the operating conditions in this final study all tailpipe retrofit technologies reduced CO approximately 50-65% and hydrocarbons were reduced by approximately 92 to 97%.

It was found that three retrofit technology combinations reduce in-cabin net $PM_{2.5}$ concentrations to values less than the baseline. The most effective technology was the combined DPF and CCVS. The results from the final study show that if only a DPF were used then it was 70% as effective as the combined DPF and CCVS. If the combination of FTF and CCVS were employed then this retrofit was approximately 50% as effective as the combined DPF-CCVS retrofit technology. It was found that for reduction in-cabin net $PM_{2.5}$ concentrations neither the CCVS nor the FTF were significantly better than the baseline condition of a standard bus.

The results of this study showed that in-cabin net ultrafine concentrations as measured by the P-Trak decreased with increasing engine oil temperature. In addition, it was found that the concentrations of ultrafines were higher in the front of the bus compared to the back of the bus for all retrofit technologies. From the analysis of the ultrafine data as a function of engine oil temperature it was determined that the use of a CCVS reduces the particle count concentrations from 50 to over 100% compared to the cases without the CCVS. The DPF or FTF used without a CCVS did not significantly reduce in-cabin net ultrafines concentrations.

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2. GLOSSARY OF TERMS

ATC	Aberdeen Test Center
CCVS	Donaldson Spiracle Crankcase Ventilation System
DPF	Diesel particulate filter, Continuously Regenerating Technology, wall flow filter, ceramic filter by Johnson Matthey
DataRAM-4	Dual wavelength nephelometer which continuously monitor's particle concentration and median particle size. Manufactured by Thermo Electron Corporation.
ESW	Environmental Solutions Worldwide
Fine PM	Particulate Matter (PM) is defined as having a diameter less than 2.5µm or $PM_{2.5}$
Ultrafine PM	Ultrafine Particulate Matter is defined as having a diameter in the 20nm to 300nm range.
GPS	Global Positioning System
JM	Johnson Matthey
PAH	Polycyclic Aromatic Hydrocarbons
PM	Particulate Matter
P-Trak	Model 8525 Ultrafine Particle Counter which uses condensation particle counting technology to continuously monitor particle number concentration. This is manufactured by TSI Incorporated.
FTF	Flow through filter, diesel oxidative catalyst, wire mesh filter, advanced diesel oxidation catalyst by Environmental Solutions Worldwide
FRM	Federal Reference Method for $PM_{2.5}$ measurements in accordance with 40 CFR part 53
DPF	Diesel Particulate Filter
RCSBC-S	Rowan Composite School Bus Cycle - Straight
RUCSBC	Rowan University Composite School Bus Cycle
ULSD	Ultra Low Sulfur Diesel Fuel
TEOM	Tapered Element Oscillating Microbalance
DECS	Diesel Emissions Control System

3. INTRODUCTION

According to the U.S. Environmental Protection Agency (EPA)[1], there are over 450,000 school buses in the United States, with an estimated 390,000 that are powered by diesel fuel. These buses carry 24 million children to and from school over a total of 4 billion miles. It is estimated that, on average each child is on a school bus each weekday for an hour and a half. [2]

Health effects studies[3,4,5] have associated diesel exhaust exposure with multiple adverse health effects such as exacerbation of asthma, headache, fatigue, nausea, irritation of eyes, nose and throat, increased risk of heart attacks, premature death, birth defects, impaired immune and neurological systems, sputum production, reduced lung function and cancer. Diesel exhaust has a variety of confirmed carcinogenic compounds like acetaldehyde, formaldehyde, dioxins and polycyclic aromatic hydrocarbons (PAHs)[6]. Emissions from diesel engines include over 40 substances listed by the U.S. Environmental Protection Agency as hazardous air pollutants and by the California Air Resource Board as toxic air contaminants[7].

Children are particularly susceptible to the adverse effects of diesel particulate matter because their lungs are still under development; they have high inhalation rates relative to body mass, high lung surface area per body weight, low lung clearance rates, narrow lung airways and immature immune systems[8,10].

The intent of Public Law 2005, c.2191, signed on Sept 7, 2005, was to reduce diesel emissions in New Jersey. As part of this legislation, the New Jersey Department of Environmental Protection (NJDEP) was charged with (1) conducting research to evaluate the relative contribution of emissions from both the crankcase and the tailpipe to in-cabin levels of fine particles in school buses; and (2) evaluate the feasibility of requiring, and the environmental and health benefits of, the reduction of fine particle levels from school bus tailpipe emissions through the use of additional retrofit devices. The monitoring study was carried out by Rowan University in collaboration with the NJDEP Division of Science, Research and Technology (DSRT).

Previous studies[9,10,11,12,13,14] have reported that emissions from both the tailpipe and crankcase contribute to high levels of particulate matter measured inside a school bus compared to a lead car and/or ambient air. These control technologies include diesel emission retrofits of both the crankcase and the tailpipe as well as alternative fuels. All the previous studies have their strengths and weaknesses, however, no previous study to date has performed triplicate runs in which the major factors that produce particulate matter are replicated such as driving the same route, having the same load on the bus, using the same bus operator, minimization of road dust, elimination of other vehicles from the road. The major variations in the Rowan study was the diesel emission retrofit technology tested and the natural variation of ambient particulate matter concentrations. One of the expected results in the Rowan study was to obtain a reduction in particulate mass concentration $PM_{2.5}$ based on previous literature. A study performed by the Clean Air Task Force[1] determined that the crankcase emissions were a major source of $PM_{2.5}$ measured inside the school buses. They also concluded that the best method to reduce particulate matter in the cabin of the bus was a combination of a Diesel Particulate Filter (DPF), a closed-crankcase filtration system, and Ultra Low Sulfur Diesel (ULSD). This combination showed good results in eliminating particulate matter, black carbon, and particle-bound polycyclic aromatic hydrocarbons (PAH's) from inside the bus[1].

Rowan University conducted two studies; in the initial study a total of 69 runs were performed in a one-mile loop track and it was concluded that emission of particulate matter can be reduced using diesel control technologies. However, the findings of the initial study were obtained using a school bus with a several leaks into the bus that allowed infiltration of particulate matter. In addition, there were a number of uncontrolled particulate sources from surrounding dust from the one-mile loop track and diesel vehicles that obfuscated the results of the study. This created the need to conduct a more controlled final study that consisted of 19 runs on a different test track and with the leaks of the bus properly sealed. This final study inferred the relative contributions from both the crankcase and the tailpipe emissions to in-cabin levels of fine and ultrafine particulate matter, and determined the efficiency of commercially available retrofit technologies towards reducing levels of particulate matter inside the school bus passenger compartment. The technologies evaluated in both studies include a Donaldson's Spiracle Crankcase Filter (CCVS) which minimizes entrainment of lubricating oil particles from the engine; Johnson Matthey's Continuous Regenerating Technology (CRT) diesel particulate filter (DPF) (a verified retrofit technology by the Environmental Protection Agency (EPA) for reducing 90% on particulate matter[15]), and Environmental Solutions Worldwide's (ESW's) Particulate Reactor flow through filter (FTF) which received a Level 2 verification from the California Air Resources Board for technologies that achieve at least a 50% reduction in particulate matter emissions[16].

4. BACKGROUND

The school bus study by Solomon et al. 2001[17] was designed to measure the level of diesel exhaust to which children are typically exposed as they ride on buses to and from school each day. In this study it was concluded that particulate concentrations inside the school bus were higher than outside of the school bus and the highest particle concentrations were observed with the bus windows closed compared to windows open and that the particulate concentrations in the back of the bus were higher than the front of the bus. The results showed that a child riding inside a school bus may be exposed to as much as 4 times the level of toxic diesel exhaust as someone riding in a car ahead of it.

It is suspected that, for self-pollution, diesel particulate matter within the cabin of a school bus originates from two major sources: tailpipe emissions and crankcase emissions. It is possible for these pollutants to enter the school bus through normal opening of the front loading door, open windows, faulty seals on doors or other bus cabin penetrations, or ventilation system vents while in operation. The main tailpipe emissions from a diesel engine are PM (size range 3 nm to ~ 10 micrometers consisting solid insoluble soot, lube oil ash, metal wear particles with a wide range of specific sizes; toxic HC substances adsorbed to solid particles; SOF, sulfate and water), and gaseous CO, CO_2, H_2O, hydrocarbons (many toxic), SO_2, NO and NO_2. These are a direct result of the combustion of diesel fuel and lubrication oil and engine wear. The other source of emissions is from the crankcase which is a metal housing that surrounds the crankshaft and other engine components. Crankcase emissions, also known as blow-by exhaust, result when the increased pressure differential during combustion forces a small amount of exhaust products from the combustion chamber past the pistons and into the crankcase. The pressure in the crankcase is controlled by releasing the blow-by gases along with an additional amount of crankcase generated entrained lube oil mist through a vent tube that is historically open to the atmosphere. Effort is made to remove, via coalescence, most of the entrained lube oil mist from the crankcase exhaust before venting. Nevertheless some entrained lube oil particles are released. These particles are found to be $PM_{2.5}$ in size and consist of lube oil with a small amount of solid combustion generated soot. For the majority of school buses in New Jersey, the engine is located in the front of the bus and the vent tube is located directly underneath the front of the bus adjacent to the front door. It is important to note that new engines have closed crankcase, however the importance of retrofitting school buses with CCVS units is based on the older busses in the fleet that are used for up to ten years.

In a recent review by Borak and Sirianni,[18] they analyzed 19 reports of 11 studies that measured in-cabin particulate concentrations of school buses. Their overall conclusion from the analysis of the data from these studies is that in-cabin levels of particulate matter can be reduced using control technologies. Of these 11 studies, they concluded that the Clean Air Task Force study[12] was a well designed study in which particulate concentrations were compared on specific buses using a number of emission control conditions. In particular it was noted that the most extensive set of data was obtained from one bus (#56) that was driven on a residential route in Ann Arbor, MI using 7 sets of emission reduction schemes. Data from duplicate runs for each of the reduction schemes were given. The advantage of the Clean Air Task Force study is that comparisons could be made between technologies since several sets of data used the same bus and a common bus route In addition runs were duplicated for each condition. What was not held constant was the exact driving cycle for this route. The length of stops, duration of the loading door open condition, and external sources of particulates were not controlled. In this study particle concentrations were measured with 4 different instruments: TSI DustTrak ($PM_{2.5}$), P-Trak (ultrafine), Black Carbon Mass Magee Scientific Aethalometer, and Ecochem Analytics personal PAH monitor.

This Clean Air Task Force study[9,12] has shown that particulate matter within the cabin of a school bus originates from both the tailpipe and the engine crankcase. This was demonstrated from measurements on a school buses retrofitted with crankcase filters and tailpipe particulate filters. The closed crankcase filter (CCVS) used in this Clean Air Task Force study was manufactured by Donaldson Spiracle and was selected for use in this CATF study. In this CATF study it is claimed that the majority of $PM_{2.5}$ particulates originated from: a) the crankcase vent and b) the ultrafine particulates found in the cabin of the bus originated primarily from the tailpipe exhaust.

Ireson et al. (2004)[19] used a fuel-based, iridium, tracer to determine the concentration of diesel particulate matter (DPM) originating from the exhaust of the school bus. Dynamometer emissions tests established the mass ratio of DPM-iridium in the exhaust which was used to determine the particulate emissions based on measured iridium concentrations. The measurement sensitivity using this method is approximately $0.001\mu g/m^3$. Sampling for DPM and iridium was conducted at two locations inside the bus, and background DPM and iridium concentrations were measured at a fixed site and in a lead vehicle driving ahead of the bus on the same routes. Twelve sets of on-road samples were collected, including six runs each with bus windows open and closed. The DPM concentrations inside the cabin were calculated by multiplying the observed in-cabin iridium concentration (subtracting the lead vehicle background measurement) by the DPM-iridium ratio. For all the on-road sampling runs, except for one, the background concentration of $PM_{2.5}$ was greater than that measured inside the bus cabin. The average fuel consumption was 0.94gal/test. For all the closed windows runs the front of the bus measured a higher concentration of $PM_{2.5}$ compared to the back of the bus with a raw (without subtracting background) average of 74μg/m^3 for the front versus 59μg/m^3 for the back. In this study by Ireson, the average measured DPM concentration with ambient subtracted was only 0.22μg/m^3. The results suggest that DPM contribution to in-cabin levels is most likely exhaust from other vehicles.

A study by Rim et al. (2008)[20] in the suburban area of Austin, Texas, assessed in-cabin concentrations of diesel-associated air pollutants in six school buses with diesel engines during typical routes. The in-cabin concentrations of diesel emissions had substantial variability across the range of tests even between similar buses. Mean in-cabin $PM_{2.5}$ concentrations were 7-20μg/m^3 and were generally lower than roadway levels. Mean ultrafine PM number concentrations measured inside the cabin were between 6100 to 32000pt#/cm^3 and were also generally lower than roadway levels. Median values for ultrafine PM number concentrations indicated that in-cabin levels were higher or approximately the same as the roadway concentrations. Tests were conducted on three buses prior to and following the installation of a Donaldson Spiracle Crankcase Filtration System and a Diesel Oxidation Catalyst (DOC). The DOC showed negligible or small reductions to in-cabin pollutant levels. The use of the Spiracle alone resulted in reduction ranging from 24 to 37% for NO_x and 26 to 62% for $PM_{2.5}$, and 6.6 to 43% for ultrafine PM number concentration. The investigation team concluded that the variation between repetitive tests implied that retrofit installation could not always be conclusively linked to the decrease of pollutant levels in the bus cabin.

Experiments were conducted by Di Yage, Cheung C.S., and Huang Z., (2009)[21] using a four cylinder direct-injection diesel engine model Isuzu 4HF1 with a maximum power of 88kW at 3200rev/min. The engine was fueled with ultra-low sulfur diesel, biodiesel from waste cooking oil, and their blends. The measurement of PM mass concentrations (μg/m^3) was determined using a R&P TEOM 1105 and particulate number concentration (pt#/cm^3) using a scanning mobility particle sizer (SMPS) TSI model 3934. The exhaust gas from the engine was diluted with a Dekati mini-diluter before passing through the SMPS and the TEOM. The following results were obtained with an increase of biodiesel in the fuel blend. The HC and CO emissions decrease while NO_x and NO_2 emissions increase. Particulate mass concentrations were reduced significantly at high engine load with the increase of biodiesel in the fuel. For submicron particles, the geometrical mean diameter of the particles becomes smaller while the total number concentration increases. The particle total number concentration results using ULSD only at 1800rev/min and engine loads of 0.20MPa, 0.38MPa, and 0.55MPa were 2.11E7pt#/cm^3, 4.27E7pt#/cm^3, and 5.27E7pt#/cm^3 respectively.

A Washington State school bus investigation[22] measured continuous $PM_{2.5}$ data collected during 85 trips aboard 43 school buses during normal driving routes. Hybrid lead vehicles were used to monitor $PM_{2.5}$ data traveling in front of the buses during 46 trips. Continuous measurements of $PM_{2.5}$ were collected using Thermo Scientific personal DataRAM (pDR-1000AN) instruments using a 2.5μm sharp-cut cyclone. TSI P-Trak 8525 instruments were used to measure real-time ultra fine particle number concentrations. The mean duration of all trips was 22 min with approximately 4 stops per trip. Windows position during the trips was not controlled, and the authors indicate a range of trips with open windows from 60% to 36%. Mean concentrations inside school buses (21μg/m^3) were four times higher than ambient and two times higher than roadway levels respectively. The average difference between the in-cabin buses levels and the lead vehicles values was 7μg/m^3.

A study conducted in Fairfax county[23] in the state of Virginia, used a sample of twelve buses to measure respirable particulates (less than 10 microns) and diesel exhaust components (elemental and organic carbon) during bus operation following the same route keeping conditions such as windows closed, heater on, and three minutes idling at each stop for each run. To measure the particulate matter, a portable SKC pump was used collecting the sample in a 37mm pre-weighted PVC filter. The particulate matter samples were analyzed in a medical laboratory using a gravimetric procedure following the NIOSH method 0600 which measures the mass concentration of any non-volatile respirable dust with a working range from 0.5 to 10mg/m^3 for a 200 L air sample. The 12 buses were driven on simulated 90 minutes routes with 5 stops that were 3 minutes each. Concentrations ranged from less than 0.051mg/m^3 to 0.205mg/m^3. The study concluded that the concentration of diesel exhaust inside the cabin of the school buses tested was below the limits of detection and that there was no significant age-related difference in the bus air quality.

The EHHI study[24] measured particulate concentrations experienced by 15 students through a school day. In addition, in-cabin particulate levels were measured for 27 simulated bus runs in which the driver drove an empty bus and stopped and opened the door to simulate picking up and dropping off students. Personal DataRAM nephelometer's (i.e. photometric monitors whose light scattering sensing configuration allows for the mass concentration measurement of the fine particle fraction of airborne dust, smoke, fumes and mists in the air) (pDR-1200) were located at the front seat and back seat of the school buses. In addition, an aethalometer (is an instrument that uses optical analysis to determine the mass concentration of "Black Carbon" particles collected from an air stream passing through a filter) from Magee Scientific was used to measure black carbon mass concentration. The results obtained for fine particles concentrations ($PM_{2.5}$) measured on this buses were often 5-10 times higher than average levels measured at 13 fixed-site $PM_{2.5}$ monitoring stations in Connecticut. The fine particle levels were higher when the buses were idling with windows opened, when buses ran through their routes with windows closed, when the buses were surrounded by intense traffic, and especially when buses were queued to load or unload students while idling.

The school bus study in Anchorage, AK[25] used a nephelometer to monitor in-cabin particulates for 4 buses on actual school routes. No students were on these buses, but they opened doors to simulate loading and unloading of students. This study found a large variability in in-cabin particulate concentrations that appeared to be related to the bus route driven rather than to the type or age of the bus. For example the lowest concentrations measured in the cabin of a bus were found on lightly used snow covered roads. Problems with entrained particulates from the road surface were noted in this study. The diesel exhaust school bus averaged sampling results for $PM_{2.5}$ ranged from

0.007 to 0.149mg/m^3. This study illustrated the importance of characterizing or controlling the amount of particulates generated and entrained from a road surface.

A comprehensive set of papers[26,27,28,29,30] have been published. One of these studies[29] examined 7 school buses driven on actual routes in Los Angeles obtaining the range of integrated $PM_{2.5}$ concentrations measured on one of the routes for windows open and closed (13-56 and 36-60μg/m^3, respectively), and also similar to the range of concentrations measured on another route with windows open (18-57μg/m^3). For a given bus on urban routes, $PM_{2.5}$ concentrations were generally higher with windows closed, except for a bus equipped with a particle-trap catalyst which had similar high concentrations (>50μg/m^3) for both windows open and closed.

The study by Hammond[31], measured in-cabin particulate concentrations for clean diesel buses (2004 model), non-retrofitted, and school buses retrofitted with DOC's. They found that old buses (1991-2002) retrofitted with DOC's resulted in similar in-cabin particulate concentrations to that of a 2004 Clean Diesel bus. In this study particle number concentrations were measured using a P-Trak (TSI Model 8525) particle counter. The particle number results for these studies are reported without ambient particle number values. The average for the non-retrofitted buses in the morning commute was in the order of 70,000pt#/cm^3, for the retrofitted buses in the morning commute was approximately 35,000pt#/cm^3, and the clean diesel buses obtained an average of less than 30,000pt#/cm^3. A similar study was conducted using transit buses in which particle count concentrations were measured ranging from 20,000 to 450,000 particles/cm^3(the ambient background concentrations were not measured for the study). The average in-vehicle particle count concentrations for oxidation-catalyst diesel, compressed natural gas and conventional diesel buses were 9,954 particles/cm^3, 10,230 particles/cm^3, and 38,106 particles/cm^3, respectively[32].

A recent Texas study by McDonald-Buller et al.[33] examined gas and particulate concentrations inside the cabin of a school bus before and after retrofits. The retrofits included the Donaldson Spiracle closed crankcase ventilation system (CCVS) and diesel oxidation catalyst. This study found that the use of the Spiracle resulted in statistically significant decreases in NOx concentrations, but could not make similar conclusions on particulate matter. Particulate matter was measured using a nephelometer (DustTrak) for particulate mass and a particle counter (P-Trak) for particle number concentrations. Mean $PM_{2.5}$ mass and number concentrations prior to retrofits ranged from 9-20μg/m^3 and 6,054-32,272pt#/cm^3 respectively. The Spiracle and Spiracle/DOC resulted in relatively larger reductions of in-cabin $PM_{2.5}$ and ultrafine particle number concentrations for one bus, but had no clear results for the other two buses. No clear conclusion could be drawn for the use of the DOC for particulate matter concentrations. $PM_{2.5}$ values may be affected by different levels of particle re-suspension as well as by ambient variations.

A series of studies have been conducted by Clark at West Virginia University[34,35] in which crankcase and tailpipe emissions were obtained for crankcase vents from 5 different engines. The particle size range was dependent on the engine type, speed, load, and oil temperature. In general, particle number concentrations for crankcase particulate matter ranged in particle size from 0.01 to less than 1µm which is within the range of measurements found in this final study.

Based on data reported in a presentation by Kittelson[36] the range of particle sizes from the crankcase vent had a maximum above 3µm for light duty diesel engines and above 7µm for heavy duty diesel engines.

Clark[34] found that the mass of particulate matter from the crankcase was equal to 5.7% of the total mass of particulates collected from the tailpipe exhaust. This result was obtained by having the crankcase emissions directed to a dilution system for measurement of regulated species without using a crankcase ventilation system. Analysis of hopanes and stearane composition of the lubricating oil and particles captured by the crankcase sampling filters showed that lubricating oil was on average 50% of the total particulate matter collected on the crankcase sample filters. The other half of the mass was attributed to combustion PM escaping past the cylinder rings and into the crankcase as well as other sources such as engine wear. In addition, the total particle number concentrations, measured using a Cambustion DMS500 analyzer, from the dilute crankcase vent were in the order of 10^7 particles/cm^3 with a mean diameter size of approximately 70nm. The total particle number concentration from the diluted tailpipe exhaust was the same order of magnitude as the crankcase.

It has been postulated that the most probable pathway for particulate matter to enter the bus cabin is when the front door of the bus is open.[9] Particulates entering in this manner will come mainly from the crankcase emissions which are normally emitted through a draft vent tube located below the bus and near the door. The tailpipe emissions can also enter the bus through this front door, but the wind direction plays a major role since it will determine the conditions for the access of particulate matter into the cabin.

It has been established from EPA and Air Resources Board (ARB) verification testing and reports in the literature that diesel exhaust retrofits are very effective in reducing the total mass of particulate matter exhausted from the tailpipe as well as eliminating particles greater than 0.04µm. Studies have been conducted showing that an increase in particles with diameters less than 0.02µm have been observed.[37]. This is limited to catalyst-based DPF and greatly decreased or eliminated with ULSD. The increase in particle number emissions is associated only with high-temperature operations, and only for some technology configurations.

Most previous studies have shown that there are high levels of particulate matter inside a school bus compared to a lead car and/or ambient air. What is missing from most studies is the ability to determine the source of these particulate emissions. These particulates could originate from self pollution by the school bus or from ambient air containing high particulate levels. School bus self pollution has been attributed to the exhaust from the tailpipe as well as the exhaust from an open engine crankcase vent. Additionally, particulates inside the cabin of the bus may also originate from the re-entrainment of road dust as a result of the motion of the school bus. This final study estimated the reduction of in-cabin PM when various combinations of control technology are employed and the relative contribution of tailpipe and crankcase emissions to in-cabin levels of PM using a school bus engine and route that is typical of that found in the state of New Jersey.

5. EXPERIMENTAL

This project determined the most effective control technology for reducing particulate matter levels inside a school bus cabin during operation and evaluated the relative contribution of emissions from both the crankcase and the tailpipe to in-cabin levels of fine and ultrafine particles.

5.1 Study Design

In order to evaluate the relative contribution of emissions from both the crankcase and the tailpipe to in-cabin levels of fine and ultrafine particles, the following experiments were performed:

1. Establish a baseline of fine and ultrafine particulate matter concentrations in the cabin of a typical New Jersey school bus operated on a characteristic New Jersey school bus route. This school bus would not have any retrofitted diesel emissions control systems (DECS) or devices.
2. Measure the in-cabin concentrations with the application of the following emission reduction technologies:
    a. Closed crankcase ventilation filtration system (CCVS)
    b. Diesel Particulate Filter (DPF) (also known as Level-3 wall flow filter)
    c. Combination of both DPF and CCVS
    d. Flow through filter (FTF) (also known as Level-2 diesel oxidative catalyst or wire mesh filter or particulate reactor)
    e. Combination of both FTF and CCVS

The mobile testing was conducted using a 1998 school bus with approximately 50,000 accumulated miles and is powered by an International DT466E engine with a displacement of 7.6L (466 in^3) and a rating of 190hp at 2300 rpm. The cab of the bus is a 1999 AmTran cab with 23 seats for a capacity of 54 children. This engine is located in the front of the bus and is representative of the most common engine type used in New Jersey school buses[38]. The bus was well maintained and most recently maintenance was performed prior the start of the final study.

The particulate matter mass concentrations were measured using three DataRAM-4 units. The DataRAM-4 is a two-wavelength nephelometer. Sample exhaust is pulled though an omnidirectional sampling inlet followed by an inertial coarse-particle impactor, which removes particles larger than 2.5µm. Using this device the diameter size range for concentration measurements from the DataRAM-4 is between 0.08µm to 2.5µm.

Particle number concentrations for ultra-fine particulate matter were measured using three TSI P-Trak Model 8525 Ultrafine Particle Counters. The particle size measurement range of the P-Trak is from 0.02 to 1µm diameter and the concentrations are reported as number of particles per cm^3 of gas.

The gaseous emissions as well as the pertinent engine parameters such as engine speed, fuel flow rate, engine oil temperature, and percent engine load were obtained from the bus engine computer using the Sensors, Inc., SEMTECH-D. This instrument is a portable PC-based data acquisition system capable of measuring emission levels along with several vehicle and engine parameters. The SEMTECH-D uses proprietary software, along with a heated sampling line and the following measurement subsystems: (1) Heated Flame Ionization Detector (FID) for Total Hydrocarbon (THC) measurement; (2) Non-Dispersive Ultraviolet (NDUV) for Nitric Oxide (NO) and Nitrogen Dioxide (NO2) Measurement; (3) Non-Dispersive Infrared (NDIR) for Carbon Monoxide (CO) and Carbon Dioxide (CO2) measurement.

Under this grant 2 sets of runs were conducted. In the first set of runs a high level of particulate matter was found inside the bus. In this set of runs the high concentration of particulate matter was primarily attributed to leaks through faulty seals at the back and front of the bus. To eliminate these leaks the bus was repaired at an experienced body shop in Maryland and then inspected by New Jersey Department of Motor Vehicles (NJDMV) personnel. Even after the back door was repaired, the bus failed the inspection. The major fault was again the back door which failed the flashlight test; which is a visual inspection of the passage of any light from a flashlight on the opposite side of the door through a gap in the seal. In addition to failing for the back door additional faults were found: 2 leaks were found through unsealed wiring grommets through the engine firewall into the front cabin of the bus; the front door seals were faulty; an exhaust connector was found to be loose allowing an exhaust leak under the passenger compartment. After these leaks were repaired, the bus passed re-inspection. Very few previous studies have reported that the buses were inspected. One exception is that in the CATF study[9] it was reported that buses were inspected. They specifically stated that the "rear doors were adequately sealed." Throughout the report the runs from the initial study are presented in numerical order from 1 to 69, and the results from the final study are presented with an "F" following the number to indicate it is a final run. For example, the numeration for the final study goes from 1F to 19F.

5.2 Testing Protocol for Initial Runs

The bus was driven following a modified form of the Rowan University Composite School Bus Cycle (RUCSBC)[39]. The original school bus cycle was modified to include the action of the school bus stopping to pick-up passengers. The cycle was developed with Global Positioning System (GPS) data from typical New Jersey school bus routes. During the stops designated in the cycle, the bus driver opened the door to simulate the access of children; this process was repeated for 16 stops with the shortest stop period of 10 seconds, and the longest of 34 seconds during the cycle. The total run time of the cycle consisted of 1300 seconds which is approximately 22 min.

The bus was driven following a modified version of the Rowan University Composite School Bus Cycle (RUCSBC) shown in Figure 1. The original school bus cycle as developed by Toback (2005)[39] was modified to include the action of the school bus stopping to pick-up or drop-off passengers. The original cycle was developed with Global Positioning System (GPS) data from typical New Jersey school bus routes.

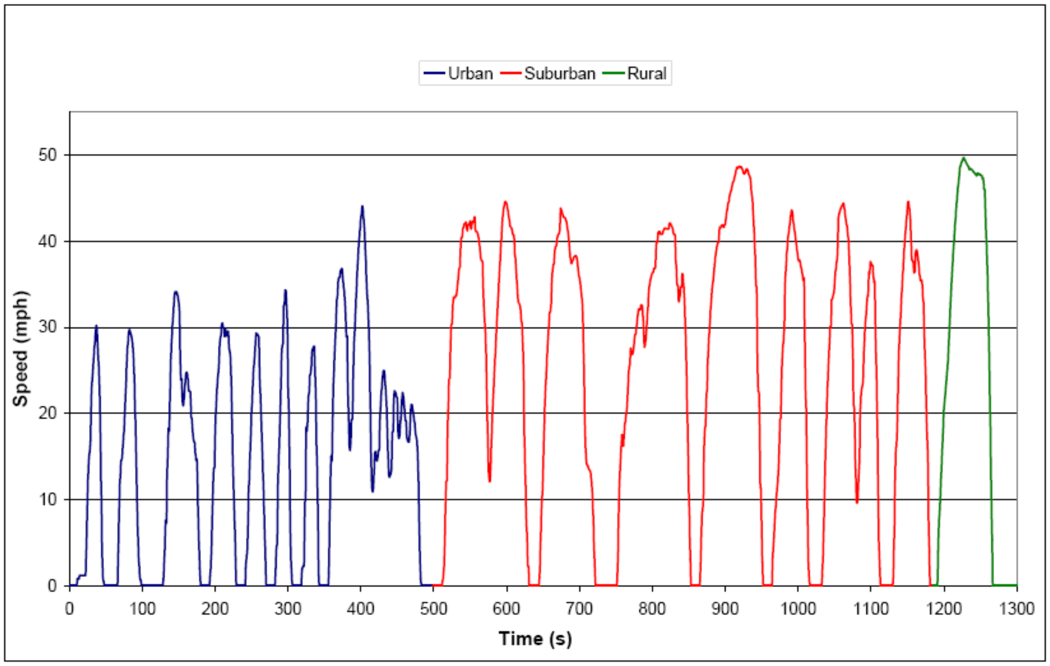

Figure 1: Modified Rowan University Composite School Bus Cycle used for Initial Set of runs 1-69 one mile loop.

The RUCSBC was designed for continuous driving which is best done on a test loop or oval track. The initial set of runs was performed on this route, but several problems with diesel operated equipment as well as the inability to minimize road dust required a shift from this track to an isolated straight track with two turnarounds at each end.

The one mile loop at ATC was selected in order to obtain repeatable runs of the modified Rowan University Composite School Bus Cycle (RUCSBC). The 1 mile loop at ATC was closed to all other traffic while the tests were being performed. In order to examine the effect of environmental conditions on the levels of particulate matter inside the bus a meteorological station that measured the wind speed and direction as well as temperature was located at the ambient monitoring station located within the track. The initial study recognized external particulate matter contributions: Diesel PM sources coming from nearby heavy duty trucks and military tanks that were driven on Aberdeen Blvd with approximate location shown in the figure below. In some instances the DataRAM-4 instruments were measuring dust coming from a construction zone when dump trucks were active in an area adjacent to the track, and/or from the wind blowing dust from the external side of the paved loop which consisted of a dust road as seen in the figure below.

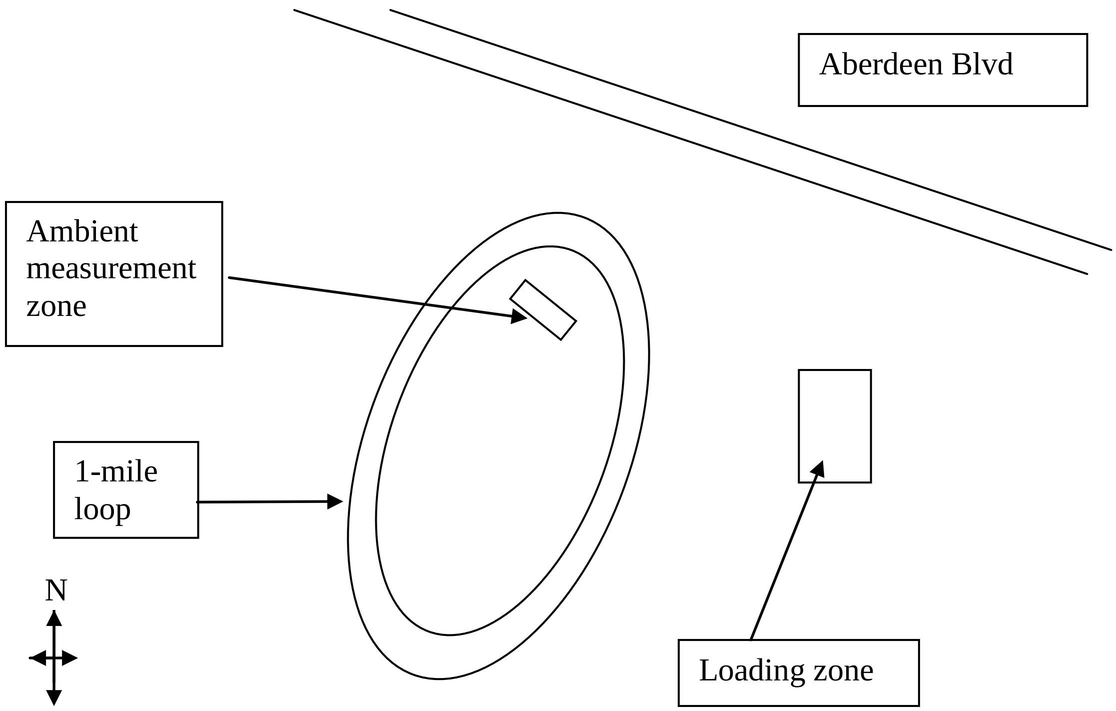

Figure 2: Testing zone scheme showing the 1-mile loop used in the initial test. A nearby road and a load zone of construction material are represented in the scheme.

5.3 Testing Protocol for Final Runs

A new series of runs was planned using a new protocol that was designed to minimize all extraneous sources of particulate matter except for that produced by the bus under normal operation. A new testing protocol was developed with input from NJDEP, USEPA and the experience gained from the previous series of tests. The full version of the protocol is given in Appendix P: Testing Protocol. Given below is a brief description of the major features of this protocol.

Several limitations were placed on testing based on the weather and air quality index predictions for the day of testing. For tests to proceed as scheduled, the following conditions must be met:

1. temperatures must be predicted to be in the operation range of instrumentation within the cabin of the bus with the windows closed ($32°\text{F} < T < 100°F$)
2. air quality index prediction less than 100 ($40\mu g/m^3$)
3. wind speed less than 30mph
4. and no precipitation

A cleaning procedure for the track and bus was designed to eliminate extraneous sources of dust from the road, outside of the school bus or the entrainment of particles within the bus from prior runs or accumulated dust from storage of bus. The day before testing the outside of the bus was cleaned and the test track was inspected and power washed of extraneous particle sources. To minimize personnel from bringing in particulates into the bus, all personnel were required to use a floor mat upon entry into the bus and wear disposable booties inside the bus.

On the day of testing the instruments were zeroed, calibrated, audited, and leak checked as specified by the manufacturer. New filters for the SEMTECH-D heated sample inlet and the DataRAM impaction head filters were installed for each retrofit condition tested. The bus was turned on and the retrofit technology was inspected for leaks using a hand test to feel for gas leakage at connections in the exhaust system. Next the bus ventilation fan was switched on to blow out any accumulated particles in the duct work of the bus heating system. After five minutes of operation the fan and bus was turned off and the walls, windows, seats, vent outlets and floors were cleaned using lint free alcohol containing disposable wipes. After cleaning the bus, the ventilation fan and/or defroster remained off for the duration of the day.

To eliminate cold start emission testing, the bus was driven with the windows closed to and then on the test track until the engine oil temperature exceeded 200°F. The time required to reach an engine oil temperature of 200°F and warm-up the engine was approximately 30 minutes while driving to the test track and by roads of the Aberdeen Proving Ground. This time exceeded the warm-up time of previous studies such as that of Holmen and Ayala for transit buses in which the bus was only driven for 15 minutes before testing began.[40] In other studies, the buses were only idled for their warm-up period. In the CATF study[9] the school buses were idled with the door open for 10 minutes and then with the door closed for 10 minutes.

While driving on the test track a final visual check was made for re-entrained visible dust. If dust was observed, then selected sections of the track were power washed again. The track needed this additional power washing before several of the test days.

Before the first run the particle concentration instruments were placed together at the designated ambient location area at the south-west end of the track, and samples of the ambient air were recorded to check for proper operation of the instruments. The proper operation of the instruments was inspected by checking different parameters such as battery life, measuring settings, no errors are displayed, and that the instruments read approximately the same ambient PM concentration among them. After this check the ambient monitoring instruments were placed on a table located approximately 300m from the track and the in-cabin bus instrumentation was placed on the bus.

Before each run the bus windows were opened to allow the in-cabin concentration to equilibrate to the outside ambient concentrations. To check for this condition a 10 minute sample was recorded using all in-cabin instrumentation. Next the windows of the bus were closed and a sequence was implemented to start recording data and the run was started. During the run the operation of the instrumentation was monitored by 3 personnel in the cabin of the bus. At the end of a run the retrofit technology was again inspected for leaks and the bus was turned off for a period of five minutes with the windows and doors closed to prevent any exhaust from entering the bus. After this period the windows were opened and the bus was re-cleaned in areas around the instrumentation. The procedure was then repeated for the next run.

It is not apparent that previous bus studies have followed this rigorous cleaning protocol of the bus as well as the bus track. If the bus is not cleaned, then any accumulation of particulate matter from previous runs could be re-entrained by movement within the bus and give false readings of particulate concentrations within the cabin of the bus. In addition, nearly all studies have reported a relationship between outside vehicle traffic and pollutant levels inside the bus. This has been especially noted with the windows open, but has also been observed with windows closed. Bus inspection reports for buses have not been given in the literature, but it would be assumed that buses in regular operation would have been inspected according to the rules and regulations of the state.

The time required to reach an engine oil temperature of 200°F and warm up the engine was approximately 30 minutes. This bus was warm-up time of at least 30 minutes exceeded the warm-up time of previous studies. For example in the Holmen and Ayala study of transit buses the bus was only driven for 15 minutes before testing began.[40]

The final study used a modification of the test cycle developed for the initial study. The modification consisted in adapting the RUCSBC shown in to the new track that, contrary to oval track used in the initial study, it was composed of a straight 1.3 miles with a 0.2 and 0.3 miles return loops at each extreme of the track. The test cycle used in the final study consisted of 28 stops, an average of 16 seconds per stop ranging from 9 to 33 seconds for some stops. The total time of each test was 28 minutes and 46 seconds and a total traveled distance of 8.6 miles. The bus did three back and forth travels in the straight track from the start to the end of the cycle.

Figure 3 shows the final cycle adapted (from the initial study) to fit a 1.3 mile straight section of track with 2 loops at each end for vehicles to turn around. This is known as a dynamometer track at ATC. This new cycle, called Rowan Composite School Bus Cycle – Straight (RCSBC-S), contains both the complete stops as shown above and additional sections for the slow speed required for the loop turnarounds. Figure 3 compares the modified cycle (RCSBC-S) in blue and the original cycle from the initial study in red. The time between the two cycles was aligned so that the changes made to the original cycle can be visually compared.

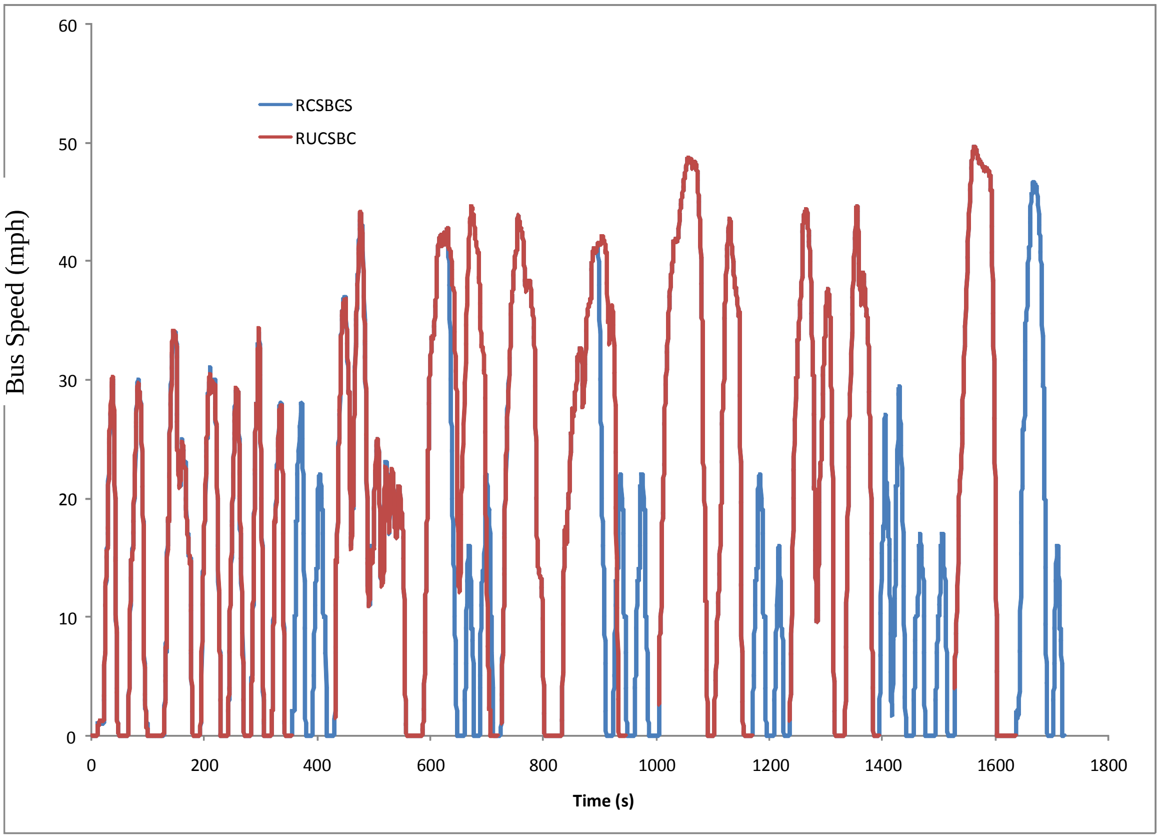

Figure 3: Comparison between RUCSBC for initial Runs 1-69 and the modified cycle (RCSBC-S) for the final study Runs 1F – 19F.

The adaptation of the cycle from the oval track used in the initial study to the straight track used in the final study is shown in Figure 3. The final cycle is shown in blue. In red is shown the initial cycle with gaps placed were the micro-trips for the final cycle was added. As can be seen from this figure, the final cycle is 426 seconds longer than the original used in the initial study. The final cycle uses all of the initial cycle plus the micro-trips shown in blue such as between 380 to 410s. Only two modifications were made to the original cycle that consisted in an early deceleration shown at 650 and 900s The real cycle used for the initial study is presented in the Figure 1.

The main differences between the two cycles are summarized in Table 1. Characteristics such as distance, cycle time, average speed, number of stops and idle time are shown for each cycle.

Table 1: Comparison between initial and final study cycles

Characteristics	Initial study cycle (RUCSBC)	Final study cycle (RCSBC-S)
Total distance (mi)	7.6	8.3
Total time (s)	1300	1726
Average speed (mph)	28	24
Number of stops	16	28
Total idle time (s)	253	437

In order to have repeatability for the testing conditions, the bus driver followed the RCSBC-S that lasts 28 minutes and 46 seconds by using the real time cycle data provided by the SEMTECH-D gas analyzer software. The SEMTECH-D is connected to the bus engine's control module obtaining real time data such as speed, by this mean the driver is able to follow the RCSBC-S on a laptop that shows his speed and time history overlaid on top of the speed vs. time values of the RCSBC-S. Figure 4 shows the bus stopped with the door open at the dynamometer track during an experimental run. The cycle used at the dynamometer track at ATC was adapted from the RUCSBC by adding new micro-trips to the 0.3 miles turnarounds in order to safely drive the bus at a lower speed while in the loops located at both extremes of the 1.3 miles straight length of track. To create the new cycle, the original RUCSBC was used in all of the straight sections of the dynamometer track at ATC and micro-trips were added in each of the loops that did not violate the maximum speed of these sections. These micro-trips were taken from original school buses routes from the New Jersey townships of: Washington, Medford, Pittsgrove, and Deptford.

Figure 4: Bus at the small loop at the SW end of the 1.3 mile straight track with 0.3 miles of turnarounds. ATC designated dynamometer track.

In order to provide realistic load conditions the bus was equipped with water dummies to simulate a half-full bus of 90-lb children. The particulate matter inside the cabin of the bus was measured using 2 DataRAM-4's and 2 P-Trak's. The location of the instrumentation is presented in a sketch of the bus cabin in Figure 5. The concentration of particulate matter in excess of the ambient concentration was calculated by subtracting the ambient particulate matter concentrations from the in cabin measurements. The ambient concentrations were determined for all runs by positioning the ambient P-Trak and DataRAM at an ambient monitoring station located 300m from the track as shown in Figure 6. In addition, data were collected for a period of 10 minutes before and 10 minutes after each run by all instruments with the windows open and with the engine off in order to provide obtain additional ambient PM measurements and to ensure the cabin PM levels have returned to ambient concentration.

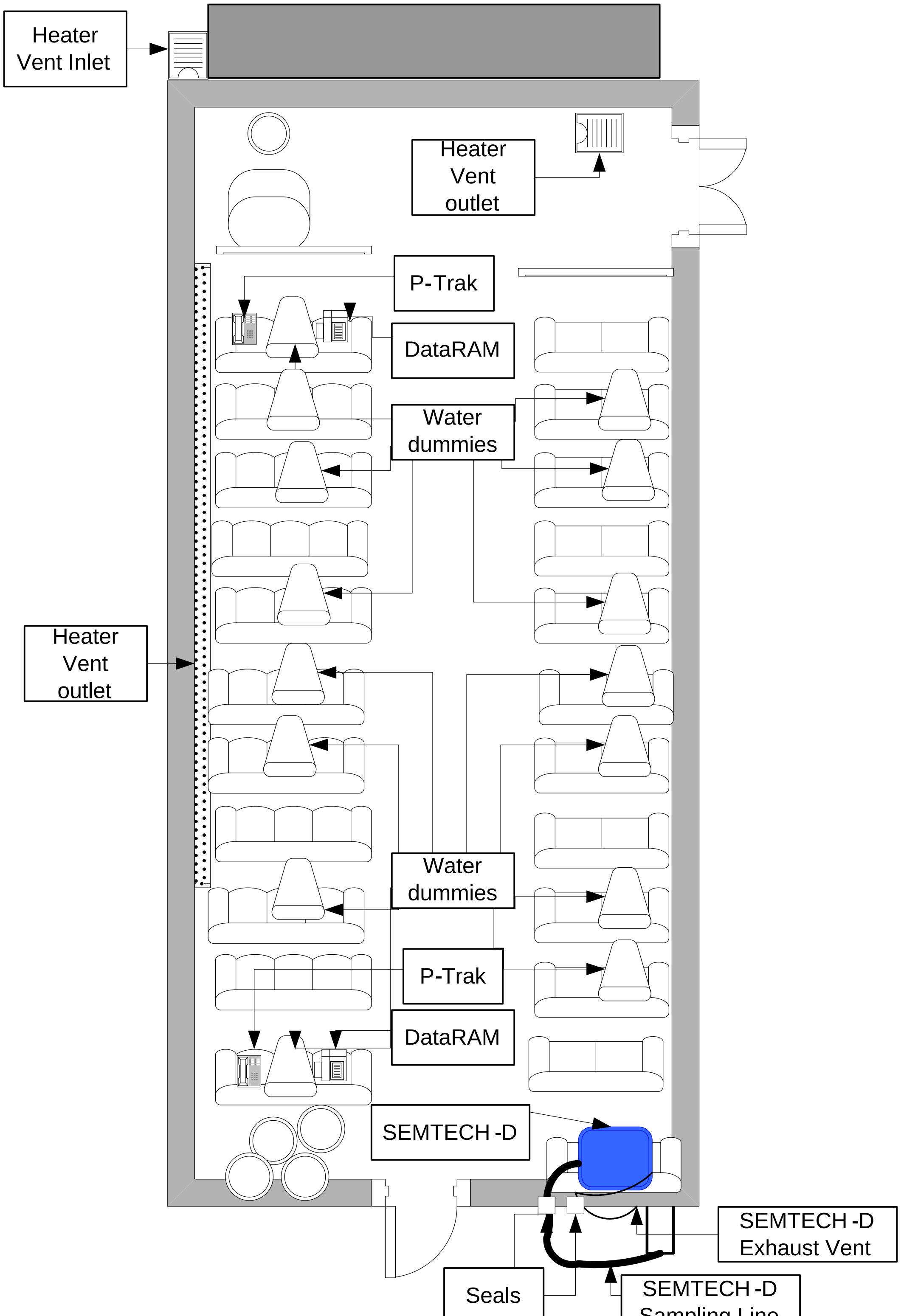

Figure 5: Sketch of instrumentation inside school bus cabin.

Figure 5 shows the position of the front DataRAM and P-Trak location in the first seat behind the driver's seat, and in the back DataRAM and P-Trak in the last seat on the left side. It also shows the location of the SEMTECH-D in the last seat at the right side.

The dynamometer track at ATC was selected in order to obtain repeatable runs of the modified Rowan University Composite School Bus Cycle (RUCSBC). The dynamometer track at ATC was closed to all other traffic while the tests were being performed. In order to examine the effect of environmental conditions on the levels of particulate matter inside the bus a meteorological station was located at the north east end of the test track as shown in Figure 6. This portable station measured wind speed and direction, temperature and humidity. Additional external events observed during the testing were logged on the protocol check list sheets. These events were rare and did not impact the overall results.

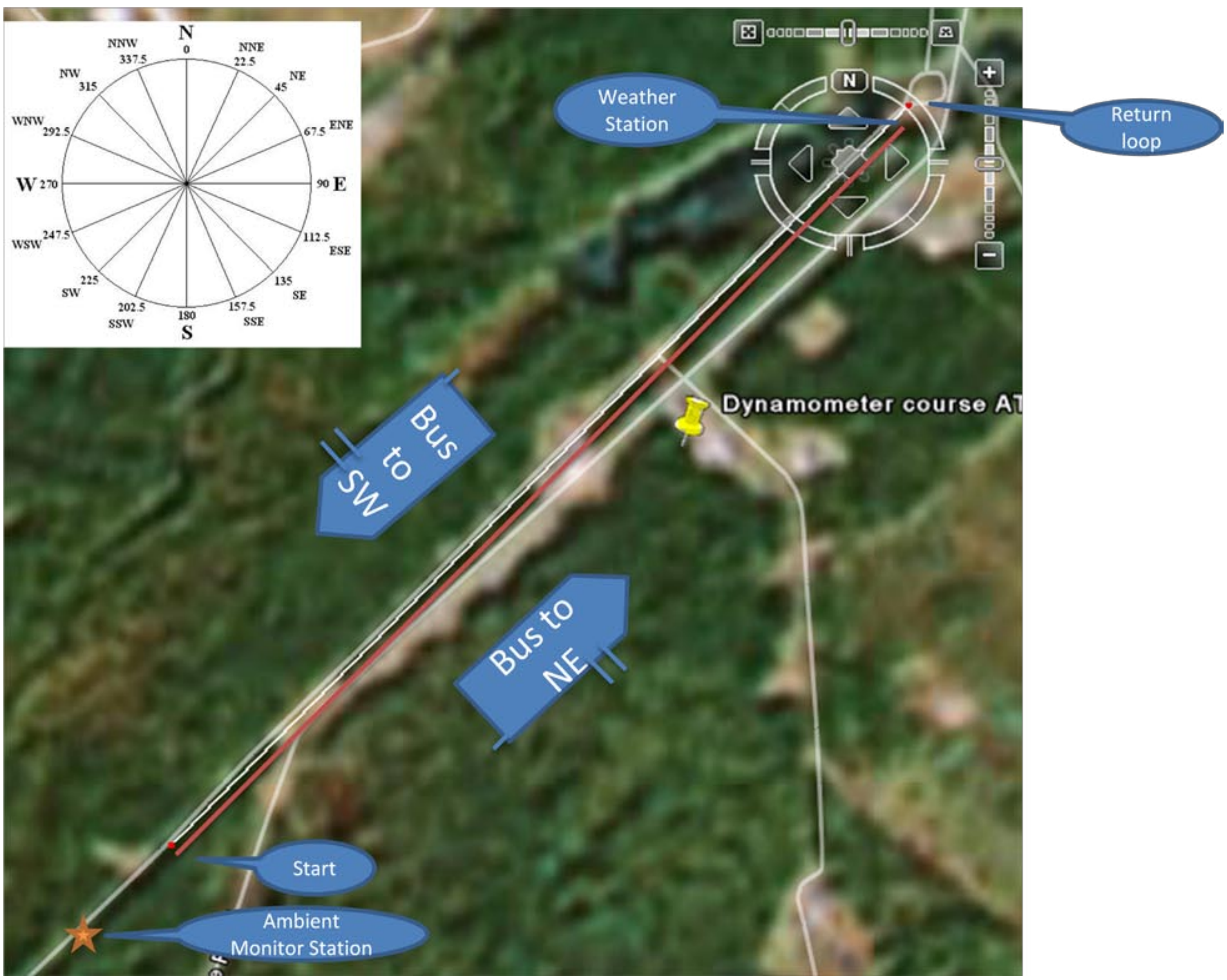

Figure 6: Test track consisting of a 1.3 mile straight section with 0.3 miles of turnarounds. ATC designated Dynamometer course. Satellite photograph obtained from Google Earth.

The test track is located at the ATC and it consists of a 1.3 straight mile course with two loops at each end, one of 0.2 miles and the other one of 0.1 miles. A satellite view is shown in Figure 6 in which the track is shown from start to end. The track direction is at an angle of approximately 45˚ southwest to northeast. For most of the track there was a protective barrier of trees that helped to reduce the dispersion of pollutants from external events. At the north east end of the track, near the large 0.2 mile loop, was a swamp on the west side of the track.

Figure 7: DataRAM and P-Trak instruments at ambient monitor station located 300 m from south west 0.1 mile turnaround loop.

Figure 7 shows the ambient monitor DataRAM and P-Trak instruments located at approximately 300m south west of the small 0.1 mile turn around loop. This monitoring station is located on an unused section of the test track and is separated from the test track by a small hill.

Figure 8: Weather station at return 0.2 mile loop at the north east end of the 1.3 mile straight track. ATC designated dynamometer track at ATC.

The ambient conditions in the track such as temperature, relative humidity, wind speed and wind direction were obtained by a portable weather station located in the return loop on the north east section of the dynamometer track. This weather station is shown in Figure 8.

Figure 9: Straight section of the test track which is 1.3 miles in length. ATC designated Dynamometer track at ATC.

This track was unique for school bus studies since it gave the ability to virtually eliminate surrounding traffic and dust sources. In addition it provided a continuous driving cycle that was free of sudden or unexpected stops. Finally there was no other traffic on the track. As seen in Figure 9, the track was lined on each side by trees reducing the amount of particulate matter that originated from outside sources.

5.4 Equipment

The tailpipe retrofits were inspected for proper functionality before the tests Since these units had been used for a number of runs prior to this study, the investigators wanted to insure that the units were in proper working order. The FTF had been used for 3 prior days of testing for a total of 12 tests. The DPF had been operated for approximately 17 hours having been used for 32 prior tests. The FTF was taken to the ESW testing and manufacturing facility in Pennsylvania. At this facility the unit was tested by sampling the inlet and outlet walls. Then the unit was heated to 1200˚F for 1 hour in an oxygen rich environment. It was next visually inspected and then placed on an engine and tested on an Itech 444 chassis dynamometer for HC, CO, and NO_x following an urban driving cycle. The DPF was sent to Johnson Matthey's testing and manufacturing location in Pennsylvania for an inspection of its condition. At this site the filter was visually inspected and then placed in an automated cleaning machine in which pressurized air was blown through it. This process is a standard practice to remove accumulated ash. The filter section as shown in Figure 10 was weighed prior to cleaning and after giving a weight difference of only 0.5g.

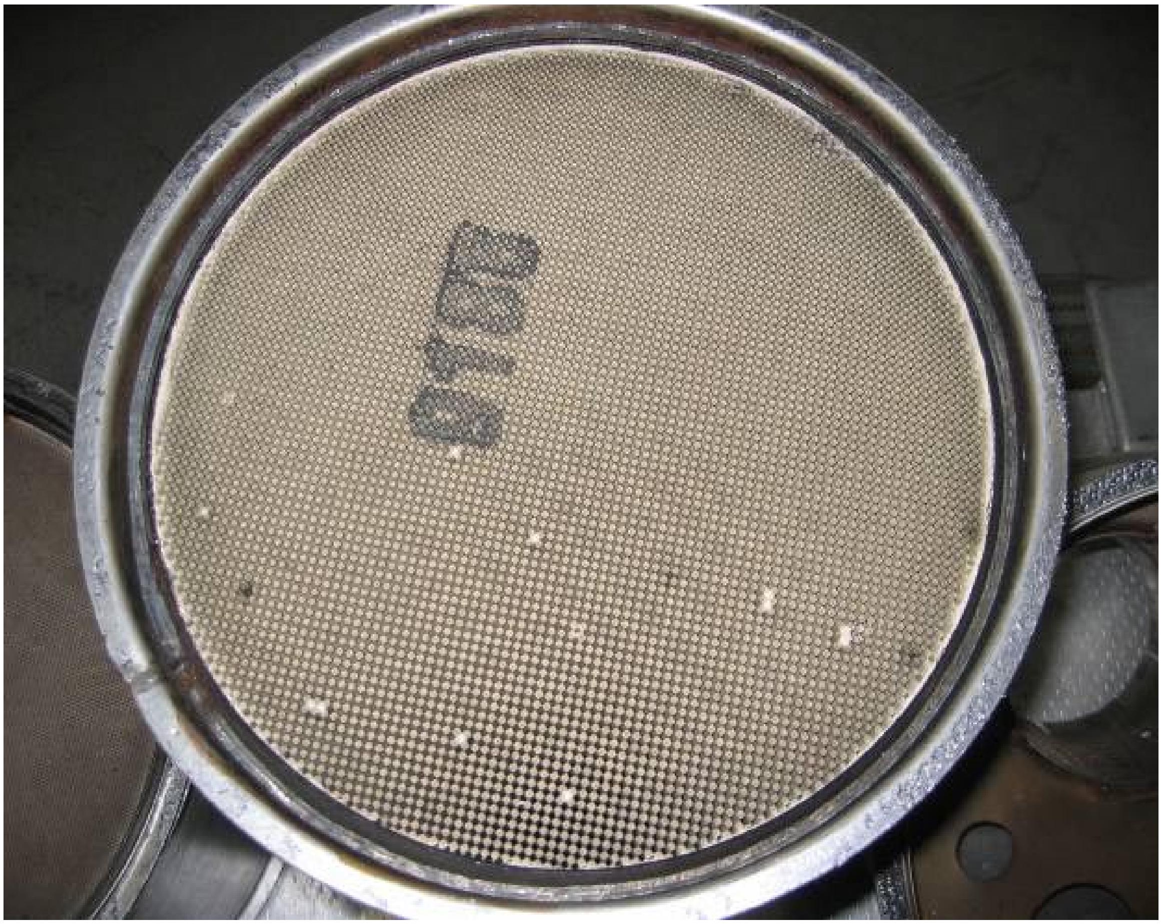

Figure 10: Exhaust intake face of DPF filter section during inspection.

The school bus engine was inspected by an International Truck and Engine Corporation representative to ensure that the engine was in normal working order for the bus mileage on the bus. The installation of the new CCVS on the engine was also inspected by Donaldson personnel.

5.5 Retrofit Devices

The retrofit devices are emission control systems designed to reduce emissions after the pollutants leave the engine. The tailpipe retrofit devices are muffler replacements that contain precious metals catalysts to reduce carbon based pollutants in the exhaust stream.

Flow through filter: The Environmental Solutions Worldwide (ESW) Particulate Reactor® (FTF) has been verified as a Level 2 DECS to reduce particulate matter from an exhaust stream by at least 50%.[16] The Level 2 CA ARV technology can be used if Level 3 is not available for retrofit. This reduction is achieved using a wire mesh design with precious metal catalysts impregnated on the wire. The removal of particulates is facilitated by having the gas flow in a tortuous pattern through the wire mesh. The flow of exhaust by the catalytic surface promotes the oxidation of hydrocarbons, soot, and CO to water and CO_2. This catalytic surface produces NO_2 for the oxidation of HC, CO and some carbon particles. The ESW Particulate Reactor® is able to oxidize particulates at lower exhaust temperatures compared to other diesel oxidation catalyst (DOC) units.[13] In addition, the ESW Particulate Reactor® has the capacity to store mass particulates between regeneration in excess of 5 times that of a conventional ceramic-based diesel particulate filter . This higher capacity for particle storage helps to prevent pollutant spikes that occur after accelerations from idle.[13] The ESW Particulate Reactor® is a CARB Level 2 verified retrofit.

The Flow through Filter has a similar operation principle to a DOC, with the main difference that the FTF catalyzed wire mesh promotes a turbulent flow by forcing the exhaust to traverse the wire mesh configuration as seen in Figure 11.

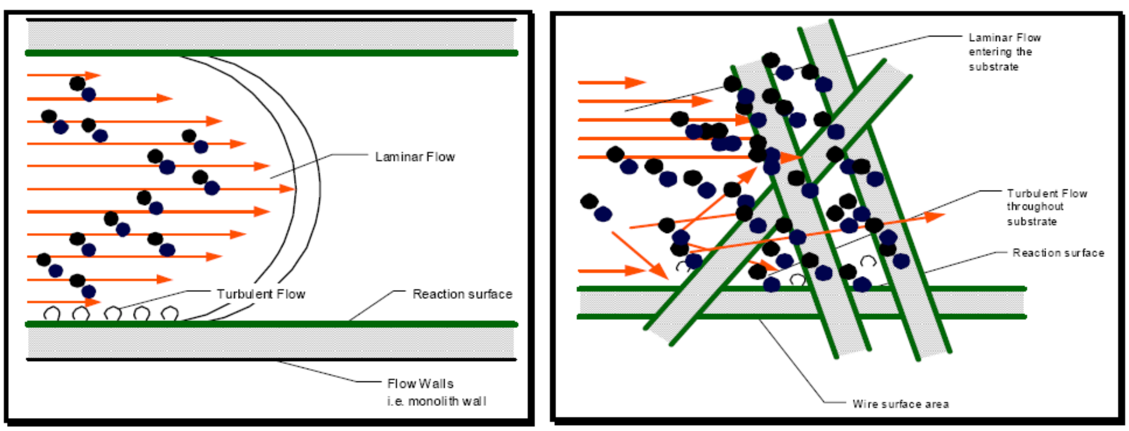

Figure 11: Representation of exhaust laminar flow through a diesel oxidation catalyst (left) and the ESW Particulate Reactor® (right). Source: M.J. Bradley & Associates, Inc. (2006)[13].

Figure 11 gives the impression that all soot particles are captured and all are the same size as seen on the right side of the figure. Actually, nanoparticles and lube oil ash particles fly through and are not captured. What is not shown is that collected larger particles are bound to the wire fiber (also can be ceramic or other material) by Van der-

Waals forces. Then they build up in dendrite form and are blown off by high exhaust velocity.

A picture showing the Flow through Filter is shown in Figure 12. In this figure the internal filter component (a catalyzed wire-mesh) of the retrofit is contained in a tubular reactor.

Figure 12: Internal component of the ESW Particulate Reactor®. Source: M.J. Bradley & Associates, Inc. (2006)[13].

The installation of the Particulate Reactor was performed one day before the test and it was checked for leaks in the installation before the testing. The Particulate Reactor installed in the bus is presented in Figure 13.

Figure 13: ESW Particulate Reactor (FTF) installed on the school bus.

Figure 13 shows the installation of the FTF, one of the brackets appears loose in this picture however the picture was taken during the installation process and the retrofit was secured and checked before the run test.

Diesel particulate filter: the DPF removes particulate matter from the exhaust as well as reducing HC and CO emissions. This device works by using a wall flow design in which the gaseous emissions diffuse through the ceramic walls of the catalyst while the liquid and solid portions of the exhaust are trapped in the filter. There are several types of Diesel particulate filter configurations. For these tests the Johnson Matthey Continuously Regenerating Technology (CRT) was chosen. This technology has been verified by the EPA[15] to achieve 90% reduction on particulate matter emissions. The CRT consists of two chambers which are shown in Figure 14. In the first chamber a ceramic monolith coated with platinum converts the carbon monoxide and hydrocarbons to carbon dioxide and water. In addition, this section oxidizes the NO to NO_2 – a strong oxidizing gas. In the second chamber a second monolith allows the gases to pass through the ceramic pores, but traps the particulate matter. The Johnson Matthey CRT has the unique feature that the particulates are continuously burned off using NO_2 as the oxidant. In this manner the carbon trapped inside the monolith can be continuously or intermittently removed during its operation.

The minimum exhaust gas temperature for the CRT to burn the trapped carbon is 275ºC. Another requirement is that the fuel sulfur content must not exceed 50ppm by weight and the exhaust must have a ratio of NOx to PM between 8:1 and 25:1 by weight.

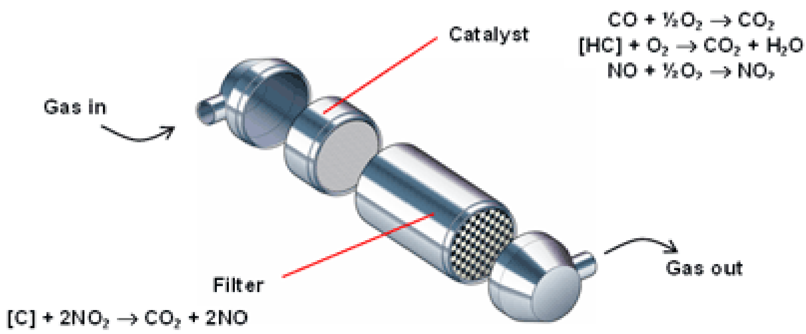

Figure 14: Components of the Johnson Matthey CRT® obtained from emission control technologies website[41].

Figure 15 shows the CRT installed in the school bus. The installation of this retrofit was also checked for leaks before the testing. The leak check on the tailpipe retrofit installation for the final set of runs, was performed by putting the hands on the connections of the retrofit and the tailpipe with the bus engine running; a leak would be detected if air was felt between these connections.

Figure 15: Johnson Matthey CRT, DPF, installed on the school bus.

Crankcase ventilation system: This filter is designed to eliminate crankcase emissions and allows the crankcase to be closed. The crankcase ventilation system chosen for this study was the Donaldson Spiracle unit. The specific retrofit kit for the International DT466 engine and the conventional Am Tran 1998 body was the X007917. The system uses a custom-designed pressure regulator and pressure relief valve in order to maintain the performance of the engine. There are two stages of the filtration: first there is a filter medium that employs a higher-velocity impaction technology to coalesce entrained lube oil hydrocarbon droplets, soot and engine oil residues. The second stage consists of lower-velocity diffusion technology for an overall efficiency of 90% reduction of crankcase PM mass emissions. The crankcase filter coalesces lube oil aerosols and particulates from the venting gases and returns it to the oil sump and has the additional benefit of reducing oil consumption from the captured aerosols; this is achieved by a bottom-drain oil connection that returns the coalesced oil to the engine sump.[42]

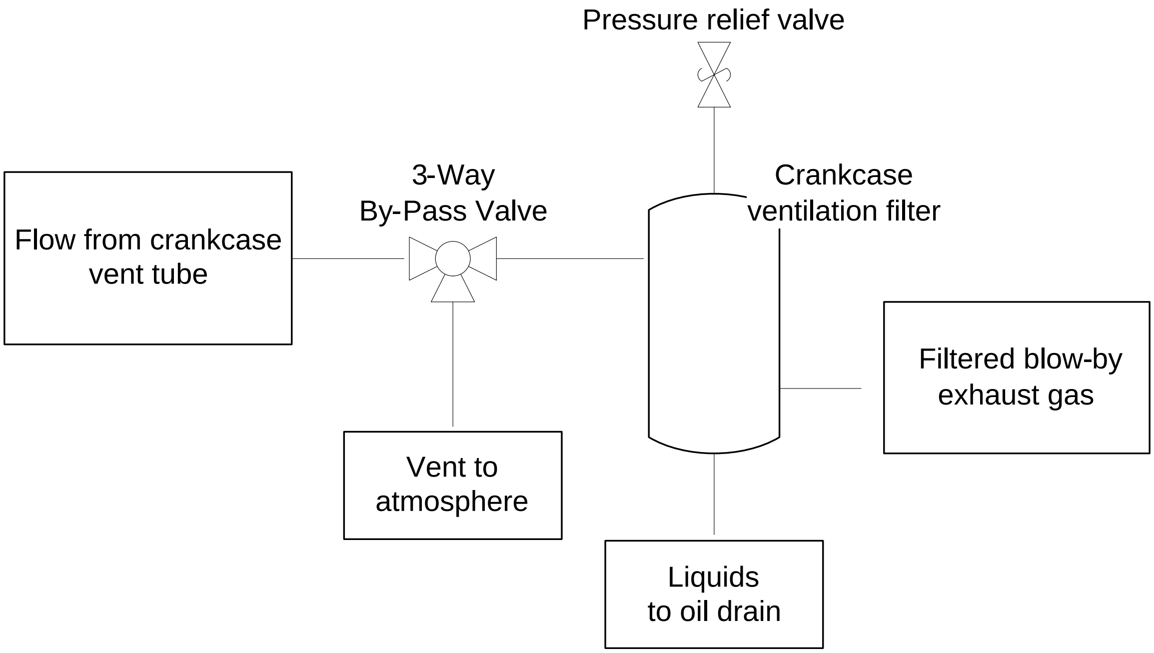

Figure 16: Crankcase ventilation system diagram.

A diagram of the crankcase ventilation system is shown in Figure 16. In operation without the crankcase ventilation system the emissions are vented to the atmosphere through what is known as the crankcase vent tube. The CCVS is installed to this crankcase vent tube using a 3-way by-pass valve. The by-pass valve is used in the event that the filter becomes plugged or there is a malfunction in the system. A safety feature of this device is a pressure relief valve that prevents the crankcase pressure from exceeding the crankcase shell limit of 4" H_2O which is the maximum operating pressure of the engine[43]. The gas only outlet of the CCVS is connected to the air inlet duct of the engine, and the liquid outlet is connected to the engine oil pan. A picture of the CCVS installed in the bus is shown in Figure 17. The inlet to the crankcase filter is connected to the reinforced plastic tubing. The 3-way value is shown with this reinforced tubing entering and exiting it. The black plastic tubing near the bottom of the crankcase filter is the return line for the filtered exhaust gases to the engine inlet air. The black plastic tubing at the bottom of the filter is for liquids that are sent back to the crankcase.

Figure 17: Donaldson Spiracle Crankcase ventilation system, CCVS, installed in the school bus tested. Picture taken prior the final set of runs.

Figure 17 shows the Donaldson's Spiracle CCVS installed in the school bus. All the original parts from the kit were used and the final installation was inspected by Donaldson staff to ensure the proper functionality of the system.

5.6 Particulate Matter Measurement Instrumentation

The particulate matter mass concentrations were measured using three DataRAM-4 units. The DataRAM-4 is a two-wavelength nephelometer. Using a diaphragm pump to draw air at a constant rate, sample exhaust is pulled though the omnidirectional sampling inlet followed by an inertial coarse-particle impactor, which removes particles larger than 2.5μm. The 2.5μm cut point was selected by adjusting the cyclone's inlet flow as specified by the manufacturer[44] and by setting the flow rate at 2 l/min. Using this device the diameter size range for concentration measurements from the DataRAM-4 is between 0.08μm to 2.5μm. The sample exhaust is then drawn through the air duct where the beam from two light sources, 660 nanometers and 880 nanometers, is alternately emitted switching 27 times per second. The light is collected by two separate detectors operating alternately, in synchronization with the light sources. The detectors measure the intensity of the light, which varies depending on the scattering of light by particles in the sensing region. The magnitude of the detected light scatter is directly proportional to the amount of particulates passing through the sensing region air duct, between the illumination beams and the field of view of the scattering detector, based on the assumption that particle size and distribution remain constant. The three DataRAM-4 instruments were cleaned and calibrated in the factory prior to the use in the final study, also additional field tests were performed to ensure proper response to ambient monitoring (see details in the instrument feasibility study section). The DataRAM-4 incorporates two wavelengths to measure particle size and perform a size correction based on Mie-Lorenz theory which is a complete analytical solution of Maxwell's equations for the scattering of electromagnetic radiation by spherical particles. For an idealized mass monitor, the response curves would measure the mass concentration independently of particle size. The inherent behavior of light scattering (as modeled by the Lorenz-Mie theory for spherical particles), however, excludes such size independence. Based on that size dependence and by measuring the ratio of the responses at two different wavelengths (featured by the DataRAM-4) it is possible to determine the particle size and, consequently, to correct the mass measurement accordingly. The data collected is reported and stored in real time in its internal computer for later downloading and analysis.

Particle number concentrations for ultra-fine particulate matter were measured using three TSI P-Trak Model 8525 Ultrafine Particle Counters. Particles are drawn through the P-Trak pass through a zone of saturated alcohol vapor. This particle/alcohol mixture then passes into a zone in which the gaseous alcohol condenses onto the particles, causing them to grow into a larger droplet. The droplets then pass through a focused laser beam, which temporarily blocks the light being sensed at the photo-detector target. The particle number concentration is obtained by counting the number of times the light flashes.[45] The particle size measurement range of the P-Trak is from 0.02 to 1μm diameter and the concentrations are reported as number of particles per cm^3 of gas.

The gaseous emissions as well as the pertinent engine parameters such as engine speed, fuel flow rate, engine oil temperature, and percent engine load were obtained from the bus engine computer using the Sensors, Inc., SEMTECH-D. These parameters from the

SEMTECH-D are necessary to verify that the school bus is operating under normal load conditions. NO and NO_2 are measured via a non-dispersive ultraviolet and important feature to evaluate catalyst-based emission control technology. Two DataRAM-4 units and two TSI P-Trak units were used to measure the particulate concentration within the school bus as well as obtain ambient concentrations. The weather conditions and all ambient particulate concentrations were measured at the ambient monitoring station located within the track.

The particulate matter instrumentation located inside the bus measured particulate levels at the front and the back of the bus. Figure 19 shows the positioning of the DataRAM-4 (grey color) and the P-Trak (blue and white). The location of each of the sampling inlets was at the approximate location of a child's breathing zone. As shown in Figure 19 the P-Trak's probe is positioned on the water dummy and the DataRAM's sampling inlet is next to the water dummy. One pair of DataRAM's and P-Trak's was located in the first seat immediately behind the driver's seat, and the other set in the last seat at the back of the bus. This configuration provides information about the distribution of particulate matter levels in the front and rear of the school bus cabin by measuring real time concentrations in an interval of 1 second per reading for both types of instruments.

5.7 Measurement Issues on Particulate Matter Instrumentation

Fine particulates tend to increase in size with increasing relative humidity. This increase in particle size is negligible at relative humidity (RH) values less than 50%, but at values of relative humidity greater than 70% this growth becomes significant[46]. Since the DataRAM reports mass concentration values that are equivalent to a gravimetric method utilizing dried samples, then a correction for relative humidity is required[46]. This size correction method is a standard software feature which was enabled on all three DataRAM-4 instruments. The magnitude of the detected light scattered at the two wavelengths of the DataRAM-4 is directly proportional to the amount of particles passing through the beam region. Without this correction feature the mass concentration reported by the DataRAM-4 could be up to 1.8 times the actual value. Since ambient humidity was measured for all runs using the weather station, a check on this feature was performed for both P-Trak and DataRAM-4 which shows no trend in particle concentration with changes in relative humidity.

The TSI Model 8525 P-Trak Ultrafine Particle Counter instruments used for this project are not affected by the relative humidity. Condensation particle counters use saturated alcohol vapor to increase particle size similar to the effect observed at high relative humidity. A restriction for operating the P-Trak's is that the ambient temperature must between 32 to 100ºF. The results from P-Trak model 8525 was compared to a more sophisticated condensation particle counter in a University of California study,[47] the TSI Inc. ultrafine particle counter (CPC) model 3022a. Good agreement was found between the results from this instrument and the P-Trak for indoor measurements with a reported correlation R^2 equal to 0.9385. For the roadside portion of the study it was found that the P-Trak detected only 25% of the concentration measured by the TSI CPC 3022a unit when located close to the road. At 15 and 40m from the road the agreement between the two instruments had an r^2 correlation coefficient higher than 0.99 and slopes within ±3% of unity at particle concentrations in the range of 1,800 to 280,000 particles/cm^3.

The characteristic range of particles produced by diesel engines is from very small nanoparticles of 3-5 nanometers in diameter to the largest above 10 micrometers in diameter. The fraction of above 1.0 microns contain almost all the total particle mass while the fraction below 1000 nanometer contains an enormous number of particles (10 to 100 million particles per cm^3) and almost all the particle surface. Particle size is important because the human breathing system cleanses larger particle from inhaled air via physical processes of mucous capture and lung expels via cilia and mucous expulsion. The smaller nanoparticles (20 to 300 nm diameter) are carried into the lung alveoli where a large percentage are captured and in a period of time pass through the membrane into the blood stream and into organs. The large surface of this nanoparticle fraction adsorbs PAH and Nitro-PAH hydrocarbons. This fraction is of the greatest health concern. The entire spectrum of particles are represented by a mixture of fine, ultrafine, and nanoparticles which include but are not limited to a composition of solids like elemental carbon and ash, and liquids such as condensed hydrocarbons, sulfuric acid and water. Size distributions from diesel particulates have a bimodal characteristic as shown in Figure 18.

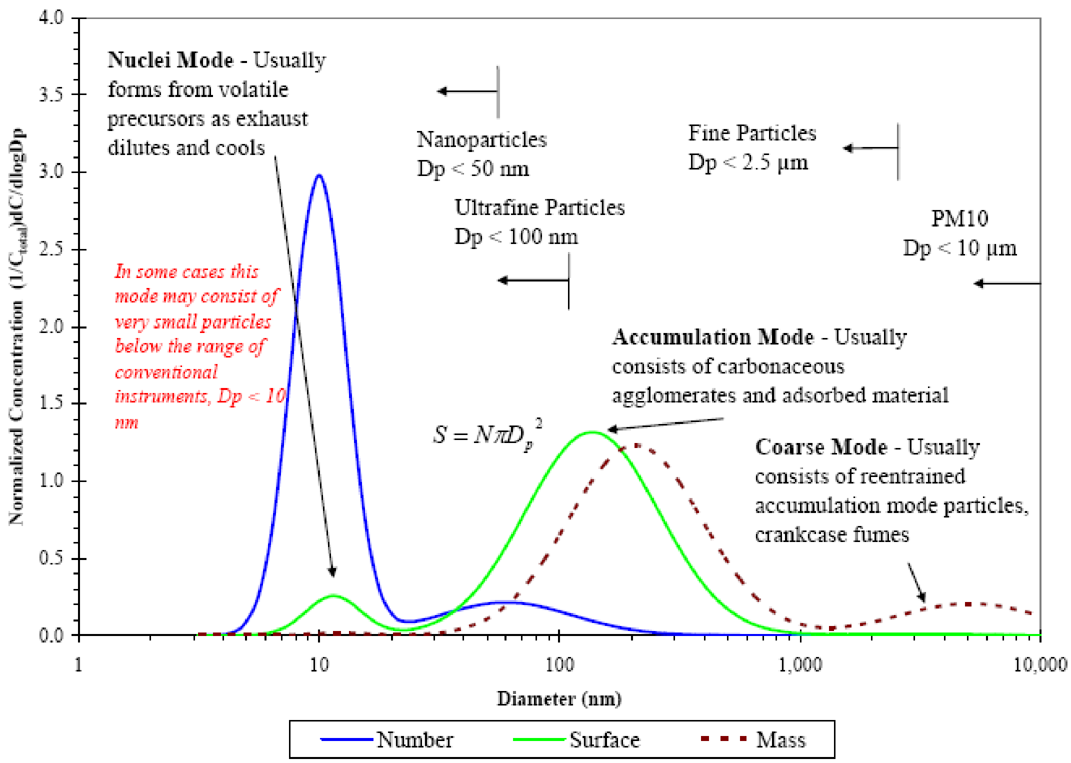

Figure 18: Typical engine particle size distribution by number, surface and mass concentration. Figure obtained from Kittelson (2007)[36].

Figure 18 shows the particle size distribution for the nuclei, accumulation and coarse modes. The nuclei mode is believed to have originated from volatiles or gases that nucleate to form particulate matter. These particles range in size between 3 to 30nm

(0.003 – 0.03μm), as postulated by Kittelson (2002)[48]. Kittelson calculates that the fraction of particles found in the nuclei mode ranged from 37 to 87 % by number and from 0.3 to 2.1 % by volume. The particulate matter in the accumulation mode is composed of sub-micron particles with diameters usually ranging from 30 to 500nm (0.03 – 0.5μm). These particles originate from small particles that have agglomerated together to form these relatively large particles. In addition gases condense on these particles resulting in a larger particle size. Kittelson states that approximately 10 % of the particle number count and 80 % to 90 % of the mass is contained in the accumulation mode. The coarse mode consists of particles with diameters above 1μm which contain 5-20% of the total particulate matter mass concentration and basically no contribution from particle numbers.[48] These particles are thought to originate primarily from crankcase fumes and agglomerated accumulation mode particles. Figure 18 shows three groupings of particles based on the type of measurement. The particles represented by the blue line (with a large peak at 10 nm) are obtained from particle number concentration measurements. The green line represents the diesel particle size distribution weighted by surface area. Finally the dashed line represents the mass of particles.

5.8 Location of Particulate Matter Instrumentation Inside Bus Cabin

The location of the PM instrumentation was selected for the front and back zones of the bus and is shown in Figure 5. The front location was selected to examine the hypothesis that crankcase emissions enter predominately through the front door of the bus. In addition high concentrations have been measured at the back of the bus in previous studies so a second monitoring location was placed at the back of the bus. The actual method of entry of particulates and gases into the bus is a function of the location of vents and un-sealed walls and floors. The mechanism of entry is a function of many effects such as wind speed and direction, front door opening, and bus speed.

The front sampling location was in the seat behind the driver and the back sampling location was on the second to last seat on the driver's side. These locations are shown in Figure 5. The probe for the P-Trak was located on the water dummy located in the center of the seat and the omnidirectional sampling inlet for the DataRAM was located on the seat location next to the isle. The inlet was approximately 120cm vertically above the bus seat. A photograph of this setup is shown in Figure 19.

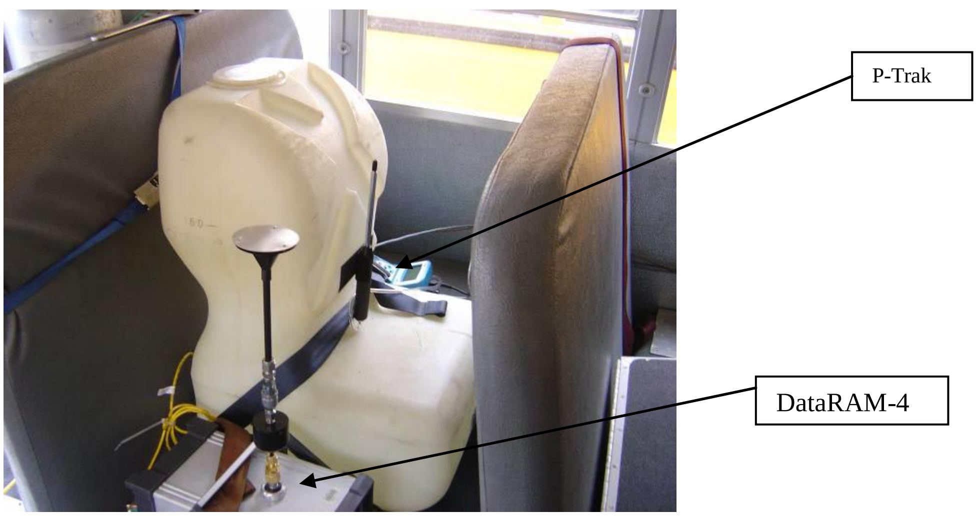

Figure 19: Location of the DataRAM-4 and P-Trak instruments in the bus.

The tailpipe emissions were measured by the SEMTECH-D gas analyzer, Figure 20 shows the positioning of the sample line fitted through a sealed orifice. This orifice was sealed to eliminate any flow of gas and particulates into the bus outside of the sampling line. This figure also shows the SEMTECH-D exhaust gas tubing that was vented to the outside of the bus.

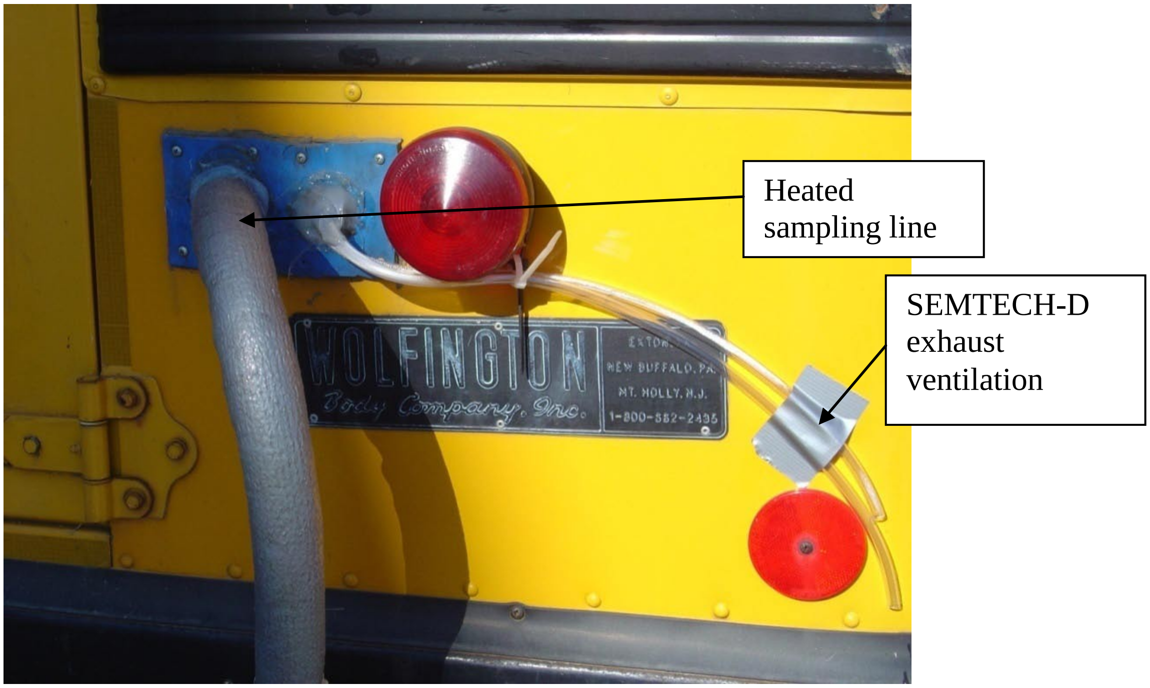

Figure 20: SEMTECH-D sampling hose installation through bus chassis.

Figure 21 shows the SEMTECH-D sampling tip before being secured to the tailpipe. This installation was easily removed in order to perform a leak check of the SEMTECH-D at the start of each day of testing. The sampling tip was located at the center of the pipe cross section and 10 inches from exhaust pipe outlet. Also shown in this figure is the exhaust gas tubing of the SEMTECH D

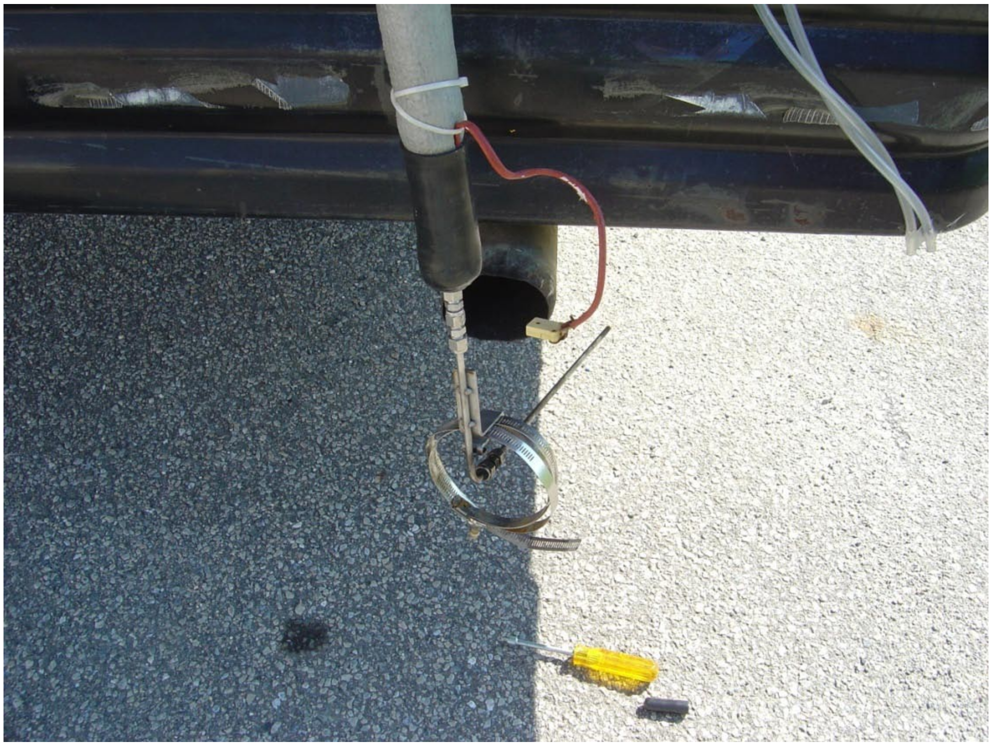

Figure 21: SEMTECH-D sampling tip before being inserted and secured to the tailpipe. Picture of the system taken for the final set of runs.

5.9 Gaseous Emissions

The tailpipe exhaust emissions were measured with the SEMTECH-D gas analyzer from Sensors Inc. This instrument is a portable PC-based data acquisition system capable of measuring emission levels along with several vehicle and engine parameters. The SEMTECH-D uses proprietary software, along with a heated sampling line and the following measurement subsystems:

- Heated Flame Ionization Detector (FID) for Total Hydrocarbon (THC) measurement. Accuracy ±2.0% or ±5ppmC whichever is greater

- Non-Dispersive Ultraviolet (NDUV) for Nitric Oxide (NO) and Nitrogen Dioxide (NO_2) Measurement. The accuracy for NO is ±3% of reading or 15ppm whichever is greater, and the accuracy for NO_2 is ±3% of reading or 10ppm whichever is greater.

- Non-Dispersive Infrared (NDIR) for Carbon Monoxide (CO) and Carbon Dioxide (CO_2) measurement. The accuracy for CO is ±5% of reading or 50ppm whichever is greater and the accuracy for CO_2 is ±3% of reading or ±0.1% whichever is greater.

All of the above instruments were zeroed and calibrated versus reference bottled gases with certified gas values. The software compares the results given by the instrument versus the reference gas to decide if the value is within the limits specified.

For all runs both the tailpipe emissions and in-cabin particulate levels were quantified, and ultra low sulfur diesel was used to fuel the bus. The lubricant oil used for the DT466E engine was SAE grade 10W30 oil which is specified to have a sulphated residue (ash) of less than of 1.25 mass percent.[49] The fuel used for this study was the Amoco Emission Control Diesel (ECD) Fuel from BP with the following specifications presented in Table 2.

Table 2: Analysis of ULSD performed by BP located in Naperville, IL. Sample ID: 22303-8 (299514).

TEST	**TEST METHOD**	**RESULT**
Cetane Index (calculated)	ASTM D-976	45.8
Cetane Number (engine rating)	ASTM D-613	47.3
Corrosion, Cu Strip, 3hr. @ 122°F	ASTM D-130	1
Distillation, °F IBP T10 T30 T50 T70 T90 FBP	ASTM D-86	 321 378 405 429 456 495 529
API Gravity	ASTM D-287	41.7
SFC – Saturates (wt%) SFC – Aromatics (wt%) Polycyclic aromatic hydrocarbon Content, GC-SFC, wt%		78.3 19.1 2.6
Cloud Point, °F	ASTM D-2500	-45°F
Sulfur, (ppm wt)	ASTM D-2622	5
Flash Point, °F	ASTM D-93	131

The ECD fuel that was used in this study was used in several emission studies. BP assembled a working validation program with the objective of evaluating the ECD fuel in combination with passive particulate filter systems in seven fleets over a twelve-month period[50]. In this demonstration program different vehicles such as class 8 trucks using an Engelhard DPX and Johnson Matthey CRT particulate filters, transit buses retrofitted with the CRT, school buses equipped with DPX and CRT, medium-duty flatbed-type trucks retrofitted with the DPX and CRT, dump trucks again using DPX and CRT were tested. Other studies using this fuel are (Sabin L. D. et al., 2005)[28], (Fitz D.R. et al., 2003)[10], (Chatterjee S. et al., 2001)[51], (Chatterjee S. et al., 2001[b])[52], (Lev-On M., et al., 2002)[53], (Le Tavec C., et al., 2002)[54], (Durbin T.D., et al., 2002)[55], (E. Behrentz, 2004)[26], (B.A. Holmén and A Ayala, 2002)[40], (B.A. Holmén, and Yingge Qu, 2004)[56].

5.10 Feasibility Study for Particulate Instrumentation

Prior to the initial study, each particulate concentration instruments were analyzed for accuracy and repeatability, and how they tracked with each other compared to gravimetric and a Tapered Element Oscillating Microbalance (TEOM) instrument previously calibrated following the Federal Reference Method standards for the determination of fine particulate matter as $PM_{2.5}$ in the atmosphere in accordance with the 40 Code of Federal Regulations (CFR) part 53. Prior to this study (in December 2006) the DataRAM and P-Trak instruments were calibrated in a controlled room environment, as well as at a NJDEP emission monitoring station in Camden, NJ on March 2007. The controlled environmental facility (CEF) is located at the Environmental and Occupational Health Sciences Institute (EOHSI) in Piscataway, New Jersey. At this facility, diesel particulate matter was generated with a diesel engine (Model YDG 5500E, Yanmar Inc.) using ULSD fuel. This engine is a 4-cycle single cylinder air cooled diesel engine and based on previous studies, produces diesel emissions representative of heavy duty diesel trucks. For the filter based gravimetric sampler a SKC Legacy pump operated at 10 L/min with a $PM_{2.5}$ sampling head was used. Three measurements were made for design concentrations of 40 and 80$\mu g/m^3$, and one measurement for the 0 and 200$\mu g/m^3$ concentration levels.

After this feasibility study was conducted 69 school bus tests were run for the initial study, and then the DataRAM and P-Trak instruments were sent back to the factory for calibration and cleaning as specified in operating manuals before the final study started. Since the instruments were recalibrated by the factory before the final study, the initial feasibility study against diesel emissions performed for initial study should only be used as a reference for the operation of the DataRAM’s and P-Trak’s relative to a TEOM and gravimetric measurements.

Ambient conditions of 75°F and 40% relative humidity were maintained constant in the CEF during testing. The mass sample collected on the filter within the SKC sampler was weighed before and after each test. The filter was equilibrated in a weight room for at least 24 hours before the testing and after collection at 20°C and 30-40% relative humidity. $PM_{2.5}$ mass concentration was calculated by the integrated sampling method based on the incremental filter net weight and the gas sampling volume. A particulate matter correlation was obtained between each of the DataRAM-4 and P-Trak devices and the gravimetric concentrations.

In order to evaluate the response of the three DataRAM-4 instruments at low concentration levels (<40$\mu g/m^3$), the instruments were placed at the ambient monitor station in Camden, New Jersey (i.e., Camden Lab) operated by the New Jersey

Department of Environmental Protection (NJDEP). The instruments measured $PM_{2.5}$ over a 6 day period. The P-Trak instruments were not tested at the Camden site.

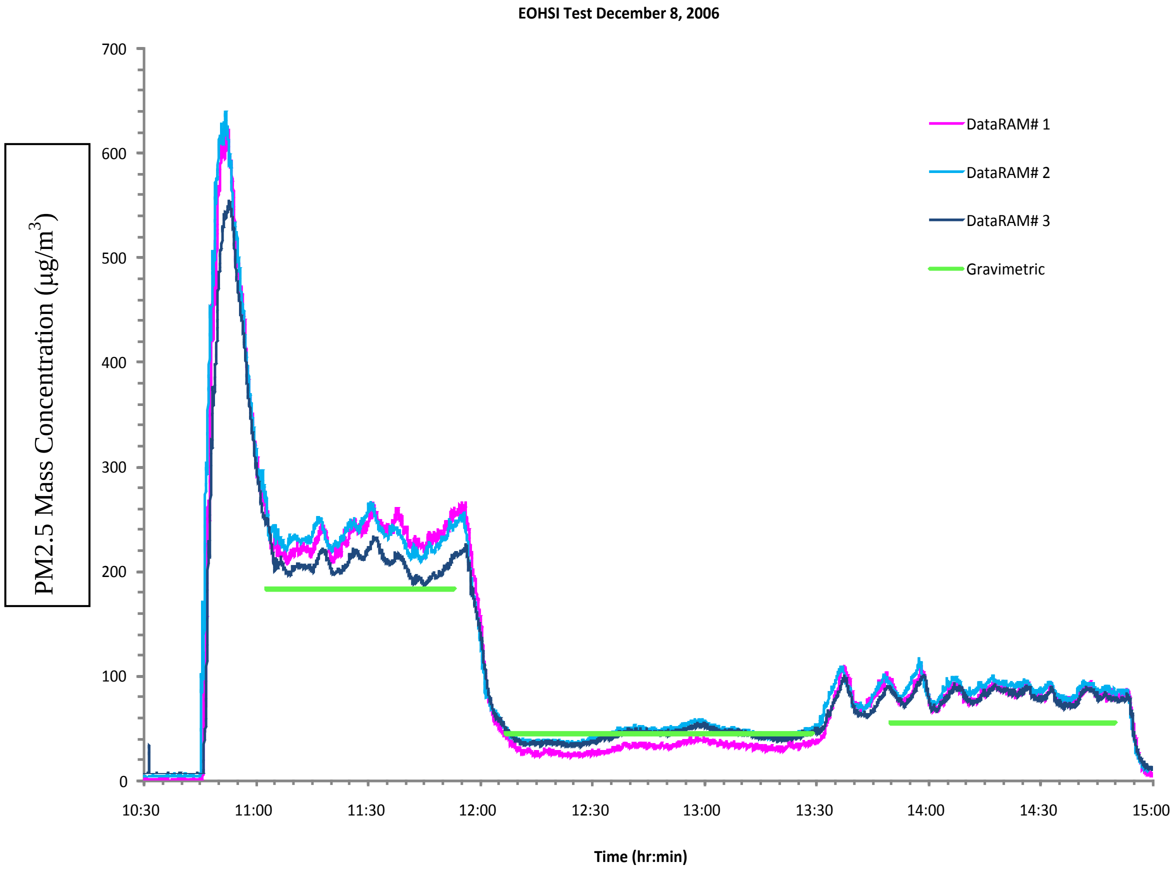

Figure 22: Real time data from the three DataRAM instruments at the EOHSI controlled chamber on December 8, 2006.

Figure 22 shows the real time data obtained by the three DataRAM instruments at the EOHSI controlled chamber. In this day of testing three concentration levels were chosen for testing: ~200µg/m^3, ~100µg/m^3 and ~50µg/m^3. The initial peak in this figure is part of the start-up process for the chamber to obtain a constant concentration of 200µg/m^3. The figure shows the three average gravimetric concentrations during the run using horizontal green lines. From this figure, DataRAM#1 corresponds to the instrument used in the front of the bus, DataRAM#2 as ambient monitor, and DataRAM#3 the one in the back of the bus. From this figure it can be seen that the DataRAM's read higher than the gravimetric values and the absolute difference between values decreases with decreasing concentration.

Table 3: **Results from the controlled environmental facility tests at EOHSI.**

Date	Gravimetric method (μg/m^3)	DataRAM-4 instrument # 1 (μg/m^3)	DataRAM-4 instrument # 2 (μg/m^3)	DataRAM-4 instrument # 3 (μg/m^3)	Mean (μg/m^3)	Standard Deviation (μg/m^3)	95% Confidence Interval (μg/m^3)	Coefficient of Variation (%)
12/6/06	4.0	2.9	3.8	4.7	3.8	0.9	1.0	24%
12/14/06	37.2	29.9	41.6	35.8	35.8	5.9	6.6	16%
12/14/06	59.5	69.8	80.3	70.7	73.6	5.8	6.6	8%
12/8/06	174.6	232.1	230.2	200.8	221.0	17.5	19.9	8%
Note: The mean, standard deviation, confidence interval, and coefficient of variation were calculated based on the three DataRAM values without including the gravimetric results.								

The values obtained from Table 3 are average values from three replicates at the middle concentrations (~37 and 59μg/m^3) and one replicate for each of the low and high concentrations (~4 and 175μg/m^3). Table 4 show the results obtained from the Camden ambient air monitoring station of the NJDEP during 6 days of continuous measurement in which the DataRAM-4 obtained a data point every 12 seconds. The low concentration values obtained at the Camden site are consistent with the EOHSI controlled chamber test values. The calculated confidence interval is a range of values. The sample mean is at the center of this range and the range is x ± the confidence interval. The mean, standard deviation, and sample size is used to construct a two-tailed test at significance level alpha (0.05) of the hypothesis that the population mean is μ_0. Then the hypothesis will not be rejected if μ_0 is in the confidence interval and will be rejected if μ_0 is not in the confidence interval. The confidence interval obtained for the low concentration values at EOHSI was ±1.0μg/m^3 and for the medium concentration values (~37 to 59μg/m^3 based on gravimetric measurements) was ±6.6μg/m^3. The coefficient of variation from the EOHSI results was higher for the low concentration values ranging from 16 to 24%, and it was 8% for the high concentration values. The coefficient of variation (C.V) is a normalized measure of dispersion of a probability distribution and it is defined as the ratio of the standard deviation to the mean. It is important to notice that when the mean value is close to zero, the coefficient of variation is sensitive to small changes in the mean, causing the higher coefficient of variation values for the low concentrations as seen.

Table 4: **Results obtained from the NJDEP ambient monitoring station at Camden, NJ.**

TEOM ($\mu g/m^3$)	DataRAM-4 instrument # 1 ($\mu g/m^3$)	DataRAM-4 instrument # 2 ($\mu g/m^3$)	DataRAM-4 instrument # 3 ($\mu g/m^3$)	Mean ($\mu g/m^3$)	Standard Deviation ($\mu g/m^3$)	95% Confidence Interval ($\mu g/m^3$)	Coefficient of Variation (%)
2.8	2.2	2.3	0.1	1.5	1.2	1.4	81%
7.2	6.2	7	4.7	6.0	1.2	1.3	20%
8.5	8.1	9.4	8.7	8.7	0.7	0.7	7%
12	11.6	12.6	11.3	11.8	0.7	0.8	6%
13.1	12.1	12.6	14.9	13.2	1.5	1.7	11%
13.2	24.5	22.7	16.1	21.1	4.4	5.0	21%
Note: The mean, standard deviation, confidence interval, and coefficient of variation were calculated based on the three DataRAM values without including the TEOM results.							

The results obtained at the Camden monitor site presented in Table 4 show a confidence interval at the 95% level ranging from approximately $\pm 1\mu g/m^3$ to $\pm 5\mu g/m^3$ and a coefficient of variation ranging from 6 to 21% for the three DataRAM values; the 81% coefficient of variation is caused by the low average measurement obtained by the DataRAM instrument # 3 of $0.1\mu g/m^3$. Since the coefficient of variation is sensitive to small mean values, the small difference of concentration creates a higher variation for low concentration values.

The low concentration values obtained at the NJDEP air monitor site at Camden NJ were combined with the feasibility study values obtained at EOHSI in order to have a complete curve ranging from low concentration to high concentration values. This analysis was performed to check the response of the DataRAM-4 instruments with two different technologies for particulate matter mass concentration measurement: the filter-gravimetric method at EOHSI and the TEOM technology system at the NJDEP ambient monitor station.

The corresponding response curves obtained for each DataRAM-4 are presented in the Appendix A. The tests for the P-Trak show the tracking correlation between the three P-Trak instruments during the changes in particulate matter concentration. The particle count instruments showed good correlation between instruments. This agreement is readily apparent in the changes in set point concentrations and miscellaneous spikes.

Table 5 shows the results of the ultrafine particle count results from the controlled environment test at EOHSI.

Table 5: Results obtained for the P-Trak ultrafine particle counters from the controlled environment tests from EOHSI.

EOHSI P-Trak Average (pt#/cm^3)	P-Trak#1 Average (pt#/cm^3)	P-Trak#2 Average (pt#/cm^3)	P-Trak#3 Average (pt#/cm^3)	P-Trak's #1,2,3 Mean (µg/m3)	P-Trak's #1,2,3 Standard Deviation (µg/m3)	P-Trak's #1,2,3 95% Confidence Interval (µg/m3)	P-Trak's #1,2,3 Coefficient of Variation
2238	2175	2249	2164	2196	46	52	2%
12405	15624	N/A[1]	14781	15203	596	675	4%
9932	11288	10996	10801	11028	245	277	2%
11556	11549	11001	10916	11155	344	389	3%
26303	33548	33267	31841	32885	915	1036	3%
21863	25002	24027	23388	24139	813	920	3%
20496	24361	23921	23378	23887	492	557	2%
19721	24707	23987	23540	24078	589	666	2%
97744	129890	118388	118857	124139	8133	9203	7%

Note: 1. Data of P-Trak# 2 is not collected due to charge problem

The results presented in Table 5 show that the Rowan University P-Trak's 1, 2, and 3 track particulate concentration among them with a coefficient of variation ranging from 2 % to 7% for a mean particle concentration of 2196 pt#/cm^3 to 124139 pt#/cm^3 respectively. However the P-Trak instrument from EOHSI did not agree in absolute values even though it showed the same trend. Since there was no reference or calibrated instrument for ultrafine particle matter measurements, the P-Trak instruments did not have any correction factor or calibration curve. The P-Trak portion of the EOHSI study was only used to demonstrate that the differences between a P-Trak reading and the average reading of the three instruments was less than 6% for all values. It should be noted that P-Trak's 2 and 3 were used for the front and back of the bus respectively. These two instruments had differences from the average measurement of less than about 2%.

A sample of the particulate mass concentration response curves (obtained by the DataRAM #1 with serial number D572) is shown in Figure 23. Additional response curves for the DataRAM instruments are given in Appendix A.

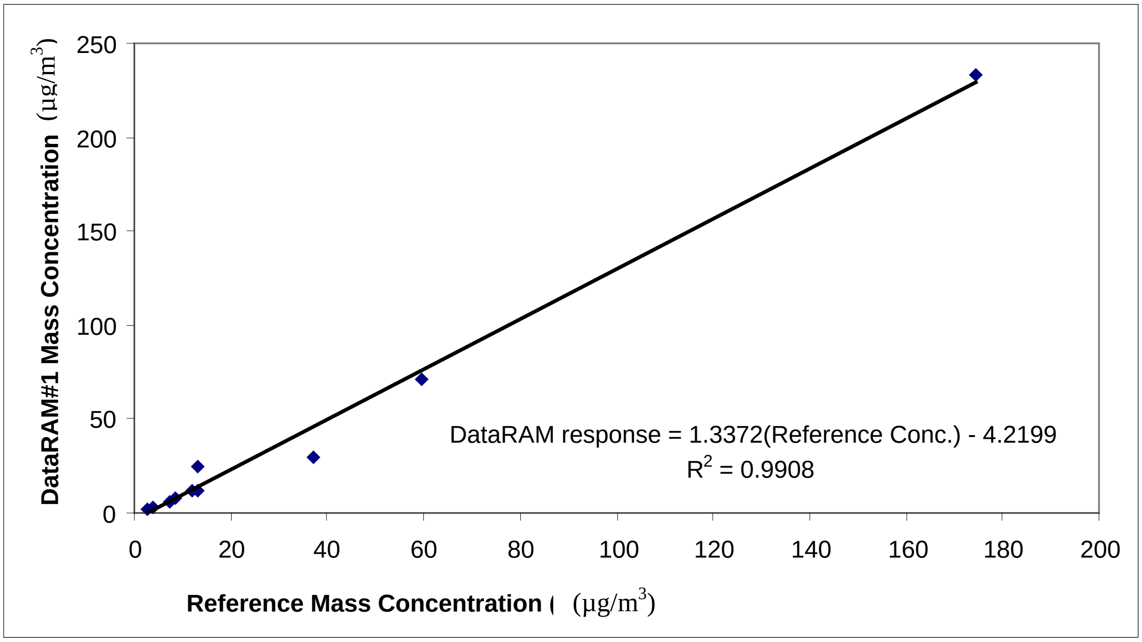

Figure 23: Feasibility study curve for DataRAM instrument No. 1 with serial number: D572.

As seen in Figure 23, only one measurement was taken at a high concentration level of ~250µg/m^3. Most of the feasibility study data obtained was at values less than 50µg/m^3 corresponding to the concentration range that was expected to be measured within the school bus cabin during the runs. These results are similar to those reported for the TSI DustTrak in several previous studies. Yanosky et al[57] reported that the 24hr averaged DustTrak readings are 2.57 times higher than the 24hr averaged FRM for indoor air pollutants. The range of particulate concentrations, as measured by the FRM, was between 5 and 20µg/m^3. Also Ramachandran et al. reported for indoor and outdoor concentrations that the TSI DustTrak was 1.94 times higher than a gravimetric study. Finally, in the CATF study[9] a comparison of the TSI DustTrak with a TEOM resulted in DustTrak values that were approximately 2.9 times higher than the TEOM values for the 30 August 2004 data. Unlike previous studies the intercept was not zero and the lowest concentration that was measured by the DustTrak was 11µg/m^3. It should be noted that the authors of the CATF study state that further calibrations should be done using diesel particulates like the one performed for the initial study.

After the instruments were sent back to the factory for maintenance and recalibration on April-9-2008, a check on the mass concentration response with respect to ambient $PM_{2.5}$ was conducted.

The DataRAM-4 and P-Trak instruments were setup on top of the NJDEP Elizabeth, NJ Ambient Monitor Station. This station was chosen, because of the high heavy duty diesel traffic on the nearby highways. The test lasted for a 3 hour period on the morning on May 3, 2008. The DataRAM-4 data were compared to data from the same time interval measured with the Tapered Element Oscillating Microbalance (TEOM), a continuous instrument located in the NJDEP monitor station. The location of the instruments is shown in Figure 24. The sampling manifold used by the TEOM is shown at the middle right of the picture with a conic head and transparent tube.

Figure 24: Instrument location at the NJDEP ambient monitor station in Elizabeth, NJ.

The average values obtained during this three hour sampling period were divided in two sets for the DataRAM instruments and the results are shown in Table 6. The 95% confidence interval gave an average of ±4.3μg/m^3, and the average coefficient of variation resulted in less than 10% based on the DataRAM values. These results are comparable to the ones obtained in the feasibility study at EOHSI shown in Table 3 in which the coefficient of variation was 16% with a 95% confidence interval of ±6.6μg/m^3 based on the mean concentration of 35.8μg/m^3 which is similar to the mean concentration of 41.7μg/m^3 from the Elizabeth data. The difference in agreement between the DataRAM instruments and the TEOM can be attributed to the sampling location of the DataRAM instruments on the roof of the monitoring station as seen in Figure 24 and to the measuring mechanism of both technologies.

Table 6: Ambient monitor data from Elizabeth, NJ on May 3, 2008.

Time Interval (hr:min)	TEOM average (μg/m^3)	DataRAM-4 instrument #1 Average (μg/m^3)	DataRAM-4 instrument #2 Average (μg/m^3)	DataRAM-4 instrument # 3 Average (μg/m^3)	Mean (μg/m^3)	Standard Deviation (μg/m^3)	95% Confidence Interval (μg/m^3)	Coefficient of Variation (%)
8:30 to 10:00	27.1	49.5	43.5	51.4	48.2	4.1	4.7	8.6%
10:01 to 11:45	26.7	37.2	31.2	37.2	35.2	3.5	3.9	9.9%
Average					41.7		4.3	9.2%
Note: The mean, standard deviation, confidence interval, and coefficient of variation were calculated based on the three DataRAM values without including the TEOM results.								

Figure 25 shows the minute averaged results obtained from the Elizabeth measurements performed by the three DataRAM instruments and the TEOM located at the ambient monitor station. This figure shows the ability of the instruments to track each other within a 10% variation. As shown in the previous feasibility study, the DataRAM's over-estimate the TEOM values in a range between 1.3 to 1.8 times the TEOM concentration for an average DataRAM concentration range from 21 to 48μg/m^3.

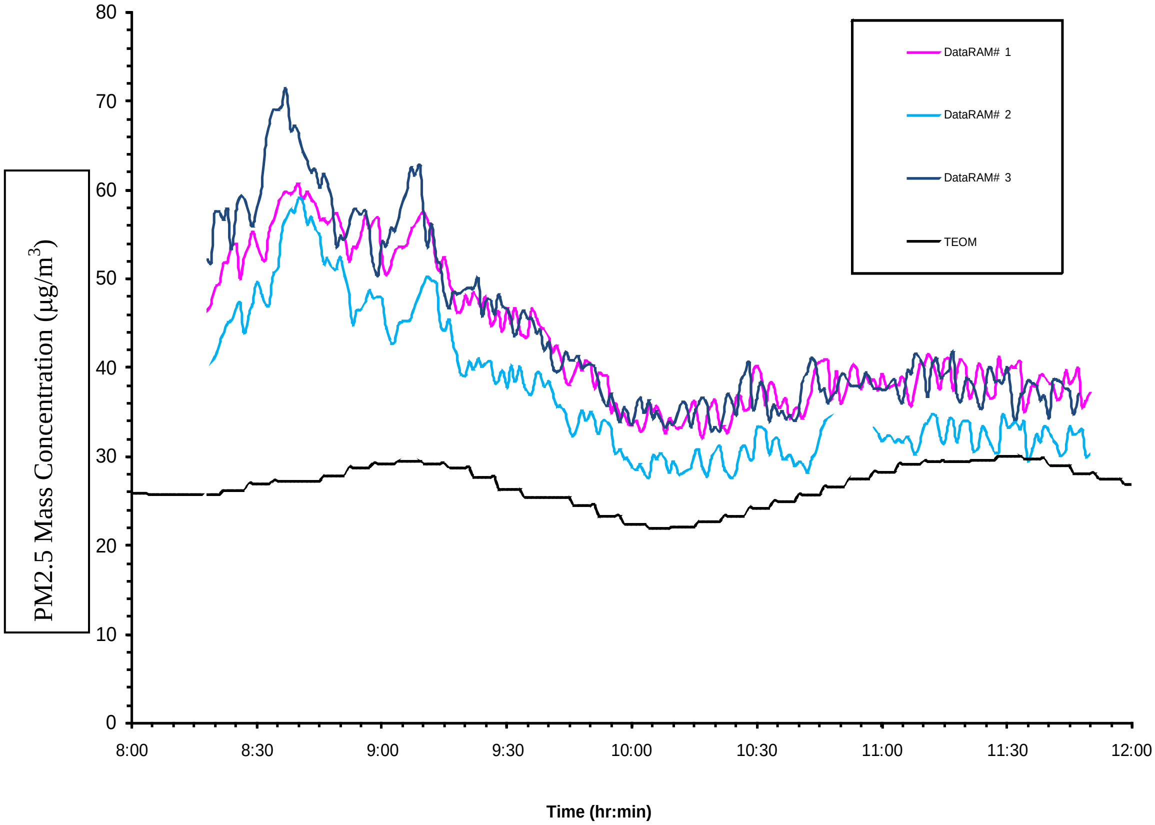

Figure 25: Measurements obtained at Elizabeth NJ, monitor station on May 3, 2008. Values are presented in one minute average for the DataRAM and TEOM instruments.

The measurements obtained by the P-Trak instruments are given in Table 7. These instruments track together extremely well and they have a coefficient of variation of less than 1%, this value is similar to the one obtained at the EOHSI feasibility study resulting in a coefficient of variation from 2 to 7% for an average concentration range of 2196 to 12,4139pt#/cm^3.

Table 7: P-Trak and TEOM values from Elizabeth, NJ site on May 3, 2008.

Time Interval (hr:min)	TEOM average (µg/m^3)	P-Trak#1 average (pt#/cm^3)	P-Trak#2 average (pt#/cm^3)	P-Trak#3 average (pt#/cm^3)	Mean (pt#/cm^3)	Standard Deviation (pt#/cm^3)	95% Confidence Interval (pt#/cm^3)	Coefficient of Variation (%)
8:19 to 11:50	27	42839	43356	43616	43271	396	448	0.9%
Note: The mean, standard deviation, confidence interval, and coefficient of variation were calculated based on the three P-Trak values without including the TEOM results.								

5.11 Total Tests Performed

Table 8 shows the 69 runs performed for the initial study during the months of February through August 2007. For the windows closed condition the following sets of runs were conducted: 8 runs without any retrofit technology (baseline condition), nine runs using only the crankcase ventilation system (CCVS) without tailpipe retrofit, 14 runs using the diesel particulate filter (DPF) in combination with the CCVS, 9 runs using the DPF alone, 3 runs using the flow through filter (FTF) with the CCVS and 3 runs using only the FTF. The numbering of the runs was done consecutively, but within any category of runs there may be several sets of numbers. For example in the CCVS runs 14-20 were conducted consecutively, followed by a set of runs 64-66 at a later date.

Table 8: Total completed test runs for the initial study.

Run No.	Bus Engine	Fuel	Device (s)	Windows
1,2,3, 7	DT466E	ULSD	None	Open
8,9,10	DT466E	ULSD	None - no exhaust emission measurements	Open
4,5,6, 17,63,67,68,69	DT466E	ULSD	None	Closed
11,12,13	DT466E	ULSD	Crankcase Filter (CCVS)	Open
14,15,16,18,19,20, 64,65,66	DT466E	ULSD	CCVS	Closed
30,31,32	DT466E	ULSD	Diesel Particulate Filter (DPF) and CCVS	Open
21,22,23, 34, 47,48,49,50, 54,55,56,57,58,59	DT466E	ULSD	DPF and CCVS	Closed
27,28,29	DT466E	ULSD	DPF	Open
24,25,26, 60,61,62, 51,52,53	DT466E	ULSD	DPF	Closed
41,42, 46	DT466E	ULSD	FTF	Open
43,44,45	DT466E	ULSD	FTF	Closed
35,36,37	DT466E	ULSD	FTF and CCVS	Open
38,39,40	DT466E	ULSD	FTF and CCVS	Closed
33	DT466E	ULSD	DPF and CCVS – Idle test	Closed

The work plan proposed three runs per configuration for windows closed. Table 9 shows the runs completed for the final set of runs.

Table 9: Number of runs per configuration and dates performed for the final study.

Run #	Retrofit	Date (dd/mm/yyyy)
1F	None	28/05/2008
2F	None	28/05/2008
3F	None	28/05/2008
4F	FTF[a]	30/05/2008
5F	FTF	30/05/2008
6F	FTF	30/05/2008
7F	DPF[b]	03/06/2008
8F	DPF	03/06/2008
9F	DPF	03/06/2008
10F	DPF & CCVS	17/06/2008
11F	DPF & CCVS	17/06/2008
12F	DPF & CCVS	17/06/2008
13F	FTF & CCVS – Faulty run[1]	18/06/2008
14F	CCVS[c]	19/06/2008
15F	CCVS	19/06/2008
16F	CCVS	19/06/2008
17F	FTF & CCVS	20/06/2008
18F	FTF & CCVS	20/06/2008
19F	FTF & CCVS	20/06/2008

[a]FTF – Environmental Solutions Worldwide's Particulate Reactor
[b]DPF – Johnson Matthey's Continuously Regenerating Technology
[c]CCVS – Donaldson's Spiracle Crankcase Filter
[1]The installation of the FTF retrofit had a leak in the joints of the tailpipe causing the run to be discarded.

The decision to test with the windows closed in the final study was determined after the previous initial study that resulted in 69 runs including an idle test. From those runs, 46 were tested with the school bus having all the windows closed and the remaining with the windows open. The particle concentrations inside the cabin of the school bus were much lower with the windows open than with the windows closed. This difference is believed to be related to fresh air exchanging with the cabin air which removes any accumulation of particulate matter in the bus. Since buses will run with windows closed for a significant fraction of the school year, it was decided to conduct all of the final runs with windows closed.

6. RESULTS

This section reports the results from the initial and final runs. The findings from the initial study showed that there is an accumulation of particulate matter within the cabin of a school bus. This accumulation was only observed when the windows of the bus were closed, since having the windows open allowed fresh air to enter the bus and remove any spikes or accumulation in particulate matter.

6.1 Initial Study Results

The initial study showed that operating the bus with the windows open did not result in accumulation of particulate matter. These low concentrations are caused by the dilution of PM inside the cabin from the increased rate of air exchange when driving with all the windows open. This dilution effect can be seen in Run 3 which was performed without any retrofit technology with the windows open and is shown in Figure 26. This figure is the time history of particulate concentrations measured by all 3 of the DataRAM's and is reported as $PM_{2.5}$ Mass Concentration. The background concentration values were measured by the DataRAM located at the ambient monitoring station and the other 2 curves are from the DataRAM's in the front and back of the bus. Three time periods are delineated in Figure 26 and are labeled as the pretest, run test and post test. The pretest shows the concentration values for all 3 instruments located at the ambient monitoring station. Next the DataRAM's for the front and back of the bus cabin were moved to the bus and the RUCSBC was performed. After this run the 2 DataRAM's were removed from the bus and placed back at ambient monitoring station. The times when no values are shown in Figure 26 correspond to when the DataRAM's were not collecting data and were being moved between the monitoring station and the bus.

As can be seen from this figure no significant accumulation in particulate matter was observed for this windows open run. It should be noted that the concentrations within the bus are higher than the ambient values as shown by the data for the front and back of the bus being above the background or ambient concentration values. In addition the concentrations for the front and back of the bus are nearly equal in concentration. There are a number of oscillations and peaks in the concentration readings, but no accumulation was observed. In Figure 26 the large peak of ambient particulate concentration with a value greater than $140 \mu g/m^3$ appears at about 2800 s. This peak of concentration is transmitted to the inside of the bus at about 2900 s for both the front and back of the bus. This is direct evidence that an event external to the school bus occurred and was transmitted with a time delay to the cabin of the school bus. In this case the external event was identified by the ambient DataRAM-4 instrument located in the mile loop which showed the background peak at approximately 2800s.

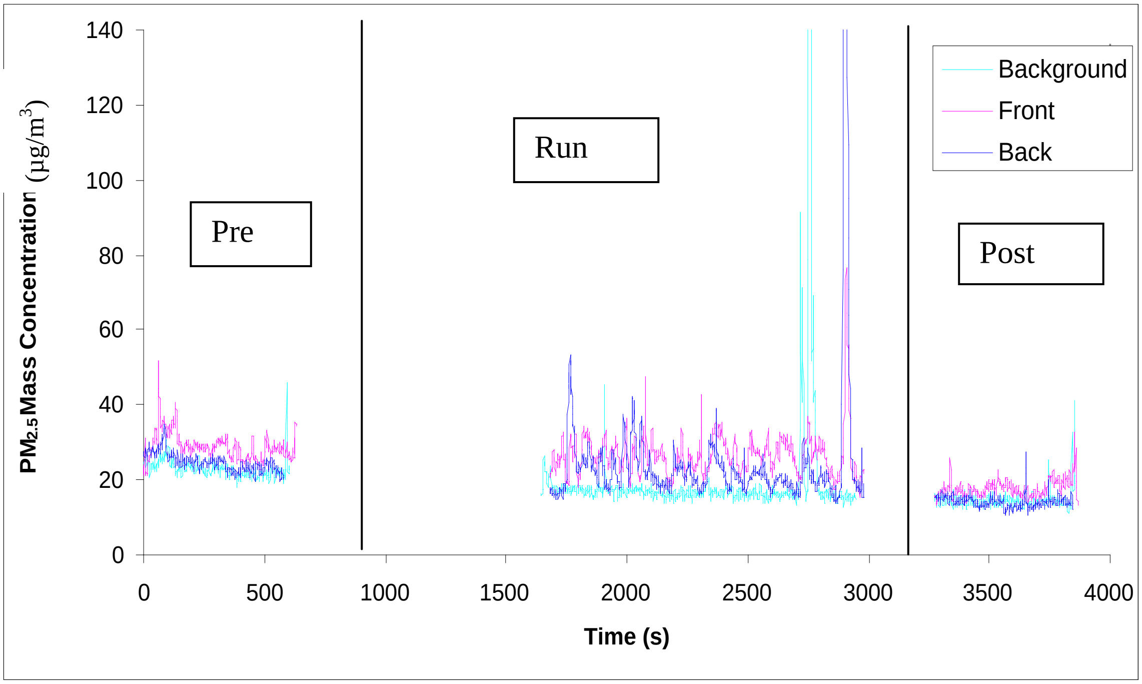

Figure 26 Run 3, measurement of $PM_{2.5}$ with the windows open and with no retrofit installed, the run was executed on April 2, 2007.

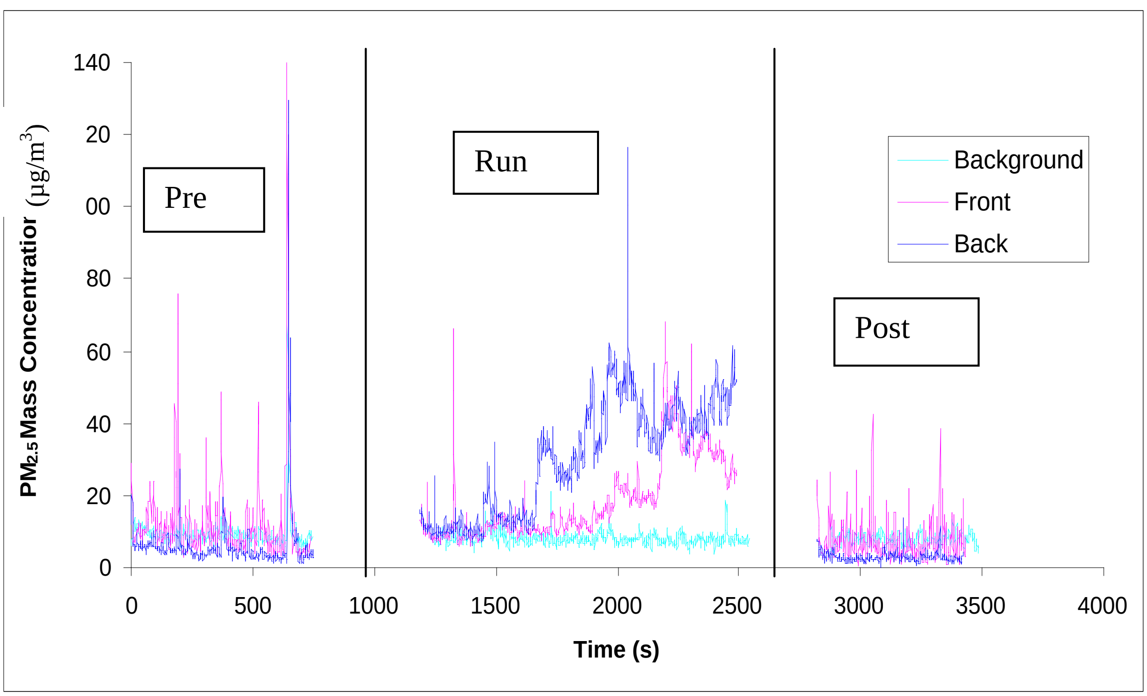

Figure 27 Run 5, $PM_{2.5}$ results from baseline run with windows closed. This run was performed on April 2, 2007.

Figure 27 gives an example of a run with the windows closed for the baseline condition of no retrofit technologies. The concentration of particulate matter for Run 5 started at approximately the ambient level which was below 20 μg/m^3 which can be seen from the time period from 0 to 600 s. After starting the RUCSBC the concentrations at both the front and back of the bus increase to over 40 μg/m^3 at about 2200 s. After this value the front concentration decreases, but the back concentration increases to an earlier peak value. This accumulation of concentration was a direct result of having the windows closed. It should also be noted that with the windows closed the back of the bus showed much higher particulate concentrations compared to the front of the bus for most of the run.

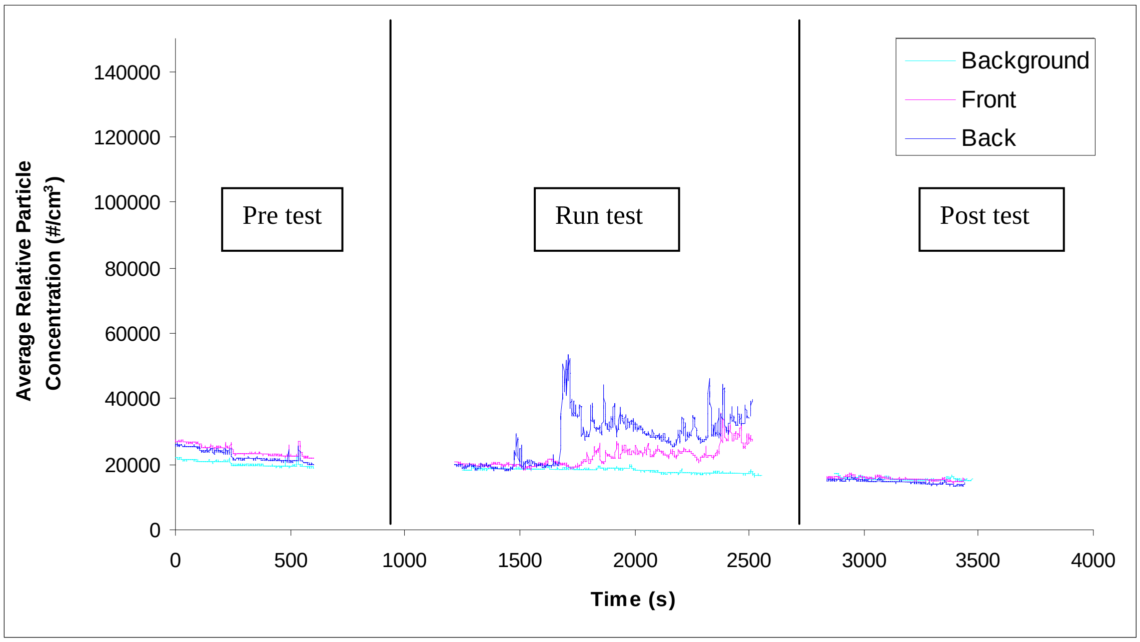

Figure 28 Run 5, baseline run with no retrofit and the windows closed results for ultra fine particulate matter. Test from April 2, 2007.

Figure 28 shows a baseline condition with no retrofit installed for the ultra fine particle concentrations measured by the P-TRAK instruments. This figure also shows that there is an accumulation of ultrafine PM within the cabin of the bus. Similar to the DataRAM values the concentration of ultrafine PM are higher at the back of the bus compared to the front of the bus.

The results of the baseline runs with no installed retrofit technologies were used for comparison with the different retrofit technologies and combinations. The following two figures show representative runs with different technologies employed.

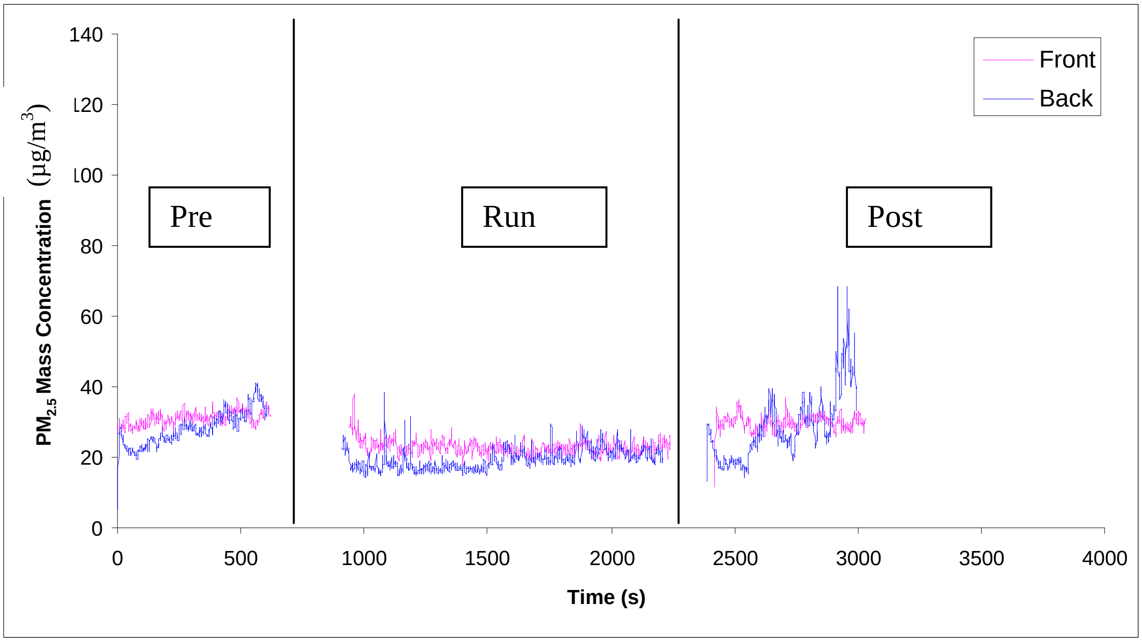

Figure 29 Run 58, result of $PM_{2.5}$ mass concentration with the bus using the DPF with the CCVS having all windows closed in the bus. Run executed on June 13, 2007.

Figure 29 shows the $PM_{2.5}$ mass concentration with the DPF and CCVS installed and with the windows closed. A visual comparison of Figure 27 with Figure 29 shows that there is a reduction in particulate concentration as a result of using the DPF and CCVS. In Figure 29 the concentration of particulates is nearly constant at approximately 20 $\mu g/m^3$ for the entire run. This is in contrast to the baseline case in Figure 27 with an accumulation in particulates for the run.

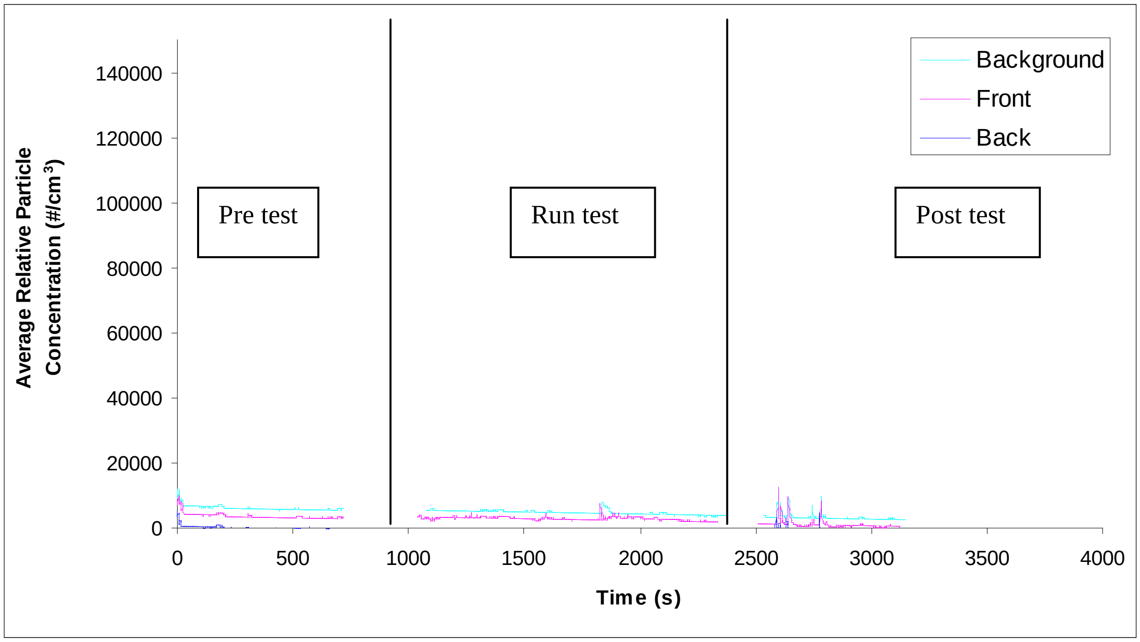

Figure 30 Run 58, Ultra fine PM results with the DPF & CCVS installed and windows closed, performed on June 13, 2007.

Figure 30 shows the results using the DPF & CCVS with the windows closed for the measurements obtained from the P-TRAK's. Again a significant reduction in the concentration was present for ultra fines for Run 58 when compared to the particle concentrations shown in Figure 28 for the baseline case.

Figure 31 shows the $PM_{2.5}$ mass concentration for the windows open configuration. As shown in the concentration-time plots the ventilated cabin resulted in a very small particulate matter accumulation for the open windows test. Negative values that are shown are a result of the concentration within the bus having a lower value than the ambient concentration.

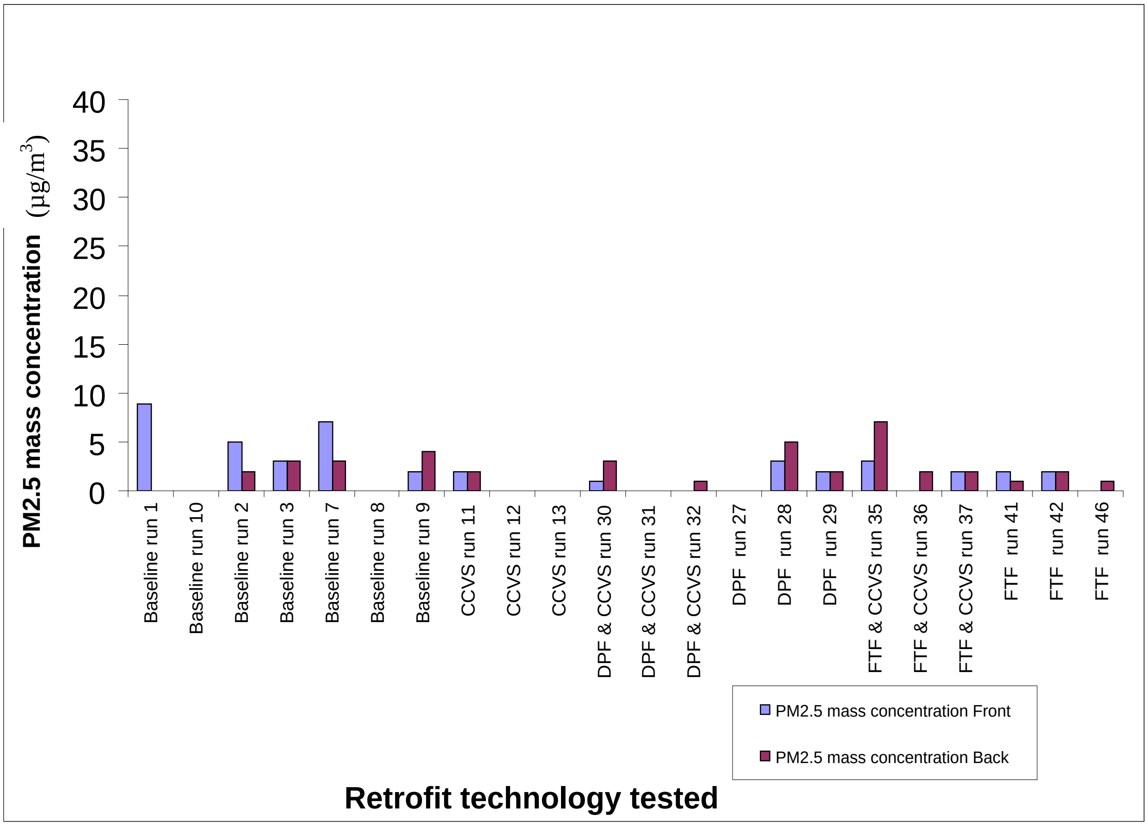

Figure 31 Average relative mass concentration results for all the performed tests with windows open. The bars that are not shown are negative values which result from having a lower in-cabin concentration than the ambient concentration.

As can be seen in Figure 31 the windows open runs have average relative mass concentrations in the range of 0 to 10μg/m^3 relative to the ambient concentrations. The x-axis in Figure 31 lists the results of the $PM_{2.5}$ mass concentration for windows open in groups by run condition. The results show only minor differences between the retrofit technologies which is a result of the air flowing through the open windows and removing the accumulating mass of particles in the cabin of the bus.

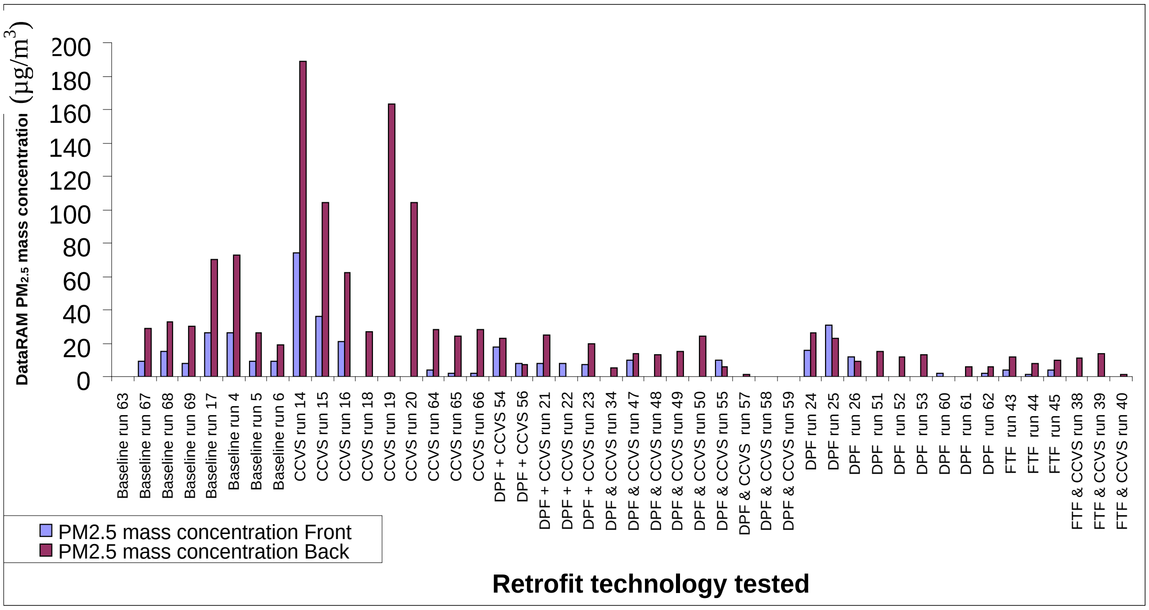

Figure 32 Average relative mass concentration results for all the windows closed runs from the initial study. The bars that are not shown are negative values which result from having a lower in-cabin concentration than the ambient concentration.

Figure 32 shows the average relative mass concentration results obtained from the DataRAM's for all runs of the initial study with the windows closed. The windows closed condition showed a particulate matter accumulation in the cabin as seen in Figure 32 for the baseline condition (left side of the figure). The use of the CCVS alone with no tailpipe retrofit resulted in a range of concentration values. Five of the runs had values of relative average mass concentrations greater than 50 $\mu g/m^3$ and 4 of the runs had values less than approximately 30$\mu g/m^3$. The runs 64, 65 and 66 show a self consistent set of values of particulate concentration. These runs were done in the evening to minimize external traffic on the base and fugitive particulate emissions from ground sources were eliminated by a recent rainstorm which had wet the track and surrounding areas.

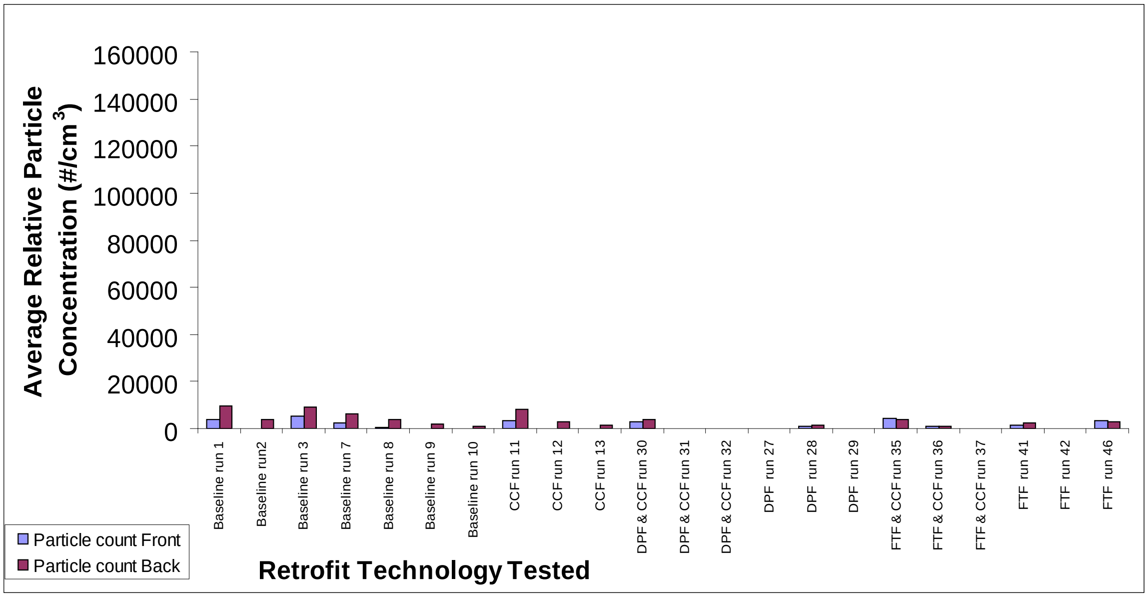

Figure 33 Average relative p**article concentration results for windows open tests of initial study.**

The results shown in Figure 33 were obtained for the windows open configuration in the initial study. This figure also shows that the ultrafine particle concentrations were lower in comparison to the windows closed condition and no retrofit effect can be discerned.

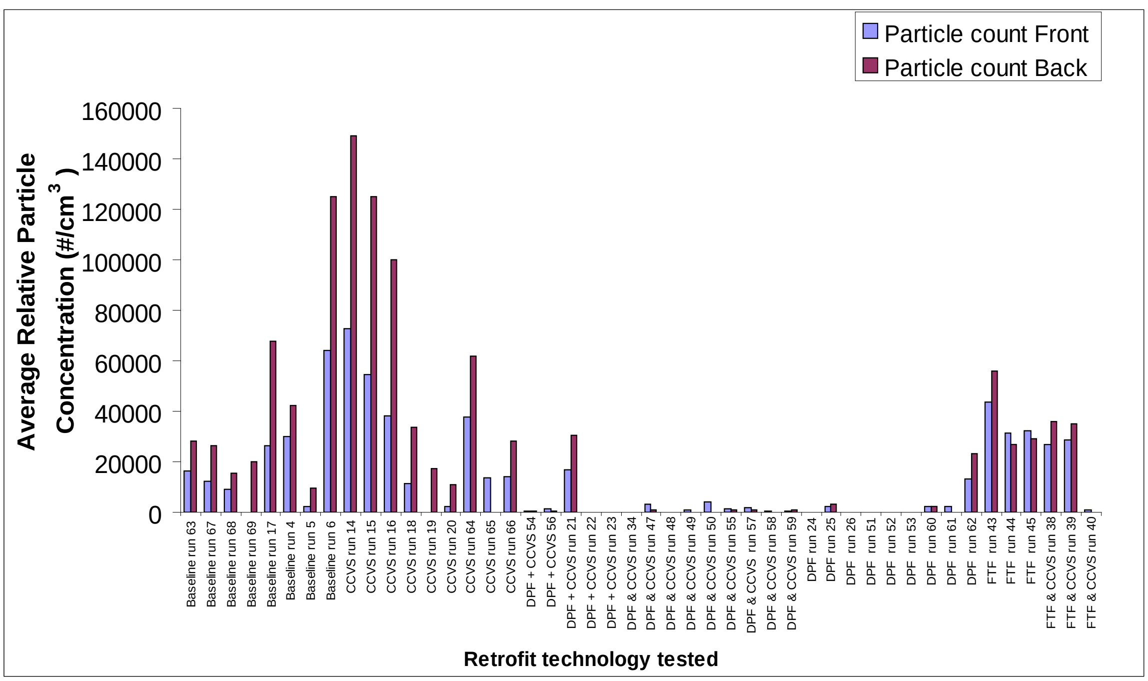

Figure 34 Average relative particle concentration results for windows closed tests from initial study. The bars that are not shown are negative values which result from having a lower in-cabin concentration than the ambient concentration except for runs 19, 61, 65, and 69 in which the values were not available.

Figure 34 shows the average relative particle number concentrations measured by the P-Trak. The numerical values of these averages are given in Appendix E. From this figure it can be noted that the particle number concentrations in the cabin of the bus when using the DPF is significantly lower than all other technologies. The ceramic wall filter design of the DPF yields reduction in particle number concentrations within the school bus of more than 90% in comparison with the baseline condition when comparing all the runs from the initial study.

The average relative mass concentration values are shown in Table 10 for each run configuration.

Table 10 Average $PM_{2.5}$ mass concentration results for three data sets according to the level of election criteria. All runs performed with windows closed.

Retrofit Technology	Front run with ambient subtracted (μg/m3)	Back with ambient subtracted (μg/m3)	# of runs
None	12	35	8
CCVS	13	81	9
FTF	3	10	3
CCVS & FTF	-2	9	3
DPF	2	12	9
CCVS & DPF	2	9	14

Table 10 shows the results of $PM_{2.5}$ mass concentration averages for each condition only for the windows closed tests. The results are given with the ambient concentration subtracted for each run; any negative value indicates that the in-cabin measurements were lower than the ambient. The lowest values in particulate matter concentration were obtained for both the DPF and the CCVS.

Table 11 shows the results of ultrafine particle count averages from each condition tested. These results are given with the ambient measurement subtracted from the average value for each run. Negative values indicate that the in-cabin particle number concentrations were lower than the ambient. In the case of the FTF with CCVS it was observed that there was an increase in ultrafine particles number concentrations. The average particle number concentrations for the CCVS run are 45,000 pt#/cm^3 compared to the base case average of only 20,000 pt#/cm^3. The values from the CCVS runs are over twice the magnitude of the baseline runs. A similar high value for the FTF is observed. It should be noted that only 3 runs were conducted using the FTF and these runs were obtained under a bus with leaks in the cabin and with uncontrolled sources of PM like road dust.

Table 11 Average ultrafine particle count results for initial study.

Retrofit Technology	Front with ambient subtracted (pt#/cm3)	Back with ambient subtracted (pt#/cm3)	# of runs
None	22953	41759	8
CCVS	30584	65783	9
FTF	35744	37330	3
CCVS & FTF	18823	23469	3
DPF	1377	2216	9
CCVS & DPF	2101	2025	14

After completing this study, leaks were found in the bus. The faulty seal in the back door was only identified upon sitting in the back and observing direct sunlight through the space between the door and the frame. This was only noticed when the bus was at a position of the track in which direct sunlight could be observed and was not noticed at other times. The high level of particulates measured in these runs shows the importance of conducting at least a rigorous inspection of the seal of the back door of the bus. Because of the high level of uncertainties in Runs 1-69.

6.2 Final Study Results

A decision was made to conduct a final set of tests in which most of the uncertainties in Runs 1-69 were removed. In addition, as a result of the initial tests the primary focus of the final set of runs was on data obtained from the window closed tests.

The final study was very carefully designed to minimize particulate matter originating from sources extraneous to the bus. To accomplish this, a test site was chosen in a remote location that was surrounded by a barrier of trees on nearly all sides of the track. Sections of the track were power-washed and the outside and inside of the bus were cleaned for each day's set of runs. Additional cleaning of the bus was also done in between runs and a waiting period of 5 minutes after shutting down the engine before the doors and windows were opened was used to avoid diesel emissions from entering the bus. These measures resulted in particulate concentrations that are primarily from the emissions from the bus as well as the ambient air. The ambient particulate concentrations were obtained from a third DataRAM and P-Trak (Ambient Monitor) located at a distance of 300m from the track.

6.3 Continuous Sampling Results

This study showed that there is an accumulation of particulate matter within the cabin of a school bus. Figure 35 shows the DataRAM values for a baseline run, Run 3F, in which no retrofits were installed on the bus. In Figure 35, the data is shown plotted using a 10 s averaged value for all DataRAM measurements. Three distinct regions can be seen in this figure. The measurements shown from 16:30 to 16:36 were from the DataRAM's (Front - Pink, and Back- Blue) located in their sampling location at the front and back of the bus with the windows and front door open and the engine turned off. This pre-run in-cabin measurements were used to determine if the air in the cabin of the bus had been restored to near ambient values before each run. Immediately before starting the run cycle all of the windows and the front door of the bus were closed and then run 3F started at approximately 16:43. The run had a duration of 28 minutes and 46 seconds, ending at approximately 17:11. After ending the cycle and waiting 5 minutes the windows were opened and a post test of the in-cabin particulate levels was conducted from 17:20 to 17:29.

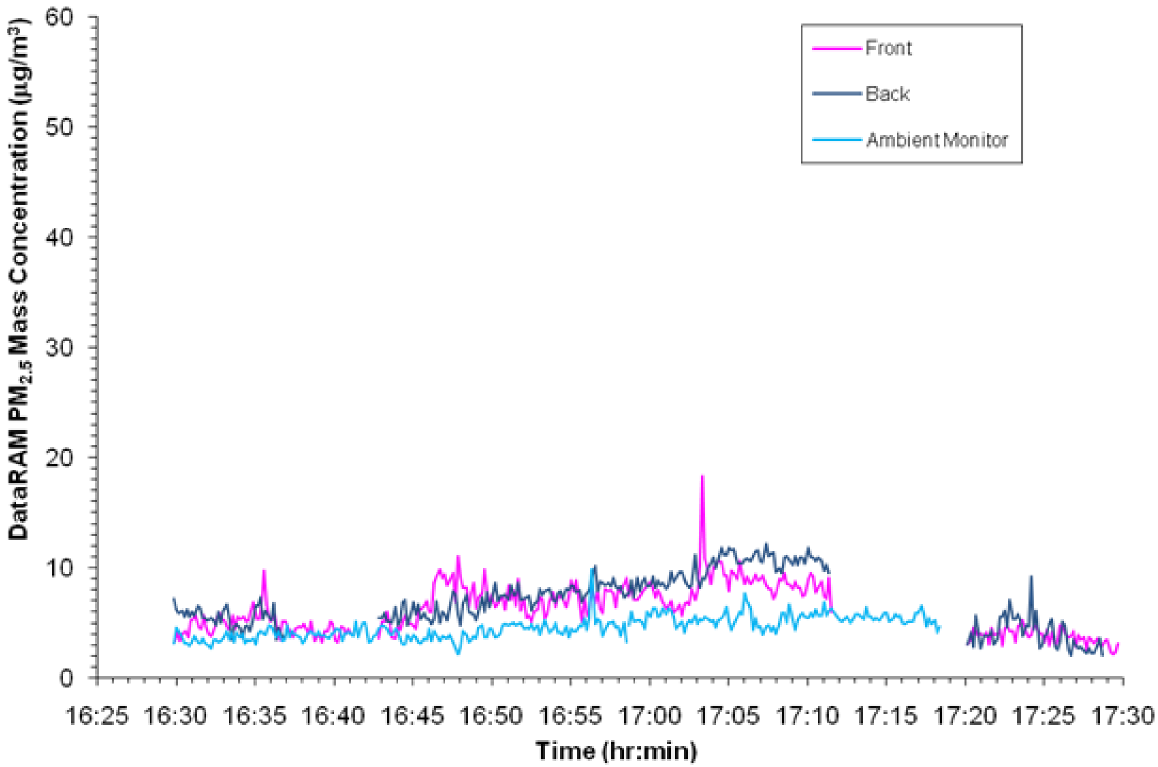

Figure 35: Baseline run #3F baseline condition, DataRAM results with 10 seconds averaging.

This baseline run shows an accumulation of $PM_{2.5}$ concentration inside the bus cabin as the run advances as evidenced by the overall positive slope of the data. It is interesting to note that the ambient monitoring station values, shown in turquoise, also show an increasing ambient concentration throughout the run. The values for all three DataRAM's at the start of the run (16:43) gave values between 3 and 6 $\mu g/m^3$.At the end of the run the ambient DataRAM increased to 6 $\mu g/m^3$ while the front monitor value was 8$\mu g/m^3$ and the back was 10$\mu g/m^3$. Another indicator of this accumulation is the pre and post run ambient measurements obtained by the front and back instruments measuring inside the bus with windows open. The average pre and post values for the front were 4.3$\mu g/m^3$ while the average of the run was 7.6$\mu g/m^3$. The average concentration for the back DataRAM for the pre and post sampling periods was 4.7μg/m^3 and the run was 8.3μg/m^3. Again this increased level over the ambient demonstrates that there was an accumulation of particulate matter in the bus.

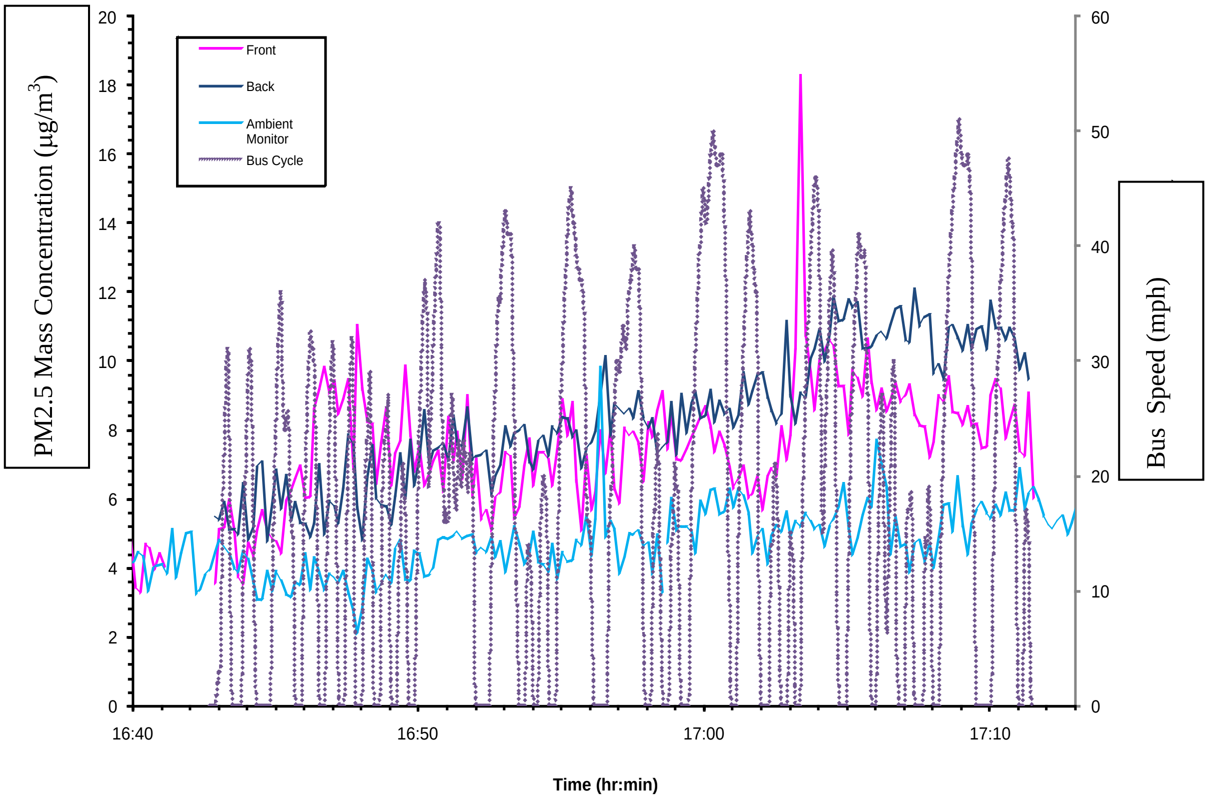

Figure 36: Baseline run #3F baseline condition, DataRAM results with 10 seconds averaging and bus cycle overlapped.

A comparison between RCSBC-S and the DataRAM concentrations is shown in Figure 36 in which the actual bus speed is presented in dashed purple line with the speed shown in the secondary "y" axis. The first part of the cycle from 16:43 to 16:50 hrs has many stops and accelerations causing the peaks observed in the front DataRAM starting at approximately 16:46hrs. Another concentration peak is observed when the bus is at a stop and then accelerating at approximately 17:03hrs.

For the particle count measurements, an identical measurement protocol was followed as with the DataRAM's. The pre and post measurements were made with the instruments in their respective seats and one ambient monitor P-Trak was located on the table next to the DataRAM at the ambient monitoring station.

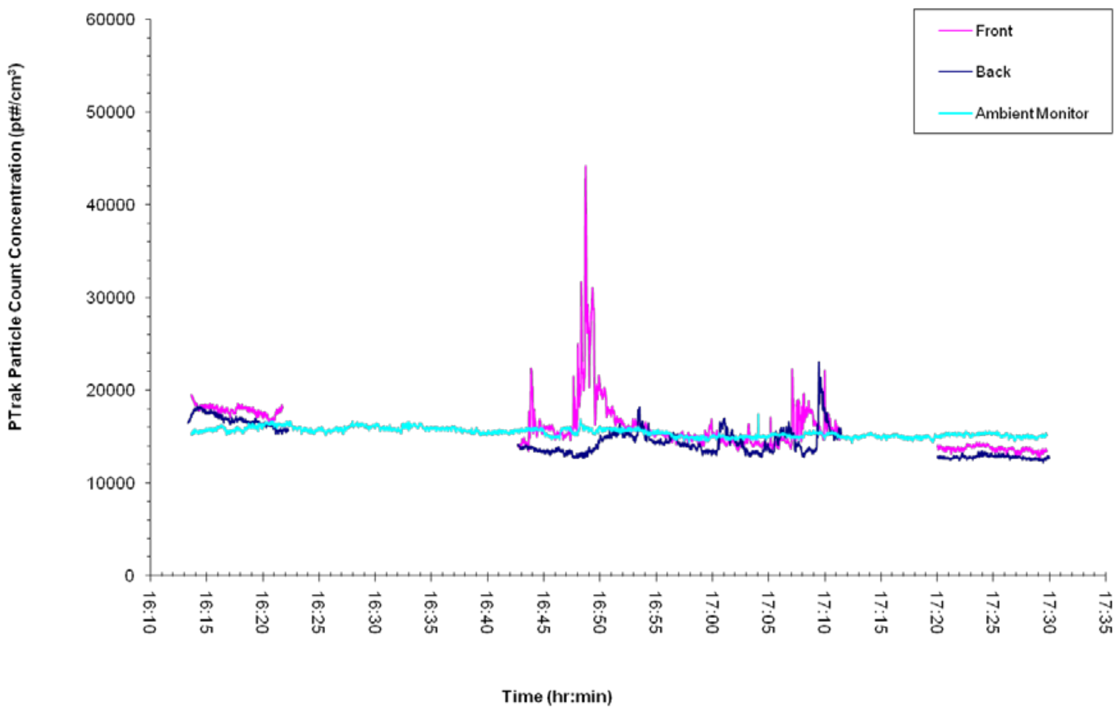

Figure 37: Baseline run #3F baseline condition, P-Trak results.

Figure 37 presents the P-Trak results for particle count concentrations during the baseline run# 3F with no retrofit. From the start of the run at 16:43 both the front and back P-Trak measured a value of approximately 14,000 pt#/cm^3. The front P-Trak measures an immediate increase in concentration resulting in a peak at 16:44 of 22,000 pt#/cm^3. This concentration is reduced to a value approximately equal to the value at the start of the run by 16:47. After this low the concentration at the front of the bus increases to a peak of 44,000 pt#/cm^3 at 16:49 hrs. These peaks corresponds to the urban section of the cycle in which there are a series of stops and accelerations that simulate bus stops in close proximity to each other which is characteristic of urban and suburban communities. The next major peak for the front of the bus is in the rural section of the cycle and corresponds to the bus accelerating resulting in a peak at 17:07 of 22,000 pt#/cm^3.

In examining the ambient concentration compared to the in-cabin concentration values it can be seen that the front and back of the bus start at a slightly higher value than the ambient at the start of the pre-run measurement at 16:13 and then decrease to nearly equal values at 16:21 of 16,000 pt#/cm^3. The ambient concentration shows a gradual decrease from this value to a value of about 15,000 pt#/cm^3 by the end of the run. The in-cabin concentration has decreased from the pre-test values to the starting value of 14,000 pt#/cm^3 at 16:43. The post-test in-cabin value for the front has returned to its initial value of 14,000 pt#/cm^3, but the post-test in-cabin value for the back is nearly equal to the minimum value of approximately 13,000 pt#/cm^3 that was measured during the cycle. This illustrates an issue with the interpretation of the ambient value for a number of runs. For run 3F, there is a difference between the ambient monitoring value of about 15,000 pt#/cm^3 and the minimum observed values for the front and back during the run as well as during the post-run check of 14,000 and 13,000 pt#/cm^3, respectively.

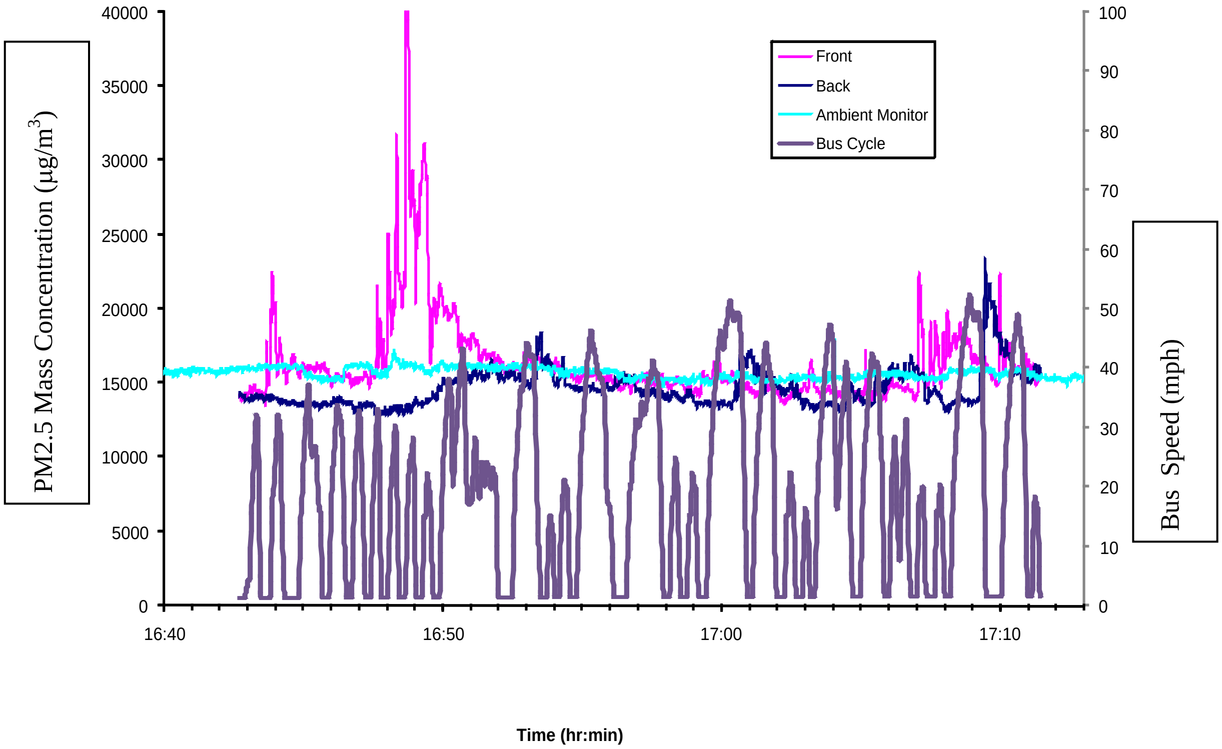

Figure 38: Baseline run #3F baseline condition, P-Trak results with bus cycle.

Figure 38 shows the P-Trak results with the bus cycle on the secondary "y" axis. The first part of the cycle from 16:43 to 16:50hrs results in the major accumulation of particle count concentration associated with the consecutive stops and accelerations. The first peak at the first stop between 16:43 and 16:44hrs resulted from the opening of the front door as measured by the front P-Trak. At approximately 17:07hrs another series of peaks is observed at the front of the bus occurred during consecutive small accelerations and stops.

The precision of the measurements taken by the three Data RAMs and the precision of the measurements taken by the three P-Trak were quantified in terms of the coefficient of variation (COV) which is a normalized measure of dispersion of a probability distribution and is defined as the ratio of the standard deviation to the mean. Table 12 presents a comparison of the three DataRAM instruments at one location measuring the same ambient air. These data were obtained at both the NJDEP ambient monitoring station in Elizabeth, N.J. and at the dynamometer track at ATC. The DataRAM and P-Trak instruments were located on the roof of the ambient monitor station at Elizabeth, right next to the TEOM sample air intake. For ATC, the instruments were located in the designated ambient location approximately 300m from the start of the test cycle point at the south section of the track. The average coefficient of variation was 16% for all the values yielding an average 95% confidence interval of ±5.1μg/m^3 around the average mean of 28.5 μg/m^3. It should be noted that the instruments do not show a trend in which one instrument is consistently reporting a higher value than the other instruments.

Table 12: Comparison of DataRAM instruments measuring at the same location during different days.

Location and Test Date (dd/mm/yy)	Front DR1 (μg/m^3)	Ambient DR2 (μg/m^3)	Back DR3 (μg/m^3)	Mean (μg/m^3)	Standard Deviation (μg/m^3)	95% Confidence Interval (μg/m^3)	Coefficient of Variation
Elizabeth, NJ 3-May-08	43.0	37.0	44.0	41.3	3.8	4.3	9%
ATC 17-Jun-08	17.9	21.2	21.8	20.3	2.1	2.4	10%
ATC 17-Jun-08	34.0	43.4	41.6	39.7	5.0	5.6	13%
ATC 19-Jun-08	11.8	9.6	13.1	11.5	1.8	2.0	15%
ATC 19-Jun-08	31.6	21.9	33.2	28.9	6.1	6.9	21%
ATC 20-Jun-08	25.9	32.2	41.3	33.1	7.7	8.8	23%
ATC 20-Jun-08	22.1	22.0	30.6	24.9	4.9	5.6	20%
Average				28.5		5.1	16%

Table 13 shows the comparison of the P-Traks. These instruments exhibit a much higher level of agreement. The average coefficient of variation is 5% and the average 95% confidence interval is ±781 pt#/cm^3 at an average mean of 18300 pt#/cm^3. It can also be seen that there is no consistent pattern of one instrument reading higher than the other. This value of 781 pt#/cm^3 is of the order of the differences seen between the in-cabin values and the ambient monitoring station in run 3F shown in Figure 37.

Table 13: Comparison of P-Trak instruments measuring at the same location during different days.

Location and Test Date (dd/mm/yy)	Ambient PT1 (pt#/cm^3)	Front PT2 (pt#/cm^3)	Back PT3 (pt#/cm^3)	Mean (pt#/cm^3)	Standard Deviation (pt#/cm^3)	95% Confidence Interval (pt#/cm^3)	Coefficient of Variation
Elizabeth, NJ 3-May-08	42839	43356	43616	43270	396	448	1%
ATC 17-Jun-08	20247	20790	19314	20117	747	845	4%
ATC 17-Jun-08	9553	9032	8759	9115	403	456	4%
ATC 19-Jun-08	11252	11593	10578	11141	517	584	5%
ATC 19-Jun-08	12456	11045	10611	11371	965	1092	8%
ATC 20-Jun-08	21381	23269	21151	21934	1162	1315	5%
ATC 20-Jun-08	11583	11413	10397	11131	641	726	6%
Average				18,297		781	4.7%

Table 14 shows an analysis of the agreement between the pairs of instruments used in the study. In the second column is a comparison of the front and back of the bus instruments using in-cabin pre – and post-run measurements. The third and fourth column show a comparison of the pairs of the back and front DataRAM's with the ambient monitor (DR2) used to calculate the net particulate mass concentration ($PM_{2.5}$) respectively. These values were obtained from the average coefficient of variation of the pre and post in-cabin run measurements during each tested technology day. These values are calculated from 6 ambient measurements for the three runs of each test day and were compared to the ambient measurements for the same time period. It should be noted that unlike the values obtained in Table 12, these instruments are not placed at the same location. All of the in-cabin measurements reported in this table were done with the windows and door open of the bus and bus engine off. The expectation is that the in-cabin measurements should be equal to the ambient table measurements.

As expected, the average values of the coefficient of variation are in general greater than those from those shown in Table 12. The average values for the coefficient of variation between the back and front of the bus compared to the ambient monitor are 21.4 and 15.3%, respectively, compared to 16% for all instruments in Table 12. These values show reasonable agreement between all instruments. Because of this small difference in values, these results validate the use of the ambient monitoring station value to calculate the net particulate concentration.

Table 14: Coefficient of variation from the three DataRAM instruments measuring at the same location during different days.

Retrofit	DR1 Front & DR3 Back pre and post C.V.	DR3 Back pre and post & DR2 Ambient Monitor C.V.	DR1 Front pre and post & DR2 Ambient Monitor C.V.
	C.V. %	C.V. %	C.V. %
None	12.4	7.1	8.2
FTF	7.5	37.8	31.1
DPF	16.2	24.1	18.6
DPF & CCVS	6.3	6.1	10.6
CCVS	51.9	40.3	14.4
FTF & CCVS	21.2	12.7	8.7
Average	**19.3**	**21.4**	**15.3**

The results of the baseline runs with no installed retrofit technologies were used for comparison with the different retrofit technologies and combinations. The following figures show a representative run with the DPF combined with CCVS.

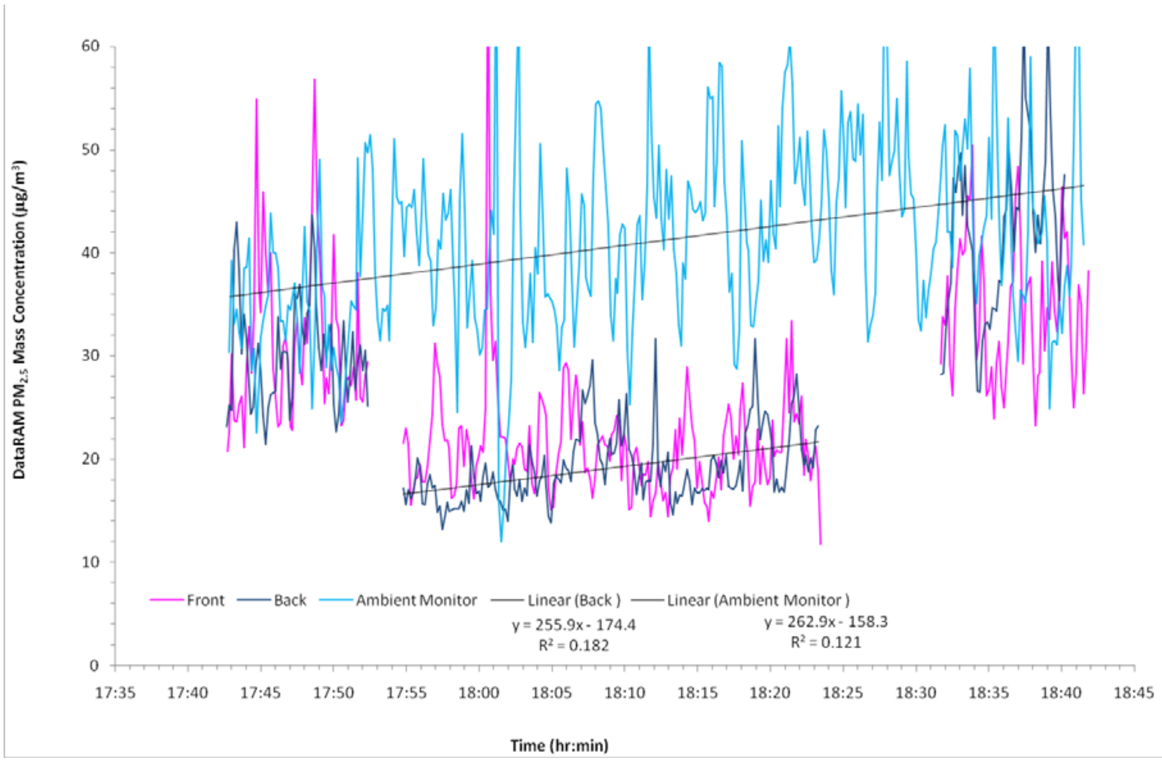

Figure 39: DataRAM results for DPF & CCVS run# 12F.

Figure 39 presents the results for DataRAM measurements for $PM_{2.5}$ mass concentration in which the DPF and the CCVS was installed on the bus. For this run it was observed that the pre- and post-run in-cabin concentrations as well as the ambient monitor concentrations were above the concentrations measured during the run. The ambient concentrations are not uniform, but show a "up-and-down" pattern with peaks and valleys between concentrations of 11 and approximately 60µg/m^3. There is an overall increase throughout the run in the background concentration as shown by the linear fit of the data depicted using the trend line shown in Figure 39. A similar trend is apparent with the peaks and values shown for the front in-cabin measurements and the back in-cabin measurements. It should be noted that the slopes for the linear regressions of the ambient monitor and the Back DataRAM with time are 263 and 256µg/m^3/min, respectively. These slopes are within 3% of each other. This shows that the changes in particulate concentrations within the bus are tracking the ambient values and appear to not be related to self pollution from the bus.

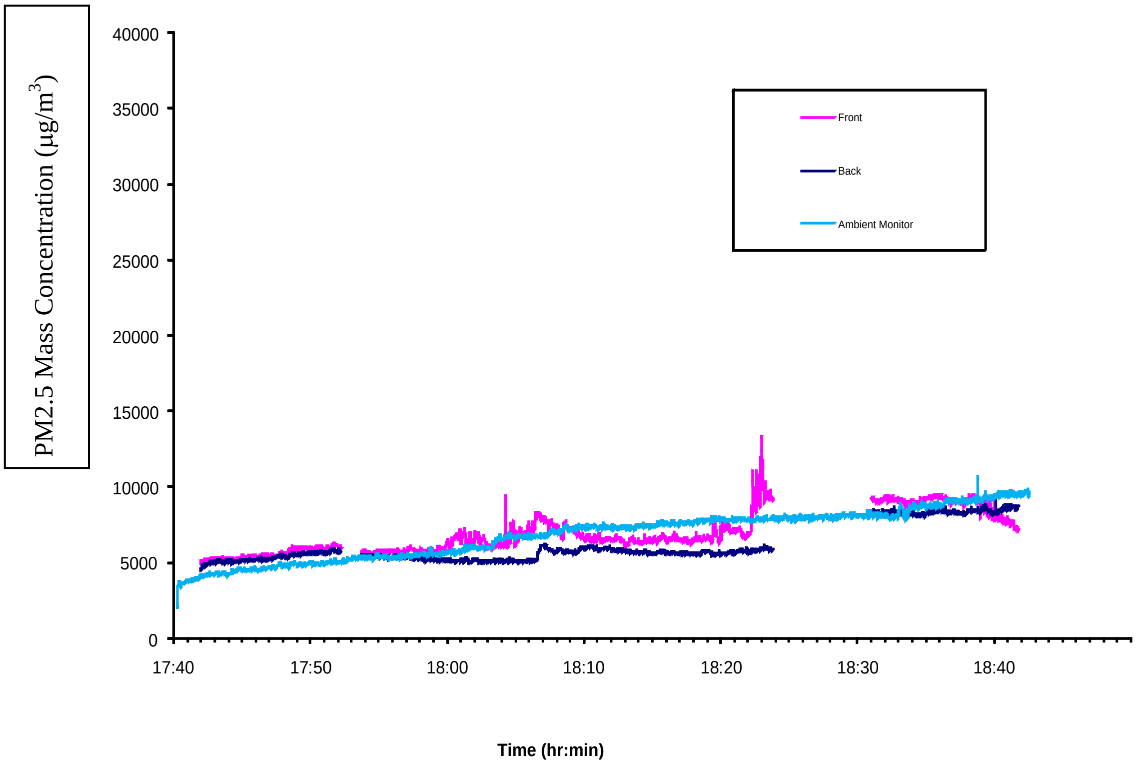

Figure 40: P-Trak results for DPF and CCVS run# 12F.

Figure 40 shows the results for the particle count concentration with both the DPF and CCVS retrofits installed on the bus. This is the same run as the shown in Figure 39. This condition of retrofits resulted in no increase of particle count and the in-cabin concentrations were lower than the ambient concentrations. The only noticable peaks obtained in the front of the bus were logged starting at 18:00, 18:04 and 18:23hrs. During the run there was an increase in the ambient particulate concentration from a value of about 6000 to 8000 pt#/cm^3. This trend continues into the post run in-cabin measurements that are about 2000 pt#/cm^3 higher than the pre-incabin measurements.
In both Figures 39 and 40 the ambient values during the run are higher than the measurements inside the cabin of the bus. This has been observed in other studies. In a recent study by McDonald-Buller et al.[33] the $PM_{2.5}$ values measured by a Dustrak had average values in the cabin of the bus being 38% lower than values measured outside of the bus. The sampling point for the ambient values was through tubing from the instrument located inside the bus through a sealed port in a window that terminated outside the bus. For the ultrafine measurements using PTrak's a similar result was obtained with the average outside value being 8% higher than the in-cabin values. In the EHHI study[24] the in-cabin average values for $PM_{2.5}$ were less than 24 hour average Connecticut background concentrations of approximately 12.5µg/m^3 for 7 of the 27 runs. Since the nephelometer is known to read from 1.3 to 3 times higher than a FRM method, then the actual ambient value recorded by a DataRAM would be significantly higher than the reported Connecticut state average. It is uncertain what is the cause of this negative difference between the background values and the values measured in the cabin of a school bus. A note was given in the Atlanta study[14] stating that the measured net

pollutant levels inside the bus cabin with respect to the ambient (the ambient value is based on the initial outdoor concentrations before the bus was turned) are sometimes below the outdoor levels. In another study it was found that the concentration inside a tunnel in which a DPF study was being conducted had values lower than the ambient. In this situation the diesel vehicles were presumed to be cleaning the air inside the tunnel.

During one episode of idling before Baseline run#3F, the front P-Trak measured an average in-cabin net particle count of 5773pt#/cm^3. The front DataRAM and back DataRAM measured in-cabin net particulate concentration values of 4.0μg/m^3 and 14.1μg/m^3, respectively. The maximum DataRAM values for the front and back were 16 and 43μg/m^3 for this period. These values are significantly higher than those obtained for the baseline runs showing that high concentrations of in-cabin particulate matter can be present when a bus is idling with only a door open.

6.4 Visual results of in-line filters for retrofit technologies

The following figures show the filters that were located on the sampling lines for the SEMTECH-D instrument which sampled the exhaust in the tailpipe of the bus. The function of these filters is to prevent (with 99.99% efficiency) particles greater than 0.1 microns from entering the analytical gas detection instrumentation. They were replaced after each retrofit configuration. These filters give a visual relative blackness intensity of the efficiency of the retrofit technology for these larger size particles. The following figures were taken after the final study tests. Each filter was used for three consecutive tests of each retrofit technology.

Figure 41: SEMTECH-D filter after use with three runs with no tailpipe retrofit for baseline condition.

Figure 41 shows the SEMTECH-D filter after being used with no tailpipe retrofit. In comparison Figure 42 shows the filter that was used during the tests with the DPF retrofit on the tailpipe. There is a distinctive difference in color and thus concentration of light—absorbing particulates exiting the tailpipe of the bus. It should be noted that the small amount of black that can be seen in Figure 42 was obtained in the removal of the filter from its housing.

Figure 42: SEMTECH-D filter after use with three runs using the DPF & CCVS retrofits configuration.

Figure 43: SEMTECH-D filter after three runs with the FTF and CCVS configuration.

Figure 43 shows the SEMTECH-D filter from the tests with FTF retrofit tailpipe technology. In this case the filter appears similar to the baseline condition since this FTF is rated to capture 50% of the particulate matter and it is not much different visually see this difference on the outside of a filter. This FTF device reduces PM by capturing larger particles by an impaction mechanism in a catalyzed wire mesh structure. Solid carbon soot and lube oil ash nanoparticle tend not to be captured and fly through. Release or blow-off of collected particles can occur at high flow rates. On the other hand the Level-3 DPF traps all solid particles large and small (in fact >99% of nanoparticles in the size range 20 to 300 nm) at all flow rates using a rugged ceramic filter. However, it should be noted that these visual demonstrations do not give information as to the size of the particles contributing to this discoloration, and in particular, it is not clear to what extent the discoloration reflects respirable size particles. The visual appearance of the filters used in the initial study were similar to the figures shown in this section.

6.5 Repeatability Measures

The quality control on the experiments performed was based on repeatability measures established by the Quality Assurance Project Plan (QAPP). An analysis of the data was done to assess the repeatability of the School Bus Cycle. For this analysis the cumulative gas concentrations, speed vs. time curves, and fuel consumption from the RCSBC-S results were quantified. The criteria stated in the QAPP for cumulative fuel consumption is that the variation for the runs should be below 10% and the variation for CO_2 emissions should be less than 8% for acceptance. A comparison of mean values as well as the coefficient of variation is given in this section. The coefficient of variation is a measure of the dispersion of a probability distribution and it is defined as the ratio of the standard deviation to the mean. This coefficient of variation is reported as a percentage.

The average fuel consumption for the eighteen runs was 2.1 gallons, with a standard deviation of 0.027 gallons, and with a variation coefficient of 1.28%. This value is well below the 10% acceptance established in the previous QAPP for fuel consumption. The CO_2 average result was 612g/bhp-hr for all the runs, with a standard deviation of 4.63g/bhp-hr and a variation coefficient of 0.76%. This is far below the criteria of less than 8% variation of CO_2 emissions. A visual depiction of these results is presented in Figure 44. In this figure it can be seen that all of the bars representing CO_2 emissions are essentially have identical vertical height.

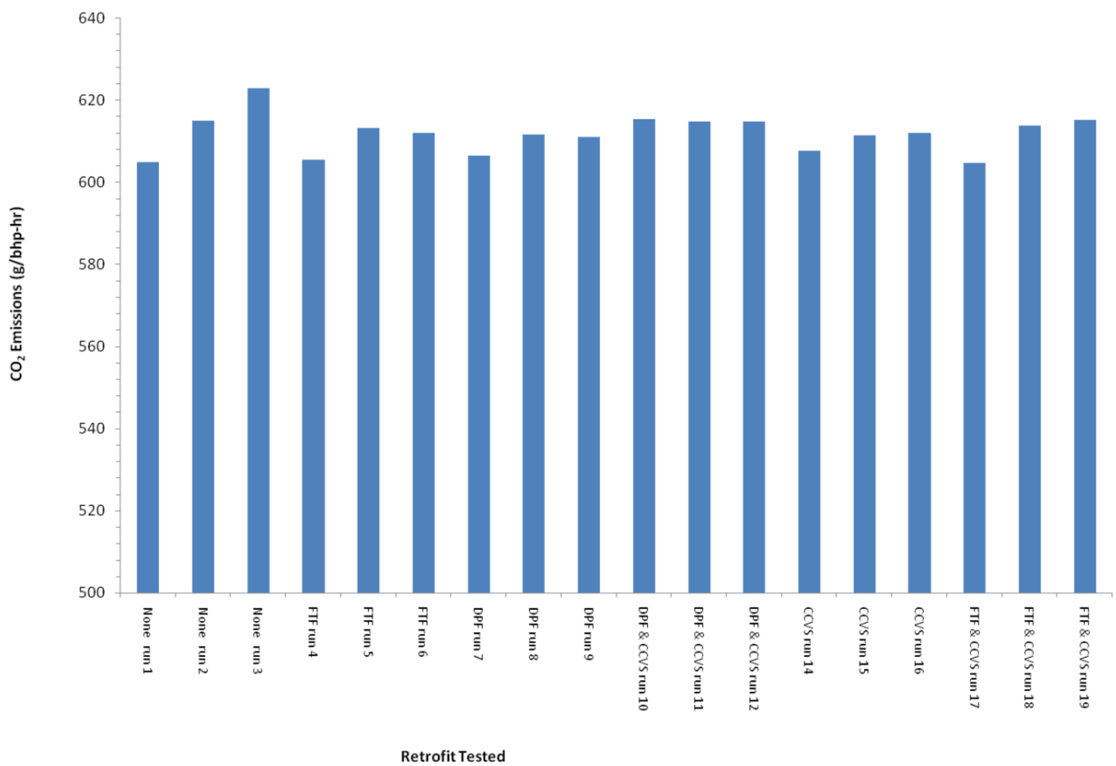

Figure 44: CO_2 emissions for all new runs.

Figure 44 shows the CO_2 emissions for all the new runs, the lowest value obtained was 604.7g/bhp-hr for run# 17F, and the highest was 623g/bhp-hr for run# 3F. From the figure it can be observed that the variability of emissions is minimal for all the runs and the bus cycle is repeatable. An analysis of variance was conducted for the CO_2 emissions resulting in a P-value of 0.68. Since this P-value for the F-test is greater than 0.05, then there is not a statistically significant difference between the means of the variables at the 95% confidence level.

Finally, the cycle repeatability (on a track with the same start and end location) can be indicated by the total distance traveled since the bus driver was following a speed vs. time curve while driving. The average distance for all the runs was 8.6 miles, with a standard deviation of 0.031 miles and with a variation coefficient of 0.36%. A comparison of the speed reported by the engine control module (ECM) and the cycle is shown in Figure 45.

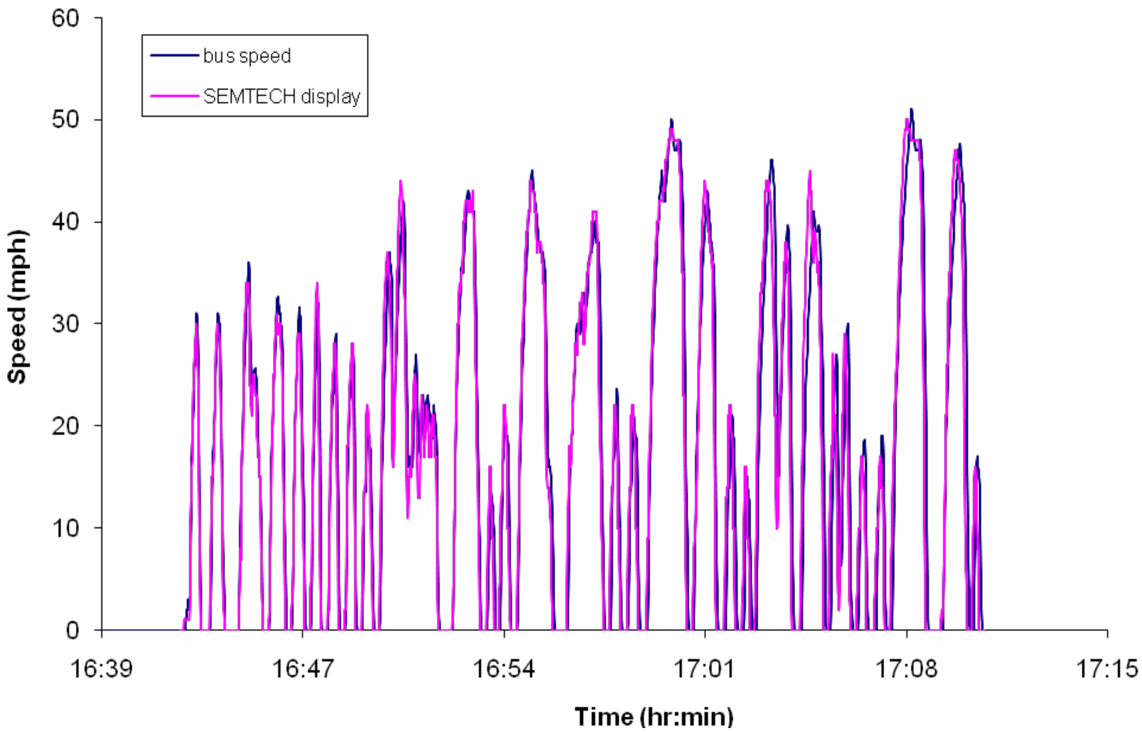

Figure 45: Bus Cycle comparison between the SEMTECH-D cycle display and the actual bus speed for run# 3F.

Figure 45 is a plot comparing the actual bus speed versus the speed designated in the cycle as a function of time. In this run the speed measured from the ECM during run# 3F is plotted together with the speed from the cycle that is displayed using the SEMTECH-D software during the run. This shows the ability of the driver to follow the cycle from a visual inspection. Because of the use of the isolated straight track, the runs were completed without any interfering traffic and only one designated driver was employed for all of the runs.

6.6 Particulate Matter Concentration Results – Bar Charts

The following results show the particulate matter concentration values measured inside the bus cabin during the run after subtracting the ambient concentration recorded by the monitoring instruments located on the table outside the bus at 300m away from the track during the same time interval as the runs. These net values are referred to as in-cabin net particulate concentrations and represent the concentrations that exceed ambient values. Two figures are presented for the DataRAM results. In Figure 46 only positive values are given, and in Figure 47 the same results are presented but showing negative net concentration values. Negative net concentration values are a result of the average ambient concentration having a higher value that the concentration measured in the cabin of the bus. In Figure 46, if the net value resulted in a negative value it was graphed as a value of zero and no bar appears on the chart.

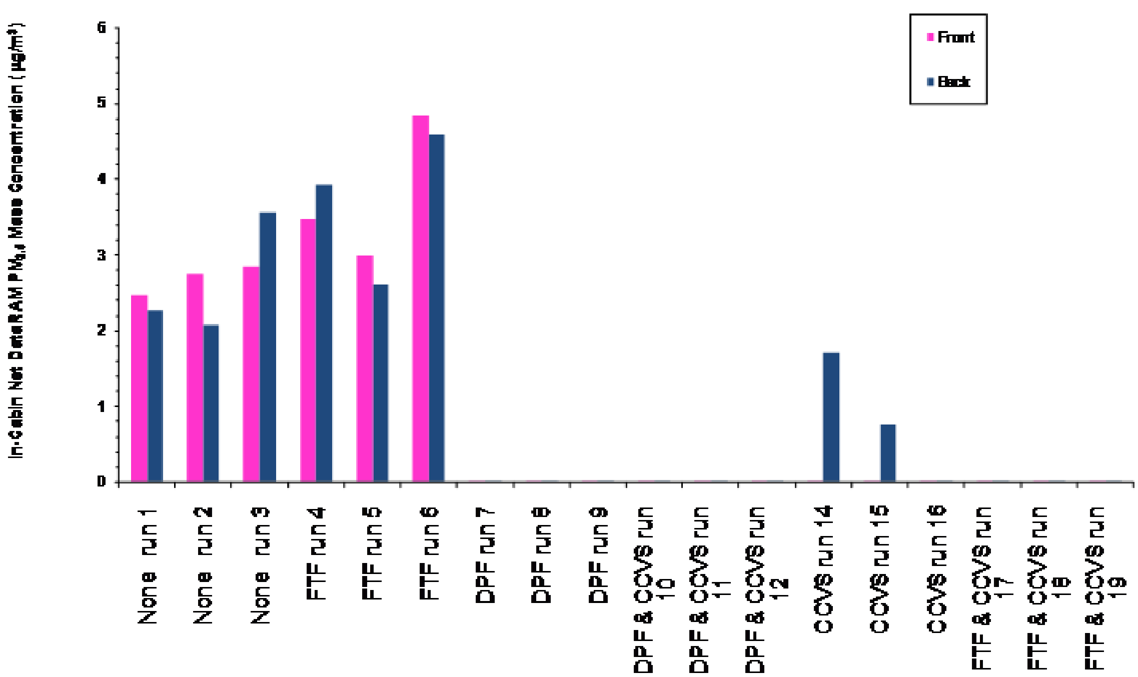

Figure 46: DataRAM results for new runs. Net values are shown with the ambient subtracted from table ambient monitor.

Figure 46 shows the DataRAM results with the ambient values subtracted. The results for the baseline runs, runs 1F to 3F, have values that are slightly lower than the values from the FTF, runs 4F to 6F. This difference is not significant since it is within the stated *precision* of the instrument at one second averaging of ± 1% of the reading or ± 1μg/m^3, whichever is greater. In addition the *accuracy* is reported as ± 2% of the reading ± the precision. The average of the three runs of the baseline was 2.7μg/m^3 for the front and back, and the average of the three runs of the FTF was 3.7μg/m^3 for the front and back. In the case of the baseline the real value would be 2.7μg/m^3 ± 1.05μg/m^3 including the precision and accuracy so that there is no significant difference between the results obtained between the baseline and the FTF technology for $PM_{2.5}$ reduction. The statistical analysis for analysis of variance gave a P-value for the F-test equal to 0.0457 indicating a statistically significant difference between the means of the net average values of the test conditions at the 95% confidence level. To determine which means were significantly different, a multiple range test was performed. This analysis shows that there is a significant difference between runs 7F – 19F and runs 1F – 6F as seen in Figure 47.

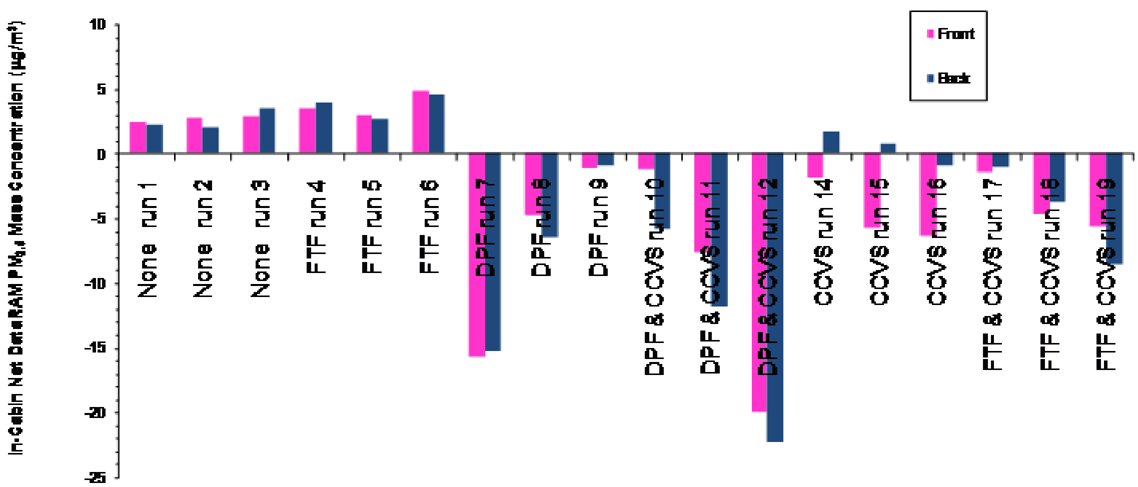

Figure 47: DataRAM net values with ambient subtracted showing the total reduction.

Figure 47 shows the DataRAM net values with negative results which again result from subtracting ambient values that are higher than the measured in-cabin values from the measurements. Since the values registered inside the cabin during runs 7F through 19F were lower than the ambient measurements, then the air in the cabin of the bus was cleaner than the air measured at the ambient monitoring station. These results indicate that there is a substantial improvement in the quality of the in-cabin air with the use of the DPF only and a tailpipe retrofit technology combined with the CCVS. Since this was not observed with the use of the FTF retrofit it can be concluded that there is a substantial decrease in particulate concentrations with the use of the crank case ventilation system.

The values shown in this study are comparable to several other studies. In the NRDC study the net diesel exhaust particulate matter ranged from 10% to 2.7 times higher than background levels. In the recent Texas study[33] the net $PM_{2.5}$ concentration values ranged from 6 to -19µg/m^3 measured by a DustTrak. They reported that the average value of the 3 runs using the crankcase filter and the Series 6000 DOC was -11µg/m^3, and using only the Donaldson Spiracle crankcase filter (CCVS) the average value was -5.3 µg/m^3 and the average of the baseline runs was -3 µg/m^3. This is similar to the pattern of results obtained in this study. In the CATF study[9] DustTrak values of $PM_{2.5}$ for Bus 56 (this bus was extensively tested in the CATF study and it represents a typical result) are shown in Table 15. The average values for the ambient and the in-cabin mean are shown for each run. The difference between the ambient and the in-cabin mean is shown in the fourth column. From this table it can be seen that four of the runs with bus 56 have net values less than or equal to zero. It is interesting to note that once again negative net values were obtained for the DPF-Spiracle crankcase filter and the Spiracle crankcase filter runs. Additionally Kittelson[58] has measured on-road exhaust plume concentrations less than the ambient for exhaust temperature less than 250˚C when a Johnson Matthey CRT or CCRT was used.

Table 15: $PM_{2.5}$ TSI DustTrak Results for Ann Arbor, MI Bus 56 CATF study[9]

Retrofit	Ambient (µg/m^3)	In-cabin Mean (µg/m^3)	Net (µg/m^3)
Baseline run1	12	50	38
Baseline run2	21	47	26
ULSD run1	40	76	36
DOC run 1	13	52	39
DOC Run 2	17	65	48
DOC-CCVS run 1	16	22	6
DOC-CCVS run 2	25	25	0
CCVS-ULSD Run 1	43	36	-7
DPF-USLD Run 1	33	45	12
DPF-USLD Run 2	22	47	25
DPF-ULSD-CCVS Run 1	50	43	-7
DPF-ULSD-CCVS Run 2	45	31	-14
DPF-ULSD-Enviroguard Run 1	11	32	21

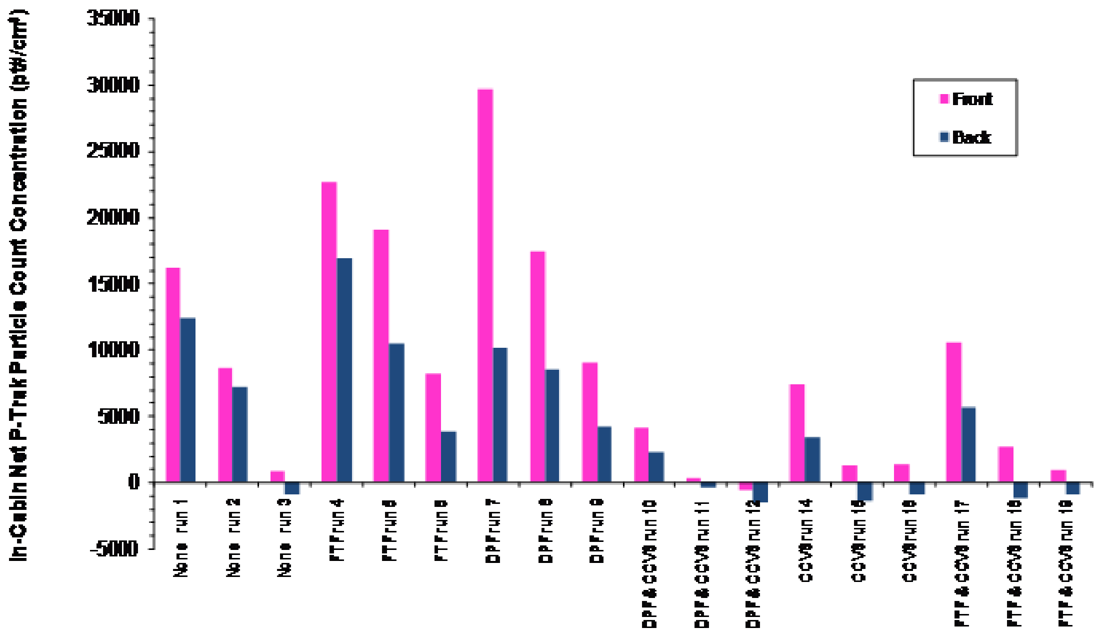

Figure 48: P-Trak net concentration results with ambient subtracted using the ambient monitor outside the bus.

Figure 48 shows the net in-cabin values for particle count measurements from the P-Trak instruments. The particle concentrations for the baseline, FTF and DPF (runs 1F-9F) show relatively high particle counts. The runs which employed the CCVS (runs 10F-19F) show much lower values than those without the CCVS. The lowest values were obtained by using a tailpipe retrofit together with the CCVS. The difference in the values using a retrofit technologies combined with a CCVS compared and not using a CCVS is evidence that ultra fine particles are coming from the crankcase. Another visible trend in each data set is the decreasing particle count with each run in a retrofit technology series. Each set of retrofit conditions was done on a single day starting with the lowest run number of the series and ending at the highest run number of the series. This trend is related to the engine oil temperature and is discussed in a later section.

The results obtained in this study can be compared with the results of ultrafine particle concentrations measured by the P-Trak (particle size of 0.02 to greater than 1μm) of a multi-city investigation on retrofit technologies performed by the Clean Air Task Force (CATF).[9] In that study, particle concentrations inside the cabin of a school bus were measured as it was driven on an actual bus routes. To determine the ambient particulate concentrations a lead car was used to measure ambient particulate concentrations as it was driven in front of the bus. The run times of the CATF study varied from 50 to 80 minutes. The CATF study used conventional diesel fuel for 7 of the 13 tests shown in Table 16. ULSD fuel was used for all DPF retrofits, a CCVS run and a baseline study.

Table 16: Ultrafine TSI P-Trak In-Cabin Results for Ann Arbor, MI Bus 56.

Retrofit	P-Trak Ambient (pt#/cm^3)	P-Trak Mean (pt#/cm^3)	P-Trak Net (pt#/cm^3)
Baseline run1	14,000	50,724	36,724
Baseline run2	11,000	28,145	17,145
ULSD run1	10,000	53,040	43,040
DOC run 1	18,000	38,091	20,091
DOC Run 2	22,000	40,782	18,782
DOC-CCVS run 1	22,000	30,969	8,969
DOC-CCVS run 2	21,000	38,139	17,139
CCVS-ULSD Run 1	9,000	26,927	17,927
DPF-USLD Run 1	11,000	15,445	4,445
DPF-USLD Run 2	5,000	9,859	4,859
DPF-ULSD-CCVS Run 1	9,000	13,029	4,029
DPF-ULSD-CCVS Run 2	11,000	9,823	-1,177
DPF-ULSD-Enviroguard Run 1	11,000	18,810	7,810

The average net particle number concentration (in-cabin value with ambient concentration subtracted) again shows the lowest particle numbers for the combined DPF and crankcase retrofit technology having values for bus 56 between -1177 to 4,029. The next lowest particle count is the DPF retrofit. The values obtained for the DPF-ULSD-CCVS in the CATF study are comparable to the final runs (ranging from -1,509pt#/cm^3 to 4,078pt#/cm^3 with ambient subtracted) with an average value for the CATF study of 1,426 pt#/cm^3 with ambient subtracted. The average value obtained for the final base line runs with ambient subtracted of 7,409pt#/cm^3 is much lower than the CATF baseline run using ULSD with ambient subtracted of 43,040 pt#/cm^3. This CATF value for ULSD is comparable to the value for the "low" sulfur fuel baseline runs 1 and 2 of the CATF and could have resulted from a sulfur contamination of low sulfur fuel with ULSD. The values obtained with the DPF retrofit range from -3,619 to 5,868 pt#/cm^3 for buses 56 and 128 with an average of 3,069 pt#/cm^3 were obtained. These values are lower than the values in the present final study using the DPF, which ranged from 4198 to 29797pt#/cm^3.

Hammond[31] measured in-cabin particulate matter concentrations in school buses using a P-Trak (TSI model 8525). They reported average values for a 2004 school bus of 16,999 pt#/cm^3 and for an older non retrofitted 1996 school bus obtained values of 71,599 pt#/cm^3. These values are raw data and do not have the ambient background values subtracted. A second study by Hammond[32] for conventional transit buses reported values ranging from 20,000 to 450,000 pt#/cm^3 without any diesel emission control device . The average in-vehicle particle number concentration using a diesel oxidation-catalyst was much lower at a value of 9,954 pt#/cm^3. This illustrates the effectiveness of using exhaust emission control technology.

6.7 Particulate Matter Concentration Results – Tabular

Table 17 shows the results obtained by the DataRAM instruments for $PM_{2.5}$ mass concentration. The results are given with the ambient concentration subtracted for each run; any negative value indicates that the in-cabin measurements were lower than the ambient. The lowest values in particulate matter concentration were obtained for both the DPF and the CCVS. All the runs were made with the windows closed.

Table 17: New set of runs net values DataRAM results with ambient monitor subtracted and particle sizes during the new runs.

Run #	Retrofit	Front Run	Front Ambient Monitor Subtracted	Back Run	Back Ambient Monitor Subtracted	Ambient Monitor $PM_{2.5}$
		Average $PM_{2.5}$ Mass Concentration ($\mu g/m^3$)	Average $PM_{2.5}$ Mass Concentration ($\mu g/m^3$)	Average $PM_{2.5}$ Mass Concentration ($\mu g/m^3$)	Average $PM_{2.5}$ Mass Concentration ($\mu g/m^3$)	Average $PM_{2.5}$ Mass Concentration ($\mu g/m^3$)
1F	None	6.4	2.5	6.2	2.3	4.0[1]
2F	None	6.9	2.8	6.2	2.1	4.1[1]
3F	None	7.6	2.8	8.3	3.6	4.8
4F	FTF	15.4	3.5	15.9	3.9	11.9
5F	FTF	17.6	3.0	17.2	2.6	14.6[1]
6F	FTF	19.1	4.8	18.9	4.6	14.3[1]
7F	DPF	20.0	-15.7	20.5	-15.2	35.7
8F	DPF	17.1	-4.8	15.4	-6.5	21.9
9F	DPF	15.3	-1.1	15.6	-0.9	16.5
10F	DPF & CCVS	22.5	-1.2	17.9	-5.8	23.7
11F	DPF & CCVS	14.7	-7.6	10.5	-11.8	22.3
12F	DPF & CCVS	21.3	-20.0	19.1	-22.2	41.3
14F	CCVS	11.2	-1.9	14.8	1.7	13.1
15F	CCVS	13.8	-5.7	20.3	0.8	19.5
16F	CCVS	18.8	-6.4	24.3	-0.9	25.2
17F	FTF & CCVS	18.7	-1.4	19.1	-1.0	20.1
18F	FTF & CCVS	13.9	-4.7	14.8	-3.7	18.6
19F	FTF & CCVS	20.4	-5.6	17.4	-8.6	26.0

[1] Incomplete ambient from table monitor station

A summary of the results shows that the baseline (no retrofit) $PM_{2.5}$ mass concentration with ambient concentration subtracted had an average of the three runs of 2.6μg/m^3 for the back of the bus and 2.7μg/m^3 for the front. For the runs using only the CCVS with no tailpipe retrofit there was an average value of 0.5μg/m^3 for the back and -4.7μg/m^3 for the front. The use of the FTF in combination with the CCVS gave values of -3.9μg/m^3 for the front and -4.4μg/m^3 for the back. Finally the use of a DPF combined with a CCVS gave values of -9.6μg/m^3 for the front and -13.3μg/m^3 for the back. From this data it can be seen that the use of retrofit devices resulted in the lowest $PM_{2.5}$ concentration and thus the highest particulate removal efficiency. Another observation from this data is the particulate matter concentration was found to be higher at the front of the bus for all the different conditions tested. This result is different from that of most previous school bus studies.

Table 18 presents the net values results for particle count concentration in which the ambient monitor value was subtracted from the raw in-cabin values.

Table 18: Results for new set of runs P-Trak values of particle count concentration with ambient subtracted using the ambient monitor instrument.

Run #	Retrofit	Front Run	Front Ambient Monitor Subtracted	Back Run	Back Ambient Monitor Subtracted	Ambient Monitor
		Average Particle Count Concentration (pt#/cm^3)	Average Particle Count Concentration (pt#/cm^3)	Average Particle Count Concentration (pt#/cm^3)	Average Particle Count Concentration (pt#/cm^3)	Average Particle Count Concentration (pt#/cm^3)
1F	None	28318	16272	24461	12415	12046
2F	None	20717	8636	19260	7179	12082
3F	None	16208	884	14394	-930	15324
4F	FTF	28853	22718	23098	16963	6136
5F	FTF	25380	19118	16716	10454	6261
6F	FTF	17338	8223	12935	3821	9115
7F	DPF	48057	29797	28449	10189	18260
8F	DPF	25002	17483	16092	8574	7518
9F	DPF	15351	9012	10537	4198	6338
10F	DPF & CCVS	14006	4078	12173	2245	9928
11F	DPF & CCVS	4745	294	4091	-359	4450
12F	DPF & CCVS	6784	-555	5830	-1509	7339
14F	CCVS	20220	7359	16295	3434	12861
15F	CCVS	15812	1221	13165	-1426	14591
16F	CCVS	14871	1317	12666	-888	13554
17F	FTF & CCVS	33338	10629	28424	5715	22709

Table 18: Results for new set of runs P-Trak values of particle count concentration with ambient subtracted using the ambient monitor instrument.

Run #	Retrofit	Front Run	Front Ambient Monitor Subtracted	Back Run	Back Ambient Monitor Subtracted	Ambient Monitor
		Average Particle Count Concentration (pt#/cm^3)	Average Particle Count Concentration (pt#/cm^3)	Average Particle Count Concentration (pt#/cm^3)	Average Particle Count Concentration (pt#/cm^3)	Average Particle Count Concentration (pt#/cm^3)
18F	FTF & CCVS	20453	2741	16537	-1175	17712
19F	FTF & CCVS	13671	961	11813	-896	12709

Table 18 shows the results of ultrafine particle count averages from each condition tested. These results are given with the ambient measurement subtracted from the average value for each run. Negative values indicate that the in-cabin particle number concentrations were lower than the ambient. The average particle number concentrations for the baseline front and back together from the three runs was 7409pt#/cm^3. The average from the CCVS runs was 1836pt#/cm^3. The average from the FTF with CCVS runs was 2996pt#/cm^3, and the average of the DPF with CCVS runs was 699pt#/cm^3.

6.8 Exhaust gas pollutant emissions

The results obtained for the exhaust gas pollutant emissions measured by the SEMTECH-D gas analyzer are presented in Figure 49. This figure shows the values obtained for each technology configuration.

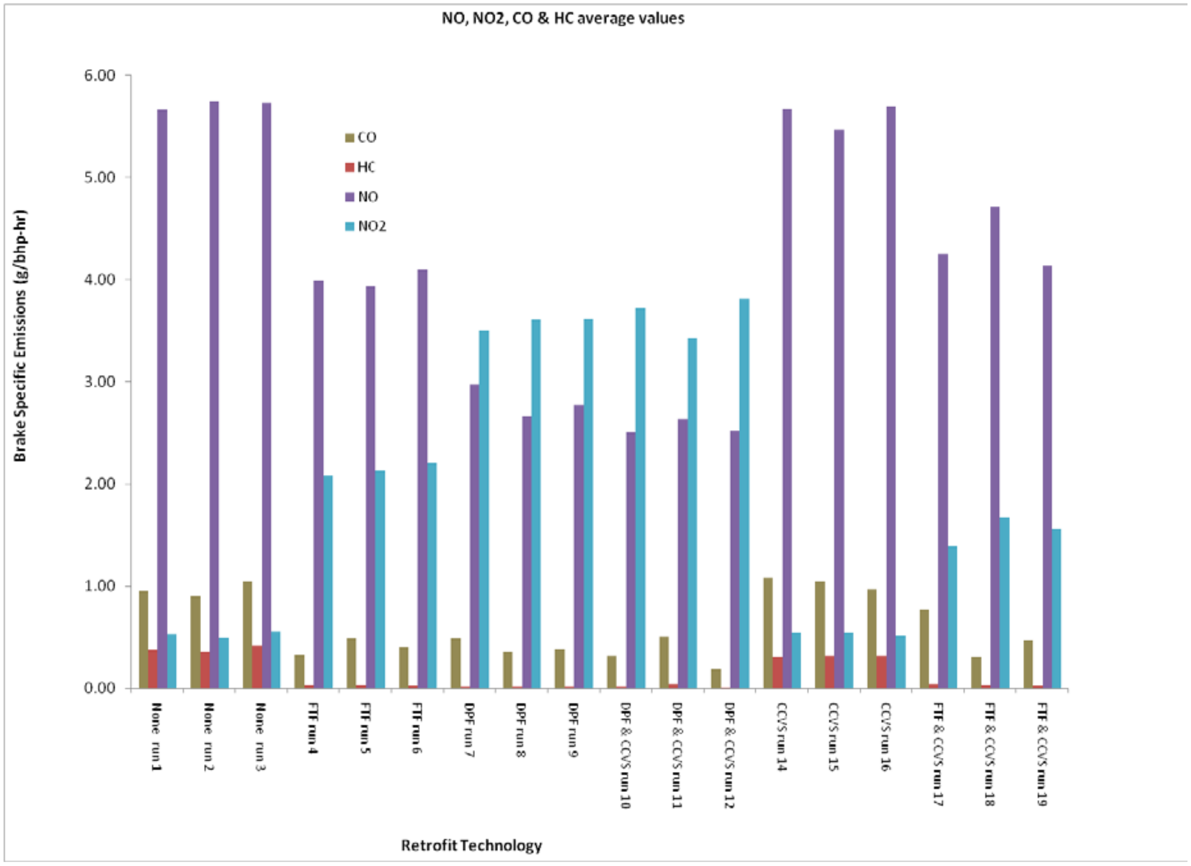

Figure 49: Gas emissions results for new set of runs with average NO, NO_2, CO, and HC values. Note: the NOx values for all the technologies resulted in a 4% coefficient of variation.

Figure 49 shows the results for NO, NO_2, CO, and HC emissions. From this plot it can be seen that the NO_2 mass emission values increase when using a tailpipe retrofit. This was expected since the catalyzed tailpipe retrofits increase the NO_2 emissions as part of their operation. The DPF produces NO_2 in the first chamber of the system to later be used in the second chamber in the oxidation process of trapped PM.

The CO and HC values are shown in brown and red respectively. This graph illustrates that the values of CO and HC have been reduced when using the tailpipe retrofit technologies compared to the baseline and the CCVS runs. The coefficient of variation for CO_2 results for all runs was only 1%; and for the NO_x values for all runs was 4%. These small numbers show that the different technologies do not affect the CO_2 and NO_x emission results.

The following table summarizes the average gas emissions results for each configuration from the final study.

Table 19: Mean values for gas emission results for the combination of retrofit technologies. Results from the final study.

Average values	HC (g/bhp-hr)	CO (g/bhp-hr)	NO (g/bhp-hr)	NO_2 (g/bhp-hr)
Baseline	0.38	0.97	5.7	0.53
FTF	0.03	0.40	4.01	2.14
DPF	0.01	0.41	2.81	3.57
DPF - CCVS	0.02	0.34	2.55	3.66
CCVS	0.31	1.03	5.62	0.53
FTF - CCVS	0.03	0.52	4.37	1.54

7. DISCUSSION AND CONCLUSIONS

Conclusions from Initial Study – These results contain higher concentrations of PM because of the additional leaks in the front and back of the bus. In addition the $PM_{2.5}$ results may have resulted from a mixture of diesel exhaust and extraneous particulate matter from the track and other nearby sources. Based on this uncertainty a second study was conducted which is designated in this report as the final study of Runs 1F – 19F.

An analysis of variance for the school bus runs was conducted to determine statistical difference among technologies. The ANOVA statistical tool, a technique that subdivides the total variation in a set of data into meaningful component parts that can be associated with specific sources of variation; allowing to test a hypothesis on the parameters of the model or to estimate variance components, decomposes the variance of the data into two components: a between-group component and a within-group component. The resulting F-ratio is a measure of the between-group estimate to the within-group estimate. When the P-value of the F-test is less than 0.05, there is a statistically significant difference between the mean values of the group variables at the 95.0% confidence level. To determine which mean values are significantly different from other mean values, a Multiple Range Test was applied. This analysis was conducted to examine the gaseous emissions, particle size measurements from the DataRAM, and the particulate concentration measurements from the P-Traks. The data presented in this discussion section has been analyzed under the hypothesis that it corresponds to a normal distribution in order to satisfy the use of ANOVA. A Variance Check (One-Way ANOVA) check was also performed for this data. This variance check has the results of four statistical tests: Cochran's C test, Bartlett's test, Levene's test, and Hartley's test. These tests confirm the assumption that the variance of the factor levels is equal. If the significance levels are greater than 0.05, then the hypothesis is not rejected and the variances are not significantly different.

When the results were not normally distributed, a nonparametric statistical analysis was performed to determine if there was a statistically significant difference between the retrofit technologies in the in-cabin net $PM_{2.5}$ concentrations, ultrafine particle count concentrations and/or gaseous emissions. The nonparametric tests performed were the Kruskal-Wallis non-parametric ANOVA, and the Mann-Whitney (Wilcoxon) W test to compare medians.

7.1 Effect of Retrofit Technology on Gaseous Emissions

An analysis of variance was conducted examining the effect of each retrofit technology on the emissions on CO_2, CO, and HC. The CO_2 values were shown in Figure 44 and the CO and HC results were shown previously in a bar chart shown in Figure 49. All of these values were obtained from the SEMTECH D gas analyzers.

7.1.2 CO_2 Results

The ANOVA test for the CO_2 emissions in (g/bhp-hr) from all the runs obtained a P-value of 0.68 which was expected and indicates that there is no statistical significant difference between the means of the variables at the 95% confidence level. This result was expected since none of the retrofit technologies reduce CO_2. In addition, the increased load on the engine through the use of tailpipe or crankcase retrofits was not expected to result in higher values of CO_2 given in mass emission per unit of energy consumed (g/bhp-hr). As mentioned previously the similar values of CO_2 for each run shows that the runs were performed in a repeatable manner.

7.1.3 CO Results

The ANOVA test for the CO emissions in (g/bhp-hr) from all the runs obtained a P-value of less than 0.05 indicating that there is a statistically significant difference between the means of the variables at the 95% confidence level. A multiple range test was performed showing that there is no statistical difference between the values of the baseline runs and the CCVS alone, but there is a statistically significant difference between the results from the DPF alone, DPF with CCVS, FTF alone, and FTF with CCVS compared to the baseline runs. These results indicate that the use of a tailpipe retrofit with either a DPF or FTF significantly reduces the CO emissions compared to a bus without these retrofits. The values from the DPF and FTF (either alone or with CCVS) showed no statistical difference between them. The box and whisker plot shown in the Figure 50 shows the average value inside the box as a black positive + sign, and the median value as a vertical blue line. The length of the box represents the maximum and minimum values from the distribution. As shown in Figure 50 the CCVS and baseline tests belong to one group while the other technologies configuration obtained similar results for CO.

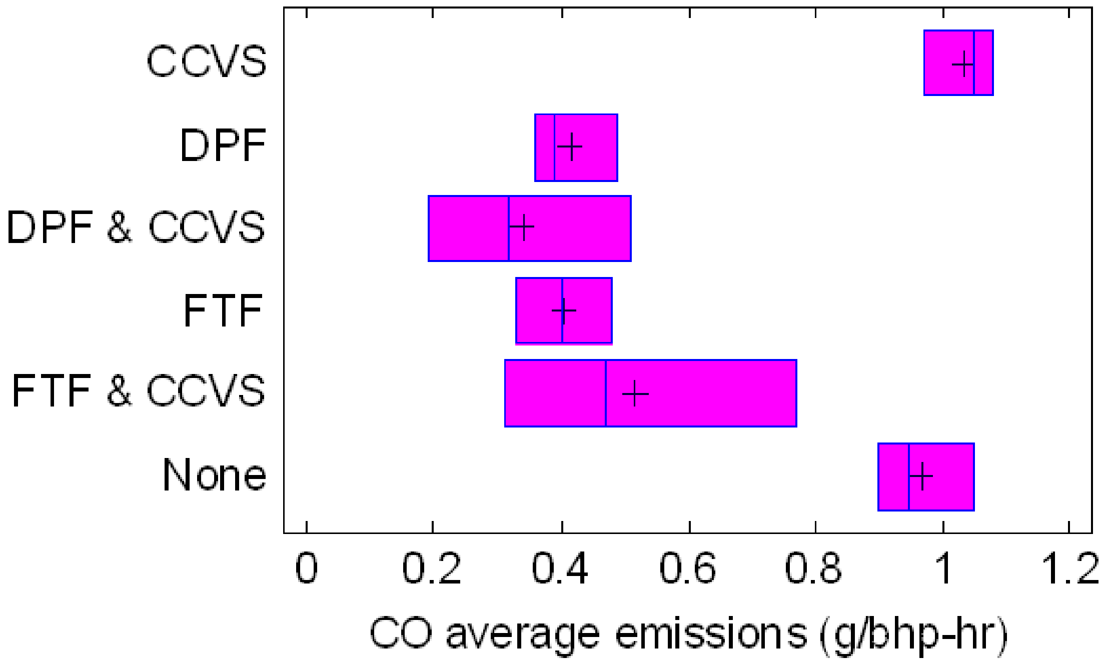

Figure 50: Box and whisker plot of average CO emissions per retrofit technology.

Figure 50 shows the Box and Whisker plot for the average CO emissions for test condition. This type of graphical summary identifies the presence of outliers in data for one or two variables. This plot divides the data into four equal areas of frequency. A box encloses the middle 50 percent, where the median is represented as a vertical line inside the box. The mean may be plotted as a point or a cross. Horizontal lines, called whiskers, extend from each end of the box. The lower (left) whisker is drawn from the lower quartile to the smallest point within 1.5 interquartile ranges from the lower quartile. The other whisker is drawn from the upper quartile to the largest point within 1.5 interquartile ranges from the upper quartile. Values that fall beyond the whiskers, but within 3 interquartile ranges (suspect outliers), are plotted as individual points. Far outside points (outliers) are distinguished by a special character. Outliers are points more than 3 interquartile ranges below the lower quartile or above the upper quartile. In this case there is no outlier from the analysis for Figure 50.

As presented in Table 20, the DPF technology obtained a reduction compared to the baseline of 57% in CO; the DPF combined with the CCVS gave a reduction of 65% compared to the baseline, the FTF gave a reduction of 58%, the FTF with CCVS reduced CO in 46%. There was no significant difference in CO emissions in using the CCVS compared to the baseline. This observation with the CCVS suggests it may be important. Since the CCVS separates by coalescing large entrained predominantly lube-oil particles from blow-by gases and routing the blow-by gas containing remaining small particles back to the combustion chamber, then there is a possibility that these small particles are not completely burned in the combustion chamber result in high CCVS solid particle emissions found in the initial study. From the results of the final study a significant increase in CO is not observed.

Table 20: Gaseous emissions reductions compared to baseline.

Gas	CCVS % Reduction	DPF % Reduction	DPF & CCVS % Reduction	FTF % Reduction	FTF & CCVS % Reduction
CO	NSSD	57	65	58	46
HC	18	97	95	92	92
NSSD: No statistical significant difference at 95% confidence level.					

<u>7.1.4 HC Emissions</u>

A normality test in the HC data resulted in a normal distribution with a standard skewness of 1.45 and a standard kurtosis value of -1.14, which is in the range of ±2 for normal distribution. The variance check test the null hypothesis that the standard deviations of the HC values within each of the levels (retrofit combination) is the same. Since the smallest of the P-values obtained in the variance check was less than 0.05, there is a statistically significant difference amongst the standard deviations; this violates one of the important assumptions underlying the analysis of variance. The nonparametric test of Kruskal-Wallis was performed resulting in a P-value of 0.018 indicating that there is a statistically significant difference amongst the medians at the 95% confidence level. A Mann-Whitney (Wilcoxon) W test was performed to compare the medians between different retrofit technologies, however this test resulted in no difference between any retrofit. Since the Kruskal-Wallis test obtained a statistical difference, which can be observed in the box and whisker plot of Figure 51, it was decided to perform an ANOVA test with the caveat that the variance check resulted in a statistical difference amongst the standard deviations.

The ANOVA test for the HC emissions in (g/bhp-hr) from all the runs obtained a P-value of less than 0.05 indicating that there is a statistically significant difference between the means of the variables at the 95% confidence level. A multiple range test was performed resulting in three groups with statistical differences as shown in Figure 51. The first group includes 4 retrofit technology combinations: DPF, DPF combined with CCVS, FTF, and FTF combined with CCVS. Four of these technologies show no statistically significant difference between them, but are significantly different from the baseline and CCVS alone. In Figure 51, a second group which corresponds to the CCVS alone is also shown which was distinct from the third group which consisted of the baseline runs with no retrofit technologies.

These results show that all the runs performed with a tailpipe retrofit of either a FTF or DPF gave significant reductions in HC emissions compared to the baseline. This was expected since, both the FTF and the DPF oxidize hydrocarbons. The FTF is a CARB PM verified Level-2 technology, but not a USEPA verified technology, and the hydrocarbon reduction is not reported as a certified technology. The DPF is an USEPA certified JMI retrofit and is rated at HC reduction of 95%[59]. It was also interesting to note that the CCVS alone also resulted in a significant, but small reduction of 18% compared to the baseline. This result is counter-intuitive, since the CCVS captures emissions from the crankcase and then sends the blow-by gas emissions back into the inlet combustion air for combustion in the cylinders. There is a possibility that this recycled gas acts to increase the engine cylinder combustion temperature by a small amount and decreases hydrocarbon emissions. Another possibility that is given in the next section is that this decrease in hydrocarbon emissions was related to a slightly higher engine oil temperature for the CCVS runs compared to the baseline. The average oil temperature for the baseline and CCVS runs was 203.5 and 204.3°F, respectively.

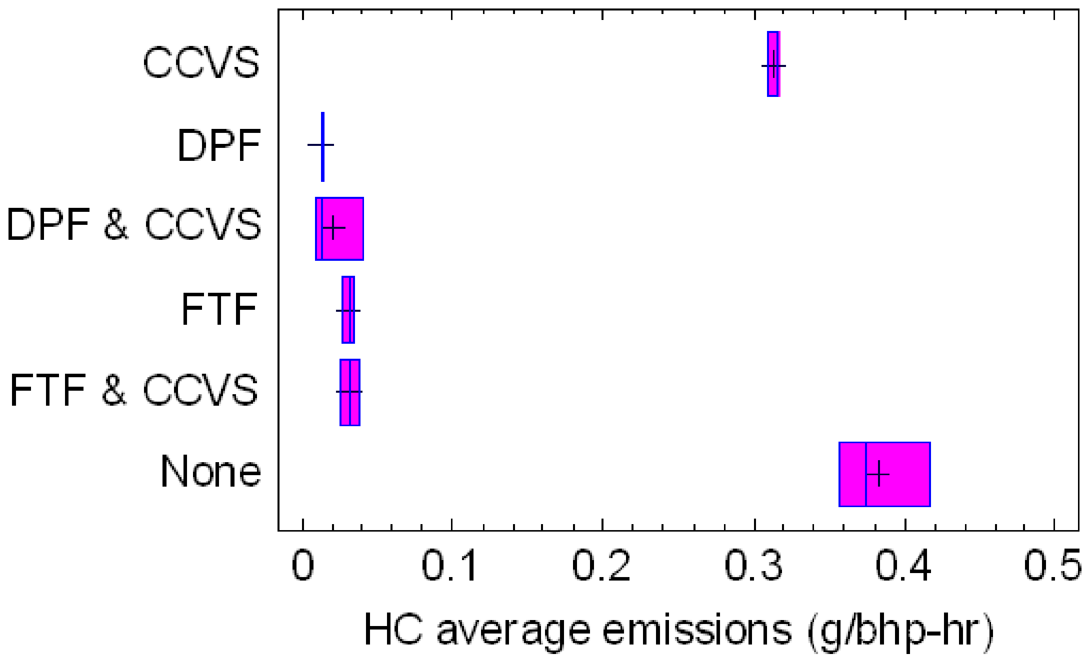

Figure 51: Box and whisker plot for average HC emissions per retrofit configuration.

As shown in Table 20, the DPF alone provided a reduction in HC of 97% compared to the baseline, the DPF combined with CCVS gave a 95% reduction, the FTF alone gave a 92% reduction in HC, the FTF with CCVS produced a 92% reduction compared to the baseline runs. These results in addition to the agreement between experimental values within each technology set gives further evidence of the repeatability of each of these runs. This reduction in hydrocarbon emissions is an additional health benefit of using these retrofit technologies since hydrocarbon vapors contribute to the formation of smog as well as contain toxic materials.

7.1.5 NO and NO2 emissions

The results from the NO and NO_2 emissions for each retrofit combination and the percent change is presented in Table 28. The increase in NO_2 emissions resulted from the use of the catalyzed tailpipe retrofits. The percent change in NOx for all technologies was less than approximately 5%.

Table 21: NO and NO_2 mean values and percent change for each retrofit combination.

Average values	NO (g/bhp-hr)	NO % change with baseline	NO_2 (g/bhp-hr)	NO_2 % change with baseline	NOx (g/bhp-hr)	NO_X % change with baseline
Baseline	5.7	0	0.53	0	6.2	0
FTF	4.01	-30	2.14	307	6.15	-1.5
DPF	2.81	-51	3.57	579	6.38	2.2
DPF - CCVS	2.55	-55	3.66	595	6.21	0.56
CCVS	5.62	-2	0.53	2	6.15	-1.5
FTF - CCVS	4.37	-24	1.54	193	5.91	-5.3

7.2 Effect of Retrofit Technology on In-Cabin Particle Size

The DataRAM 4 instruments record the average median volume particle diameters from a Lorenz-Mie calculation from the data obtained from the two light sources with different wavelengths of the DataRAM nephelometer. The values of the average median volume particle diameters for each run are shown in Figure 52. From this figure it can be seen that there is a distinct difference between the particle sizes measured in the cabin of the bus during a run and the ambient monitor values. Secondly, there is a difference between the baseline particle sizes having values between 0.44 and 0.72 μm and all retrofit technologies having particle sizes less than about 0.4 μm.

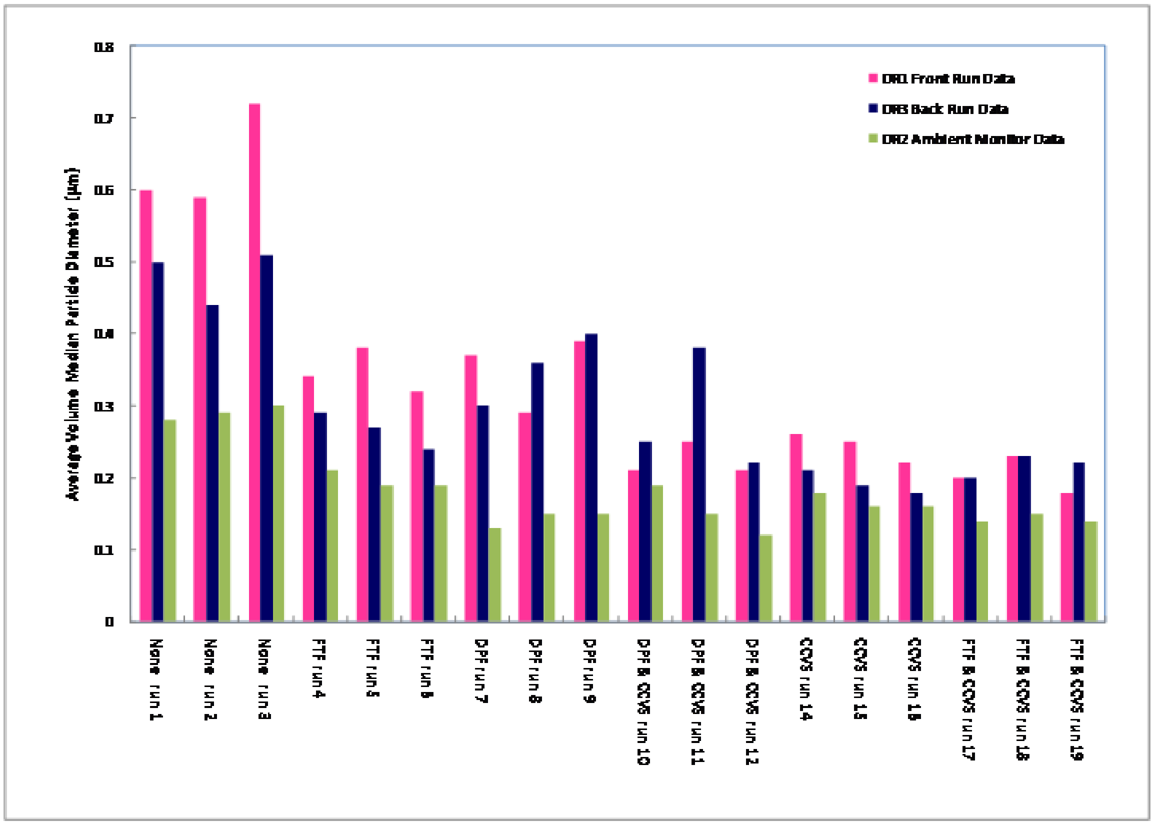

Figure 52: Comparison of average volume median particle diameters with retrofit technologies and ambient measurements.

The results for the back of the bus were normally distributed, there was independence of the data points, and the variances were equal; these results allow the use of ANOVA for the back of the bus volume median particle diameter values. The results for the front of the bus were not normally distributed and nonparametric tests were performed. The Kruskal-Wallis test for the front of the bus values obtained a P-value of 0.0097 which indicates a statistically significant difference amongst the medians at the 95.0% confidence level. A Mann-Whitney (Wilcoxon) W test was performed to compare the medians between different retrofit technologies, however this test resulted in no difference between any retrofit. Since the Kruskal-Wallis test obtained a statistical difference, it was decided to perform an ANOVA test with the caveat that the front values were not normally distributed.

An ANOVA was performed on this data using the averaged values calculated from instantaneous measurements for each run which are shown in Figure 52. From this analysis it was determined that there is a statistically significant difference in particle size for the various retrofit conditions. When using a CCVS retrofit alone or with the FTF or DPF, there was a significant difference from all other conditions. In addition there is a significant difference between using either the DPF or FTF without the CCVS compared to the baseline and CCVS combination retrofits.

Figure 55, shows the particle size data for the front sampling location. It can be seen that the baseline condition (crankcase vent open under the bus) results in the largest average particle size of ±0.64µm compared to all other conditions at the 95% confidence level. When using the DPF or FTF (crankcase vent open under the bus) the average particle size is approximately ±0.35 µm which is significantly larger than when the FTF or DPF is combined with the CCVS. The particle size for the CCVS combined with either the FTF or DPF is approximately 0.22 µm. This analysis gives evidence that in-cabin larger particles come from the crankcase and this appears to be the main source of $PM_{2.5}$.

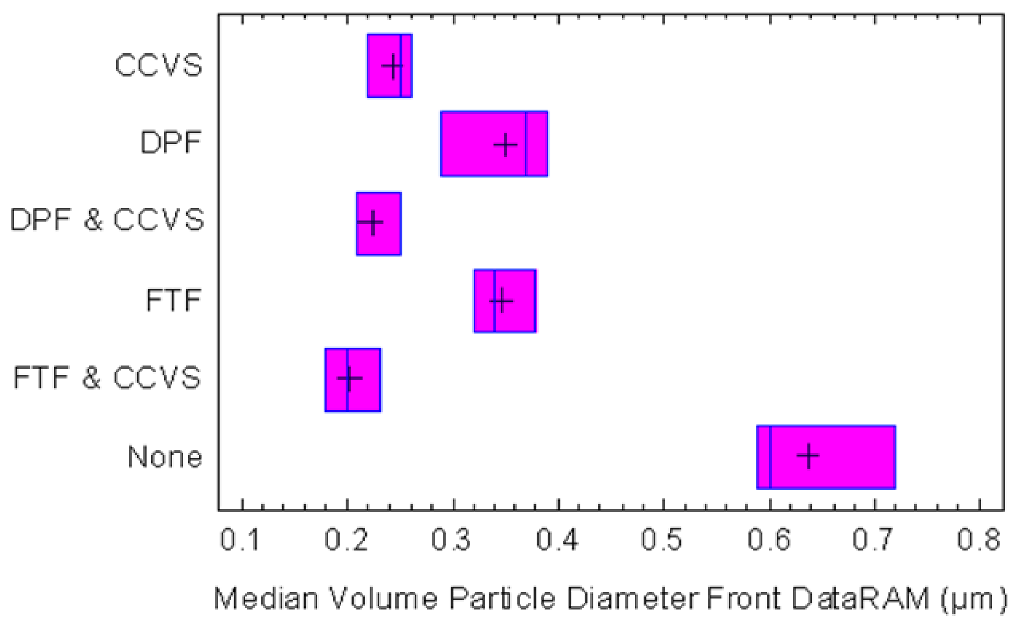

Figure 53: Box and whisker plot for particle size results from the DataRAM located in the front of the bus.

Figure 54 also shows a box and whisker plot for particle size obtained for the back of the bus. Similar to the front of the bus, the baseline condition resulted in the largest average particle size of ±0.48µm at the 95% confidence level. It should be noted that the average particle size for the ambient measurements during the baseline runs was 0.29µm which was much smaller than the baseline value of 0.56µm. Unlike the front of the bus, the back of the bus was only significantly different between the baseline and all other conditions.

From Figure 54 it can be seen that the CCVS related technologies results in a lower particle size because the crankcase vent under bus was eliminated. Since particle size distributions from the crankcase vent have been measured and contain a fraction with larger particles than the exhaust, then most certainly the CCVS directing blow-by gases to the engine, through the combustion process and out tailpipe has greatly reduced the fraction of larger particles from the crankcase vent from entering the final study with the sealed bus. This is especially noticeable from 'None (baseline)' where large particle sizes were found in the front of the bus and these particles enter primarily through the front door which is located near the crankcase exhaust vent.

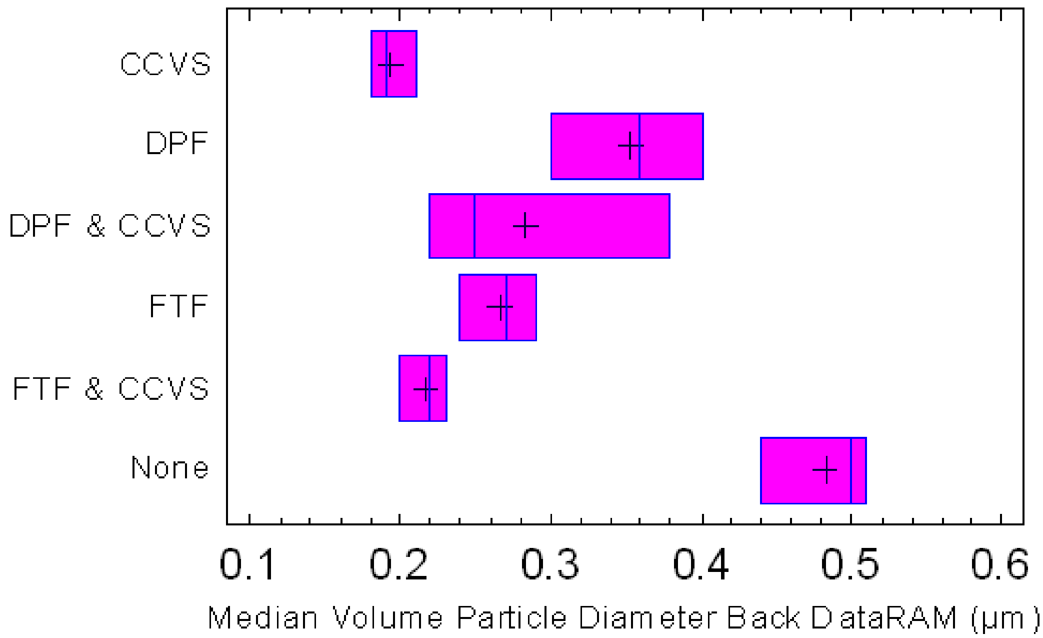

Figure 54: Box and whisker plot for particle size results from the DataRAM located in the back seat.

7.3 Effect of Retrofit Condition on In-Cabin Net Particulate $PM_{2.5}$ Concentrations

The present experimental procedure was designed for the bus running only with windows closed. This decision was made based on the preliminary initial study in which no significant PM accumulation was observed when the bus windows were open. An ANOVA for the baseline runs concluded that there was a statistically significant difference between windows closed compared to windows open for the initial study baseline runs, resulting in a P-value of 0.001 for the DataRAM results, and a P-value of 0.003 for the P-Trak results indicating the statistically significant difference since the P-value is less than 0.05.

This final study found that the average in-cabin particulate concentrations for a bus driving on a school bus route with windows closed was 2.7 $\mu g/m^3$ without any retrofit technology as shown in the results section Table 17 and summarized in this section in Table 22. The low $PM_{2.5}$ values obtained in this final study are comparable to the results obtained by Ireson et al. (2004)[19] where for all the on-road sampling runs, except for one, the background concentration of $PM_{2.5}$ was greater than that measured inside the bus cabin. In this study by Ireson, the average measured diesel particulate matter concentration with ambient subtracted was only 0.22$\mu g/m^3$. In another study by Rim et al. (2008)[20] it was also reported that mean in-cabin $PM_{2.5}$ concentrations were generally lower than roadway levels. This value of 2.7 μg/m^3, obtained in this final study, was measured by DataRAM4 instruments located in the front and back of the bus. Based on the data presented in the section, "Feasibility Study for Particulate Instrumentation " this value is 1.3 to 1.8 times higher than the FRM standard measurement techniques. This sealed in-cabin baseline value is substantially lower than those found from previous school bus studies. In addition this value is much lower than the national ambient air quality standard[60] for $PM_{2.5}$ of 15μg/m^3. It is believed that this low $PM_{2.5}$ value resulted from operating a well-maintained and carefully sealed school bus in an environment free of other point or moving sources of particulate matter. The unsealed initial bus study shows the other extreme when a leaky school bus is utilized.

Higher in-cabin particulate levels than measured in this study have been found within a school bus. Though the mandate of this study was not to examine school bus idling, it was observed that idling the school bus with the door open resulted in a concentration of PM2.5 for the front and back of 16 and 43μg/m^3. Additionally, high particulate emissions will result from a school bus operated from a cold start compared to a warmed-up bus. For this final study the school bus was idled and then driven before each run until the engine oil temperature reached 200°F.

Since these results are not normally distributed, a nonparametric statistical analysis was performed to determine if there was a statistically significant difference between the retrofit technologies in the resultant in-cabin net $PM_{2.5}$ concentrations. This analysis used the mean in-cabin net $PM_{2.5}$ values for each retrofit technology. This resulted in 3 front and 3 back in-cabin net $PM_{2.5}$ values for each technology. The averages for these 6 in-cabin values per technology are shown in Table 22.

The nonparametric tests performed were Kruskal-Wallis non-parametric ANOVA, and the Mann-Whitney (Wilcoxon) W test to compare medians. These nonparametric tests were conducted using both the front and back in-cabin net concentrations for each of the retrofit technologies resulting in 6 values for each condition. The net concentration in the cabin of the bus was determined from the difference between the measured values and the average of the ambient values taken from the ambient monitor station. Four homogeneous groups were identified in these tests and the results for the in-cabin net $PM_{2.5}$ concentrations are shown Table 22 and graphically in the box and whisker plot in Figure 55.

Table 22: Nonparametric summary of in-cabin net $PM_{2.5}$ concentrations.

Retrofit Technology	Mean In-Cabin net $PM_{2.5}$ (μg/m^3)	Homogeneous Groups				% Reduction from Baseline	Fraction of maximum reduction
DPF & CCVS	-11.4	1				531%	100%
DPF	-7.4	1	2			378%	71%
FTF & CCVS	-4.2	1	2			257%	48%
CCVS	-2.1		2			177%	33%
Baseline (None)	2.7			3		0%	0%

FTF	3.7				4	-41%	-8%

FTF: Environmental Solutions Worldwide Particulate Reactor, DPF - Johnson Matthey CRT, CCVS-Donaldson Spiracle Crankcase Ventilation System

No statistical significant difference was found between the DPF-CCVS, DPF, and FTF-CCVS (group #1); and the DPF, FTF-CCVS, and CCVS (group #2)$PM_{2.5}$ values. This can be seen in Table 22 which shows these retrofit technologies in the homogeneous groups of 1 and 2.

The results of the nonparametric Kruskal-Wallis tests is presented in Table 23. The Kruskal-Wallis test tests the null hypothesis that the medians of the retrofit configuration within each of the 6 levels are the same. The data from all the levels is first combined and ranked from smallest to largest. The average rank is then computed for the data at each level. Since the P-value is less than 0.05, there is a statistically significant difference amongst the medians at the 95.0% confidence level. To determine which medians are significantly different, the Mann-Whitney (Wilcoxon) W was used.

Table 23: Kruskal-Wallis Test for front and back combined in each retrofit configuration (front and back combined).

Retrofit	Sample Size	Average Rank
--		
CCVS	6	17.4167
DPF	6	11.4167
DPF & CCVS	6	7.16667
FTF	6	32.6667
FTF & CCVS	6	14.0
None	6	28.3333
--		
Test statistic = 26.8951 P-Value = 0.0000597907		

The results from the Mann-Whitney (Wilcoxon) W test to compare medians for front and back combined in each retrofit configuration (6 points each) are presented in Tables 24 through 26. This test is constructed by combining the two samples, sorting the data from smallest to largest, and comparing the average ranks of the two samples in the combined data. When the P-value is less than 0.05, then there is a statistically significant difference between the medians at the 95.0% confidence level.

From the results presented in Table 24, it can be seen that all of the retrofit combinations obtained a statistical significant difference as indicated by having p-values less than 0.05.

Table 24: Mann-Whitney (Wilcoxon) W test to compare medians of baseline versus FTF, DPF, CCVS, FTF-CCVS, and DPF-CCVS.

	None Vs FTF	None Vs DPF	None Vs CCVS	None Vs FTF-CCVS	None Vs DPF-CCVS
Average rank of sample 1:	4.33333	9.5	9.5	9.5	9.5
Average rank of sample 2:	8.66667	3.5	3.5	3.5	3.5
W	31	0	0	0	0
P-value	**0.044951**	**0.004998**	**0.004998**	**0.004998**	**0.004998**

Table 25 show that there is a statistical difference between the medians of FTF Vs. DPF, FTF Vs. CCVS, and FTF Vs. DPF-CCVS. The other two comparisons between DPF Vs. CCVS, and DPF Vs. FTF-CCVS did not show any significant difference.

Table 25: Mann-Whitney (Wilcoxon) W test to compare medians of FTF versus DPF, CCVS, DPF-CCVS; and DPF versus CCVS, FTF-CCVS.

	FTF Vs DPF	FTF Vs CCVS	FTF Vs DPF-CCVS	DPF Vs CCVS	DPF Vs FTF-CCVS
Average rank of sample 1:	9.5	9.5	9.5	4.92	5.83
Average rank of sample 2:	3.5	3.5	3.5	8.08	7.17
W	0	0	0	27.5	22
P-value	**0.00507**	**0.00507**	**0.00507**	0.1488	0.5752

Finally, the results from Table 26 show that there is a significant difference between the median values of CCVS Vs. DPF-CCVS, and FTF Vs. FTF-CCVS.

Table 26: Mann-Whitney (Wilcoxon) W test to compare medians of CCVS versus DPF-CCVS, FTF-CCVS; DPF Vs. DPF-CCVS; DPF-CCVS Vs. FTF-CCVS; and FTF Vs. FTF-CCVS.

	CCVS Vs DPF-CCVS	CCVS Vs FTF-CCVS	DPF Vs DPF-CCVS	DPF-CCVS Vs FTF-CCVS	FTF Vs FTF-CCVS
Average rank of sample 1:	8.83	7.5	7.67	4.67	9.5
Average rank of sample 2:	4.17	5.5	5.33	8.33	3.5
W	4	12	11	29	0
P-value	**0.03064**	0.3785	0.29795	0.092695	**0.00507**

The box and whisker plot shown in the Figure 55 shows the average value inside the box as a black positive sign, and the median value as a vertical blue line. The range of values is shown by the blue "whiskers" and the length of the box represents the first and third quartile from the distribution. The largest significant difference between mean values was between the DPF and CCVS combination compared to either the FTF or the baseline. Additionally the retrofit technologies of the DPF alone and the combined FTF and CCVS resulted in significant differences from the baseline.

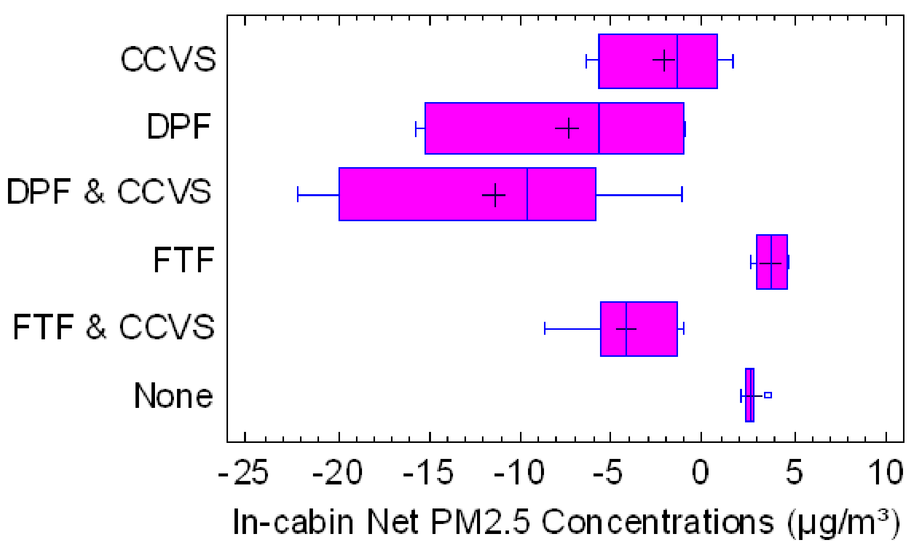

Figure 55: Box and whisker plot for in-cabin net $PM_{2.5}$concentration values.

The relative percent reduction of particulate matter concentration for each retrofit technology compared to the baseline is presented in the Table 22. Using the 6 run values for each retrofit condition, the percent reduction from the baseline (no retrofit) concentrations are calculated as $\left(C_{retrofit} - C_{baseline}\right)/C_{baseline}$. The positive values indicate a reduction and the negative values indicate an increase in particle matter concentration compared to the baseline.

The overall percent reduction of particulate matter by the best technology, DPF and CCVS combined, is 532% or 5.32 times lower than the base line. Since the mean value for the DPF and CCVS combined retrofit technology was less than zero, this has resulted in a reduction greater than 100%. Another method that can be used to examine these technologies is to rank them according to their effectiveness at reducing in-cabin particulate matter compared to the best technology of DPF-CCVS combined. This ranking assumes that the baseline has a value of 0 and the best technology has a value of 100. In this manner it can be seen that the DPF is approximately 70% as effective as the DPF-CCVS combined and the FTF and CCVS combined is only 50% effective in reducing in-cabin particulate matter compared to the best retrofit technology.

In conclusion from the $PM_{2.5}$ analysis it can be seen that for the in-cabin net $PM_{2.5}$ concentrations the FTF and CCVS are similar to the baseline. The combined technology of the DPF and CCVS, the DPF alone and the FTF and CCVS combined resulted in significant different net values compared to the baseline.

7.4 Effectiveness of CCVS in reducing in-cabin ultrafine particulate concentrations

An analysis of variance was attempted for the P-Trak results for the front of the bus, back of the bus and in-cabin P-Trak values. From these analyses there was no significant difference between the baseline and all other technologies. The lack of significant differences between most of the conditions is related to the large differences in particle counts with sequential runs in a given day. It is shown in the following section that the variation in P-Trak results is related to the engine oil temperature and the lack of significance in the results was based on the large variation in particle count concentrations for each retrofit technology.

A comparison of particle number concentrations and the engine oil temperature, obtained from the ECM through the SEMTECH D software, is shown in Figure 56. The first major conclusion that can be drawn from this data is that the crankcase ventilation system CCVS, either alone or combined with the DPF and FTF, appears to be effective in reducing the particle number concentration because it eliminates the crankcase vent which is located underneath the bus near the front door. This result gives evidence that the CCVS is reducing emissions from the crankcase vent that is entering the bus. In addition, the particle count concentrations in the front of the bus are always higher than the back of the bus. This again gives evidence that the crankcase vent emissions are entering the bus through the front door.

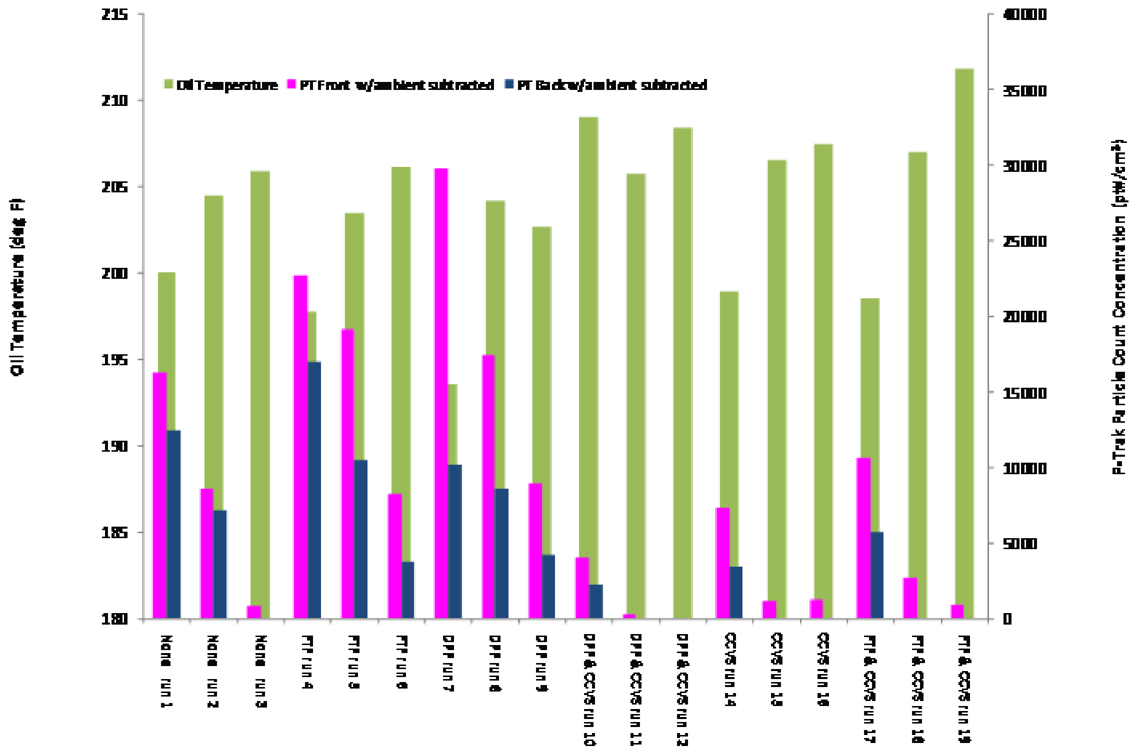

Figure 56: Trend between particle count results and engine oil temperature.

7.4.1 Effect of Oil temperature on Ultrafine Particle Concentration

A trend can be observed in Figure 56 in which the oil temperature increases for each set of runs in a particular day. With an increasing in oil temperature it is observed that there is a decrease in in-cabin particle count concentration. This pattern is observed for all runs except for those runs with the DPF and DPF combined with the CCVS. The protocol required that the bus be driven until the engine oil temperature reached 200°F. This allowed the engine and subsequently the exhaust gases to be warmed-up, so that none of the tests included a cold start. Since the average engine oil temperature increases with each run, this data seem to indicate that a significantly longer time of operation is required to obtain a steady state operating condition. Evidence of this phenomenon is given by Tatli and Clark.[35] In that study they show that the particle number concentration from the crankcase vent decreases by over an order of magnitude from cold start to hot idle. This data was reported for a 1995 Mack engine. Results for a 1992 Detroit Diesel engine showed a small drop in particle number at idle, but an additional drop from the cold start value of 4.5×10^7 at approximately 800 rpm to about 1.2×10^7 dN/d(logDp)/cm^3 at steady state conditions of 1600rpm with 1200 ft-lb load. The engine oil temperatures were reported for this engine ranging from 17°C at a cold start to 81°C for the hot idle tests. The oil temperatures of the Detroit Diesel engine ranged from 82 to 106°C during the dynamometer runs. The oil temperatures for this study are comparable ranging from 90°C (194°F) to 100°C (212°F) during the school bus runs. The data from the literature and this study indicate that crankcase emissions appear to be a related to the engine oil temperature. In conclusion, both this study and the literature give evidence that increases in engine oil temperature correspond to a decrease in the number of particles emitted through the crankcase vent.

A plot of the in-cabin net particle count concentrations as a function of engine oil temperature is given in Figure 57. In this figure a general overall trend of engine oil temperature related to the front and back in-cabin net particulate concentration is apparent having correlation coefficients of -0.80 and -0.73, respectively. As expected from the previous presentation of this data the front has higher concentrations compared to the back.

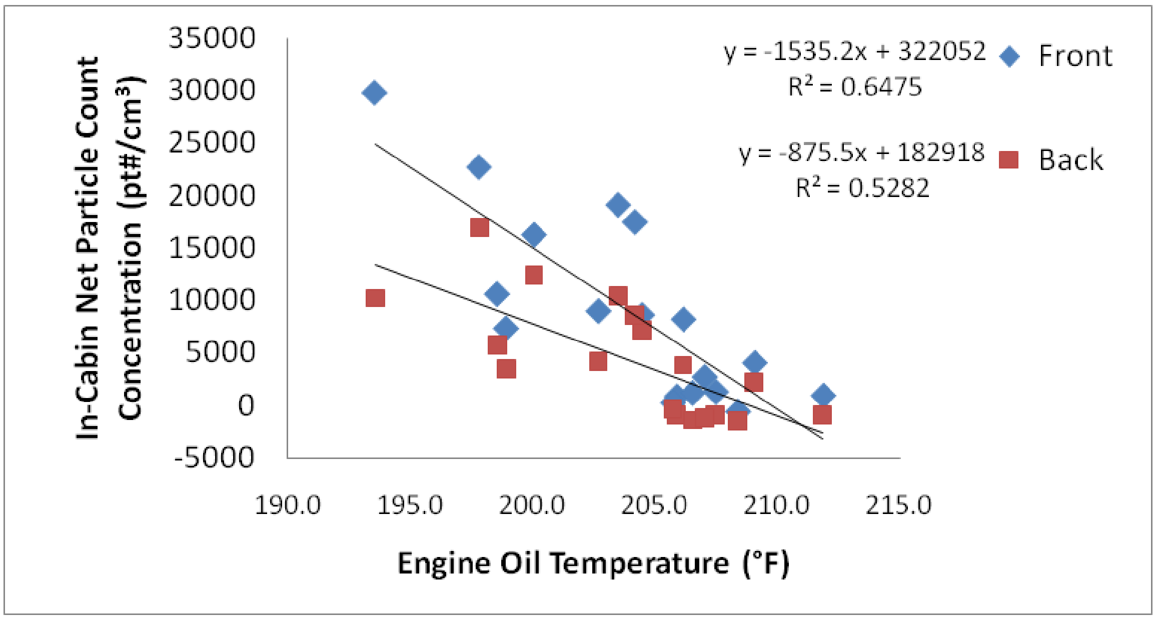

Figure 57: Effect of Engine Oil Temperature on In-Cabin Net Ultrafine Concentrations.

A detailed summary of the in-cabin particle count as a function engine oil temperature for each run is shown in Figure 58 for the front and Figure 59 for the back sampling location. The value plotted for the engine oil temperature is the average value for the entire run. In these figures each of the runs without the CCVS is shown with open symbols and the runs using the CCVS are shown with filled symbols. The runs using the DPF show the lowest set of engine oil temperatures from 194 to 204°F as well as one the highest particle count concentrations of 30,000 pt#/cm^3. The FTF set of runs also show a relatively low set of engine oil temperatures ranging from 198 to 206°F as well as comparatively high particle count concentrations. The runs using the DPF and CCVS combined have one of the highest sets of engine oil temperatures for the 3 runs ranging from 206 to 209°F with net particle count concentrations of -555 to 4078 pt#/cm^3.

7.4.2 Ultrafine Particulate Matter Reductions

Unfortunately, a full analysis of the reduction in ultrafine particulate matter cannot be conducted from this data since values for each retrofit technology are not available for the range of engine oil temperatures measured. A preliminary analysis of this data can be performed based on selected pairs of data sets. This can be done by using actual points, where available or by using an extrapolation of the data for one point and actual data values for the comparison point. The extrapolations of the data are based on a linear regression of the 3 data points obtained for the front or back measurements of a particular run.

The effect of the CCVS retrofit on the in-cabin concentrations is apparent by examining pairs of points. For example, in Figure 58, at an engine oil temperature of approximately 198-199°F the use of the FTF compared to using the FTF combined with the CCVS reduces the particle count concentration from 22,720 to 10,630 pt#/cm^3. A second comparison for the FTF and the FTF combined with a CCVS can be made. Using a temperature in the range of 206-207°F the particle count concentration drops from 8,220 to 2,740 pt#/cm^3. If the DPF-alone data are extrapolated, using a linear regression of the 3 data points to comparable temperatures of the DPF combined with the CCVS, there is also a reduction in particle count at 206°F from about 10,000 to 300 pt#/cm^3. A similar comparison point can be made between the baseline and the CCVS alone. At a temperature of 199°F the extrapolated value of the baseline particle count would be approximately 19,600 compared to the experimental value of 7,360 pt#/cm^3.

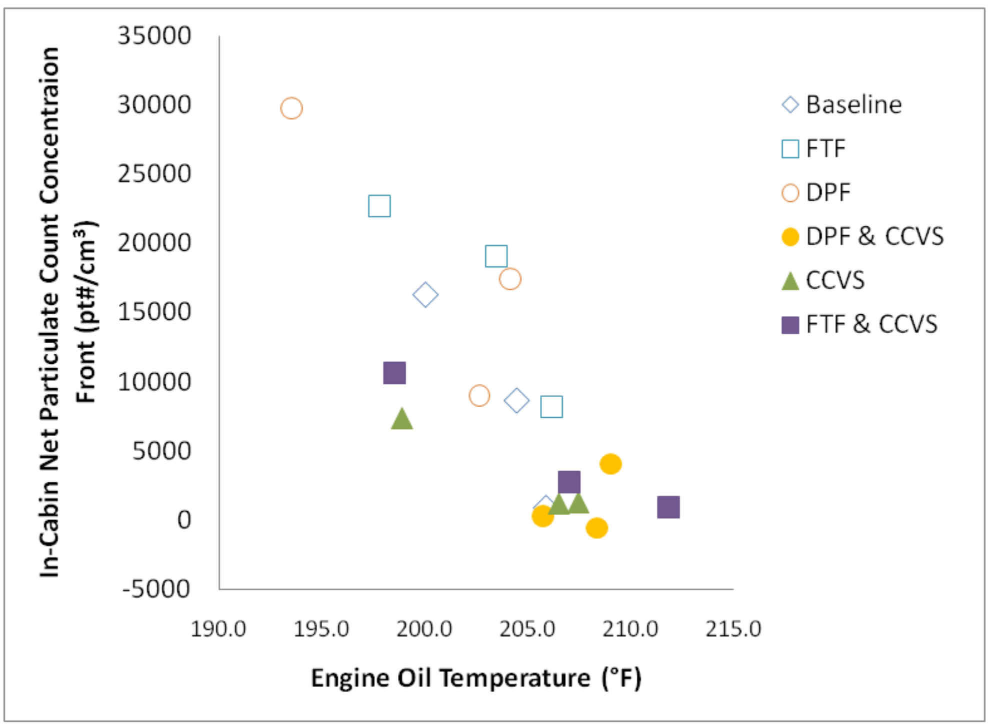

Figure 58: Detailed Summary of In-Cabin Net Particle Count Concentrations for the Front Sampling Location.

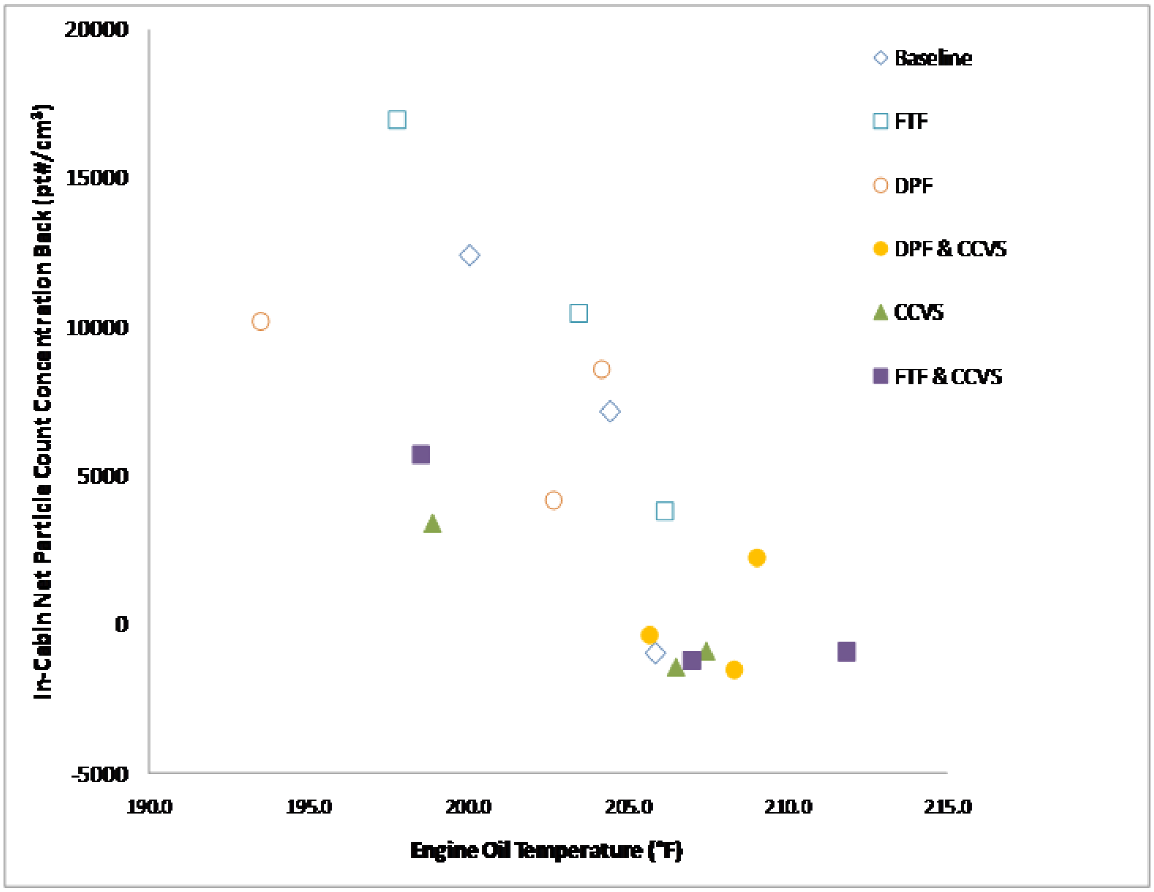

Figure 59: Detailed Summary of In-Cabin Net Particle Count Concentrations for the Back Sampling Location.

In Figure 59 four comparisons can be made between the use of the CCVS retrofits and either the baseline or a tailpipe retrofit without the CCVS for the back sampling location. At 199°F the particle count concentration from an extrapolated baseline can be compared to the CCVS alone resulting in a reduction in particle count from 15500 to -360 pt#/cm^3. Similarly the extrapolated particle count value of 270pt#/cm^3 at 205°F for the CCVS is much lower than the baseline value of 7180 pt#/cm^3. For the DPF alone compared to the DPF combined with a CCVS there is a reduction in particle count of 5820 to -359 pt#/cm^3 at 206°F. For the FTF and CCVS combined retrofits two comparisons can be made with FTF data. Using the combined FTF and CCVS at 199°F the particle count is reduced from 16,400 to 5715 and at 207°F the particle count is reduced from 3605 to -1175 pt#/cm^3.

A summary of these observations is shown in Tables 27 and 28. In these tables the retrofit technologies are listed in the first two columns and the engine oil temperature from the ECM is listed in the third column. The first column in these tables is the retrofit technology that had the lowest net particle number concentration measured in the cabin of the bus. In the second column a second technology is compared at the same engine oil temperature. The technology in the second column has resulted in a high net particle number concentration in the cabin of the bus.

The engine oil temperature used is from an actual experimental value. The extrapolated values are shown in boldface. These extrapolations were obtained from a linear regression of the 3 data points. For example in Table 27 in the first row, the value of 22,894 pt#/cm^3 was obtained from a correlation of the FTF runs at an engine oil temperature of 198.5°F. This was compared to the experimental data point for the combined FTF and CCVS of 10,629 pt#/cm^3 to obtain a reduction of 54%.

Table 27: Summary of Ultrafine Particulate Concentration Reductions for Front P-Trak.

Low Concentration Retrofit	High Concentration Retrofit	Engine Oil Temperature (°F)	Front Low Concentration (pt#/cm^3)	Front High Concentration (pt#/cm^3)	Front Percent Reduction
FTF-CCVS	**FTF**	198.5	10629	**22894**	54%
FTF-CCVS	**FTF**	207	2741	**9606**	71%
DPF-CCVS	**DPF**	205.7	300	**10117**	97%
CCVS	**Baseline**	198.9	7360	**19643**	63%
CCVS	Baseline	204.5	**3149**	8636	64%
FTF-CCVS	Baseline	200	**9125**	16272	44%
FTF-CCVS	Baseline	204.5	**5754**	8636	33%

Table 28: Summary of Ultrafine Particulate Concentration Reductions for Back P-Trak.

Low Concentration Retrofit	High Concentration Retrofit	Engine Oil Temperature (°F)	Back Low Concentration (pt#/cm^3)	Back High Concentration (pt#/cm^3)	Back Percent Reduction
FTF-CCVS	**FTF**	198.5	5715	**16415**	65%
FTF-CCVS	**FTF**	207	-1175	**3605**	133%
DPF-CCVS	**DPF**	205.7	-359	**5820**	106%
CCVS	**Baseline**	198.9	3434	**15456**	78%
CCVS	Baseline	204.5	**262**	7179	96%
FTF-CCVS	Baseline	200	**4303**	12415	65%
FTF-CCVS	Baseline	204.5	**1908**	7179	73%

An estimation of the overall percent reduction is presented in Table 29. This was calculated by averaging the overall percent reduction values from both the front and back for a given pair of retrofit technologies.

Table 29: Summary of Overall Ultrafine Particulate Concentration Reductions.

Low Concentration Retrofit	High Concentration Retrofit	Engine Oil Temperature (°F)	Front Percent Reduction	Back Percent Reduction	Overall Percent Reduction
FTF-CCVS	**FTF**	198.5	54%	65%	81%
FTF-CCVS	**FTF**	207	71%	133%	
DPF-CCVS	**DPF**	205.7	97%	106%	102%
CCVS	**Baseline**	198.9	63%	78%	75%
CCVS	Baseline	204.5	64%	96%	
FTF-CCVS	Baseline	200	44%	65%	54%
FTF-CCVS	Baseline	204.5	33%	73%	

From this analysis it is evident that the use of a CCVS reduces the particle count concentrations from 50 to over 100% compared to the cases without the CCVS since the crankcase vent under the bus near front door is eliminated and the sealed bus largely prevents tailpipe particle penetration to the bus cabin. The highest percent reduction with an overall value of 75% appears to be in using the CCVS compared to the baseline. Other significant reductions are observed by using the CCVS with a tailpipe retrofit technology. If a CCVS is added to a FTF a reduction of 81% in ultrafines is observed. In addition of a CCVS is added to a DPF then a reduction of over 100% was observed. Each of these percent reductions is dependent on the engine oil temperature and an overall percent reduction that is independent of engine oil temperature cannot be given in this report. Further research is required to determine this complex relationship between the state of the engine and the ultrafine emissions. Nevertheless, this study gives strong evidence that the use of the CCVS will substantially reduce ultrafine particulate matter.

This study gives evidence that a major source of ultrafines into the school bus is from the crankcase vent. From the evidence shown above, any retrofit combination using the CCVS reduces the ultrafines measured in the cabin of the school bus. This appears to occur because the CCVS is filtering out particles in the range of sizes being measured by the P-Trak (0.02 to 1μm). If the back door had leaks or other leaks were present, then the tailpipe retrofit would become more important in reducing ultrafines.

At high engine oil temperatures (T>207°F) the baseline value of in-cabin net particle count appears to decrease to very small values and there were insufficient data to make a comparison between the use of the CCVS and other technologies at these temperatures. What is shown from this data is the importance of using the CCVS for engine oil temperatures from 198 to 208°F. What were not shown from this data are the cold start emissions values. Again based on the data presented by Tatli and Clark[35] the amount of particulate emissions from the crankcase vent increases with decreasing temperature. So it would be expected that at engine temperatures from cold-start to 198°F, a range not investigated in this study, the use of a CCVS would result in larger decreases of the in-cabin particulate concentration than observed for the range of temperatures in this study.

8. CONCLUSIONS

This study was designed using a testing environment and school bus that enabled in-cabin particulate measurements to be made that were free of confounding factors related to extraneous particulate production. These procedures resulted in a test track that was free of diesel pollutant sources on the track and in the near vicinity. The track was also free of road dust sources because of the required power washing. The school bus was free of particulates that had collected on the outside of the bus or inside the bus. In addition, the bus was inspected following NJDMV protocols to insure that the condition of the bus with respect to rear door leaks and other gas/particle infiltration paths through the bus body and with respect to emissions met the rigorous State of New Jersey standards. In the initial study the rear door and other seals had deteriorated allowing substantial tailpipe exhaust penetration.

1. This study found that the average net in-cabin particulate concentrations for a bus driven on a simulated school bus route with windows closed was 2.7 $\mu g/m^3$ as shown in Table 22. This value of 2.7 $\mu g/m^3$ was measured by DataRAM4 instruments located in the front and back of the bus. Based on the data presented in the section, "Feasibility Study for Particulate Instrumentation ," this value is 1.3 to 1.8 times higher than the gravimetric values. This in-cabin baseline value is substantially lower than those found in previous school bus studies. In addition this value is much lower than the national ambient air quality standard for $PM_{2.5}$ of 15$\mu g/m^3$. It is believed that this low $PM_{2.5}$ value resulted from operating a well-maintained school bus in an environment free of bus body leaks and other point or moving sources of particulate matter. This finding shows the high significance of school bus inspections that are designed in part to minimize the influx of air containing pollutants into the school bus and especially those from the bus tailpipe.
2. The in-cabin net ultrafine concentrations as measured by the P-Trak decreased with increasing engine oil temperature. In addition, it was found that the concentrations of ultrafines were higher in the front of the bus compared to the back of the bus for all retrofit technologies. Since for this bus the crankcase vent tube was located under the front of the school bus, these results indicate the importance of replacing the crankcase vent with a CCVS.
3. Based on an examination of particle size from a 2-wavelength nephelometer, it was observed that all technologies that were combined with a CCVS reduced average median volume particle diameter. Since particle size distributions from the crankcase vent have been measured and contain a fraction with larger particles than the exhaust, it then appears that the CCVS is reducing the fraction of larger particles from the crankcase vent from entering the bus. This is especially noticeable from the particle sizes in the front of the bus since particles enter primarily through the front door which is located near the exhaust vent of the crankcase.
4. It was found that three retrofit technology combinations reduce in-cabin net $PM_{2.5}$ concentrations to values less than the ambient. It was found that the most

effective technology was the combined DPF and CCVS. Use of a DPF only with the crankcase vent tube in place was 70% as effective as the combined DPF and CCVS. The combination of FTF and CCVS was approximately 50% as effective as the combined DPF-CCVS retrofit technology. It was found for $PM_{2.5}$ that the CCVS was approximately 30% as effective as the DPF-CCVS. The FTF alone was shown to result in a slight increase in PM2.5 of approximately 1 µg/m^3.

5. The use of a CCVS alone or combined with other retrofit technologies reduces the particle count concentrations from 50 to over 100% compared to the cases with the crankcase vent. The DPF or FTF used without a CCVS did not significantly reduce in-cabin net ultrafines concentrations since the crankcase vent was still in place adjacent to the front door. This study gives evidence that a major source of ultrafines into the school bus is from the crankcase vent. From the evidence shown above, any retrofit combination using the CCVS reduces the ultrafines measured in the cabin of the school bus. This appears to occur because the CCVS is filtering out particles in the range of sizes being measured by the P-Trak (0.02 to 1µm). If the back door had leaks or other leaks were present, then the tailpipe retrofit would become more important in reducing ultrafines.
6. What is shown from this data is the importance of using the CCVS for engine oil temperatures from 198 to 208°F. What is not shown from this data are the cold start emissions values. Again based on the data presented by Tatli and Clark[35] the amount of particulate emissions from the crankcase vent increases with decreasing temperature. So it would be expected that at engine temperatures from cold-start to 198°F, a range not investigated in this study, the use of a CCVS would result in larger decreases of the in-cabin particulate concentration than observed for the range of temperatures in this study. Since all school bus routes start with a cold bus engine, this should be an important consideration.
7. However, when the rear door has leaks or there are other bus cabin leaks, the use of CCVS only eliminates the crankcase vent source but not the tailpipe particle source as found in the initial study. However, the DPF removes all tailpipe particles and thus the tailpipe source of particles. The combination of CCVS (which removes the crankcase vent source of particles) and DPF (removes tailpipe particle source) shows the highest reduction of particulate matter within the bus cabin from contamination by its own engine.
8. The use of retrofit technologies resulted in large reductions of gaseous pollutants normally emitted from the tailpipe. For the operating conditions in this final study all tailpipe technologies reduced CO from 50-65%. Hydrocarbons were reduced for all tailpipe retrofit technologies from 92 to 97% - diesel exhaust contains 5 or 6 toxic HCs and PAH. This is an added benefit of using tailpipe retrofit technologies to reduce in-cabin particulate concentrations. NO_x, however, was not significantly reduced by any of the technologies.

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[60] Environmental Protection Agency 40 CFR Part 50 National Ambient Air Quality Standards for Particulate Matter; Final Rule. Federal Register / Vol. 62, No. 138 / Friday, July 18, 1997 / Prepublication.

Appendix A: Feasibility Study for Particulate Instrumentation

After the experiments at EOHSI, the next data set was reported:
The following results are the average values obtained from the EOHSI results that were used to produce a mass concentration response curve of the DataRAM's.

Table 30: Results from the controlled environment tests at EOHSI.

Gravimetric method ($\mu g/m^3$)	DataRAM-4 instrument # 1 Front ($\mu g/m^3$)	DataRAM-4 instrument # 2 Ambient Monitor ($\mu g/m^3$)	DataRAM-4 instrument # 3 Back ($\mu g/m^3$)
4.0	2.9	3.8	4.7
37.2	29.9	41.6	35.8
59.5	69.8	80.3	70.7
174.6	232.1	230.2	200.8

From the Camden results the following average values were obtained:

Table 31: Results obtained after 6 days of continuous measurement at the ambient monitor station from the NJDEP at Camden New Jersey.

TEOM ($\mu g/m^3$)	DataRAM-4 instrument # 1 ($\mu g/m^3$)	DataRAM-4 instrument # 2 ($\mu g/m^3$)	DataRAM-4 instrument # 3 ($\mu g/m^3$)
2.8	2.2	2.3	0.1
7.2	6.2	7.0	4.7
8.5	8.1	9.4	8.7
12.0	11.6	12.6	11.3
13.1	12.1	12.6	14.9
13.2	24.5	22.7	16.1

Combining both data sets:

Table 32: Combination set of EOHSI and NJDEP results.

Source of value	Reference (TEOM or Gravimetric) (μg/m³)	DataRAM-4 instrument # 1 (μg/m³)	DataRAM-4 instrument # 2 (μg/m³)	DataRAM-4 instrument # 3 (μg/m³)
Camden – TEOM	2.8	2.2	2.3	0.1
EOHSI – Gravimetric	4.0	2.9	3.8	4.7
Camden – TEOM	7.2	6.2	7.0	4.7
Camden – TEOM	8.5	8.1	9.4	8.7
Camden – TEOM	12.0	11.6	12.6	11.3
Camden – TEOM	13.1	12.1	12.6	14.9
Camden – TEOM	13.2	24.5	22.7	16.1
EOHSI – Gravimetric	37.2	29.9	41.6	35.8
EOHSI – Gravimetric	59.5	69.8	80.3	70.7
EOHSI - Gravimetric	174.6	232.1	230.2	200.8

The combination of the low concentration values obtained at the NJDEP air monitor site at Camden NJ were combined with the values obtained at EOHSI as shown in Table 32 in order to have a complete response curve ranging from low concentration to high concentration values. This analysis was performed to check the response of the DataRAM-4 instruments with two different technologies for particulate matter mass concentration measurement: the filter-gravimetric method and the TEOM technology. The TEOM is a Federal Reference Method recognized instrument for measurements of particulate matter; whereas the gravimetric method used in the EOHSI measurements is not. For this study most of the measurements fell in the range of the TEOM values.

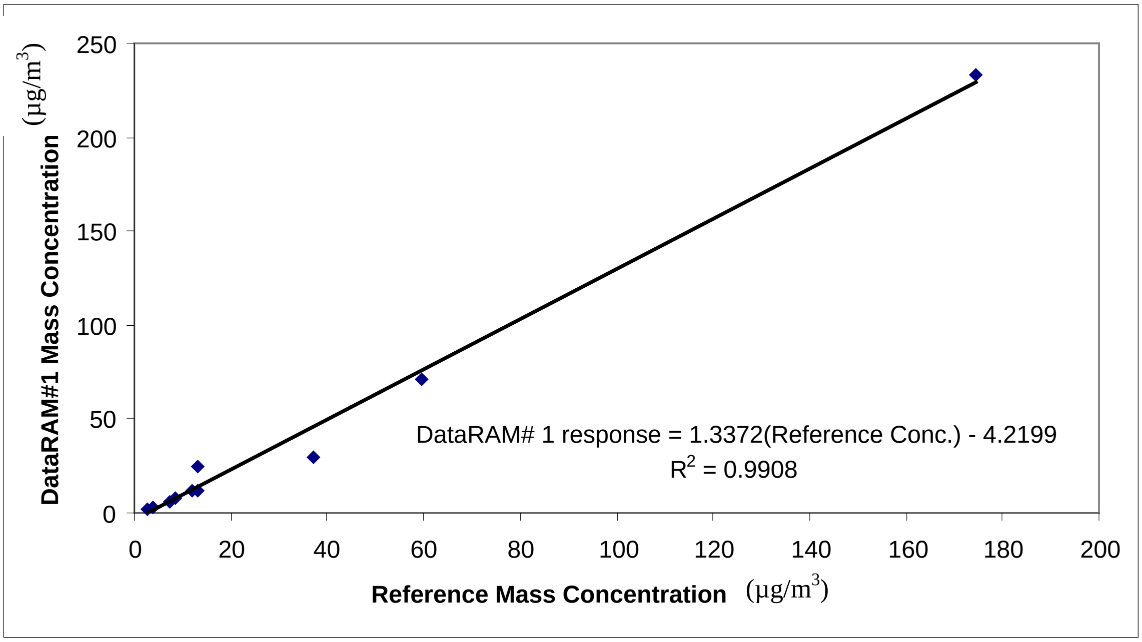


Figure 60: Instrument response curve for DataRAM-4 instrument #1 from EOHSI and NJDEP tests.

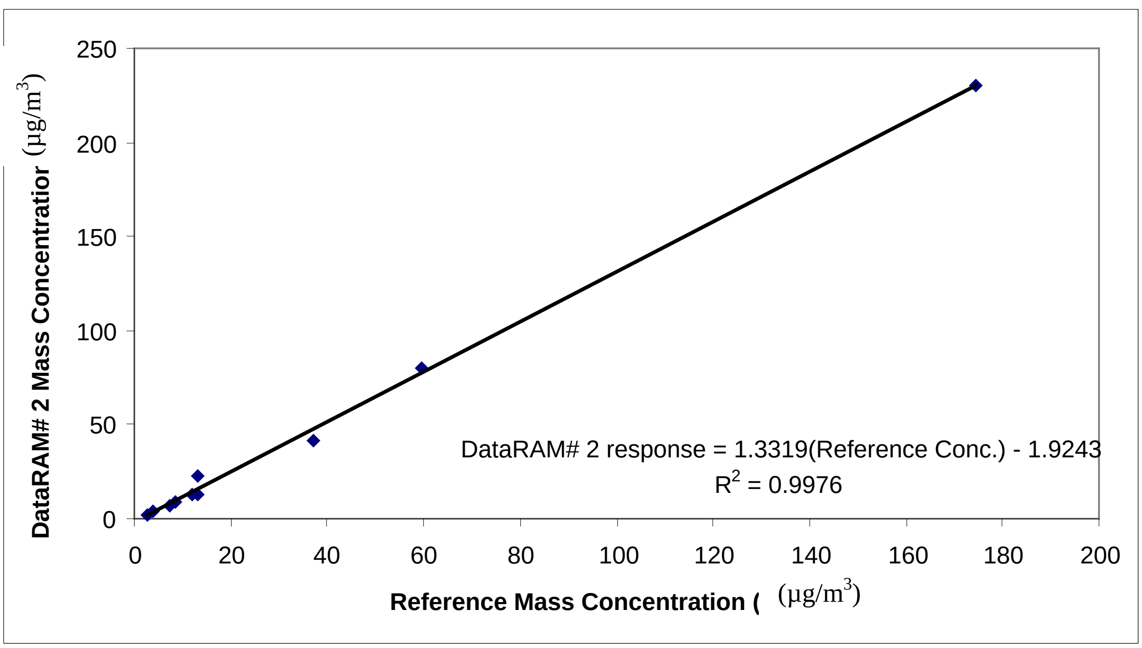


Figure 61: Instrument response curve for DataRAM-4 instrument #2 from EOHSI and NJDEP tests.

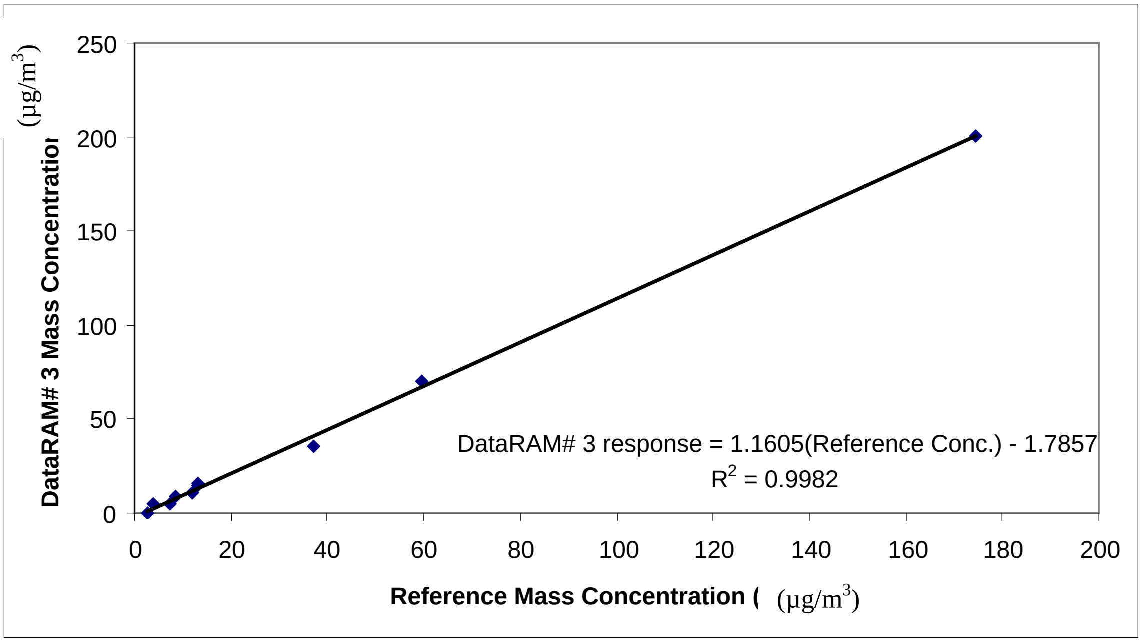


Figure 62: Instrument response curve for DataRAM-4 instrument #3 from EOHSI and NJDEP tests.

The P-Trak instrumentation did not have a particle concentration response curve, because a particle counting reference instrument was not available for either the tests at EOHSI or the Camden laboratory. At the EOHSI lab another P-Trak was available but this was not calibrated against a laboratory standard particle counting instrument. The tests however showed good correlation between the three P-Trak instruments.

Table 33: Particle count results from the controlled environment test at EOHSI.

EOHSI P-Trak Value #/cm^3	PTRACK1 Value #/cm^3	PTRACK2 Value #/cm^3	PTRACK3 Value #/cm^3
2238	2175	2249	2164
12405	15624	N/A[1]	14781
9932	11288	10996	10801
11556	11549	11001	10916
26303	33548	33267	31841
21863	25002	24027	23388
20496	24361	23921	23378
19721	24707	23987	23540
97744	129890	118388	118857

Note: 1. *Data of PTRACK2 is not collected due to charge problem*

Appendix B: DataRAM $PM_{2.5}$ Mass Concentration Results Raw Data Initial Study

Appendix B – DataRAM-4 $PM_{2.5}$ mass concentration initial study									
Run #	Condition tested	Front Average run with ambient subtracted (μg/m^3)	Front Median run with ambient subtracted (μg/m^3)	Front Ambient from pre and post average values (μg/m^3)	Front Pre-Post difference in absolute values (μg/m^3)	Back Average run with ambient subtracted (μg/m^3)	Back Median run with ambient subtracted (μg/m^3)	Back Ambient from pre and post average values (μg/m^3)	Back Pre-Post difference in absolute values (μg/m^3)
1	Baseline windows open	9	1	25	1	-1	-1	19	2
2	Baseline windows open	5	5	28	12	2	1	30	8
3	Baseline windows open	3	3	24	11	3	2	20	11
4	Baseline windows closed	26	25	20	11	73	67	13	9
5	Baseline windows closed	9	6	10	4	26	29	7	3
6	Baseline windows closed	9	8	47	2	19	21	51	1
7	Baseline windows open	7	4	46	0	3	1	52	2
8	Baseline windows open	0	0	50	11	0	-1	54	11
9	Baseline windows open	2	1	44	2	4	2	47	4
10	Baseline windows open	0	0	43	0	0	-1	46	3
11	CCVS windows open	2	2	17	1	2	1	10	2
12	CCVS windows open	-11	0	28	24	-2	-1	14	5
13	CCVS windows open	-10	0	29	22	-3	-2	16	1
14	CCVS windows closed	74	79	9	2	189	202	7	0
15	CCVS windows closed	36	31	9	2	104	89	7	0
16	CCVS windows closed	21	19	9	3	62	57	7	1
17	Baseline windows closed	26	18	20	10	70	82	9	3

Appendix B – DataRAM-4 $PM_{2.5}$ mass concentration initial study									
Run #	Condition tested	Front Average run with ambient subtracted (μg/m³)	Front Median run with ambient subtracted (μg/m³)	Front Ambient from pre and post average values (μg/m³)	Front Pre-Post difference in absolute values (μg/m³)	Back Average run with ambient subtracted (μg/m³)	Back Median run with ambient subtracted (μg/m³)	Back Ambient from pre and post average values (μg/m³)	Back Pre-Post difference in absolute values (μg/m³)
18	CCVS windows closed	-4	-5	44	4	27	26	31	5
19	CCVS windows closed	-12	-12	42	0	163	104	34	10
20	CCVS windows closed	-2	-9	36	11	104	74	33	12
21	DPF + CCVS windows closed	8	7	8	1	25	26	7	1
22	DPF + CCVS windows closed	8	5	9	1	NA	NA	9	1
23	DPF + CCVS windows closed	7	6	9	1	20	14	8	1
24	DPF windows closed	16	16	8	1	26	23	8	1
25	DPF windows closed	31	22	12	0	23	20	12	4
26	DPF windows closed	12	4	11	1	9	13	13	6
27	DPF windows open	0	1	6	2	-3	1	11	9
28	DPF windows open	3	1	5	1	5	2	6	0
29	DPF windows open	2	1	4	0	2	1	6	0
30	DPF + CCVS windows open	1	1	7	1	3	1	8	2
31	DPF + CCVS windows open	-5	-1	13	14	-3	-1	13	12
32	DPF + CCVS windows open	-1	0	14	11	1	1	15	8
33	Idle test DPF + CCVS windows closed	0	3	12	NA	12	10	10	NA
34	DPF + CCVS windows closed	0	1	9	2	5	5	7	1

Appendix B – DataRAM-4 $PM_{2.5}$ mass concentration initial study

Run #	Condition tested	Front Average run with ambient subtracted (μg/m³)	Front Median run with ambient subtracted (μg/m³)	Front Ambient from pre and post average values (μg/m³)	Front Pre-Post difference in absolute values (μg/m³)	Back Average run with ambient subtracted (μg/m³)	Back Median run with ambient subtracted (μg/m³)	Back Ambient from pre and post average values (μg/m³)	Back Pre-Post difference in absolute values (μg/m³)
35	FTF + CCVS windows	3	-2	43	6	7	1	31	1
36	FTF + CCVS windows open	-3	-5	47	3	2	0	32	4
37	FTF + CCVS windows open	2	-1	50	3	2	-1	37	5
38	FTF + CCVS windows closed	-2	-2	21	3	11	11	13	4
39	FTF + CCVS windows closed	-1	-1	19	1	14	14	11	0
40	FTF + CCVS windows closed	-4	-4	16	8	1	1	10	2
41	FTF windows open	2	0	11	3	1	1	9	2
42	FTF windows open	2	0	12	4	2	1	9	1
43	FTF windows closed	4	5	19	5	12	13	12	2
44	FTF windows closed	1	2	17	2	8	8	10	1
45	FTF windows closed	4	6	16	5	10	11	9	1
46	FTF windows open	0	-1	14	0	1	0	9	0
47	DPF + CCVS windows closed	10	10	53	7	14	13	44	10
48	DPF + CCVS windows closed	0	-1	37	4	13	11	35	2
49	DPF + CCVS windows closed	-9	-9	28	4	15	13	11	0
50	DPF + CCVS windows closed	-5	-5	27	2	24	22	11	1
51	DPF windows closed	-4	-4	29	2	15	13	10	1

Appendix B – DataRAM-4 $PM_{2.5}$ mass concentration initial study

Run #	Condition tested	Front Average run with ambient subtracted (μg/m^3)	Front Median run with ambient subtracted (μg/m^3)	Front Ambient from pre and post average values (μg/m^3)	Front Pre-Post difference in absolute values (μg/m^3)	Back Average run with ambient subtracted (μg/m^3)	Back Median run with ambient subtracted (μg/m^3)	Back Ambient from pre and post average values (μg/m^3)	Back Pre-Post difference in absolute values (μg/m^3)
52	DPF windows closed	-15	-14	35	11	12	11	10	1
53	DPF windows closed	-24	-24	46	12	13	11	11	0
54	DPF + CCVS windows closed	18	16	22	2	23	21	26	2
55	DPF + CCVS windows closed	10	9	21	1	6	3	24	0
56	DPF + CCVS windows closed	8	7	20	NA	7	2	24	NA
57	DPF + CCVS windows closed	-7	-8	28	6	1	3	32	7
58	DPF + CCVS windows closed	-8	-8	30	1	-9	-8	28	0
59	DPF + CCVS windows closed	-6	-6	28	3	-23	-26	41	25
60	DPF windows closed	2	1	26	0	-6	-11	40	28
61	DPF windows closed	-1	-1	25	3	6	1	26	1
62	DPF windows closed	2	2	23	2	6	4	22	7
63	Baseline windows closed	-4	-5	58	4	-1	-1	78	10
63	Dust test	179	NA	58	NA	61	NA	78	NA
64	CCVS windows closed	4	2	23	3	28	28	16	1
65	CCVS windows closed	2	2	26	3	24	27	18	3
66	CCVS windows closed	2	2	28	2	28	31	20	2
67	Baseline windows closed	9	8	28	3	29	32	23	3

Appendix B – DataRAM-4 $PM_{2.5}$ mass concentration initial study									
Run #	Condition tested	Front Average run with ambient subtracted (μg/m^3)	Front Median run with ambient subtracted (μg/m^3)	Front Ambient from pre and post average values (μg/m^3)	Front Pre-Post difference in absolute values (μg/m^3)	Back Average run with ambient subtracted (μg/m^3)	Back Median run with ambient subtracted (μg/m^3)	Back Ambient from pre and post average values (μg/m^3)	Back Pre-Post difference in absolute values (μg/m^3)
68	Baseline windows closed	15	15	26	1	33	34	23	3
69	Baseline windows closed	8	9	30	10	30	31	23	3

Appendix C: DataRAM $PM_{2.5}$ Mass Concentration Results Raw Data Final Study

Retrofit	Date	Run Time		DR1 Front Run Raw Data	DR3 Back Run Raw Data	DR2 Ambient Monitor Data
	mm/dd/yyyy	start (hr:min:sec)	end (hr:min:sec)	Average $PM_{2.5}$ Mass Concentration (μg/m³)	Average $PM_{2.5}$ Mass Concentration (μg/m³)	Average $PM_{2.5}$ Mass Concentration (μg/m³)
None run 1F	5/28/2008	13:23:08	13:51:54	6.4	6.2	4.0[2]
None run 2F	5/28/2008	14:21:46	14:50:32	6.9	6.2	4.1[3]
None run 3F	5/28/2008	16:42:42	17:11:28	7.6	8.3	4.8
FTF run 4F	5/30/2008	13:47:28	14:16:14	15.4	15.9	11.9
FTF run 5F	5/30/2008	15:09:06	15:37:52	17.6	17.2	14.6[4]
FTF run 6F	5/30/2008	16:23:19	16:52:05	19.1	18.9	14.3[5]
DPF run 7F	6/3/2008	12:05:03	12:33:49	20.0	20.5	35.7
DPF run 8F	6/3/2008	13:21:31	13:50:17	17.1	15.4	21.9
DPF run 9F	6/3/2008	14:53:45	15:22:31	15.3	15.6	16.5
DPF & CCVS run 10F	6/17/2008	13:59:39	14:28:25	22.5	17.9	23.7
DPF & CCVS run 11F	6/17/2008	17:00:02	17:28:48	14.7	10.5	22.3
DPF & CCVS run 12F	6/17/2008	17:54:37	18:23:23	21.3	19.1	41.3
FTF & CCVS run 13F	6/18/2008	NA	NA	NA	NA	NA
CCVS run 14F	6/19/2008	15:45:34	16:14:20	11.2	14.8	13.1
CCVS run 15F	6/19/2008	16:50:10	17:18:56	13.8	20.3	19.5
CCVS run 16F	6/19/2008	17:51:44	18:20:30	18.8	24.3	25.2
FTF & CCVS run 17F	6/20/2008	13:49:56	14:18:42	18.7	19.1	20.1
FTF & CCVS run 18F	6/20/2008	15:44:05	16:12:51	13.9	14.8	18.6
FTF & CCVS run 19F	6/20/2008	17:14:44	17:43:30	20.4	17.4	26.0

[2] Used only average from 13:23:08 to 13:33:33hrs because battery died during the run.
[3] Averaged 14min and 23sec of pre run, with 14min and 23sec of post run.
[4] Measured only 1594 seconds during the run instead of normal run length of 1727s because battery died.
[5] Used the pre run ambient, because battery died before the run started.

Appendix D: DataRAM $PM_{2.5}$ Mass Concentration Results pre and post ambient concentrations final study

Retrofit	Date	DR1 Front Pre & Post Run Ambient	DR3 Back Pre & Post Run Ambient
	mm/dd/yyyy	Average $PM_{2.5}$ Mass Concentration ($\mu g/m^3$)	Average $PM_{2.5}$ Mass Concentration ($\mu g/m^3$)
None run 1F	5/28/2008	3.8	3.2
None run 2F	5/28/2008	5.0	3.8
None run 3F	5/28/2008	4.3	4.7
FTF run 4F	5/30/2008	18.2	21.5
FTF run 5F	5/30/2008	21.6	25.0
FTF run 6F	5/30/2008	24.1	23.9
DPF run 7F	6/3/2008	26.7	33.2
DPF run 8F	6/3/2008	27.5	31.9
DPF run 9F	6/3/2008	21.6	29.9
DPF & CCVS run 10F	6/17/2008	27.0	25.8
DPF & CCVS run 11F	6/17/2008	24.3	21.5
DPF & CCVS run 12F	6/17/2008	32.8	36.1
FTF & CCVS run 13F	6/18/2008	NA	NA
CCVS run 14F	6/19/2008	13.3	21.9
CCVS run 15F	6/19/2008	15.5	36.1
CCVS run 16F	6/19/2008	17.5	47.1
FTF & CCVS run 17F	6/20/2008	19.5	22.1
FTF & CCVS run 18F	6/20/2008	16.0	27.3
FTF & CCVS run 19F	6/20/2008	21.5	27.7

Appendix E: P-Trak Particle Count Concentration Results Raw Data Initial Study

Appendix E – P-Trak Ultrafine Particle count results initial study									
		Front Average run with ambient subtracted	Front Median run with ambient subtracted	Front Ambient from pre and post average values	Front Pre-Post difference in absolute values	Back Average run with ambient subtracted	Back Median run with ambient subtracted	Back Ambient from pre and post average values	Back Pre-Post difference in absolute values
Run #	Condition Tested	(pt#/cm^3)	(pt#/cm^3)	(pt#/cm^3)	(pt#/cm^3)	(pt#/cm^3)	(pt#/cm^3)	(pt#/cm^3)	(pt#/cm^3)
1	Baseline windows open	3954	-193	8717	565	9587	-503	7940	2035
2	Baseline windows open	NA	NA	6500	1274	3938	65	6873	1632
3	Baseline windows open	5210	2515	10190	3629	8986	2535	10255	3589
4	Baseline windows closed	30005	33000	20220	-11775.3	42435	10600	20398	5800
5	Baseline windows closed	2467	2500	22872	7006	9548	10600	23273	5912
6	Baseline windows closed	63877	79000	9209	2858	125017	135828	11041	3887
7	Baseline windows open	2356	-698	7437	813	6144	533	8095	2079
8	Baseline windows open	574	580	10451	1147	3885	830	10799	1445
9	Baseline windows open	12	125	9775	205	1694	330	9968	218
10	Baseline windows open	-507	-545	10395	65	828	263	10541	254
11	CCVS windows open	3376	910	3861	180	8040	1145	3779	140
12	CCVS windows open	58	250	5243	2583	2847	505	5239	2781
13	CCVS windows open	228	-160	5815	1439	1381	-85	6058	1144
14	CCVS windows closed	72838	93785	5549	391	149038	173000	5629	359
15	CCVS windows closed	54758	64230	5385	164	125130	138870	5591	38
16	CCVS windows closed	38381	34270	5135	250	100024	117320	5294	297
17	Baseline windows closed	26388	31168	5363	801	67543	77343	5495	1241

Appendix E – P-Trak Ultrafine Particle count results initial study									
		Front Average run with ambient subtracted	Front Median run with ambient subtracted	Front Ambient from pre and post average values	Front Pre-Post difference in absolute values	Back Average run with ambient subtracted	Back Median run with ambient subtracted	Back Ambient from pre and post average values	Back Pre-Post difference in absolute values
Run #	Condition Tested	(pt#/cm^3)	(pt#/cm^3)	(pt#/cm^3)	(pt#/cm^3)	(pt#/cm^3)	(pt#/cm^3)	(pt#/cm^3)	(pt#/cm^3)
18	CCVS windows closed	11339	13465	4195	59	33596	33215	4070	254
19	CCVS windows closed	NA	NA	4483	759	17133	18945	4421	955
20	CCVS windows closed	2084	2430	6316	2907	11115	9380	6063	2329
21	DPF + CCVS windows closed	16997	17188	9664	-4375	30364	24485	10357	-3370
22	DPF + CCVS windows closed	-928	-1060	11798	400	-1574	-1447.5	11755	605
23	DPF + CCVS windows closed	-743	-890	11270	400	-1224	-978	10756	505
24	DPF windows closed	-3309	-2950	21597	700	-4137	-3800	20999	1200
25	DPF windows closed	2480	4800	12165	490	3034	5893	11495	935
26	DPF windows closed	-3348	-1438	10139	5826	-2917	-1325	9294	4561
27	DPF windows open	-10	-350	8019	1587	-52	-550	7821	1613
28	DPF windows open	1010	1765	13210	8797	1214	1625	13860	10465
29	DPF windows open	-4125	-4450	20897	6577	-5007	-5500	22599	7012
30	DPF + CCVS windows open	2949	3250	19753	3687	3720	4100	21957	4586
31	DPF + CCVS windows open	-5189	-1575	21644	97	-4741	-900	24094	313
32	DPF + CCVS windows open	-4197	-950	19608	4169	-4908	-1450	20735	6405
33	Idle test DPF + CCVS w. closed	574	250	8210	NA	348	-33	7818	NA

Appendix E – P-Trak Ultrafine Particle count results initial study

		Front Average run with ambient subtracted	Front Median run with ambient subtracted	Front Ambient from pre and post average values	Front Pre-Post difference in absolute values	Back Average run with ambient subtracted	Back Median run with ambient subtracted	Back Ambient from pre and post average values	Back Pre-Post difference in absolute values
Run #	Condition Tested	(pt#/cm^3)	(pt#/cm^3)	(pt#/cm^3)	(pt#/cm^3)	(pt#/cm^3)	(pt#/cm^3)	(pt#/cm^3)	(pt#/cm^3)
34	DPF + CCVS windows closed	-107	-350	8210	3596	-1201	-1143	7818	3175
35	FTF + CCVS windows open	4326	2435	9085	2918	3683	1630	9820	1743
36	FTF + CCVS windows open	837	440	9445	2197	976	350	9723	1937
37	FTF + CCVS windows open	-164	-563	8978	1263	-477	-543	9294	1078
38	FTF + CCVS windows closed	26923	28225	25337	18570	35858	40700	28479	20276
39	FTF + CCVS windows closed	28658	29500	33250	2744	34790	40100	36982	3271
40	FTF + CCVS windows closed	888	350	31354	1049	-241	-500	34799	1096
41	FTF windows open	1601	1450	29077	3504	2166	1900	32063	4375
42	FTF windows open	-2339	-2100	21347	11956	-2594	-2150	22942	13867
43	FTF windows closed	43567	50550	2651	548	55927	69383	3163	179
44	FTF windows closed	31474	40245	3097	344	26828	24905	3441	377
45	FTF windows closed	32190	38555	4934	3331	29235	35903	5039	2820
46	FTF windows open	3201	2995	9265	5331	2942	2573	9203	5508
47	DPF + CCVS windows closed	3114	-5540	8689	6126	844	7375	9248	7718
48	DPF + CCVS windows closed	30	203	9318	1028	-514	-315	9167	1596

Appendix E – P-Trak Ultrafine Particle count results initial study

Run #	Condition Tested	Front Average run with ambient subtracted (pt#/cm^3)	Front Median run with ambient subtracted (pt#/cm^3)	Front Ambient from pre and post average values (pt#/cm^3)	Front Pre-Post difference in absolute values (pt#/cm^3)	Back Average run with ambient subtracted (pt#/cm^3)	Back Median run with ambient subtracted (pt#/cm^3)	Back Ambient from pre and post average values (pt#/cm^3)	Back Pre-Post difference in absolute values (pt#/cm^3)
49	DPF + CCVS windows closed	721	1150	13492	5634	202	1000	13370	5719
50	DPF + CCVS windows closed	4161	-1000	11799	2248	-1745	-2520	11720	2418
51	DPF windows closed	-814	-550	11694	2460	-1927	-1605	11637	2584
52	DPF windows closed	-83	0	10567	206	-1012	-890	10380	69
53	DPF windows closed	-316	-230	9475	2390	-648	-705	9028	2772
54	DPF + CCVS windows closed	613	1080	6312	630	499	690	6006	480
55	DPF + CCVS windows closed	1240	1310	6506	888	719	880	6354	1010
56	DPF + CCVS windows closed	1587	1180	6950	NA	328	-150	6735	NA
57	DPF + CCVS windows closed	1794	1340	8232	1964	860	1055	7335	1415
58	DPF + CCVS windows closed	488	670	7170	160	56	310	6614	27
59	DPF + CCVS windows closed	440	495	6566	1048	729	618	6207	787
60	DPF windows closed	2350	1360	5771	540	2082	678	5272	1082
61	DPF windows closed	2356	685	7183	3364	NA	NA	6861	4259
62	DPF windows closed	13073	7580	6770	4189	23250	18120	6739	4503
63	Baseline windows closed	16487	19575	6204	250	27986	32905	5914	210
63	Dust test	-557	-634	6204	NA	-306	-444	5914	NA

Appendix E – P-Trak Ultrafine Particle count results initial study									
		Front Average run with ambient subtracted	Front Median run with ambient subtracted	Front Ambient from pre and post average values	Front Pre-Post difference in absolute values	Back Average run with ambient subtracted	Back Median run with ambient subtracted	Back Ambient from pre and post average values	Back Pre-Post difference in absolute values
Run #	Condition Tested	(pt#/cm^3)	(pt#/cm^3)	(pt#/cm^3)	(pt#/cm^3)	(pt#/cm^3)	(pt#/cm^3)	(pt#/cm^3)	(pt#/cm^3)
64	CCVS windows closed	37623	40878	4781	204	62021	65470	4310	310
65	CCVS windows closed	13729	16075	5541	1315	NA	NA	4757	1204
66	CCVS windows closed	13919	15085	7137	1877	28210	31980	6017	1315
67	Baseline windows closed	12290	13390	7094	1962	26426	30505	5909	1530
68	Baseline windows closed	9159	13578	9927	7628	15340	16548	9649	9010
69	Baseline windows closed	NA	NA	11096	5291	19780	25773	10507	7296

Appendix F: P-Trak Particle Count Concentration Results Raw Data Final Study

Retrofit	Date	Run Time		PT2 Front Run Raw Data	PT3 Back Run Raw Data	PT1 Ambient Monitor Data
	mm/dd/yyyy	start (hr:min:sec)	end (hr:min:sec)	Average Particle Count Concentration (pt#/cm^3)	Average Particle Count Concentration (pt#/cm^3)	Average Particle Count Concentration (pt#/cm^3)
None run 1F	5/28/2008	13:23:08	13:51:54	28318	24461	12046
None run 2F	5/28/2008	14:21:46	14:50:32	20717	19260	12082
None run 3F	5/28/2008	16:42:42	17:11:28	16208	14394	15324
FTF run 4F	5/30/2008	13:47:28	14:16:14	28853	23098	6136
FTF run 5F	5/30/2008	15:09:06	15:37:52	25380	16716	6261
FTF run 6F	5/30/2008	16:23:19	16:52:05	17338	12935	9115
DPF run 7F	6/3/2008	12:05:03	12:33:49	48057	28449	18260
DPF run 8F	6/3/2008	13:21:31	13:50:17	25002	16092	7518
DPF run 9F	6/3/2008	14:53:45	15:22:31	15351	10537	6338
DPF & CCVS run 10F	6/17/2008	13:59:39	14:28:25	14006	12173	9928
DPF & CCVS run 11F	6/17/2008	17:00:02	17:28:48	4745	4091	4450
DPF & CCVS run 12F	6/17/2008	17:54:37	18:23:23	6784	5830	7339
FTF & CCVS run 13F	6/18/2008	NA	NA	NA	NA	NA
CCVS run 14F	6/19/2008	15:45:34	16:14:20	20220	16295	12861
CCVS run 15F	6/19/2008	16:50:10	17:18:56	15812	13165	14591
CCVS run 16F	6/19/2008	17:51:44	18:20:30	14871	12666	13554
FTF & CCVS run 17F	6/20/2008	13:49:56	14:18:42	33338	28424	22709
FTF & CCVS run 18F	6/20/2008	15:44:05	16:12:51	20453	16537	17712
FTF & CCVS run 19F	6/20/2008	17:14:44	17:43:30	13671	11813	12709

Appendix G: P-Trak Particle Count Concentration Results pre and post ambient concentrations final study

Retrofit	Date	PT2 Front Pre & Post Run Ambient	PT3 Back Pre & Post Run Ambient
	mm/dd/yyyy	Average Particle Count Concentration (pt#/cm^3)	Average Particle Count Concentration (pt#/cm^3)
None run 1F	5/28/2008	24845	23737
None run 2F	5/28/2008	20607	20125
None run 3F	5/28/2008	15800	14815
FTF run 4F	5/30/2008	7071	6840
FTF run 5F	5/30/2008	8552	8194
FTF run 6F	5/30/2008	8304	8164
DPF run 7F	6/3/2008	13802	13927
DPF run 8F	6/3/2008	10832	10758
DPF run 9F	6/3/2008	7604	7035
DPF & CCVS run 10F	6/17/2008	12241	12940
DPF & CCVS run 11F	6/17/2008	4887	4880
DPF & CCVS run 12F	6/17/2008	7320	7161
FTF & CCVS run 13F	6/18/2008	NA	NA
CCVS run 14F	6/19/2008	12419	11297
CCVS run 15F	6/19/2008	12871	12006
CCVS run 16F	6/19/2008	11249	11264
FTF & CCVS run 17F	6/20/2008	30643	28811
FTF & CCVS run 18F	6/20/2008	17977	16566
FTF & CCVS run 19F	6/20/2008	12047	11052

Appendix H: DataRAM Results for Volume Median Particle Diameter for Initial Study

Appendix H - Particle Size Data Initial Study

Average Particle Size (µm) reported by the DataRAM-4 instruments

			Background			Front				Back			
Run #	Date - 2007	Condition	Pre (µm)	Post (µm)	Run (µm)	Pre (µm)	Post (µm)	Run (µm)	DataRAM-4 designated	Pre (µm)	Post (µm)	Run (µm)	DataRAM-4 designated
1	21-Feb	Baseline windows open	0.20	0.18	0.17	0.19	0.18	0.51	2	0.22	0.23	0.24	3
2	20-Mar	Baseline windows open	NA	NA	NA	0.29	0.27	0.28	2	0.33	0.27	0.31	3
3	2-Apr	Baseline windows open	0.40	0.47	0.49	0.24	0.25	0.26	2	0.36	0.45	0.45	3
4	2-Apr	Baseline windows closed	0.41	0.46	0.46	0.20	0.22	0.76	2	0.33	0.55	0.97	3
5	2-Apr	Baseline windows closed	0.46	0.37	0.40	0.22	0.20	0.64	2	0.55	0.44	0.92	3
6	3-Apr	Baseline windows closed	0.44	0.46	0.47	0.35	0.33	0.45	2	0.35	0.34	0.54	3
7	3-Apr	Baseline windows open	0.46	0.45	0.48	0.33	0.39	0.36	2	0.34	0.40	0.40	3
8	3-Apr	Baseline windows open	0.40	0.34	0.35	0.36	0.36	0.37	2	0.37	0.34	0.36	3
9	3-Apr	Baseline windows open	0.34	0.32	0.35	0.36	0.32	0.38	2	0.34	0.33	0.37	3
10	3-Apr	Baseline windows open	0.32	0.33	0.32	0.32	0.32	0.43	2	0.33	0.32	0.38	3
11	12-Apr	CCVS windows open	0.23	0.26	0.25	0.20	0.22	0.21	2	0.36	0.34	0.38	3
12	12-Apr	CCVS windows open	0.26	0.32	0.27	0.22	0.28	0.23	2	0.34	0.33	0.40	3
13	12-Apr	CCVS windows open	0.32	0.26	0.28	0.28	0.26	0.31	2	0.33	0.29	0.34	3
14	18-Apr	CCVS windows closed	0.31	0.29	0.28	0.23	0.27	1.31	2	0.55	0.62	1.37	3
15	18-Apr	CCVS windows closed	0.29	0.23	0.28	0.27	0.21	1.21	2	0.62	0.43	1.42	3
16	18-Apr	CCVS windows closed	0.23	0.25	0.27	0.21	0.26	1.05	2	0.43	0.72	1.21	3

Appendix H - Particle Size Data Initial Study

Average Particle Size (µm) reported by the DataRAM-4 instruments

			Background			Front				Back			
Run #	Date - 2007	Condition	Pre (µm)	Post (µm)	Run (µm)	Pre (µm)	Post (µm)	Run (µm)	DataRAM-4 designated	Pre (µm)	Post (µm)	Run (µm)	DataRAM-4 designated
17	18-Apr	Baseline windows closed	0.20	0.19	0.17	0.17	0.14	0.83	2	0.48	0.59	1.15	3
18	24-Apr	CCVS windows closed	NA	0.22	0.23	0.18	0.17	0.44	2	0.22	0.23	0.55	3
19	24-Apr	CCVS windows closed	0.22	0.21	0.22	0.17	0.17	0.34	2	0.23	0.20	1.22	3
20	24-Apr	CCVS windows closed	0.21	0.21	0.21	0.17	0.18	0.28	2	0.20	0.25	1.15	3
21	7-May	DPF + CCVS windows closed	NA	NA	NA	0.27	0.32	0.76	2	0.47	0.63	0.23	1
22	7-May	DPF + CCVS windows closed	NA	NA	NA	0.32	0.29	0.73	2	0.63	0.51	NA	1
23	7-May	DPF + CCVS windows closed	NA	NA	NA	0.29	0.28	0.65	2	0.51	0.51	1.30	1
24	7-May	DPF windows closed	NA	NA	NA	0.31	0.30	0.80	2	0.48	0.53	1.10	1
25	8-May	DPF windows closed	NA	NA	NA	0.29	0.34	0.96	2	0.33	0.37	0.89	1
26	8-May	DPF windows closed	NA	NA	NA	0.34	0.44	0.83	2	0.37	0.53	0.96	1
27	8-May	DPF windows open	NA	NA	NA	0.44	0.40	0.55	2	0.53	0.40	0.66	1
28	8-May	DPF windows open	NA	NA	NA	0.40	0.33	0.55	2	0.40	0.44	1.05	1
29	8-May	DPF windows open	NA	NA	NA	0.33	0.39	0.55	2	0.44	0.52	0.90	1
30	8-May	DPF + CCVS windows open	NA	NA	NA	0.45	0.41	0.62	2	0.62	0.55	0.67	1
31	8-May	DPF + CCVS windows open	NA	NA	NA	0.41	0.51	0.36	2	0.55	0.57	0.67	1
32	8-May	DPF + CCVS windows open	NA	NA	NA	0.51	0.37	0.50	2	0.57	0.57	0.68	1

Appendix H - Particle Size Data Initial Study

Average Particle Size (µm) reported by the DataRAM-4 instruments

			Background			Front				Back			
Run #	Date - 2007	Condition	Pre (µm)	Post (µm)	Run (µm)	Pre (µm)	Post (µm)	Run (µm)	DataRAM-4 designated	Pre (µm)	Post (µm)	Run (µm)	DataRAM-4 designated
33	14-May	Idle test DPF + CCVS windows closed	NA	NA	NA	NA	NA	0.47	2	NA	NA	0.71	1
34	14-May	DPF + CCVS windows closed	NA	NA	NA	0.23	0.21	0.42	2	0.49	0.37	0.84	1
35	16-May	FTF + CCVS windows open	NA	NA	NA	0.23	0.21	0.29	2	0.31	0.31	0.40	1
36	16-May	FTF + CCVS windows open	NA	NA	NA	0.21	0.20	0.27	2	0.31	0.27	0.40	1
37	16-May	FTF + CCVS windows open	NA	NA	NA	0.20	0.20	0.23	2	0.27	0.31	0.31	1
38	17-May	FTF + CCVS windows closed	NA	NA	NA	0.18	0.18	0.48	2	0.25	0.30	0.62	1
39	17-May	FTF + CCVS windows closed	NA	NA	NA	0.18	0.15	0.38	2	0.30	0.26	0.61	1
40	17-May	FTF + CCVS windows closed	NA	NA	NA	0.15	0.17	0.31	2	0.26	0.29	0.44	1
41	17-May	FTF windows open	NA	NA	NA	0.17	0.19	0.22	2	0.29	0.34	0.37	1
42	17-May	FTF windows open	NA	NA	NA	0.19	0.16	0.21	2	0.34	0.32	0.41	1
43	21-May	FTF windows closed	NA	NA	NA	0.17	0.16	0.48	2	0.27	0.70	0.70	1
44	21-May	FTF windows closed	NA	NA	NA	0.16	0.16	0.35	2	0.70	0.34	0.64	1
45	21-May	FTF windows closed	NA	NA	NA	0.16	0.19	0.44	2	0.34	0.29	0.67	1
46	21-May	FTF windows open	NA	NA	NA	0.19	0.18	0.25	2	0.29	0.30	0.47	1
47	31-May	DPF + CCVS windows closed	NA	NA	NA	0.21	0.23	0.32	2	0.26	0.29	0.45	1
48	4-Jun	DPF + CCVS windows closed	0.11	0.10	NA	0.26	0.27	0.41	2	0.32	0.33	0.58	3

Appendix H - Particle Size Data Initial Study

Average Particle Size (µm) reported by the DataRAM-4 instruments

			Background			Front				Back			
Run #	Date - 2007	Condition	Pre (µm)	Post (µm)	Run (µm)	Pre (µm)	Post (µm)	Run (µm)	DataRAM-4 designated	Pre (µm)	Post (µm)	Run (µm)	DataRAM-4 designated
49	5-Jun	DPF + CCVS windows closed	NA	NA	NA	0.16	0.17	0.33	2	0.56	0.48	0.93	3
50	5-Jun	DPF + CCVS windows closed	NA	NA	NA	0.17	0.15	0.45	2	0.48	0.56	1.05	3
51	5-Jun	DPF windows closed	NA	NA	NA	0.15	0.14	0.42	2	0.56	0.47	0.77	3
52	5-Jun	DPF windows closed	NA	NA	NA	0.14	0.13	0.37	2	0.47	0.46	0.81	3
53	5-Jun	DPF windows closed	NA	NA	NA	0.13	0.11	0.32	2	0.46	0.42	0.74	3
54	7-Jun	DPF + CCVS windows closed	NA	NA	NA	0.34	0.38	0.69	1	0.24	0.27	0.61	3
55	7-Jun	DPF + CCVS windows closed	NA	NA	NA	0.38	NA	0.46	1	NA	NA	0.40	3
56	7-Jun	DPF + CCVS windows closed	NA	NA	NA	0.33	NA	0.47	1	0.26	NA	0.33	3
57	13-Jun	DPF + CCVS windows closed	NA	NA	NA	0.35	0.37	0.41	1	0.30	1.01	0.23	3
58	13-Jun	DPF + CCVS windows closed	NA	NA	NA	0.37	0.30	0.38	1	1.01	1.65	0.56	3
59	13-Jun	DPF + CCVS windows closed	NA	NA	NA	0.30	0.28	0.35	1	1.65	3.58	0.81	3
60	13-Jun	DPF windows closed	NA	NA	NA	0.28	0.29	0.50	1	3.58	0.28	0.38	3
61	13-Jun	DPF windows closed	NA	NA	NA	0.29	0.29	0.46	1	0.28	0.27	0.38	3
62	13-Jun	DPF windows closed	NA	NA	NA	0.29	0.30	0.53	1	0.27	0.38	0.48	3
63	18-Jun	Baseline windows closed	0.25	0.25	0.26	0.23	0.20	0.37	2	0.28	0.19	0.35	3
63b	18-Jun	Dust test	NA	NA	0.50	NA	NA	0.40	2	NA	NA	0.31	3
64	22-Aug	CCVS windows closed	0.26	0.27	0.26	0.22	0.21	0.49	2	0.42	0.43	0.69	3

Appendix H - Particle Size Data Initial Study

Average Particle Size (μm) reported by the DataRAM-4 instruments

			Background			Front				Back			
Run #	Date - 2007	Condition	Pre (μm)	Post (μm)	Run (μm)	Pre (μm)	Post (μm)	Run (μm)	DataRAM-4 designated	Pre (μm)	Post (μm)	Run (μm)	DataRAM-4 designated
65	22-Aug	CCVS windows closed	0.27	0.28	0.28	0.21	0.22	0.44	2	0.43	0.44	0.72	3
66	22-Aug	CCVS windows closed	0.28	0.29	0.30	0.22	0.23	0.49	2	0.44	0.43	0.69	3
67	22-Aug	Baseline windows closed	0.29	0.37	0.32	0.23	0.31	0.45	2	0.43	0.41	0.67	3
68	22-Aug	Baseline windows closed	0.37	0.38	0.37	0.31	0.28	0.49	2	0.41	0.49	0.64	3
69	22-Aug	Baseline windows closed	0.38	0.33	0.36	0.28	0.23	0.50	2	0.49	0.37	0.70	3

Appendix I: DataRAM Results for Volume Median Particle Diameter for Final Runs

Retrofit	Date	Run Time		DR1 Front Run Data	DR3 Back Run Data	DR2 Ambient Monitor Data
	mm/dd/yyyy	start (hr:min:sec)	end (hr:min:sec)	Average Volume Median Particle Diameter (µm)	Average Volume Median Particle Diameter (µm)	Average Volume Median Particle Diameter (µm)
None run 1F	5/28/2008	13:23:08	13:51:54	0.60	0.50	0.28[6]
None run 2F	5/28/2008	14:21:46	14:50:32	0.59	0.44	0.29[7]
None run 3F	5/28/2008	16:42:42	17:11:28	0.72	0.51	0.30
FTF run 4F	5/30/2008	13:47:28	14:16:14	0.34	0.29	0.21
FTF run 5F	5/30/2008	15:09:06	15:37:52	0.38	0.27	0.19[8]
FTF run 6F	5/30/2008	16:23:19	16:52:05	0.32	0.24	0.19[9]
DPF run 7F	6/3/2008	12:05:03	12:33:49	0.37	0.30	0.13
DPF run 8F	6/3/2008	13:21:31	13:50:17	0.29	0.36	0.15
DPF run 9F	6/3/2008	14:53:45	15:22:31	0.39	0.40	0.15
DPF & CCVS run 10F	6/17/2008	13:59:39	14:28:25	0.21	0.25	0.19
DPF & CCVS run 11F	6/17/2008	17:00:02	17:28:48	0.25	0.38	0.15
DPF & CCVS run 12F	6/17/2008	17:54:37	18:23:23	0.21	0.22	0.12
FTF & CCVS run 13F	6/18/2008	NA	NA	NA	NA	NA
CCVS run 14F	6/19/2008	15:45:34	16:14:20	0.26	0.21	0.18
CCVS run 15F	6/19/2008	16:50:10	17:18:56	0.25	0.19	0.16
CCVS run 16F	6/19/2008	17:51:44	18:20:30	0.22	0.18	0.16
FTF & CCVS run 17F	6/20/2008	13:49:56	14:18:42	0.20	0.20	0.14
FTF & CCVS run 18F	6/20/2008	15:44:05	16:12:51	0.23	0.23	0.15
FTF & CCVS run 19F	6/20/2008	17:14:44	17:43:30	0.18	0.22	0.14

[6] Used only average from 13:23:08 to 13:33:33hrs because battery died during the run.
[7] Averaged 14min and 23sec of pre run, with 14min and 23sec of post run.
[8] Measured only 1594 seconds during the run instead of normal run length of 1727s, because battery died.
[9] Used the pre run ambient, because battery died before the run started.

Appendix J: SEMTECH-D Gas Emissions Results Initial Study

Appendix J - Semtech-D results for gaseous emissions initial study						
		Cumulative brake specific CO_2 emissions	Cumulative break specific CO emissions	Corrected cumulative break specific NO emissions	Corrected cumulative break specific NO_2 emissions	Cumulative break specific HC emissions
Run #	Condition	g/bhp-hr	g/bhp-hr	g/bhp-hr	g/bhp-hr	g/bhp-hr
1	Baseline windows open	900.29	0.87	6.68	0.60	0.54
2	Baseline windows open	851.88	0.76	6.56	0.62	0.69
3	Baseline windows open	913.89	0.89	7.17	0.52	0.48
4	Baseline windows closed	NA	NA	NA	NA	NA
5	Baseline windows closed	940.46	0.92	7.95	0.59	0.40
6	Baseline windows closed	785.61	0.80	6.14	0.47	0.40
7	Baseline windows open	963.42	0.65	6.99	0.47	0.51
8	Baseline windows open	NA	NA	NA	NA	NA
9	Baseline windows open	NA	NA	NA	NA	NA
10	Baseline windows open	NA	NA	NA	NA	NA
11	CCVS windows open	916.58	1.11	6.51	0.41	0.47
12	CCVS windows open	991.13	1.32	7.51	0.41	0.44
13	CCVS windows open	807.81	1.12	6.50	0.35	0.37
14	CCVS windows closed	891.08	1.10	5.94	0.47	0.43
15	CCVS windows closed	767.17	0.93	6.31	0.47	0.34

Appendix J - Semtech-D results for gaseous emissions initial study

		Cumulative brake specific CO_2 emissions	Cumulative break specific CO emissions	Corrected cumulative break specific NO emissions	Corrected cumulative break specific NO_2 emissions	Cumulative break specific HC emissions
Run #	Condition	g/bhp-hr	g/bhp-hr	g/bhp-hr	g/bhp-hr	g/bhp-hr
16	CCVS windows closed	844.36	0.99	6.90	0.55	0.38
17	Baseline windows closed	879.19	0.89	6.57	0.50	0.37
18	CCVS windows closed	821.96	1.27	6.84	0.51	0.35
19	CCVS windows closed	807.26	1.14	6.85	0.61	0.33
20	CCVS windows closed	922.39	1.20	8.25	0.68	0.34
21	DPF + CCVS windows closed	875.62	0.30	3.34	3.61	0.03
22	DPF + CCVS windows closed	963.02	0.26	4.14	4.42	0.01
23	DPF + CCVS windows closed	1035.28	0.40	4.60	4.71	0.01
24	DPF windows closed	823.26	0.51	3.66	3.75	0.01
25	DPF windows closed	865.73	0.61	3.31	3.38	0.03
26	DPF windows closed	937.88	0.46	3.77	4.54	0.00
27	DPF windows open	897.99	0.32	4.02	3.93	0.02
28	DPF windows open	831.27	0.55	3.62	3.61	0.03
29	DPF windows open	916.23	0.57	4.00	3.95	0.03
30	DPF + CCVS windows open	750.23	0.40	3.59	3.37	0.03

Appendix J - Semtech-D results for gaseous emissions initial study

		Cumulative brake specific CO_2 emissions	Cumulative break specific CO emissions	Corrected cumulative break specific NO emissions	Corrected cumulative break specific NO_2 emissions	Cumulative break specific HC emissions
Run #	Condition	g/bhp-hr	g/bhp-hr	g/bhp-hr	g/bhp-hr	g/bhp-hr
31	DPF + CCVS windows open	809.91	0.40	3.76	3.84	0.00
32	DPF + CCVS windows open	859.09	0.38	4.08	4.10	0.00
34	DPF + CCVS windows closed	896.75	0.58	3.75	3.40	0.10
35	FTF + CCVS windows open	823.09	0.14	5.63	1.86	0.03
36	FTF + CCVS windows open	824.69	0.56	5.37	1.93	0.02
37	FTF + CCVS windows open	747.40	1.13	4.84	1.70	0.01
38	FTF + CCVS windows closed	820.60	0.61	5.56	1.65	0.16
39	FTF + CCVS windows closed	898.15	0.80	6.13	2.12	0.06
40	FTF + CCVS windows closed	817.36	1.12	5.03	2.17	0.00
41	FTF windows open	842.82	0.94	5.64	1.93	0.03
42	FTF windows open	898.39	2.09	5.91	1.93	0.05
43	FTF windows closed	811.80	1.32	5.11	1.84	0.21
44	FTF windows closed	781.04	0.96	4.98	2.05	0.02
45	FTF windows closed	931.02	1.19	6.01	2.55	0.03

Appendix J - Semtech-D results for gaseous emissions initial study

		Cumulative brake specific CO_2 emissions	Cumulative break specific CO emissions	Corrected cumulative break specific NO emissions	Corrected cumulative break specific NO_2 emissions	Cumulative break specific HC emissions
Run #	Condition	g/bhp-hr	g/bhp-hr	g/bhp-hr	g/bhp-hr	g/bhp-hr
46	FTF windows open	838.60	0.95	5.54	2.04	0.03
47	DPF + CCVS windows closed	965.92	0.79	3.84	4.08	0.02
48	DPF + CCVS windows closed	898.40	0.66	3.36	4.31	0.01
49	DPF + CCVS windows closed	831.57	0.28	3.37	3.27	0.03
50	DPF + CCVS windows closed	912.88	0.93	3.21	3.93	0.00
51	DPF windows closed	901.20	0.48	3.76	3.50	0.02
52	DPF windows closed	961.59	0.92	3.48	4.25	0.00
53	DPF windows closed	849.53	0.75	3.09	3.83	0.00
54	DPF + CCVS windows closed	918.75	1.16	3.54	3.74	0.01
55	DPF + CCVS windows closed	817.71	0.99	3.44	3.38	0.00
56	DPF + CCVS windows closed	913.47	0.97	3.96	3.77	0.00
57	DPF + CCVS windows closed	877.49	0.82	4.14	3.85	0.00
58	DPF + CCVS windows closed	952.17	1.56	4.61	3.88	0.00
59	DPF + CCVS windows closed	900.78	0.73	4.68	3.84	0.00

Appendix J - Semtech-D results for gaseous emissions initial study

		Cumulative brake specific CO_2 emissions	Cumulative break specific CO emissions	Corrected cumulative break specific NO emissions	Corrected cumulative break specific NO_2 emissions	Cumulative break specific HC emissions
Run #	Condition	g/bhp-hr	g/bhp-hr	g/bhp-hr	g/bhp-hr	g/bhp-hr
60	DPF windows closed	912.76	1.04	4.58	3.77	0.00
61	DPF windows closed	817.49	0.54	4.69	2.87	0.00
62	DPF windows closed	NA	NA	NA	NA	NA
63	Baseline windows closed	867.38	1.72	7.71	0.42	0.35
64	CCVS windows closed	922.98	2.75	9.74	0.34	NA
65	CCVS windows closed	952.36	2.25	10.36	0.55	NA
66	CCVS windows closed	895.59	2.08	10.03	0.56	NA
67	Baseline windows closed	984.61	2.34	11.34	0.66	NA
68	Baseline windows closed	938.65	2.13	10.37	0.58	NA
69	Baseline windows closed	953.46	2.04	10.73	0.64	NA

Appendix K: SEMTECH-D Gas Emissions Results Final Study

Retrofit	Date	CO2	CO	NOx Corrected[10]	HC
	mm/dd/yyyy	(g/bhp-hr)	(g/bhp-hr)	(g/bhp-hr)	(g/bhp-hr)
None run 1F	5/28/2008	605.0	0.95	6.20	0.373
None run 2F	5/28/2008	615.0	0.90	6.25	0.357
None run 3F	5/28/2008	623.0	1.05	6.28	0.417
FTF run 4F	5/30/2008	605.6	0.33	6.08	0.034
FTF run 5F	5/30/2008	613.3	0.48	6.07	0.032
FTF run 6F	5/30/2008	612.0	0.40	6.31	0.026
DPF run 7F	6/3/2008	606.5	0.49	6.48	0.013
DPF run 8F	6/3/2008	611.8	0.36	6.28	0.014
DPF run 9F	6/3/2008	611.1	0.39	6.39	0.013
DPF & CCVS run 10F	6/17/2008	615.5	0.32	6.23	0.012
DPF & CCVS run 11F	6/17/2008	614.8	0.51	6.07	0.041
DPF & CCVS run 12F	6/17/2008	614.8	0.19	6.33	0.009
FTF & CCVS run 13F	6/18/2008	NA	NA	NA	NA
CCVS run 14F	6/19/2008	607.8	1.08	6.22	0.310
CCVS run 15F	6/19/2008	611.4	1.05	6.02	0.316
CCVS run 16F	6/19/2008	612.0	0.97	6.21	0.316
FTF & CCVS run 17F	6/20/2008	604.7	0.77	5.64	0.038
FTF & CCVS run 18F	6/20/2008	613.8	0.31	6.38	0.032
FTF & CCVS run 19F	6/20/2008	615.3	0.47	5.70	0.025

[10] Correction for humidity performed by SEMTECH-D software following the CFR40-86.1342-94 method.

Appendix L: SEMTECH-D Engine Parameter Results Final Study

Retrofit	Date	Average oil temperature	Total Cycle Work	Average Oil Pressure	Average Boost Pressure
	mm/dd/yyyy	(ºF)	(bhp-hr)	(kPa)	(kPa)
None run 1F	5/28/2008	200.0	35.9	288.8	38.5
None run 2F	5/28/2008	204.5	34.7	282.7	37.3
None run 3F	5/28/2008	205.9	34.5	282.4	35.9
FTF run 4F	5/30/2008	197.8	35.3	298.4	34.3
FTF run 5F	5/30/2008	203.5	35.5	286.0	34.4
FTF run 6F	5/30/2008	206.1	35.7	282.9	34.4
DPF run 7F	6/3/2008	193.5	34.9	298.1	34.5
DPF run 8F	6/3/2008	204.2	35.3	284.0	35.0
DPF run 9F	6/3/2008	202.7	35.5	286.1	35.2
DPF & CCVS run 10F	6/17/2008	209.1	34.1	277.1	34.6
DPF & CCVS run 11F	6/17/2008	205.7	35.4	273.9	35.6
DPF & CCVS run 12F	6/17/2008	208.4	34.5	273.8	34.7
FTF & CCVS run 13F	6/18/2008	NA	NA	NA	NA
CCVS run 14F	6/19/2008	198.9	34.8	288.8	37.8
CCVS run 15F	6/19/2008	206.5	35.4	279.3	38.1
CCVS run 16F	6/19/2008	207.5	35.4	278.1	38.3
FTF & CCVS run 17F	6/20/2008	198.5	34.9	291.1	34.2
FTF & CCVS run 18F	6/20/2008	207.0	35.5	279.5	34.0
FTF & CCVS run 19F	6/20/2008	211.9	34.8	273.4	34.5

Appendix M: Weather Conditions from Portable Weather Data Initial Study

Appendix M - Weather Conditions initial study											
Date	Run No.	Run Direction	Test Condition	WS	WD	Peak WS	Average	Maximum	Minimum	Dew Point	RH
		On mile loop		(m/s)	(°)	(m/s)	Temp. (°C)	Temp. (°C)	Temp. (°C)	Temp. (°C)	(%)
21-Feb	1	Clock Wise	Baseline windows open	2.6	316.0	5.2	9.1	NA	NA	1.7	60.2
20-Mar	2	CW	Baseline windows open	3.8	308.3	7.1	13.9	14.2	13.6	0.7	41.0
2-Apr	3	CW	Baseline windows open	1.9	139.6	4.6	19.8	20.3	19.4	11.6	59.3
2-Apr	4	Counter Clock Wise	Baseline windows closed	3.7	230.9	8.3	23.6	24.	23.1	9.7	42.2
2-Apr	5	CCW	Baseline windows closed	5.5	263.9	11.8	25.7	26.1	25.4	6.6	29.5
3-Apr	6	CW	Baseline windows closed	2.1	69.5	4.9	9.5	9.8	9.2	8.3	92.4
3-Apr	7	CW	Baseline windows open	2.2	105.5	4.8	12.2	12.6	11.8	8.8	80.1
3-Apr	8	CCW	Baseline windows open	2.0	120.6	4.5	14.8	15.2	14.4	9.2	69.2
3-Apr	9	CCW	Baseline windows open	2.1	120.2	4.9	15.6	16.0	15.2	9.4	66.5
3-Apr	10	CCW	Baseline windows open	2.3	135.	4.9	16.6	17.0	16.3	9.3	61.9
12-Apr	11	CCW	CCVS windows open	1.7	158.2	3.9	12.8	13.3	12.4	8.8	76.4
12-Apr	12	CCW	CCVS windows open	1.7	83.1	4.2	14.	14.5	13.5	8.8	71.0
12-Apr	13	CCW	CCVS windows open	2.0	70.0	3.4	14.7	15.3	14.2	8.8	67.6
18-Apr	14	CW	CCVS windows closed	1.6	69.1	5.9	9.0	9.2	8.8	2.5	63.6
18-Apr	15	CW	CCVS windows closed	1.9	207.7	4.3	9.3	9.4	9.1	2.6	63.2

Appendix M - Weather Conditions initial study

Date	Run No.	Run Direction	Test Condition	WS	WD	Peak WS	Average	Maximum	Minimum	Dew Point	RH
		On mile loop		(m/s)	(°)	(m/s)	Temp. (°C)	Temp. (°C)	Temp. (°C)	Temp. (°C)	(%)
18-Apr	16	CW	CCVS windows closed	1.9	296.5	4.1	9.6	9.8	9.4	2.8	62.8
18-Apr	17	CCW	Baseline windows closed	1.2	140.9	3.9	10.7	10.9	10.5	3.3	59.9
24-Apr	18	CW	CCVS windows closed	3.6	290.6	6.5	15.6	15.9	15.2	8.2	67.8
24-Apr	19	CW	CCVS windows closed	3.1	280.7	4.6	14.4	14.8	14.0	9.1	70.8
24-Apr	20	CW	CCVS windows closed	4.3	293.4	4.4	12.3	12.6	12.0	6.2	66.6
7-May	21	CW	DPF + CCVS windows closed	2.4	50.9	6.3	16.6	19.6	18.7	5.9	50.7
7-May	22	CW	DPF + CCVS windows closed	2.7	54.6	7.4	19.7	20.1	19.3	9.1	55.9
7-May	23	CW	DPF + CCVS windows closed	2.5	61.1	5.3	14.5	14.9	14.1	8.1	67.8
7-May	24	CCW	DPF windows closed	2.5	75.2	4.7	11.9	12.2	11.6	5.3	65.1
8-May	25	CW	DPF windows closed	1.5	90.0	3.4	12.0	12.4	11.7	4.3	59.2
8-May	26	CW	DPF windows closed	1.7	72.6	3.9	14.3	14.8	13.80	5.4	55.0
8-May	27	CW	DPF windows open	1.7	81.9	3.4	15.6	16.0	15.2	5.7	51.8
8-May	28	CW	DPF windows open	1.7	88.6	3.3	16.5	16.9	16.2	5.2	47.2
8-May	29	CW	DPF windows open	1.7	100.1	4.0	18.5	18.8	18.1	8.0	50.6
8-May	30	CCW	DPF + CCVS windows open	1.4	164.7	4.2	20.4	20.7	20.1	10.6	53.4
8-May	31	CCW	DPF + CCVS windows open	1.7	166.5	4.9	21.4	21.8	21.0	11.3	52.6

Appendix M - Weather Conditions initial study											
Date	Run No.	Run Direction	Test Condition	WS	WD	Peak WS	Average	Maximum	Minimum	Dew Point	RH
		On mile loop		(m/s)	(°)	(m/s)	Temp. (°C)	Temp. (°C)	Temp. (°C)	Temp. (°C)	(%)
8-May	32	CCW	DPF + CCVS windows open	1.4	197.0	4.8	22.4	22.7	22.1	12.0	51.9
14-May	33	CW	Idle test DPF + CCVS windows closed	2.1	98.5	4.7	14.9	15.3	14.6	6.2	57.4
14-May	34	CW	DPF + CCVS windows closed	2.2	99.7	3.9	18.5	18.8	18.1	8.2	51.1
16-May	35	ccw	FTF + CCVS windows open	6.5	167	9.3	26.7	27.0	26.4	16.8	54.8
16-May	36	ccw	FTF + CCVS windows open	7.6	161	10.4	27.1	27.5	26.9	16.6	52.4
16-May	37	ccw	FTF + CCVS windows open	8.3	158	11.3	27.4	27.8	27.1	16.6	51.6
17-May	38	cw	FTF + CCVS windows closed	2.1	262	4.0	16.8	17.2	16.5	11.5	70.8
17-May	39	cw	FTF + CCVS windows closed	2.1	202	3.9	17.6	18.0	17.3	11.2	66.0
17-May	40	cw	FTF + CCVS windows closed	2.3	151	4.2	18.1	18.5	17.9	10.7	61.8
17-May	41	cw	FTF windows open	2.3	238	4.5	18.9	19.3	18.5	9.3	53.8
17-May	42	cw	FTF windows open	2.3	289	4.5	19.4	19.8	19.1	8.2	47.9
21-May	43	cw	FTF windows closed	3.0	330	6.0	16.2	16.5	15.9	6.0	51.0
21-May	44	cw	FTF windows closed	2.9	326	5.9	16.9	17.2	16.5	6.3	49.6
21-May	45	cw	FTF windows closed	3.0	323	6.1	17.5	17.8	17.2	6.6	48.8
21-May	46	cw	FTF windows open	3.0	315	6.2	18.6	18.9	18.2	7.0	46.7

Appendix M - Weather Conditions initial study

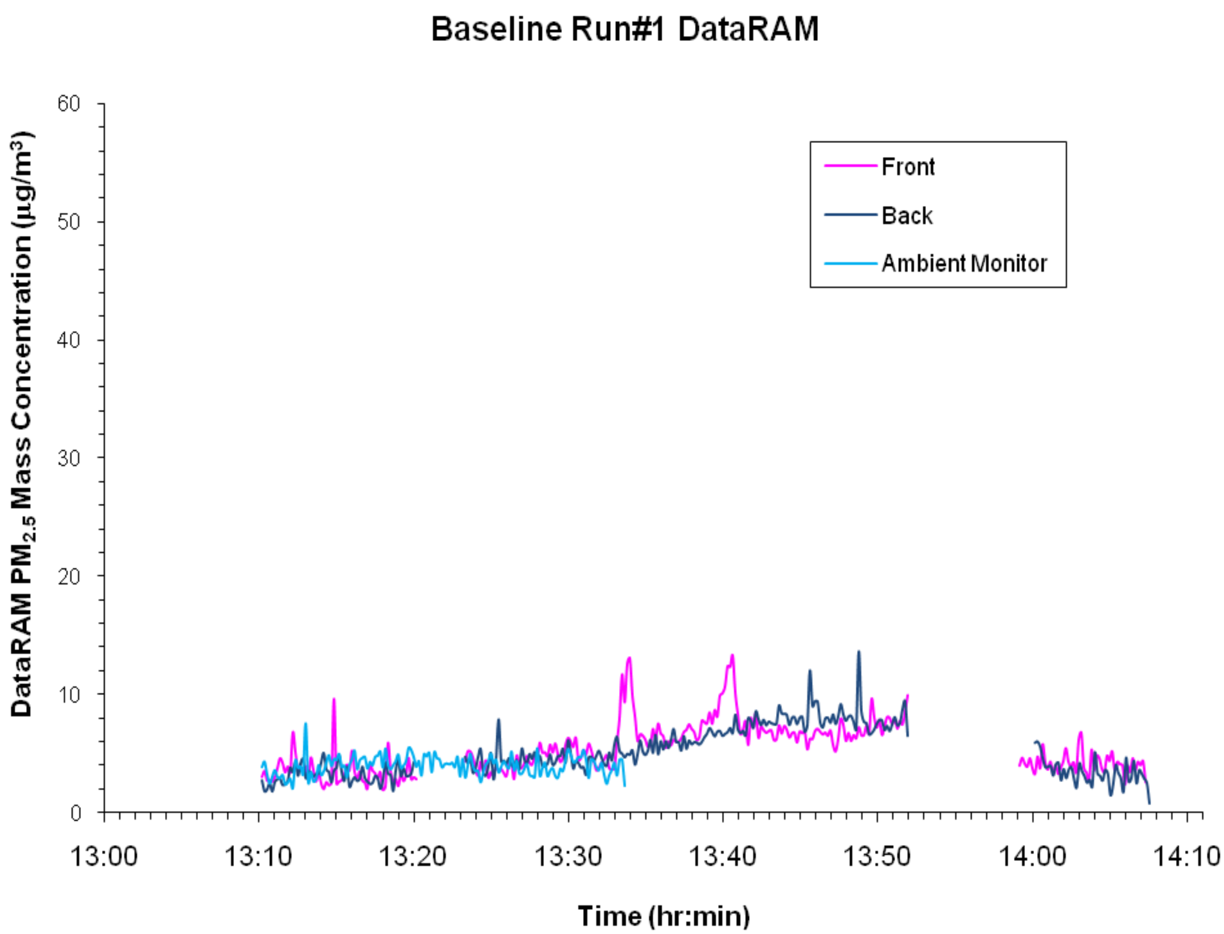
Date	Run No.	Run Direction	Test Condition	WS	WD	Peak WS	Average	Maximum	Minimum	Dew Point	RH
		On mile loop		(m/s)	(°)	(m/s)	Temp. (°C)	Temp. (°C)	Temp. (°C)	Temp. (°C)	(%)
31-May	47	ccw	DPF + CCVS windows closed	3.3	200	4.8	30.2	30.4	29.9	19.4	52.4
4-Jun	48	ccw	DPF + CCVS windows closed	4.4	255.0	7.3	28.1	28.3	27.8	18.3	55.4
5-Jun	49	cw	DPF + CCVS windows closed	3.0	242.6	9.2	25.82	26.4	25.3	15.0	51.2
5-Jun	50	ccw	DPF + CCVS windows closed	4.0	251.9	10.0	26.3	27.0	25.6	14.8	49.3
5-Jun	51	ccw	DPF windows closed	3.8	253.0	10.1	26.4	26.8	26.0	14.1	46.7
5-Jun	52	ccw	DPF windows closed	4.0	252.5	9.6	26.0	26.2	25.7	13.6	46.4
5-Jun	53	ccw	DPF windows closed	3.7	256.2	9.5	26.7	27.1	26.3	13.7	44.8
7-Jun	54	CCW	DPF + CCVS windows closed	1.8	170.0	6.0	26.2	26.6	25.8	16.9	56.9
7-Jun	55	CCW	DPF + CCVS windows closed	2.02	170.6	5.7	27.0	27.4	26.7	15.2	48.5
7-Jun	56	CCW	DPF + CCVS windows closed	1.4	172.0	5.3	27.4	27.6	27.2	16.7	51.9
13-Jun	57	cw	DPF + CCVS windows closed	1.2	170.7	2.3	23.0	23.4	22.6	19.9	83.1
13-Jun	58	cw	DPF + CCVS windows closed	1.2	107.0	2.9	23.9	24.3	23.5	19.3	75.8
13-Jun	59	cw	DPF + CCVS windows closed	1.5	110.7	3.9	24.7	25.2	24.4	19.2	71.4
13-Jun	60	cw	DPF windows closed	2.0	71.3	5.3	25.3	25.6	24.9	19.5	70.2
13-Jun	61	ccw	DPF windows closed	2.0	111.7	5.6	25.4	25.8	25.0	18.7	66.8

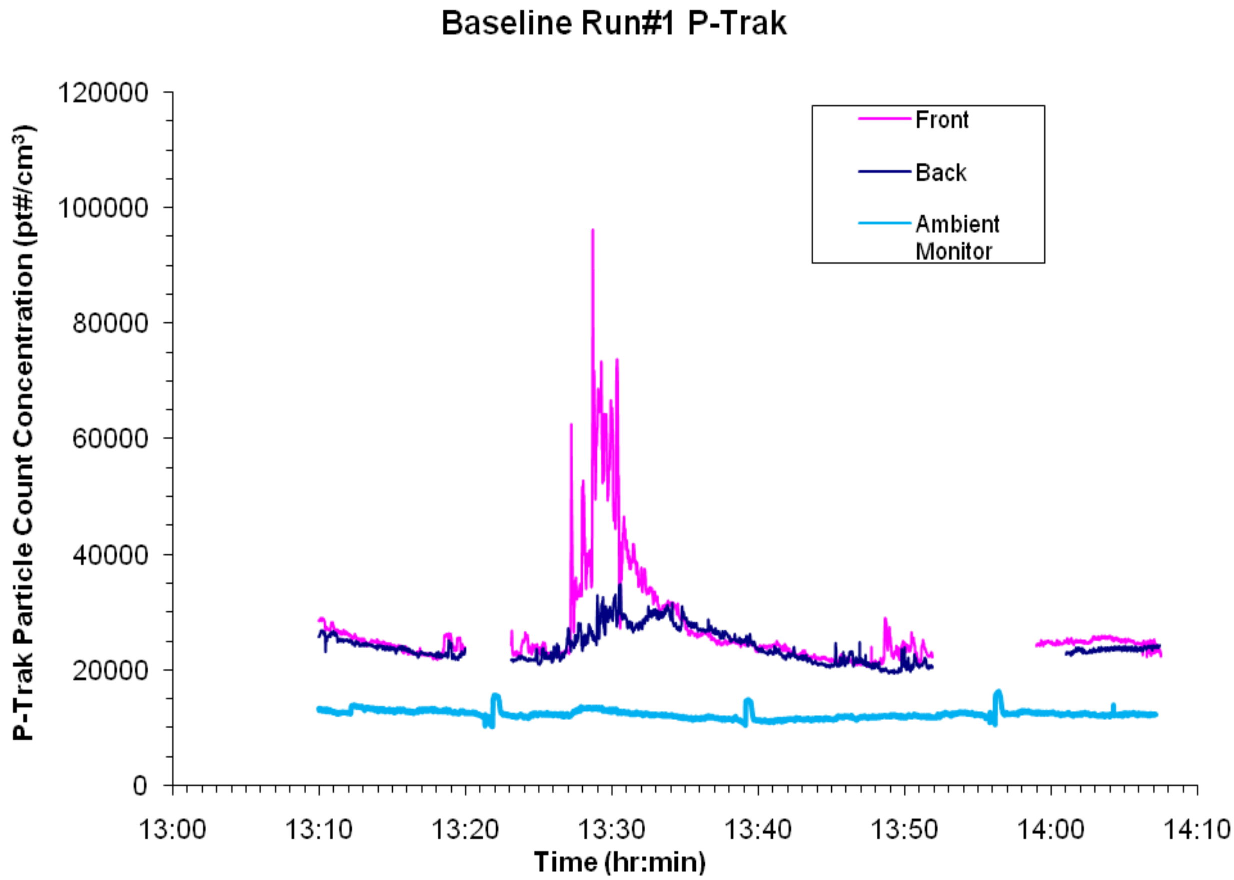
Appendix M - Weather Conditions initial study											
Date	Run No.	Run Direction	Test Condition	WS	WD	Peak WS	Average	Maximum	Minimum	Dew Point	RH
		On mile loop		(m/s)	(°)	(m/s)	Temp. (°C)	Temp. (°C)	Temp. (°C)	Temp. (°C)	(%)
13-Jun	62	CCW	DPF windows closed	1.9	123.8	5.1	26.2	26.6	25.9	18.0	60.6
18-Jun	63	CW	Baseline windows closed	2.3	83.1	3.8	29.2	29.6	28.8	17.8	51.2
22-Aug	64	ccw	CCVS windows closed	2.9	65.0	4.2	20.7	20.9	20.6	18.4	86.5
22-Aug	65	CCW	CCVS windows closed	2.7	68.3	4.0	21.0	21.2	20.8	18.5	85.7
22-Aug	66	CCW	CCVS windows closed	2.7	67.0	3.9	20.9	21.1	20.8	18.5	86.0
22-Aug	67	CCW	Baseline windows closed	2.8	65.0	4.1	21.0	21.2	20.9	18.5	85.7
22-Aug	68	CCW	Baseline windows closed	2.8	68.0	3.8	20.9	21.0	20.7	18.5	86.3
22-Aug	69	CCW	Baseline windows closed	3.1	64.3	4.0	20.7	20.9	20.6	18.5	87.0

Appendix N: Weather Conditions from Portable Weather Data Final Study

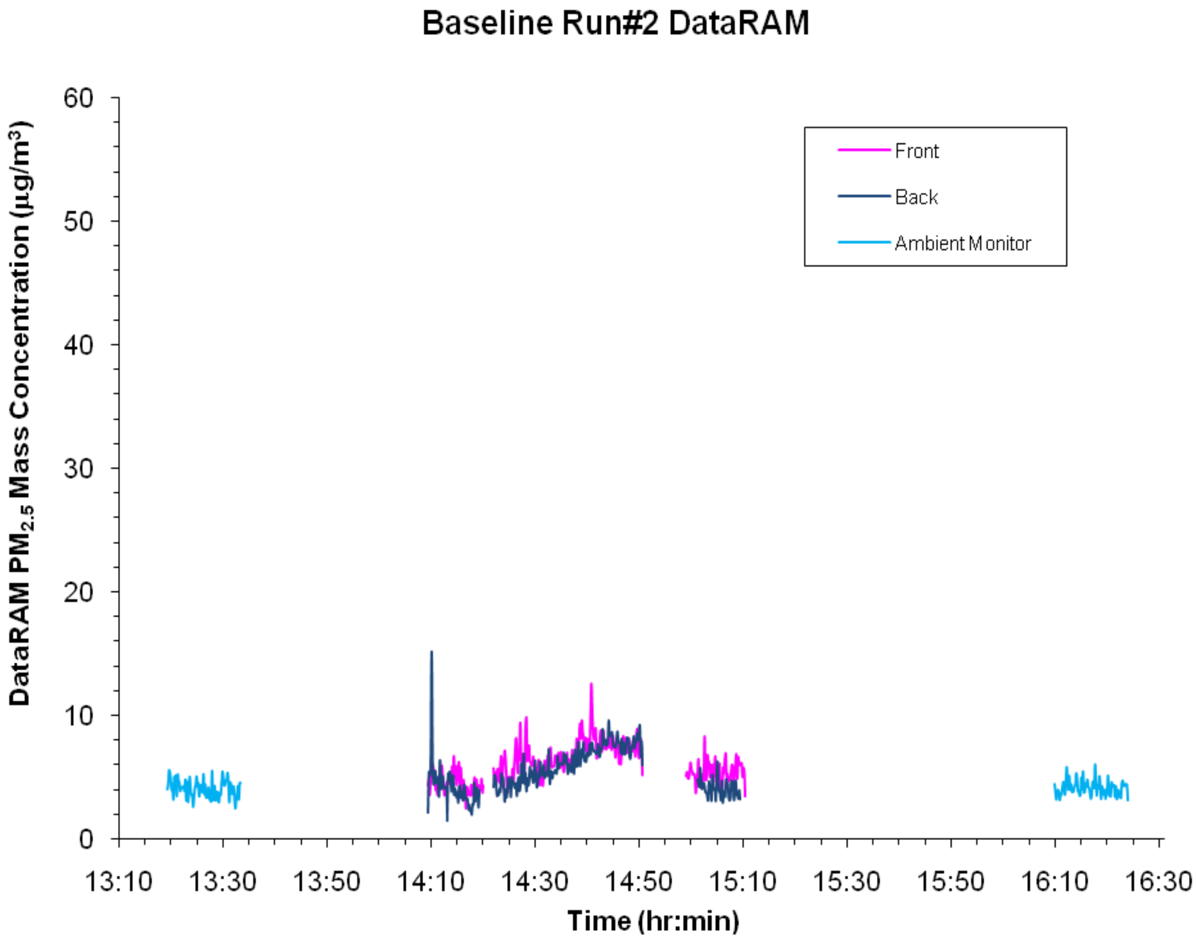
Retrofit	Wind Speed average	Wind Direction average	Standard Deviation wind direction (60s)	Temperature average	Temperature average	R.H. average
	(m/s)	(º)	(°)	(ºC)	(ºF)	(%)
None run 1F	1.4	161.4	35.5	18.6	65.5	40.3
None run 2F	1.3	174.3	32.7	18.7	65.7	38.7
None run 3F	1.1	106.9	24.1	19.9	67.8	34.0
FTF run 4F	1.8	233.6	39.3	26.7	80.1	42.7
FTF run 5F	1.4	218.2	47.0	27.0	80.7	48.7
FTF run 6F	0.8	208.1	44.7	26.7	80.1	52.3
DPF run 7F	1.0	224.7	42.2	26.1	79.0	47.0
DPF run 8F	1.3	221.1	51.9	26.3	79.3	49.7
DPF run 9F	1.3	205.0	43.0	26.5	79.6	46.3
DPF & CCVS run 10F	1.9	289.2	37.8	24.5	76.1	43.7
DPF & CCVS run 11F	1.5	284.7	34.5	23.7	74.6	45.0
DPF & CCVS run 12F	2.0	270.9	35.5	23.6	74.4	43.0
CCVS run 14F	1.2	261.4	32.7	23.9	75.1	43.3
CCVS run 15F	1.0	245.4	39.7	24.0	75.2	41.7
CCVS run 16F	0.7	222.7	25.0	24.1	75.4	42.7
FTF & CCVS run 17F	1.0	209.0	48.5	26.3	79.3	51.0
FTF & CCVS run 18F	1.3	249.1	29.9	27.4	81.4	44.7
FTF & CCVS run 19F	0.8	212.9	38.3	27.2	80.9	47.7

Appendix O: Real Time DataRAM and P-Trak Charts for Final Study

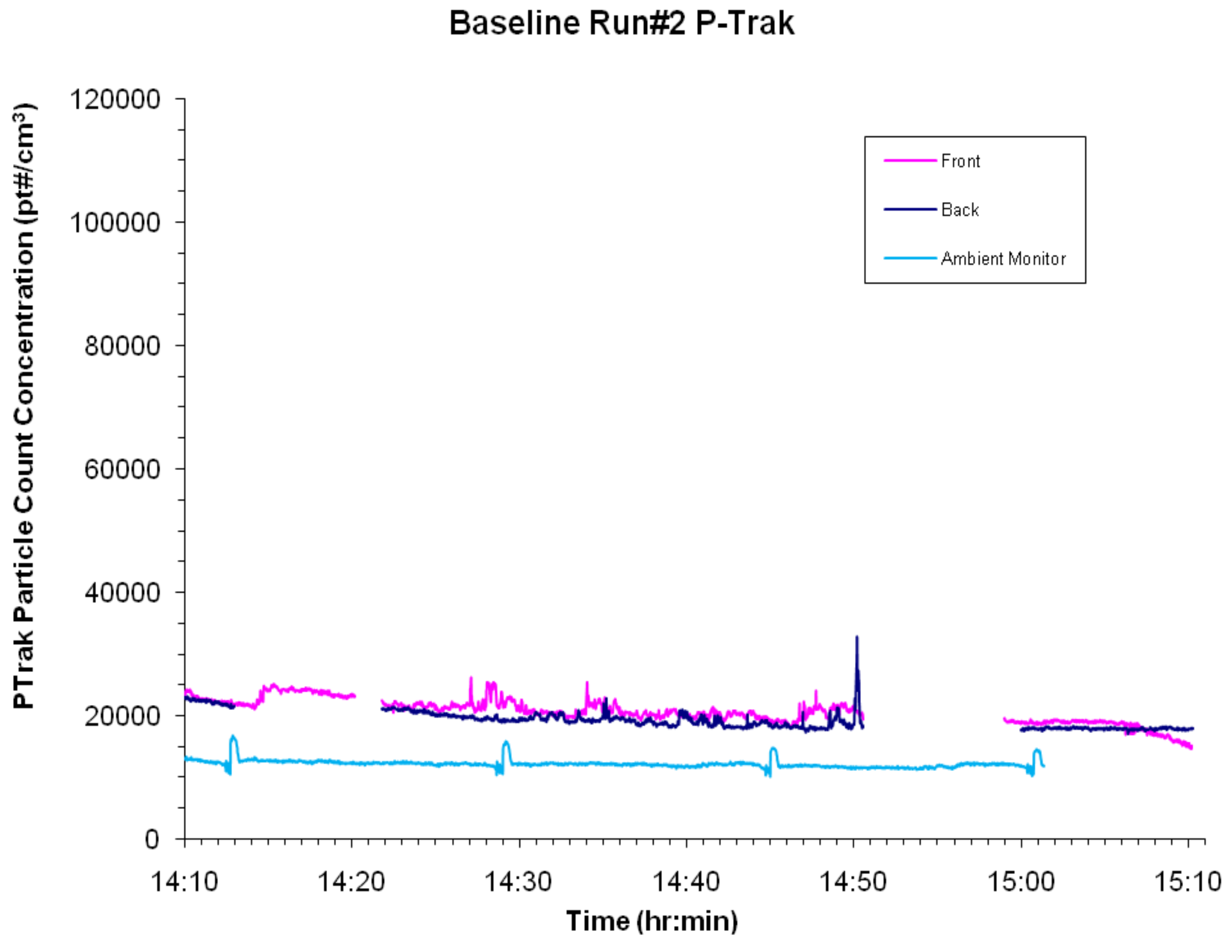




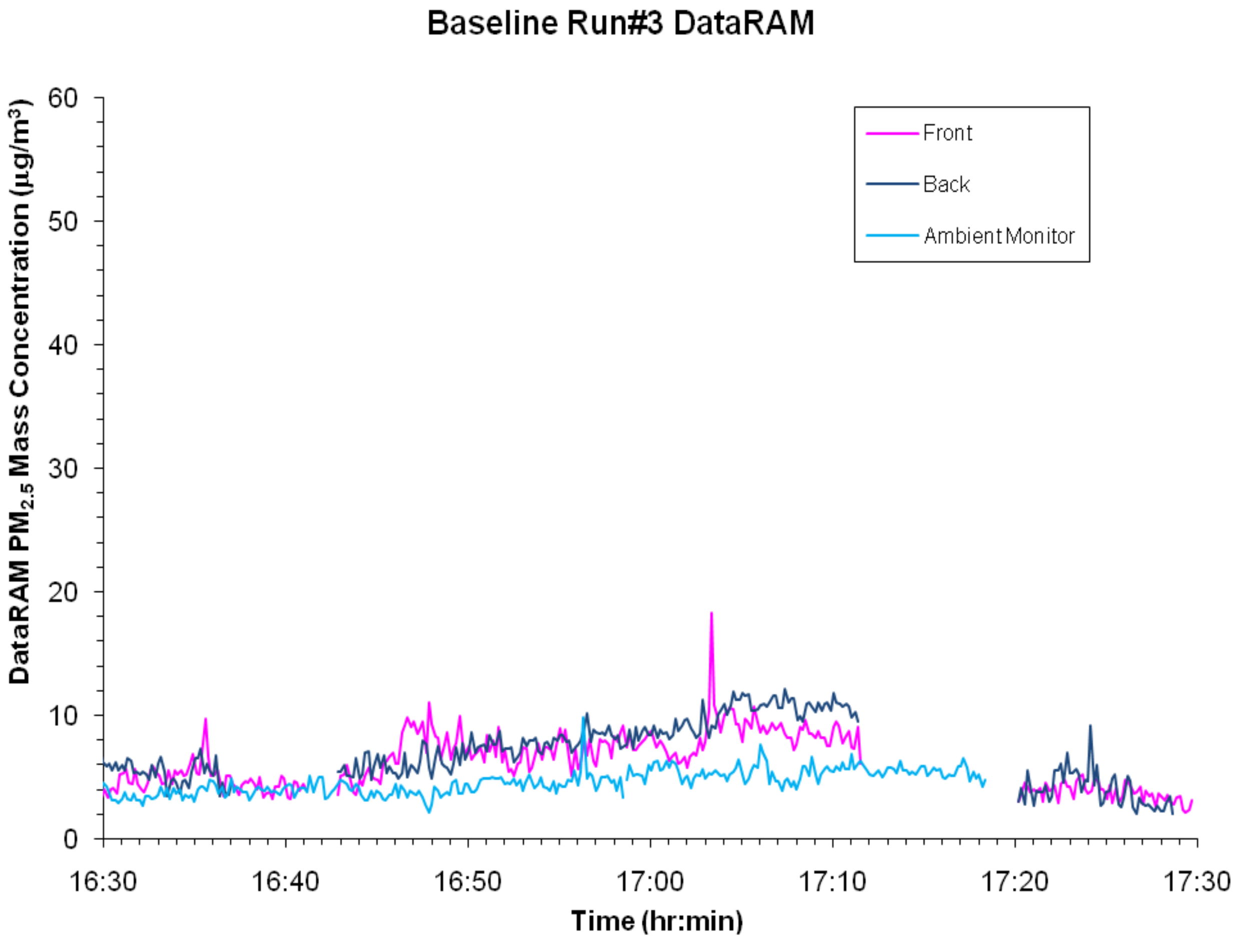
Baseline Run#1 P-Trak
P-Trak Particle Count Concentration (pt#/cm³)
120000
100000
80000
60000
40000
20000
0
13:00
13:10
13:20
13:30
13:40
13:50
14:00
14:10
Time (hr:min)
Front
Back
Ambient Monitor

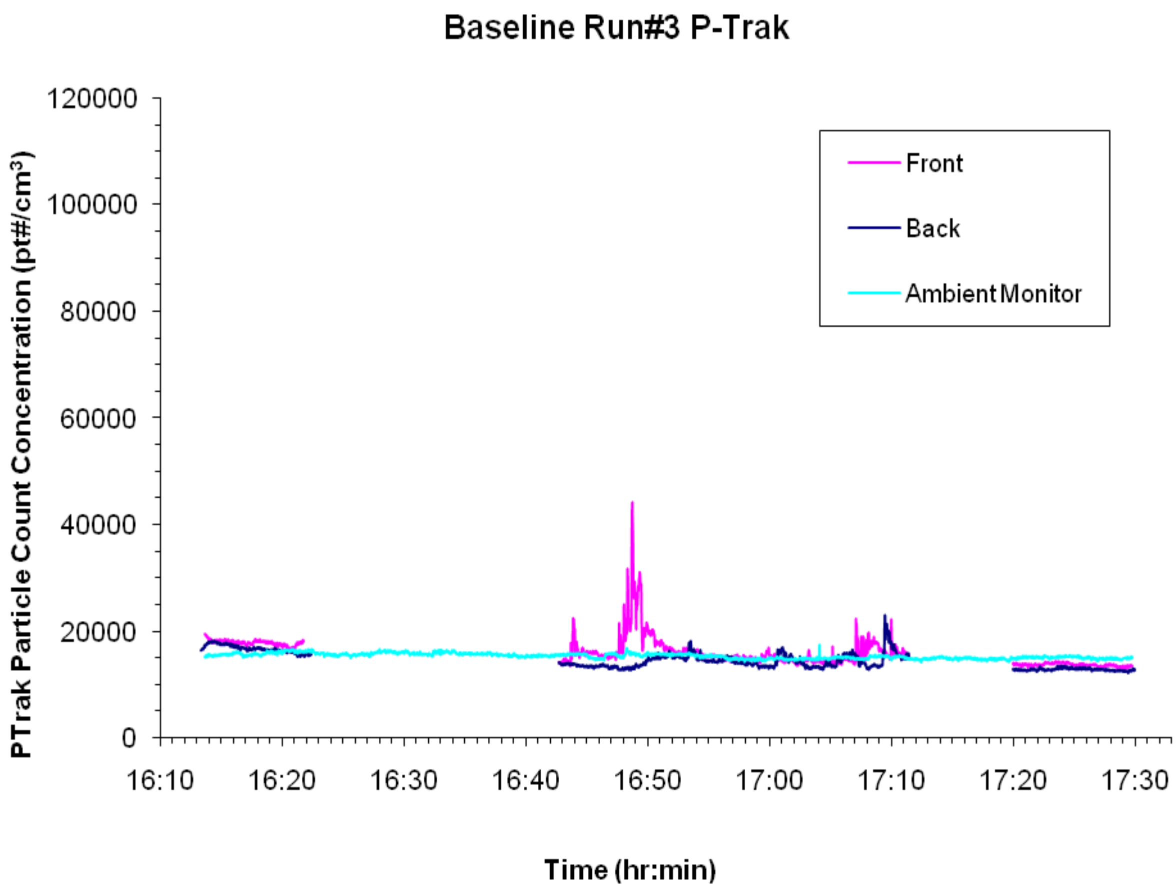


Baseline Run#2 DataRAM
DataRAM PM2.5 Mass Concentration (µg/m³)
60
50
40
30
20
10
0
13:10
13:30
13:50
14:10
14:30
14:50
15:10
15:30
15:50
16:10
16:30
Time (hr:min)
Front
Back
Ambient Monitor

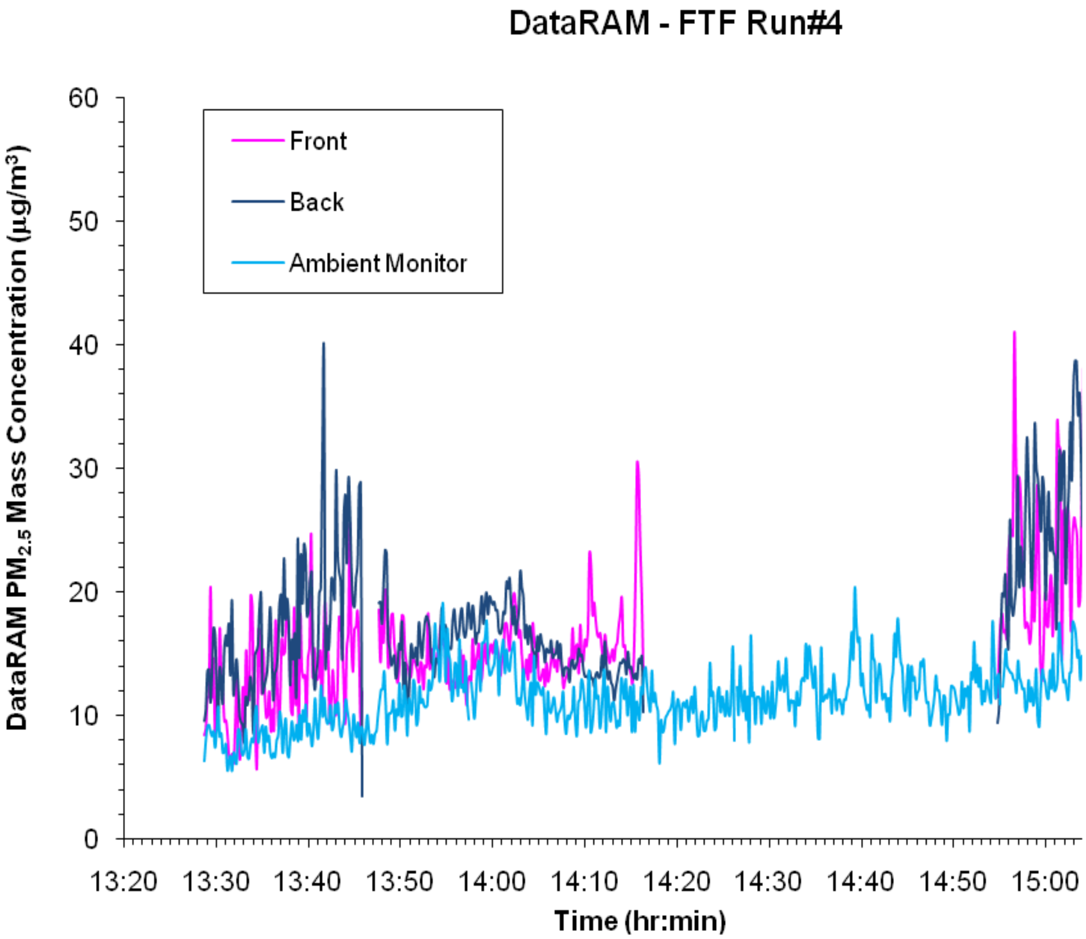


Baseline Run#2 P-Trak
PTrak Particle Count Concentration (pt#/cm³)
120000
100000
80000
60000
40000
20000
0
14:10
14:20
14:30
14:40
14:50
15:00
15:10
Time (hr:min)
Front
Back
Ambient Monitor

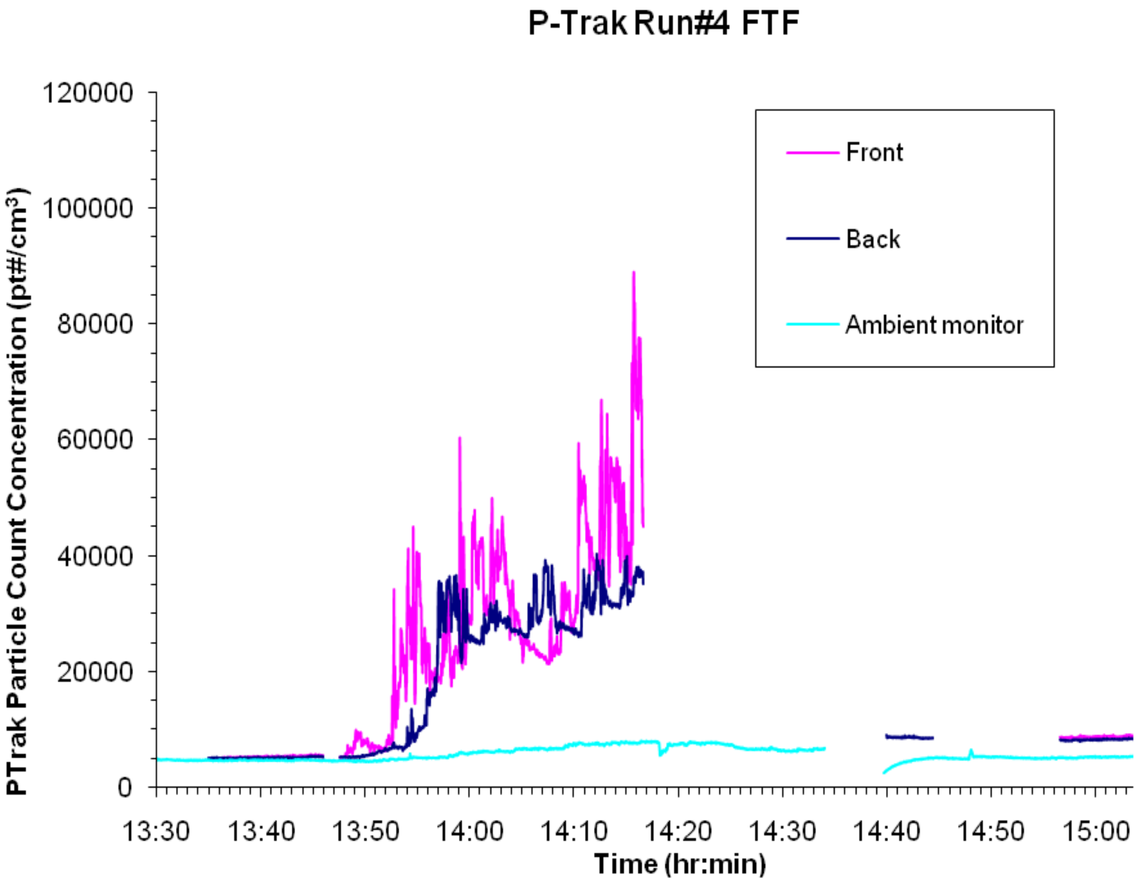

Baseline Run#3 DataRAM
DataRAM $PM_{2.5}$ Mass Concentration (µg/m³)
Time (hr:min)
Front
Back
Ambient Monitor
0
10
20
30
40
50
60
16:30
16:40
16:50
17:00
17:10
17:20
17:30

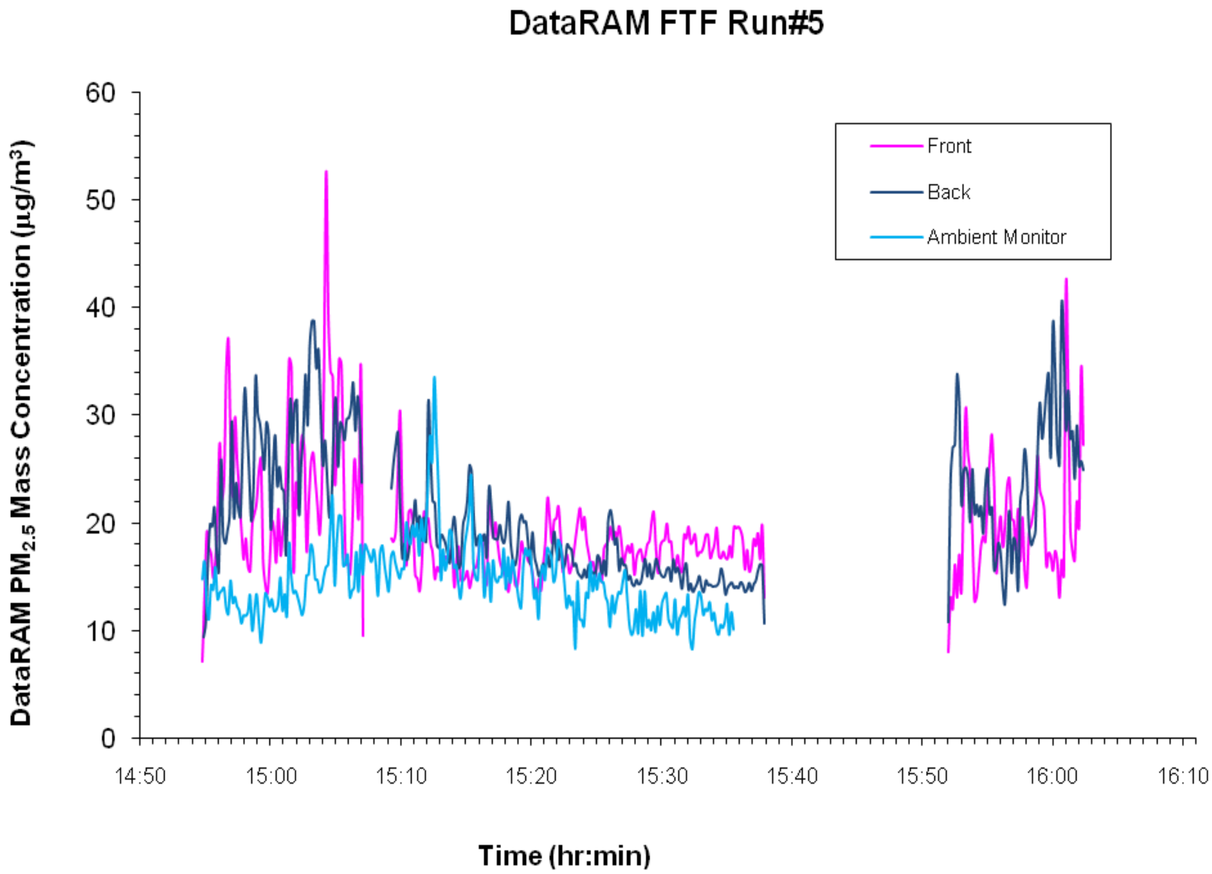


Baseline Run#3 P-Trak
PTrak Particle Count Concentration (pt#/cm³)
120000
100000
80000
60000
40000
20000
0
16:10
16:20
16:30
16:40
16:50
17:00
17:10
17:20
17:30
Time (hr:min)
Front
Back
Ambient Monitor

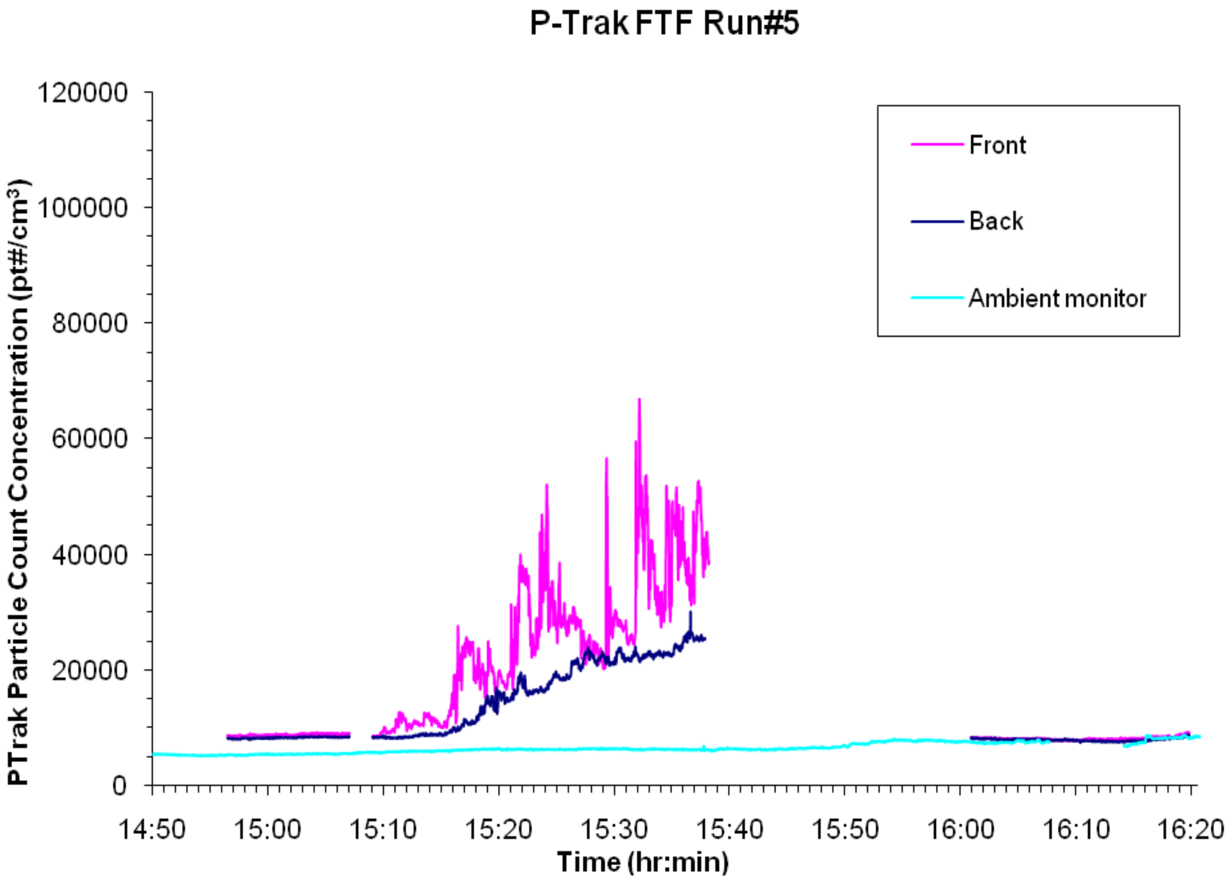


DataRAM - FTF Run#4
DataRAM PM2.5 Mass Concentration (µg/m3)
Front
Back
Ambient Monitor
0
10
20
30
40
50
60
13:20
13:30
13:40
13:50
14:00
14:10
14:20
14:30
14:40
14:50
15:00
Time (hr:min)

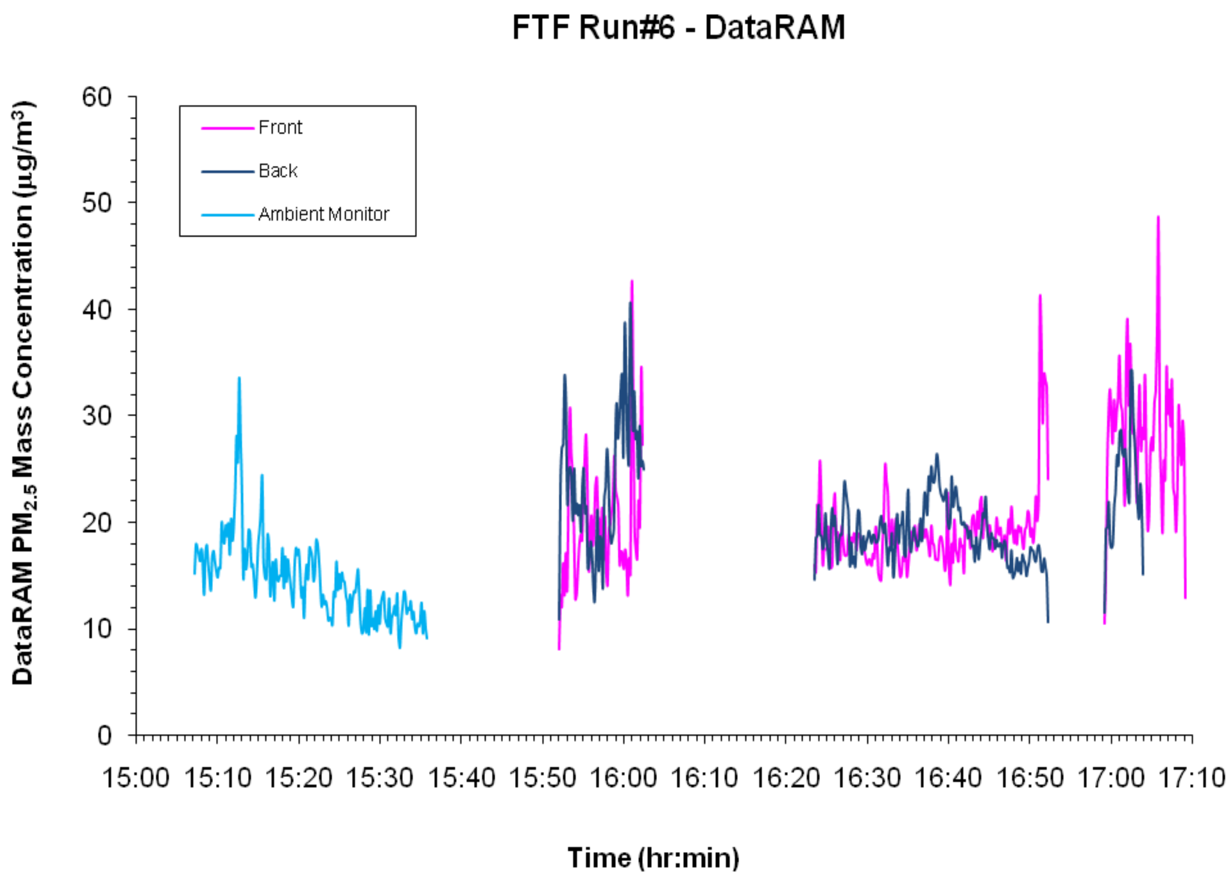

P-Trak Run#4 FTF
PTrak Particle Count Concentration (pt#/cm³)
Time (hr:min)
Front
Back
Ambient monitor
120000
100000
80000
60000
40000
20000
0
13:30
13:40
13:50
14:00
14:10
14:20
14:30
14:40
14:50
15:00

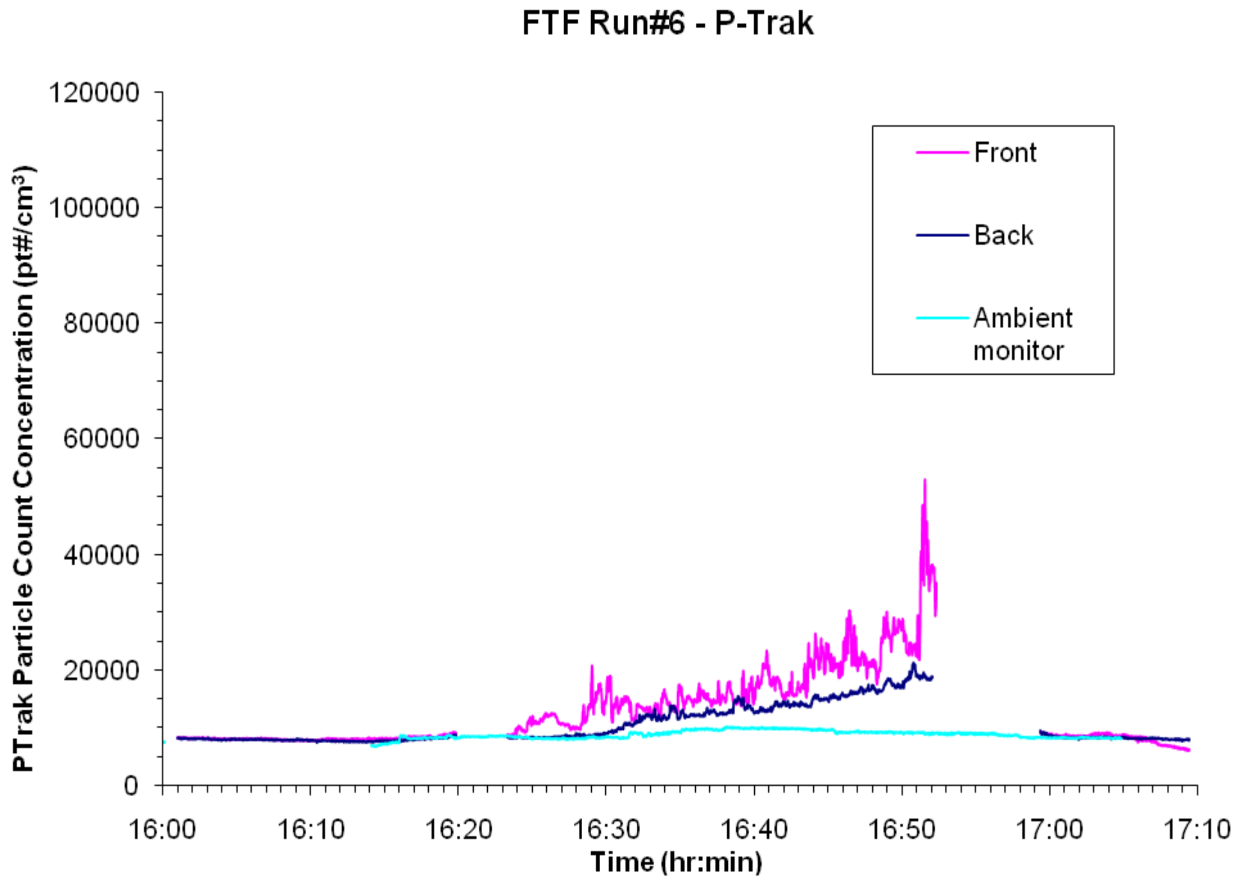


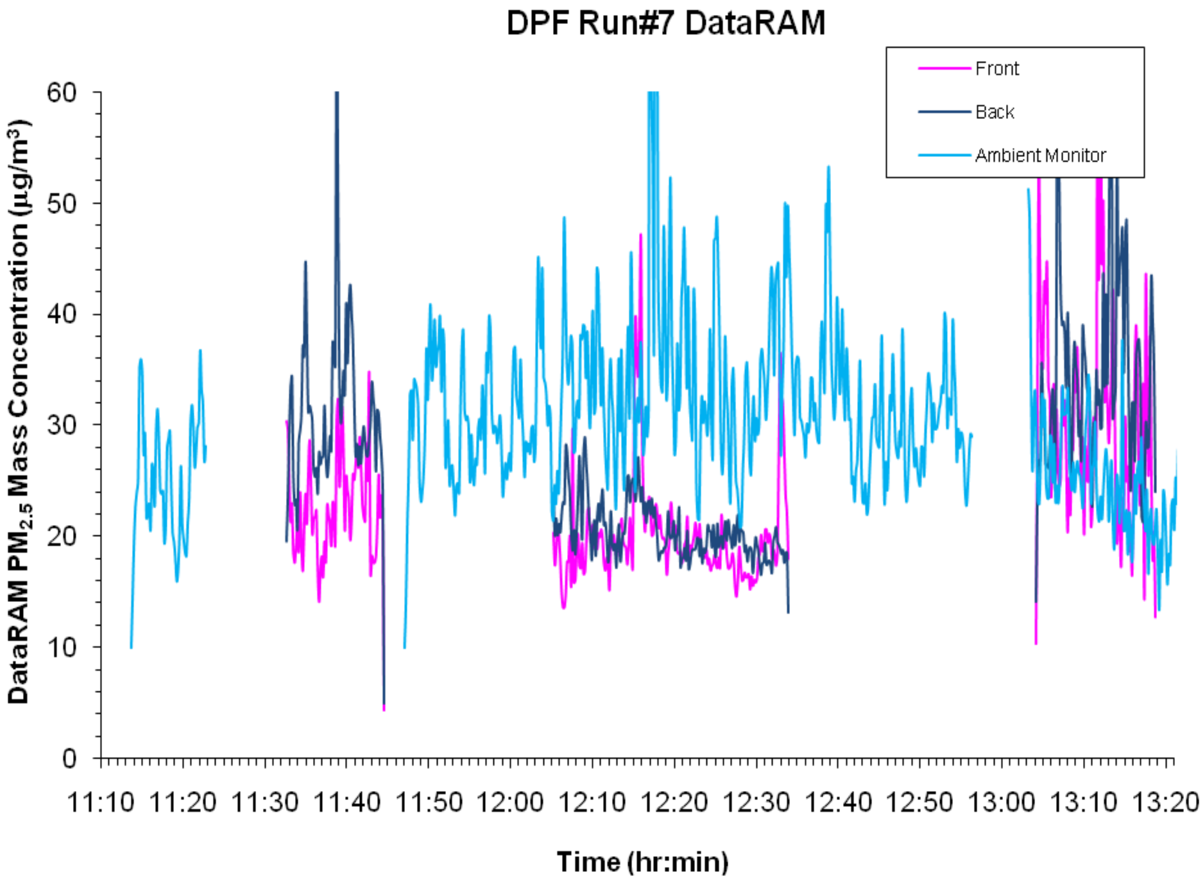
DataRAM FTF Run#5
DataRAM PM2.5 Mass Concentration (µg/m³)
Time (hr:min)
Front
Back
Ambient Monitor
60
50
40
30
20
10
0
14:50
15:00
15:10
15:20
15:30
15:40
15:50
16:00
16:10



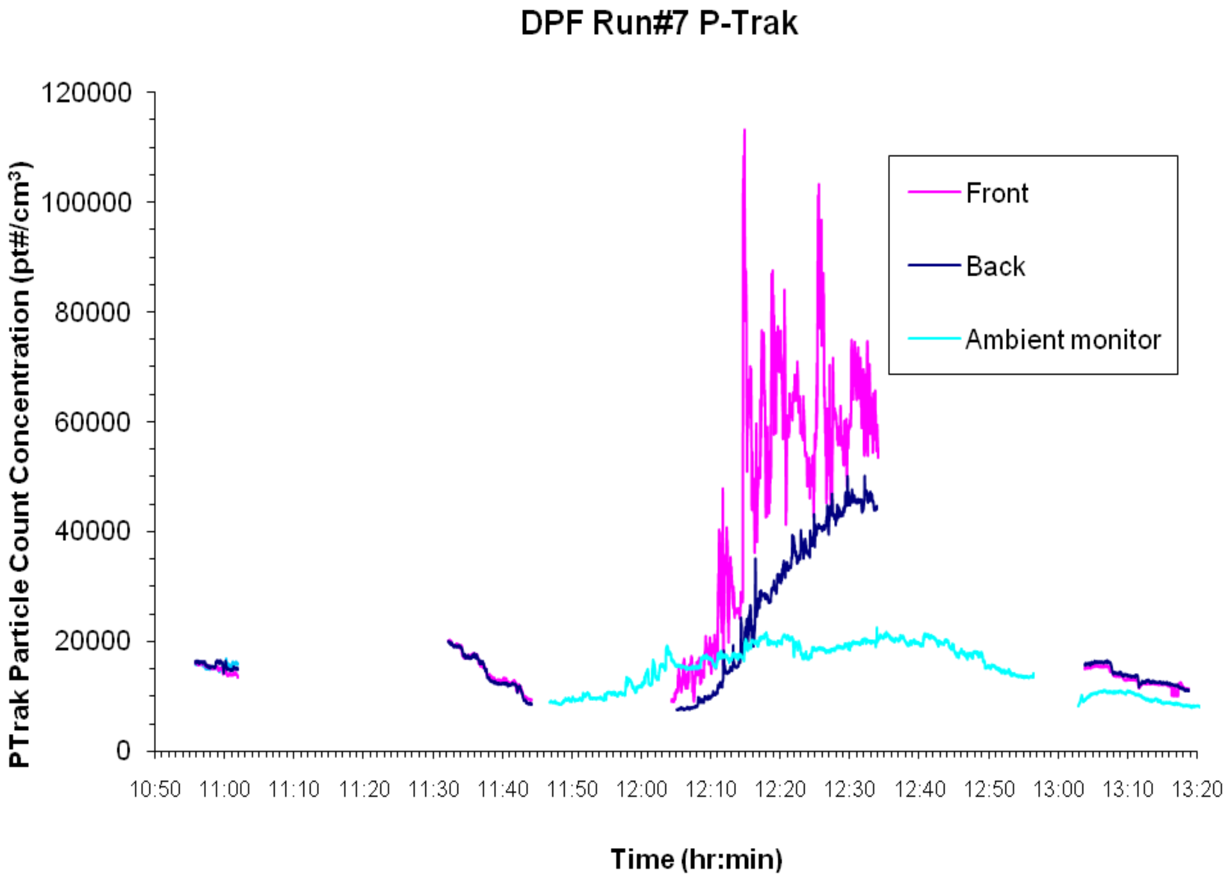
P-Trak FTF Run#5
PTrak Particle Count Concentration (pt#/cm³)
120000
100000
80000
60000
40000
20000
0
14:50
15:00
15:10
15:20
15:30
15:40
15:50
16:00
16:10
16:20
Time (hr:min)
Front
Back
Ambient monitor


FTF Run#6 - DataRAM
DataRAM PM2.5 Mass Concentration (µg/m3)
Time (hr:min)
Front
Back
Ambient Monitor
0
10
20
30
40
50
60
15:00
15:10
15:20
15:30
15:40
15:50
16:00
16:10
16:20
16:30
16:40
16:50
17:00
17:10

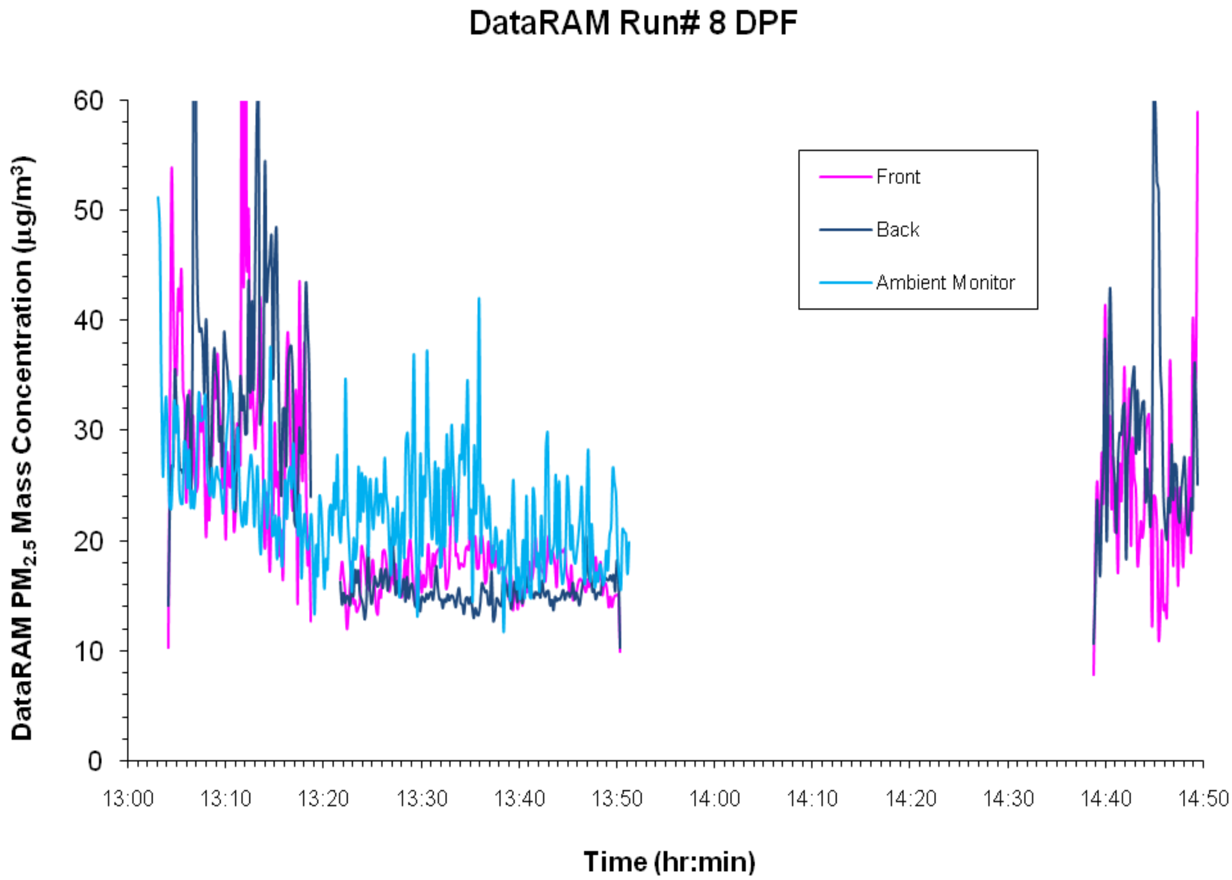

FTF Run#6 - P-Trak
PTrak Particle Count Concentration (pt#/cm³)
120000
100000
80000
60000
40000
20000
0
16:00
16:10
16:20
16:30
16:40
16:50
17:00
17:10
Time (hr:min)
Front
Back
Ambient monitor

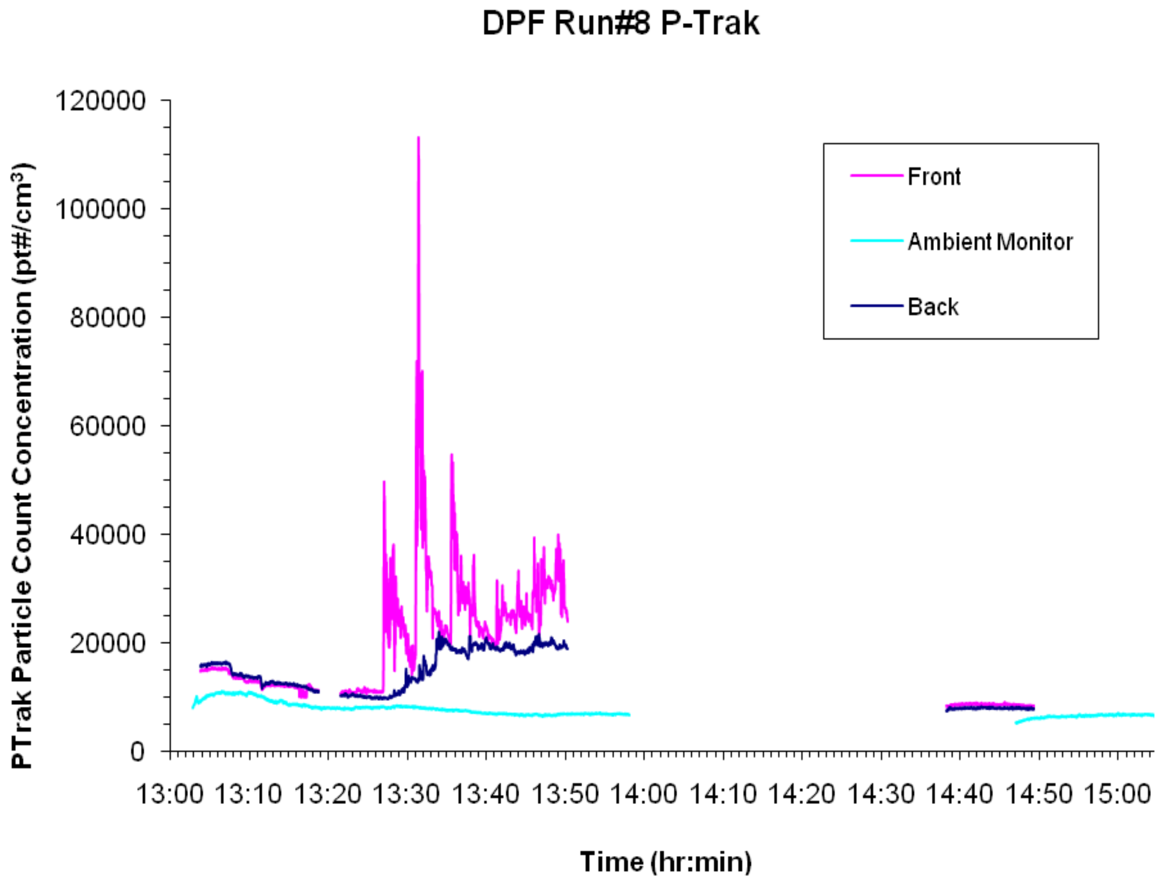


DPF Run#7 DataRAM
Front
Back
Ambient Monitor
DataRAM PM2.5 Mass Concentration (µg/m³)
0
10
20
30
40
50
60
11:10
11:20
11:30
11:40
11:50
12:00
12:10
12:20
12:30
12:40
12:50
13:00
13:10
13:20
Time (hr:min)

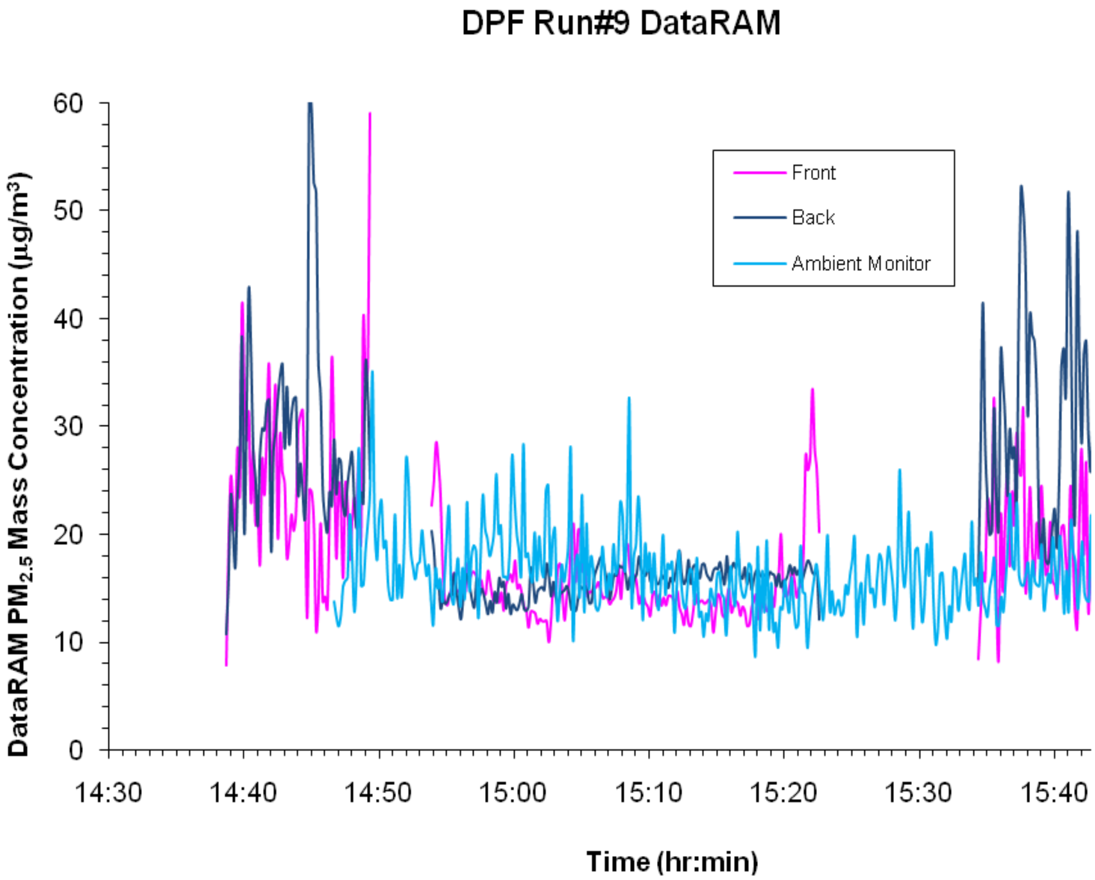


DPF Run#7 P-Trak
PTrak Particle Count Concentration (pt#/cm³)
120000
100000
80000
60000
40000
20000
0
10:50
11:00
11:10
11:20
11:30
11:40
11:50
12:00
12:10
12:20
12:30
12:40
12:50
13:00
13:10
13:20
Time (hr:min)
Front
Back
Ambient monitor

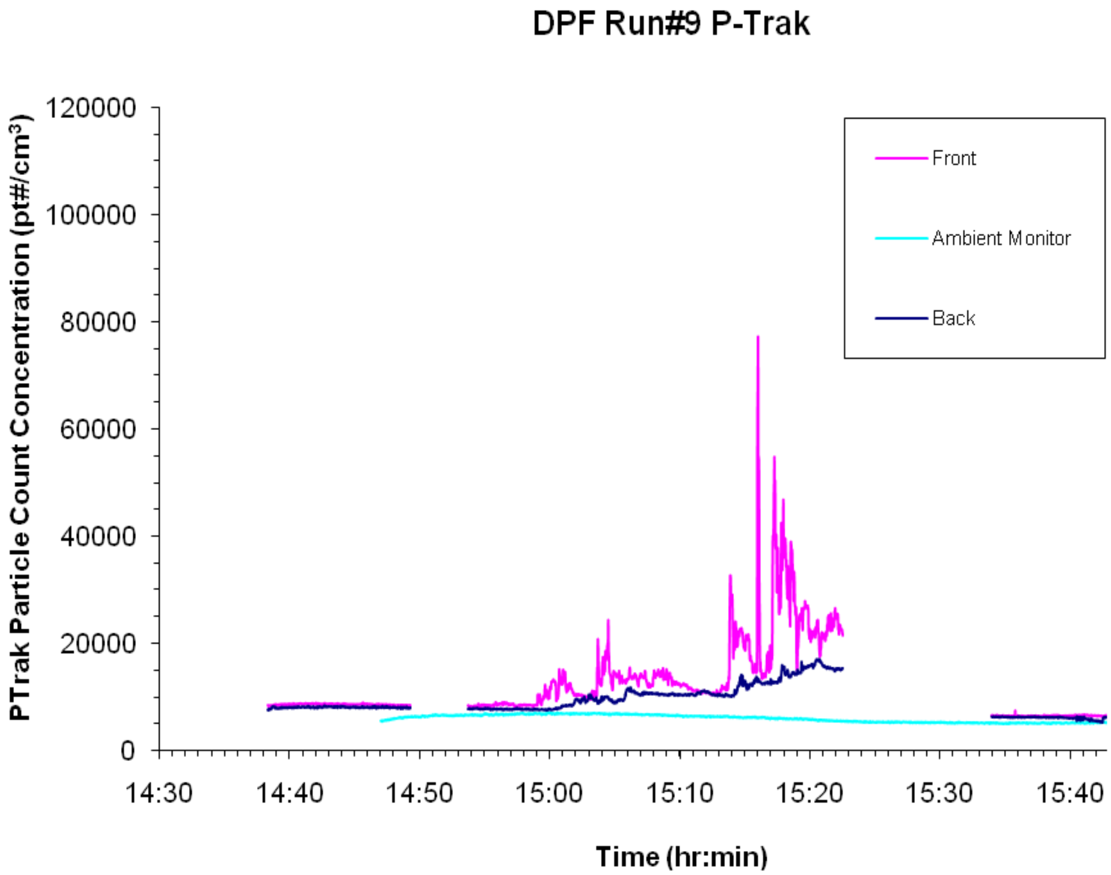

DataRAM Run# 8 DPF
DataRAM PM$_{2.5}$ Mass Concentration (µg/m^3)
60
50
40
30
20
10
0
13:00
13:10
13:20
13:30
13:40
13:50
14:00
14:10
14:20
14:30
14:40
14:50
Time (hr:min)
Front
Back
Ambient Monitor



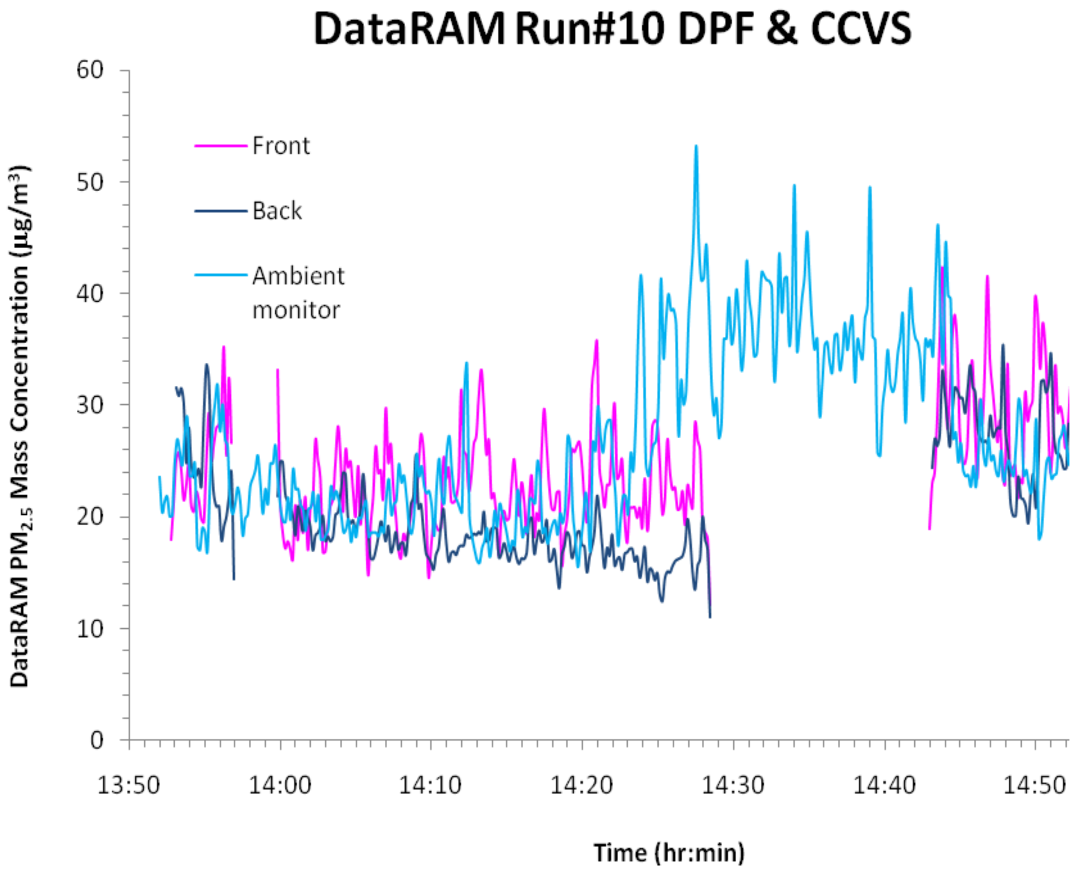
DPF Run#8 P-Trak
PTrak Particle Count Concentration (pt#/cm³)
120000
100000
80000
60000
40000
20000
0
13:00
13:10
13:20
13:30
13:40
13:50
14:00
14:10
14:20
14:30
14:40
14:50
15:00
Time (hr:min)
Front
Ambient Monitor
Back



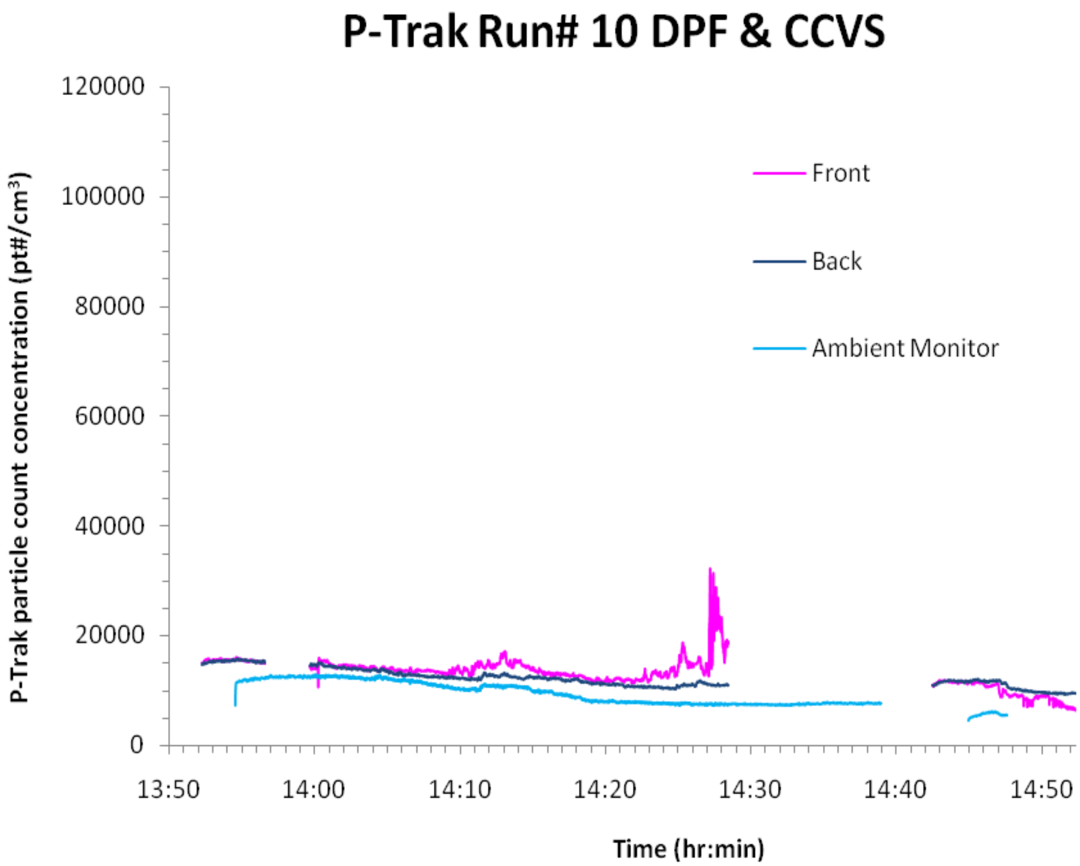
DPF Run#9 DataRAM
DataRAM PM2.5 Mass Concentration (µg/m3)
Time (hr:min)
Front
Back
Ambient Monitor
60
50
40
30
20
10
0
14:30
14:40
14:50
15:00
15:10
15:20
15:30
15:40



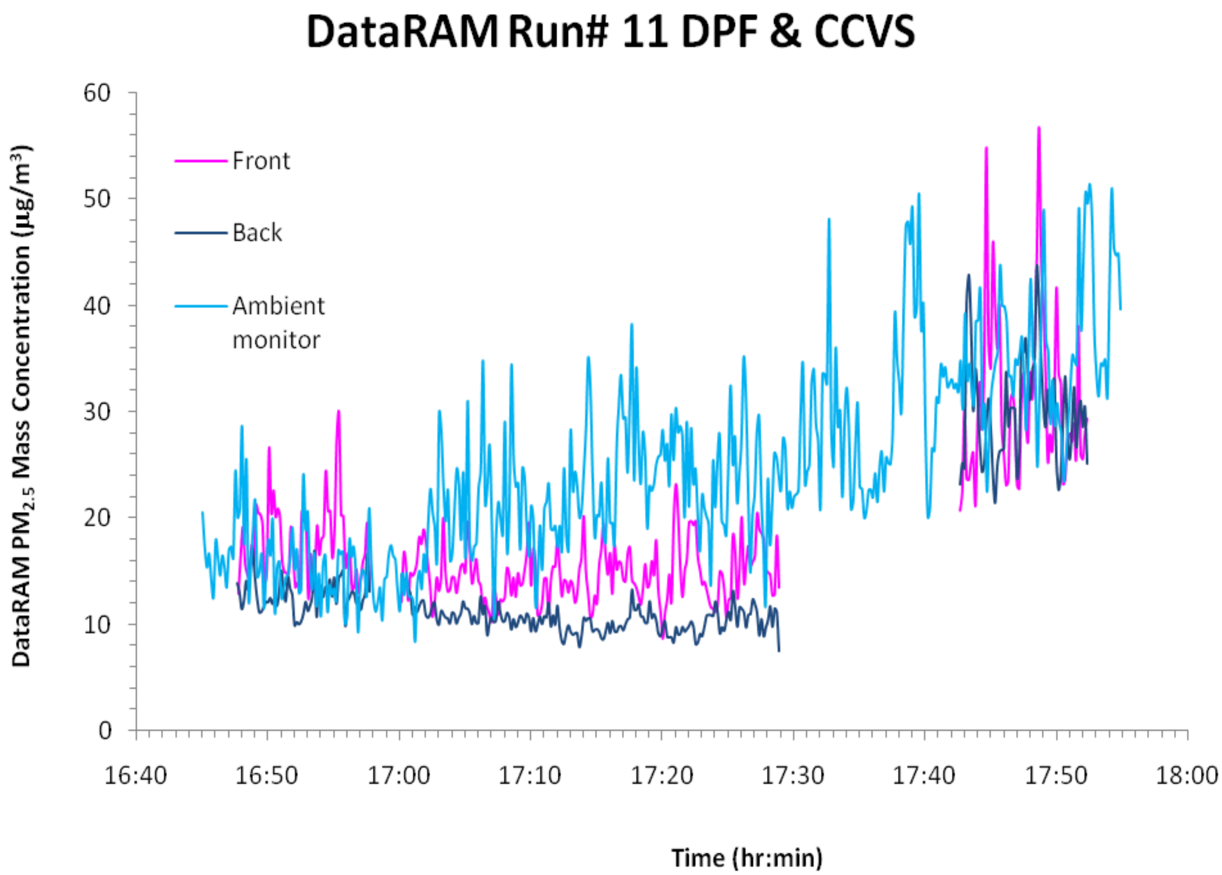
DPF Run#9 P-Trak
PTrak Particle Count Concentration (pt#/cm³)
120000
100000
80000
60000
40000
20000
0
14:30
14:40
14:50
15:00
15:10
15:20
15:30
15:40
Time (hr:min)
Front
Ambient Monitor
Back



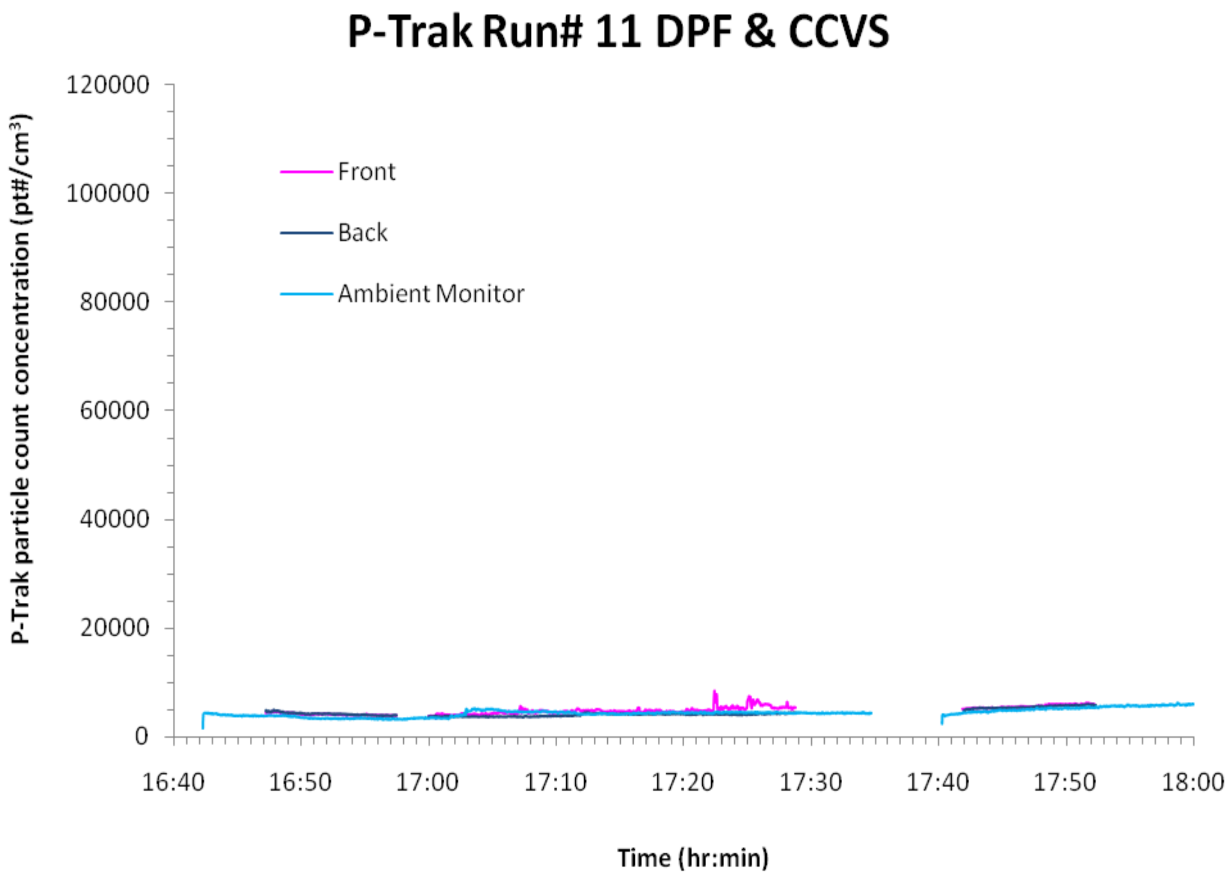
DataRAM Run#10 DPF & CCVS
DataRAM PM2.5 Mass Concentration (µg/m³)
Time (hr:min)
Front
Back
Ambient monitor
60
50
40
30
20
10
0
13:50
14:00
14:10
14:20
14:30
14:40
14:50

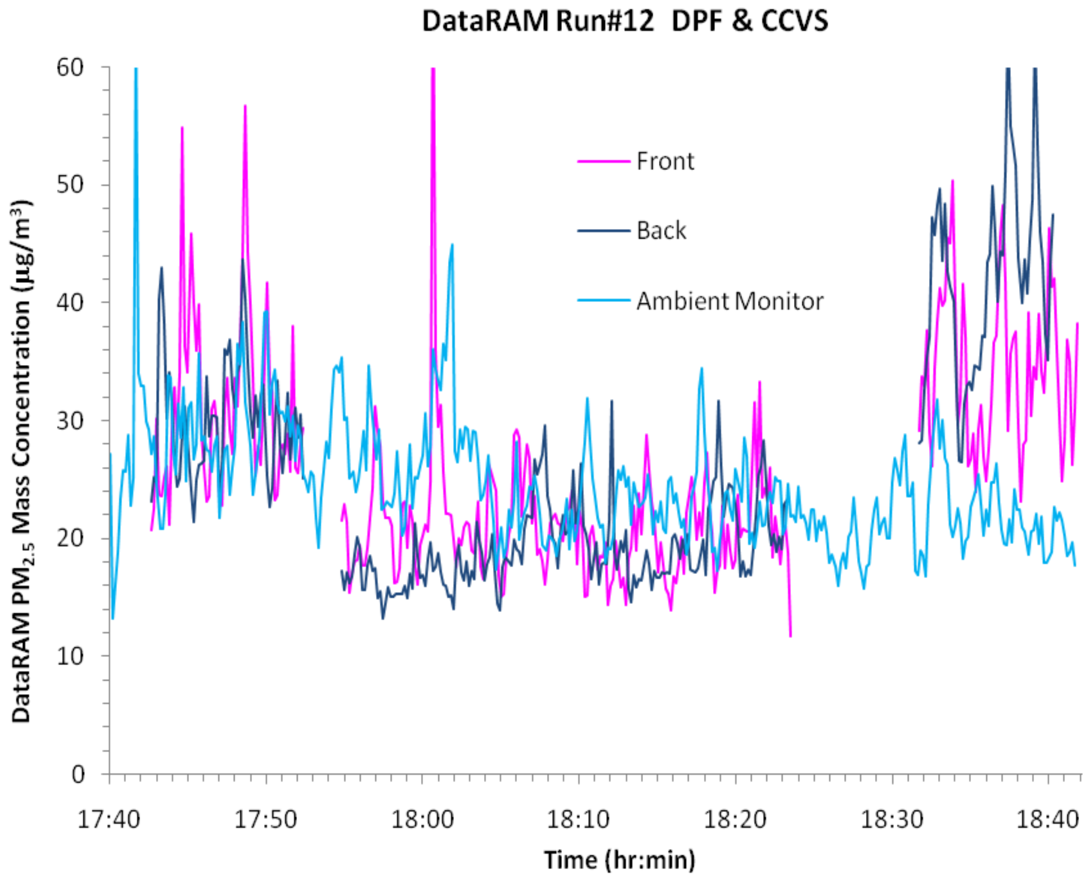


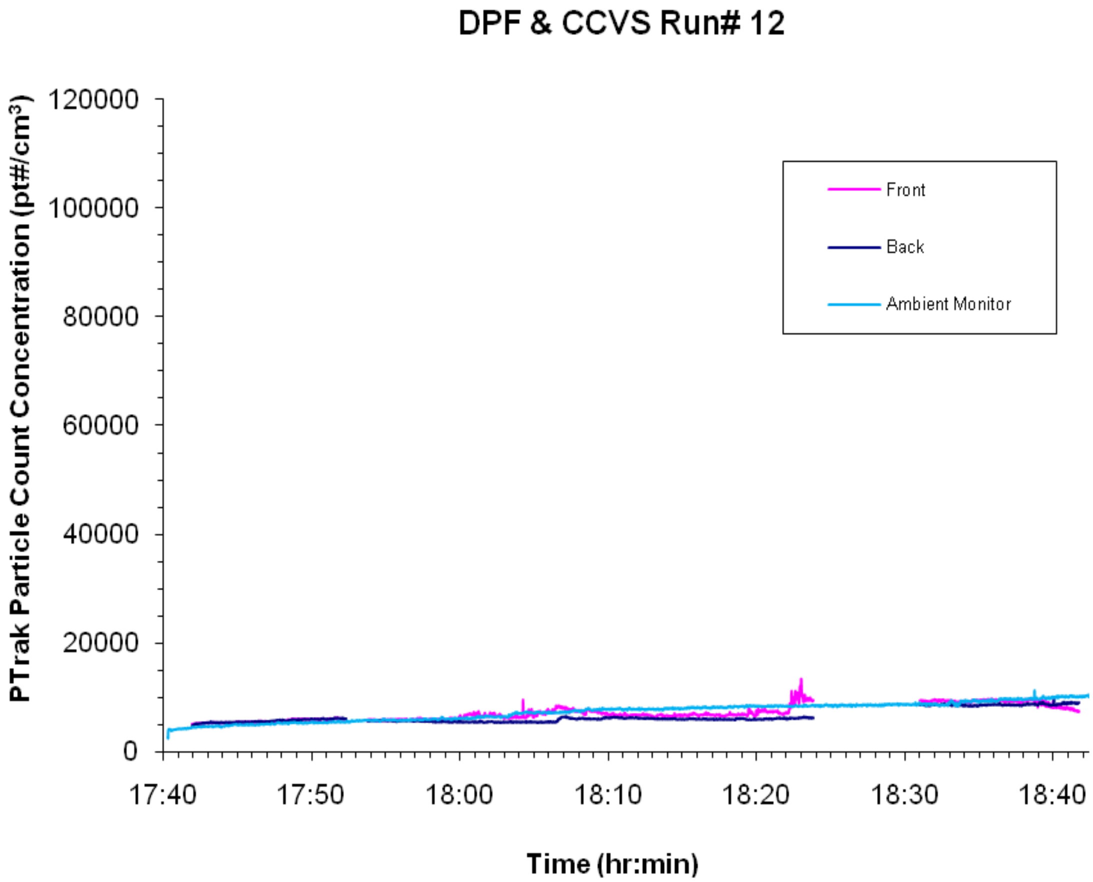
P-Trak Run# 10 DPF & CCVS
P-Trak particle count concentration (pt#/cm³)
120000
100000
80000
60000
40000
20000
0
13:50
14:00
14:10
14:20
14:30
14:40
14:50
Time (hr:min)
Front
Back
Ambient Monitor

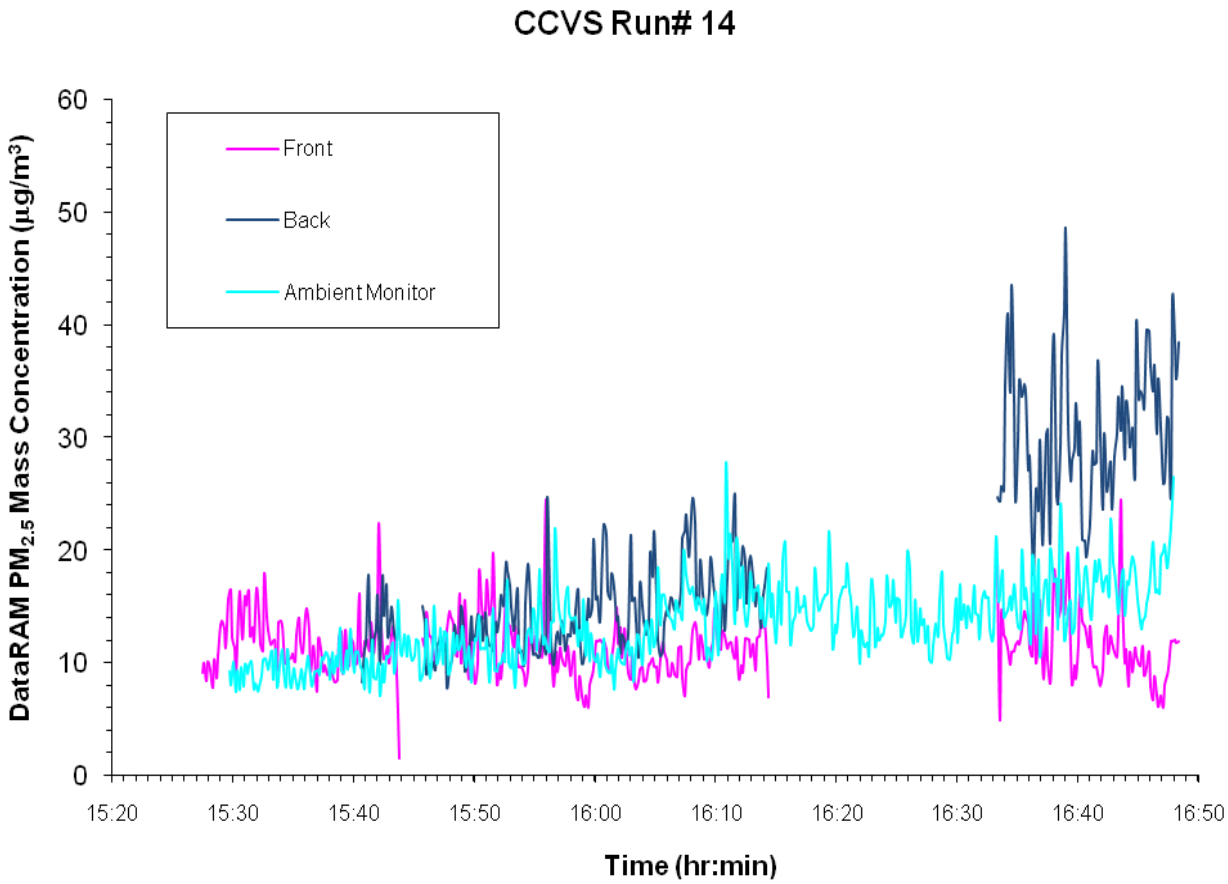


DataRAM Run# 11 DPF & CCVS
DataRAM PM2.5 Mass Concentration (µg/m3)
Time (hr:min)
Front
Back
Ambient monitor
0
10
20
30
40
50
60
16:40
16:50
17:00
17:10
17:20
17:30
17:40
17:50
18:00

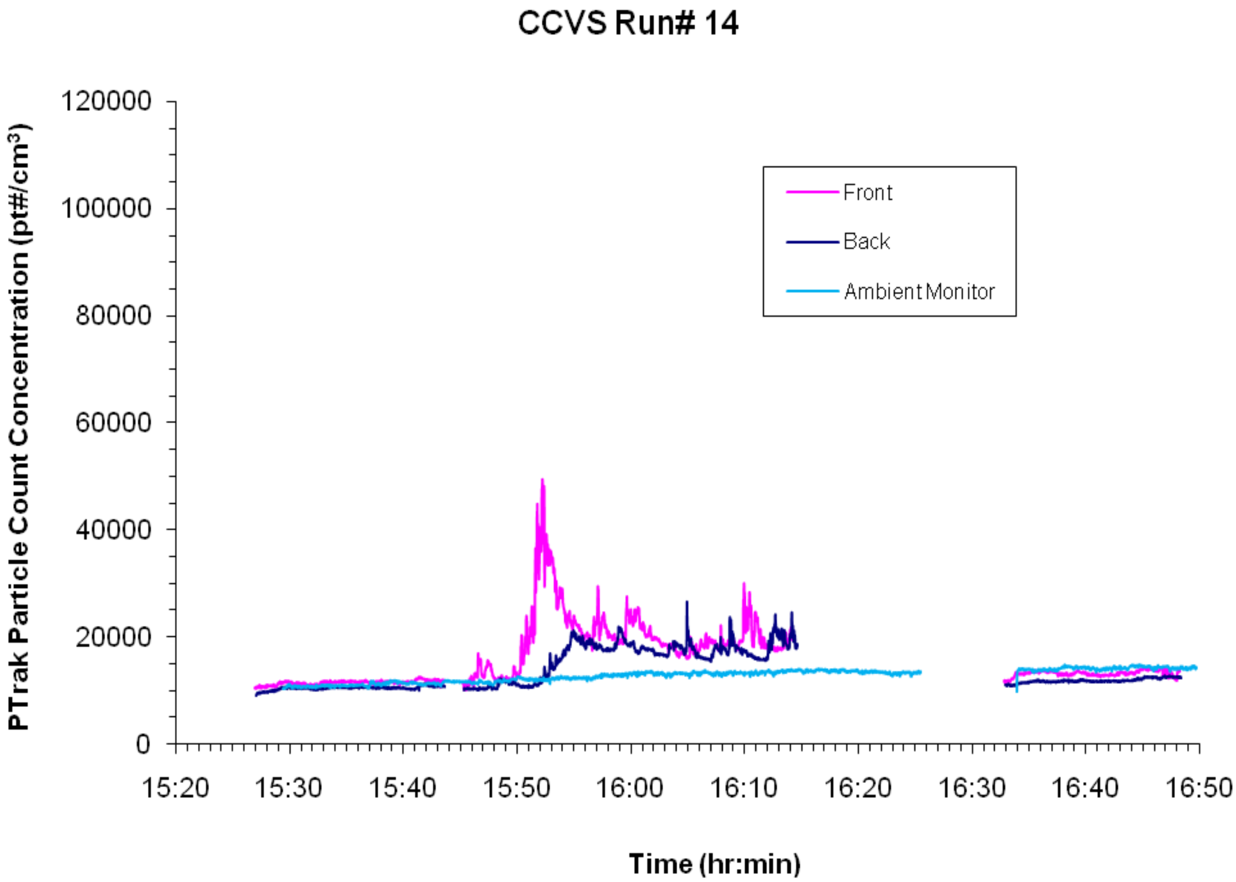

P-Trak Run# 11 DPF & CCVS
P-Trak particle count concentration (pt#/cm³)
120000
100000
80000
60000
40000
20000
0
Front
Back
Ambient Monitor
16:40
16:50
17:00
17:10
17:20
17:30
17:40
17:50
18:00
Time (hr:min)

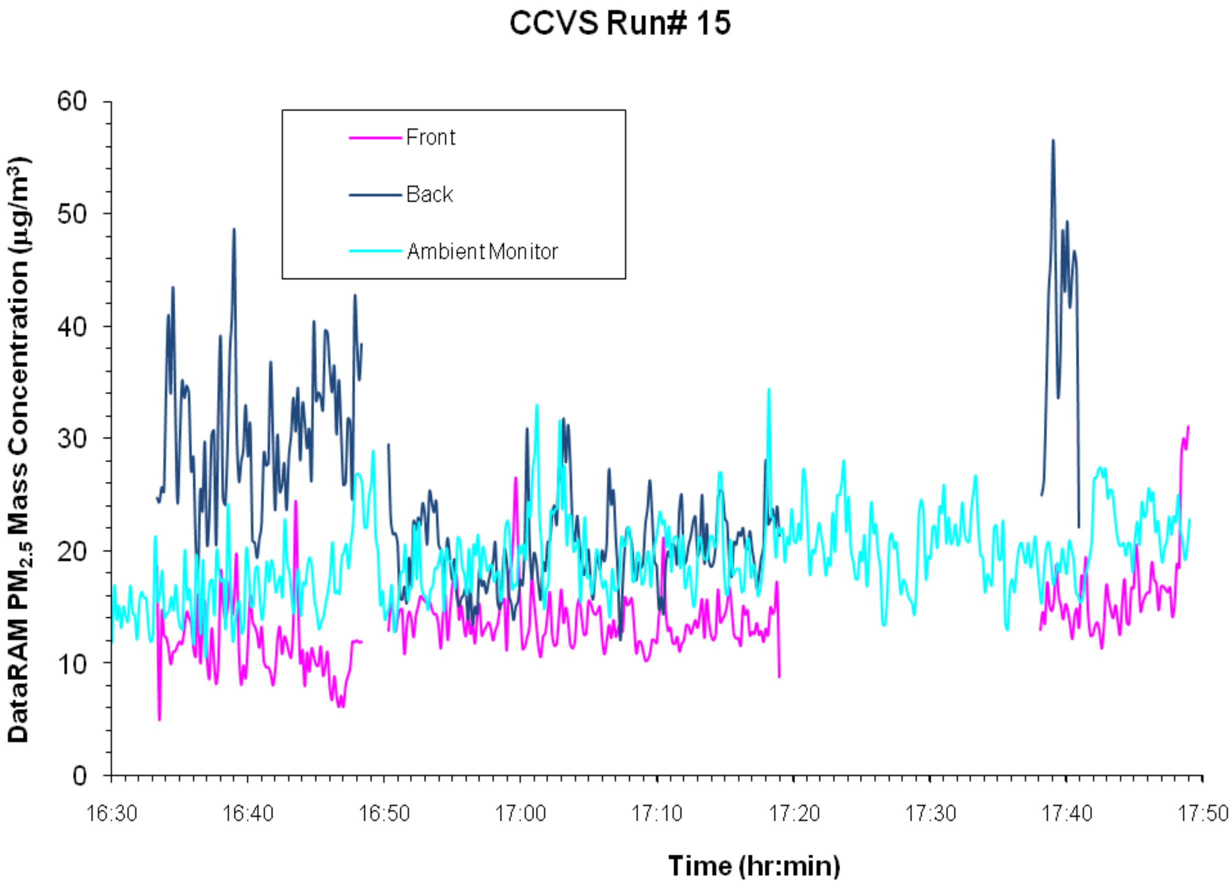

DataRAM Run#12 DPF & CCVS
Front
Back
Ambient Monitor
DataRAM PM2.5 Mass Concentration (µg/m³)
0
10
20
30
40
50
60
17:40
17:50
18:00
18:10
18:20
18:30
18:40
Time (hr:min)


DPF & CCVS Run# 12
PTrak Particle Count Concentration (pt#/cm³)
120000
100000
80000
60000
40000
20000
0
17:40
17:50
18:00
18:10
18:20
18:30
18:40
Time (hr:min)
Front
Back
Ambient Monitor

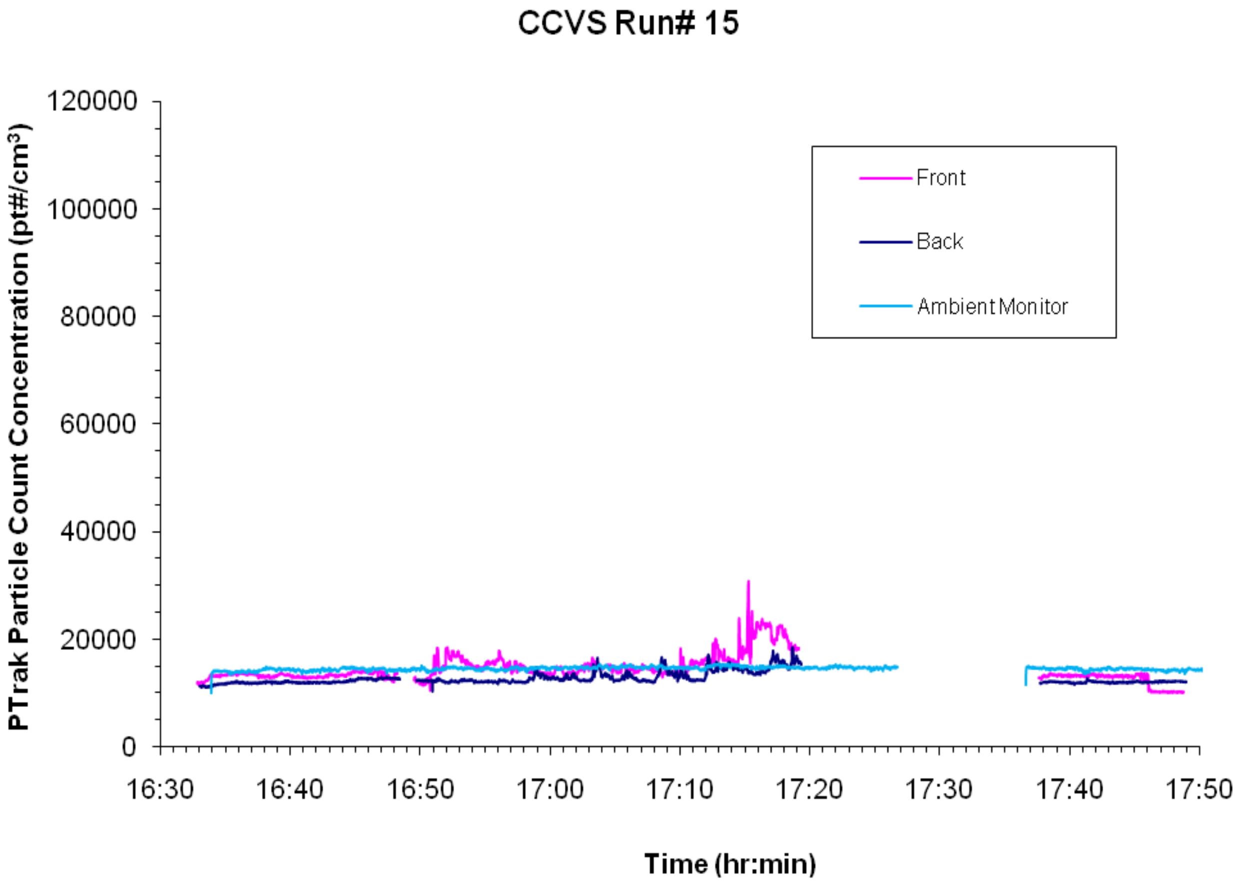


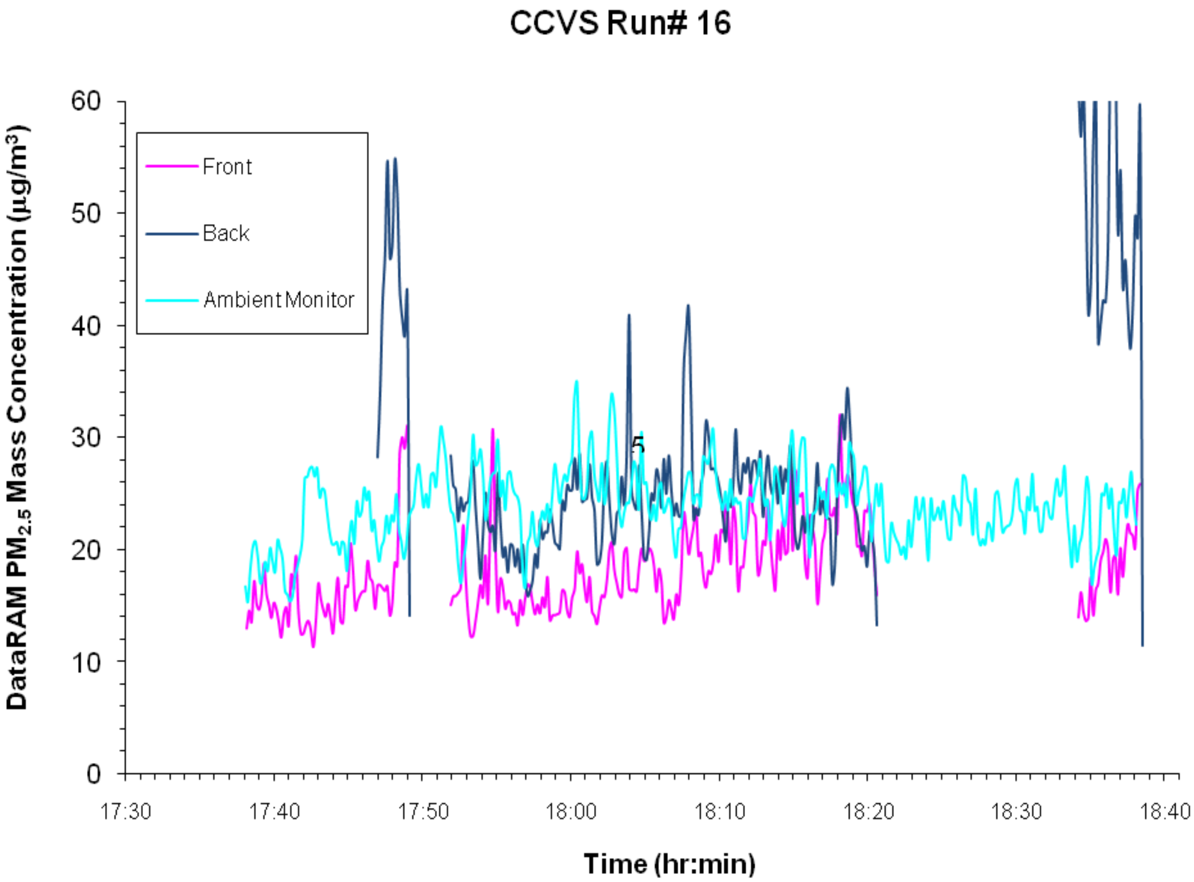
CCVS Run# 14
DataRAM PM2.5 Mass Concentration (µg/m3)
Time (hr:min)
Front
Back
Ambient Monitor
0
10
20
30
40
50
60
15:20
15:30
15:40
15:50
16:00
16:10
16:20
16:30
16:40
16:50


CCVS Run# 14
PTrak Particle Count Concentration (pt#/cm³)
120000
100000
80000
60000
40000
20000
0
15:20
15:30
15:40
15:50
16:00
16:10
16:20
16:30
16:40
16:50
Time (hr:min)
Front
Back
Ambient Monitor

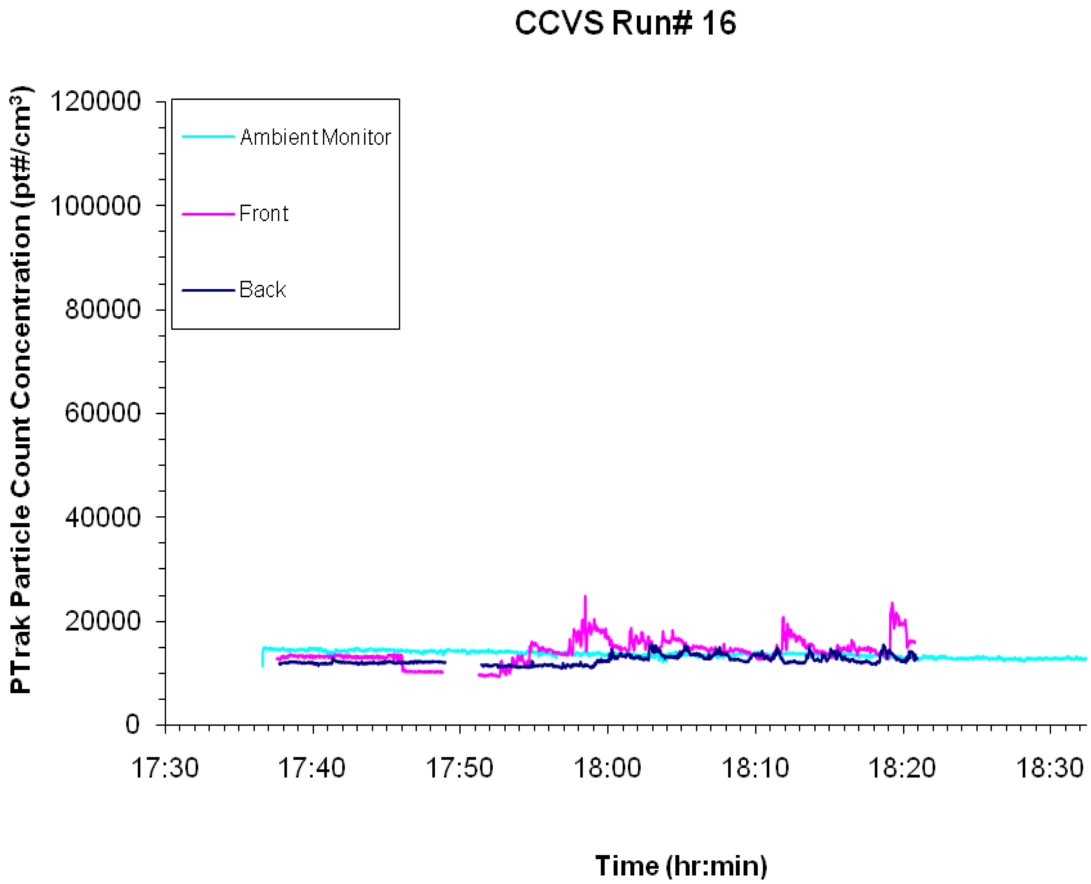


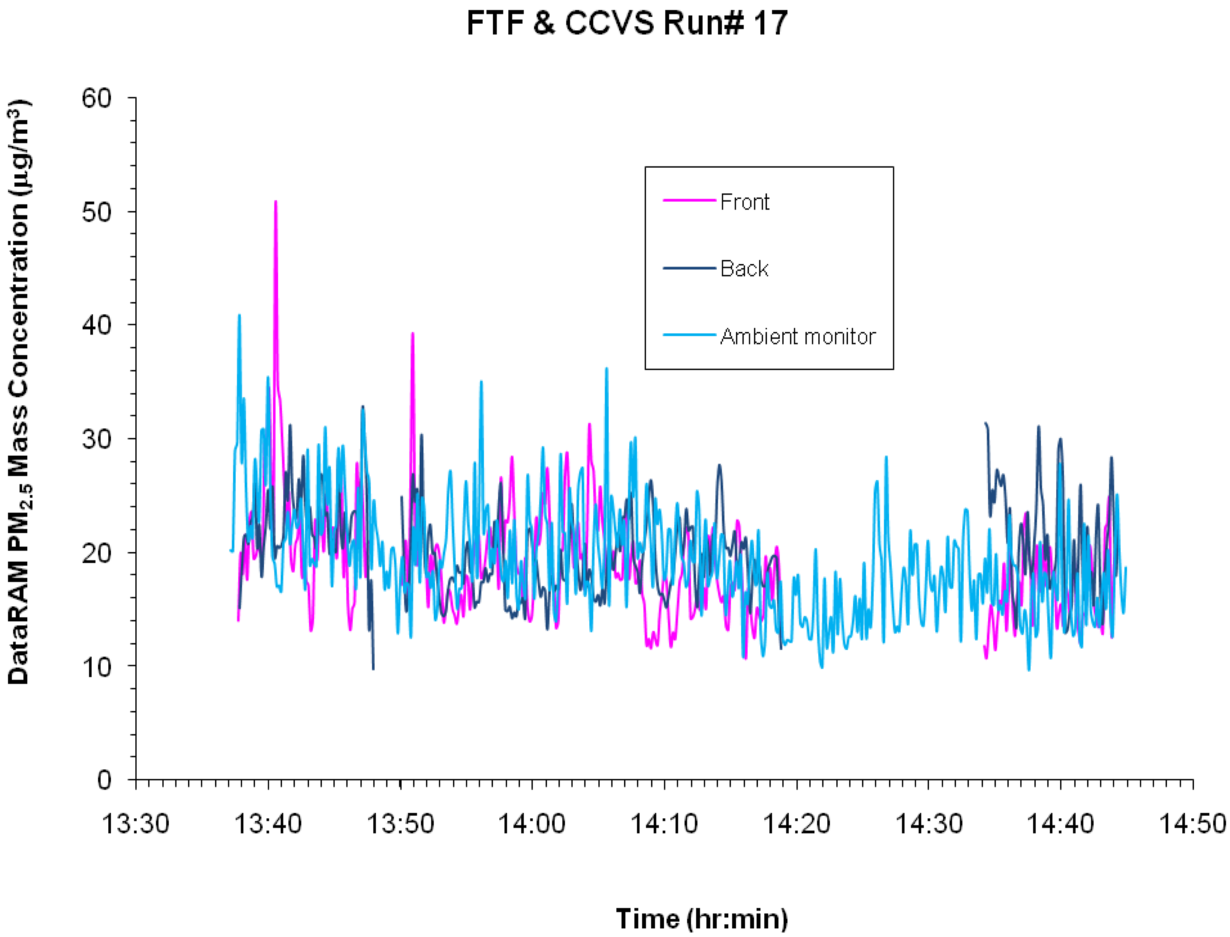
CCVS Run# 15
DataRAM PM2.5 Mass Concentration (µg/m3)
Time (hr:min)
Front
Back
Ambient Monitor
0
10
20
30
40
50
60
16:30
16:40
16:50
17:00
17:10
17:20
17:30
17:40
17:50

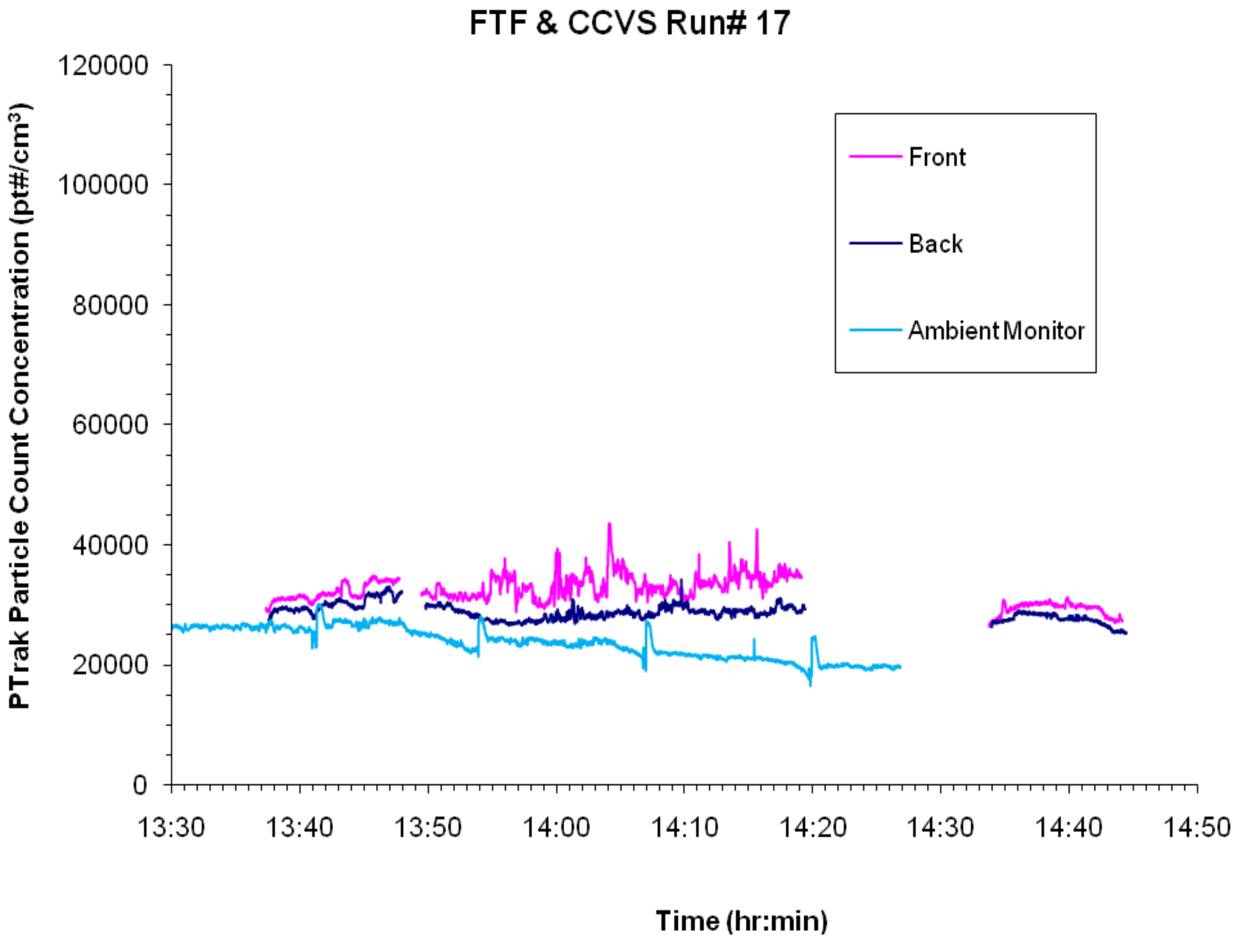

CCVS Run# 15
PTrak Particle Count Concentration (pt#/cm³)
120000
100000
80000
60000
40000
20000
0
16:30
16:40
16:50
17:00
17:10
17:20
17:30
17:40
17:50
Time (hr:min)
Front
Back
Ambient Monitor



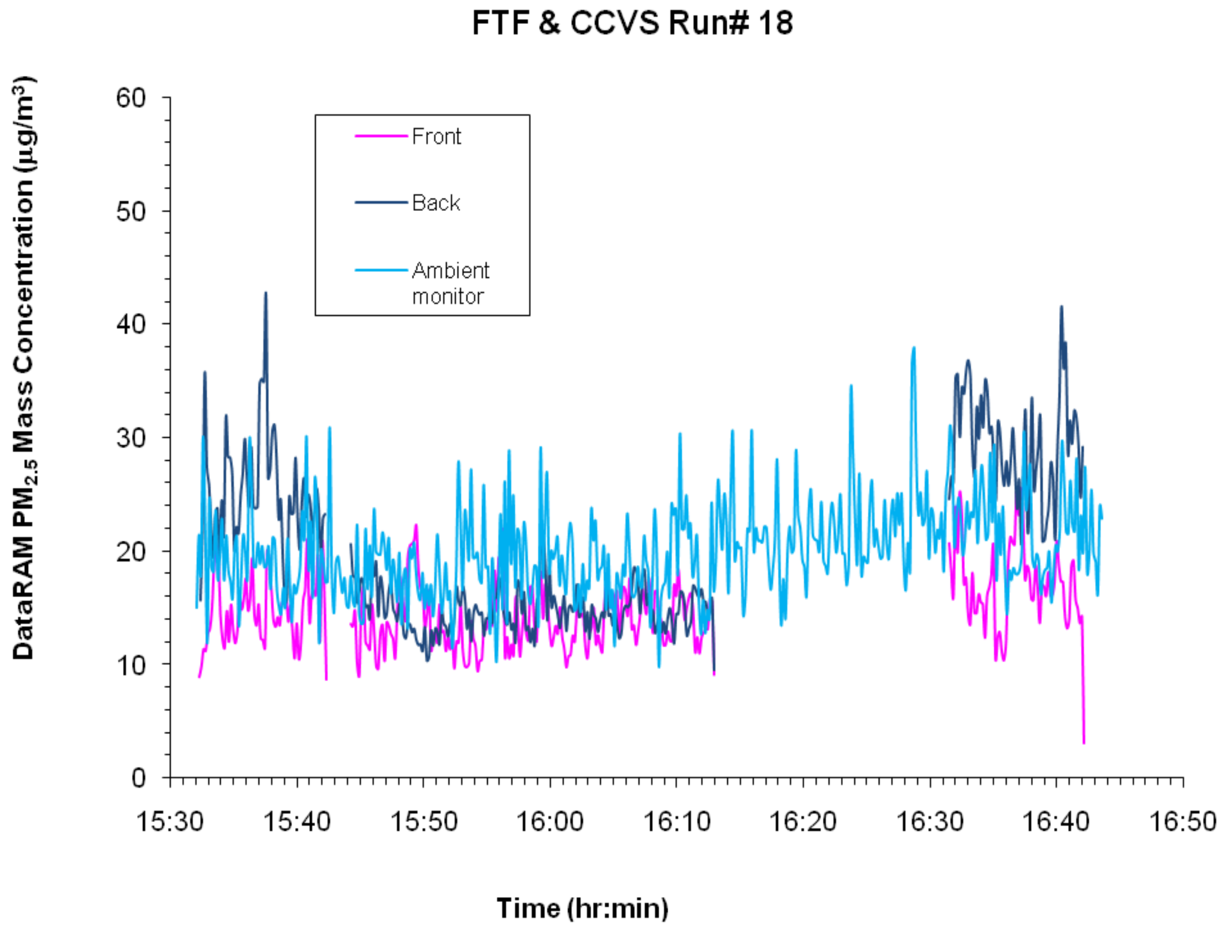
CCVS Run# 16
DataRAM PM2.5 Mass Concentration (µg/m³)
60
50
40
30
20
10
0
Front
Back
Ambient Monitor
5
17:30
17:40
17:50
18:00
18:10
18:20
18:30
18:40
Time (hr:min)

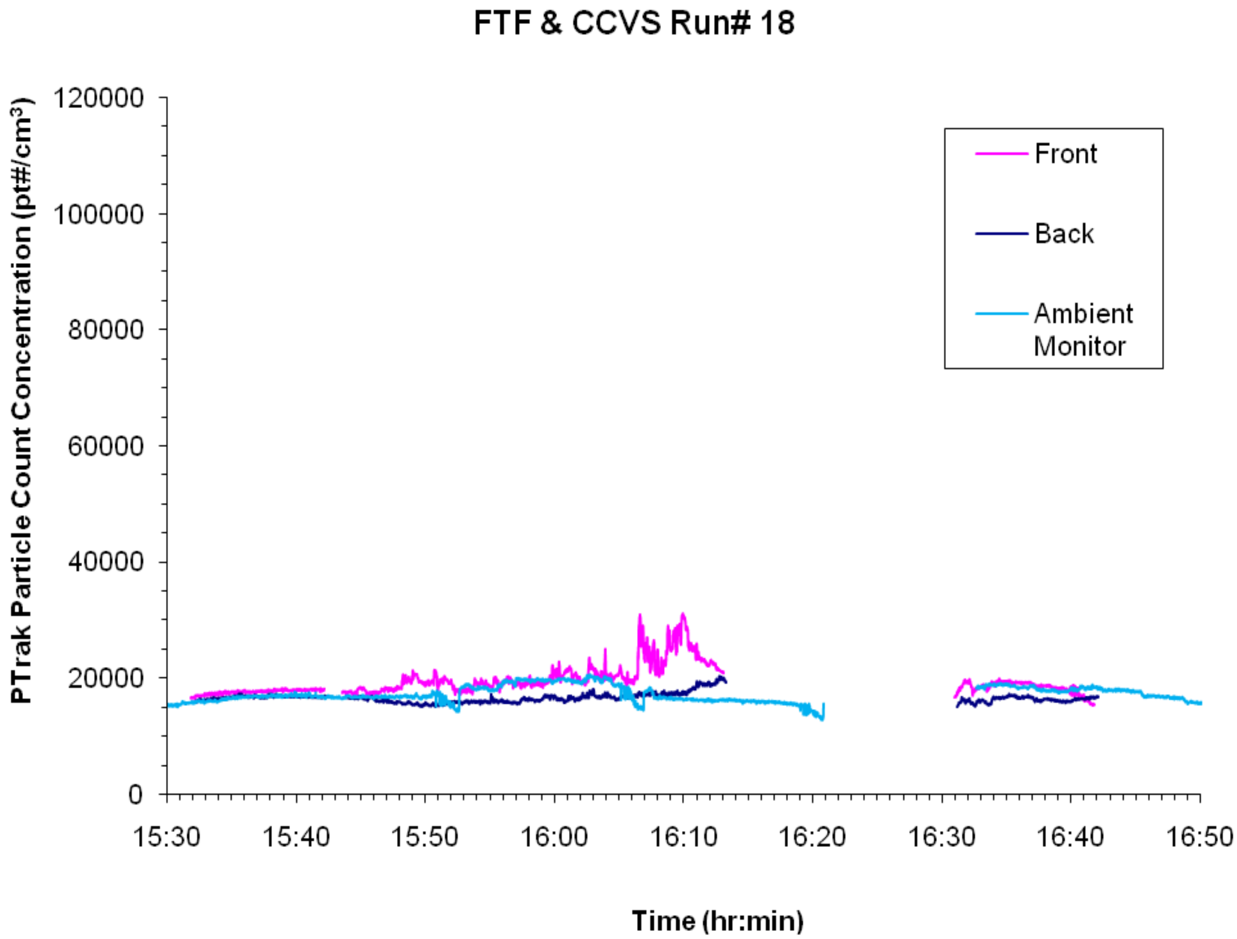

CCVS Run# 16
PTrak Particle Count Concentration (pt#/cm³)
120000
100000
80000
60000
40000
20000
0
Ambient Monitor
Front
Back
17:30
17:40
17:50
18:00
18:10
18:20
18:30
Time (hr:min)


FTF & CCVS Run# 17
DataRAM $PM_{2.5}$ Mass Concentration (µg/m³)
Front
Back
Ambient monitor
0
10
20
30
40
50
60
13:30
13:40
13:50
14:00
14:10
14:20
14:30
14:40
14:50
Time (hr:min)

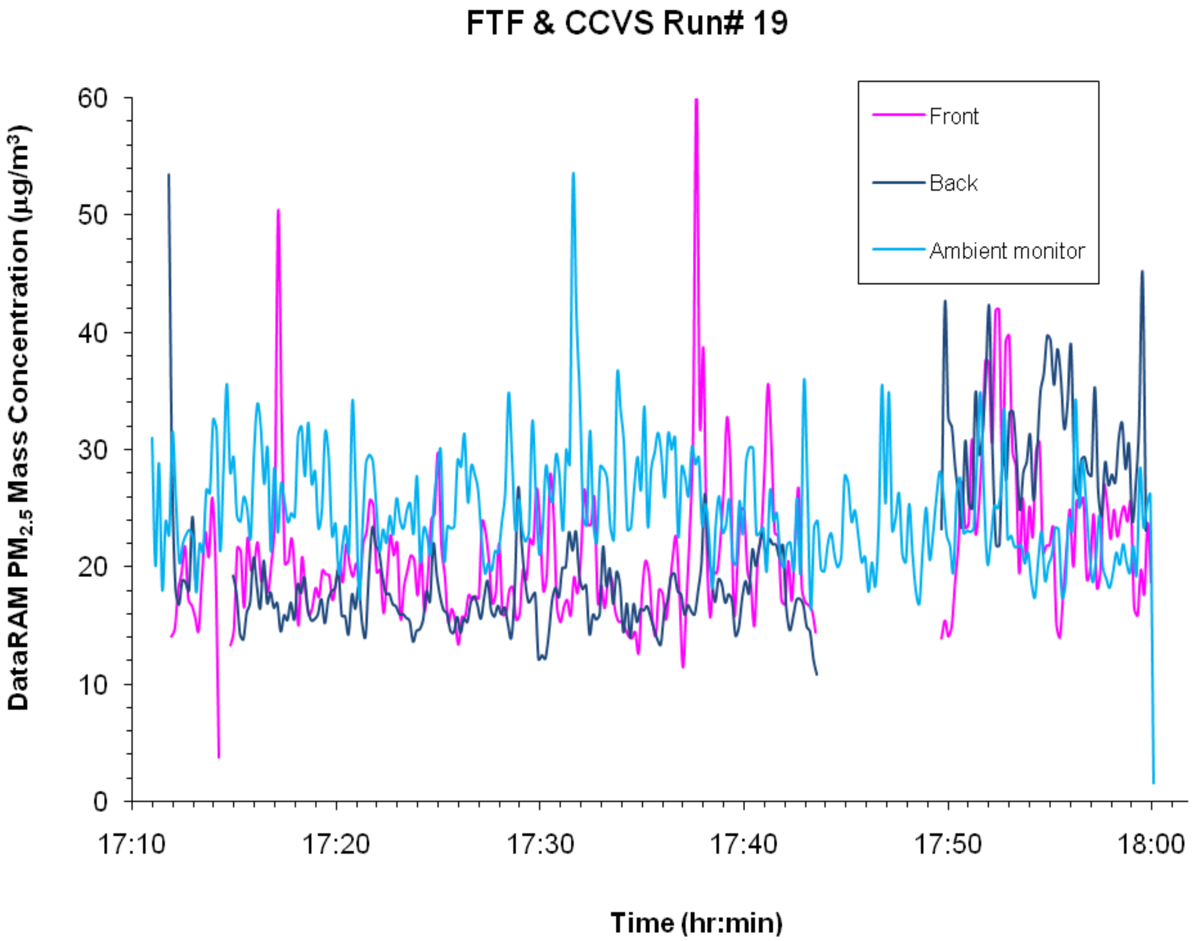


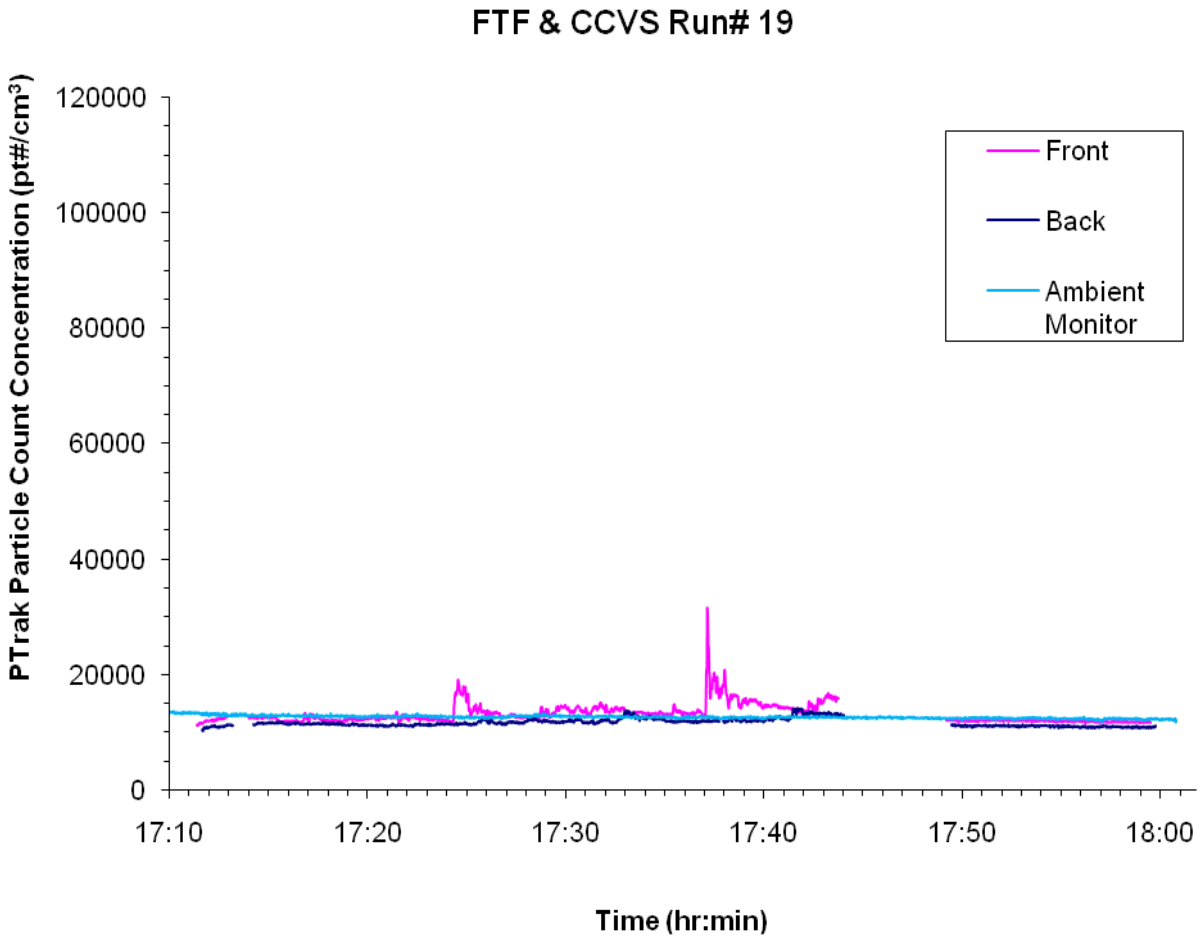
FTF & CCVS Run# 17
PTrak Particle Count Concentration (pt#/cm3)
120000
100000
80000
60000
40000
20000
0
13:30
13:40
13:50
14:00
14:10
14:20
14:30
14:40
14:50
Time (hr:min)
Front
Back
Ambient Monitor


FTF & CCVS Run# 18
DataRAM PM2.5 Mass Concentration (µg/m3)
Front
Back
Ambient monitor
0
10
20
30
40
50
60
15:30
15:40
15:50
16:00
16:10
16:20
16:30
16:40
16:50
Time (hr:min)



FTF & CCVS Run# 18
PTrak Particle Count Concentration (pt#/cm³)
120000
100000
80000
60000
40000
20000
0
15:30
15:40
15:50
16:00
16:10
16:20
16:30
16:40
16:50
Time (hr:min)
Front
Back
Ambient Monitor


FTF & CCVS Run# 19
DataRAM PM2.5 Mass Concentration (µg/m³)
60
50
40
30
20
10
0
17:10
17:20
17:30
17:40
17:50
18:00
Time (hr:min)
Front
Back
Ambient monitor


FTF & CCVS Run# 19
PTrak Particle Count Concentration (pt#/cm³)
120000
100000
80000
60000
40000
20000
0
17:10
17:20
17:30
17:40
17:50
18:00
Time (hr:min)
Front
Back
Ambient Monitor

Appendix P: Testing Protocol

School Bus Testing Protocol **Revision 24**

Note:

1. The rear door should not be opened at any time with the engine running or within 5 minutes of engine shut down.
2. All items should be secured to prevent any movement during testing. DataRAM's and P-Traks will be visually inspected for dirt or dust and if needed will be cleaned prior to entering the bus. The AC power cord should not be moved within the bus. A power strip can be secured near the SEMTECH and extension cord extended to the front of the bus.
3. Booties will always be worn while in the bus after it has been cleaned. Any time someone leaves the bus he/she should remove their booties. When re-entering the bus they will place these booties on their shoes or boots. New booties will be used each test day or if visual dirt is observed on the cloth bootie.
4. Only equipment and materials that are needed for the testing will be in the cabin of the bus.
5. Todd Morris will take charge of SEMTECH D operation while David Martinez will take care of DataRAM and P-Trak's operation. Robert Hesketh will assist. Linda Bonanno will be present for all test runs.
6. SEMTECH D will be zeroed and audited before and after each run.
7. A new printout of this document should be used for each run in order to document time and event markers for references. Use blue or black pen to fill.
8. Instrument readings will be hand recorded on forms during each run to enable assessment of runs at the end of the day.
9. Each box should be checked off upon completion of the task.

Day before Testing

	10. One day before testing verify from a forecast that the following run criteria will be satisfied:
☐	10.1. T > 32°F,
☐	10.2. No precipitation at time of testing (primarily for safety problems with driving on a slick road surface)
☐	10.3. AQI needs to be less than 100 which is symbolized by either a green (good) or yellow (moderate) symbol at the following website: http://airnow.gov/index.cfm?action=airnow.fcsummary&stateid=25. The AQI of 100 corresponds to a PM2.5 concentration of less than 40 micrograms/m^3
☐	10.4. The wind speed should be less than 30mph based on safety issues while testing.
☐	10.5. The vehicles used to wet the asphalt and dirt tracks should be reserved for the day of testing.
☐	10.6. Visually inspect the track to ensure there is no visual dirt on the test track or other impediments to perform a safe run.
☐	11. Check bus to make sure there has been no damage to the bus. A check should be made of the front and rear doors and windows.

☐	12. Inform Rowan and NJDEP if test can proceed the next day.
☐	13. Wash exterior of the bus with water and brush.
☐	14. Check the fuel level in bus. There should be at a minimum of ¼ tank of fuel. If needed fill tank with ULSD ordered by Rowan, supplied from BP refinery and stored in designated area.
☐	15. Make sure the three DataRAM instruments are being charged overnight. Check for 24 spare AA batteries for additional replacement in the field in case the P-Traks need them.
☐	16. Check condition of track, power wash if needed.

Day of Test (time and date_____________).

☐	17. Recheck condition of test track. If needed, clean the track and set up cones to prevent entry from by other vehicles during testing.
☐	18. Bring a table and place it in the bus for the ambient collection zone.
☐	19. Get a radio for bus communication with ATC
☐	20. Check that the SEMTECH D Power supply is connected to an electric main.
☐	21. Turn on the Sensors Power supply unit and then the SEMTECH D unit. The power switches are located on the front panels of both the power supply unit and SEMTECH D. The SEMTECH D should be on AC power (start time______) for a warm up of approximately 60 minutes
☐	22. Check bus for visible damage, integrity of all seals (grommets under hood, doors, windows, power cord to bus battery, venting port of SEMTECH), installation of retrofit technology(ies) 23. Check that the DataRAM's are connected to electric mains.
☐	24. With engine off, mount laptop on dash and connect laptop power and SEMTECH D Ethernet connection.
☐	25. Login to the SENSOR Tech-PC software program from laptop to operate the SEMTECH D.
☐	26. Check from the Status-Summary screen that all temperatures of the SEMTECH D components are rising to their operation temperatures and allow 60 minutes for warm up. During the 60 minute warm-up period of the SEMTECH D perform the following procedures:
☐	27. Check FID pressure level in SEMTECH D, change if the pressure is less than 600psig. Before installing a new bottle in the SEMTECH D, the regulator of the fuel bottle must be set to 30 psig. The FID fuel bottle should remain closed during the warm up period until it is time to light the FID.
☐	28. Check that the SEMTECH D vents are connected to the venting port on the back wall of the bus.
☐	29. Install filter in heated line of SEMTECH D so that a new filter is in place for every set of runs using the same retrofit technology. Save filter in labeled plastic bag.
☐	30. Perform a leak test on the SEMTECH D and exhaust sampling line. This procedure should only be done before the first run of the day. Go to the System Setup and Leak Test window from the software. Block the sampling line of flow using the provided cap and click the start test button.

	30.1. If the leak check through the sample probe fails, repeat the leak check from the SEMTECH-D sample inlet. If it now passes, then the sample probe is leaking. If the leak check still fails, then check for leaks in the following places first:
	30.2. Make sure the heated filter handle is tightly secured. This is a common source of leakage.
	30.3. Make sure the drain bowl is tight and the O-ring is properly seated. Open the top cover, and look for loose hose connections. Using the sample system diagram as a guide, attempt to trace the leak. This can be accomplished by pinching the sample hose at various locations in the sample path until you find the leak.
☐	31. Remove and place old filters from impactor head into labeled plastic bags.
☐	32. Install the new filters in DataRAM impactor heads using clean surface & tweezers
☐	33. Put new batteries into the three P-Trak instruments.
☐	34. Synchronize the time of the SEMTECH D from the GPS receiver; go to the Tech Support window from the Sensor Tech-PC software, in the System Info screen you can set the system date and time to the GPS. Make sure the Time zone Offset from GMT is set to -5. Push the click on the read button on the SEMTECH D Software to synchronize the time given by the GPS for the watches used to record observations during the runs.
☐	35. Turn on bus
☐	36. Check for leaks on installed retrofit technology and proper installation using hand test to feel for gas leaks as suggested by retrofit distributor.
☐	37. Run the ventilation heating fan to blow out any particles that may have become trapped in the ventilation for a period of about 5 minutes.
☐	38. Turn the ventilation heating fan off.
☐	39. Turn off bus
☐	40. Clean the bus floors using lint free alcohol disposable wipes. Clean the walls, seats, vents and floors. The windows and their tracks should also be cleaned. After cleaning the bus, the ventilation fan and/or defroster should remain turned off.
☐	40.1. Start bus (time______) after a full 60 minutes of SEMTECH D warm up and check systems: normal school bus safety inspections should be performed (check oil, tire pressure, lights, emergency exit door operation, brake operation, door & window operation, door & window gasket integrity, tailpipe connections).
☐	41. Switch SEMTECH D power from AC to bus battery.
☐	42. Connect the DataRAM's to the power inverter.
☐	43. Verify that communications have been established between the ECM and SEMTECH D.
☐	44. Open the session manager button of the SENSOR Tech-PC software which is located on the TEST – TEST SETUP window.

☐	45. Drive the bus until oil temp reaches at least 200° F on asphalt road in order to warm up.
☐	46. During the warm-up driving, check the condition of track, power wash if needed. If the track is clean, then the windows of the bus can be opened to obtain an ambient value within the bus.
☐	47. After engine oil temperature reaches 200°F, then drive the bus to the ambient monitoring station.

During Testing

48. NOTE: Bus doors/windows should not be opened until the engine has been shut off for at least 5 minutes. If health concerns are present (unhealthy heat/humidity, air quality, etc) then the time will be reduced and noted here.________________________
49. The SEMTECH D (with the FID lit), DataRAM's, and P-Trak's will be powered on during all procedures.
50. Record on these sheets the time and description of external events that are potential sources of particulate matter. Surrounding activities that could have an effect in the results:
    - Heavy duty diesel vehicles passing nearby
    - Gravel from entryways and maintenance building
    - Other

____
____
____
____

Ambient Collection and pre-run

☐	51. Re-clean the bus around instrumentation, in the entryway and backdoor entrance.
☐	52. Open the FID fuel bottle and light the FID flame. (time_____).
☐	53. Place foot mat at the bottom of the bus steps to facilitate removing booties from shoes or boots. Remove booties upon exiting bus. Always replace booties when entering the bus.
☐	54. Setup portable table at ambient monitoring station location located at least 300 m from track.
☐	55.
☐	56. P-Trak Set up
☐	56.1. Insert filled alcohol cartridge into P-Traks
☐	56.2. Install sampling heads on P-Traks
☐	56.3. Zero the P-Traks by adapting the HEPA filter to the inlet screen assembly of the instruments and check that the concentration reads 0 pt/cm^3 for 30 seconds
☐	56.4. Delete stored data on PTrak's
☐	56.5.
	57. DataRAM Instrument Set-Up
☐	57.1. Assemble the DataRAM units with their corresponding impactor heads and sample heads

☐	57.2. Power up DataRAM's keeping them connected to AC power extension cord. 57.3. Synchronize the time of the DataRAMs and PTrak's to the watches previously set from from the GPS receiver on SEMTECH D
☐	57.4. Perform a zero operation on the DataRAM's. To perform a zero for the DataRAM's go to the MAIN MENU and select the ZERO/INITIALIZE option by moving the cursor to that line.
☐	57.5. Check that the DataRAM is working properly. This is done by examining the status of the light sources. The sources can be reviewed by clicking the NEXT button during the zero operation and they include: the two nephelometric wavelength light sources (SOURCE 1 and SOURCE 2) should read NORMAL, the MEMORY LEFT (should be 100% prior the first run of the day), the BATT CHARGE reading is the charging current when the DataRAM is connected to AC line (if the charger is not used, that line on the screen will indicate BATTERY LEFT). The required zero time is 300 seconds.
☐	57.6. Delete stored data on DataRAM's and set file tags to 1
	58. Place all DataRam and P-Trak instruments outside the bus on portable table. Setup and connect external power supply for DataRAM#2 which consits of an external battery, charger, inverter, voltmeter and cable. Using the P-Traks and DataRAMs record a simultaneous ambient sample for 5 minutes
☐	59. Leave ambient P-Trak #1, DataRAM #2, external battery, charger, inverter, voltmeter and cable on the portable and The P-Trak may need additional alcohol or batteries during sampling time. Under hot and humid conditions the P-Trak may need a new wick. Store additional batteries, alcohol, wick in P-Trak suitcase under table out of the sun's radiation to limit alcohol evaporation.
☐	60. Place P-Trak #2 and DataRAM #1 in front and P-Trak #3 and DataRAM #3 in the back of the bus for ambient collection. .
☐	61. Drive bus to start position
☐	62. Start the ambient collection 5 minutes after the bus is out of sight of the ambient monitoring station
☐	63. **(Starting Point for Consecutive New Run)** Perform the 10 minute ambient collection for P-Traks and DataRAM's inside the bus with windows open. Instruments inside the bus should stabilize reading for 10 minutes to be considered valid.
☐	63.1. Click the START button from the MAIN MENU to start ambient measurement for the DataRAM's and click on the LOG MODE 1 using the enter button on the P-Traks.
☐	63.2. Check ambient concentrations after 30 seconds and if the DataRAM concentrations exceed 40μg/m^3 do the following:
☐	63.2.1. Power down by clicking the ON/OFF button, turn back on and re-zero the instruments by following the zero operation described 57.4.

☐	63.2.2. Start DataRAM data collection and check to see if the ambient concentrations exceed 40µg/ m^3.If readings are still high, replace filter, clean sampling head with zero air and chem wipes.
☐	63.2.3. If DataRAM average values are still greater than 40 µg/m^3 persist consult Rowan and NJDEP staff to determine if run should continue.
☐	63.3. Record stabilized ambient concentration for instruments on data recording sheets.
	NOTE: The following steps can be done during the ambient collection time period (steps 64-69)
☐	64. If this is the 2nd or 3rd run of the day, then replenish the alcohol wick of the ambient P-Trak. Check the battery status of the P-Trak and DataRAM. Use the voltmeter to check external DataRAM battery. Install new batteries in the P-Trak if needed. If necessary bring DataRAM back to the bus and recharge for approximately 40 minutes to complete the next run.
☐	65. Record P-Trak #1 and DataRAM #2 averages at ambient monitoring station
☐	66. Check that the sampling line of the SEMTECH D is properly located and installed.
☐	67. Check that the FID has been lit for at least 15 minutes before performing the zero and audit calibration.
☐	68. Perform a ZERO of the SEMTECH D:
☐	68.1. Open the zero air bottle, check that the delivery pressure of the regulator is 30psig.
☐	68.2. Open the zero valve from the valve set attached to the SEMTECH D power supply.
☐	68.3. Click the ZERO button on the Pre-Test screen of the session manager.
☐	68.4. Check the gas analyzer boxes and click the START button to begin the zero process.
☐	68.5. If the zero test fails, check the connections of the zero bottle and the SEMTECH D and look for any warning or fault messages. Do another zero calibration after correcting/checking the proper conditions.
☐	68.6. If the zero procedure is passed, close the zero calibration bottle and the zero valve from the valves set. (time______).
☐	69. Perform a SPAN calibration. This procedure should only be done before the first run of the day. In this calibration you will use the two span calibration bottles, repeat the procedure for each one.
☐	69.1. Open the SPAN calibration bottle and check that the regulator delivers a pressure of 30 psig.
☐	69.2. Open the SPAN valve from the valve set attached to the SEMTECH D power supply.
☐	69.3. Click the SPAN button on the Pre-Test screen of the session manager. This step needs to be done only once for the use of the two calibration bottles.
☐	69.4. Check the gas analyzers boxes and click the START button to begin the SPAN process.

☐	69.5. If the SPAN passes, close the corresponding SPAN calibration bottle and the SPAN valve from the valve manifold. (time______).
☐	70. Perform an Audit. This procedure requires the use of two audit bottles. Repeat the procedure for each one.
☐	70.1. Open the audit calibration bottle and check that the regulator delivers a pressure of 30 psig.
☐	70.2. Open the Audit valve from the valve set attached to the SEMTECH D power supply.
☐	70.3. Click the AUDIT button on the Pre-Test screen of the session manager. This step needs to be done only once for the use of the two calibration bottles.
☐	70.4. Check the gas analyzers boxes and click the START button to begin the AUDIT process.
☐	70.5. If the AUDIT test fails, perform a SPAN calibration. Follow this procedure using the span calibration bottle.
☐	70.6. After the span test is performed, check the connections of the AUDIT bottle and the SEMTECH D. Also check that the calibration bottle gas concentrations correspond to the concentrations given in the audit parameter screen. Perform a new audit.
☐	70.7. If the audit passes, close the corresponding audit calibration bottle and the audit valve from the valve manifold. (time______).
☐	71. Verify that P-Traks and DataRAM's concentrations have stabilized at ambient concentrations measured before starting the run.
☐	72. Verify that the SEMTECH D software shows no warnings or faults.
☐	73. Stop recording Dataram's and P-Traks. Record averages on Datasheets
☐	74. Close windows. (time______).
☐	75. Start engine. (time______).
☐	76. Record engine oil temperature at start of run. (The optimum temperature is 200°F)
	77. Start recording in the following order:
☐	77.1. Start recording SEMTECH D - Click the START button on the Test section of the Session Manager window. (time______).
☐	77.2. Verify that vehicle speed is set to Vehicle
☐	77.3. Start P-Traks, by first selecting the LOG MODE 1 using the arrow cursor and press enter to start. (time______).
☐	77.4. Start DataRAM's, click ENTER on the START RUN option from the Main Menu. (time______).
☐	77.5. Start the drive cycle clicking the START CYCLE button on the TEST – DRIVE CYCLE window of SEMTECH D software.
☐	77.6. Open Door and follow the drive cycle on the laptop; the ball represents the bus's actual speed and the line is the target speed that needs to be followed.
☐	77.7. Log time bus starts moving (time______).

During the run

	78. The P-Trak's, DataRAM's, and SEMTECH D should be monitored during the run. For front and back locations, a technician will sit in an adjacent seat so they can observe the instruments and record instantaneous readings each time the bus stops. Technicians will not move around unnecessarily. See page 202 for sample figures of proper instrument display panels
	79. The run needs to be stopped for the following conditions:
	79.1. SEMTECH D
	79.1.1. Lost connection between SEMTECH D and laptop – run stop
	79.1.2. SEMTECH D unit shut down – run stop
	79.2. P-Traks
	79.2.1. TILT message – try to put horizontal or wait until the bus gets out of a curve. The TILT will only add an error message to the one second concentration in the file, if the tilt condition persists then the P-Trak will stop recording.
	79.2.2. Instrument stops recording (Log Mode1 is not active) – immediately start measuring again by activating Log Mode1. This can be the result of a tilt condition, the data file will keep recording and only the time in which the tilt condition persists will be lost, this should not be more than 10 seconds.
	79.3. DataRAM's
	79.3.1. Instrument stops recording – restart recording data
	79.3.2. Flow Fault reading – look for any flow obstructions and correct
☐	80. For the last stop of the cycle (time_____), the main door should remain closed.
☐	81. Stop recording DataRAM's (key **EXIT**, and then to confirm the run termination key **ENTER)** and stop recording P-Trak's (click the ENTER "↵" key)/SEMTECH D (click the STOP button on the Test section of the Session Manager window).
☐	82. Upon completion of a run, prior to engine shut down, proper analyzer operation should be noted in the logs. (time______).
☐	83. Drive to start position of next test.
☐	84. Re-inspect retrofit technology for leaks and then shut engine down. (time____).
☐	85. Record average values on data sheets for the P-Traks and DataRAM's
☐	86. Without opening windows and doors remain seated for five minutes. If health concerns are present (unhealthy heat/humidity, air quality, etc) then the time will be reduced and recorded. (Time duration between engine power-down and doors opening: _____)
☐	87. Zero and audit the SEMTECH D as described in step 68.

☐	88. Check FID Fuel pressure from SEMTECH D software. If less than 200 psig replace with new bottle.
☐	89. Re-clean bus
☐	90. Open Bus windows and front door. (Time____________).
☐	91. Place clean mat on ground in front of steps. Remove booties from shoes.
☐	92. Inspect SEMTECH D sample line to insure that a valid tailpipe sample was taken.
☐	93. Start New Protocol Sheet for next Run by starting at step 63 (omitting zero and audit of SEMTECH since this was done in step 87. If this is the last run of the day then continue to next step.
☐	94. Perform the 10 minute ambient collection for P-Traks and DataRAM's inside the bus as given in step 63. Instruments inside the bus should stabilize reading for 10 minutes to be considered valid. Record instrument averages on data sheets. (time______).
☐	95. Shut down SEMTECH D
☐	96. Disconnect battery cable from SEMTECH
☐	97. Connect SEMTECH D to SENSORS power supply unit
☐	98. Drive bus to its overnight parking location.
☐	99. Transfer data from SEMTECH D and P-Trak to computer.
☐	100. Shut off P-Traks and put P-Trak's alcohol cartridge back to alcohol fill capsule. Empty used alcohol and put in new alcohol every 2 days of testing, every week, every six runs, or if the alcohol in the fill capsule looks contaminated (whichever comes first).
☐	101. Switch off the DataRAM's and start recharging batteries.
☐	102. Close valves on SEMTECH D FID fuel gas bottle and all calibration cylinders.
☐	103. Take DataRAM's to Rowan for Data Transfer to computer
☐	104. David will take laptop to Rowan with all data files stored in to analyze.
☐	105. Close all windows/doors to prevent rain/dust from entering the bus during the night.

Quality Control Notes

- All external events that may generate particulates during the testing (e.g. a tank passing by the testing track at 12:32) will be recorded on the protocol sheets. Additional information should also be logged including such as bus/instrumentation problems, and any information that could be useful for analysis of the data. The protocol sheets will be marked using pen.
- SEMTECH D's heated line filter will be replaced after a change in retrofit set: one filter for baseline runs, one filter for FTF (ESW Particulate Reactor), etc. The replaced filters will be stored and labeled corresponding to the retrofit technology tested
- DataRAM's impactor head filters will also be replaced and stored before every run day. The SEMTECH D operation manual recommends changing the heated line filter after every 8 run hours, and the DataRAM manual recommends changing the impactor head filter when it is "obviously soiled". Changing these filters at the specified period of time will not violate the recommended replacement schedule by the manufacturer.
- Always wipe feet on floor mat before entering bus
- Do not open windows or doors within 5 minutes of engine shutdown unless unhealthy conditions exist.

- NOTE: Technicians should limit their movement in the cabin of the bus. The P-Trak's, DataRAM's, and SEMTECH D should be monitored during the run. For front and back locations, a technician will sit in an adjacent seat so they can observe the instruments. Technicians will not move around unnecessarily.

Sample Instrument Displays while recording data:
P-Traks should display the particulate concentration and the words "Log Mode 1" as shown Figure 63:

4048 **PT**

CC
MIN 4032 08:32:00
MAX 4950 09:27:00
98 % MEM
LOG MODE 1 ↵ TO STOP

Figure 63: P-Trak display during measurement Log Mode 1

If the P-Trak display is as shown in Figure 64 then the P-Trak is no longer recording data. This usually occurs if a Tilt condition last more than 10 seconds. To start recording data again, you must immediately click the LOG MODE 1 option and press ENTER.

3670 PT/CC

· SAMPLE
▸SETUP
· LOG MODE 1

Figure 64: P-Trak display during main menu

- The **DataRAMs** should appear as shown in Figure 65

16:08:09	10 May 2000
CONC:	5.7 ug/m3
TWA:	11.0 ug/m3
RUN TIME:	00000:02:25

Figure 65: DataRAM display during measurement

Clicking the NEXT button will display the following screens which do not require any action because the measurement is still running and data is being stored in a file. The following figures are examples of each of the screen displays of the DataRAM's:

MEMORY LEFT	87%
BATT. LEFT	76%
FLOW RATE	1.99 LPM
TEMP= 25.3C	RH= 59%

Figure 66: Run operation display 1

FLOW:	NORMAL
SOURCE 1:	NORMAL
SOURCE 2:	NORMAL
DETECTOR:	NORMAL

Figure 67: Run operation display 2

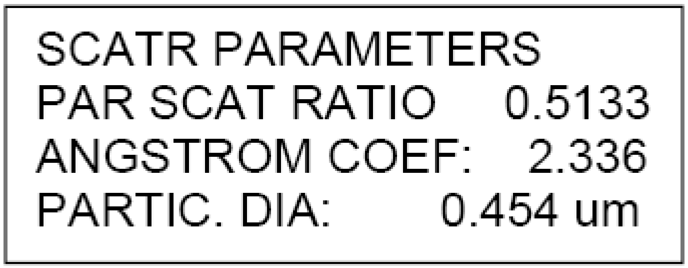


Figure 68: Run operation display 3

If the DataRAM has stopped recording then the display will return to the main menu as shown Figure 69

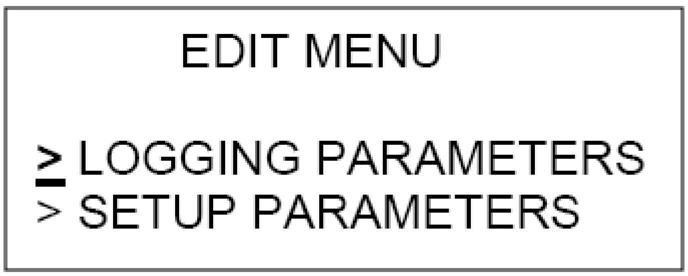


Figure 69: Main Menu of DataRAM

The **SEMTECH-D** Session Manager window in the main screen of the laptop should read the STOP warning in the Test section as shown in Figure 70. This indicates that the run is being recorded.

Figure 70: Session Manager window from the SENSOR Tech-PC application

Appendix Q: Real Time DataRAM and P-Trak Charts for Initial Study

Run# 1: Unsuccessful Run: Did not finish cycle due to bus break problems.

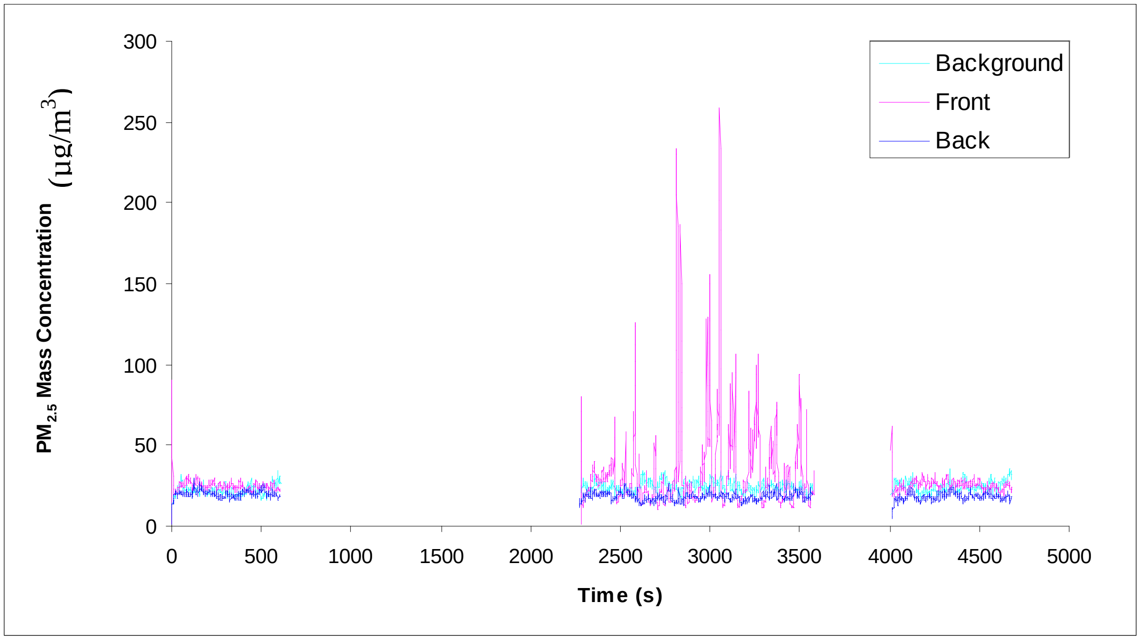


Figure 1 Run 1, Baseline windows open Feb 21-07. DR1 was background instrument; DR2 was located in the front and DR3 in the back of the bus.

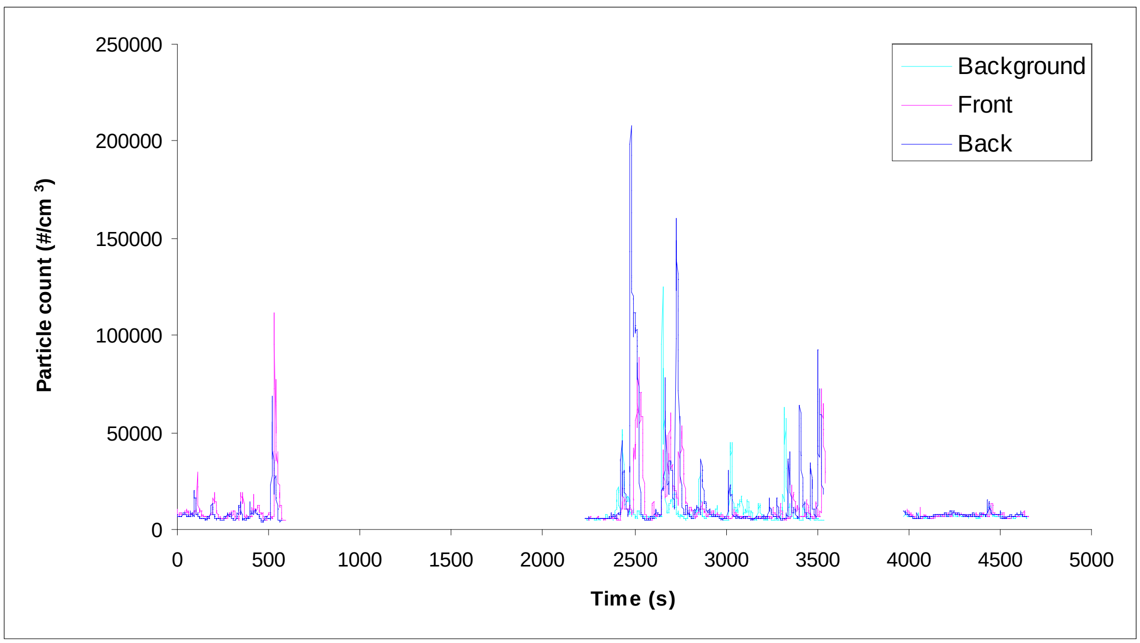


Figure 2 Run 1, Baseline windows open Feb 21. PT1 was background, PT2 front, and PT3 back of the bus.

Run# 2: No external events observed. Background DataRAM not available for test because of flow obstruction

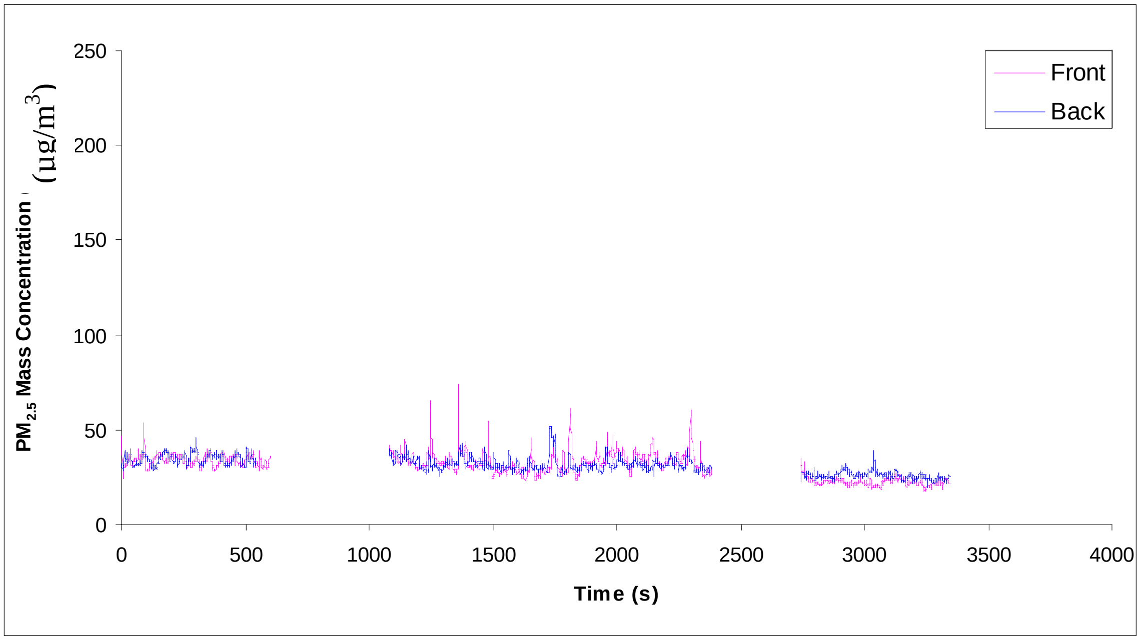


Figure 3 Run 2, Baseline windows open PM2.5 mass concentration March 20-07.

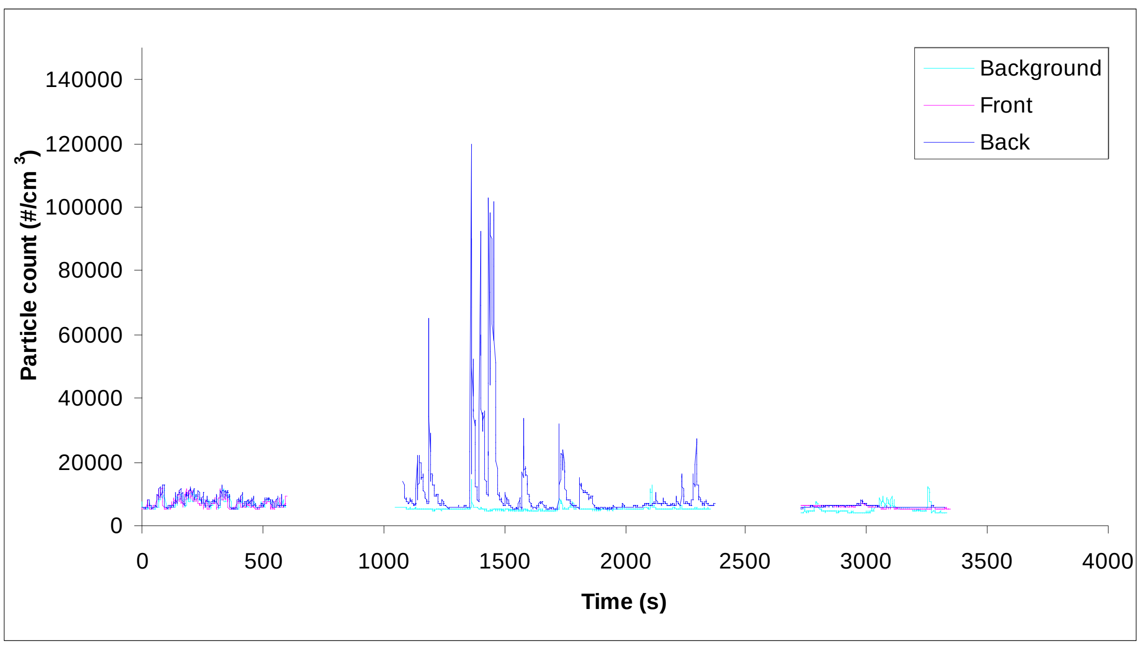


Figure 4 Run 2, Baseline windows open Particle Count March 20-07. Front instrument P-Trak#2 only recorded one point during the test due to operation error.

Run# 3

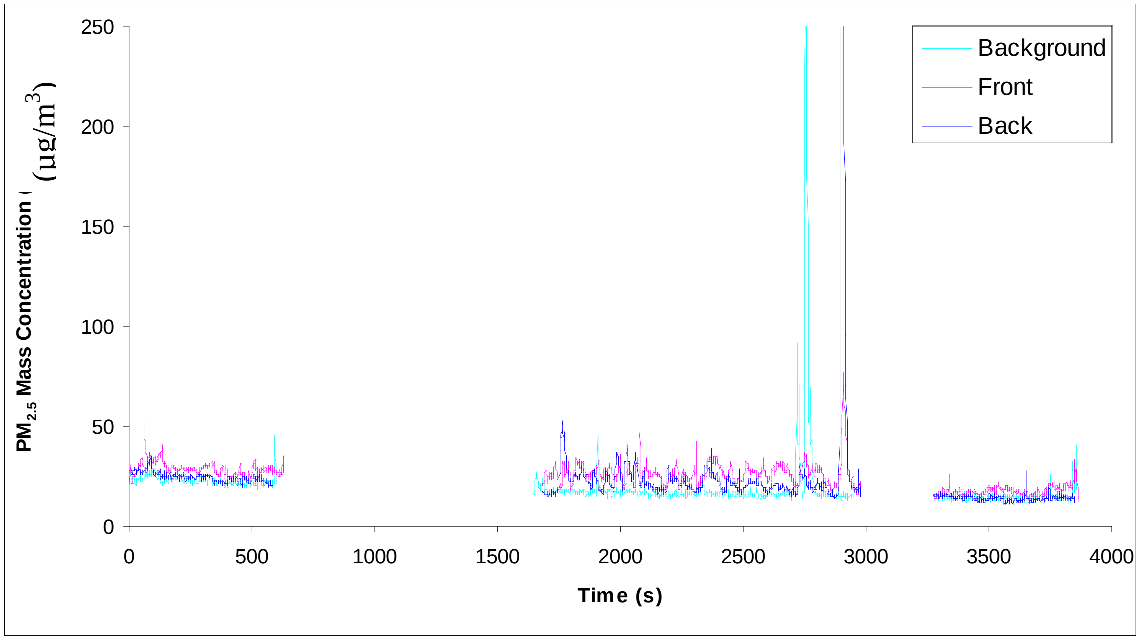


Figure 5 Run 3, Baseline windows open PM2.5 mass concentration April 2-07.

External peak from an external source appeared first appeared in background instrument. Palladin field artillery piece drove by during run on the tank access trail next to the course. Could be the effect seen on high peak during the run.

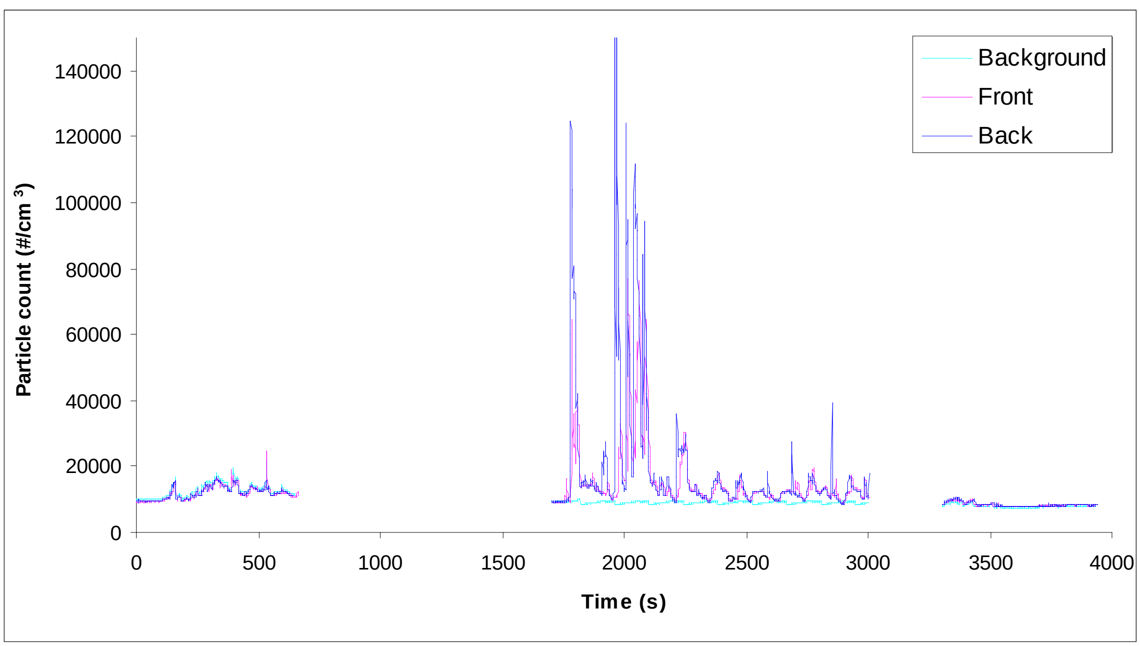


Figure 6 Run 3, Baseline windows open Particle Count April 2-07.

Run #4: Unsuccessful Run: build up in particulates

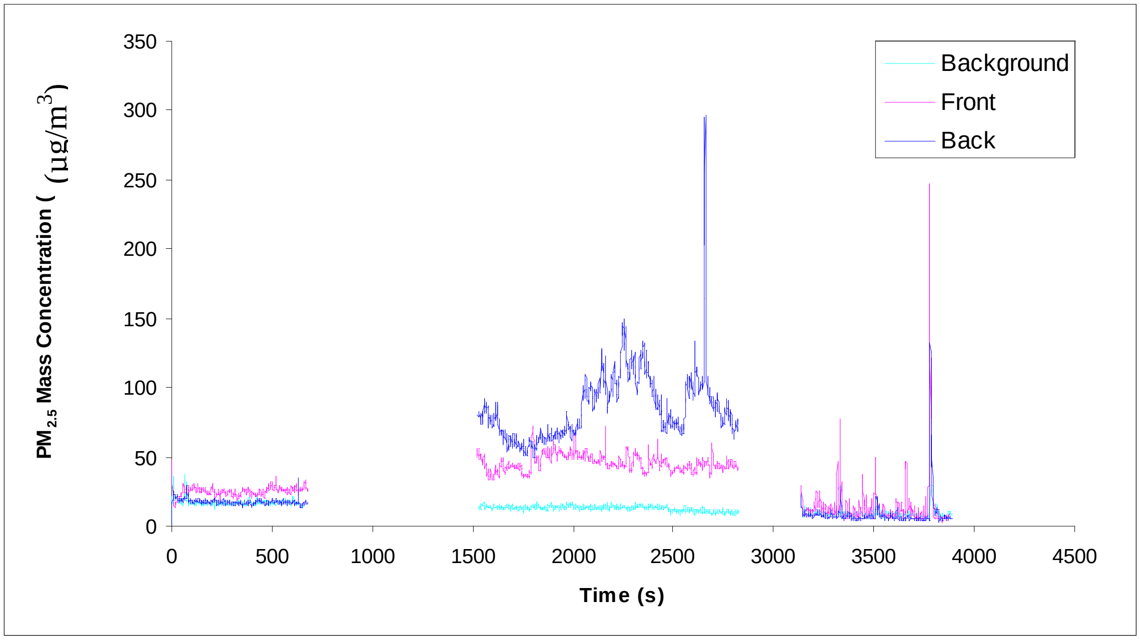


Figure 7 Run 4, Baseline windows closed, April 2-07.

Build up of more than 20μg/m^3 occurred at the beginning of the test.

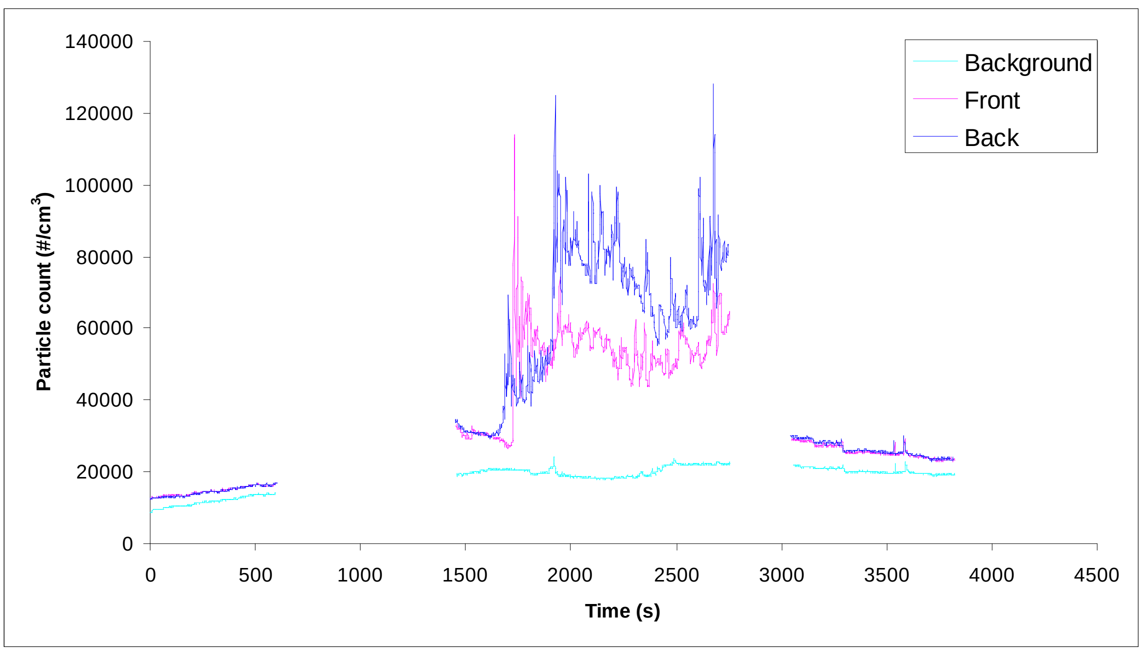


Figure 8 Run 4, Baseline windows closed, April 2-07.

Run #5

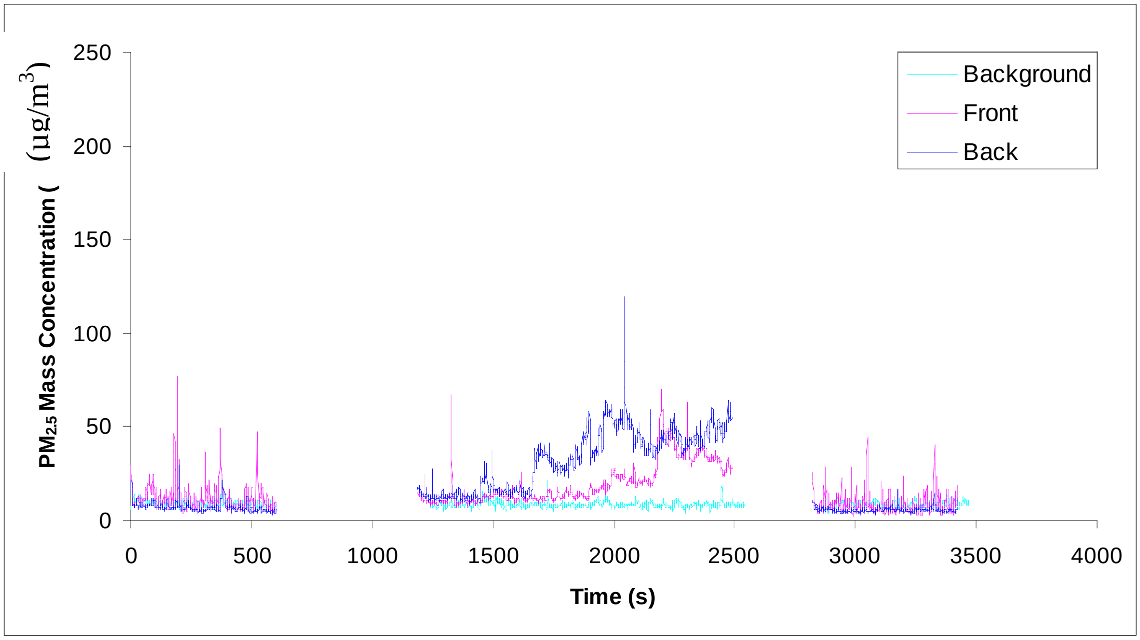


Figure 9 Run 5, Baseline windows closed PM2.5 mass concentration April 2-07.

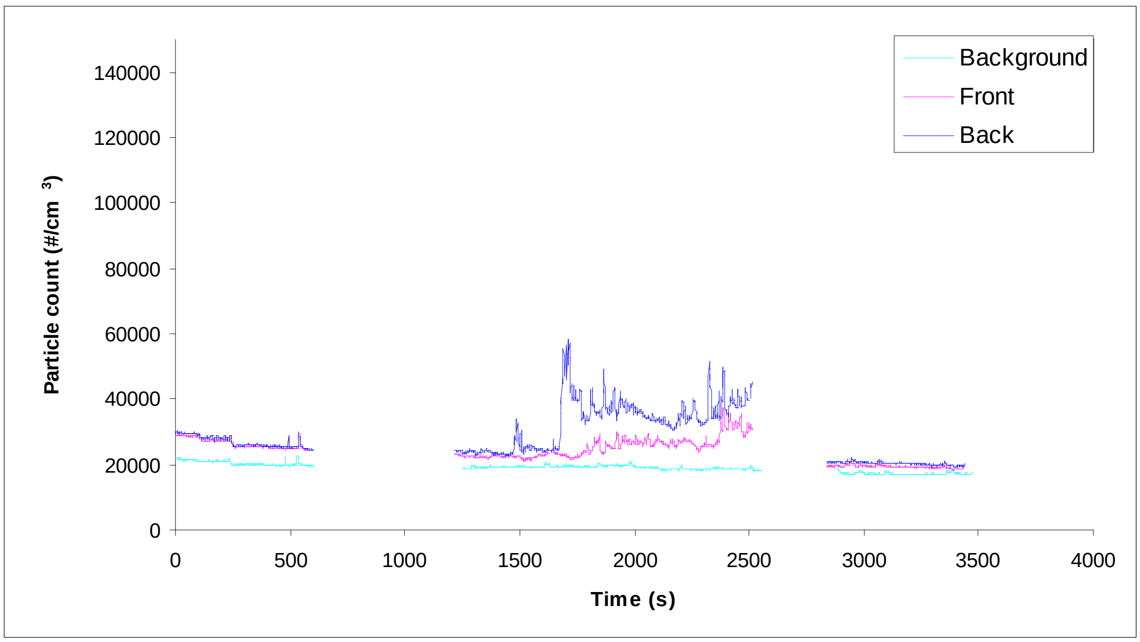


Figure 10 Run 5, Baseline windows closed Particle Count April 2-07.

Run #6:

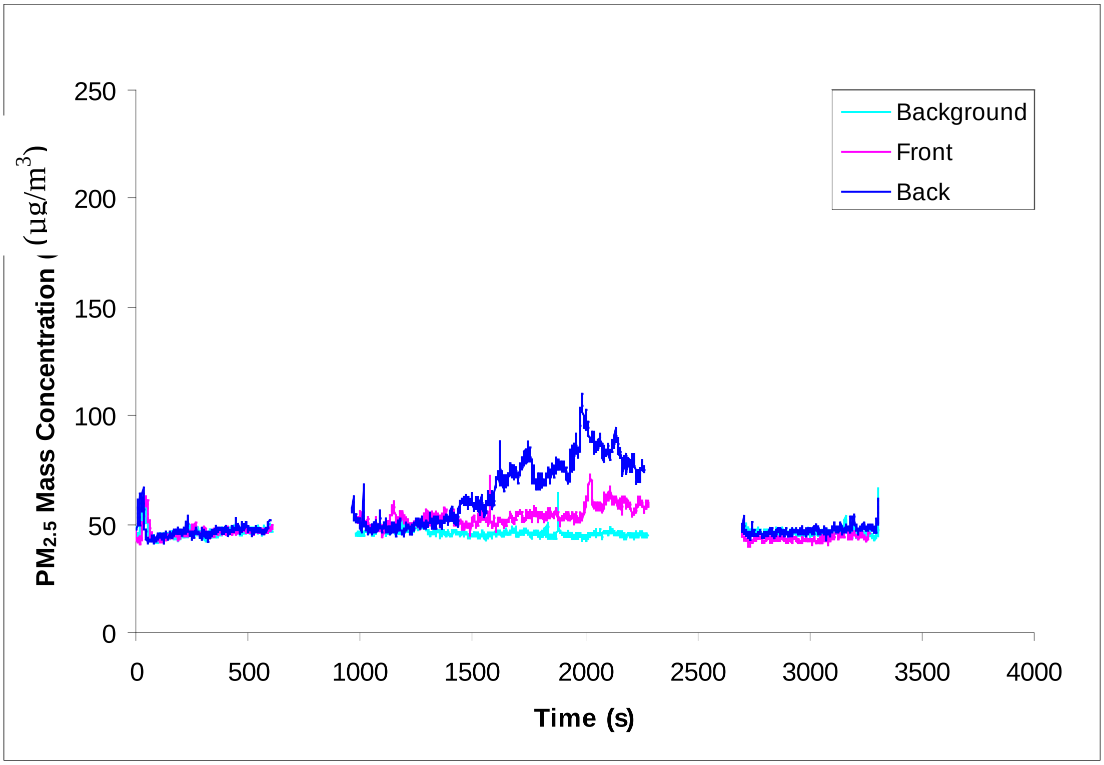


Figure 11 Run 6, Baseline windows closed PM2.5 mass concentration April 3.-07

Ambient PM2.5 mass concentration was higher than 40µg/m^3

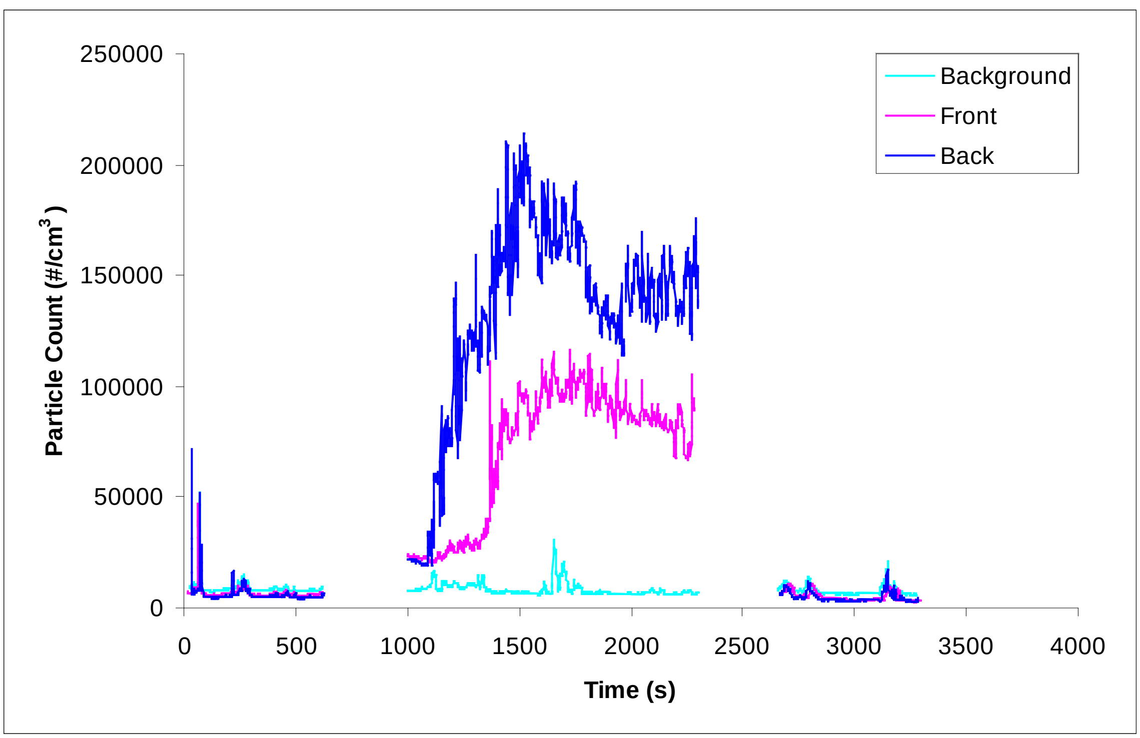


Figure 12 Run 6, Baseline windows closed Particle Count April 3-07.

Run #7:

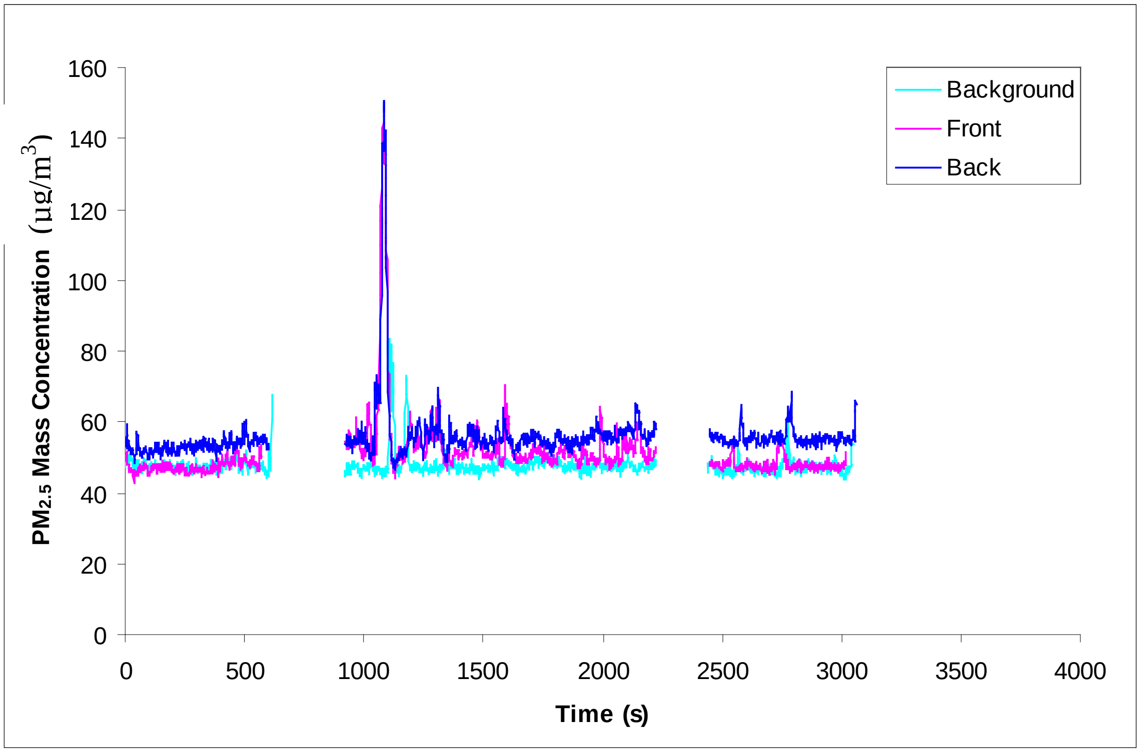


Figure 13 Run 7, Baseline windows open PM2.5 mass concentration April 3-07.

High ambient PM2.5 mass concentration greater than 40µg/m^3

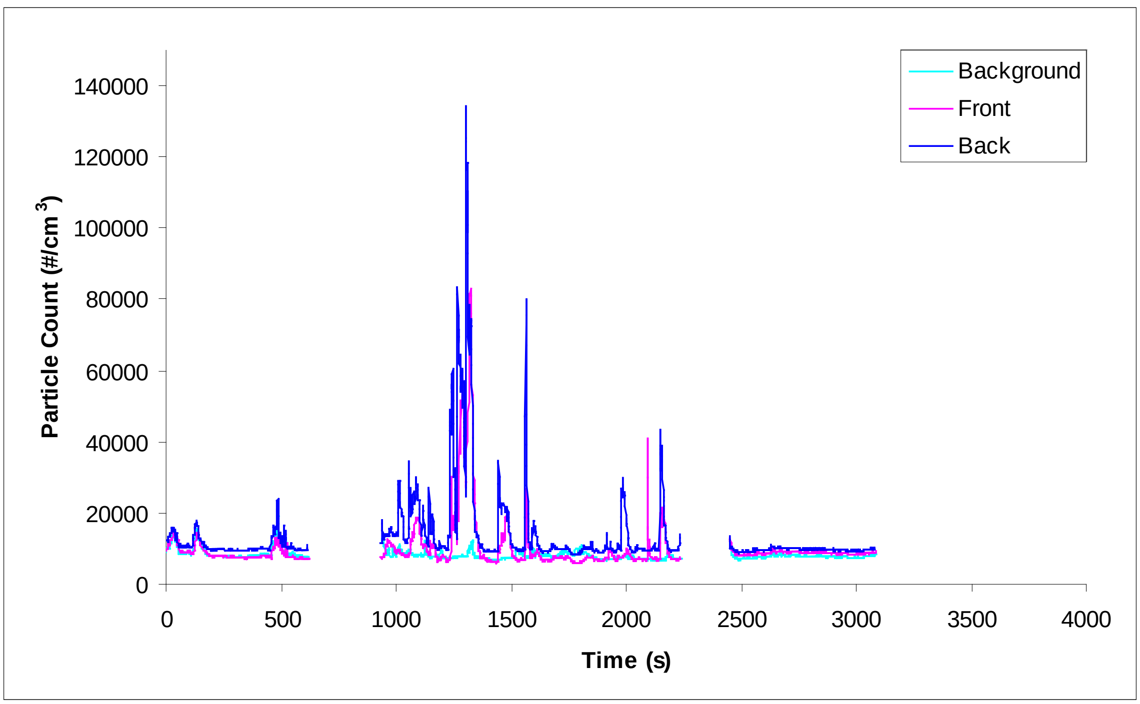


Figure 14 Run 7, Baseline windows open Particle Count April 3-07.

Run #8:

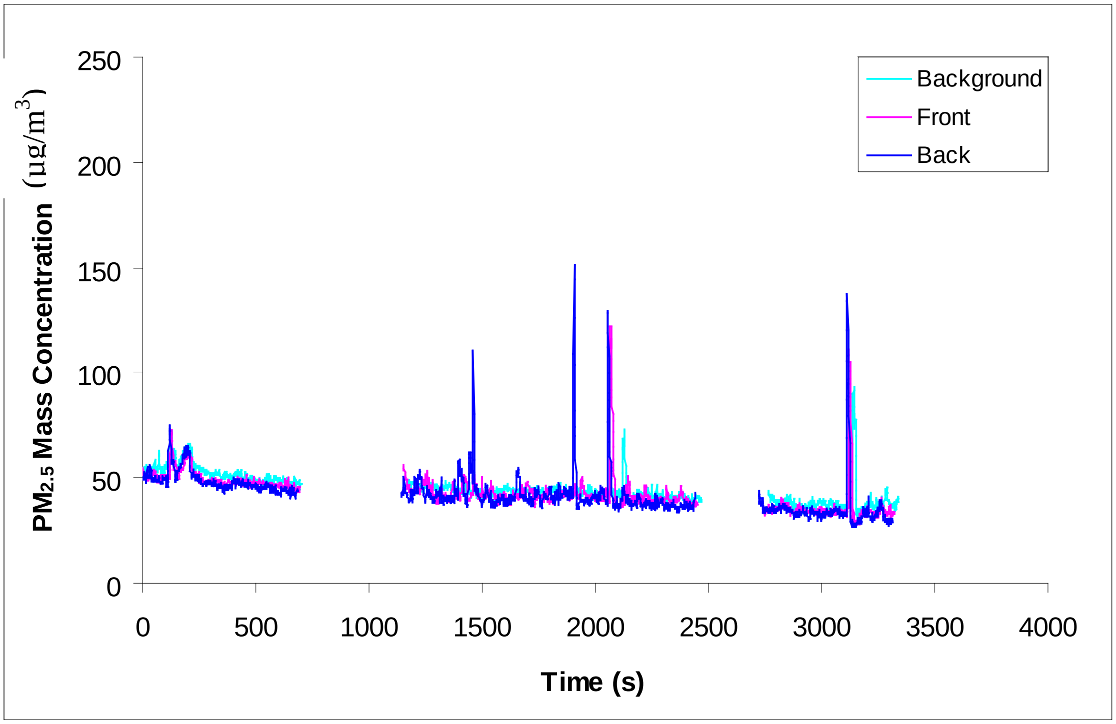


Figure 15 Run 8, Baseline windows open PM2.5 mass concentration April 3-07.

High ambient PM2.5 mass concentration greater than 40μg/m^3

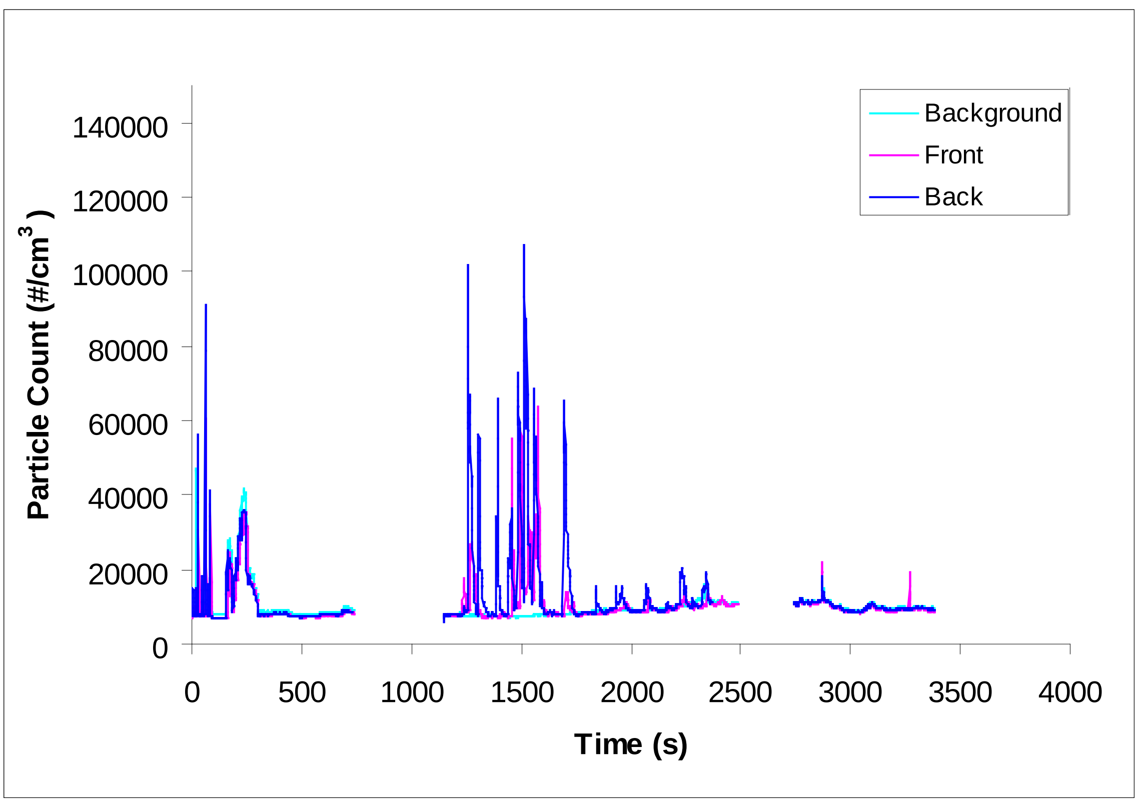


Figure 16 Run 8, Baseline windows open Particle Count April 3-07.

Run #9:

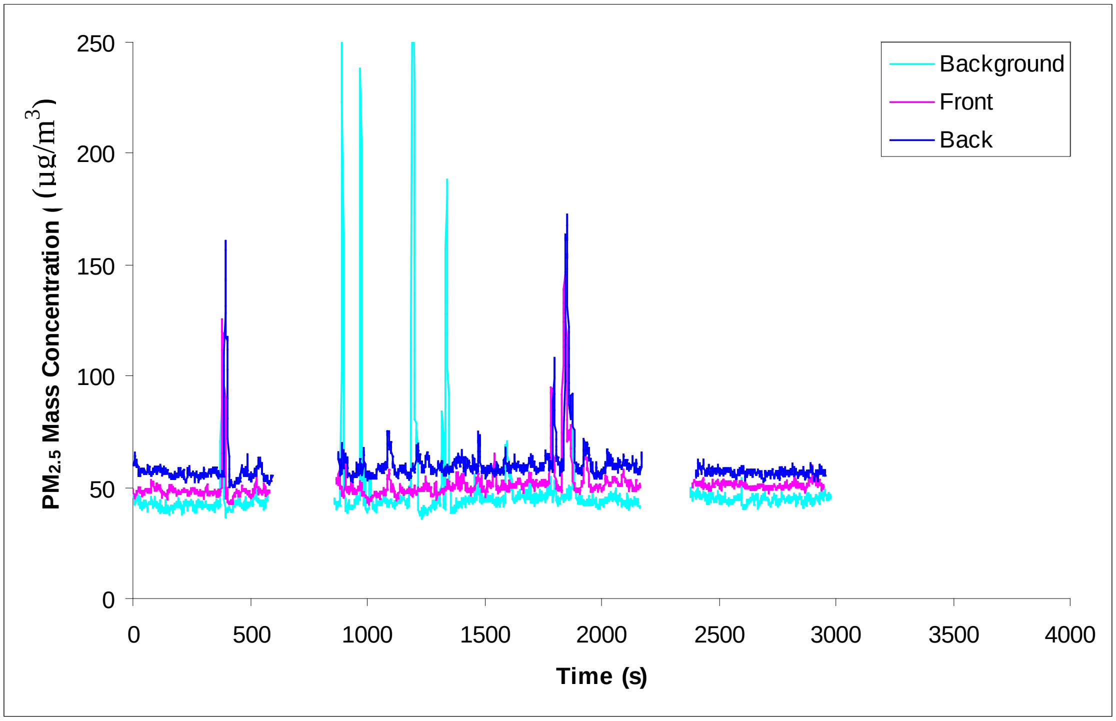


Figure 17 Run 9, Baseline windows open $PM_{2.5}$ mass concentration April 3-07.

Background instrument for $PM_{2.5}$ and particle count recorded high concentration peaks not reflected in the bus cabin.

High ambient PM2.5 mass concentration greater than 40µg/m^3.

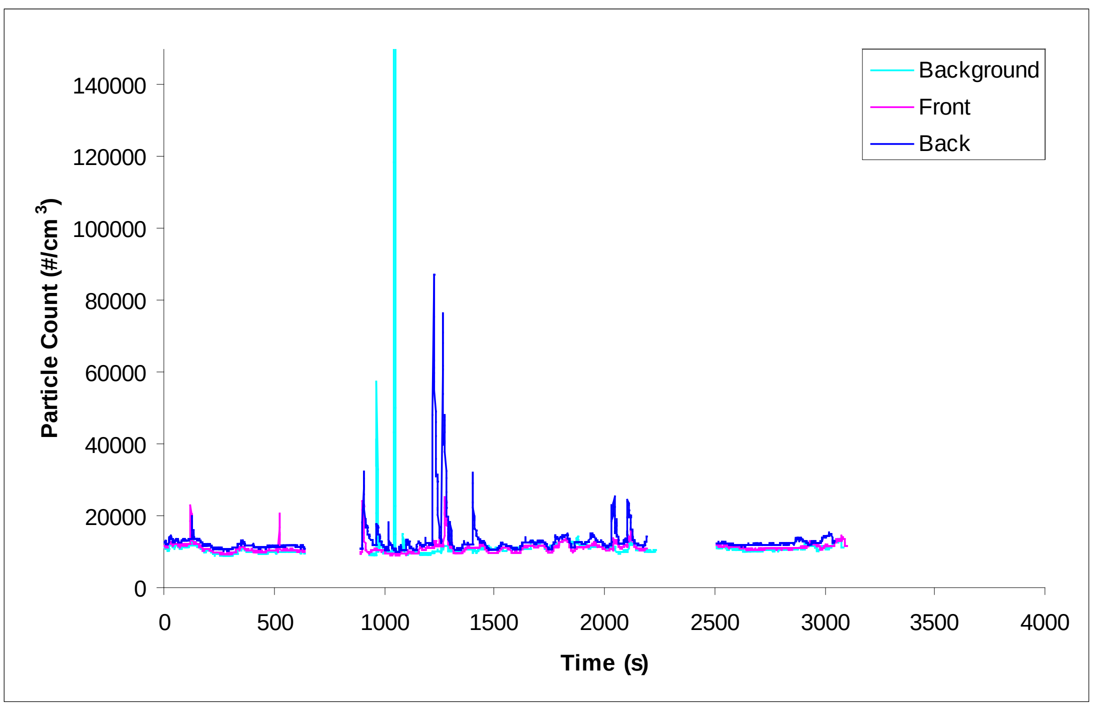


Figure 18 Run 9, Baseline windows open Particle Count April 3-07.

Run #10:

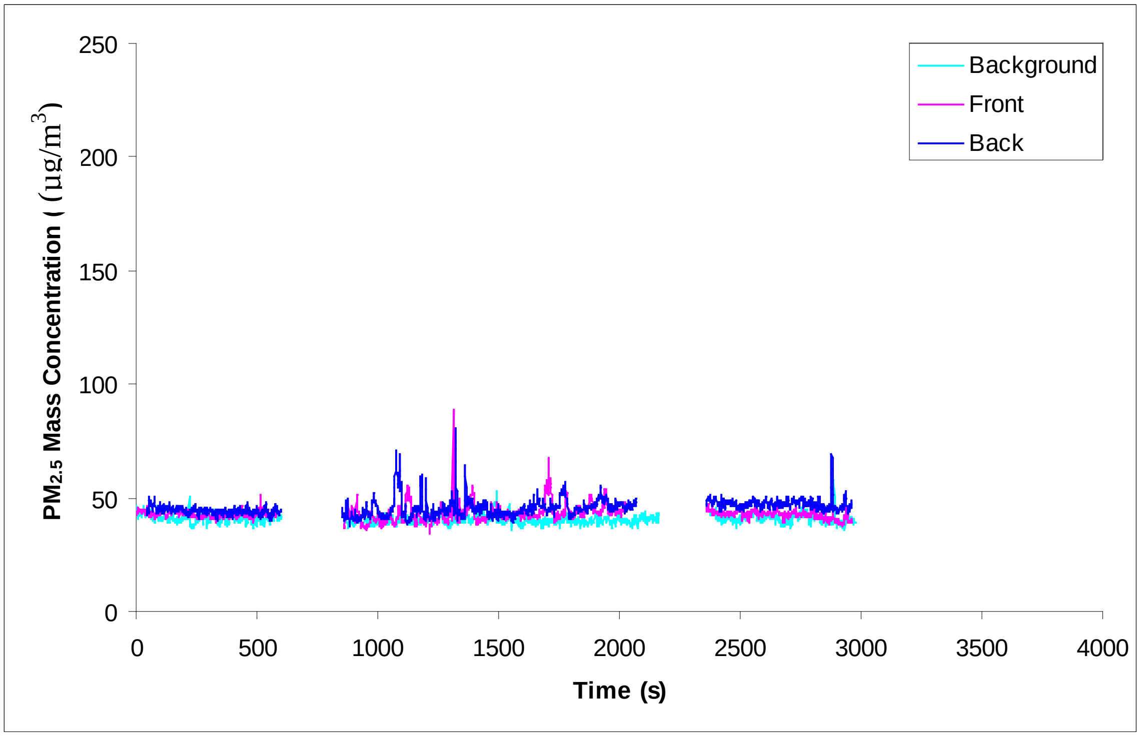


Figure 19 Run 10, Baseline windows open PM2.5 mass concentration, April 3-07.

High ambient PM2.5 mass concentration greater than 40µg/m^3.

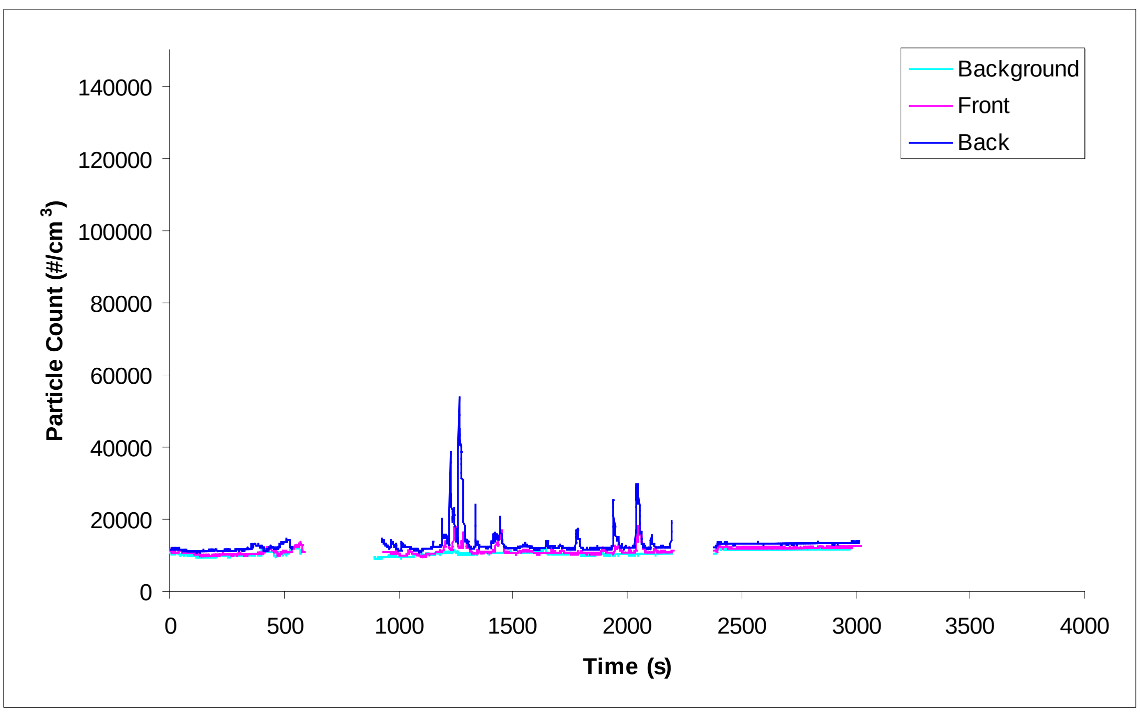


Figure 20 Run 10, Baseline windows open Particle Count, April 3-07.

Run #11:

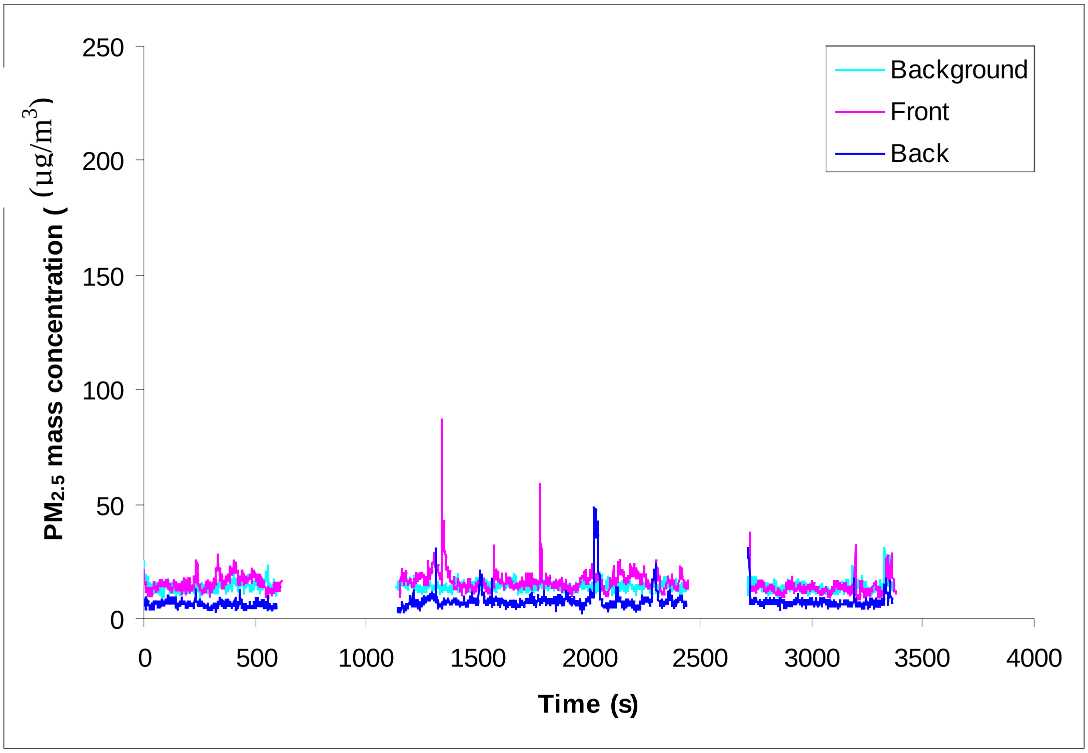


Figure 21 Run 11, CCF windows open PM2.5 mass concentration, April 12-07.

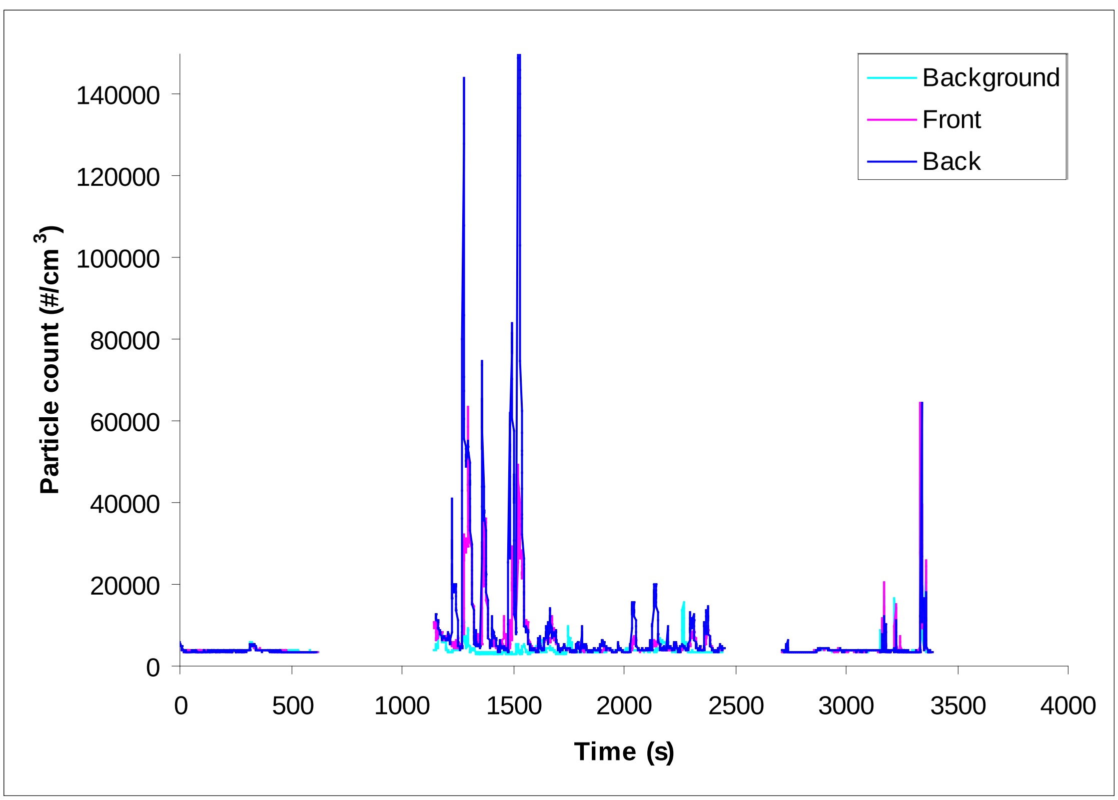


Figure 22 Run 11, CCF windows open Particle Count, April 12-07.

Run #12:

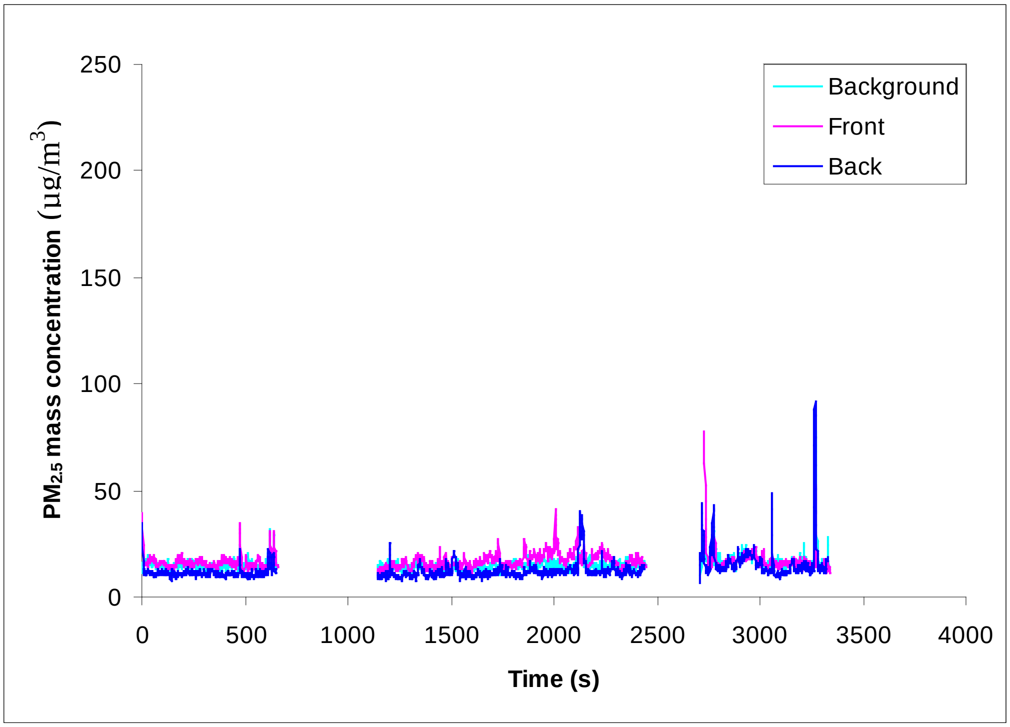


Figure 23 Run 12, CCF windows open PM2.5 mass concentration, April 12-07.

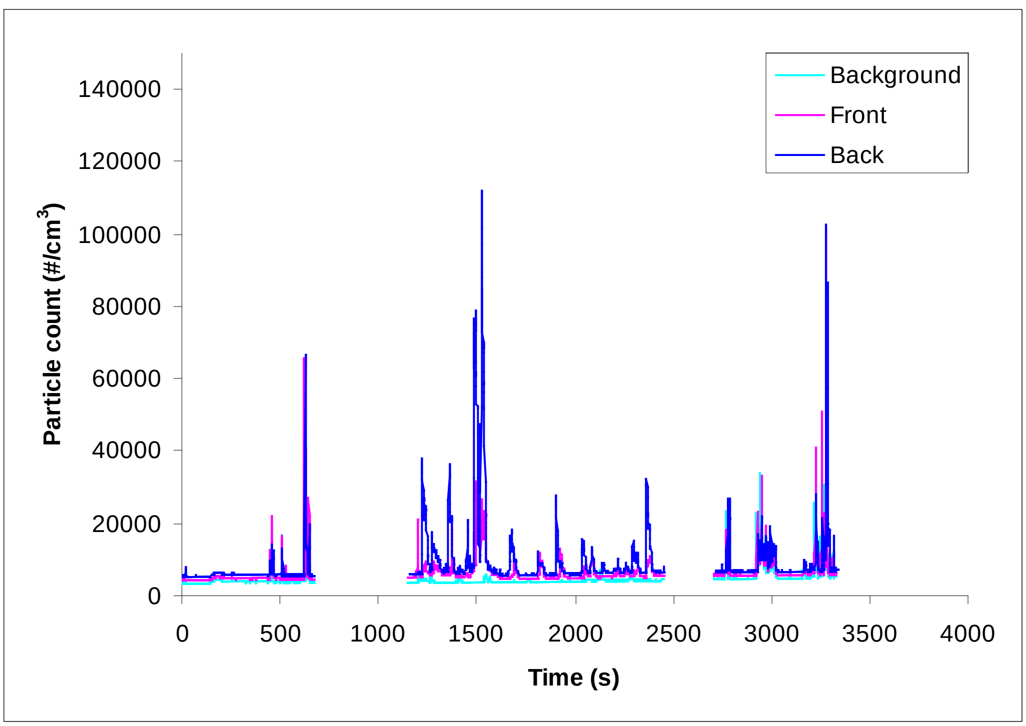


Figure 24 Run 12, CCF windows open Particle Count, April 12-07.

Run #13:

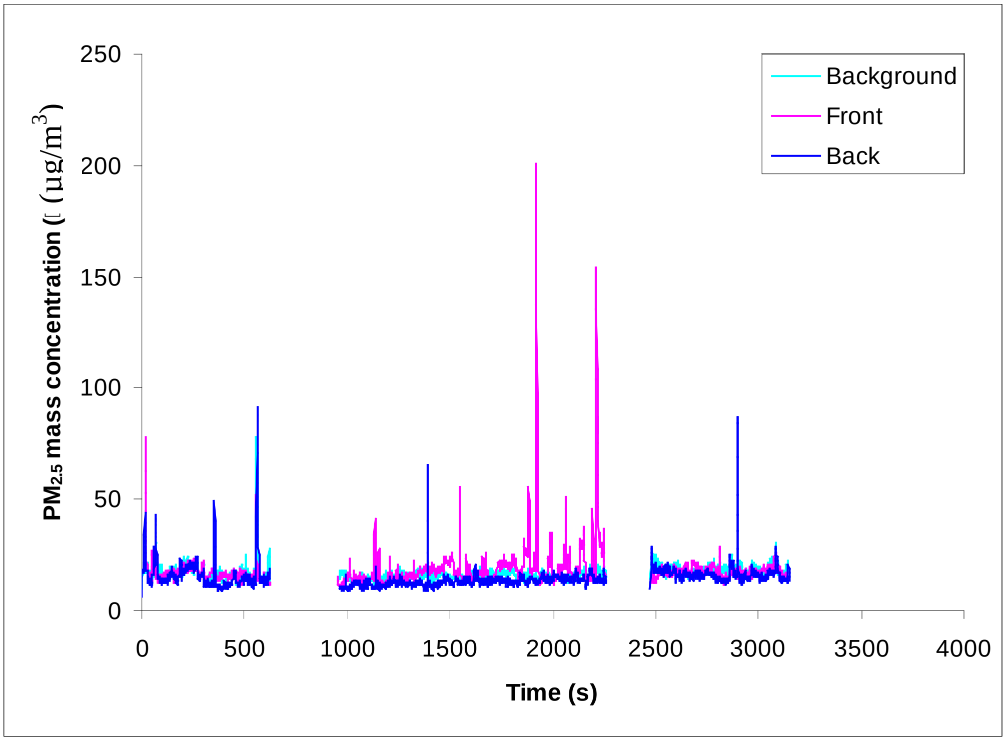


Figure 25 Run 13, CCF windows open PM2.5 mass concentration, April 12-07.

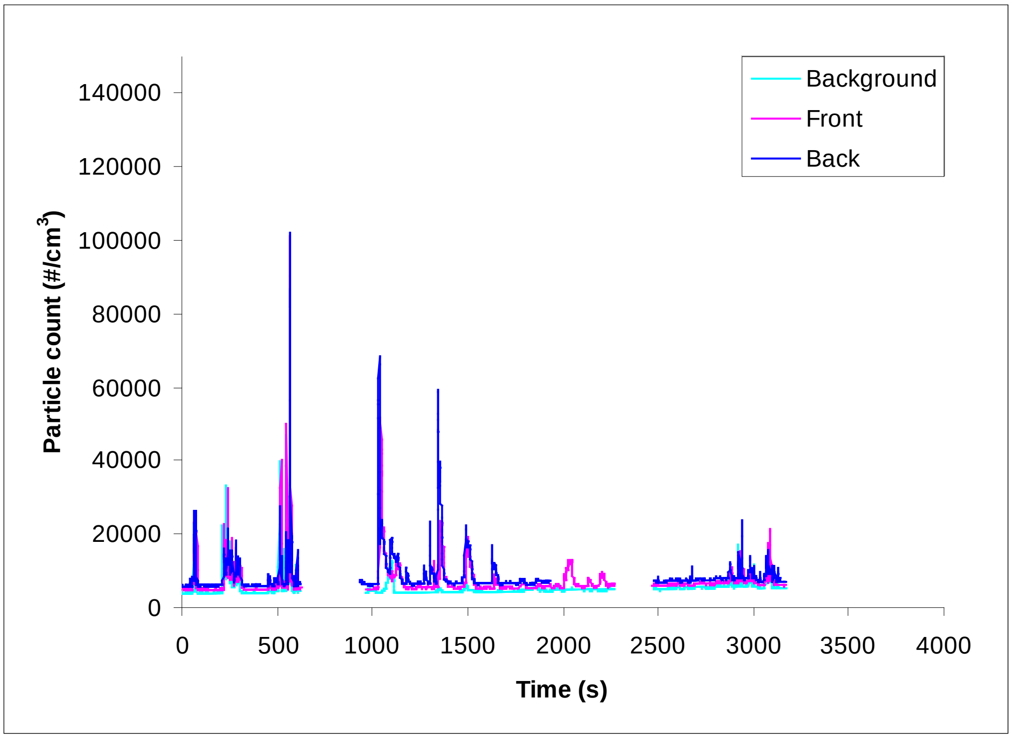


Figure 26 Run 13, CCF windows open Particle Count, April 12-07.

Run #14

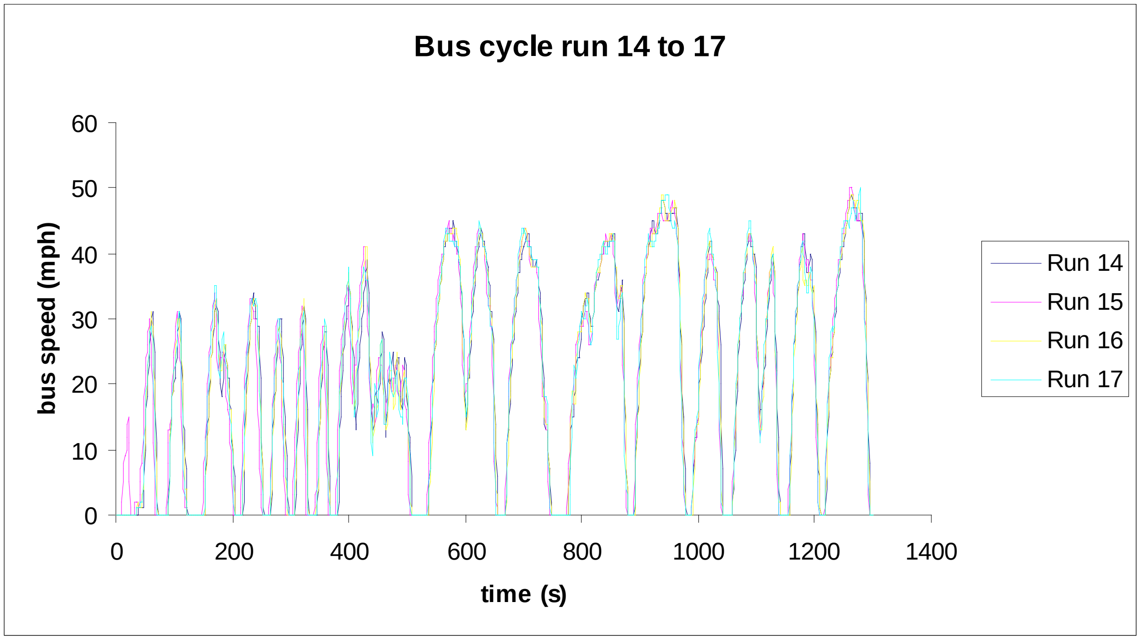


Figure 27 Run 14 bus cycle comparisons with other cycles. No visible difference on vehicle speed is observed between runs 14 to 17.

- GPS data was selected for speed at the beginning of the run and then changed back to the engine control module information. There was no visual difference on the bus cycle as seen on Figure 27.

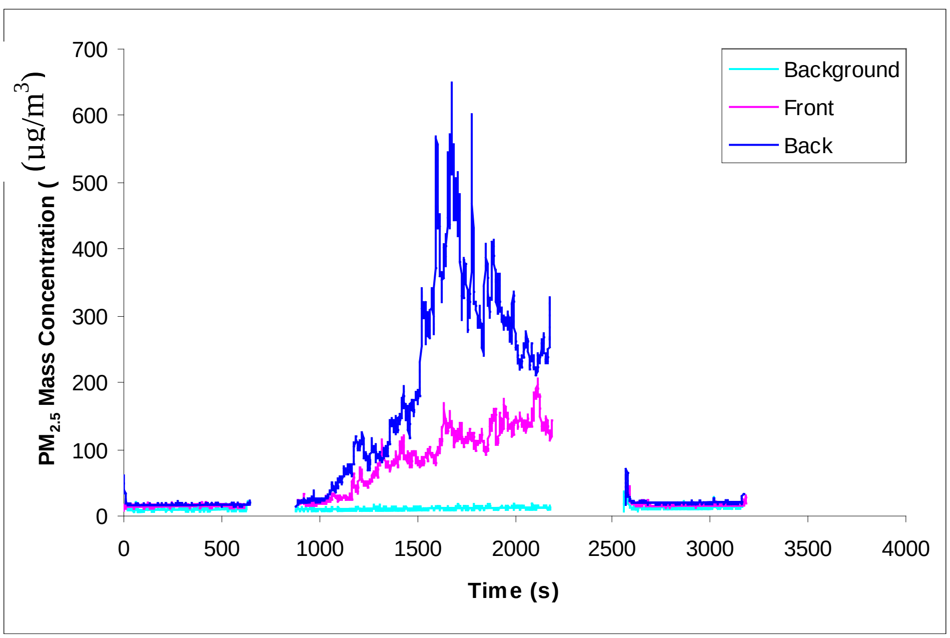


Figure 28 Run 14, CCF windows closed PM2.5 mass concentration, April 18-07.

No external events registered

Particle diameter was greater than 1.0µm

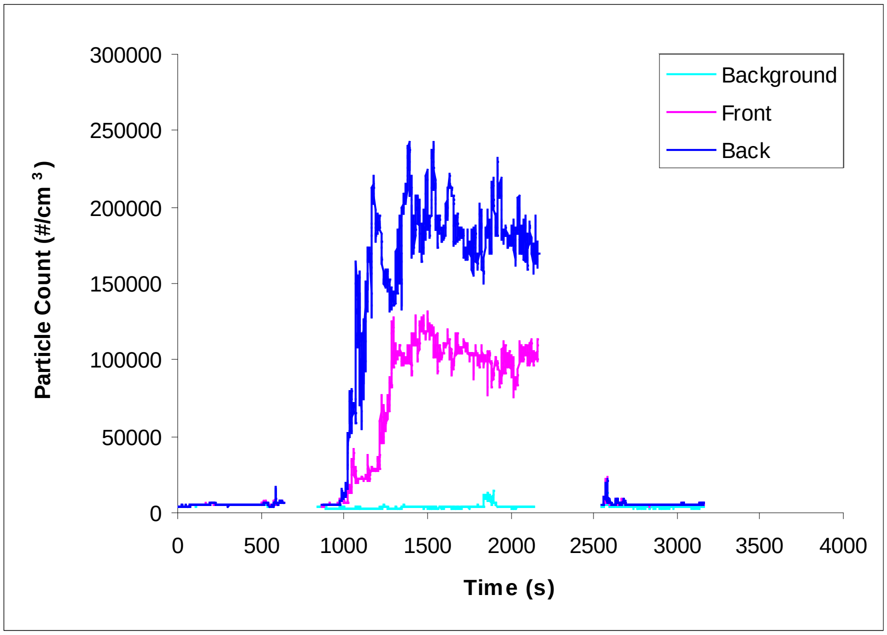


Figure 29 Run 14, CCF windows closed Particle Count, April 18-07.

Run #15:

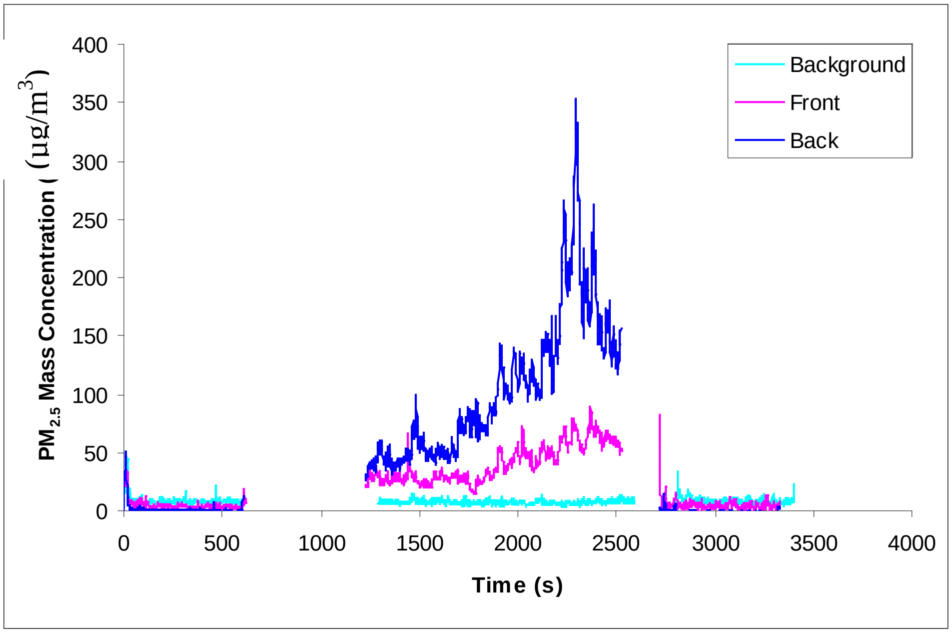


Figure 30 Run 15, CCF windows closed PM2.5 mass concentration, April 18-07.

Run had particle size >1.0µm, and build up of >20µg/m3 before the run

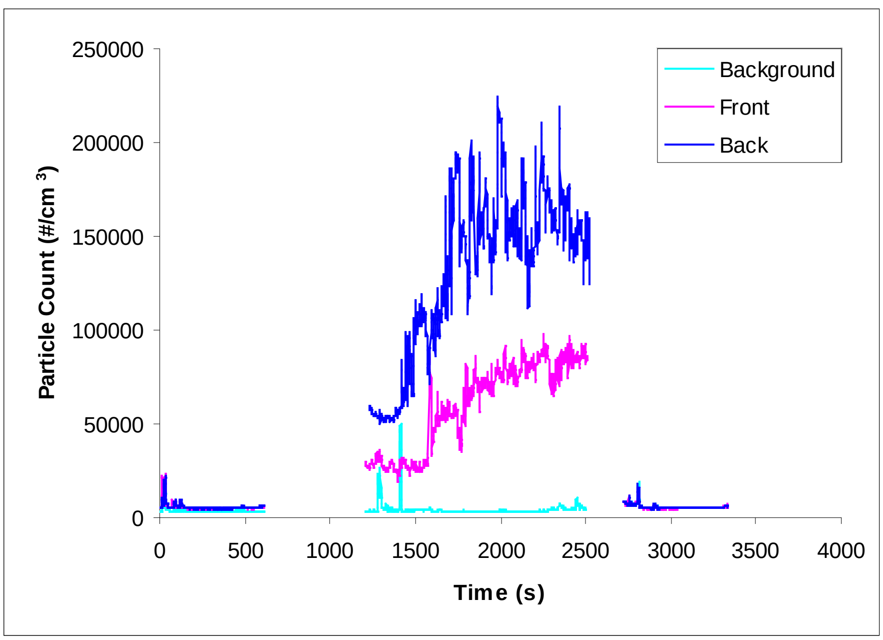


Figure 31 Run 15, CCF windows closed Particle Count, April 18-07.

Run #16:

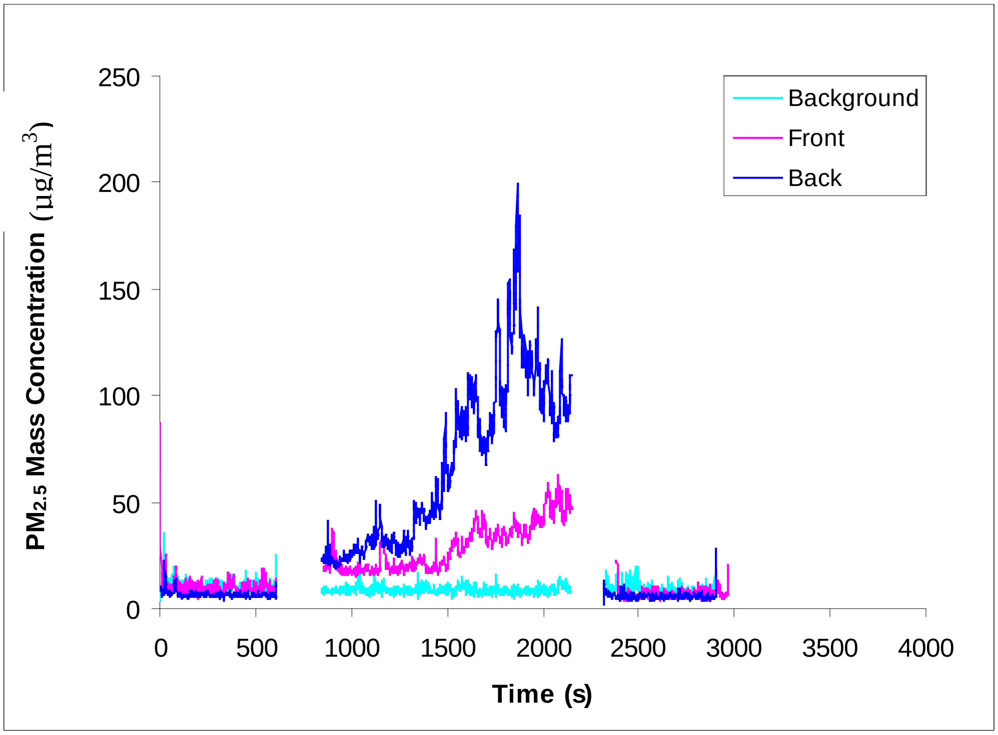


Figure 32 Run 16, CCF windows closed PM2.5 mass concentration, April 18-07.

Run had particle size >1.0µm, and build up of >20µg/m3 before the run

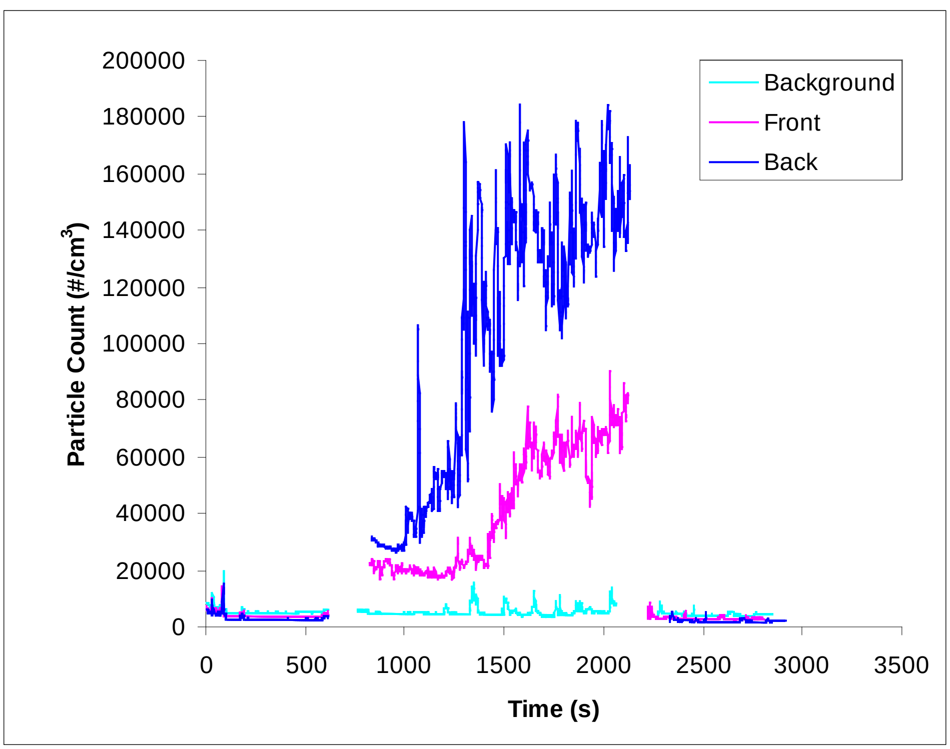


Figure 33 Run 16, CCF windows closed Particle Count, April 18-07.

Run #17:

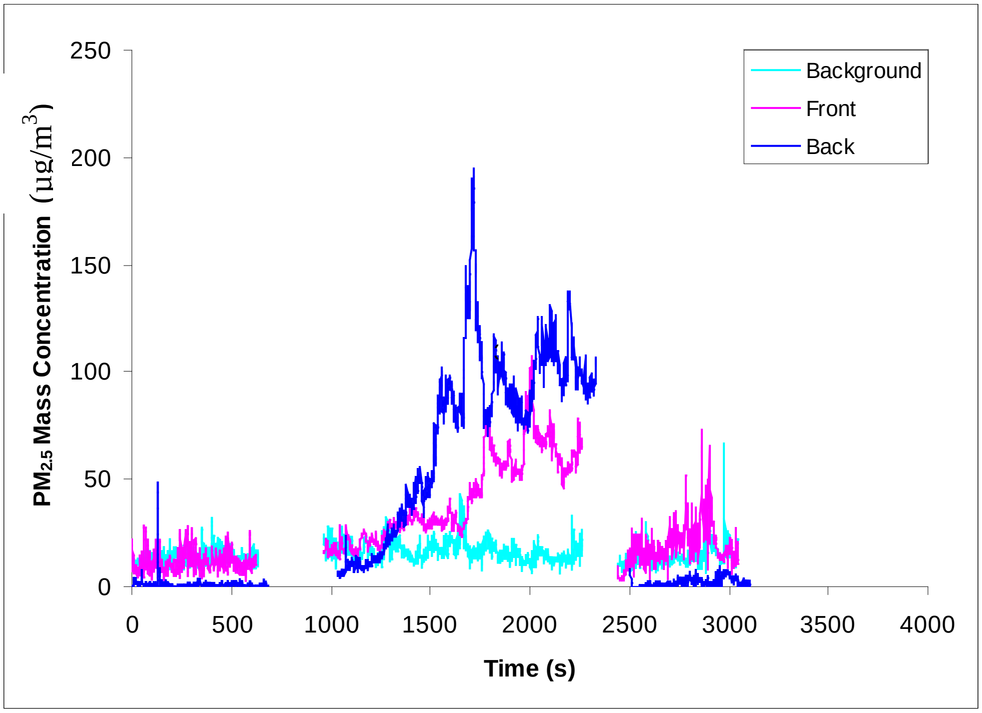


Figure 34 Run 17, Baseline windows closed PM2.5 mass concentration, April 18-07.
Particle size for Back instrument during run =1.15 µm

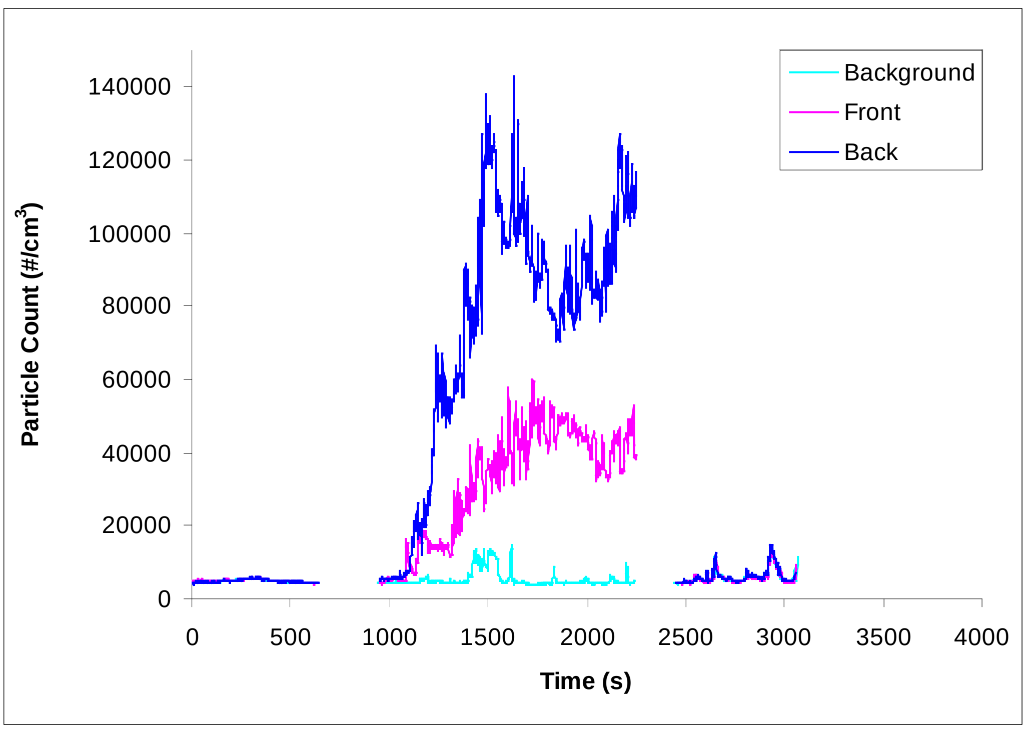


Figure 35 Run 17, Baseline windows closed Particle Count, April 18-07.

Run #18:

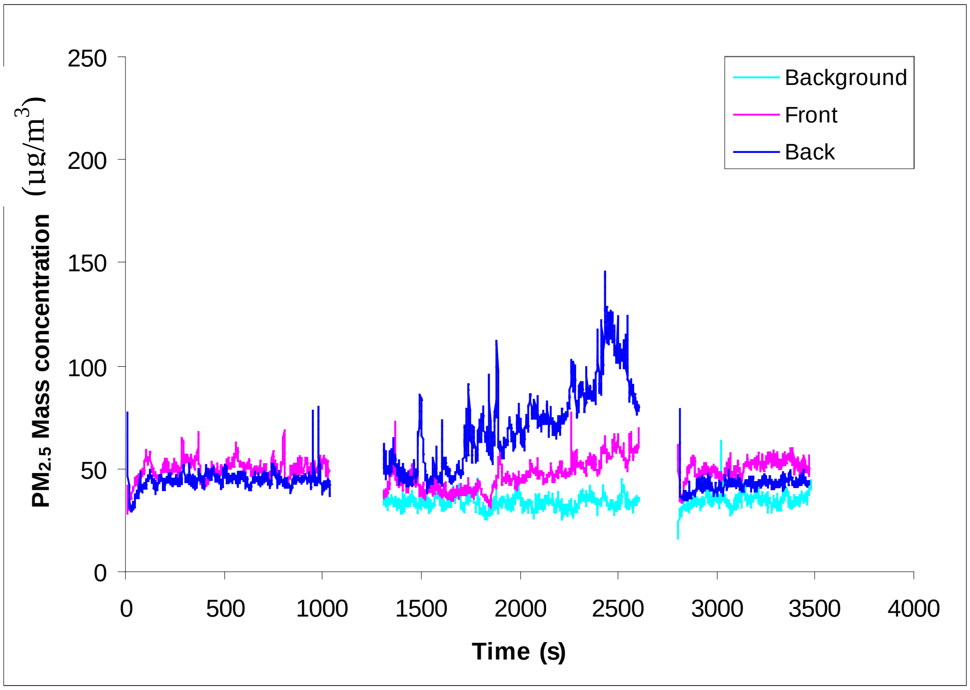


Figure 36 Run 18, CCF windows closed PM2.5 mass concentration, April 24-07.
Ambient PM2.5 mass concentration = 44µg/m^3

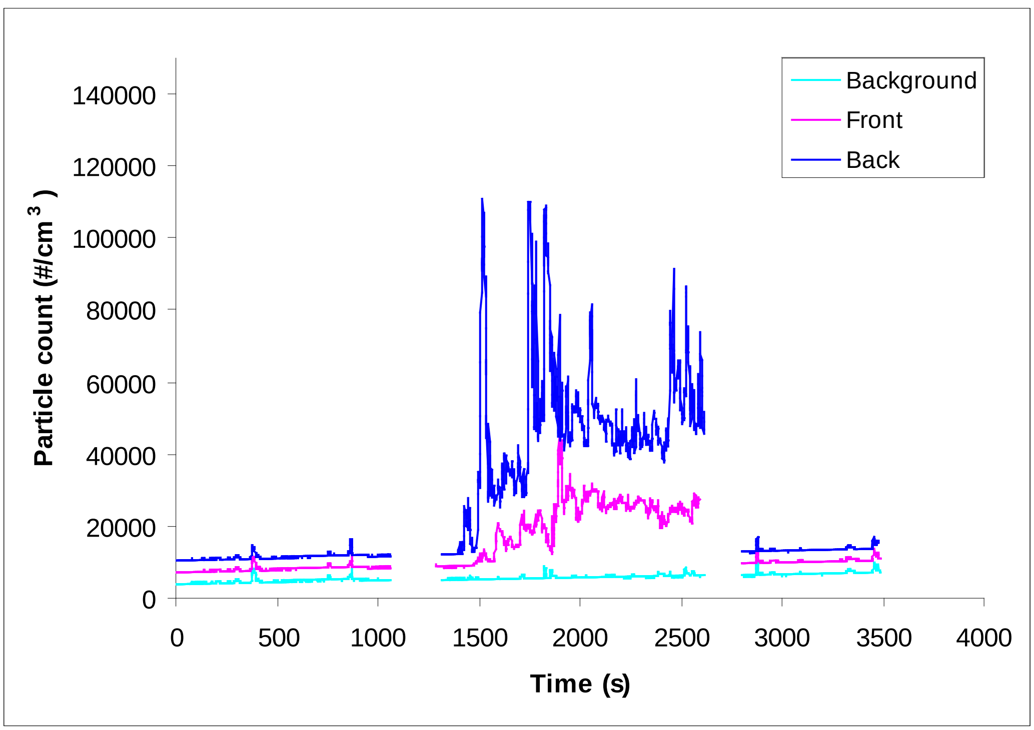


Figure 37 Run 18, CCF windows closed Particle Count, April 24-07.

Run 19:

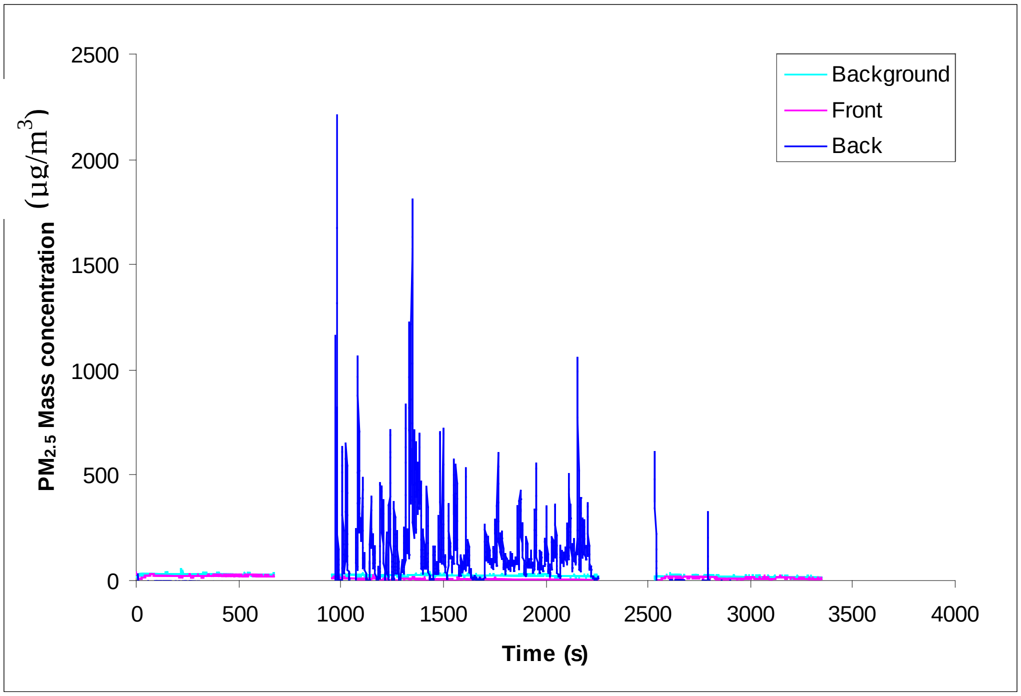


Figure 38 Run 19, CCF windows closed PM2.5 mass concentration, April 24-07.

Particle size for Back instrument during Run = 1.22µm

Ambient PM2.5 mass concentration = 42µg/m^3

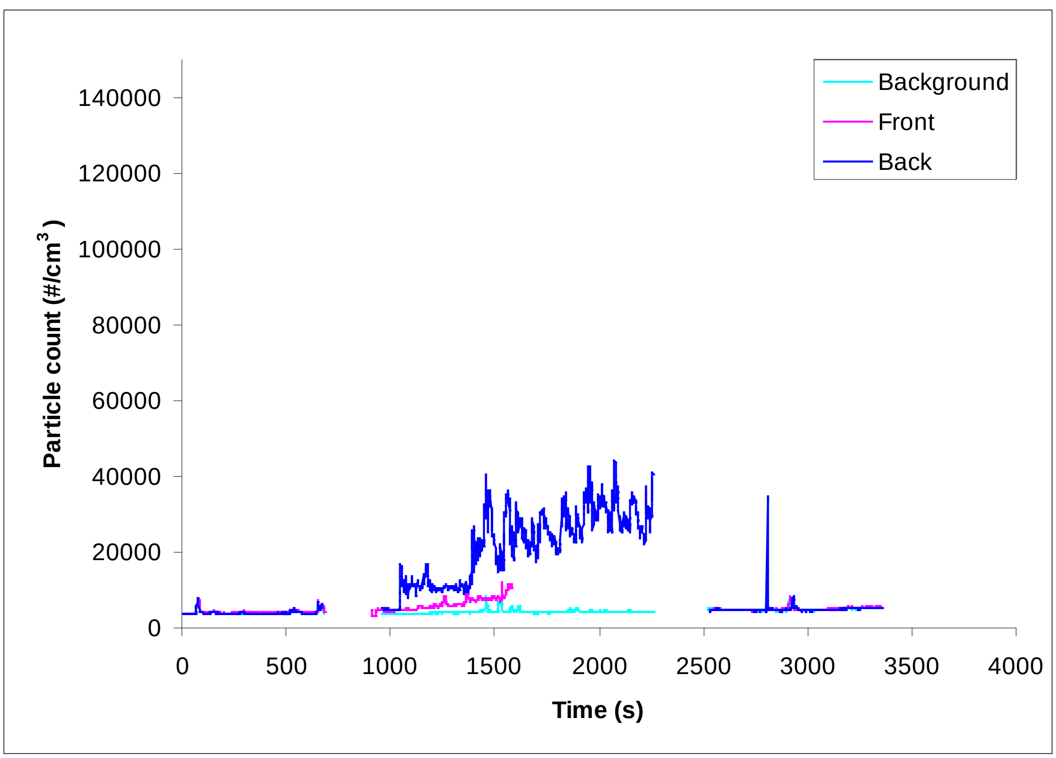


Figure 39 Run 19, CCF windows closed Particle Count, April 24-07.

Front P-trak#2 stopped measurement at half way run.

Run 20:

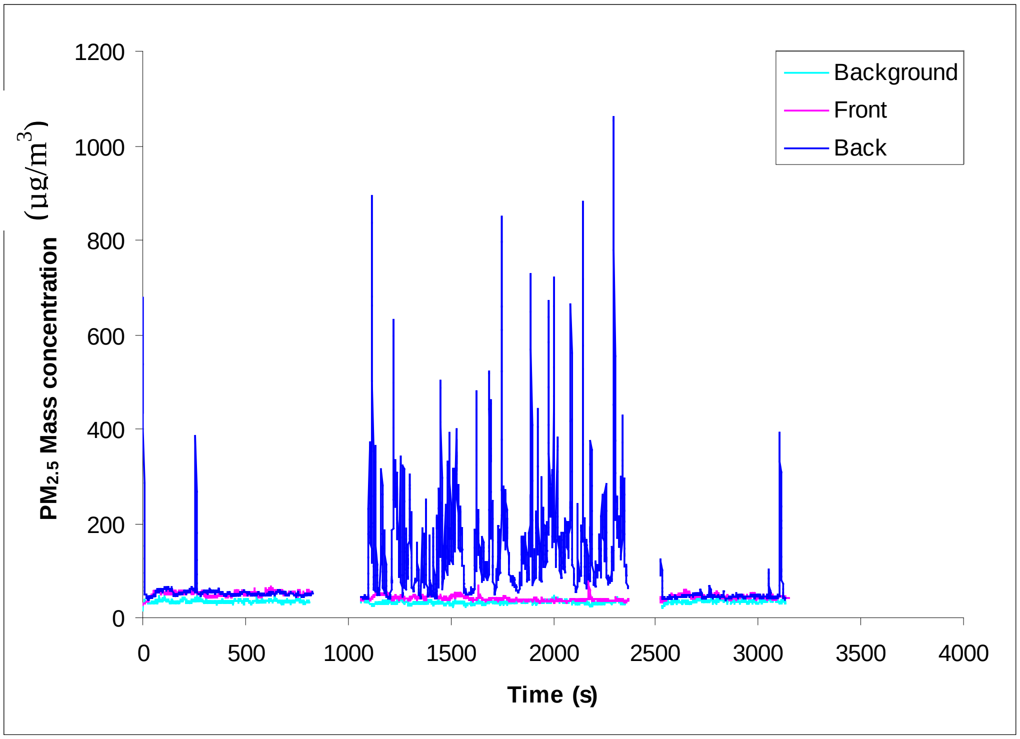


Figure 40 Run 20, CCF windows closed PM2.5 mass concentration, April 24-07.

Particle size for Back instrument during run = 1.15μm

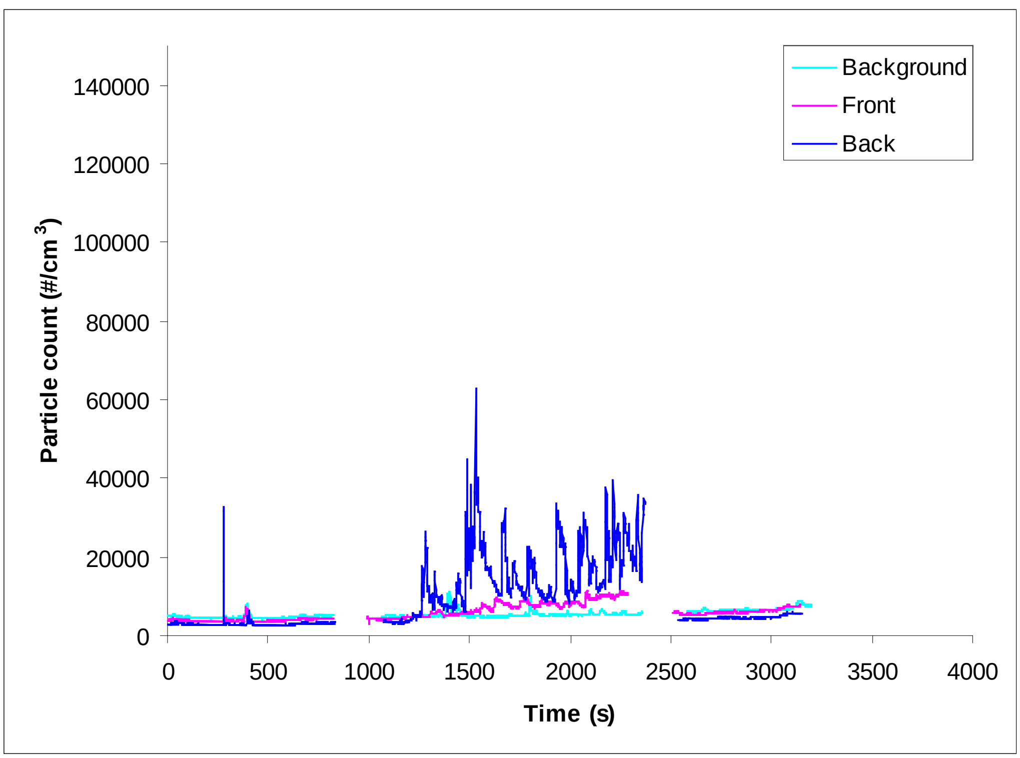


Figure 41 Run 20, CCF windows closed Particle Count, April 24-07.

Run 21: Unsuccessful Run initial build up

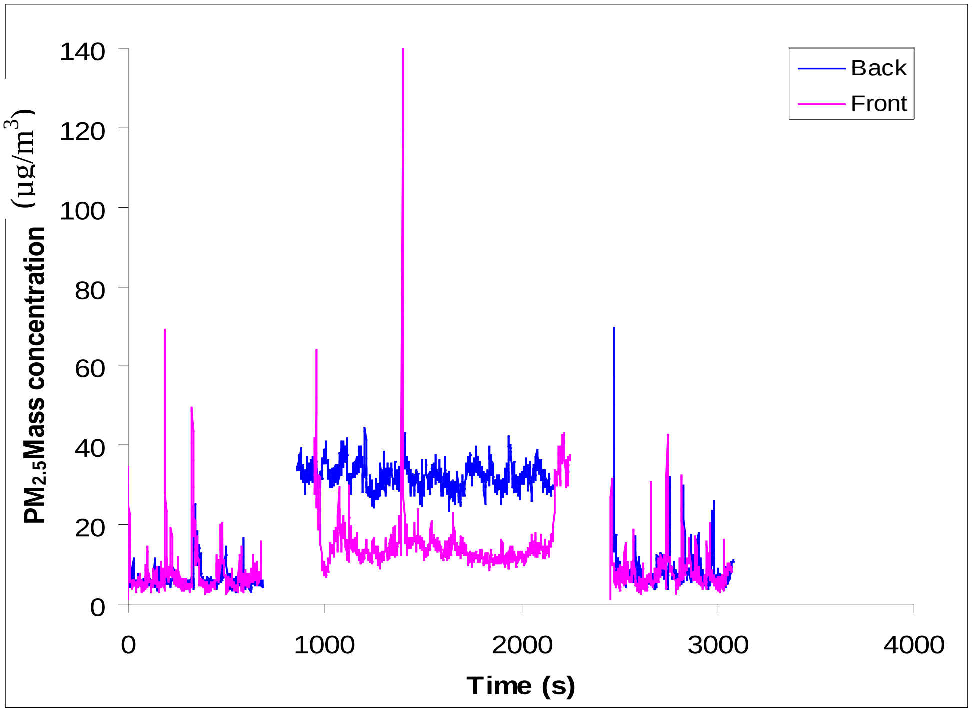


Figure 42 Run 21, DPF & CCF windows closed, May 7-07.

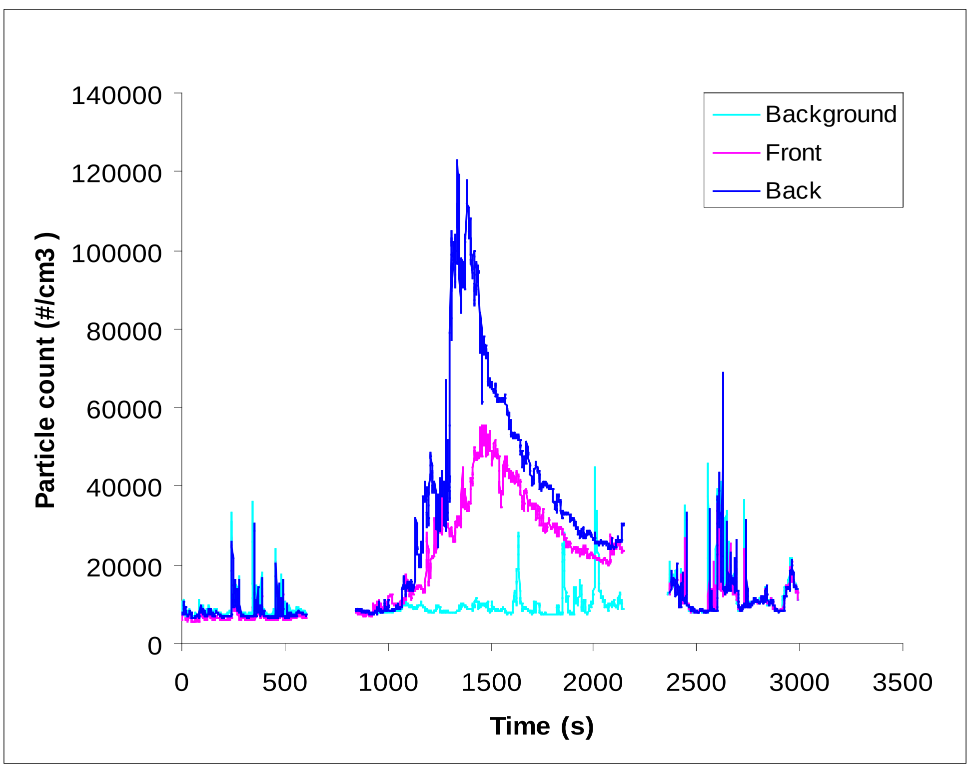


Figure 43 Run 21, DPF & CCF windows closed, May 7-07.

Run 22: Unsuccessful Run

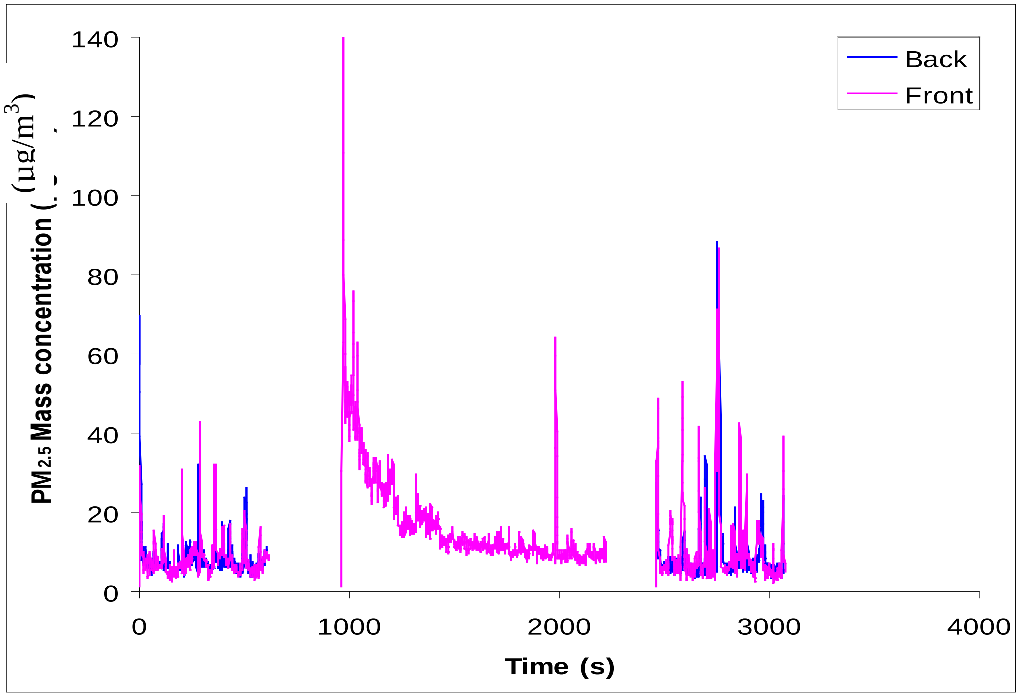


Figure 44 Run 22, DPF & CCF windows closed, May 7-07.

Initial build up before the run stared. No Back instrument value during run due to data transfer problem.

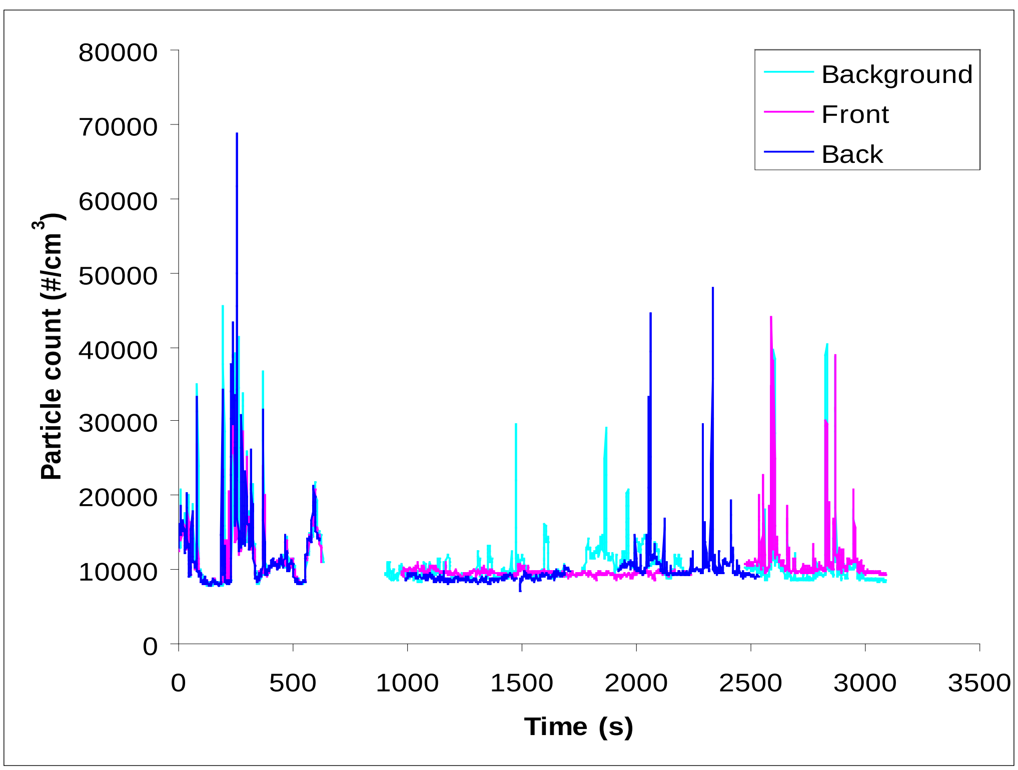


Figure 45 Run 22, DPF & CCF windows closed, May 7-07.

Run 23: Unsuccessful Run

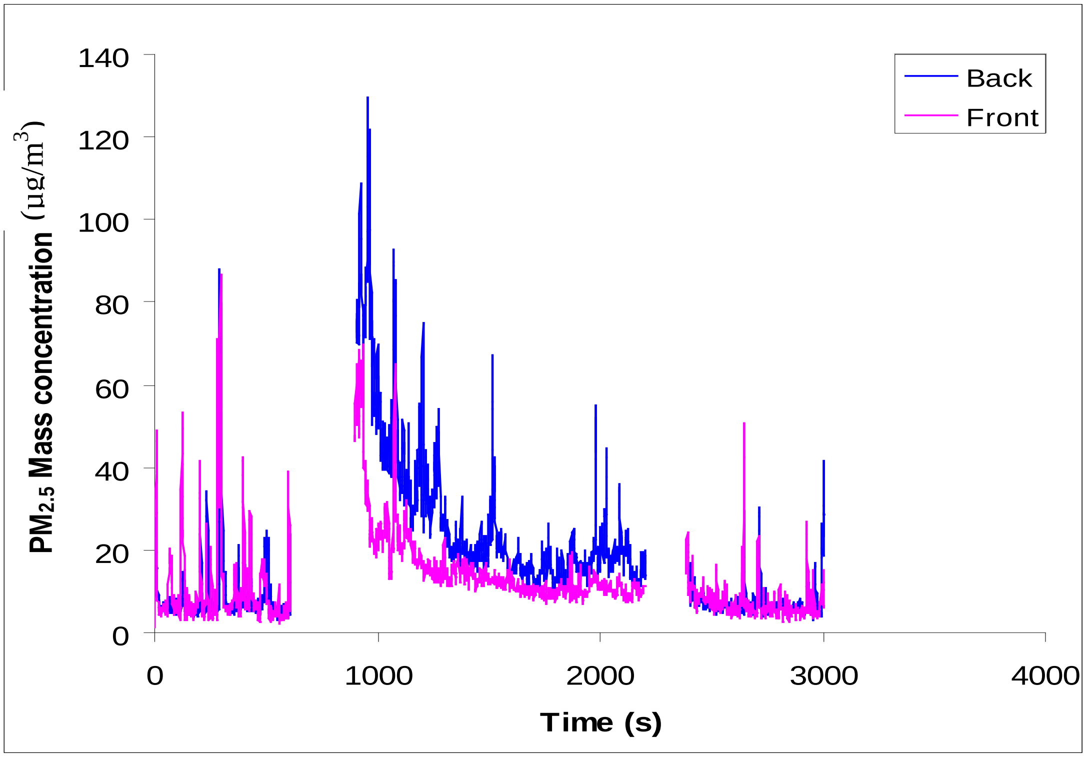


Figure 46 Run 23, DPF & CCF windows closed, May 7-07. DR1 Back , DR2 Front of bus

Initial build up of concentration before the test stated. Particle size for Back instrument during run = 1.30μm

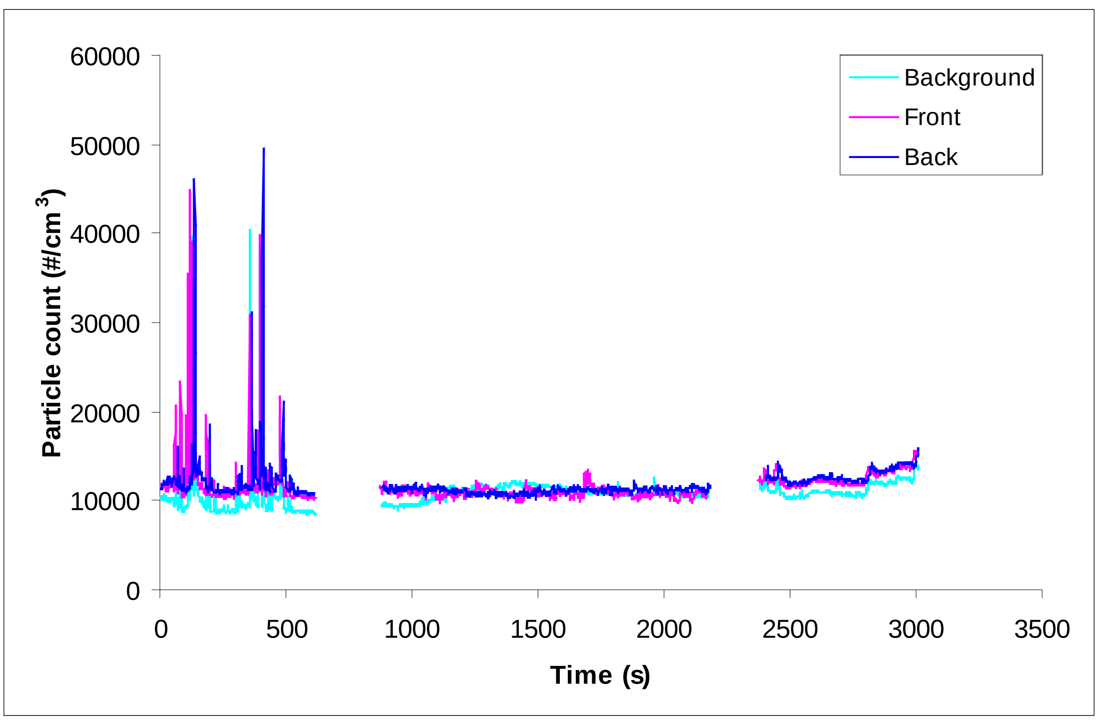


Figure 47 Run 23, DPF & CCF windows closed, May 7-07. PT1 background, PT2 front, PT3 back

Run 24: Unsuccessful Run

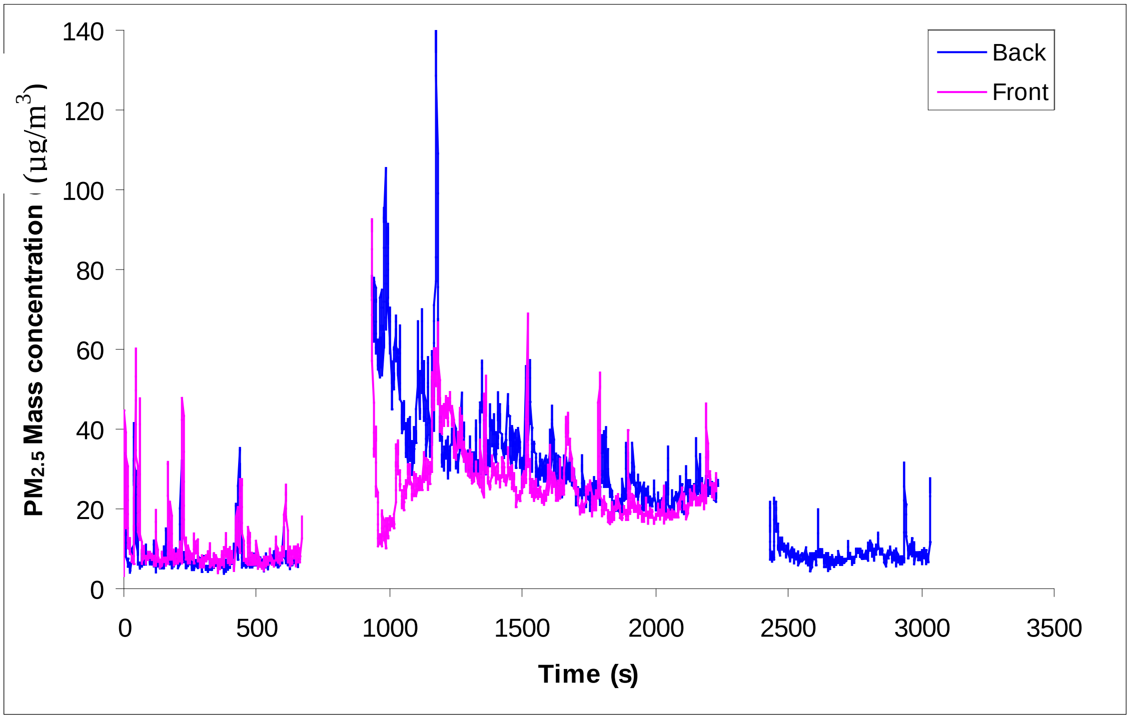


Figure 48 Run 24, DPF windows closed, May 7-07. DR1 back, DR2 front

Initial build up of concentration before run started. Particle size for Back instrument during Run = 1.10μm

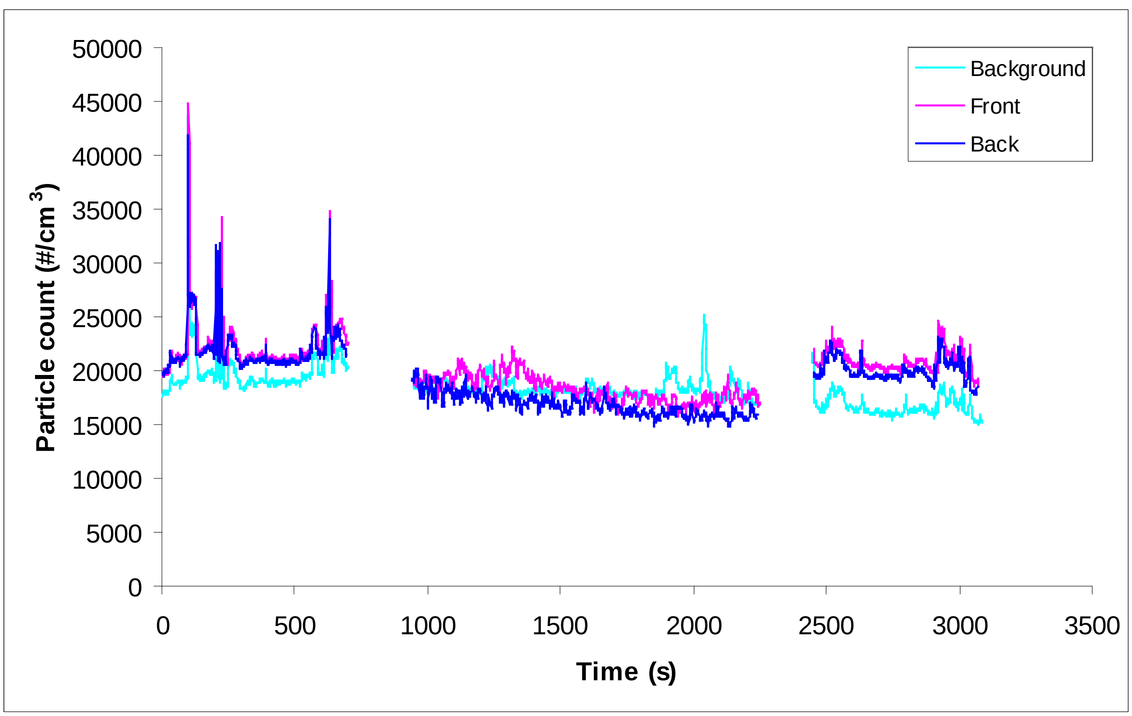


Figure 49 Run 24, DPF windows closed, May 7-07. PT1 background, PT2 front, PT3 back

Run 25: Unsuccessful Run

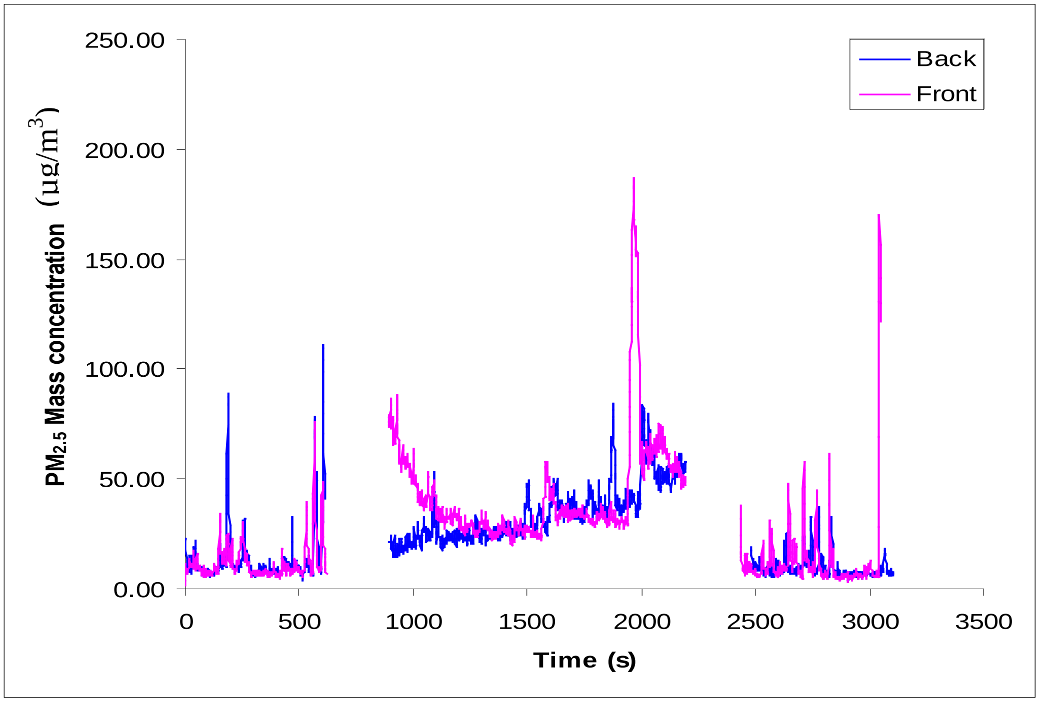


Figure 50 Run 25, DPF windows closed, May 8-07. DR1 back, DR2 front

M-1 tank drove on nearby access road. Initial build up of mass concentration

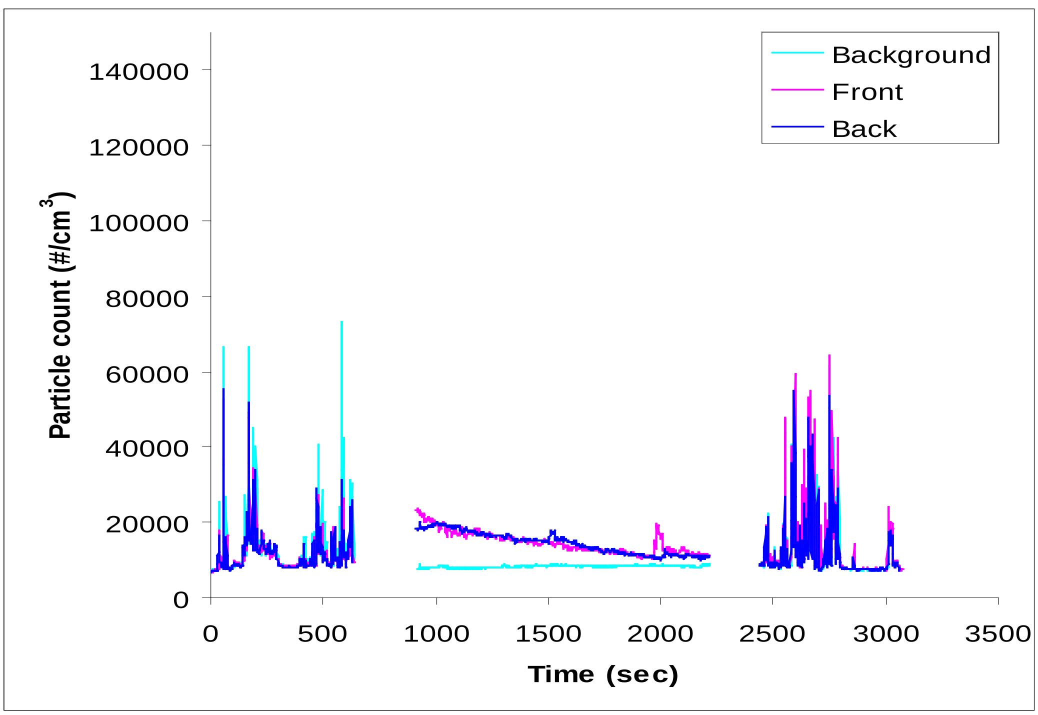


Figure 51 Run 25, DPF windows closed, May 8-07.

Run 26

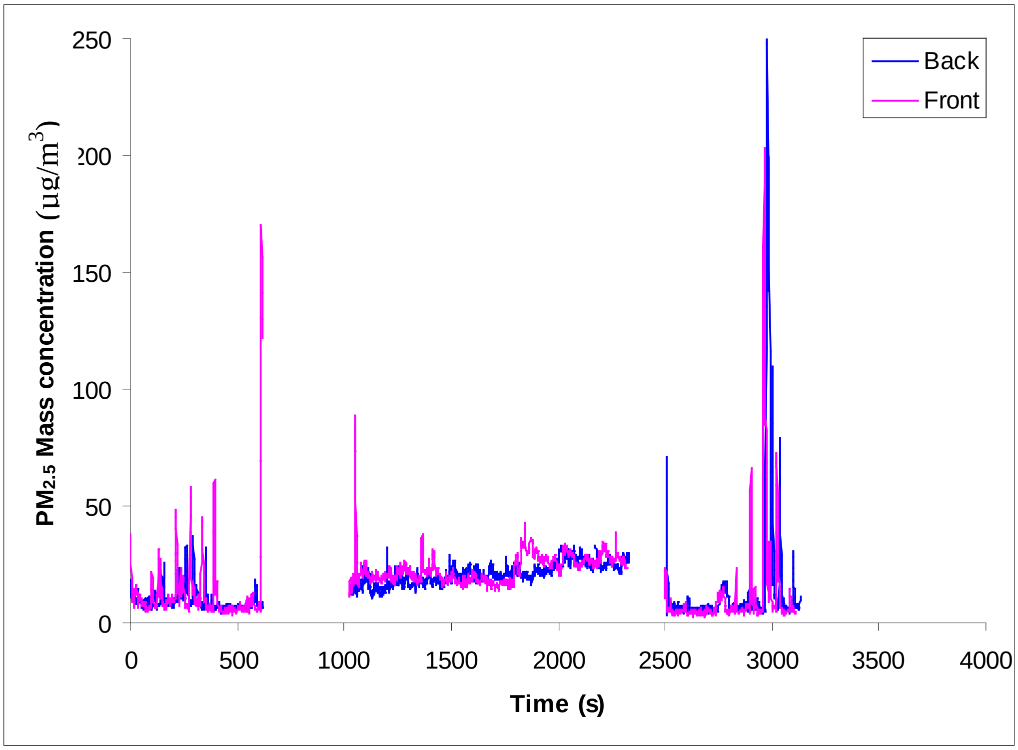


Figure 52 Run 26, DPF windows closed PM2.5 mass concentration, May 8-07.

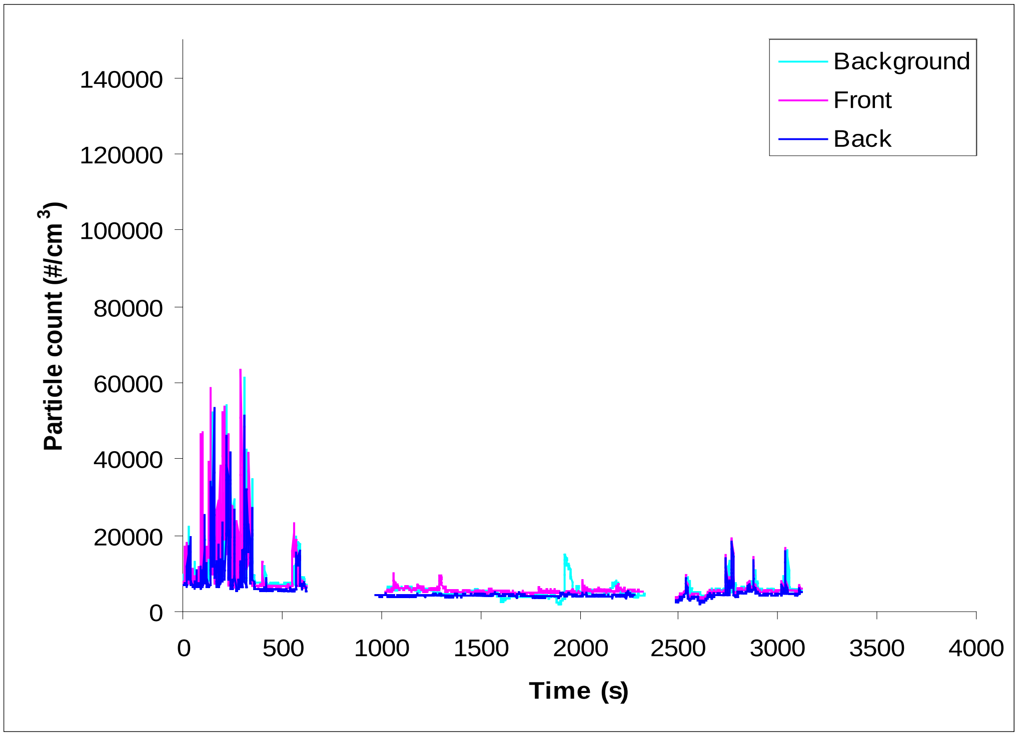


Figure 53 Run 26, DPF windows closed Particle Count, May 8-07.

Run 27

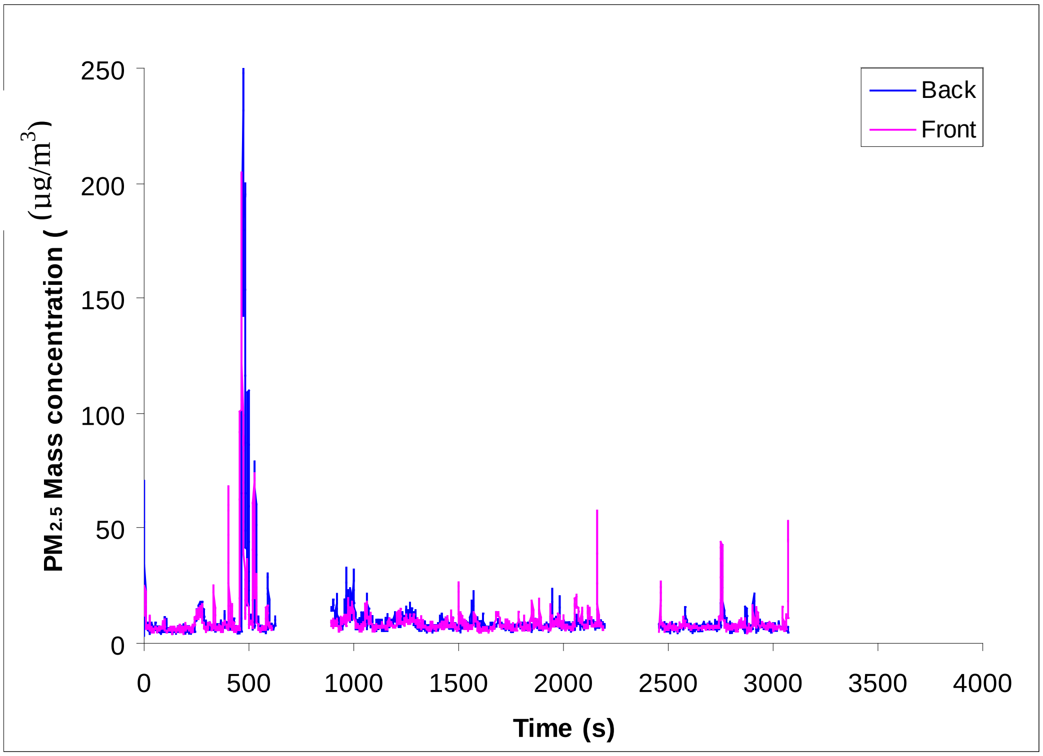


Figure 54 Run 27, DPF windows open PM2.5 mass concentration, May 8-07.

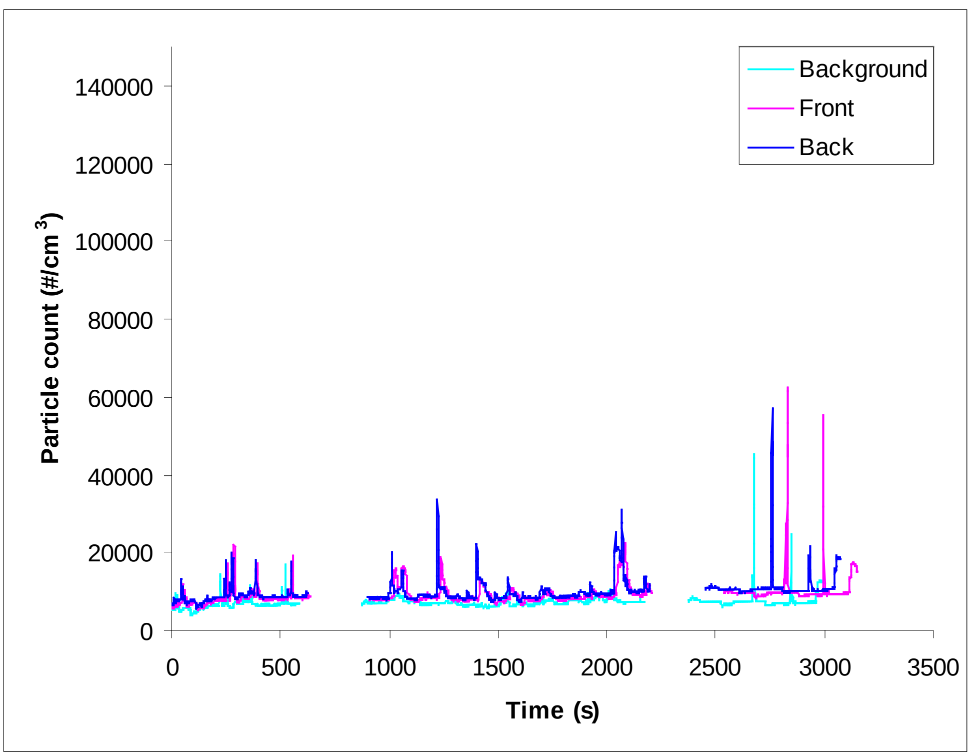


Figure 55 Run 27, DPF windows open Particle Count, May 8-07.

Run 28:

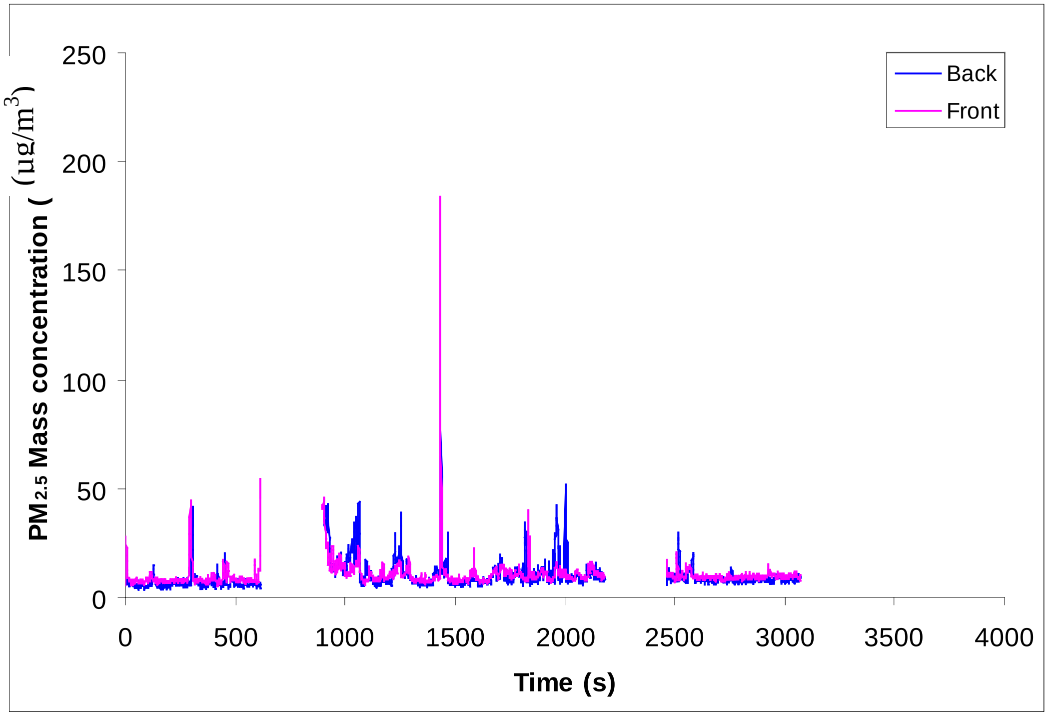


Figure 56 Run 28, DPF windows open PM2.5 mass concentration, May 8-07.

Particle size: Back Run=1.049 µm

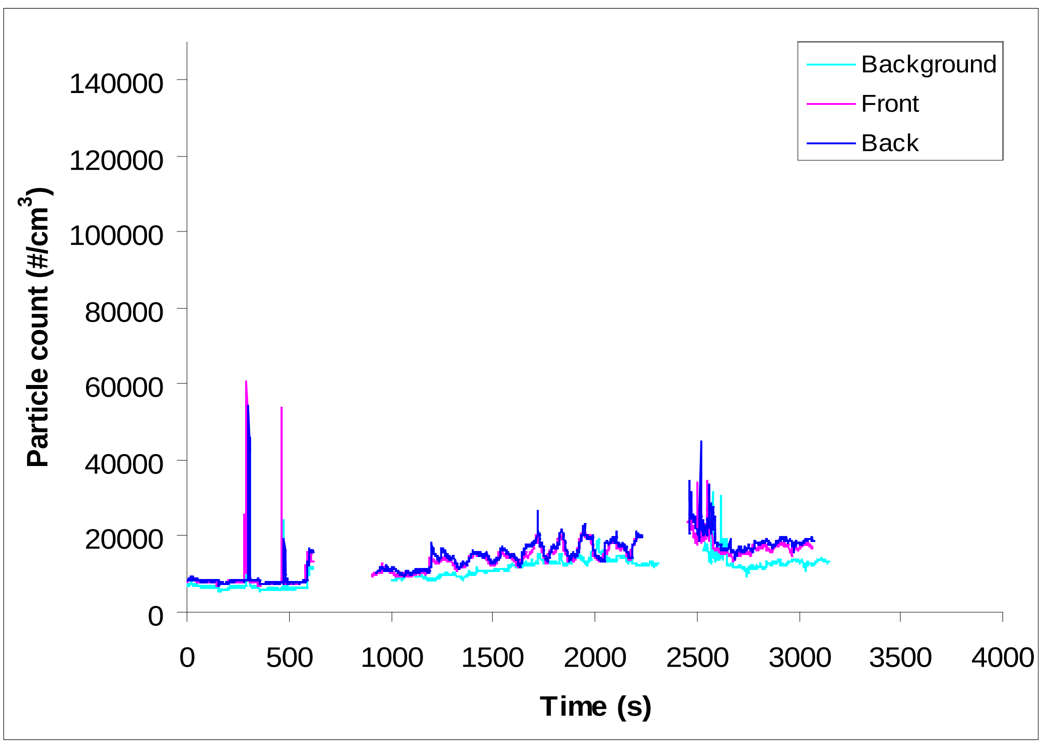


Figure 57 Run 28, DPF windows open Particle Count, May 8-07.

Run 29:

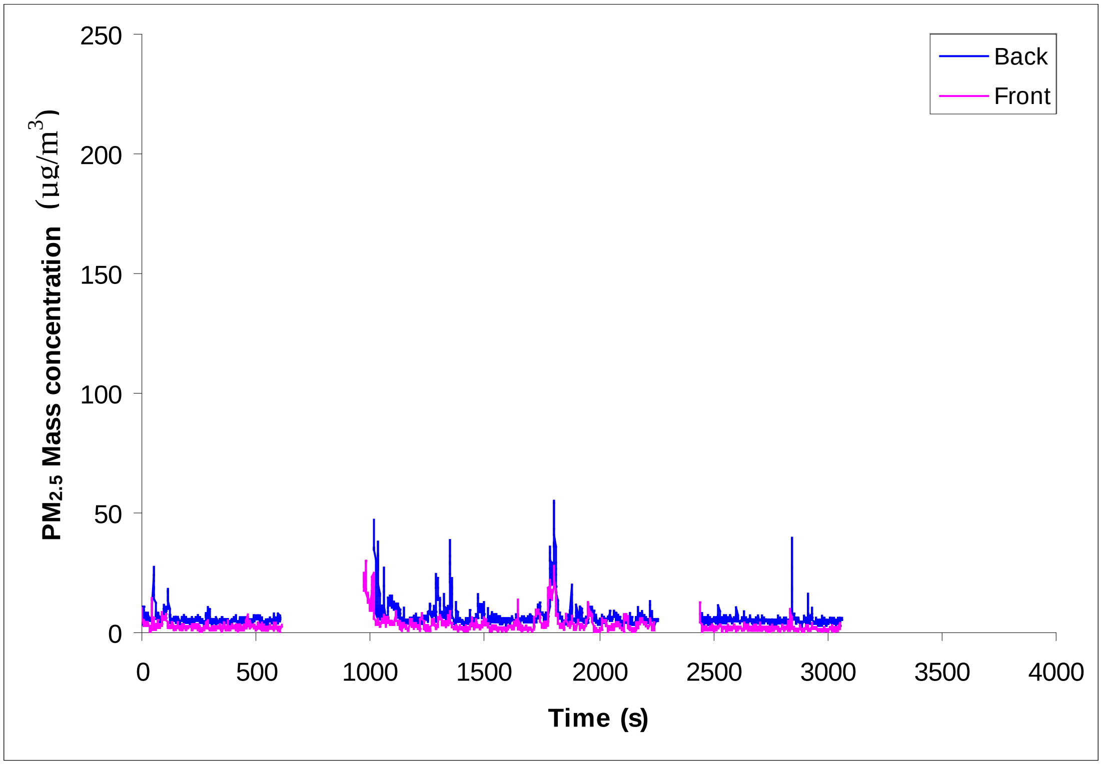


Figure 58 Run 29, DPF windows open PM2.5 mass concentration, May 8-07.

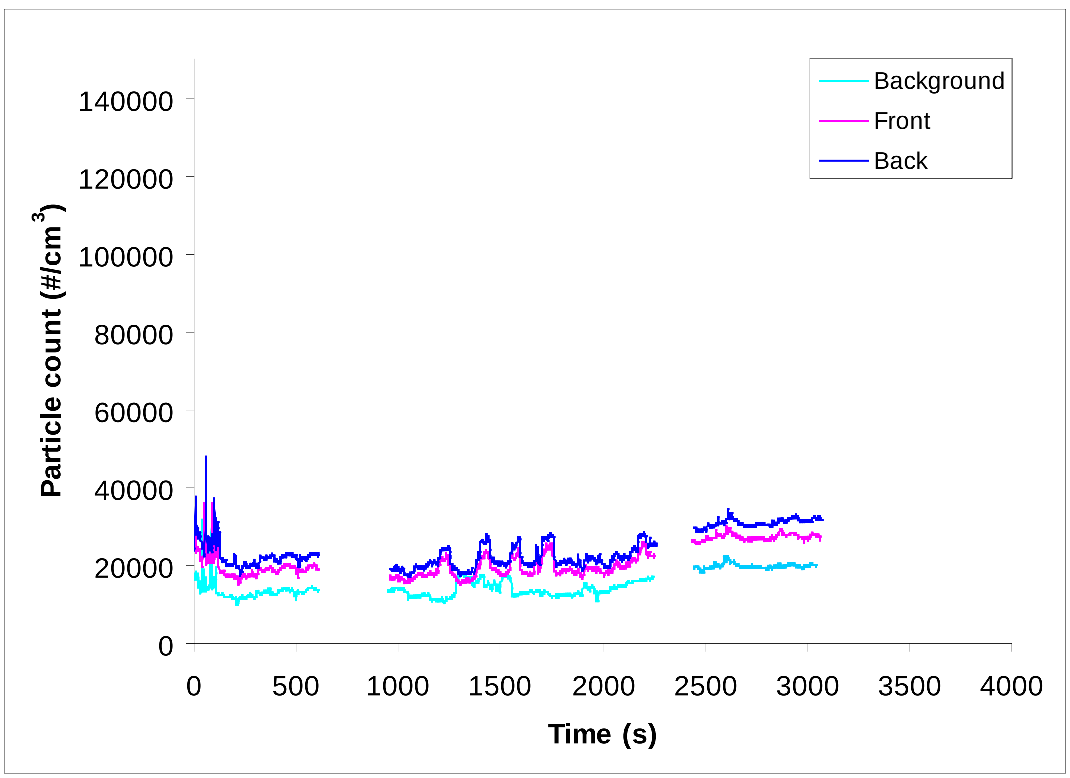


Figure 59 Run 29, DPF windows open Particle Count, May 8-07.

Run 30

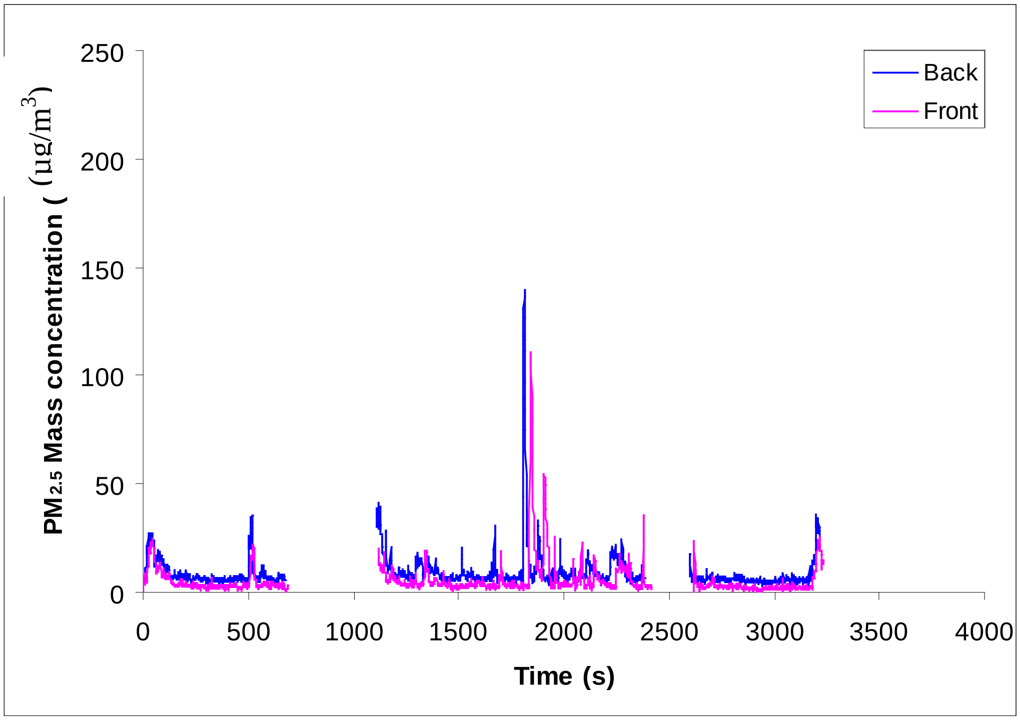


Figure 60 Run 30, DPF & CCF windows open PM2.5 mass concentration, May 8-07.
M-88 tank retriever drove on nearby access road

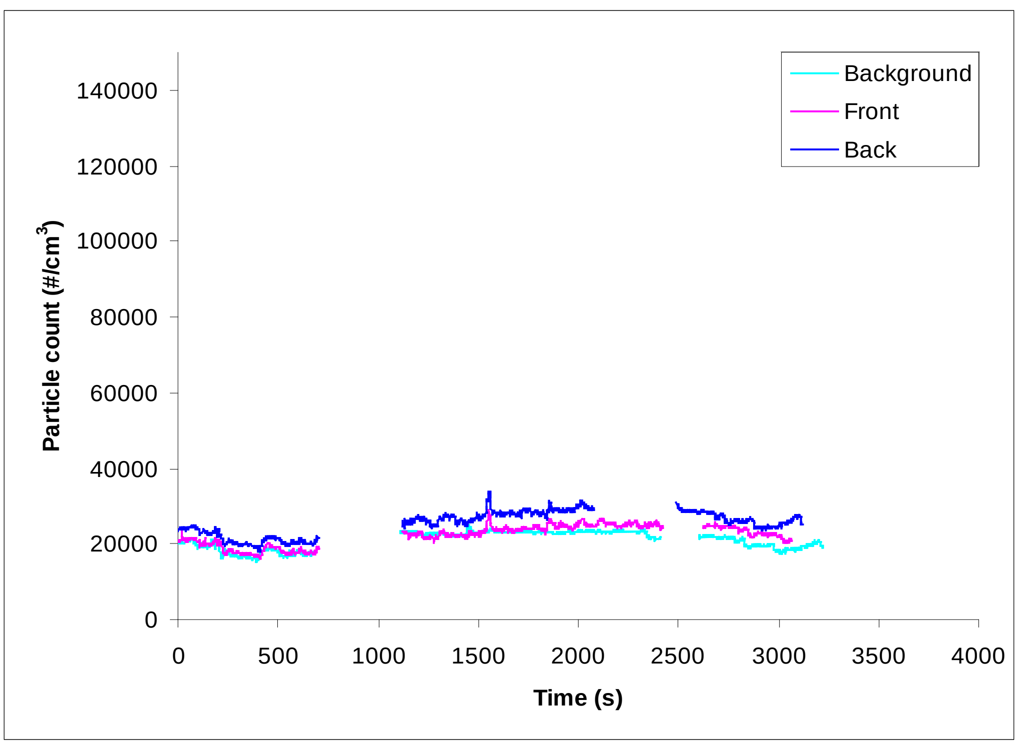


Figure 61 Run 30, DPF & CCF windows open Particle Count, May 8-07.

Run 31

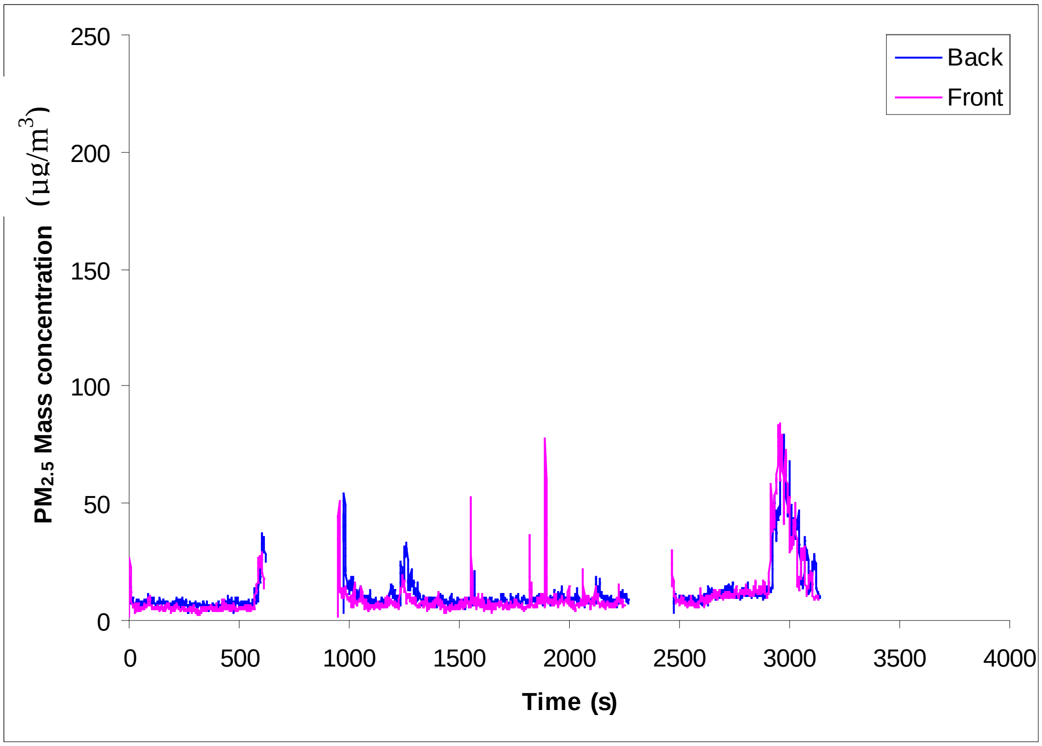


Figure 62 Run 31, DPF & CCF windows open PM2.5 mass concentration, May 8-07.

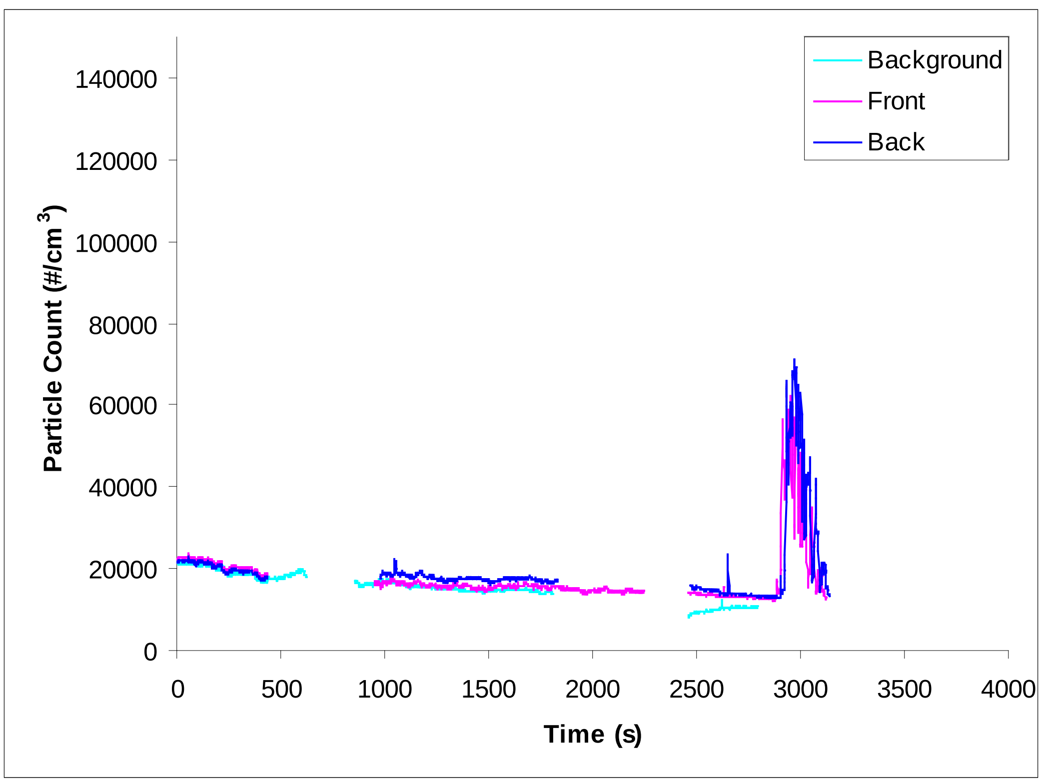


Figure 63 Run 31, DPF & CCF windows open Particle Count, May 8-07.

Run 32

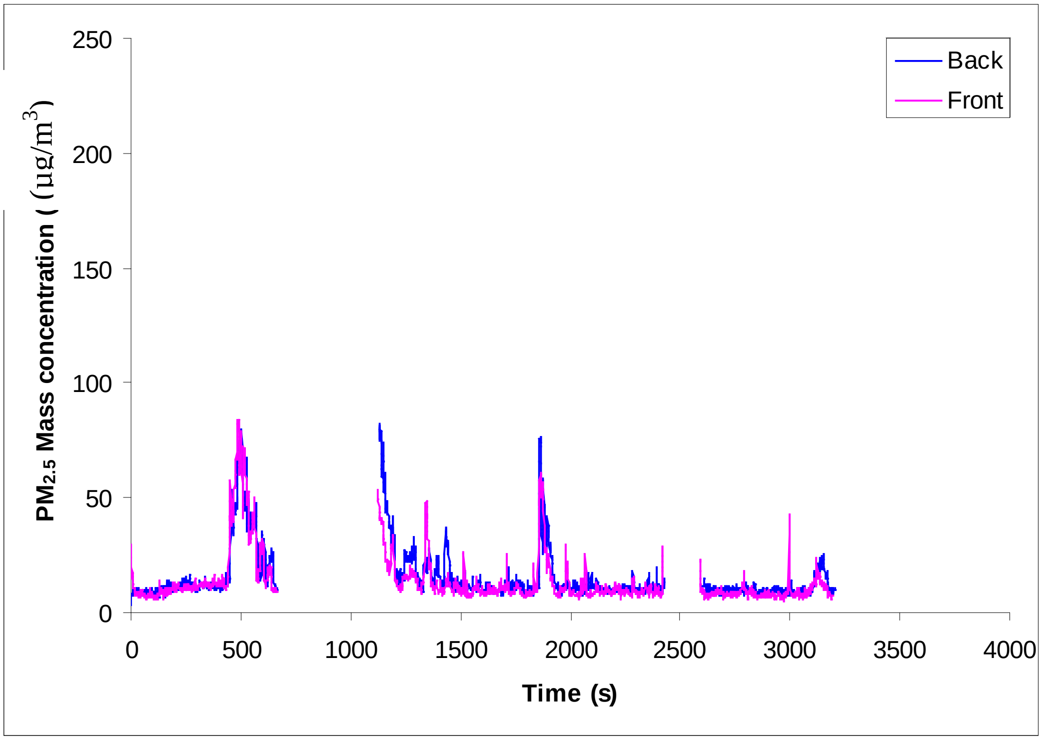


Figure 64 Run 32, DPF & CCF windows open PM2.5 mass concentration, May 8-07.

Ambient instrument ran out of batteries during this run and was unavailable for the post run; forklift drove by on access road

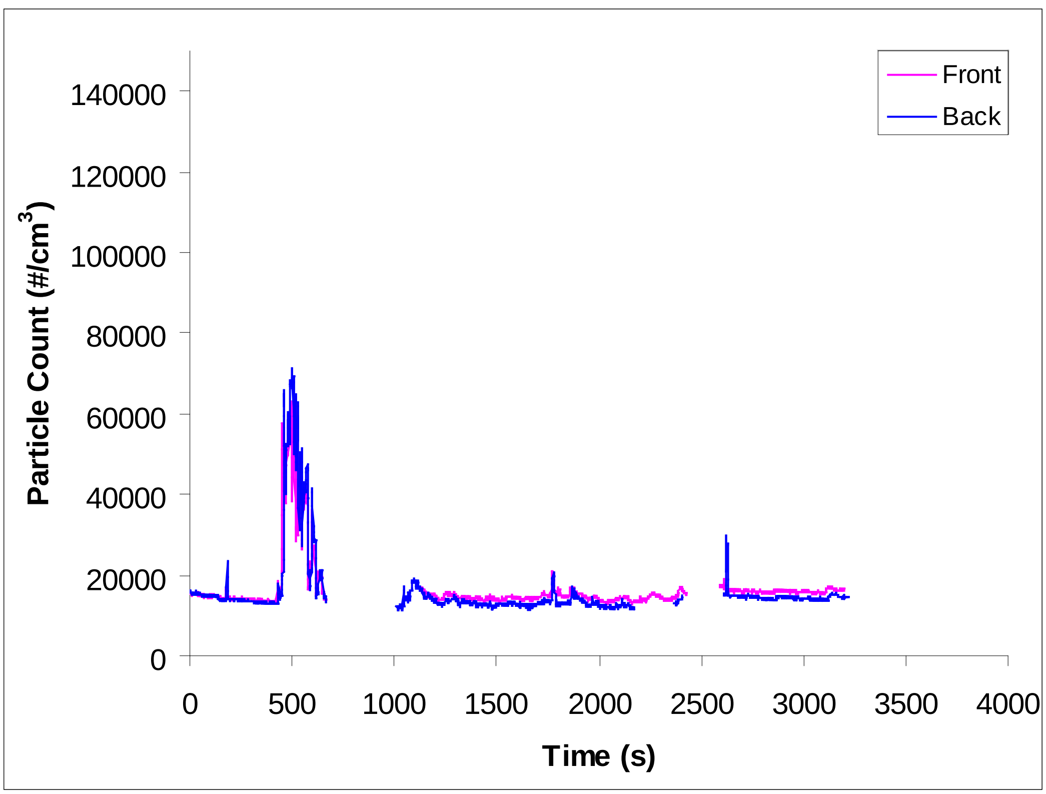


Figure 65 Run 32, DPF & CCF windows open Particle Count, May 8-07.

Run 33

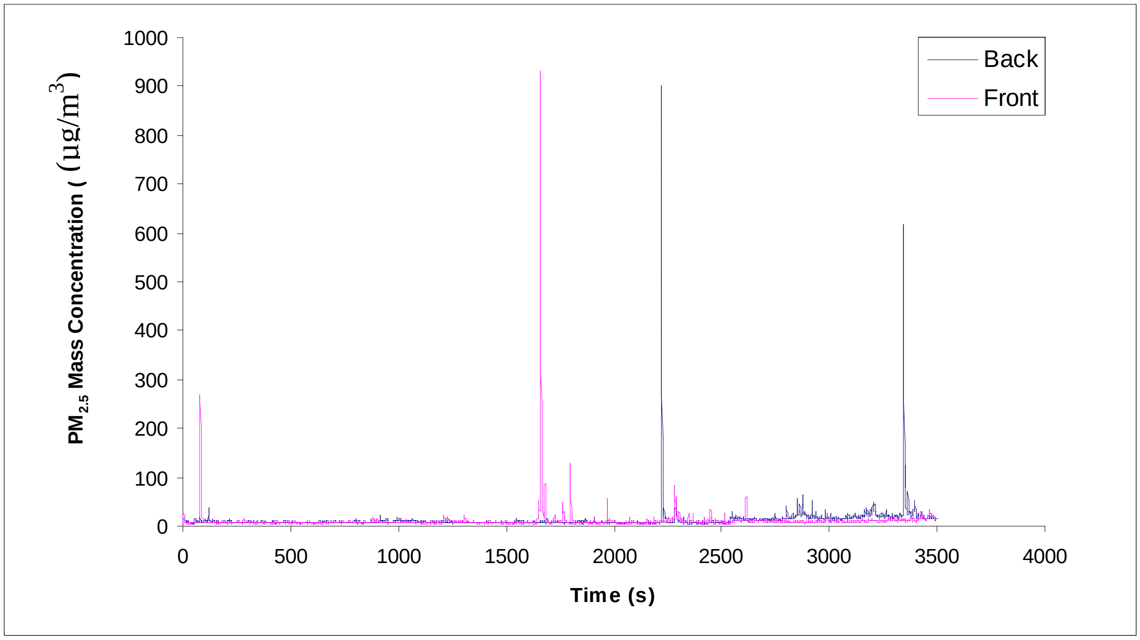


Figure 66 Run 33, Idle test with DPF & CCF windows closed PM2.5 mass concentration, May 14-07.

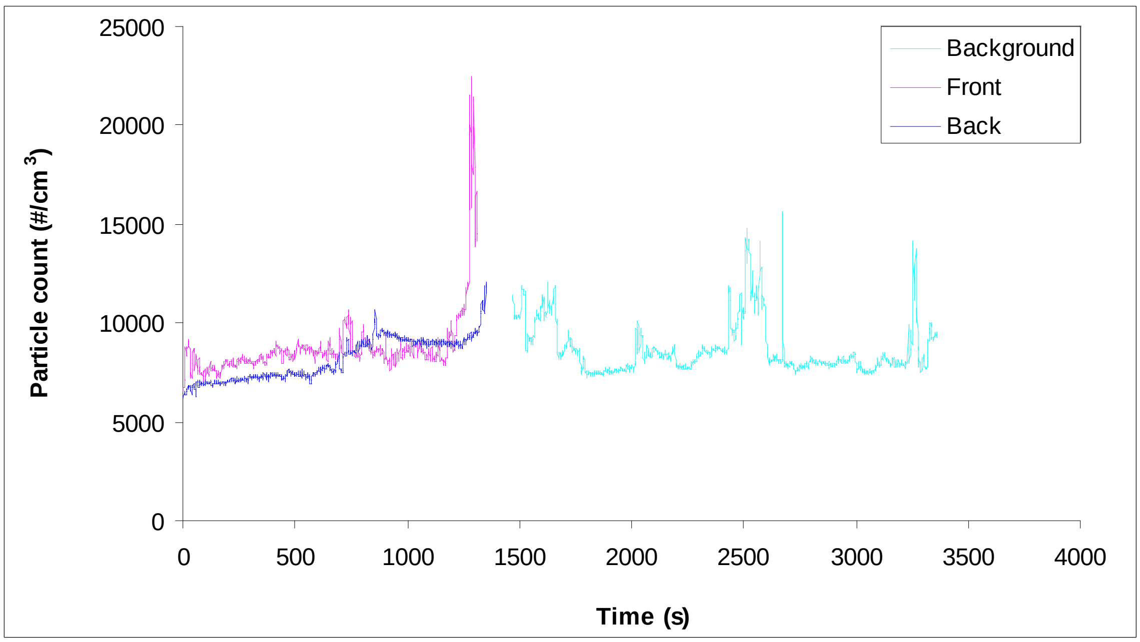


Figure 67 Run 33, Idle test with DPF & CCF windows closed Particle Count, May 14-07.

Run 34:

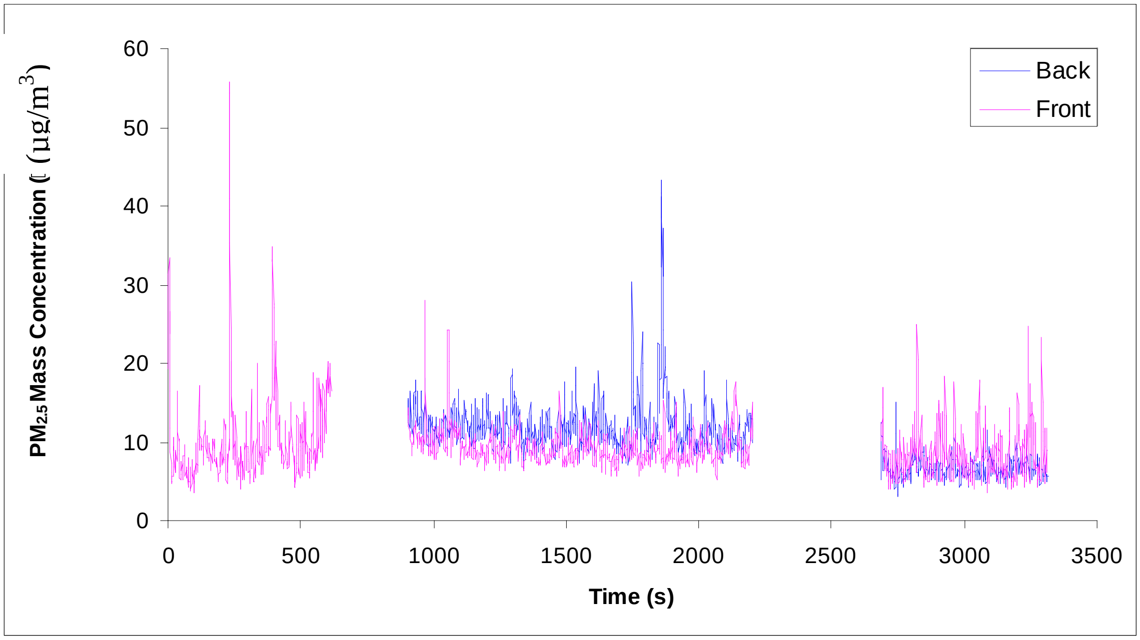


Figure 68 Run 34, DPF & CCF windows closed PM2.5 mass concentration, May 14.

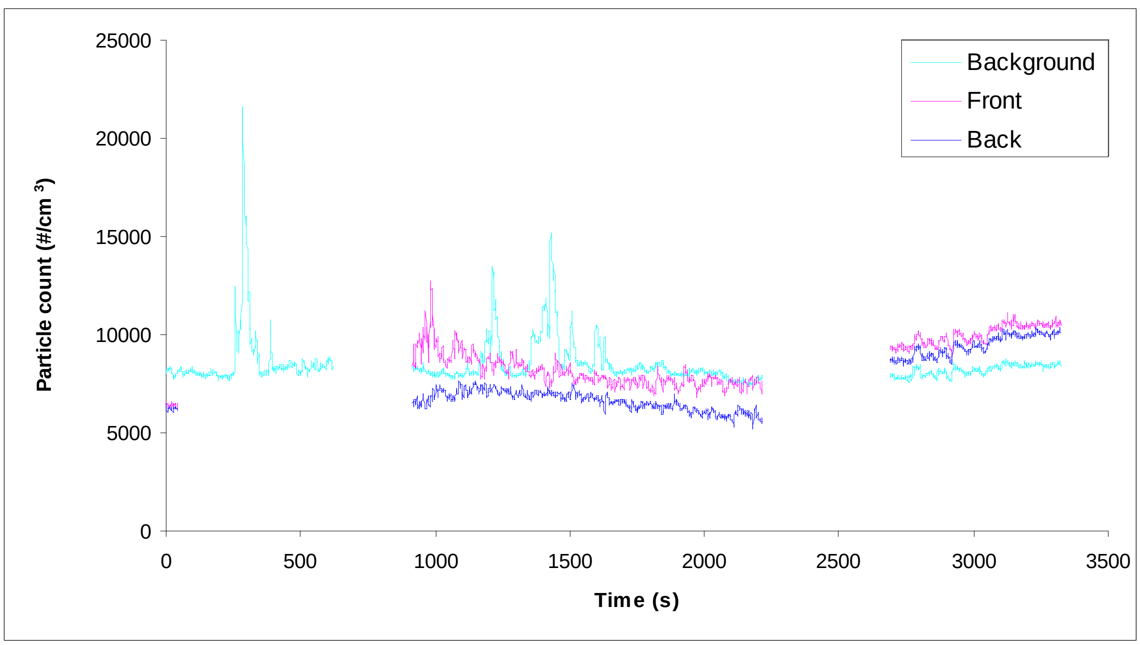


Figure 69 Run 34, DPF & CCF windows closed Particle Count, May 14.

Run 35

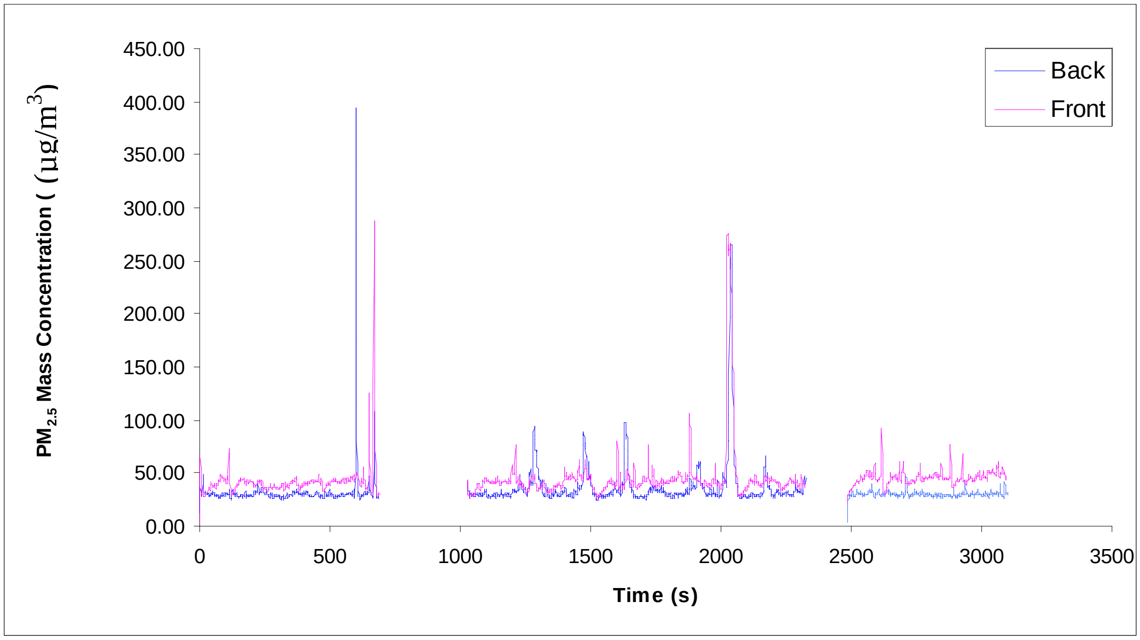


Figure 70 Run 35, FTF & CCF windows open PM2.5 mass concentration, May 16.

Pickup drove by on access road

Ambient = 43µg/m3

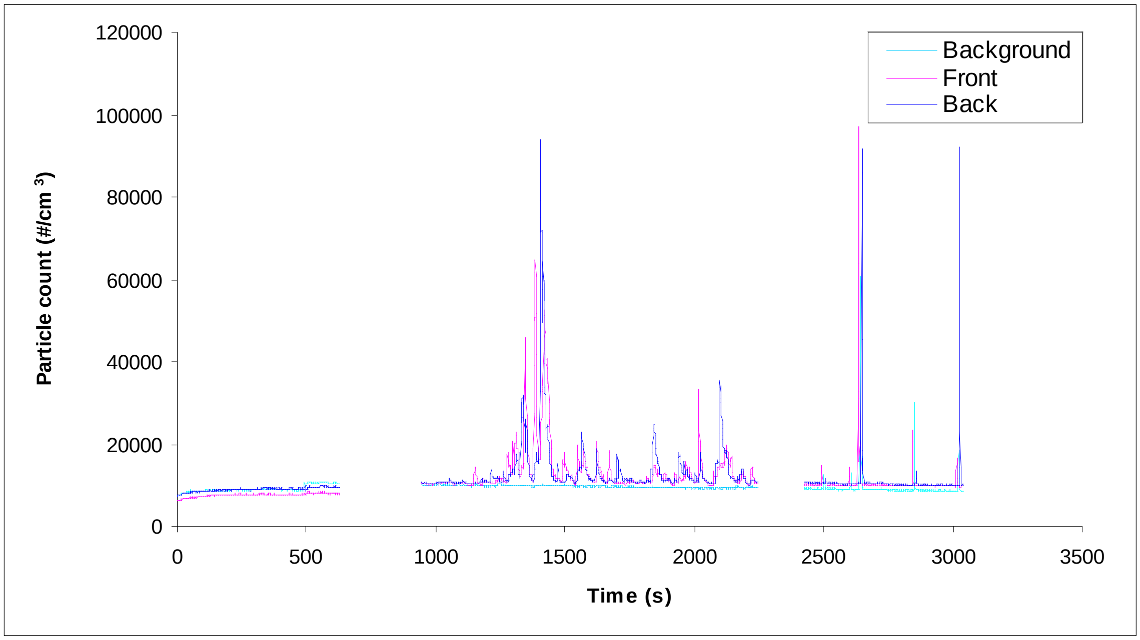


Figure 71 Run 35, FTF & CCF windows open Particle Count, May 16.

Run 36

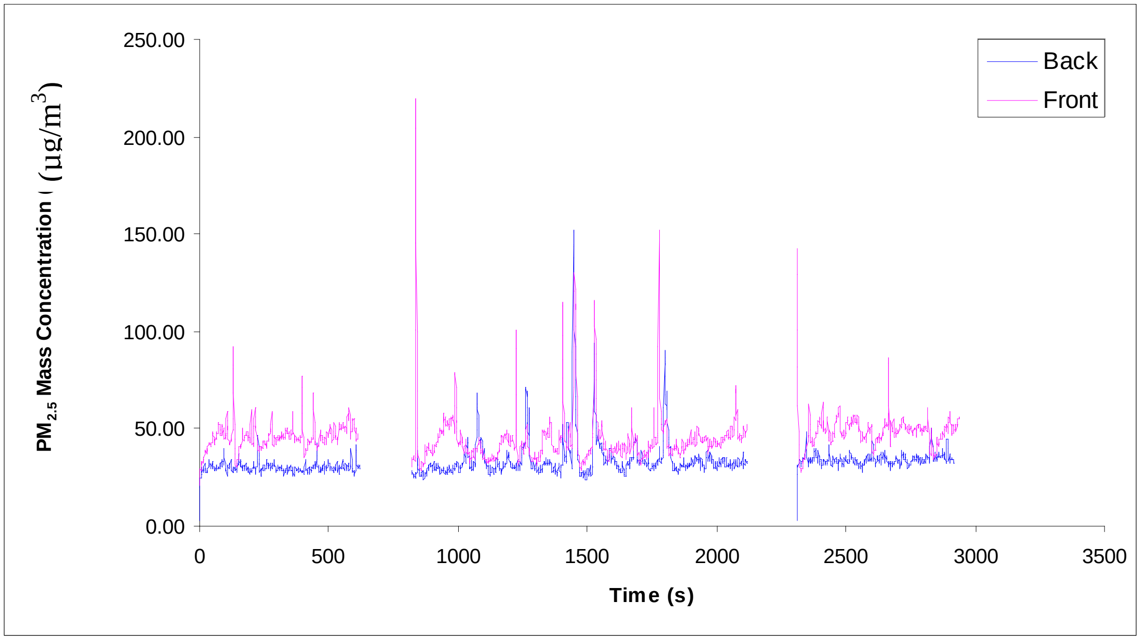


Figure 72 Run 36, FTF & CCF windows open PM2.5 mass concentration, May 16.

Pickup drove by on access road, and Bradley drove by too

High ambient > 40µg/m^3

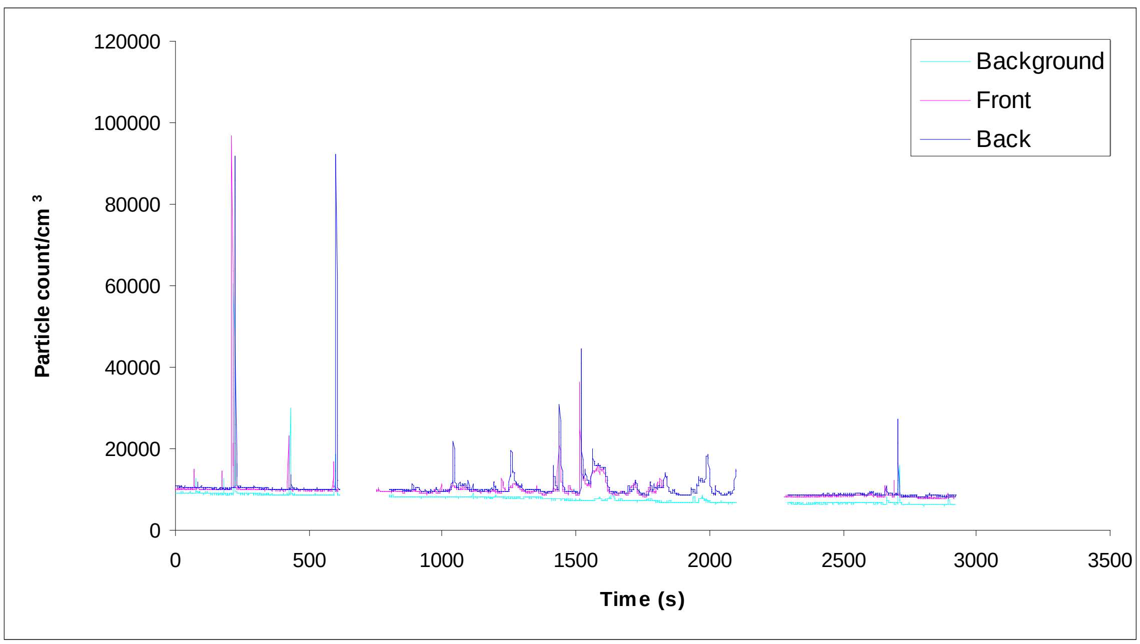


Figure 73 Run 36, FTF & CCF windows open Particle Count, May 16.

Run 37

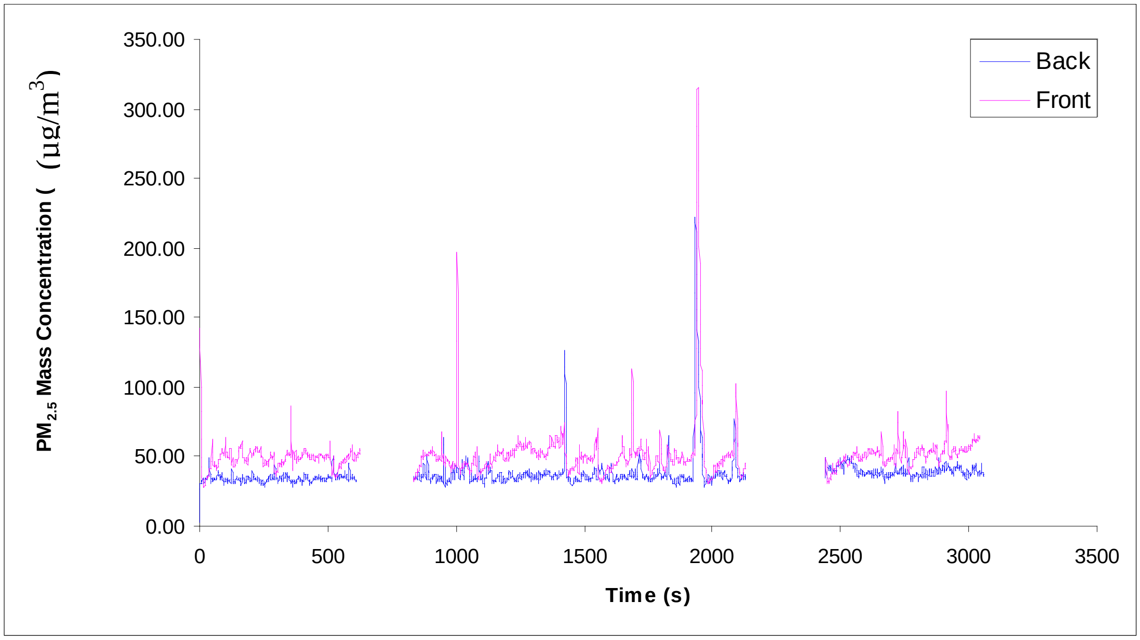


Figure 74 Run 37, FTF & CCF windows open PM2.5 mass concentration, May 16.
High ambient > 40µg/m^3

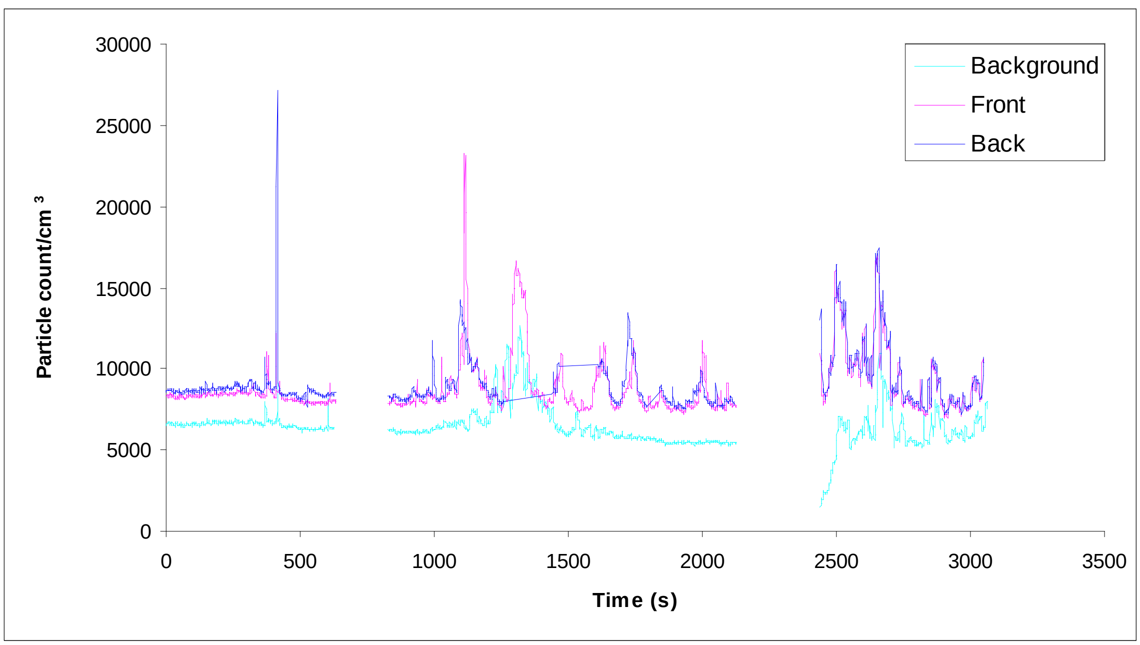


Figure 75 Run 37, FTF & CCF windows open Particle Count, May 16.

Run 38

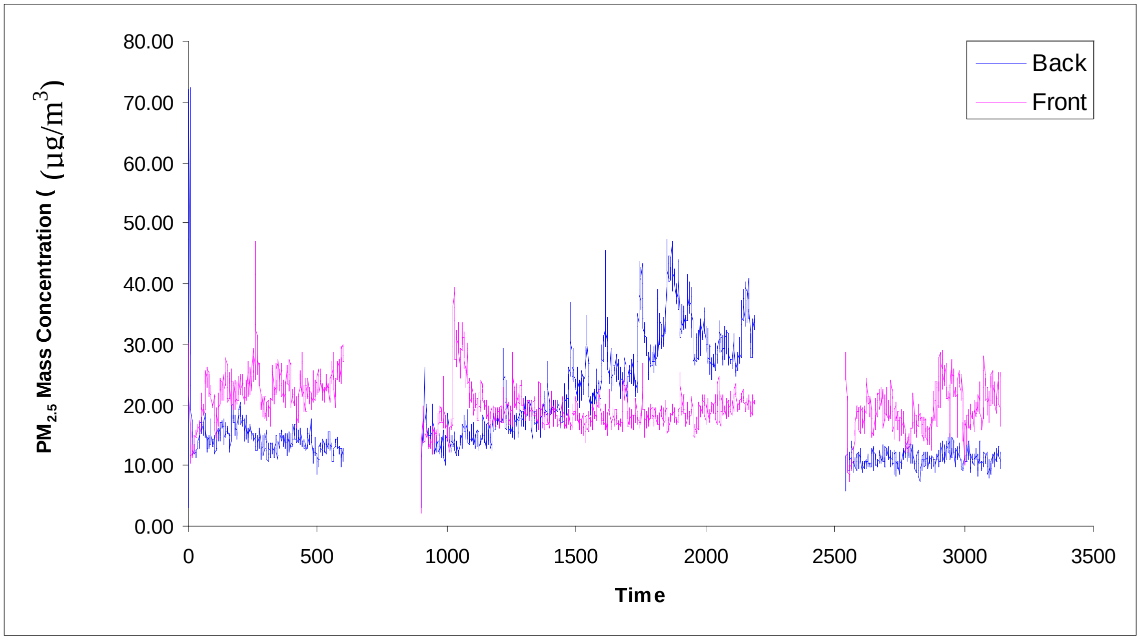


Figure 76 Run 38, FTF & CCF windows closed PM2.5 mass concentration, May 17.

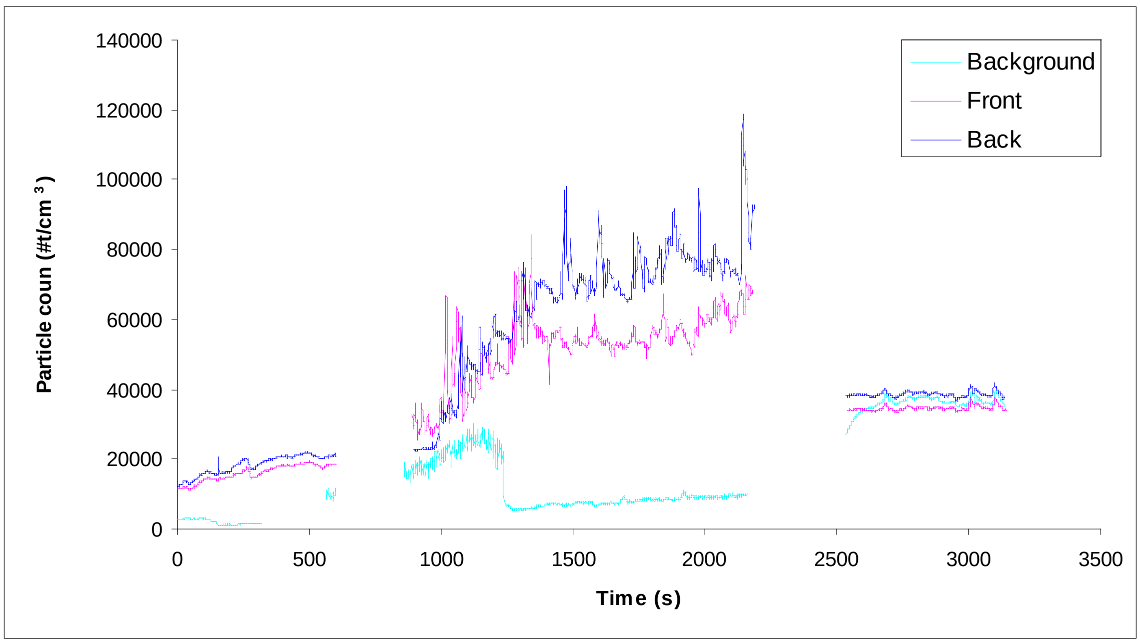


Figure 77 Run 38, FTF & CCF windows closed Particle Count, May 17.

Run 39

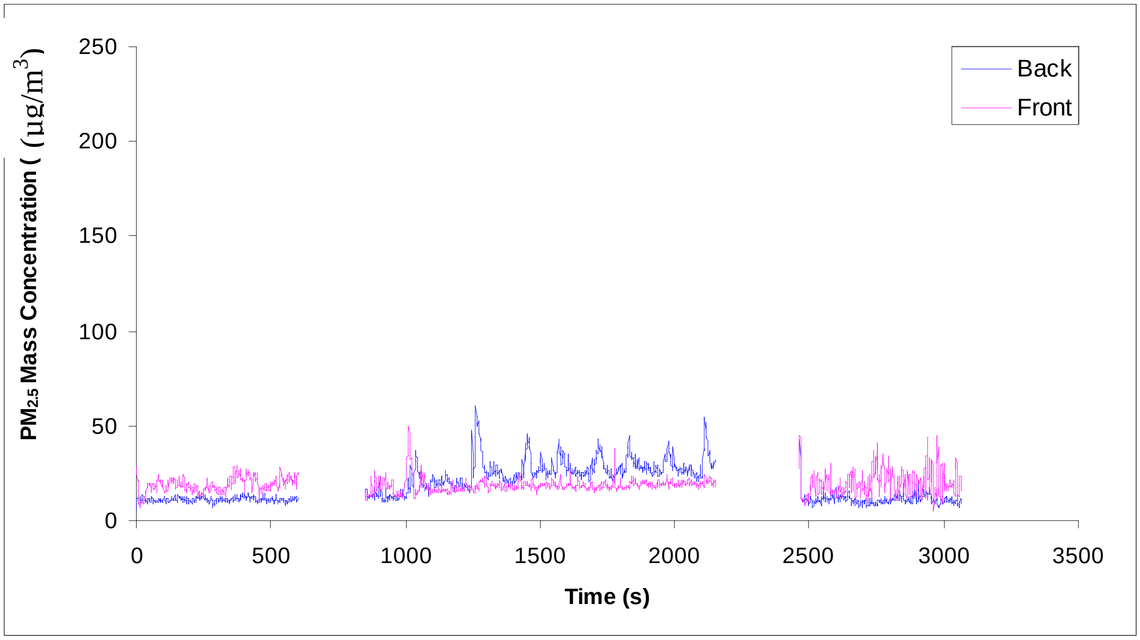


Figure 78 Run 39, FTF & CCF windows closed PM2.5 mass concentration, May 17.

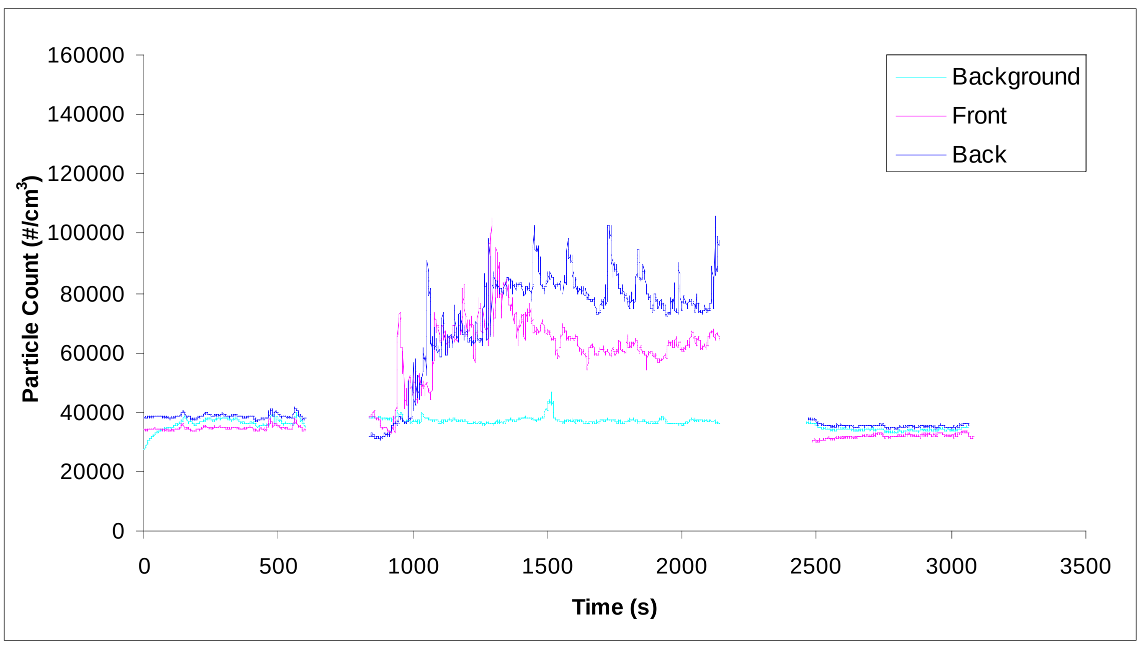


Figure 79 Run 39, FTF & CCF windows closed Particle Count, May 17.

Run 40

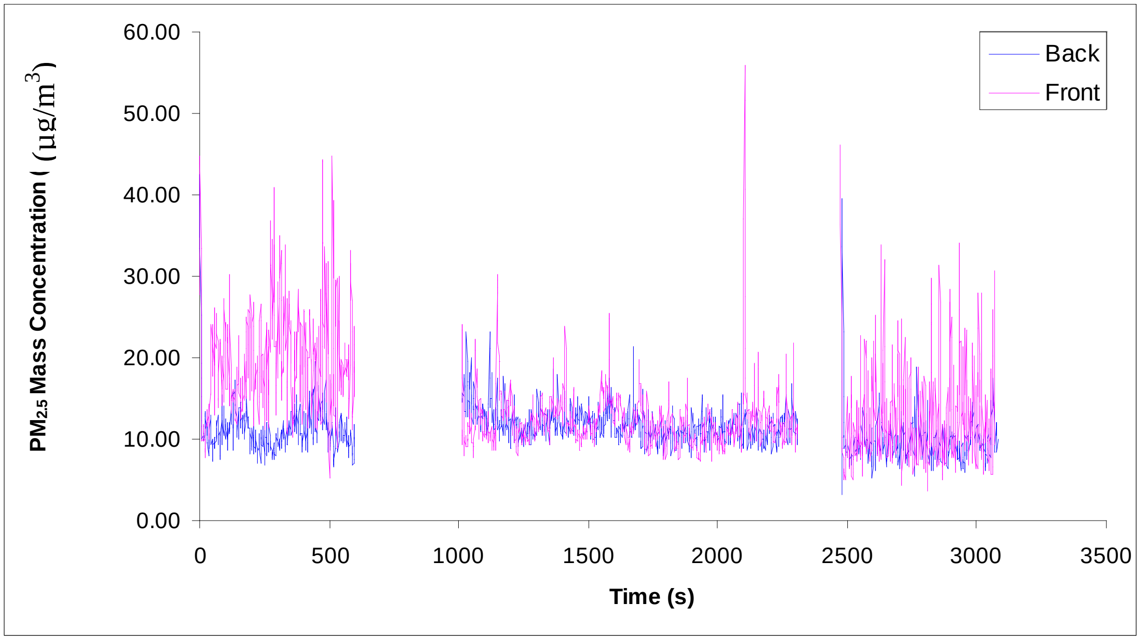


Figure 80 Run 40, FTF & CCF windows closed PM2.5 mass concentration, May 17.

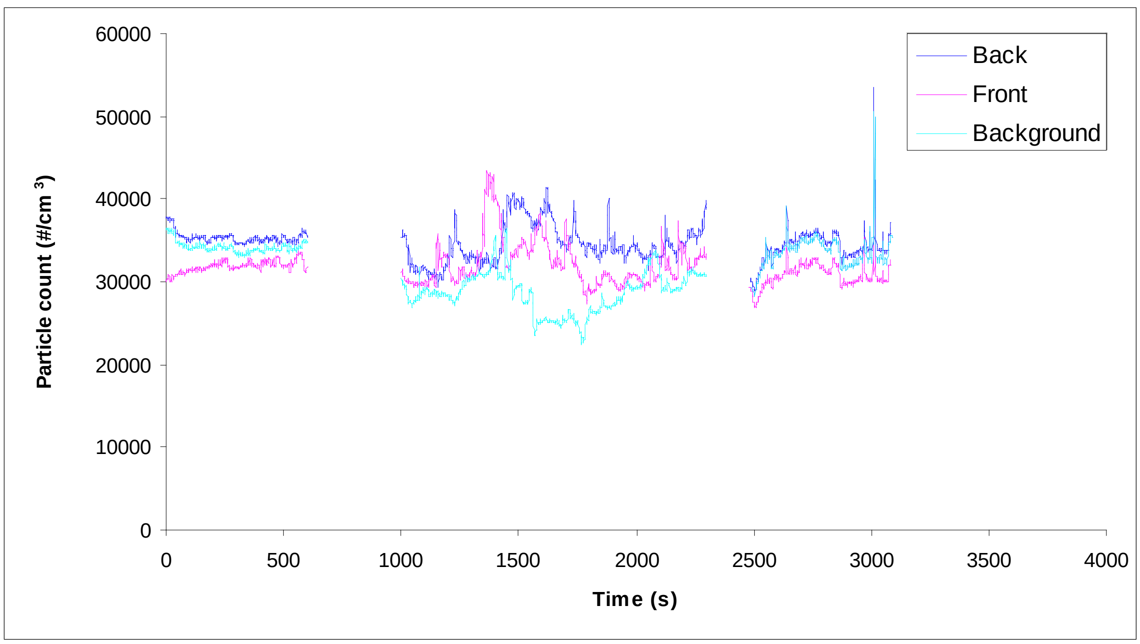


Figure 81 Run 40, FTF & CCF windows closed Particle Count, May 17.

Run 41

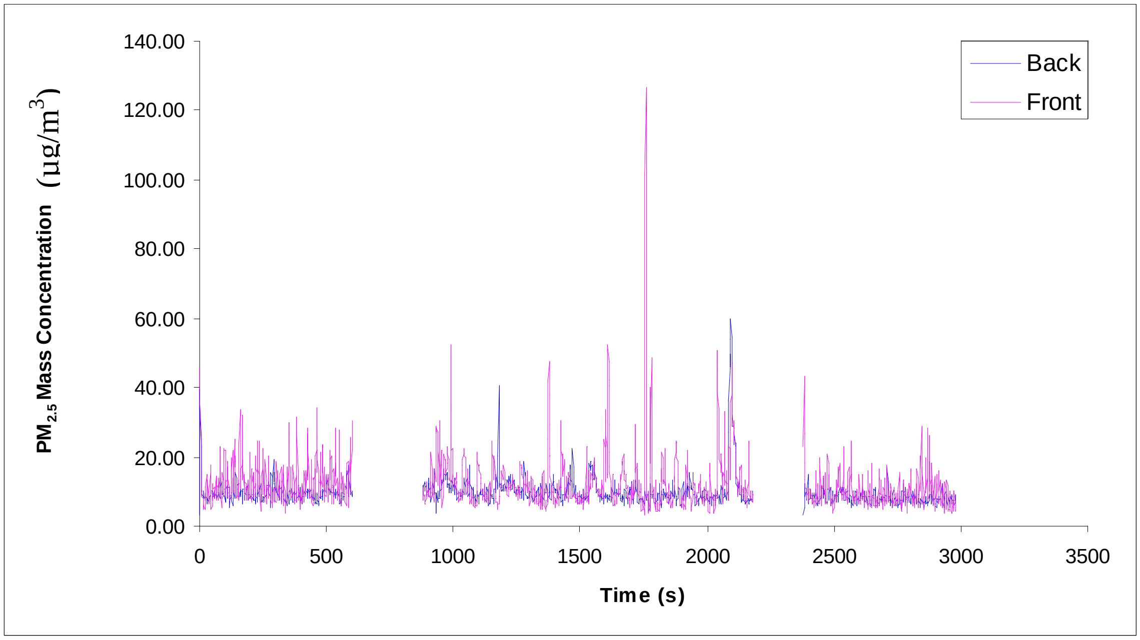


Figure 82 Run 41, FTF windows open PM2.5 mass concentration, May 17.

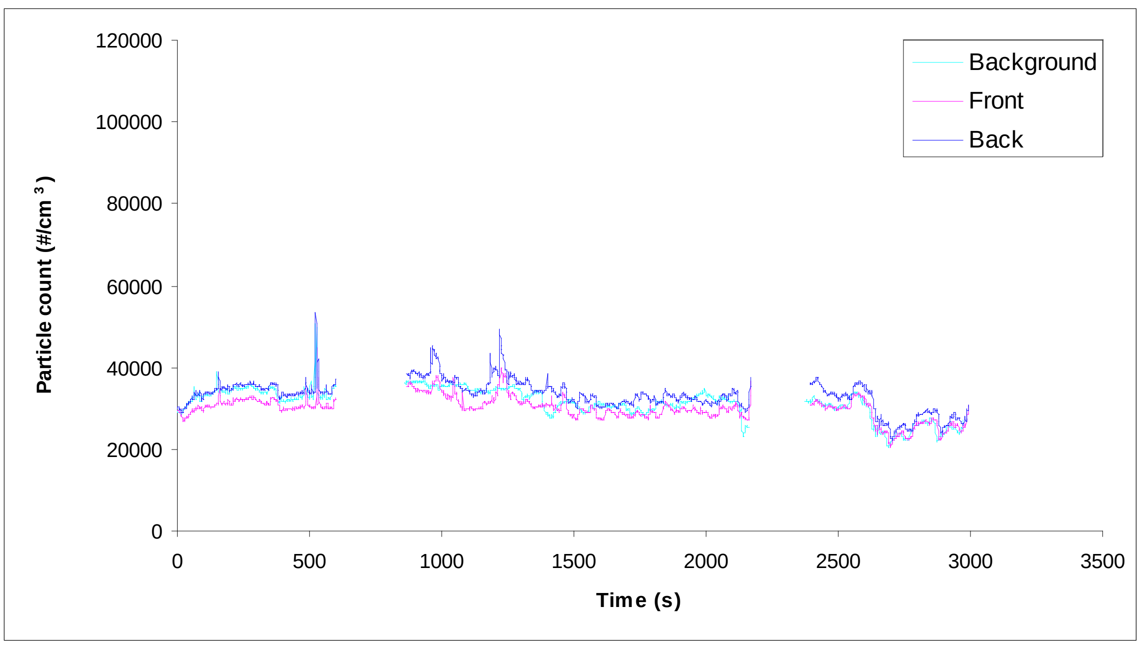


Figure 83 Run 41, FTF windows open Particle Count, May 17.

Run 42

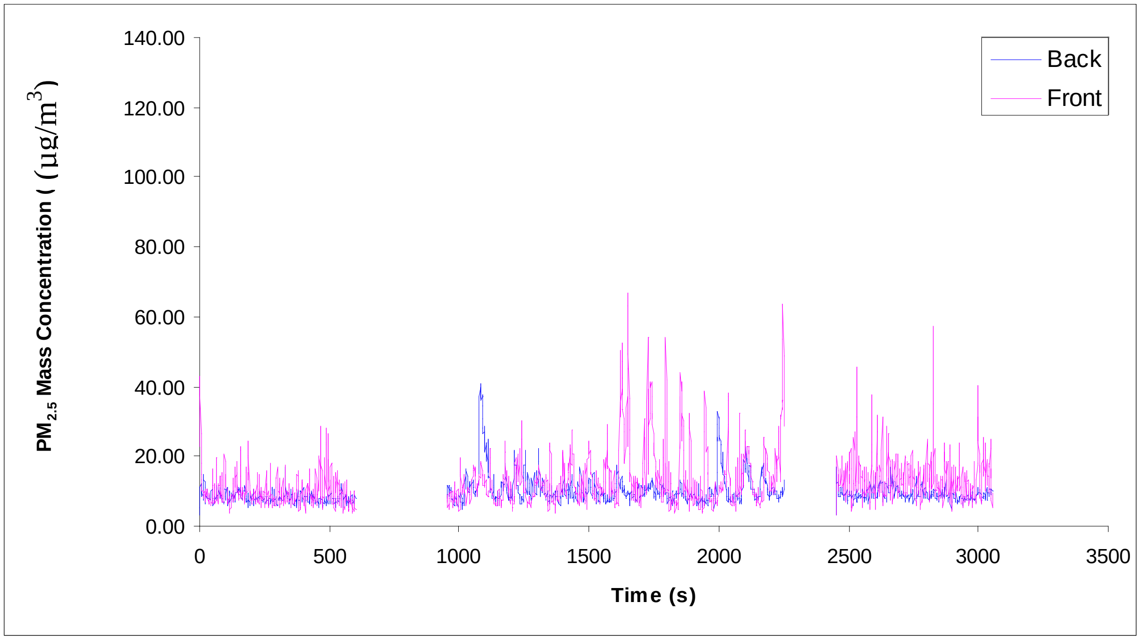


Figure 84 Run 42, FTF windows open PM2.5 mass concentration, May 17.

FID went out (low fuel) with about four minutes left in the run

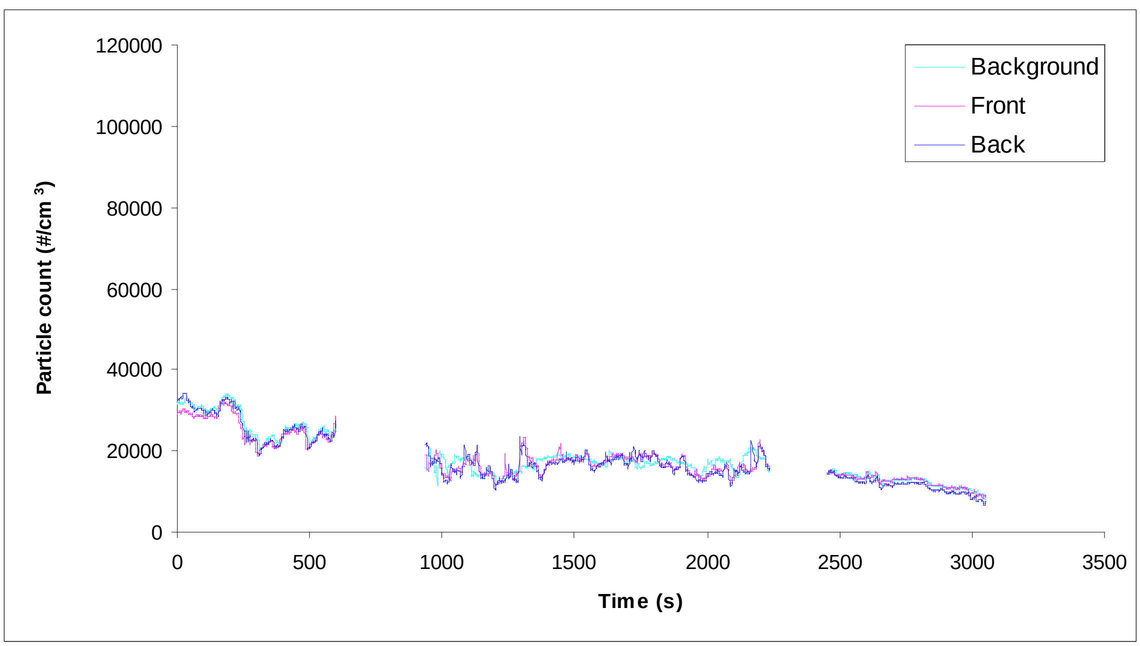


Figure 85 Run 42, FTF windows open Particle Count, May 17.

Run 43

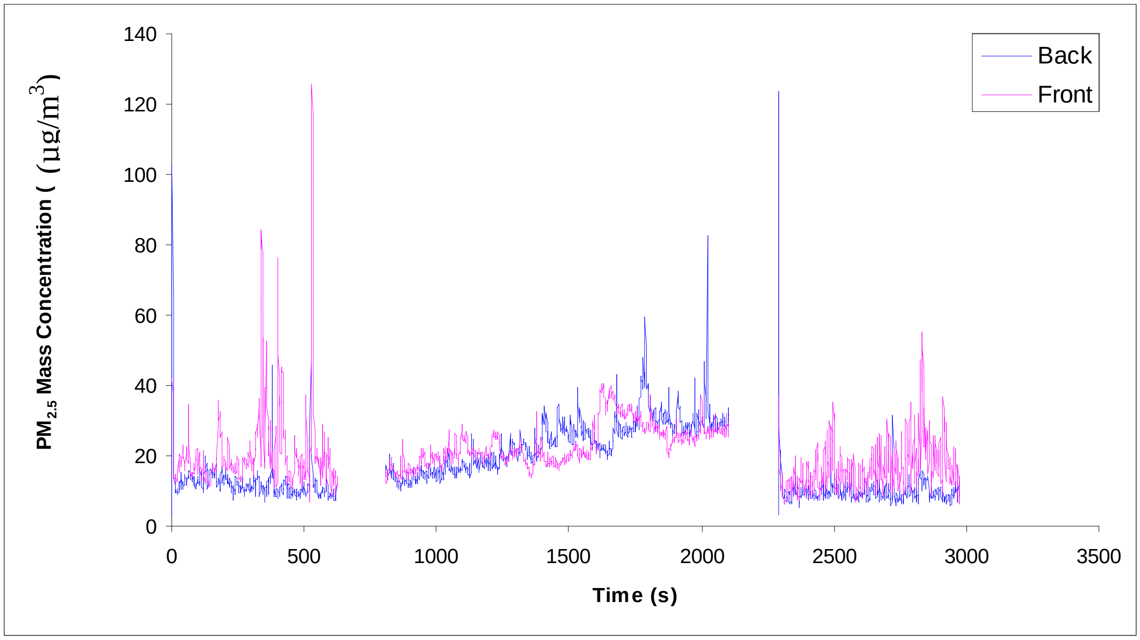


Figure 86 Run 43, FTF windows closed PM2.5 mass concentration, May 21.

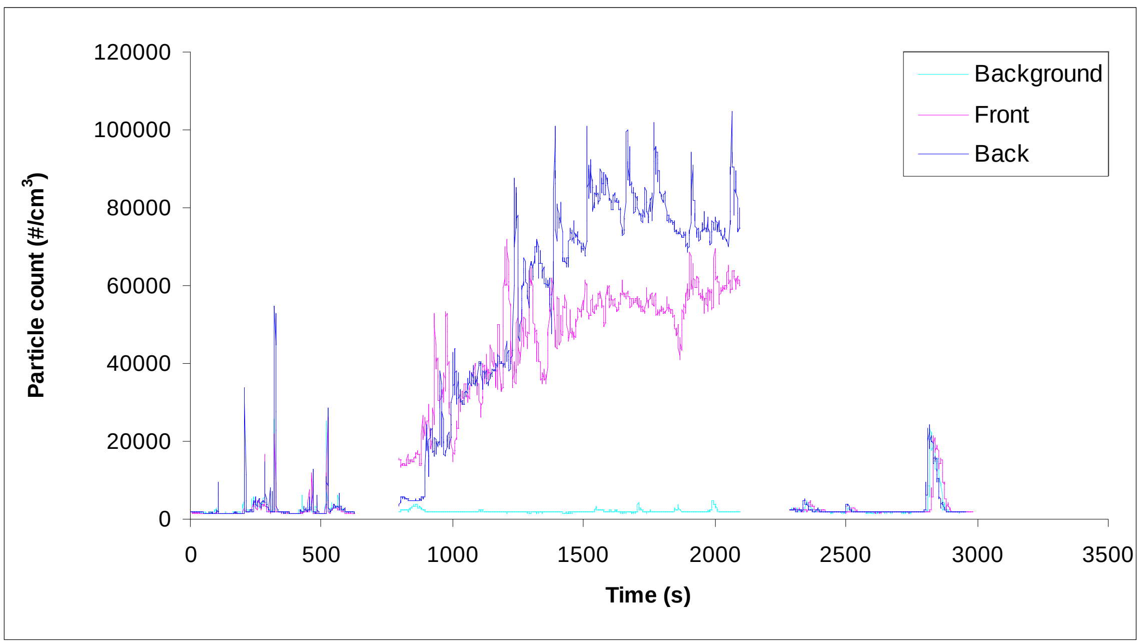


Figure 87 Run 43, FTF windows closed Particle Count, May 21.

Run 44

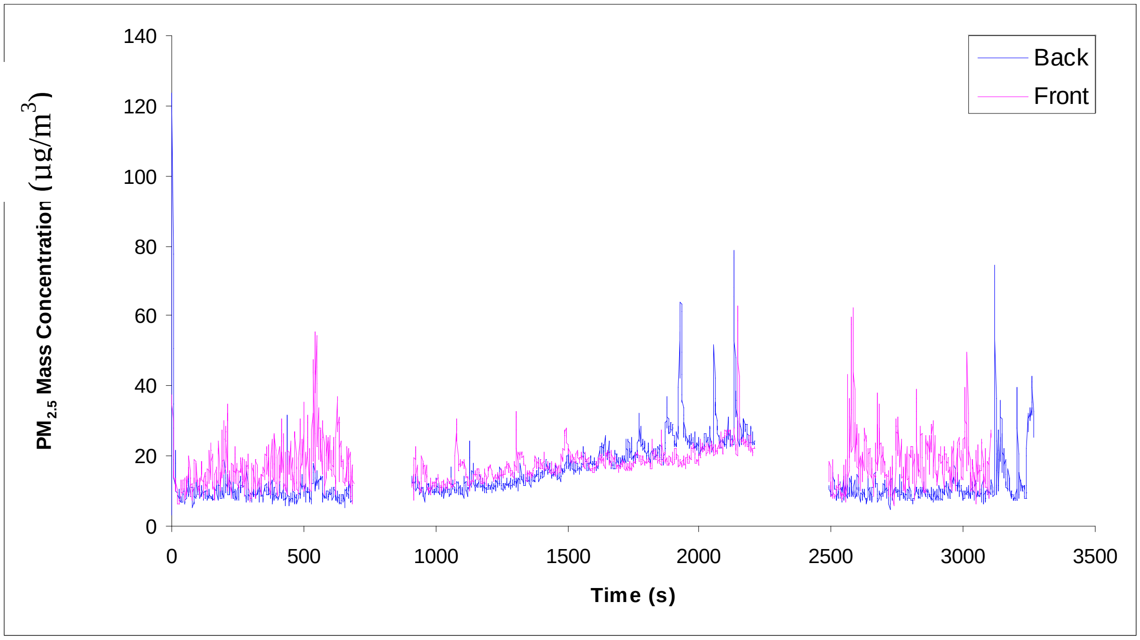


Figure 88 Run 44, FTF windows closed PM2.5 mass concentration, May 21.

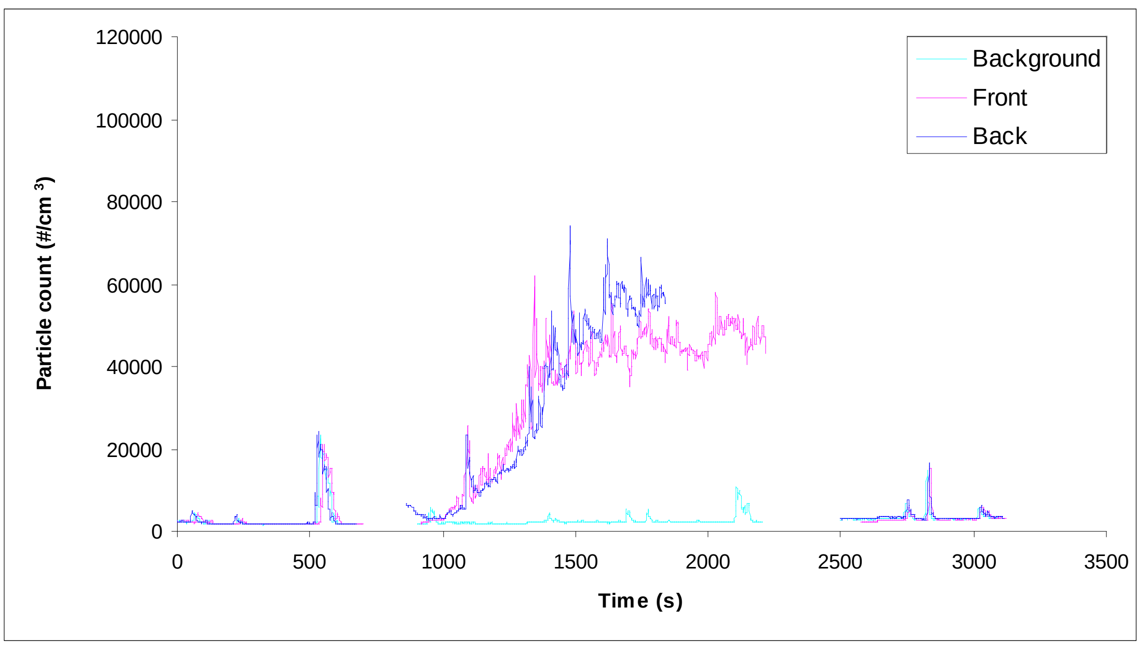


Figure 89 Run 44, FTF windows closed Particle Count, May 21.

Ptrak D-3 (back instrument) stopped recording about 17 minutes into the run

Run 45

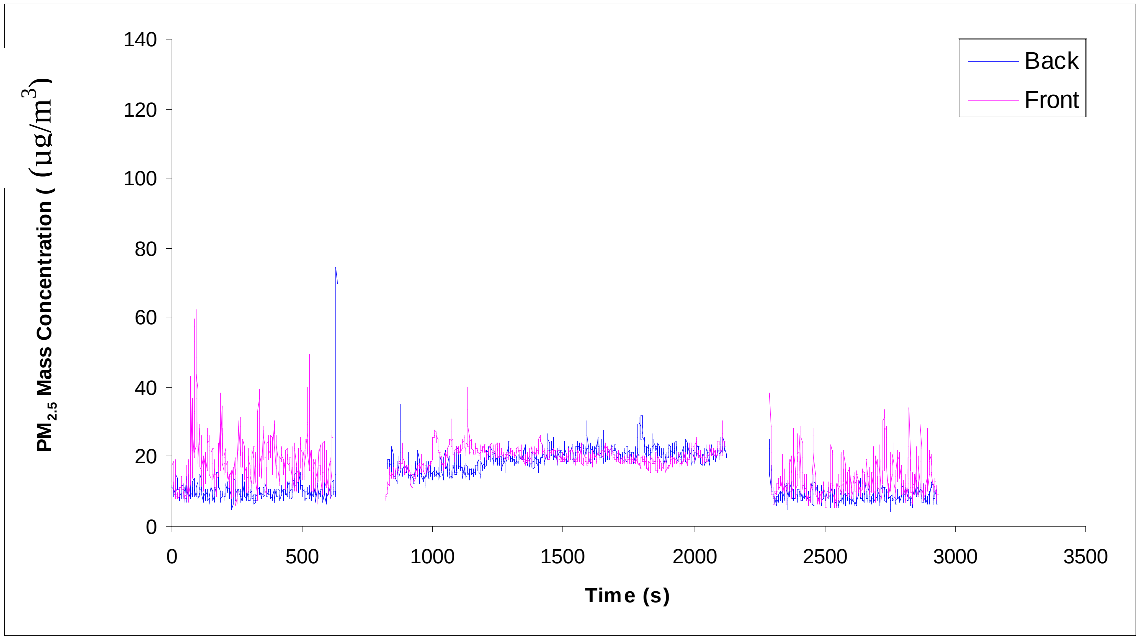


Figure 90 Run 45, FTF windows closed PM2.5 mass concentration, May 21.

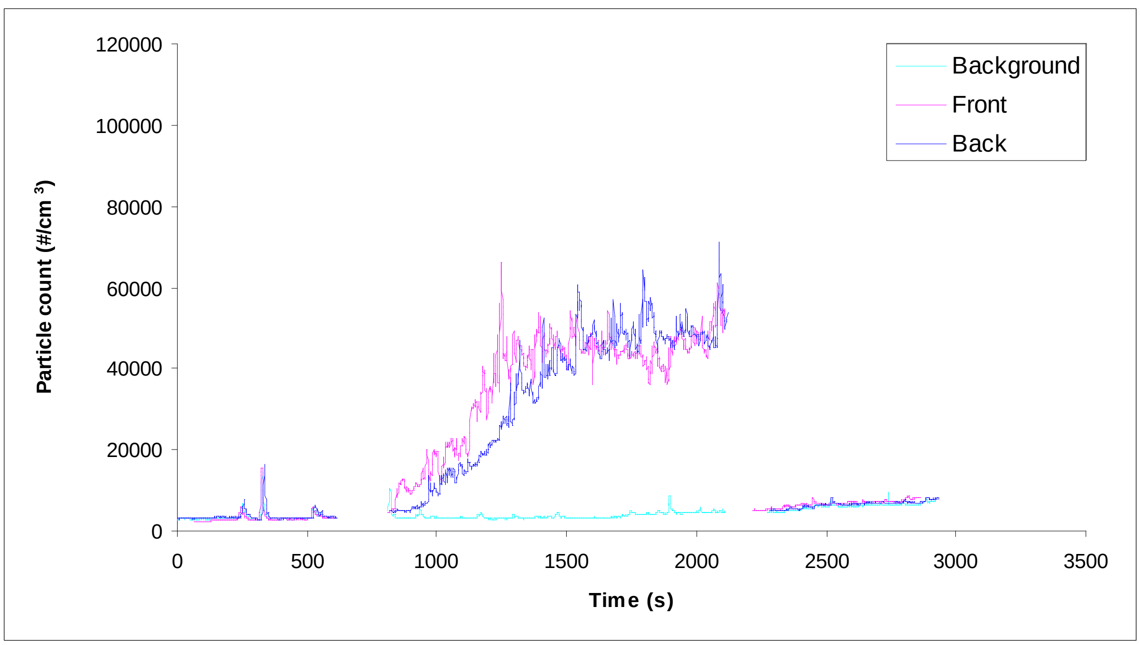


Figure 91 Run 45, FTF windows closed Particle Count, May 21.

Run 46

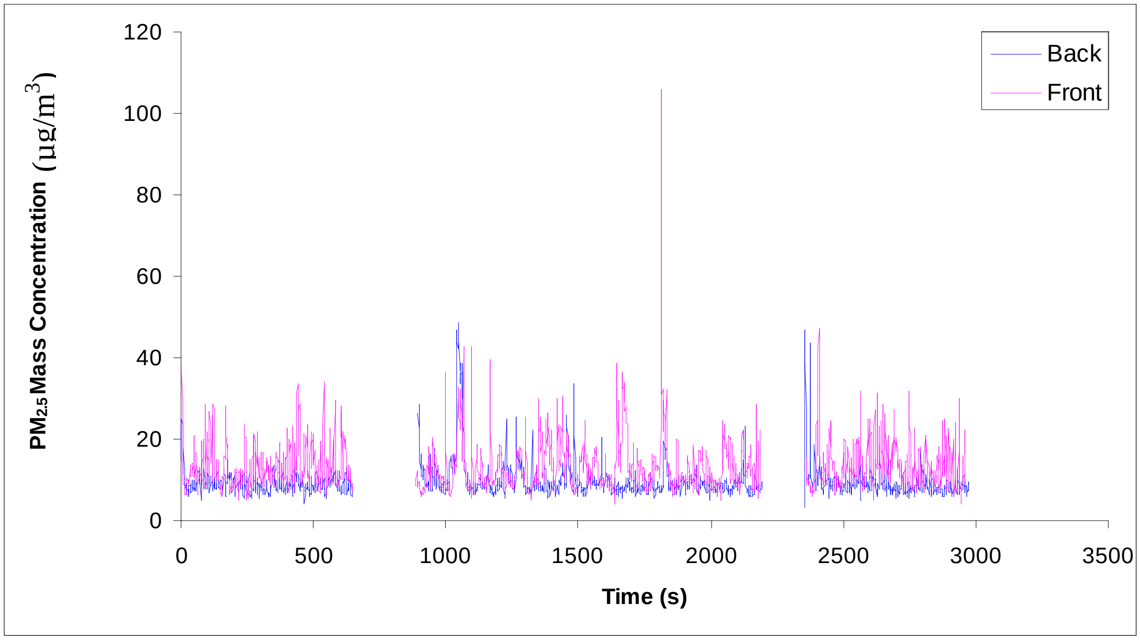


Figure 92 Run 46, FTF windows open PM2.5 mass concentration, May 21.

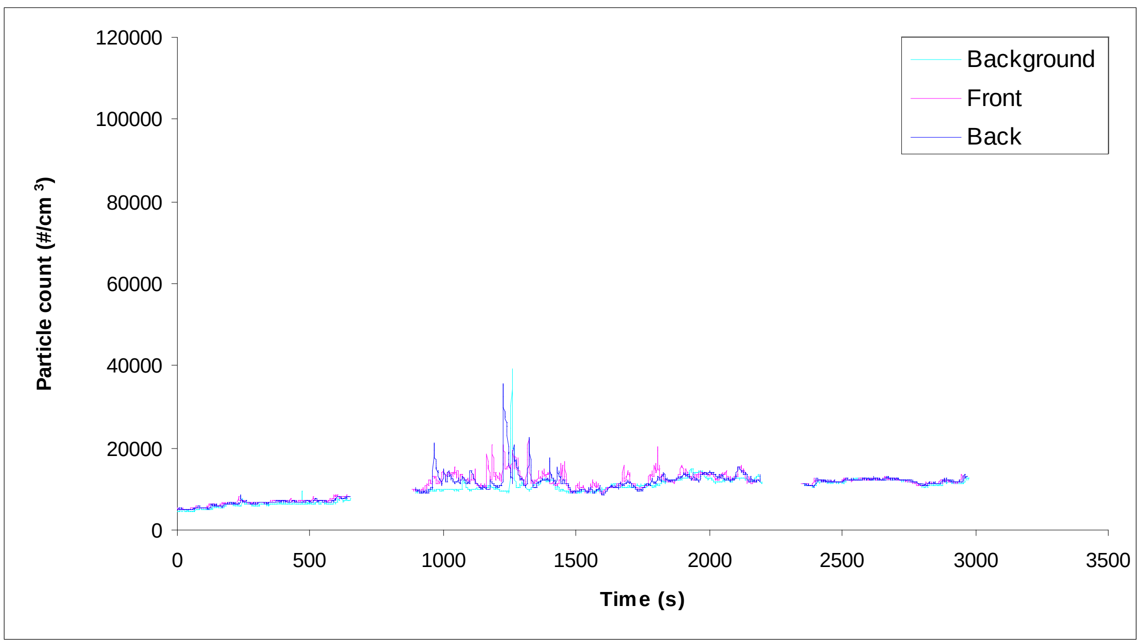


Figure 93 Run 46, FTF windows open Particle Count, May 21.

Run 47

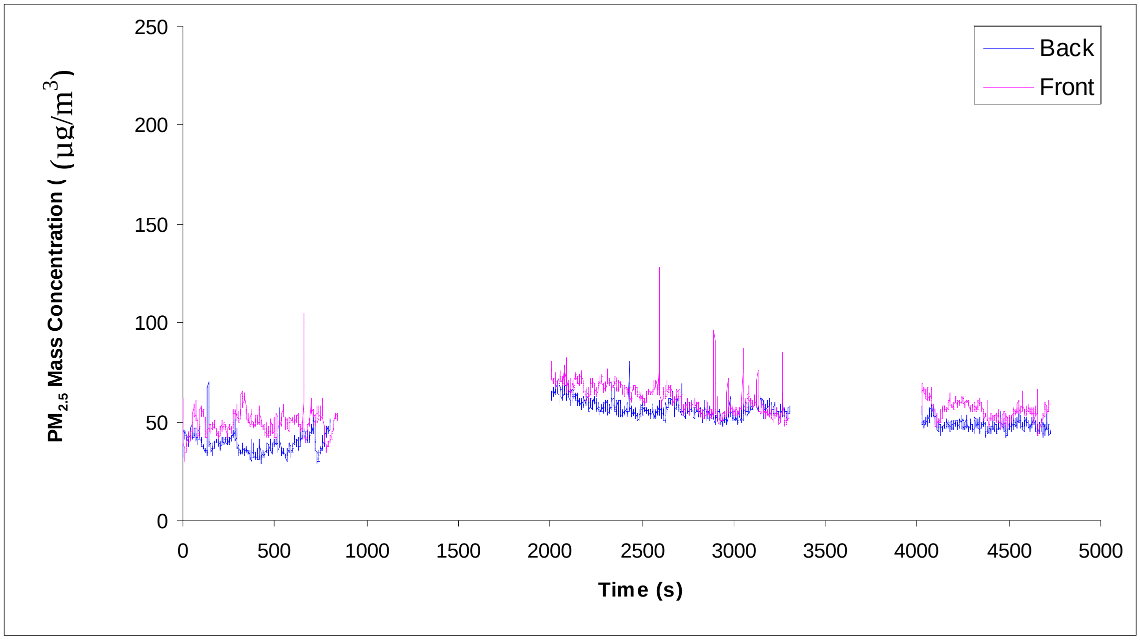


Figure 94 Run 47, DPF & CCF windows closed PM2.5 mass concentration, May 31.
Ambient = 53μg/m^3

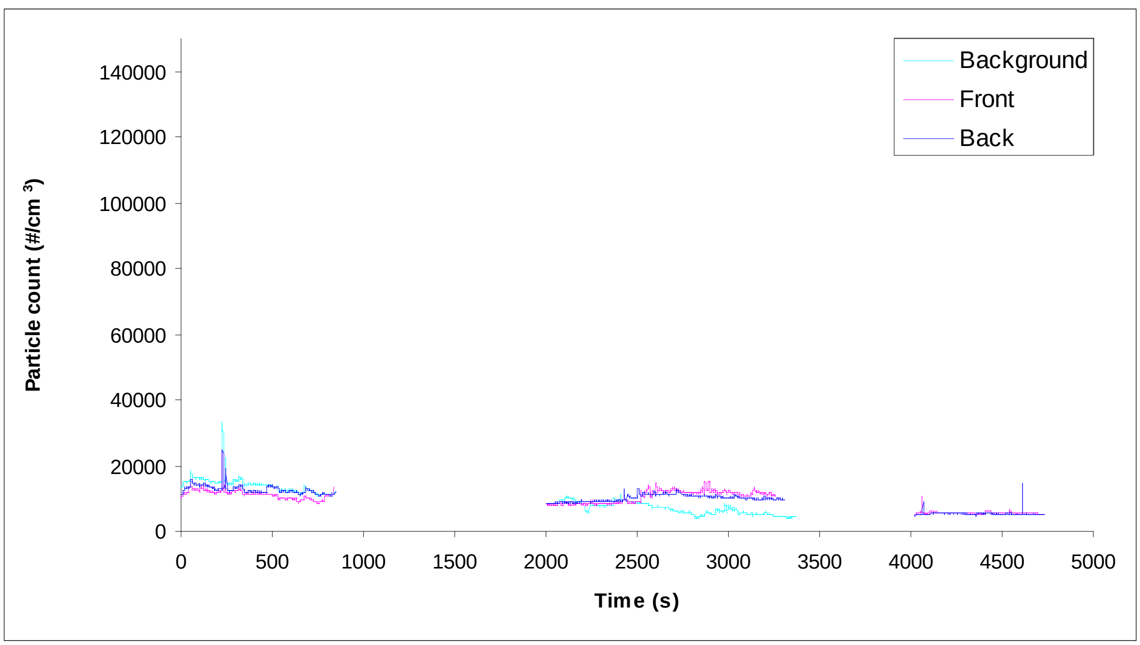


Figure 95 Run 47, DPF & CCF windows closed Particle Count, May 31.

Run 48

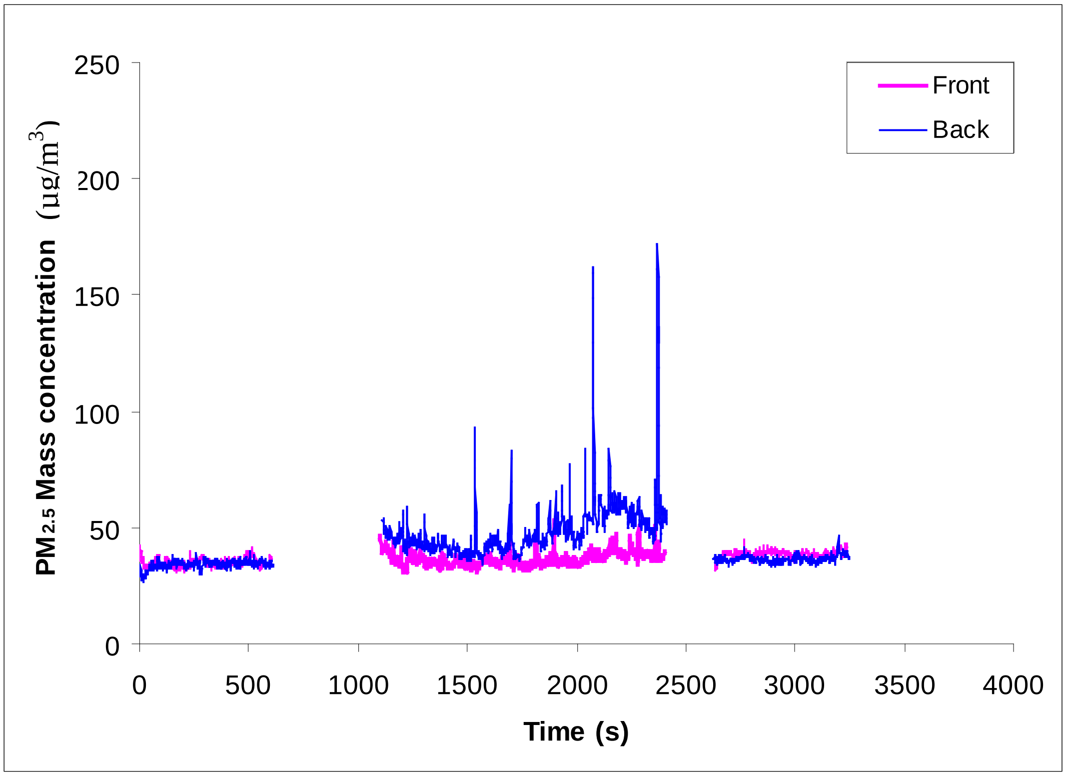


Figure 96 Run 48, DPF & CCF windows closed PM2.5 mass concentration, June 4.

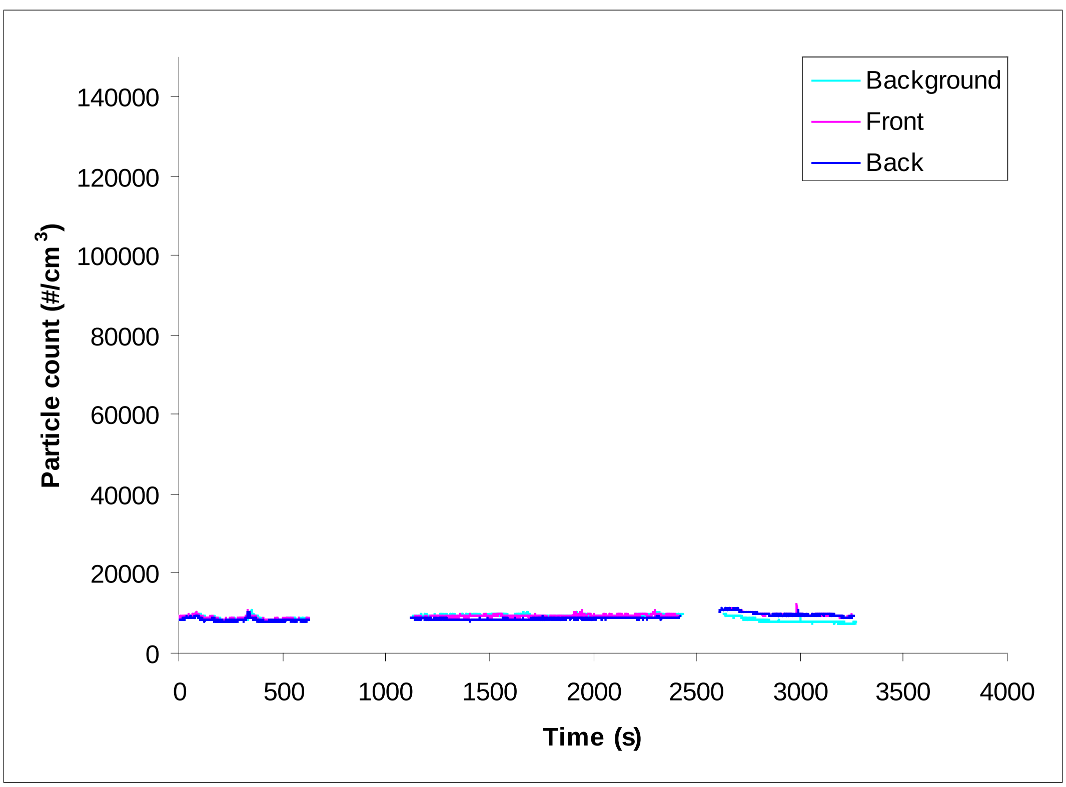


Figure 97 Run 48, DPF & CCF windows closed Particle Count, June 4.

Run 49

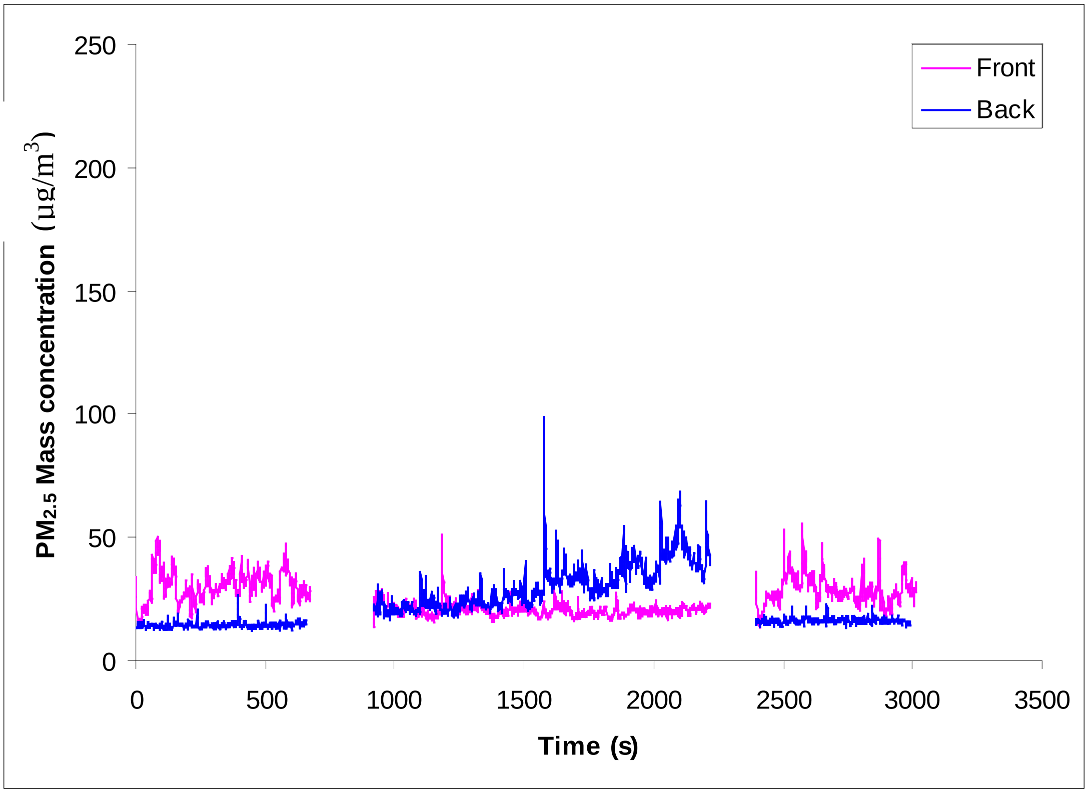


Figure 98 Run 49, DPF & CCF windows closed PM2.5 mass concentration, June 5.

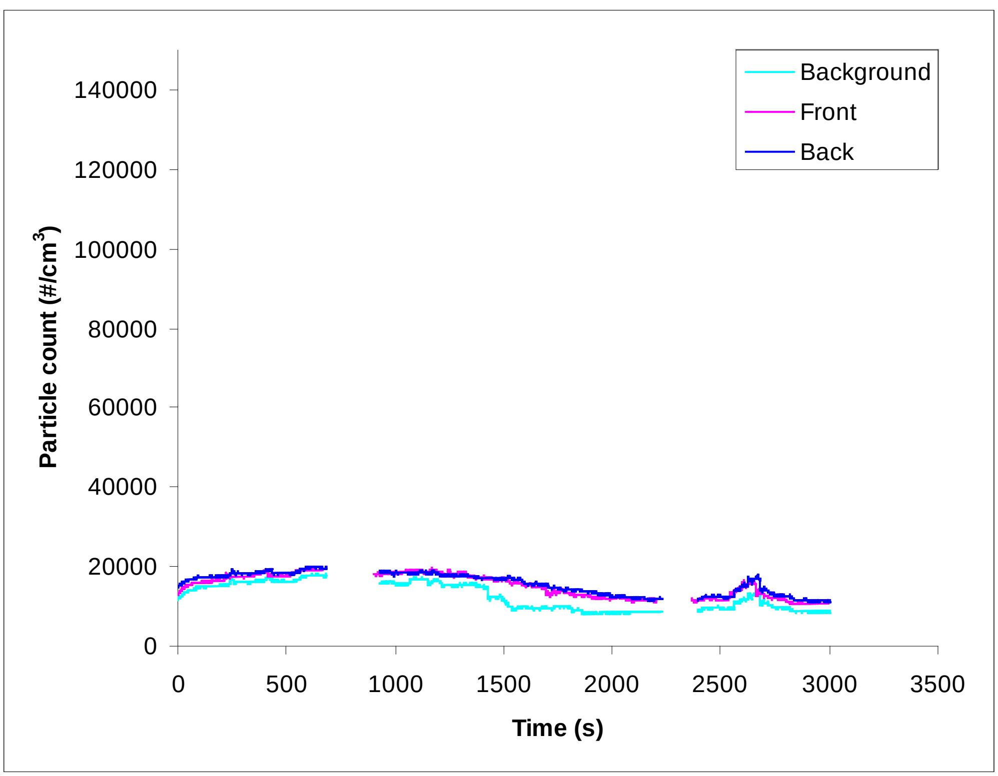


Figure 99 Run 49, DPF & CCF windows closed Particle Count, June 5.

Run 50

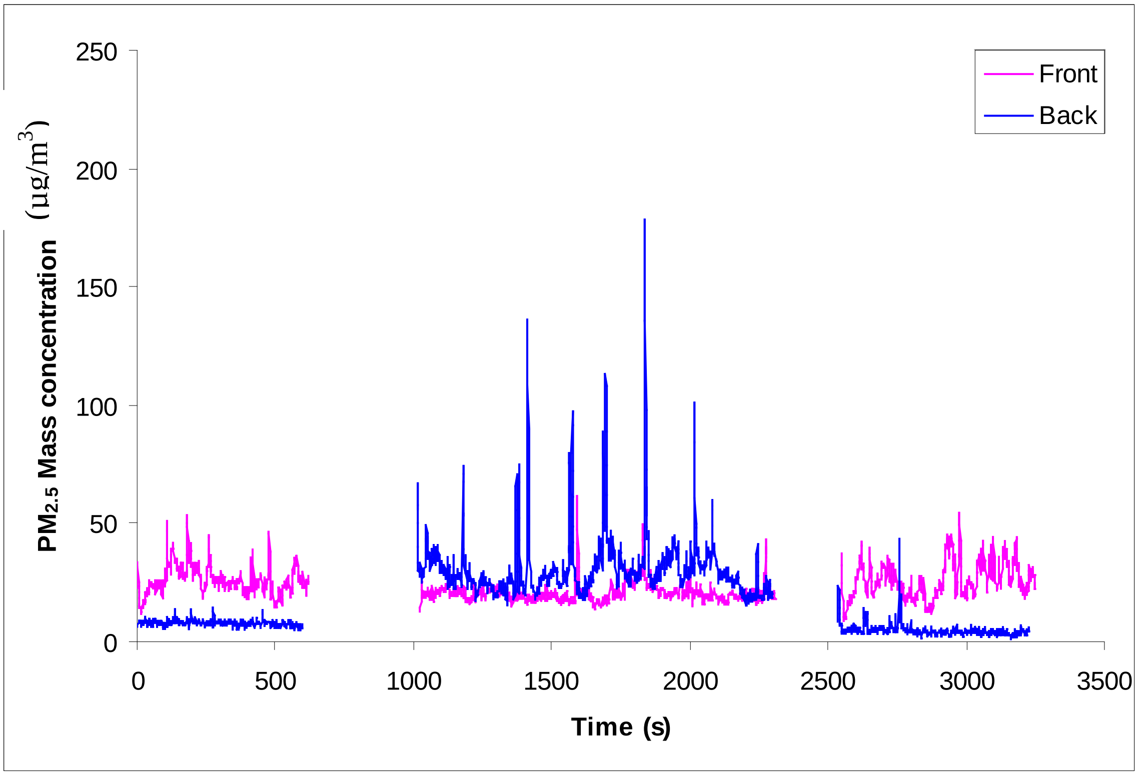


Figure 100 Run 50, DPF & CCF windows closed PM2.5 mass concentration, June 5.

Back instrument during run had a particle size = 1.05µm

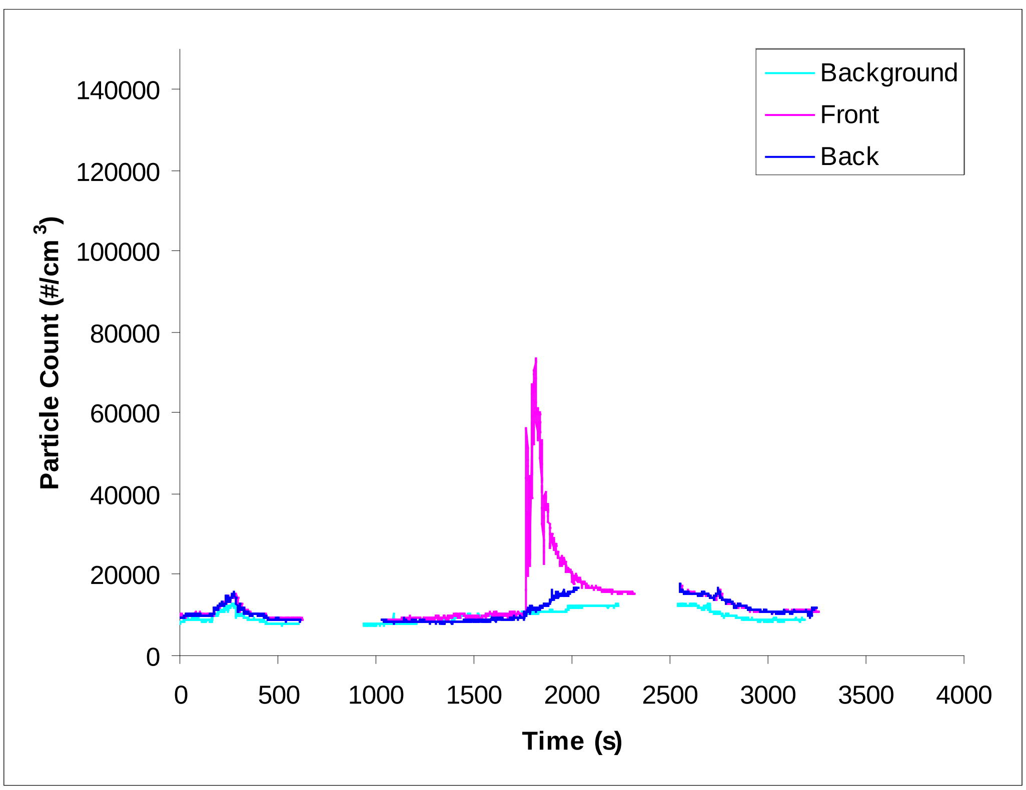


Figure 101 Run 50, DPF & CCF windows closed Particle Count, June 5.

Run 51

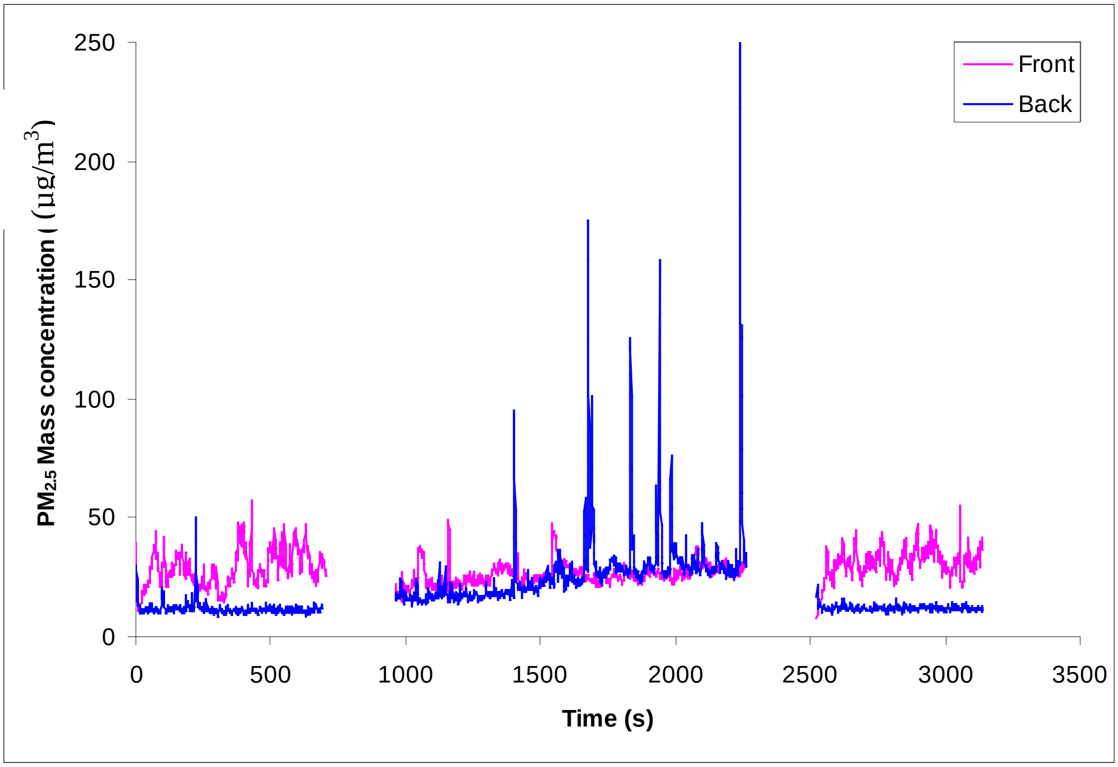


Figure 102 Run 51, DPF windows closed PM2.5 mass concentration, June 5.

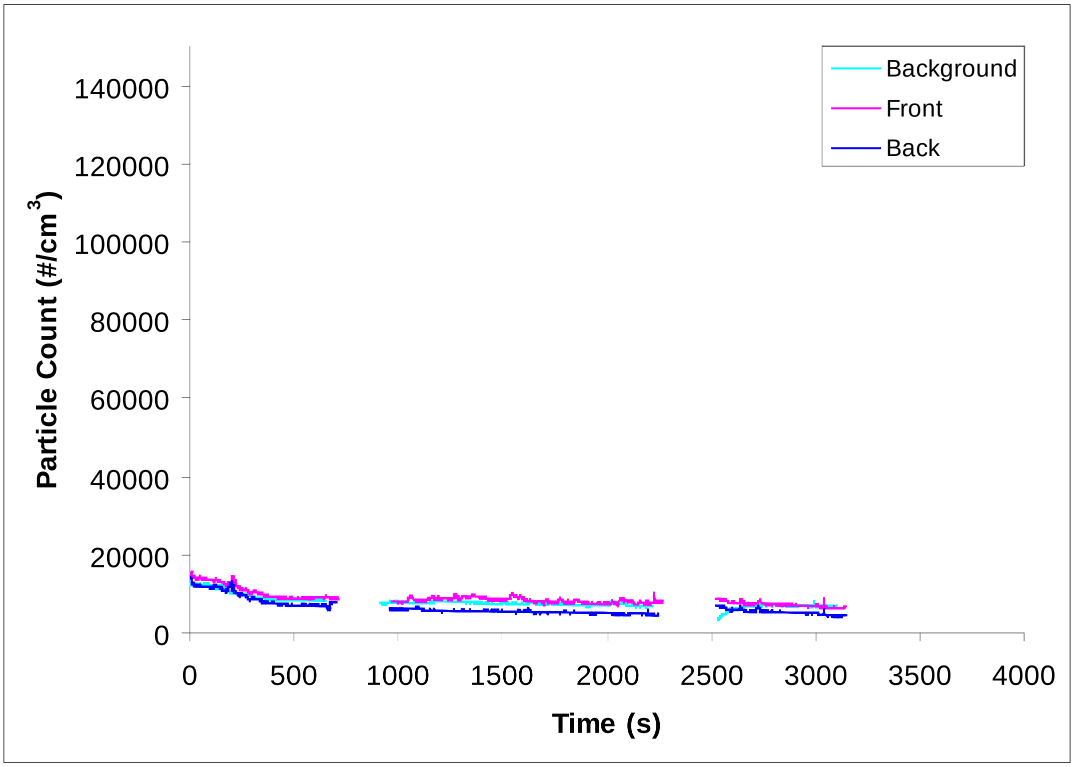


Figure 103 Run 51, DPF windows closed Particle Count, June 5.

Run 52

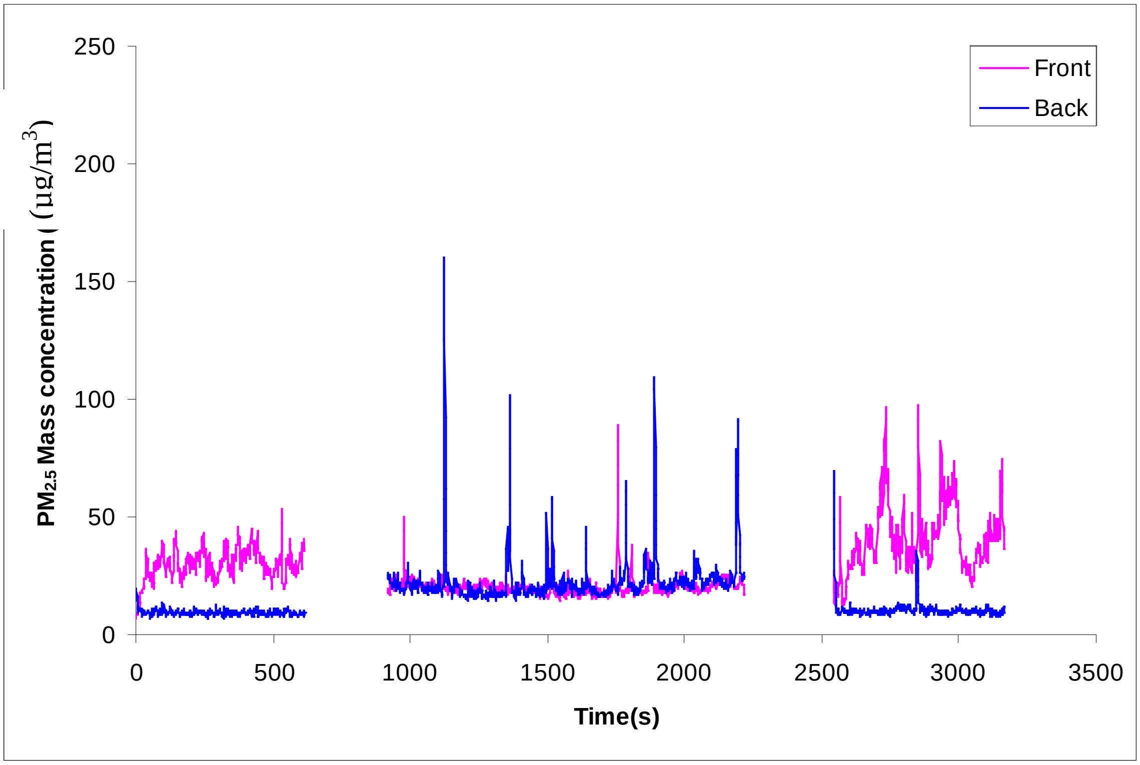


Figure 104 Run 52, DPF windows closed PM2.5 mass concentration, June 5.

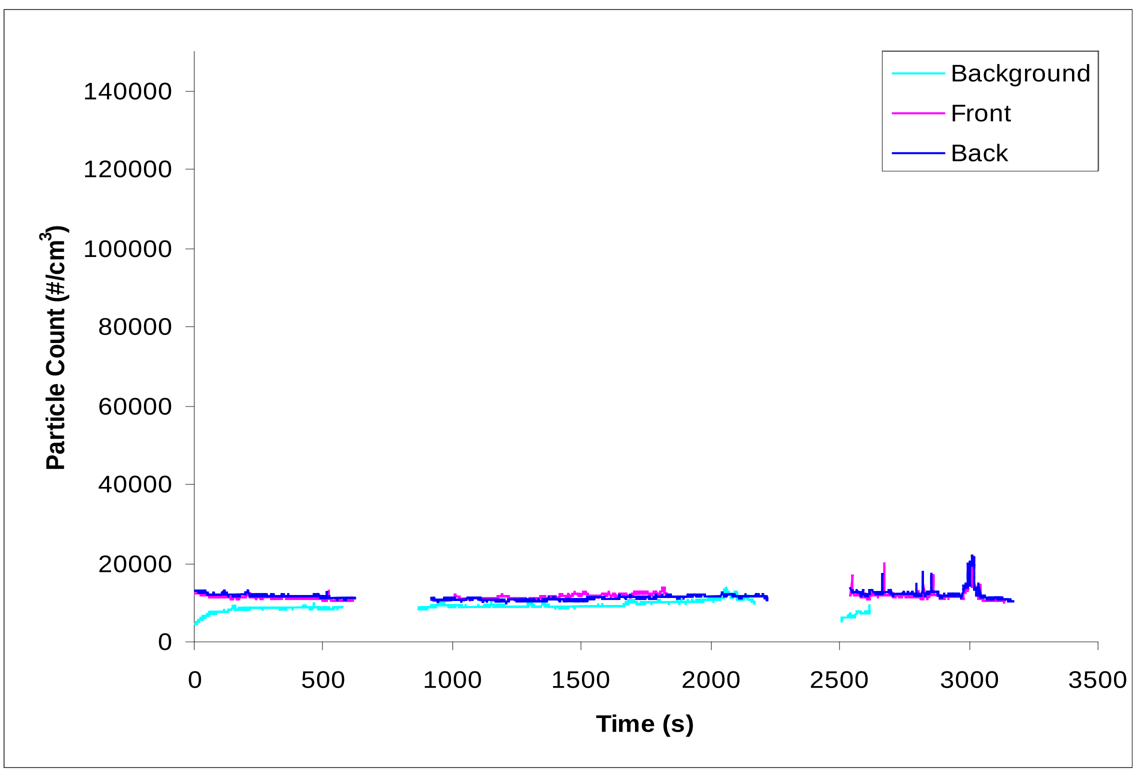


Figure 105 Run 52, DPF windows closed Particle Count, June 5.

Run 53

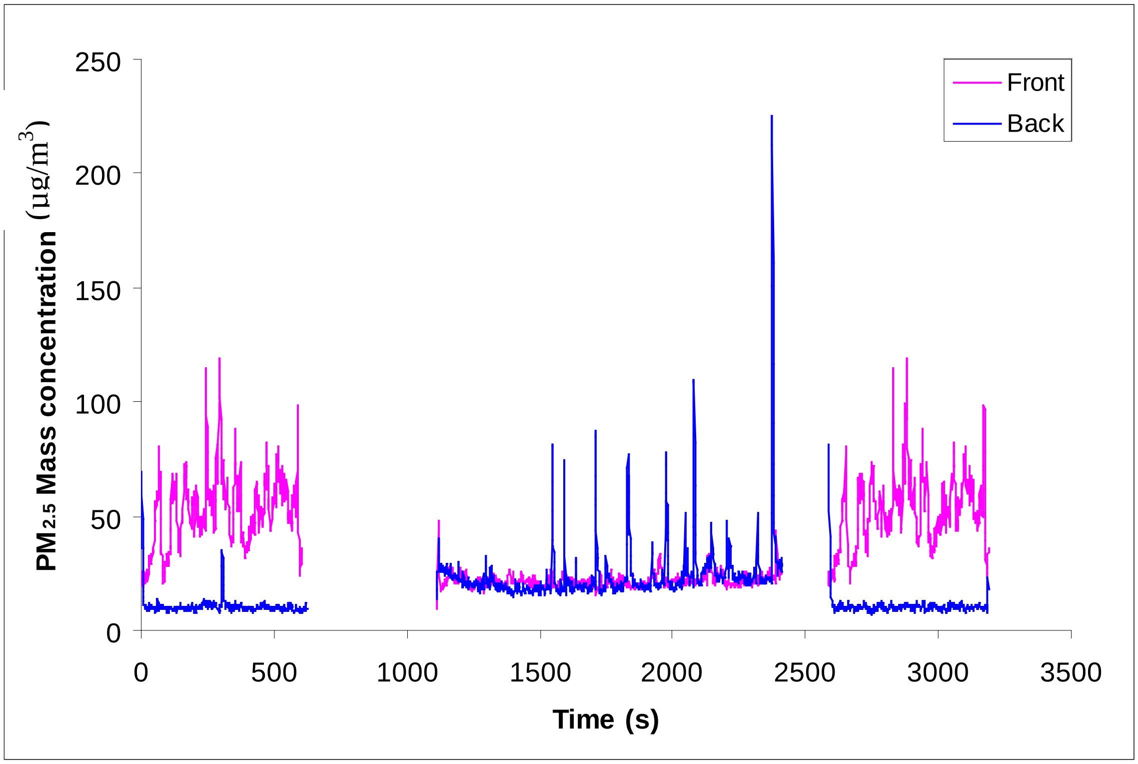


Figure 106 Run 53, DPF windows closed PM2.5 mass concentration, June 5.

Ambient = 46 µg/m3

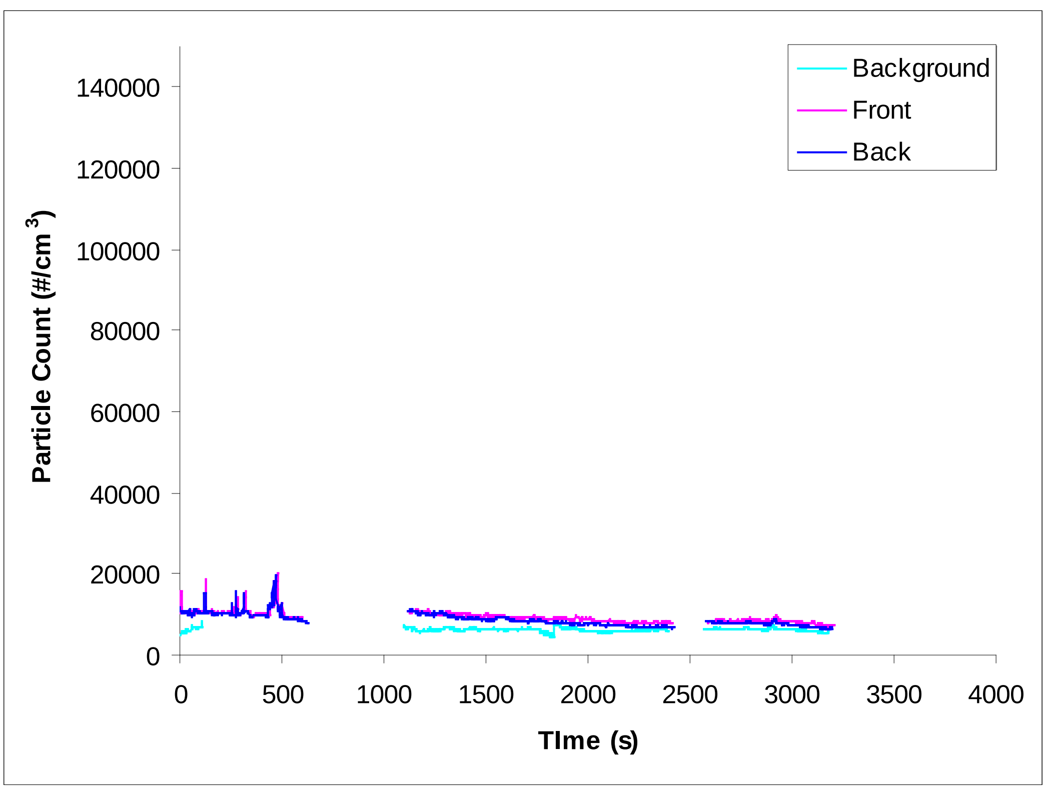


Figure 107 Run 53, DPF windows closed Particle Count, June 5.

Run 54- Unsuccessful Run

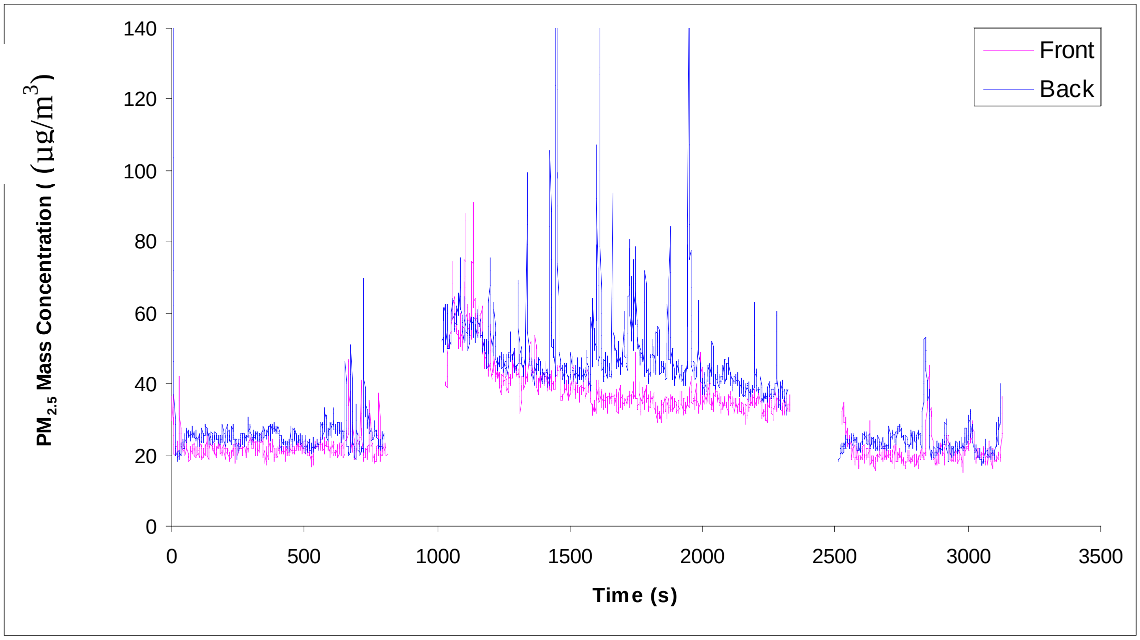


Figure 108 Run 54, DPF & CCF windows closed, June 7.

Initial build up of PM2.5 mass concentration before start of run

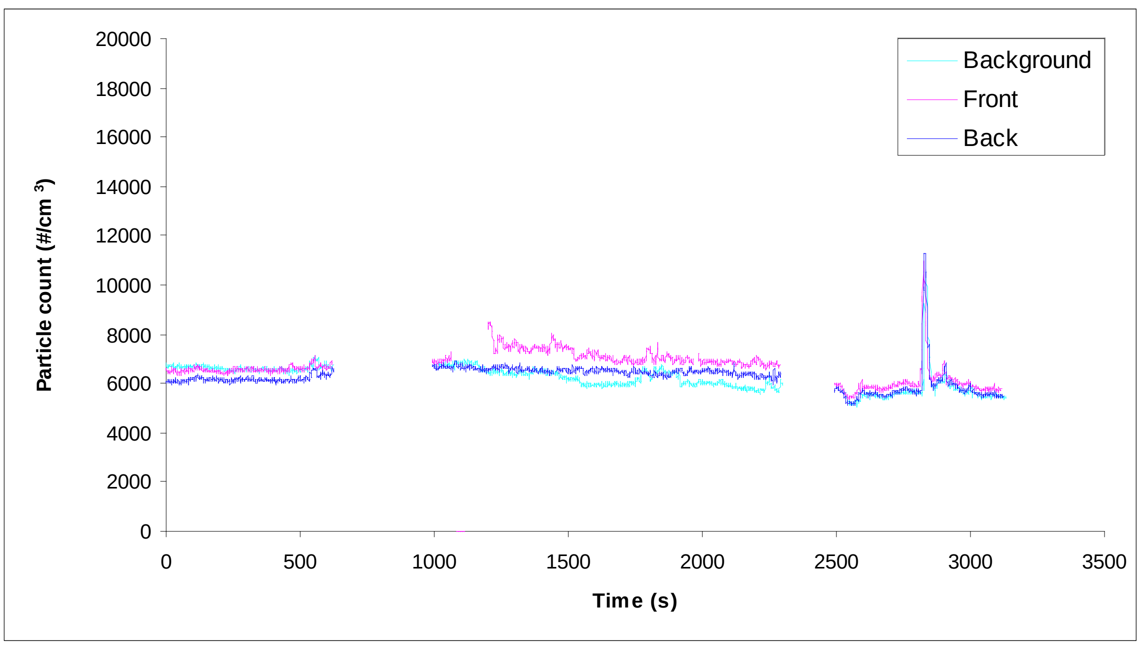


Figure 109 Run 54, DPF & CCF windows closed particle count, June 7.

Run 55

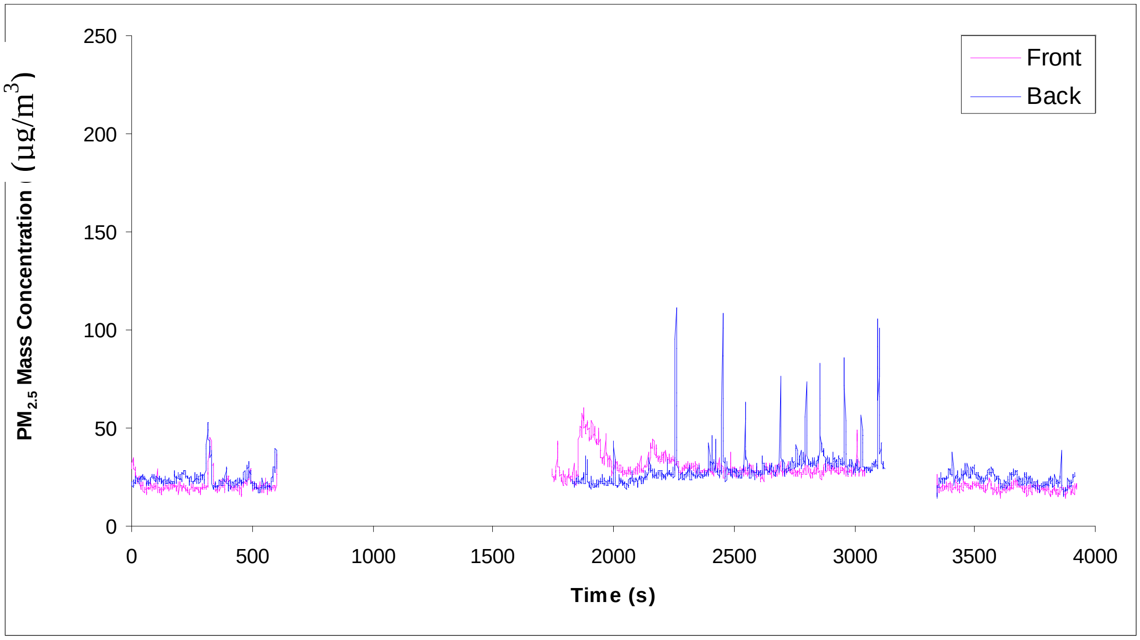


Figure 110 Run 55, DPF & CCF windows closed PM2.5 mass concentration, June 7.
No airing out of bus, intentionally started with stale air in the bus

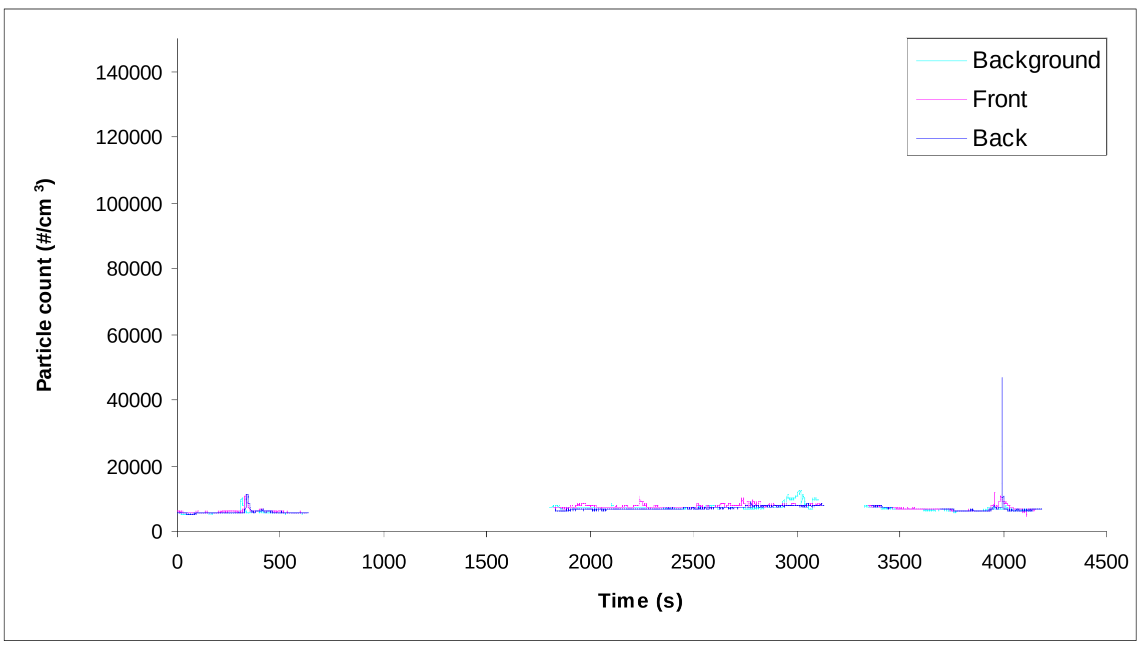


Figure 111 Run 55, DPF & CCF windows closed Particle Count, June 7.

Run 56- Unsuccessful Run

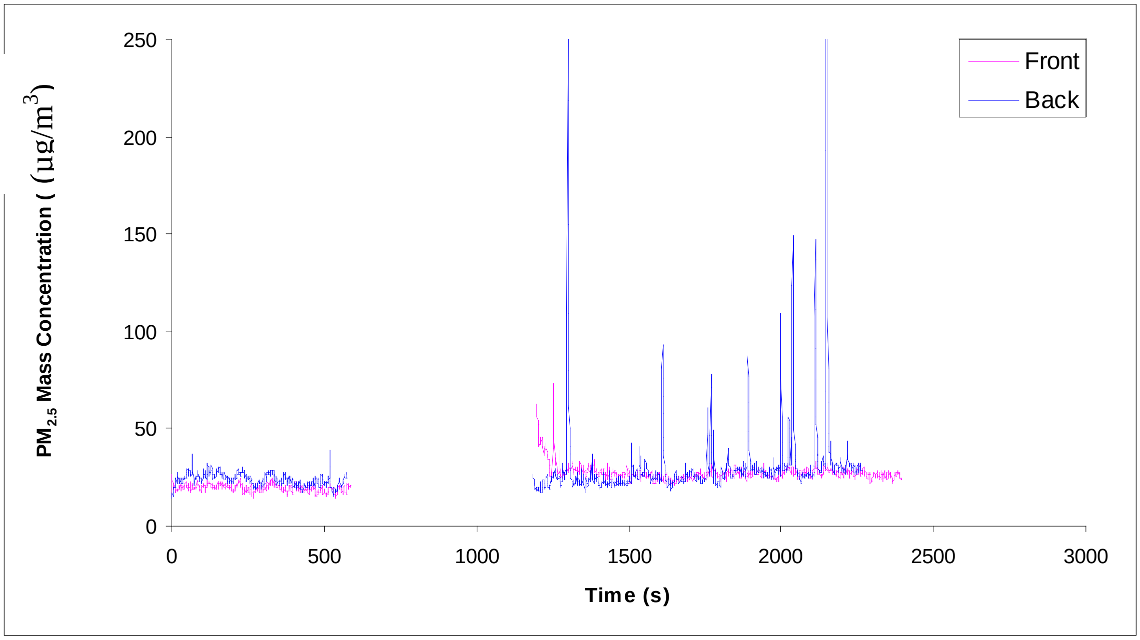


Figure 112 Run 56, DPF & CCF windows closed, June 7.

Ran out of fuel with about 3 minutes left.

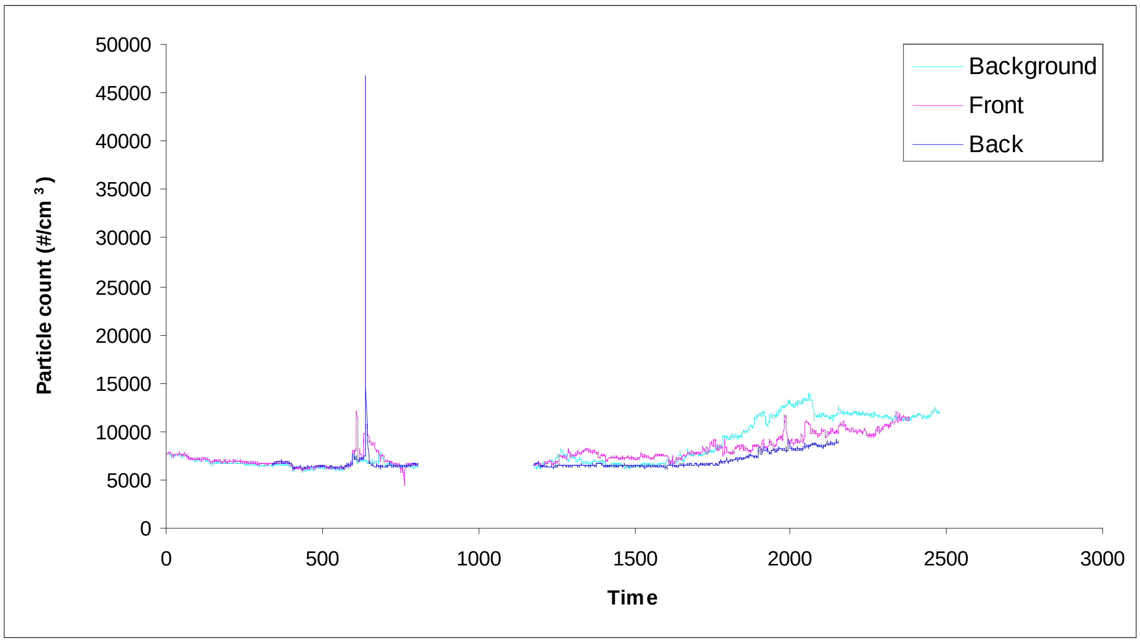


Figure 113 Run 56, DPF & CCF windows closed, June 7.

Run 57

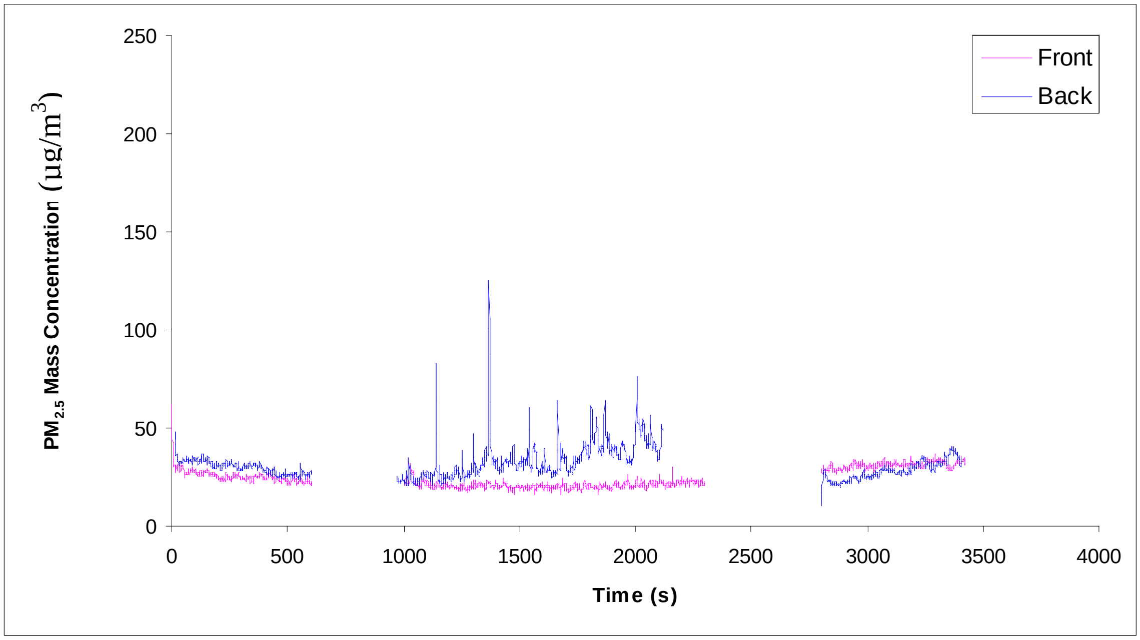


Figure 114 Run 57, DPF & CCF windows closed PM2.5 mass concentration, June 13.

Particle size for Back instrument at Post-run ambient = 1.014 µm.

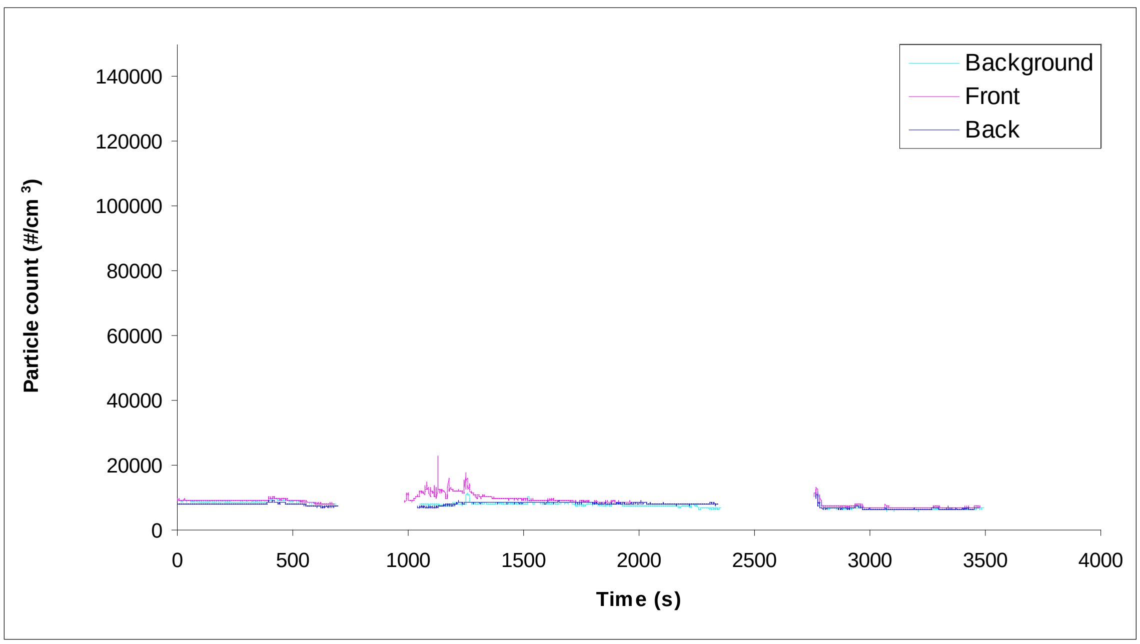


Figure 115 Run 57, DPF & CCF windows closed Particle Count, June 13.

Run 58

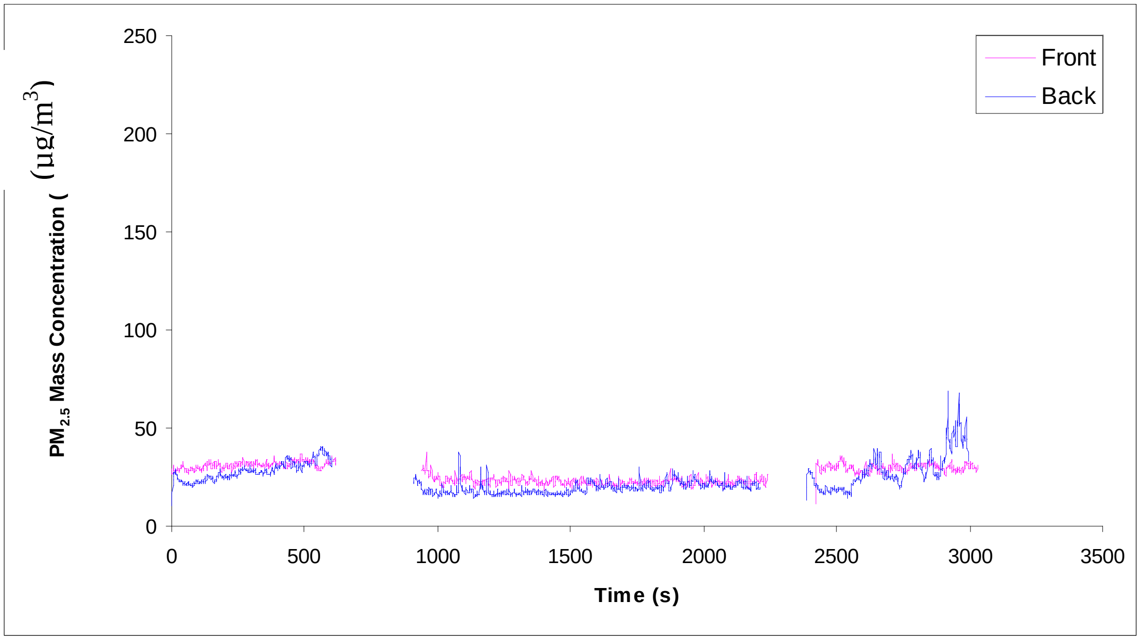


Figure 116 Run 58, DPF & CCF windows closed PM2.5 mass concentration, June 13.

Particle Size: Back Pre-run = 1.014µm, and Back Post = 1.651µm.

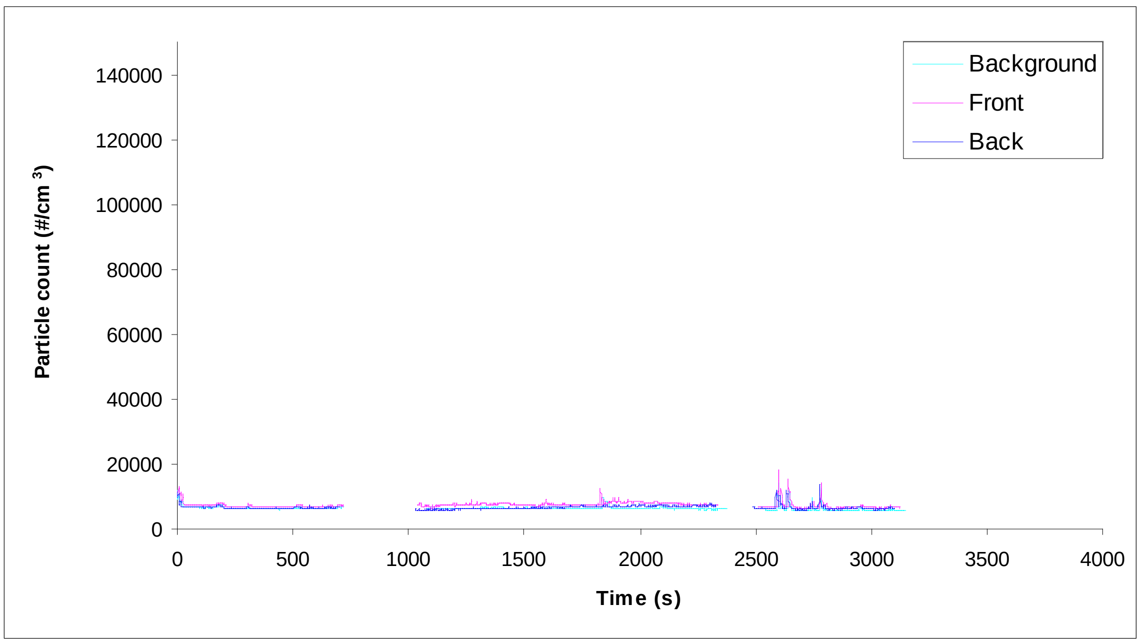


Figure 117 Run 58, DPF & CCF windows closed Particle Count, June 13.

Run 59

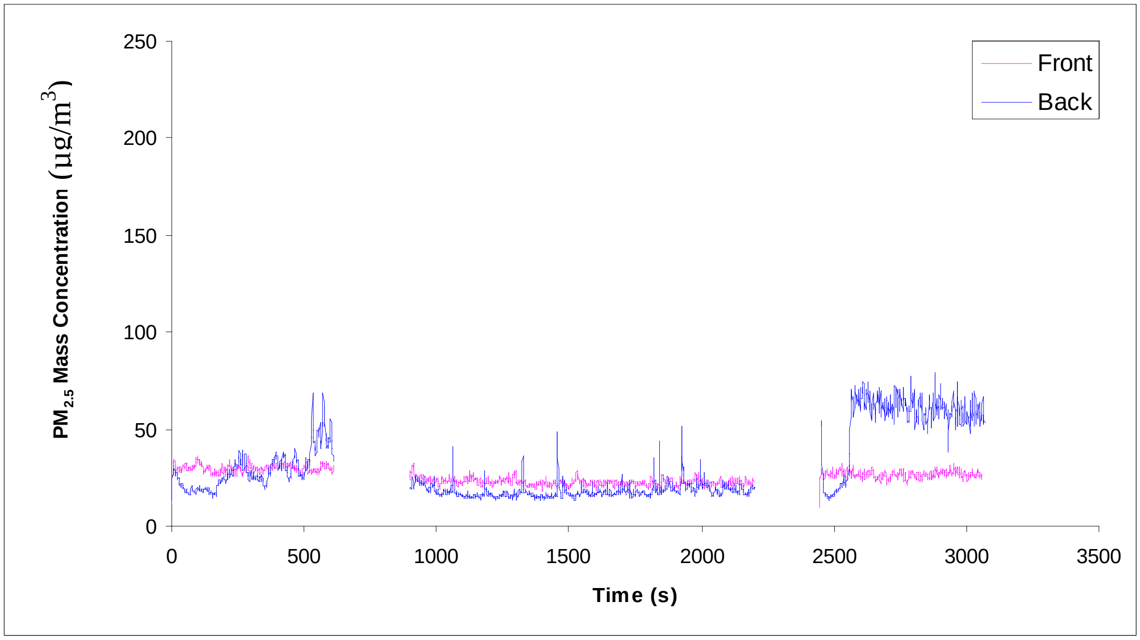


Figure 118 Run 59, DPF & CCF windows closed PM2.5 mass concentration, June 13.
Particle Size: Back Pre=1.651µm, Back Post=3.584µm

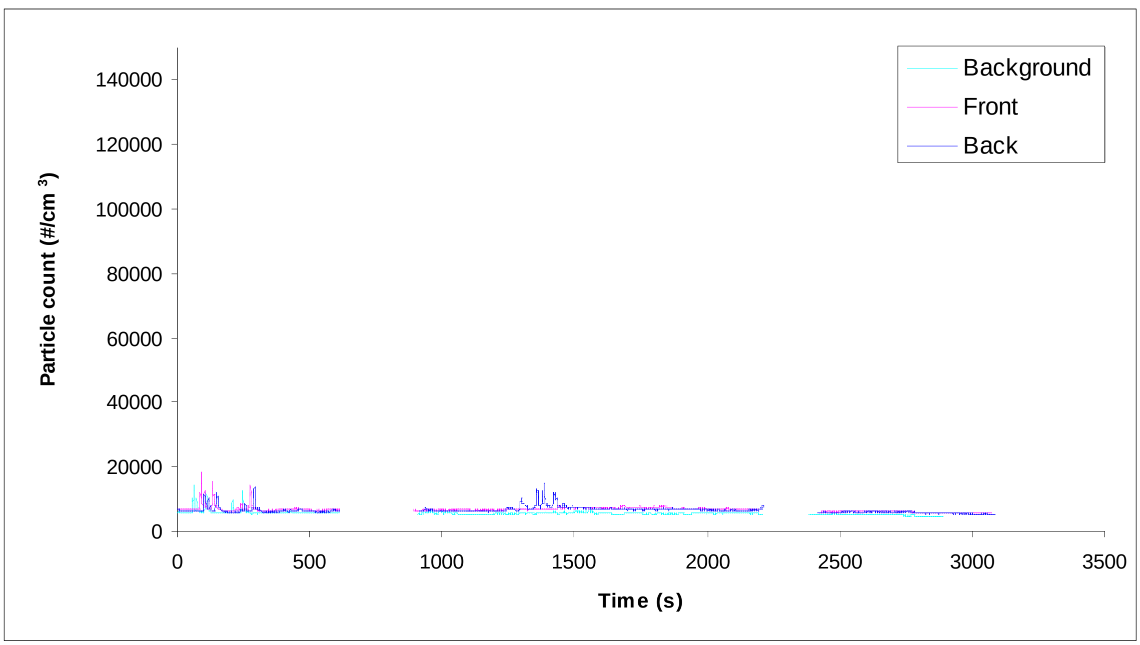


Figure 119 Run 59, DPF & CCF windows closed Particle Count, June 13.

Run 60

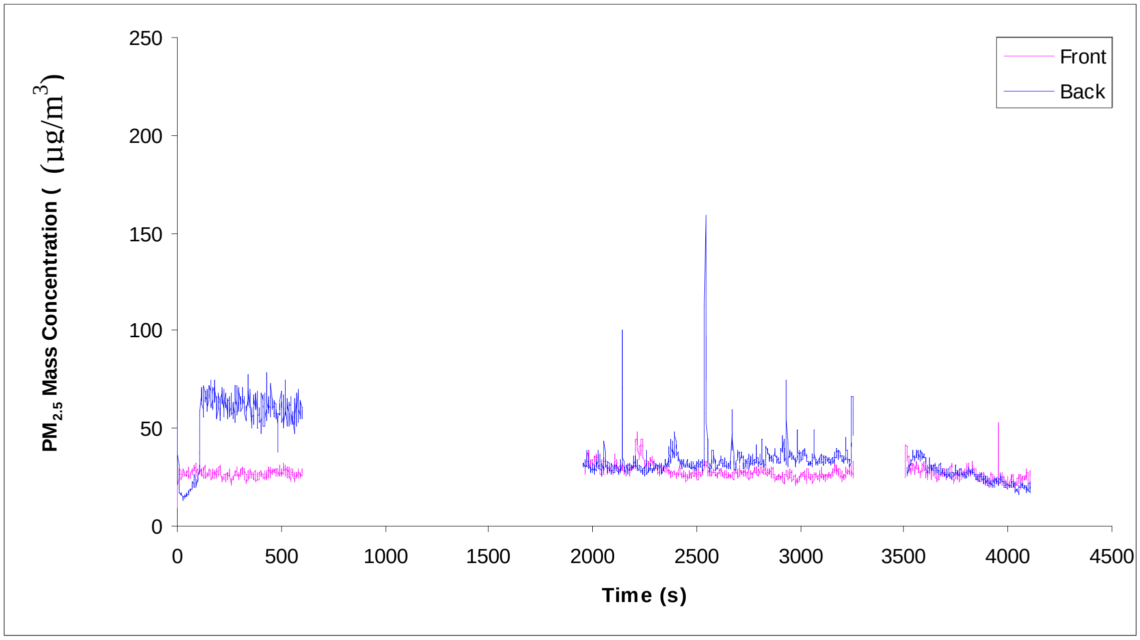


Figure 120 Run 60, DPF windows closed PM2.5 mass concentration, June 13.

Particle size: Back Pre= 3.584µm

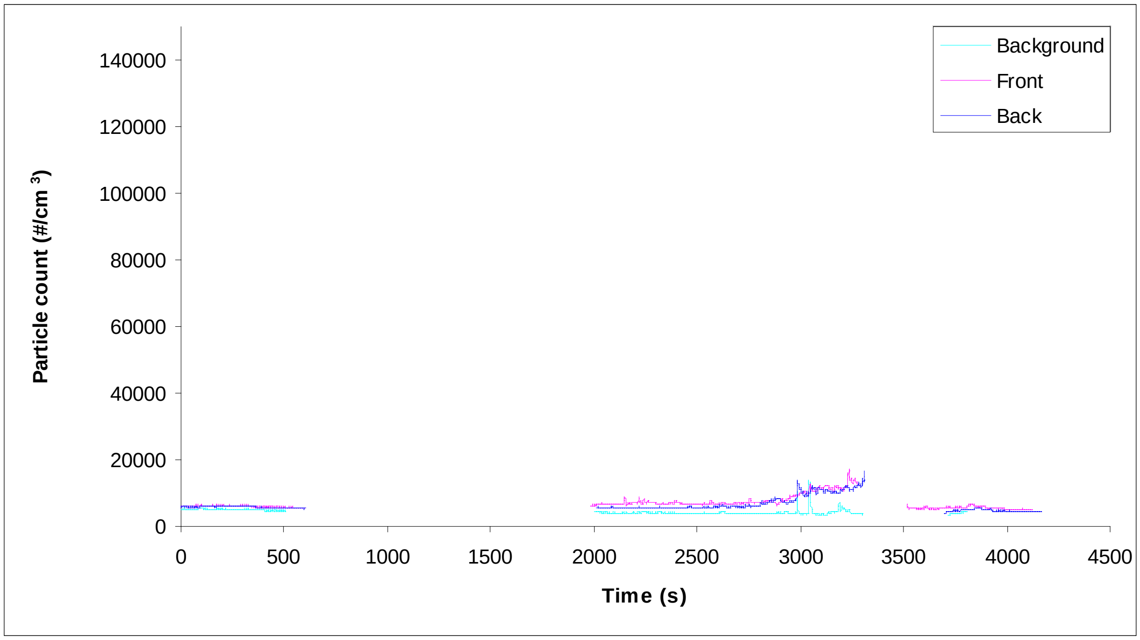


Figure 121 Run 60, DPF windows closed Particle Count, June 13.

Run 61

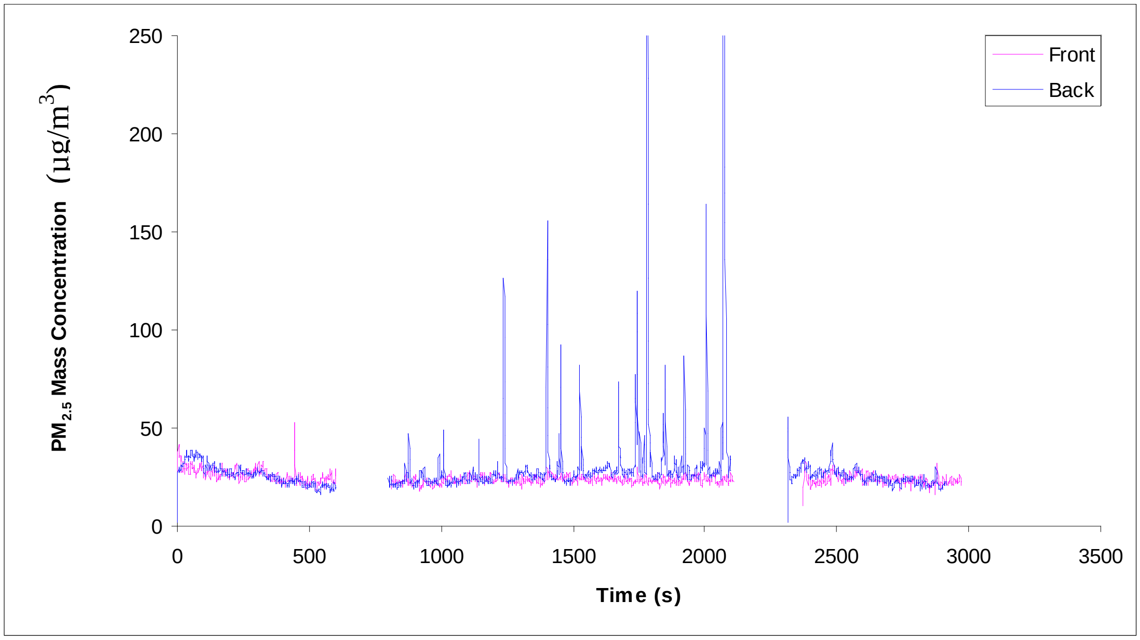


Figure 122 Run 61, DPF windows closed PM2.5 mass concentration, June 13.

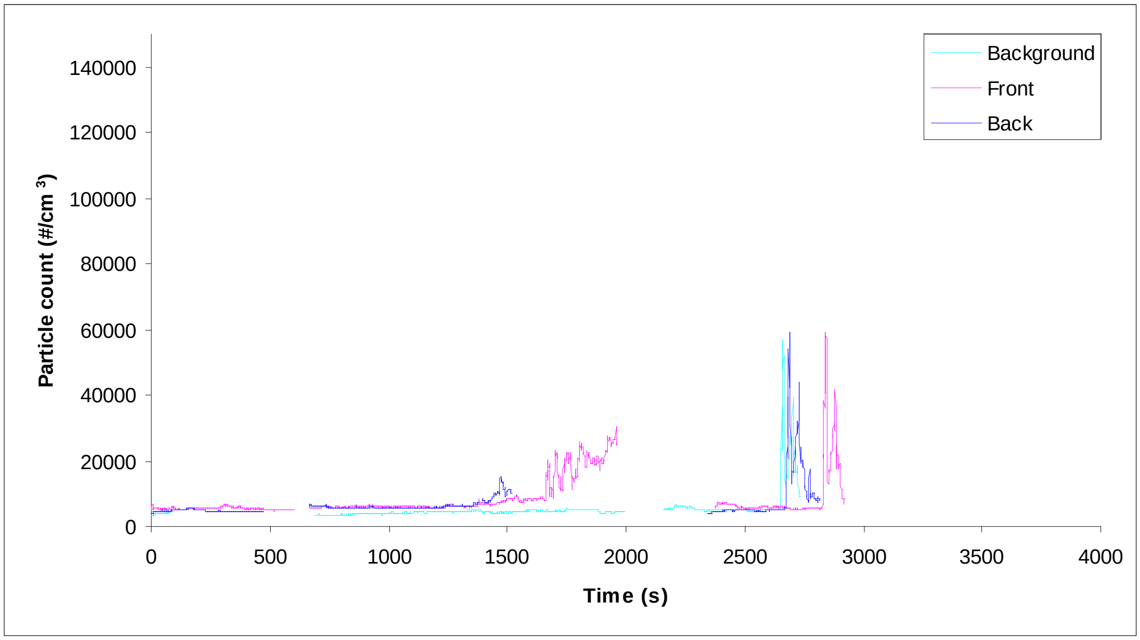


Figure 123 Run 61, DPF windows closed Particle Count, June 13.

The Ptrak located in the back stopped recording at half way of the run.

Run 62

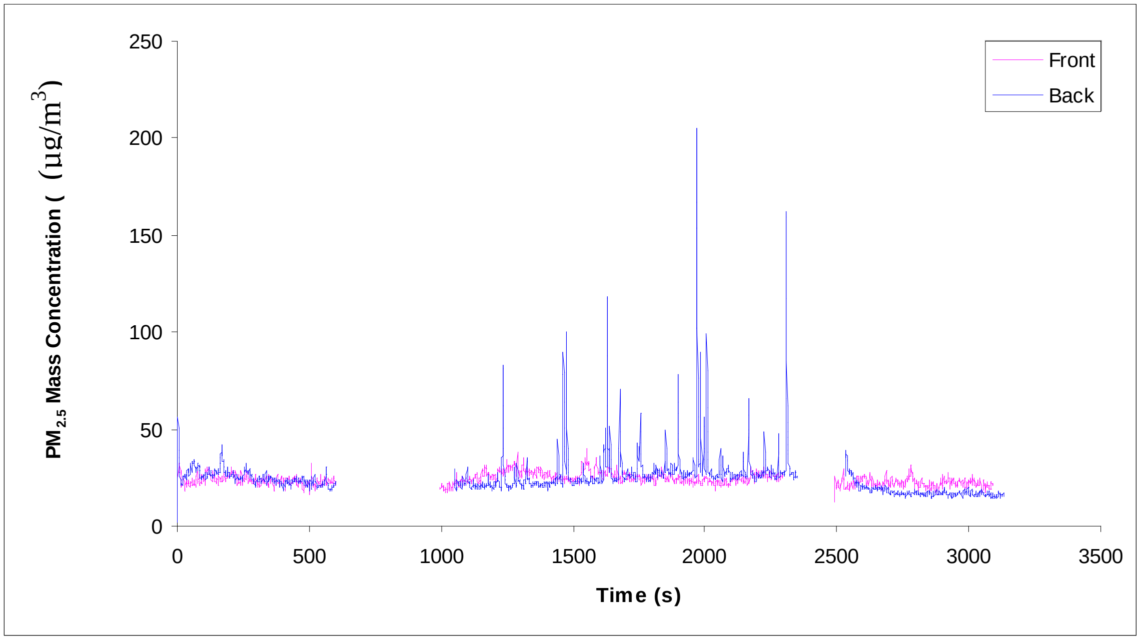


Figure 124 Run 62, DPF windows closed PM2.5 mass concentration, June 13.

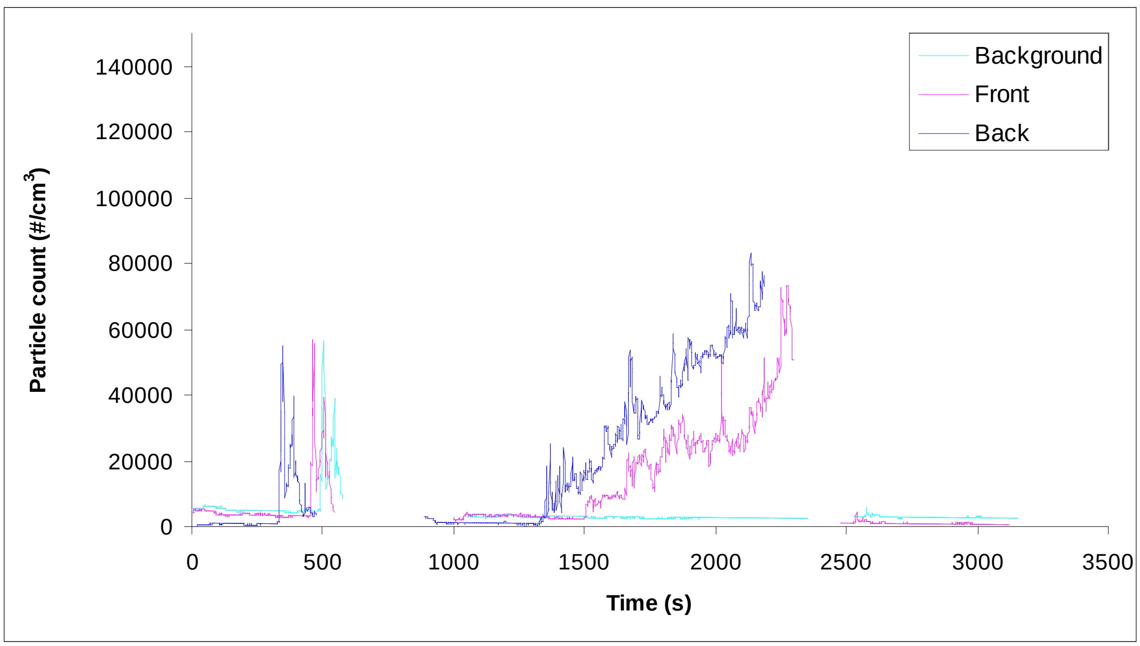


Figure 125 Run 62, DPF windows closed Particle Count, June 13.

Run 63: Unsuccessful Run

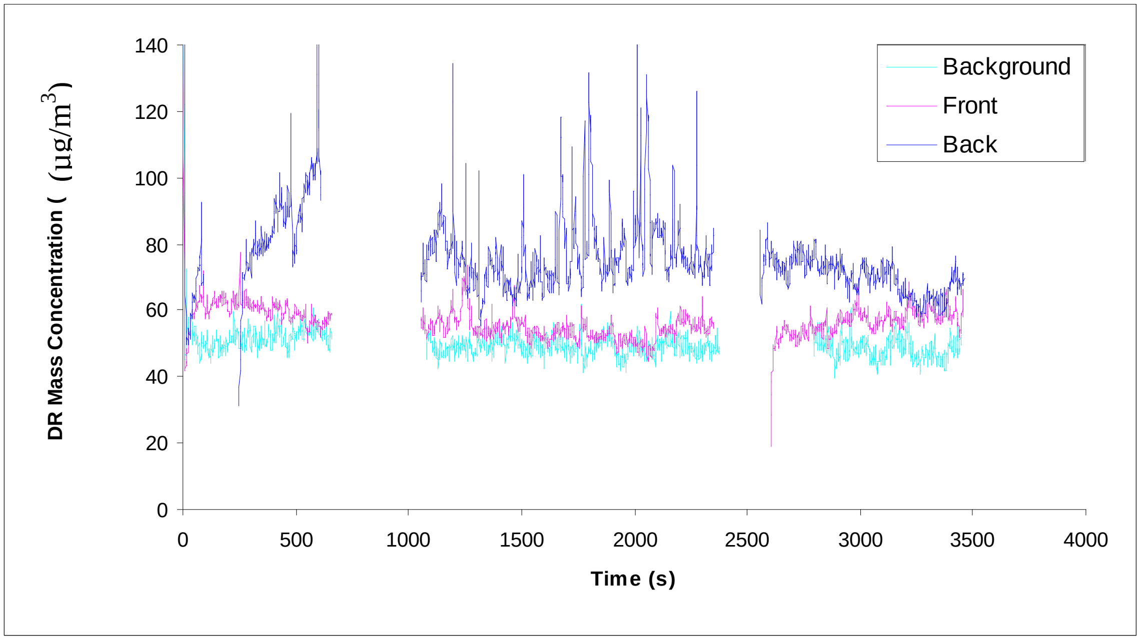


Figure 126 Run 63, Baseline windows closed, June 18.

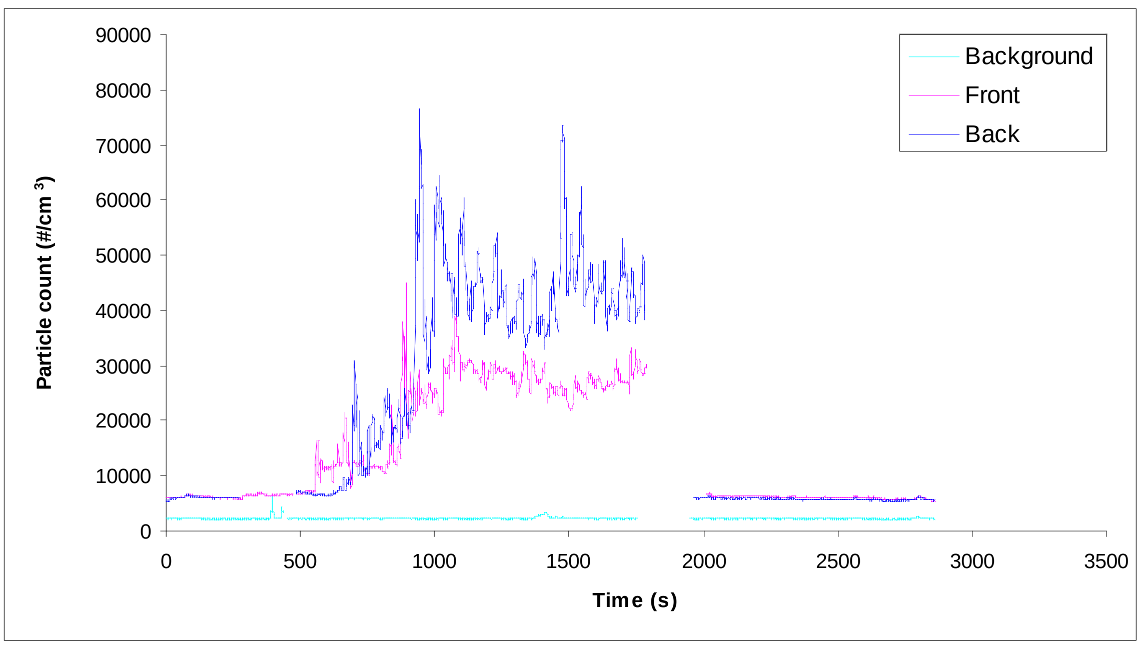


Figure 127 Run 63, Baseline windows closed, June 18.

Run 64

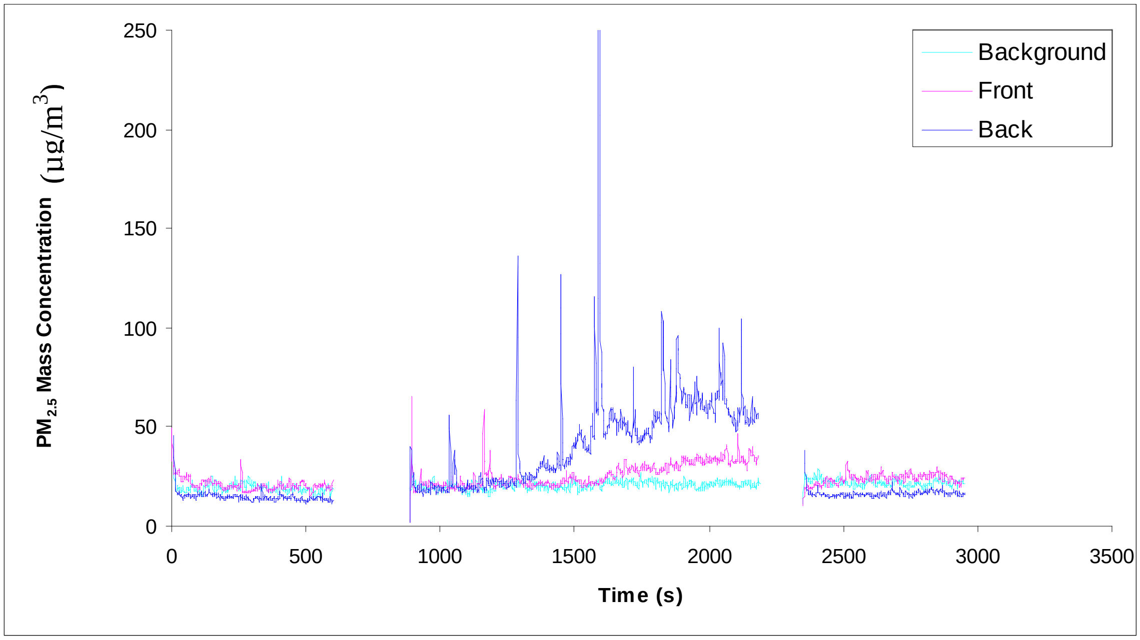


Figure 128 Run 64, CCF windows closed, August 22.

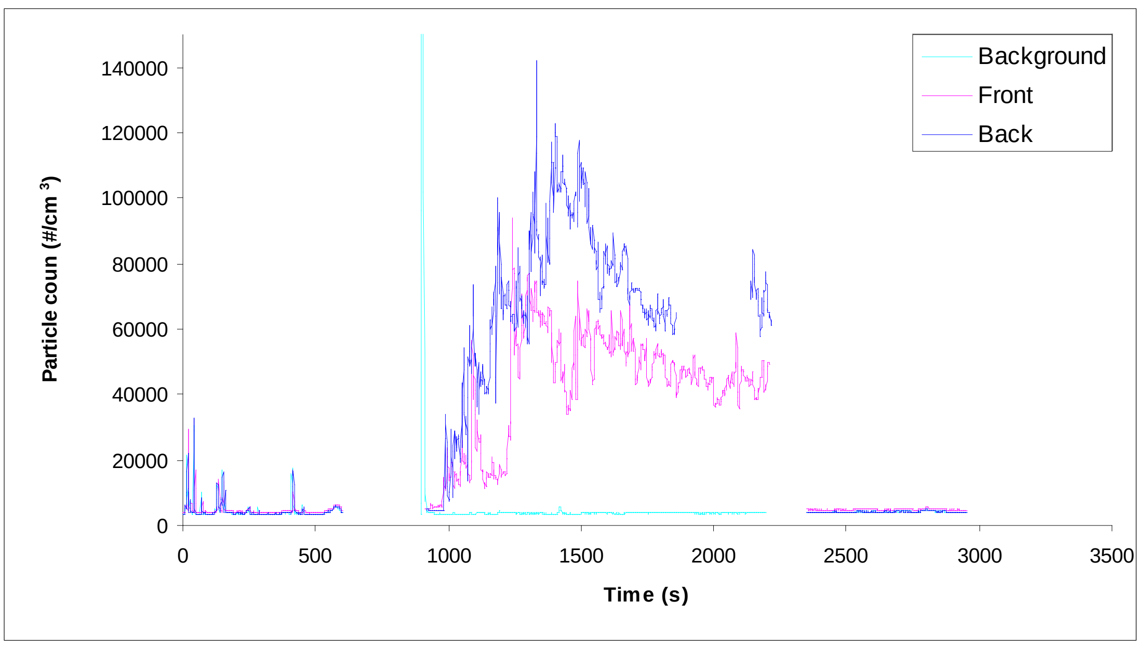


Figure 129 Run 64, CCF windows closed, August 22.

Run 65

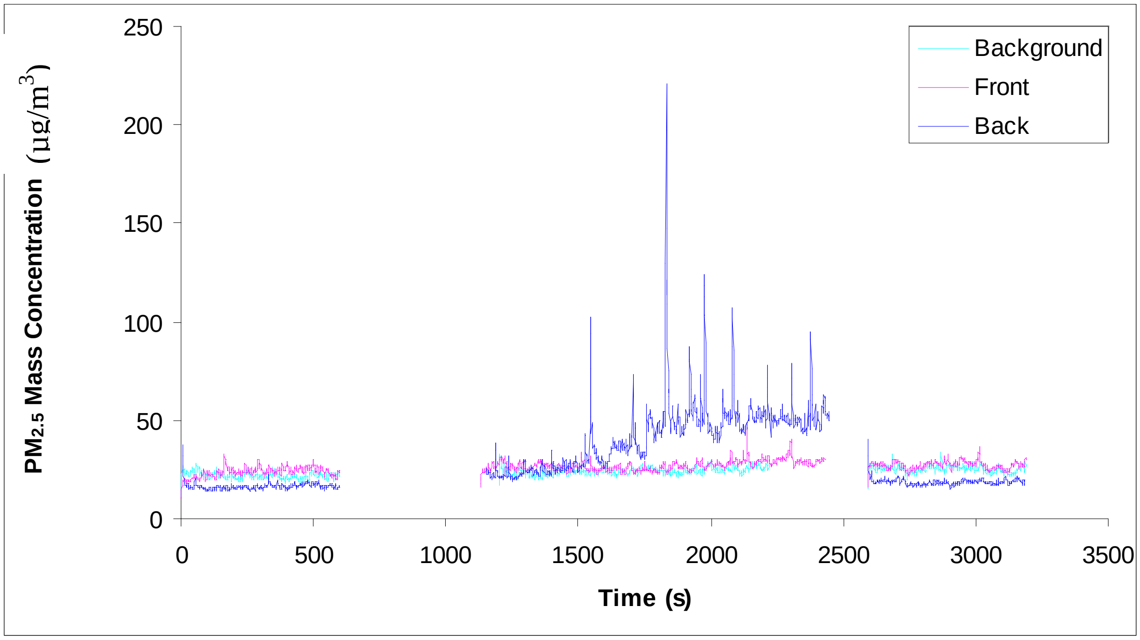


Figure 130 Run 65, CCF windows closed, August 22.

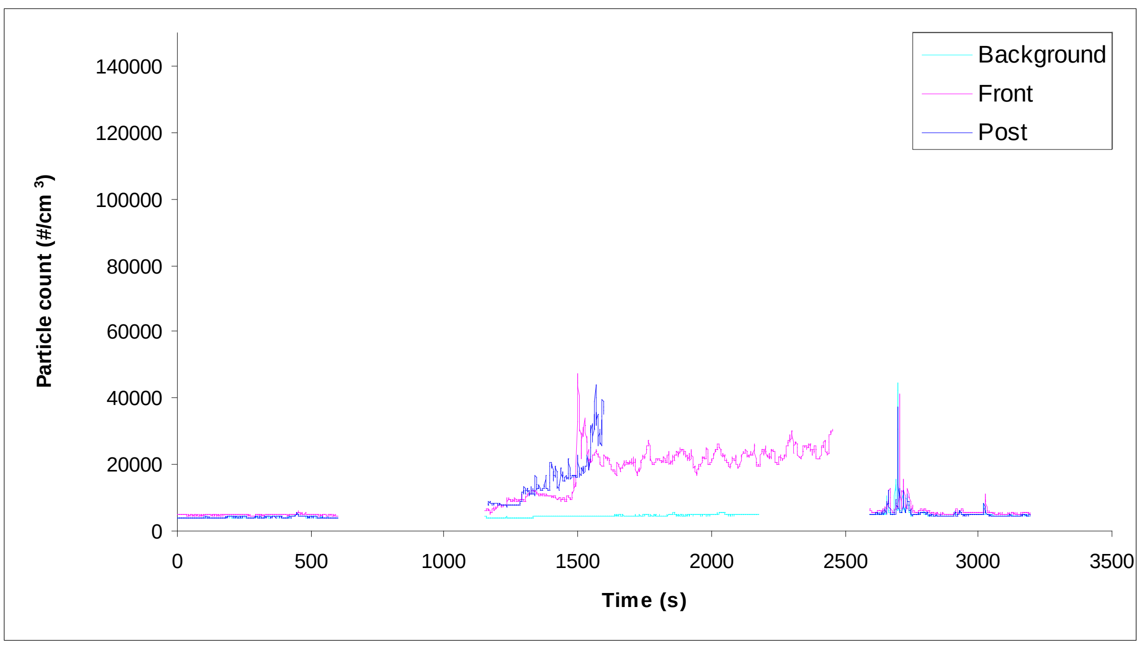


Figure 131 Run 65, CCF windows closed, August 22.

Back particle count lasted less than half run measuring

Run 66

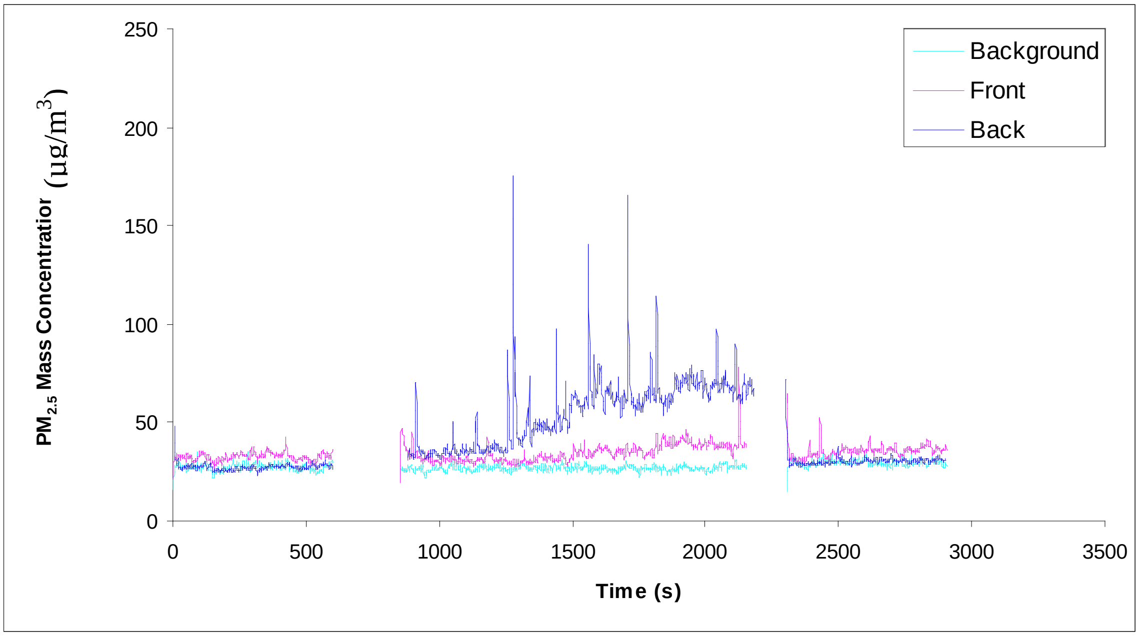


Figure 132 Run 66, CCF windows closed, August 22.

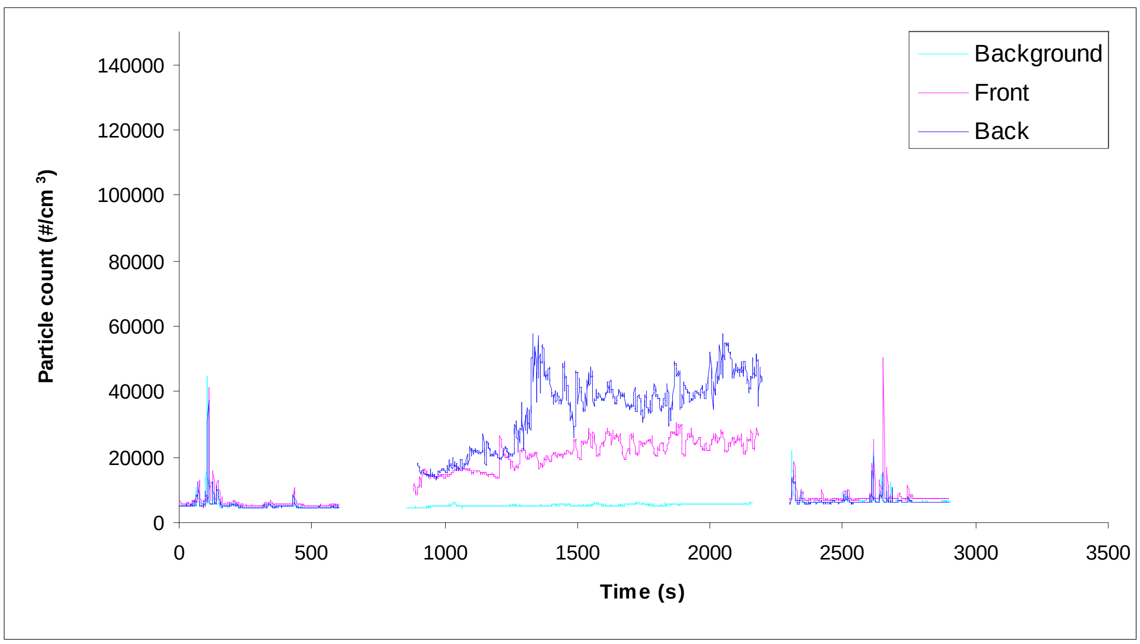


Figure 133 Run 66, CCF windows closed, August 22.

Run 67

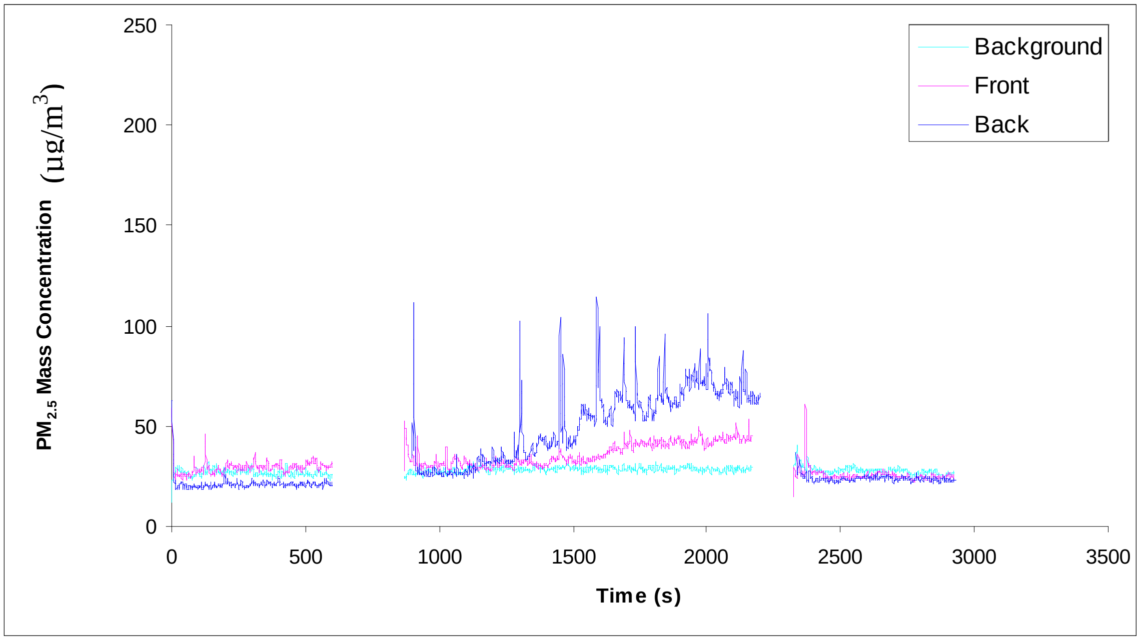


Figure 134 Run 67, Baseline windows closed, August 22.

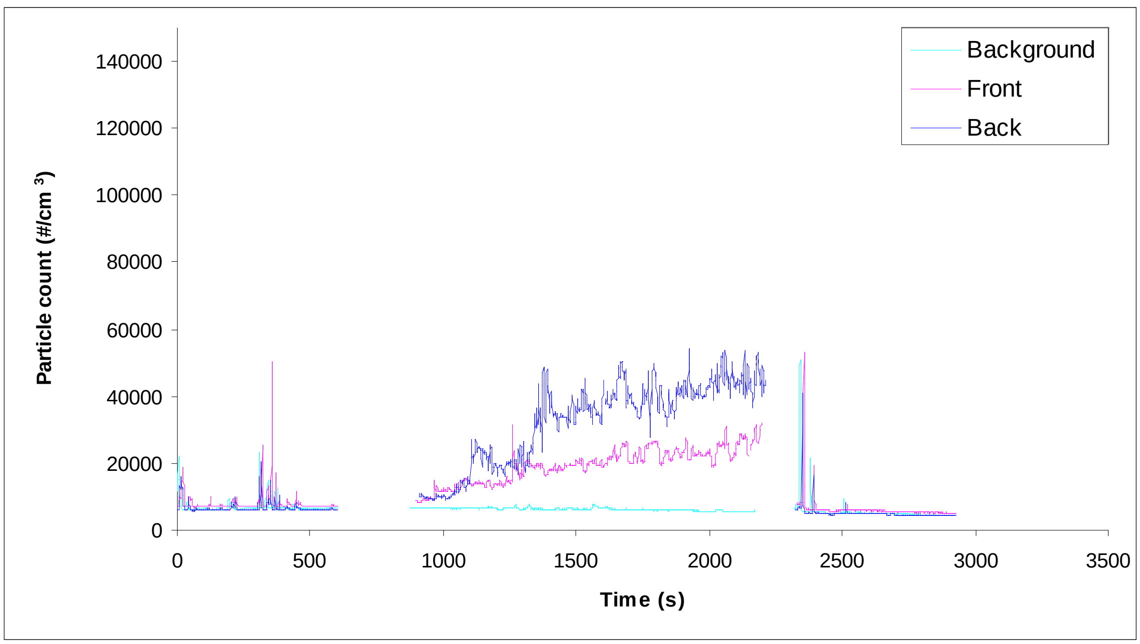


Figure 135 Run 67, Baseline windows closed, August 22.

Run 68

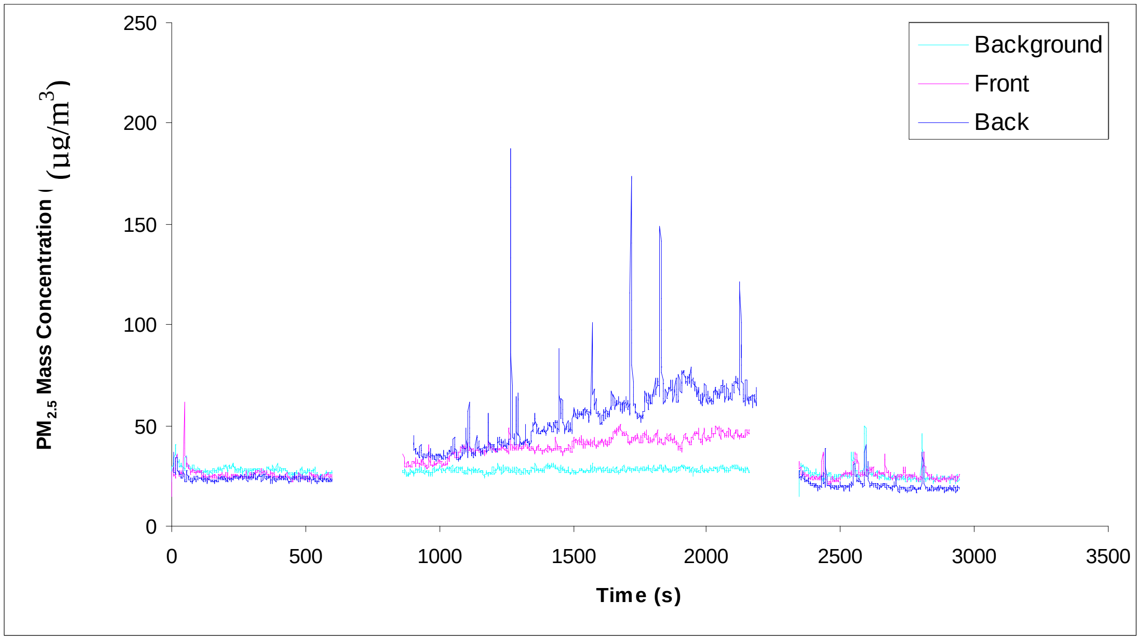


Figure 136 Run 68, Baseline windows closed, August 22.

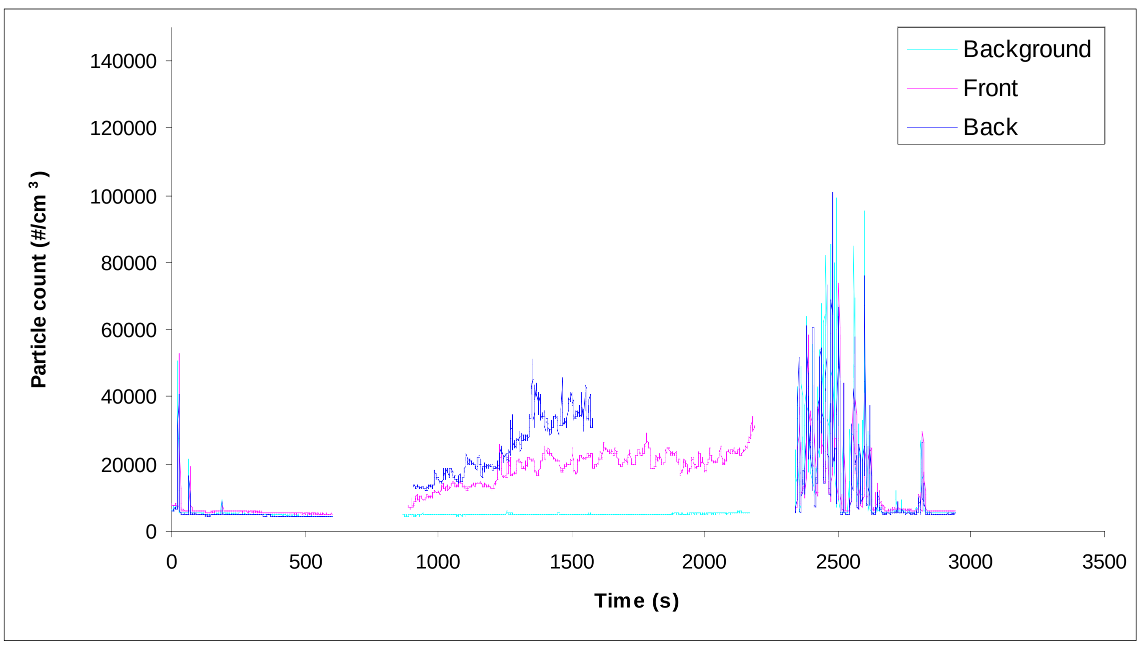


Figure 137 Run 68, Baseline windows closed, August 22.

Run 69

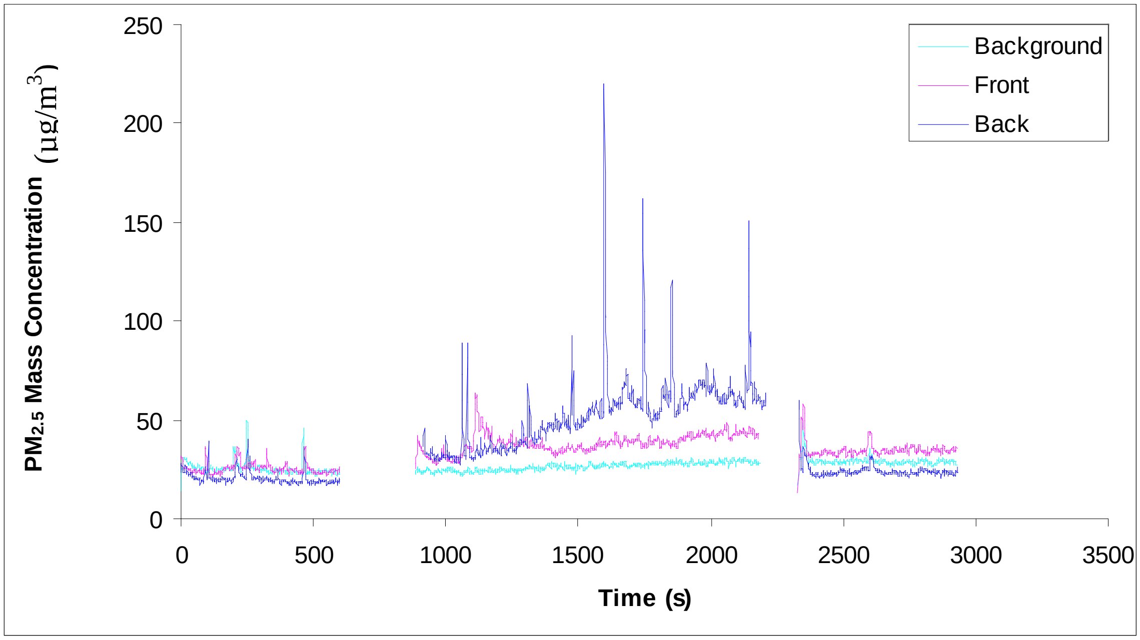


Figure 138 Run 69, Baseline windows closed, August 22.

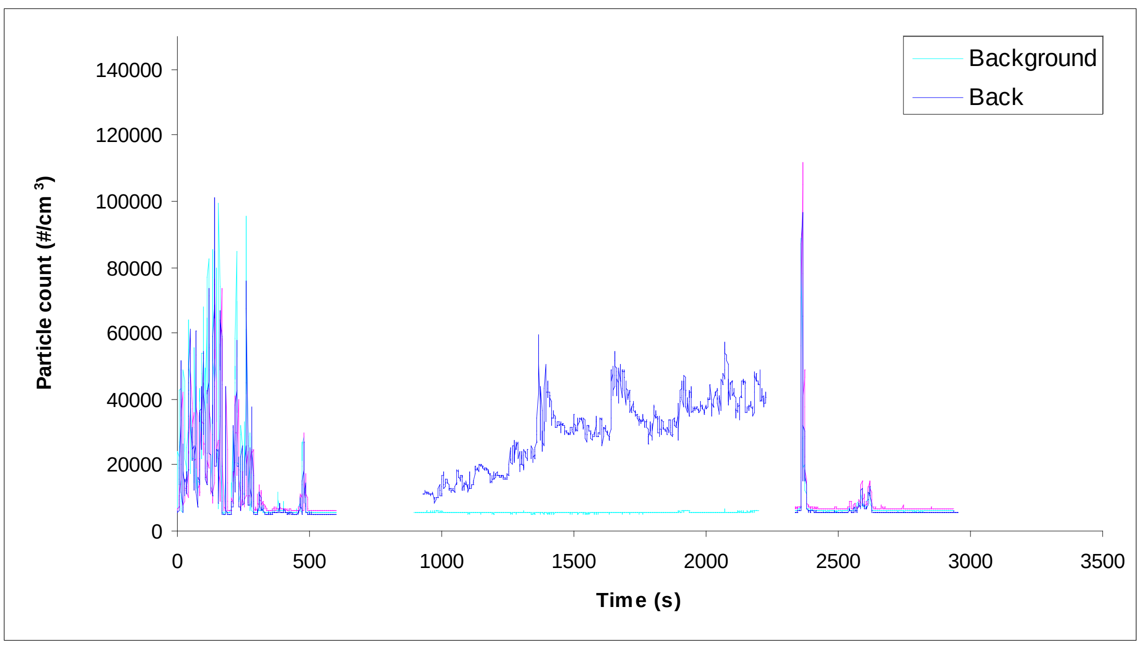


Figure 139 Run 69, Baseline windows closed, August 22.

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Dear Dr. Bonanno:

Following please find my review comments on the "In-Cabin Particulate Matter Quantification and Reduction Strategies Final Report" by Investigators at Rowan University, dated 12/8/2008. The review was conducted focusing on the six charge questions provided by New Jersey Department of Environmental Protection.

Charge Questions:

1. Based on your interpretation of the report, can you identify one or more technologies that would be effective in significantly reducing in-cabin $PM_{2.5}$, and /or Ultrafne Particulate Matter (UFPM)?

Based on data presented in the report, the efficiency of various retrofit technologies to reduce in-cabin $PM_{2.5}$ levels ranked as: DPF+CCVS>DPF>FTF+CCVS. All of these three technologies achieved over 250% $PM_{2.5}$ reduction from the baseline. Neither CCVS nor FTF produced significant reductions on $PM_{2.5}$.

For UFPs, a single CCVS or its combinations with DPF or TFT helped to reduce the in-cabin particle number concentrations. A single DPF or TFT did not contribute significantly to the reduction of UFPs.

For gaseous pollutants, two tailpipe retrofit technologies (DPF and TFT) showed significant reduction.

2. Are there major problems with the data analysis and/or interpretation that require correction before the results of the study are useable?

I have three major concerns about the study design, data analysis and interpretation, and the conclusions made in the study.

First, although the investigators took great care to make sure there was no other major PM source other than the bus own emissions when designed the study, sealing the rear door and windows may not reflect realistic driving conditions under which the bus is used to pick up and drop-off children. Using an over sealed bus also makes it difficult to draw any conclusions on retrofit technologies targeting on tailpipe emissions. In fact, the apparently high efficiency of CCVS and low efficiency of DPF for in-cabin pollutant concentration reduction may be due to the fact that DPF's effects, if any, were diminished by not allowing tailpipe emissions entering the school bus cabin.

Second, the crank system usually emits greater amount of larger particles than ultrafine particles, as the investigators mentioned in the report. Thus, a CCVS is expected to produce more benefits for larger particles, say $PM_{2.5}$, than ultrafines. However, the data reported in this study suggested that CCVS works better to reduce in-cabin ultrafine particles than $PM_{2.5.}$ This is confusing and needs better explanation.

Third, greater variability of $PM_{2.5}$ levels from Run 7F to 19F, and UFPs levels throughout the study were observed, which may weaken the conclusions made in the report. This is especially true for UFPs analysis. Since the engine oil temperature is a major factor affecting UFP emissions, extrapolating the data out of the measured temperature range to draw conclusions is risky. It is better to control the engine oil temperature and reduce its variation before compare the in-cabin pollutant concentrations.

3. On pages 93-95, the investigators perform an ANOVA on the $PM_{2.5}$ and UFPM in- cabin concentrations with and without retrofit devices.

3a. Is this an appropriate statistical test for this data?

ANOVA is a statistical method to analyze if the mean of variables are different. It is an appropriate statistical test for the type of data reported in the current study. However, to use ANOVA, several assumptions should be satisfied: (1) normality of the data (2) variances are equal, and (3) independence of the data points. If more than one of these assumptions is violated, transformation is needed or non-parametric test has to be used. So in this report the assumptions should be checked and stated before using ANOVA.

3b. If yes, are the investigators' conclusions based on the results of this test appropriate? See Conclusion #5, i.e., that the crankcase ventilation system (CCVS) alone does not reduce $PM_{2.5}$ based on the results of the ANOVA analysis

As mentioned in 3a, although ANOVA is appropriate for this type of data analysis, it is important to check for the three assumptions that ANOVA requires. It is not clear from the report whether these assumptions hold for the data used in achieving the conclusions regarding CCVS reducing $PM_{2.5}$ levels.

RE: High Ambient $PM_{2.5}$ Measurements: see Figure 47, page 77
4a. During runs 7F-19F, is it reasonable that the ambient measurements were higher than the in-bus measurements?

This may be due to the over sealed study design. When there is no significant PM sources penetrate into the school bus cabin, the PM concentrations inside the bus could decay due to particle deposition onto interior surfaces. Thus, for a well-sealed bus, it is possible for in-bus concentrations to be lower than the ambient concentrations.

4b. In your opinion, does this reflect actual conditions or to what extent do you think that this may reflect inaccuracies in data handling or in the measurement of either the ambient particulates or the in-bus particulates?

This may not reflect actual conditions when a regular (not sealed) bus was driven on roadways. It has little to do with inaccuracies in data handling or in the measurement of either the ambient or in-bus particulates. Instead, it came from a study design issue where a usually leaky bus was over sealed.

4c. Additionally, since runs 7F, 11F and 12F had extremely high ambient measurements resulting in large negative values for in-bus particulates when the ambient values are subtracted out, would this be justification to not use those runs in analysis/conclusions?

Data from these runs should be eliminated in any analysis regarding retrofit technology efficiency. As mentioned above, this phenomenon is likely due to particle deposition inside the bus under well-sealed conditions not a benefit from retrofit technologies.

4d. In your opinion, is it appropriate to conclude that a technology (or combination of technologies) was more effective because that condition produced a more negative value when the high ambient value was subtracted out?

It depends. If all the runs were conduced under the same ambient condition, following the same protocol, then such conclusion can be made. However, the data suggest a huge variability in both ambient and in-bus particulate concentration levels. Thus, making conclusions simply based on more negative values is risky.

5. Is it reasonable that while the DPF alone did not impact ultrafine particulate matter (UFPM) and possibly increased them, and the CCVS reduced UFPM somewhat, that the combination of DPF and CCVS almost completely eliminates UFPM?

It is reasonable that the efficiency of DPF+CCVS was much higher than any single one if the following assumptions are met:

(1) There were much more large size particles than small size particles emitted from the crankcase vent.
(2) The crankcase emission is the major source of in-cabin UFPs.
(3) CCVS only worked to remove large size particles and turn them into smaller size particle.
(4) DPF only worked to remove smaller size particles.

If all above assumptions were met, we could explain the result as follow:

(1) Since the in-cabin UFPs mainly came from the crankcase emission, the tailpipe retrofit technology did not work efficiently to reduce UFPs. However, due to the over sealed study design; it is difficulty to make any conclusions on the tailpipe retrofit technology based on data collected in this study.
(2) CCVS removes large size particles so that the result of single CCVS application showed some efficiency.
(3) Since large size particles were more than small size in crankcase emission and CCVS turned them into smaller size, most of the particulate matters became smaller size particles which could be removed by DPF.
(4) The small size particles in the tailpipes were removed efficiently by DPF.

If any of the assumptions could not be satisfied, it will be not reasonable to expect such high reduction of UFPs from CCVS+DPF, while either single technology did not work very well.

6. The study claims that the use of a CCVS alone reduces UFPM and not $PM_{2.5}$. Is that reasonable in your opinion?

As mentioned in question No. 2, one of my major concerns is the conclusion on CCVS on reducing UFPM but not $PM_{2.5}$. UFPM tested in this study is the number concentration of ultrafine particles whose diameters range from 0.02 µm ~ 1 µm. $PM_{2.5}$ is the mass concentration of fine particles with diameters less than 2.5 µm. For vehicular emitted particles, over 90% by number was in the UFP size range, but their mass concentrations were quite low because of the small size. UFPM number concentrations and PM2.5 mass concentrations usually don't correlate. This, it is possible for one technology to remove a large amount of UFPs but not reduce the mass concentration of $PM_{2.5}$. However, it is well-know, as the investigators also mentioned in the report, that the crank system usually emits greater amount of larger particles than UFPM. Thus, a CCVS is expected to produce more benefits for larger particles, say $PM_{2.5}$, than ultrafines. However, the data reported in this study suggested that CCVS works better to reduce in-cabin UFPM than $PM_{2.5}$. In addition, the investigators stated that the sizes of the particles in the bus equipped with CCVS were smaller than the baseline (page 91), and concluded that CCVS had greatly reduced the fraction of larger particles from the crankcase vent, rather than small size particles. Overall, the investigators' conclusions on CCVS are confusing and needs better explanation.

Thank you for providing me with this opportunity to review the final report. Should you have any questions, please do not hesitate to contact me by phone: 310-923-6932 or email: yifang.zhu@tamuk.edu.

Sincerely yours,

Yifang Zhu
Assistant Professor

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I find the experimental measurements disappointing. The instruments chosen are not the most accurate and precise that could have been used. They could have used batteries and an inverter to power a much better quality CPC and a nephelometer that had better response below 0.1 μm. If they had been on a bus with people riding on it or where making personal measurements, their choice of measurement systems would make sense, but given the nature of the study, the lack of best practice instruments is disappointing. They have missed an opportunity to make a real contribution to the problem. Since diesel has a peak around 70 nm, they are underestimating the PM2.5 mass with the DataRAM. Since 70 nm particles deposit much more effectively than 0.25 μm particles, lack of data in this size range is a significant deficiency. An instrument like an FMPS would have proven much more useful because they could get high time resolution measurements from 5.6 to 560 nm.

They also substantially underestimate the ultrafine particles (<20nm) with the PTrak. They state "This study illustrates that the P-Trak is a good instrument for measuring particulates that have aged." However, their set-up is such that the particles have not had time to age and thus, they are missing the large number of 10 to 20 nm particles. Even the 3022 that was used in comparison in the quoted study is an old design instrument. I would have looked at a 3781 with a 50% cut point of 6 nm to properly characterize the ultrafine particle number concentrations.

I have never used the DataRAM-4 monitors. These are the next generation monitors after the DataRAM 2000s. We have the personal DataRAM 1000 and 1200s, which are meant to be worn. The DataRAM-4 is a portable but not a personal monitor. Regardless, I expect that some of the same limitations will hold. The investigators did a decent job characterizing the instruments before the initial study at different concentrations using a like source of particles. However, you see that the coefficient of variation (Tables 3 and 4) is fairly high, especially for low concentrations. Also, there appears to be a predictable bias among the monitors (e.g., Fig 22 and calibration curves).

As far as I can tell from the report, the calibration curves that were developed were not used to correct the data from the monitors, even though the slopes and intercepts are not close to 1 and 0, respectively. Also, the monitors were recalibrated before the final study so the calibration curves would not be applicable. No collocation experiment was conducted following the recalibration, unless I missed something. Therefore, the reported results likely have a monitor bias. This could be why the ambient monitor is higher than the monitors in the bus. However, there is also the issue of pollutants building up in the vicinity of the track from the exhaust and resuspended dust (a bigger issue for the initial study where the ambient measurement was in the center of the track).

I did not see calibration curves for the gaseous species using the SEMTECH-D gas analyzer. We have no information on its accuracy and precision.

The work they did to seal the leaks may make the bus they used unrepresentative of the bus fleet. Are most buses really sealed properly? Thus, in actual practice, the exposure would be much higher.

I found the beginning of the report hard to read since they outlined the experimental design with the names of the instruments before defining the nature of the instruments. I knew what they were, but I suspect that many less versed in particle measurements will have a tough time with that section.

I am not sure why they made runs with the windows open. One would have expected dilution and infiltration of the ambient aerosol. Why seal the doors and then open the windows? Those runs could have been used more profitably.

They have evaluated the technology on a bus. However, I wonder how well the retrofits are installed on a fleet and how well they are maintained. Such information was beyond the scope of this study, but clearly there is a need to look at how these technologies work in real applications and over time.

A reference they should review is

Title: Predicting airborne particle levels aboard Washington State school buses
Author(s): Adar SD, Davey M, Sullivan JR, et al.
Source: ATMOSPHERIC ENVIRONMENT Volume: 42 Issue: 33 Pages: 7590-7599
Published: OCT 2008

Understanding the Results of an Emissions Control School Bus Study and Health Risk Assessment

This document was prepared by the New Jersey Department of Environmental Protection
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Why did the NJDEP conduct an emissions control study of diesel school buses?

The Diesel Retrofit Law, signed in September 2005, establishes the framework for reducing diesel exhaust fine particles ($PM_{2.5}$) from certain diesel powered vehicles including school buses. The law requires that all school bus owners install technologies to reduce fine particle emissions from the engine crankcase (where the major engine components of a vehicle are housed), with a closed crankcase ventilation system or CCVS. The CCVS is designed to capture and filter diesel engine compartment vent emissions and redirect them into the combustion process.

The Diesel Retrofit Law required the New Jersey Department of Environmental Protection (NJDEP) to undertake a study and do a health risk assessment to determine whether in-cabin exposure could be further reduced by tailpipe controls, such as a diesel particulate filter or a flow through filter. If so, the Department could require that tailpipe controls be installed on school buses in addition to the already required CCVS.

Why was a CCVS required on diesel school buses?

On existing school buses and many other diesel vehicles, gases and fine particles that escape from the crankcase during the combustion process (often called blow-by gases) are directed to the outside by a vent that runs under the bus and comes out near the front door. It is believed that these emissions enter the cabin of the school bus each time the front doors are opened and closed, and possibly when bus windows were open, thus increasing exposure to potentially dangerous toxins. A CCVS prevents emissions from the engine compartment from entering the cabin.

What studies were conducted?

There were two studies done by Rowan University. The results of the first study which was conducted in 2007 could not be used because upon review, it was learned that the bus used in the study was damaged and would not have passed the required NJ Motor Vehicle Commission's school bus inspection. In particular, the seals around the doors were faulty allowing particulates from the outside diesel exhaust to enter the bus. A second study using an undamaged bus was conducted in 2008, and its data have been accepted.

What were the results of the second study?

The second study concluded that equipping school buses with CCVS's and ensuring that all school buses meet New Jersey Motor Vehicle Commission's school bus inspection requirements, including a properly sealed school bus cabin, substantially reduces the levels of fine particles to below health standards used by the Department in evaluating air pollution exposure risks. In addition, the NJDEP concluded from the second study that equipping diesel school buses with tailpipe control devices such as a diesel particulate filter would not provide a significant further reduction in health risks associated with exposure to fine particles in the cabin of a school bus.

How do NJ's school bus laws help reduce emissions from entering the cabin of school buses?

New Jersey's school bus inspection system and mandatory bus retirement law (12 years for most school buses) are important for ensuring that the school bus fleet is in good condition. Compliance with the New Jersey Motor Vehicle Commission's Inspection Standards, particularly with regard to properly sealed front/back doors, engine compartment and exhaust system, and proper installation of a CCVS substantially reduces in-cabin fine particles and ultra fine particles levels. For information on the New Jersey Motor Vehicle Commission program, visit: state.nj.us/mvc/inspections/schoolbus.htm

What is particulate matter?

Particulate matter is a complex mixture of tiny particles that consist of dry solid fragments, solid cores with liquid coatings, and small droplets of liquid. These particles vary greatly in shape, size and chemical composition, and can be made up of many different materials such as metals and other toxics, soot, soil and dust. Particulate matter can be coarse, fine, or ultra fine.

Fine particles are about 2.5 microns or less in diameter. You would need about 40 fine particles measuring about 2.5 microns in diameter to equal the average width of a human hair.

Ultra fine particles are a subset of fine particles. This is any particle that is less than 0.1 microns in diameter. Often these particles are so small that thousands of them could fit in the period at the end of this sentence. Because these particles are so small, they can easily penetrate deep into the lungs causing respiratory illnesses.

What are the health effects associated with Particulate Matter?

Diesel exhaust is a likely human carcinogen. Both short and long-term exposures to particulate matter have been shown to cause harmful health effects. Scientists have observed higher rates of hospitalizations, emergency room visits and doctor's visits for respiratory illnesses and heart disease as particulate matter concentrations rise. Scientists have also observed the worsening of both asthma symptoms and acute and chronic bronchitis and a reduction in lung function from exposure to particulate matter. Particulate matter has many sources including diesel exhaust.

In addition, ultra fine particles can penetrate deep into the alveolar portion of the lungs and can enter the bloodstream and be transported to other parts of the body because they are so small. There is evidence linking both moderate and long-term exposure to ultra fine particles to an increased risk of premature mortality and risk of stroke. Ultra fine particles have not been directly linked with asthma, but have been implicated in respiratory effects in asthmatics.

Why are children at risk from health effects of PM?

Children are especially vulnerable to the effects of PM because their lungs are still developing and they breathe more air per pound of body weight than adults. Children who already have asthma are particularly sensitive to PM. PM might increase their incidence of an asthma attack. In New Jersey, between 10 to 13 percent of all children in grades K-12 have asthma.

How will installation of a CCVS on a school bus affect my child's health?

The results of this study demonstrate that the installation of a CCVS reduces fine and ultra fine particles entering the school bus cabin. This will result in a considerable reduction in asthma attacks and other adverse respiratory effects such as bronchitis and upper/lower respiratory symptoms. CCVSs may also slightly reduce the risk of developing cancer.

What are the results of the health risk assessment?

There were two risk assessments conducted. One for non cancer health effects and the other for cancer risk. The overall conclusion of these risk assessments is that for fine particles, installing a CCVS will result in a considerable reduction in asthma attacks and to a lesser extent, other adverse respiratory effects such as bronchitis and upper/lower respiratory symptoms in addition to a reduction in cancer risk. Installation of a tailpipe retrofit would only provide marginal additional health benefits.

The cancer risk assessment concluded that the risk of cancer from inhalation of fine particles from diesel emissions in school buses that just meet inspection requirements is five in a million. The risk assessment also concluded that the risk of developing cancer from diesel emissions from school buses with a CCVS retrofit was less than one in a million.

A five in a million cancer risk means that in a population of one million there would be five additional cancers resulting from this exposure over a lifetime. A one in a million risk means that in a population of one million you would see one additional cancer resulting from this exposure over a lifetime. It should be noted that both numbers fall within the risk range of one-in-a-million to one-in-ten thousand, which is the public health risk range often applied nationally to the setting of standards and guidelines for exposure to carcinogens for the protection of human health. The NJDEP considers a less than one in a million risk as negligible when evaluating permit applications for individual air pollution emission sources.

What did the risk assessment conclude regarding ultra fine particles?

There are currently no exposure guidelines for ultra fine particles, which are needed in order to develop a risk assessment. However, the significant reduction in ultra fine particles achieved with a CCVS or a CCVS with a diesel particle filter, would suggest that health risks are reduced because ultra fine particles are removed from the in-cabin air of school buses by these devices.

What is a risk assessment?

A risk assessment is a tool that is used to evaluate the potential for a chemical to cause adverse health effects including, but not limited to, cancer or other illnesses. In certain applications, risk assessments can be used to estimate the extent of adverse effects that will result from a specific level of exposure to toxic chemicals, including substances in the air such as diesel exhaust particulates.

Risk assessments rely on data from both human and animal studies to estimate the relationship between exposure to a contaminant and health effects. Conclusions from these studies are then combined with assumptions about the conditions of exposure, including how long and how often a person is exposed.

There are several risk assessment tools for assessing the risk of different adverse health effects from diesel fine particles. Most are based on the assumption of lifetime exposure (70 years) at the levels that were measured in the cabin. As a result, some of these tools do not apply to the short term daily exposure a child would experience riding on a school bus. Therefore, the risk calculations used to evaluate health effects in this risk assessment may overestimate the actual risk.

What actions will the NJDEP take as a result of the two studies and the risk assessment?

As a result of the second study, the NJDEP concluded that tailpipe emission control technologies do NOT significantly reduce in-cabin particulate levels and therefore do not provide significant health benefits. Therefore, the NJDEP will NOT require tailpipe emission control technologies and will recommend that the NJMVC school bus inspection process continue.

The existing requirement for all regulated school buses to install CCVSs by July 2010 will remain.