In-Cabin Particulate Matter Quantification and Reduction Strategies

Final Report

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1. EXECUTIVE SUMMARY

This study evaluated the relative 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 tailpipe emissions analyzer. Tests were conducted with no 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 using the Johnson Matthey-Continuous Regenerating Technology and a Flow Through Filter using an Environmental Solutions Worldwide Particulate Reactor. All the tests were performed using ultra-low sulfur diesel fuel. Three runs were completed for each device combination for the windows closed position.

A testing protocol was designed to minimize all extraneous sources of particulate matter except for that produced by the bus under normal operation. The test track was 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. A bus cleaning procedure was employed before each set of runs to eliminate re-entrainment of particulate matter from previous 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 standards.

From the analysis of the data from preliminary testing, 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 study found that the average in-cabin particulate concentrations for a bus driving on a school bus route with windows closed was 2.7$\mu g/m^3$ as shown in Table 16. 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 calibration data presented in the section, "Calibration Particulate Instrumentation Check," this value is 1.3 to 1.8 times higher than the 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 school bus in an environment free of 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.

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 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 ambient. The most effective technology was the combined DPF and CCVS. 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 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.

Table of Contents

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 less than 0.1μm
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
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

3. INTRODUCTION

In a recent review by Borak and Sirianni[1], they identified 11 experimental studies that measured pollutant levels inside the cabin 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.

Health effects studies[2,3,4] 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)[5].

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[6,8].

Previous studies[7,8,9,10,11,12] 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 study to date has performed triplicate runs in which all factors that produce particulate matter are equal except a diesel emission retrofit technology and the variation of ambient particulate matter. 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].

This study evaluated 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 include a Donaldson's Spiracle Crankcase Filter (CCVS); the 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[13]), and the Flow Through Filter (FTF) used was the Environmental Solutions Worldwide-Particulate Reactor which received a Level 2 verification from the California Air Resources Board given to technologies that achieve at least a 50% reduction in particulate matter emissions[14].

4. BACKGROUND

The school bus study by Solomon et al.[15] was the first highly publicized study of particulate concentrations inside the cabin of a school bus. 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 the particulate concentrations in the back of the bus were higher than the front of the bus.

According to the Environmental Protection Agency (EPA)[16], 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.[17]

It is suspected that 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 the door, open windows, faulty seals, ventilation system vents etc. while in operation. The main tailpipe emissions from a diesel engine are PM, CO, CO_2, H_2O, hydrocarbons, SO_2, NO and NO_x. These are a direct result of the combustion of diesel fuel in the engine. 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, result when the increased pressure during combustion forces gases and particulates in the combustion chamber past the pistons and into the crankcase. The pressure in the crankcase is controlled by releasing gases and particles through a vent tube that is open to the atmosphere. 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.

In the review by Borak and Sirianni,[1] they analyzed 19 reports of 11 studies that measured in-cabin particulate concentrations of school buses. Of these 11 studies, they concluded that the Clean Air Task Force study[10] 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. Duplicate runs for each of the reduction schemes was given. The advantage of this study is that a comparison could be made between the emission reduction schemes while attempting to hold constant several variables: single bus driven on a single bus route. In addition runs were duplicated for each condition. What was not held constant was the exact driving cycle for this route. Factors of length of stops, duration of the 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[7,10] 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 study. In this study it is claimed that the majority of $PM_{2.5}$ particulates originated from the crankcase vent and the ultrafine particulates found in the cabin of the bus originated primarily from the tailpipe exhaust.

A study conducted in Fairfax county[18] measured particulates using a gravimetric method for 12 buses driven on simulated 90 minutes routes with 5 stops that were 3 minutes each. With the gravimetric method employed, only concentrations above $50\mu g/m^3$ could be detected. Concentrations for 4 out of 12 runs were obtained ranging from $123\text{-}205\mu g/m^3$. The EHHI study[19] 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 (pDR-1200) were located at the front seat and back seat of the school buses. In addition, an aethalometer from Magee Scientific was used to measure Black carbon.

The school bus study in anchorage[20] 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 particulate concentrations within a bus that appeared to be related to the bus route driven as opposed 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.

A comprehensive set of papers[21,22,23,24,25,] have been published by Winer's research group at UCLA based on the study for the California Air Resources Board.[8] This study examined 7 school buses driven on actual routes in Los Angeles. Extensive gas and particulate concentration measurements were conducted with two of the instruments similar to this study nephelometer and optical particle counter.

The study by Hammond[26], measured in-cabin particulate concentrations for 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 particulate concentrations were measured using a particle counter. The results for these studies are reported without ambient values. A similar study was conducted for transit buses.[27]

A recent Texas study by McDonald-Buller et al.[28] examined gas and particulate concentrations inside the cabin of a school bus before and after retrofits. The retrofits included the Donaldson Spiracle crankcase ventilation system 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) and a particle counter (P-Trak).

A series of studies have been conducted by Clark's group at West Virginia University[29,30] 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 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 study. Based on data reported in a presentation by Kittelson[31] the range of particle sizes from the crankcase vent had a maximum above 3 for light duty diesel engines and above 7μm for heavy duty diesel engines.

Clark[29] 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. 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 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 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[1], this pollution will come mainly from the crankcase emissions which are normally emitted through a draft tube located below the bus and near the door. The tailpipe emissions can also enter the bus through this 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 certified tests 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 elimination of particles greater than 0.04μm. Studies have been conducted showing that an increase in particles with diameters less than 0.02μm has been observed.[32].

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. 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 study will estimate 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 evaluated the relative contribution of emissions from both the crankcase and the tailpipe to in-cabin levels of fine and ultrafine particles.

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 aftermarket emission reduction 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 wall flow filter)
    c. Combination of both DPF and CCVS
    d. Flow through filter (FTF) (also known as 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 representative of the most common engine type used in New Jersey school buses[33].

An initial set of runs was performed using this school bus on a 1 mile oval track. After completing a very extensive series of runs, it was determined that the back door of the bus was not sealed. Since all New Jersey school buses are inspected twice per year, NJDEP invited representatives from the New Jersey Department of Motor Vehicles (NJDMV) to perform an inspection of the school bus. Even after the back door was repaired by an experienced body shop in Maryland, the bus failed the inspection. The major fault was again the back door which failed the flashlight test. This test 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 was repaired and then re-inspected and passed. Very few previous studies have reported that the buses were inspected. One exception, is that in the CATF study[7] it was reported that buses were inspected. They specifically stated that the "rear doors were adequately sealed."

For the new set of tests each retrofit technology was inspected and cleaned if necessary. Proper installation of each technology was also verified by a representative of the manufacturer of the equipment.

Testing Protocol

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 K: Testing Protocol. Given below is a brief description of the major features of this protocol.

Several limitations were placed 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 ($32°\mathrm{F} < T < 100°F$)
2. air quality index prediction less than 100 (40μg/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 leaked checked as specified by the manufacturer. New 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. Next the ventilation fan was switched on to blow out any accumulated particles in the duct work of the 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. 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.[34] In other studies, the buses were only idled for their warm-up period. In the CATF study[7] 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 and samples were recorded of the ambient air to check for proper operation of the instruments. 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 time was at least minutes which 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.[34]

The test was done by driving the bus on a modified Rowan University Composite School Bus Cycle (RUCSBC)[35], on a 1.3 straight-mile with one 0.1 mile loop at one end, and a 0.2 mile loop at the other end of the track at Aberdeen Test Center (ATC) located in Aberdeen, MD. In order to provide realistic 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 1. 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 2. In addition, data was collected for a period of 10 minutes before and 10 minutes after each run by all instruments with the windows open.

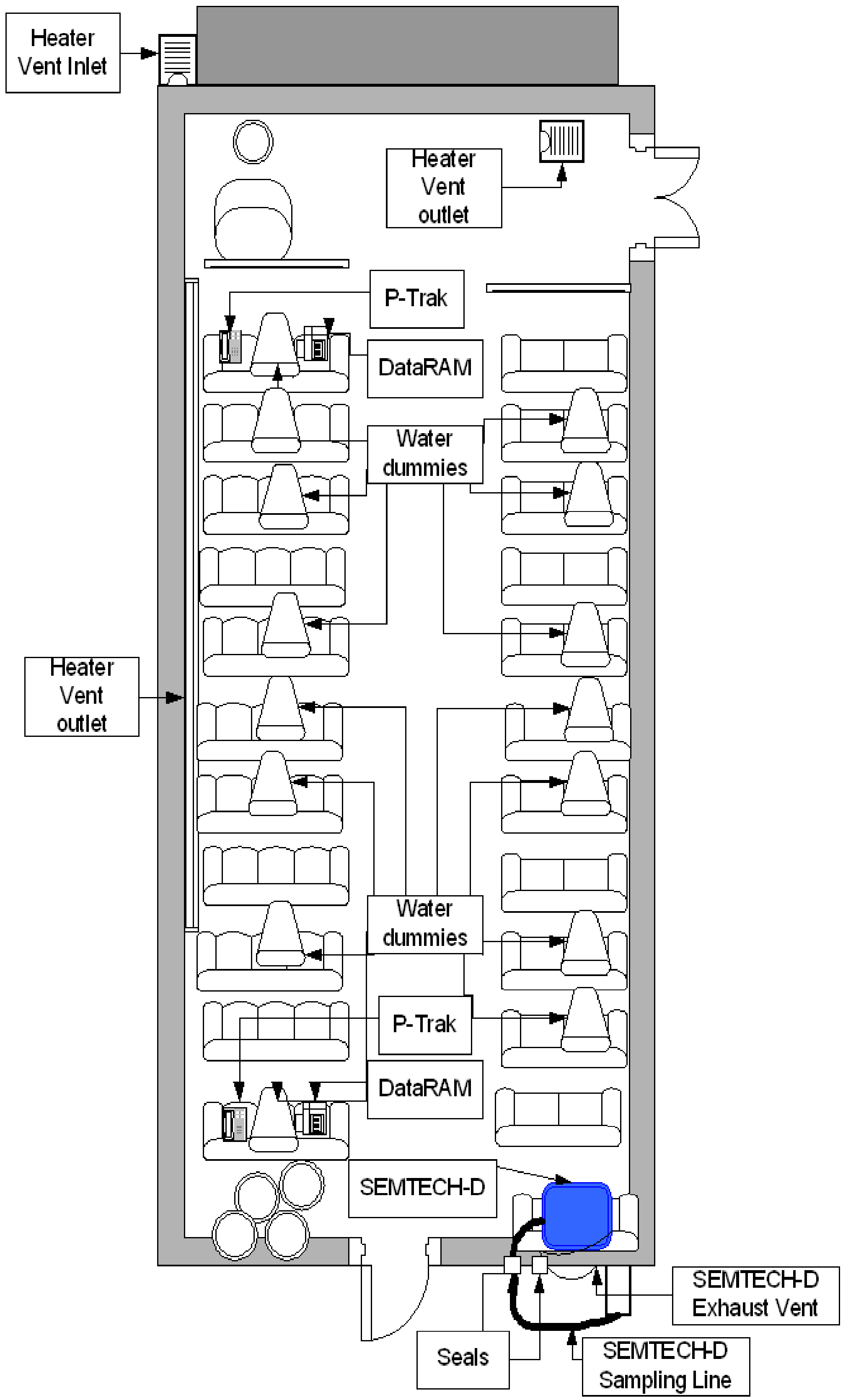

Figure 1: Sketch of instrumentation inside school bus cabin.

Figure 1 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 2. 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.

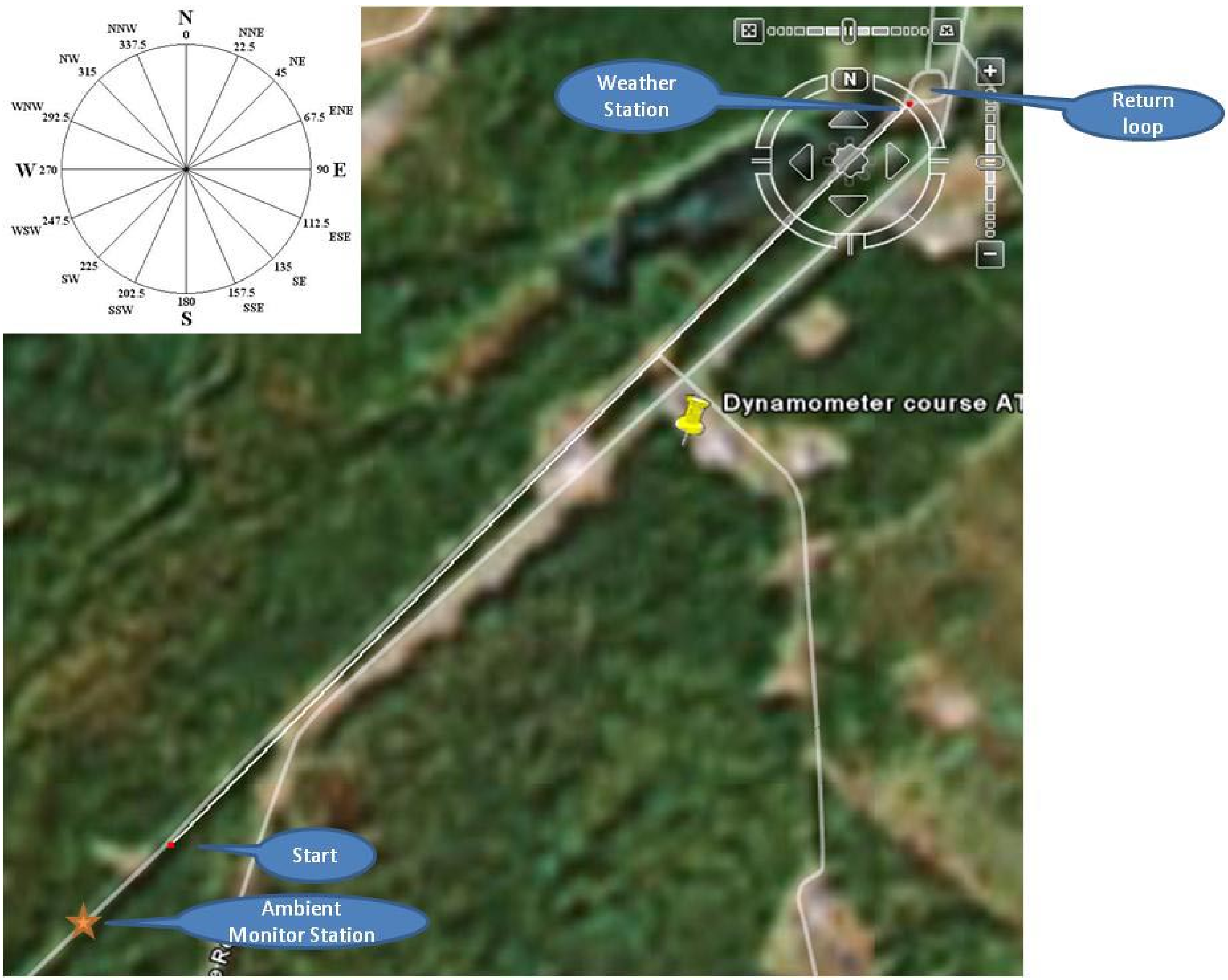

Figure 2: Test track consisting of a 1.3 mile straight section with 0.3 miles of turnarounds. ATC designated Dynamometer course. Satellite photograph obtained from Google Earth.

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 2 in which the track is highlighted by the orange line. 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 3: DataRAM and P-Trak instruments at ambient monitor station located 300 m from south west 0.1 mile turnaround loop.

Figure 3 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 4: 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 4.

Figure 5: Straight section of the test track which is 1.3 miles in length. ATC designated Dynamometer track at ATC.

This track was unique for the study since it gave the ability to virtually eliminate surrounding traffic, dust sources, and it provided a continuous driving of the cycle without sudden or unexpected stops. As seen in Figure 5, the track was lined on each side by trees which reduced the amount of particulate matter that originated from outside sources.

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 it 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 6 was weighted prior to cleaning and after giving a weight difference of only 0.5g.

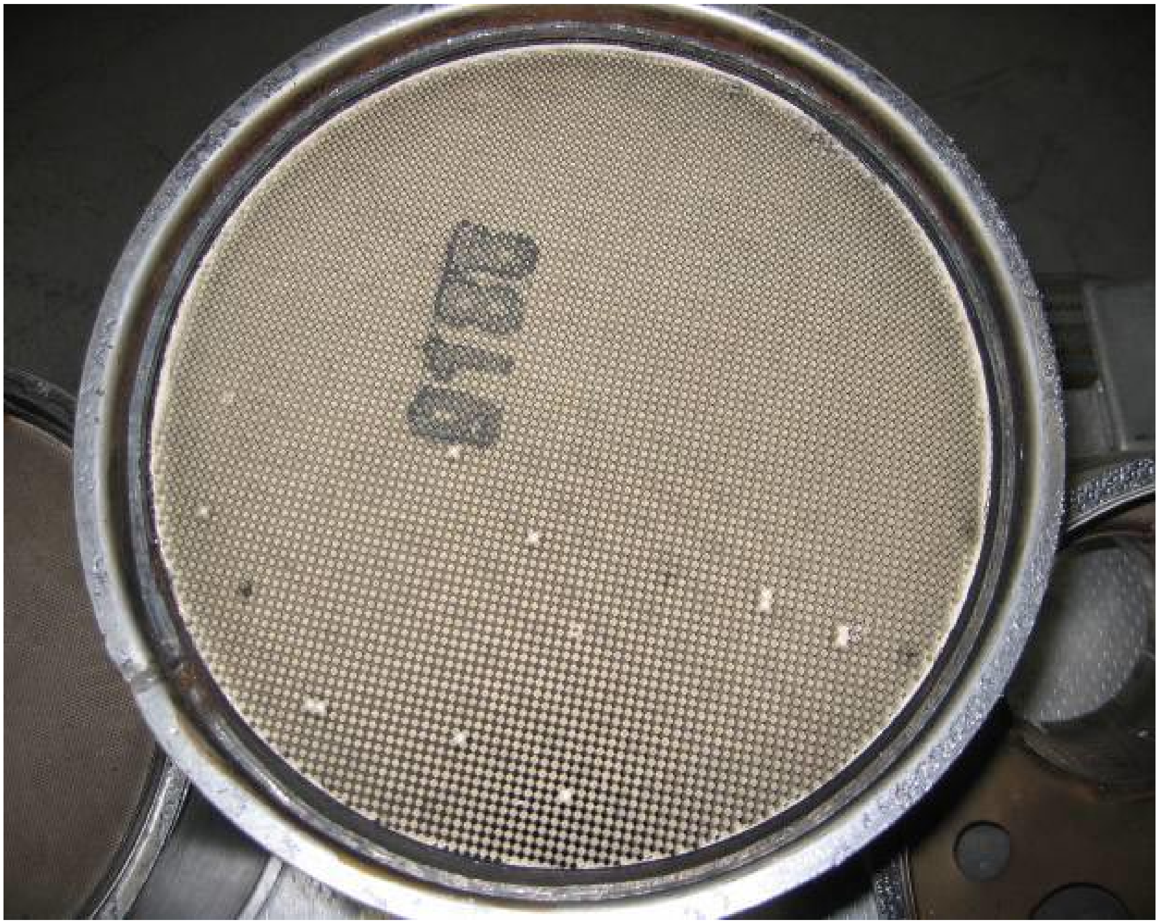
Figure 6: Exhaust intake face of DPF filter section during inspection.

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

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 to reduce particulate matter from an exhaust stream by at least 50%.[14] 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. The ESW Particulate Reactor® is able to oxidize particulates at lower exhaust temperatures compared to other diesel oxidation catalyst (DOC) units.[11] In addition, the ESW Particulate Reactor® has the capacity to store mass particulates in excess of 5 times that of a conventional ceramic-based diesel particulate filter between regenerations. This higher capacity for particle storage helps to prevent pollutant spikes that occur after accelerations from idle.[11] The ESW Particulate Reactor® is a CARB Level 2 verified retrofit and does not require a special fuel such as ULSD.

The Flow through Filter has a similar operation principle as 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 7.

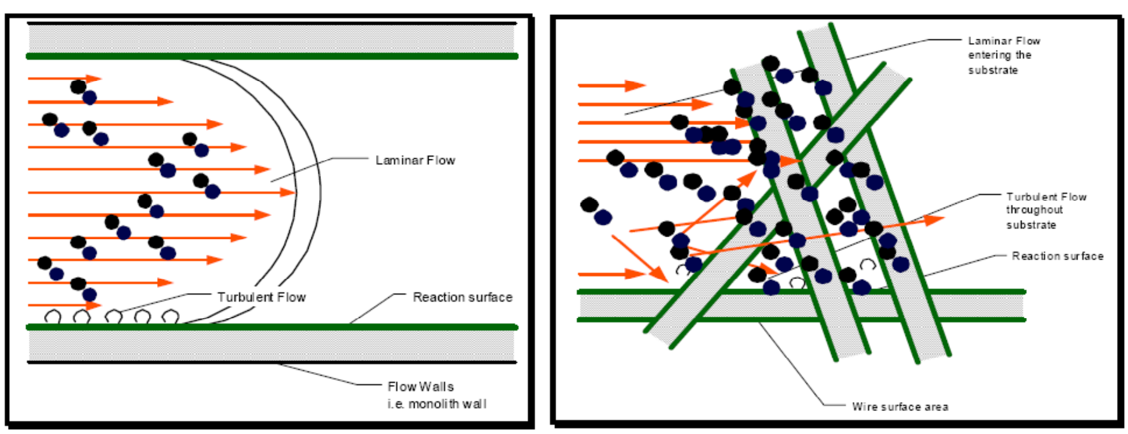

Figure 7: Representation of exhaust laminar flow through a diesel oxidation catalyst (left) and the ESW Particulate Reactor® (right). Source: M.J. Bradley & Associates, Inc. (2006)[11].

A picture showing the Flow through Filter is shown in Figure 8. In this figure the internal filter component (a catalyzed wire-mesh) of the retrofit is contained in a tubular reactor.

Figure 8: Internal component of the ESW Particulate Reactor®. Source: M.J. Bradley & Associates, Inc. (2006)[11].

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 9.

Figure 9: ESW Particulate Reactor (FTF) installed on the school bus.

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[13] to achieve 90% reduction on particulate matter emissions. The CRT consists of two chambers which are shown in Figure 10. In the first chamber a ceramic monolith coated with platinum converts the carbon monoxide and hydrocarbons to carbon dioxide and water. In addition the this section oxidizes the NO to NO_2. In the second chamber a second monolith allows the gas 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 is continuously 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.

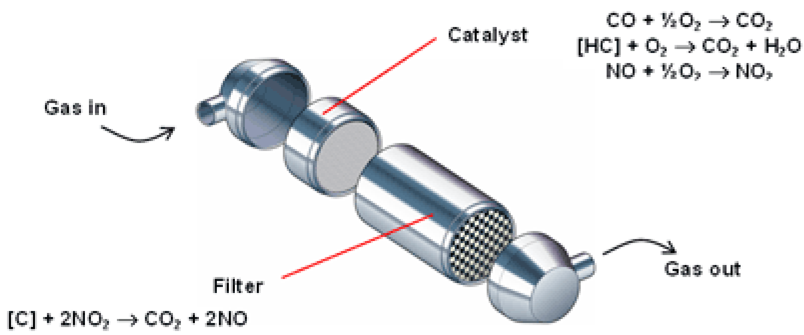

Figure 10: Components of the Johnson Matthey CRT® obtained from emission control technologies website[36].

Figure 11 shows the CRT installed in the school bus. The installation of this retrofit was also checked for leaks before the testing.

Figure 11: Johnson Matthey CRT, DPF, installed on the school bus.

Crankcase ventilation system: This filter is designed to reduce 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 media which employs a high-velocity impaction technology to coalesce airborne hydrocarbon vapor, soot and engine oil residues. The second stage consists of low-velocity diffusion technology for an overall efficiency of 90% reduction. The crankcase filter separates aerosols and particulates from the venting gases and has an overall benefit 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.[37]

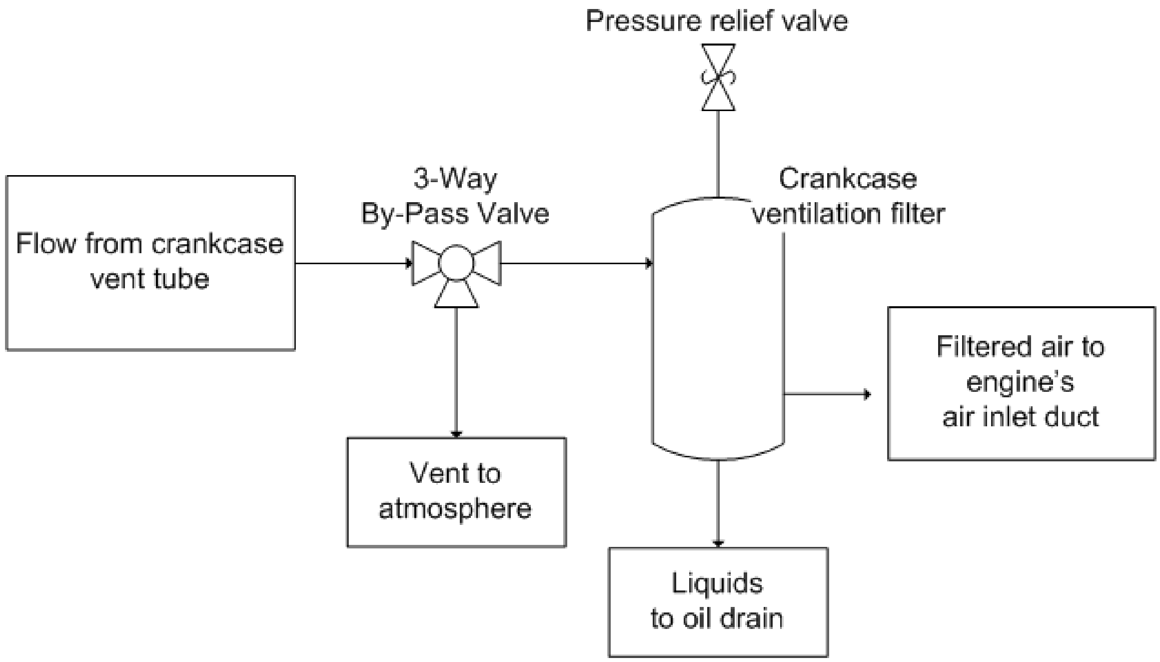

Figure 12: Crankcase ventilation system diagram.

A diagram of the crankcase ventilation system is shown in Figure 12. 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 from being out of the normal operation of the engine which should be maintained at approximately 4 inches of water[38]. 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 13. 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 smaller clear plastic tubing near the bottom of the crankcase filter is the return line for the filter gases to the engine. The black plastic tubing at the bottom of the filter is for liquids that are sent back to the crankcase.

Figure 13: Donaldson Spiracle Crankcase ventilation system, CCVS, installed in the school bus tested.

Figure 13 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.

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 air 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[39] 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 air is then drawn through the air duct where the beam from two light sources, 660 nanometers and 880 nanometers, emit alternately 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 intensity of the light is directly proportional to the amount of particulates passing through the air duct, based on the assumption that particle size and distribution remain constant. The DataRAM-4 incorporates two wavelengths to measure particle size and perform a size correction based on Mie-Lorenz theory. The data 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 from the sensing photo-detector. The particle number concentration is obtained by counting the number of times the light flashes.[40] The particle size measurement range of the P-Trak is from 0.02 to 1µm 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 using the Sensors, Inc., SEMTECH-D tailpipe emissions analyzer. These measurements from the SEMTECH-D are necessary to verify that the school bus is operating under normal load conditions. 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 15 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 15 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.

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. 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[41]. 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 relative humidity with concentration.

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 which corresponds to the liquid phase of alcohol. The results from P-Trak model 8525 was compared to a more sophisticated condensation particle counter in a University of California study.[42] Good agreement was found between the more sophisticated TSI Inc. ultrafine particle counter (CPC) model 3022a 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. This study illustrates that the P-Trak is a good instrument for measuring particulates that have aged. For example the particulates coming from the engine of the bus have a sufficient time to age during their travel from the engine through the tailpipe and into the cabin of a bus.

The size distributions of particulates produced by diesel engines have a significant number and mass of particles less than 1μm. These 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. Size distributions from diesel particulates have a bimodal characteristic as shown in Figure 14.

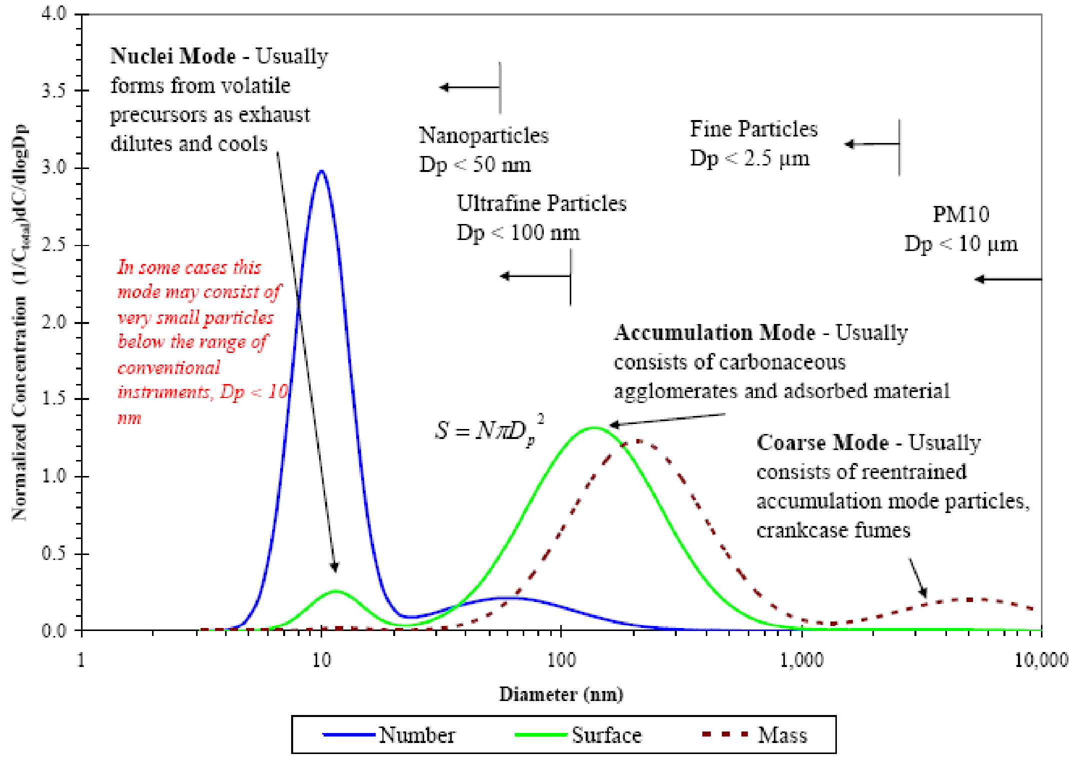

Figure 14: Typical engine particle size distribution by number, surface and mass concentration. Figure obtained from Kittelson (2007)[31].

Figure 14 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 condense to form particulate matter. These particles range in size between 3 to 30nm (0.003 – 0.03µm) as postulated by Kittelson (2002)[43]. 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 labeled 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.[43] These particles are thought to originate primarily from crankcase fumes and agglomerated accumulation mode particles. Figure 14 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 that have been collected on a filter following the Federal Reference Method.

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 1. 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 1. 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 15.

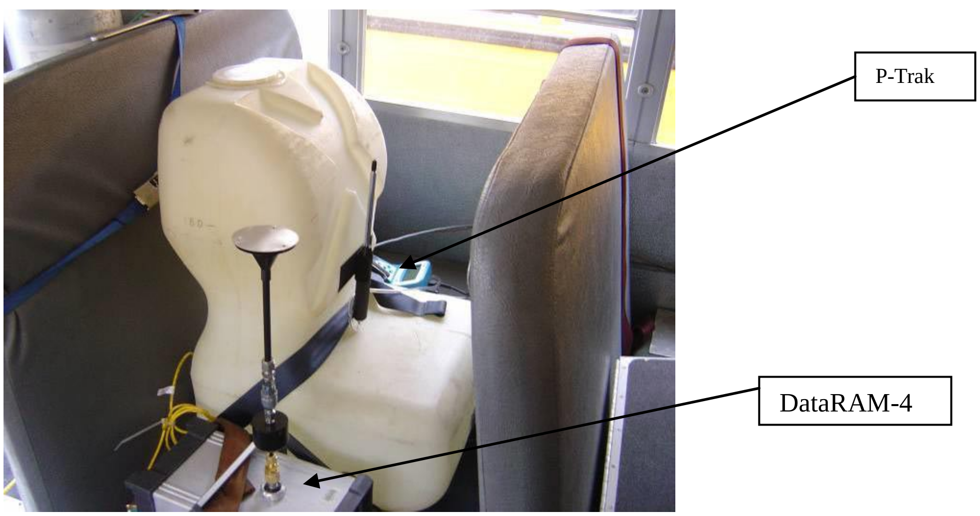

Figure 15: Location of the DataRAM-4 and P-Trak instruments in the bus.

The tailpipe emissions were measured by the SEMTECH-D gas analyzer, Figure 16 shows the positioning of the sampling probe 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.

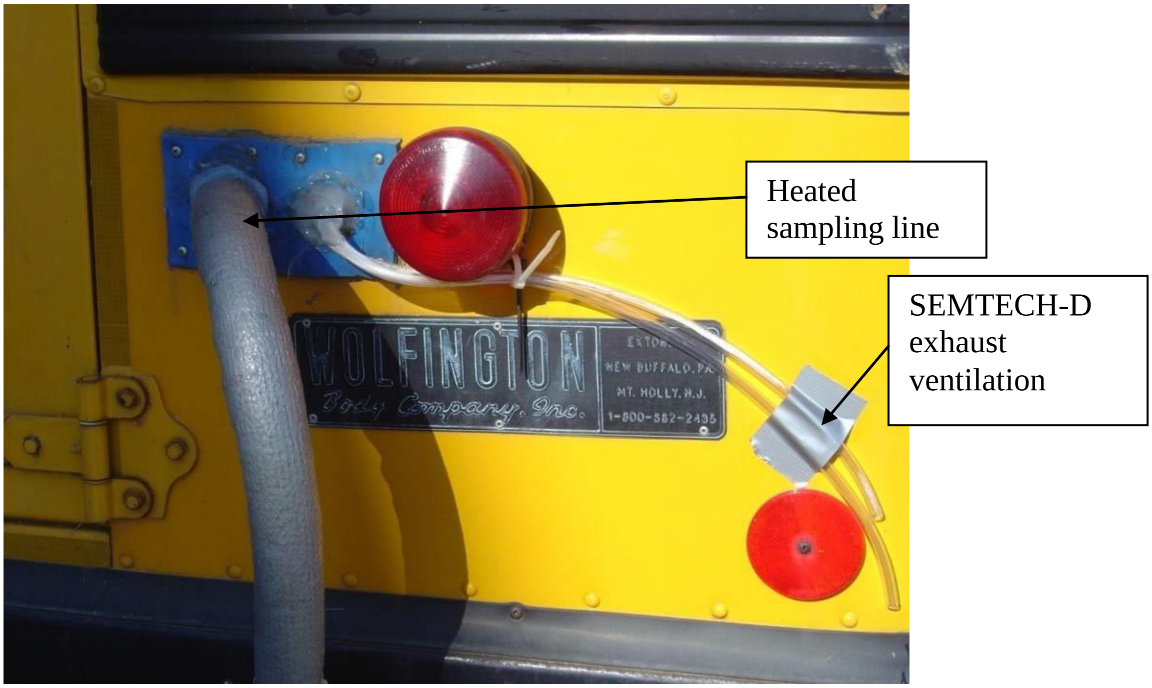

Figure 16: SEMTECH-D sampling hose installation through bus chassis.

Figure 17 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 are the exhaust gas tubing of the SEMTECH D

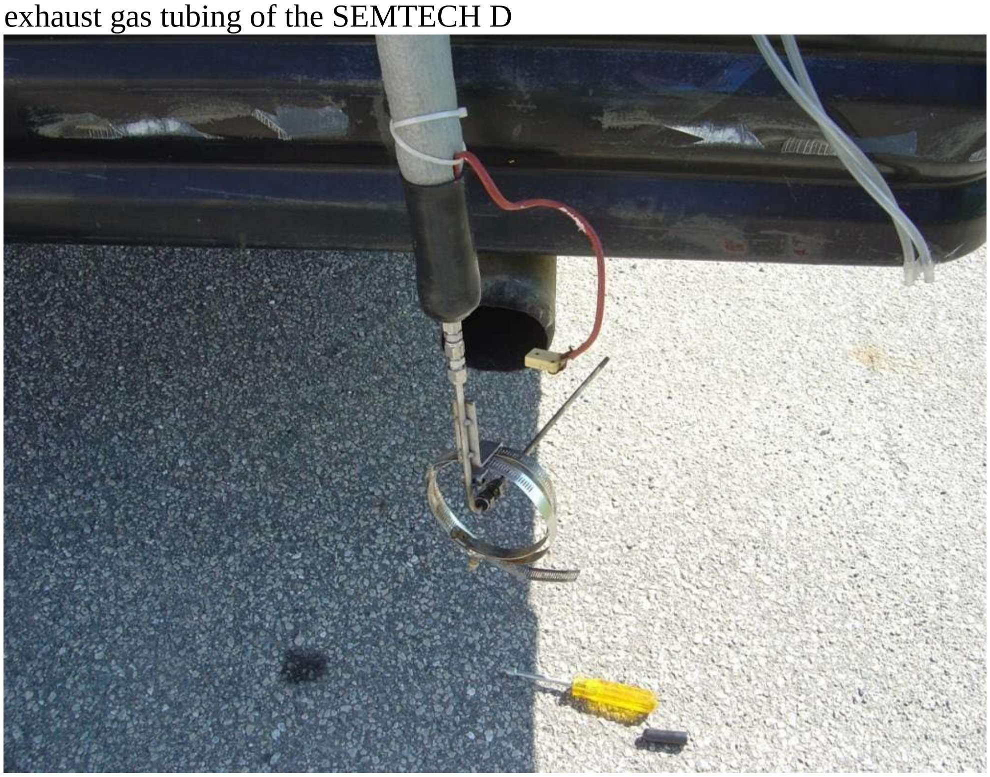
Figure 17: SEMTECH-D sampling tip before being secured to the tailpipe.

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
- Non-Dispersive Ultraviolet (NDUV) for Nitric Oxide (NO) and Nitrogen Dioxide (NO_2) Measurement
- Non-Dispersive Infrared (NDIR) for Carbon Monoxide (CO) and Carbon Dioxide (CO_2) measurement
- Electrochemical sensor for Oxygen (O_2) measurement

Driving Cycle

Modified Rowan University Composite School Bus Cycle

The bus was driven following a modified version of the Rowan University Composite School Bus Cycle (RUCSBC) shown in Figure 18. The original school bus cycle 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. 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.

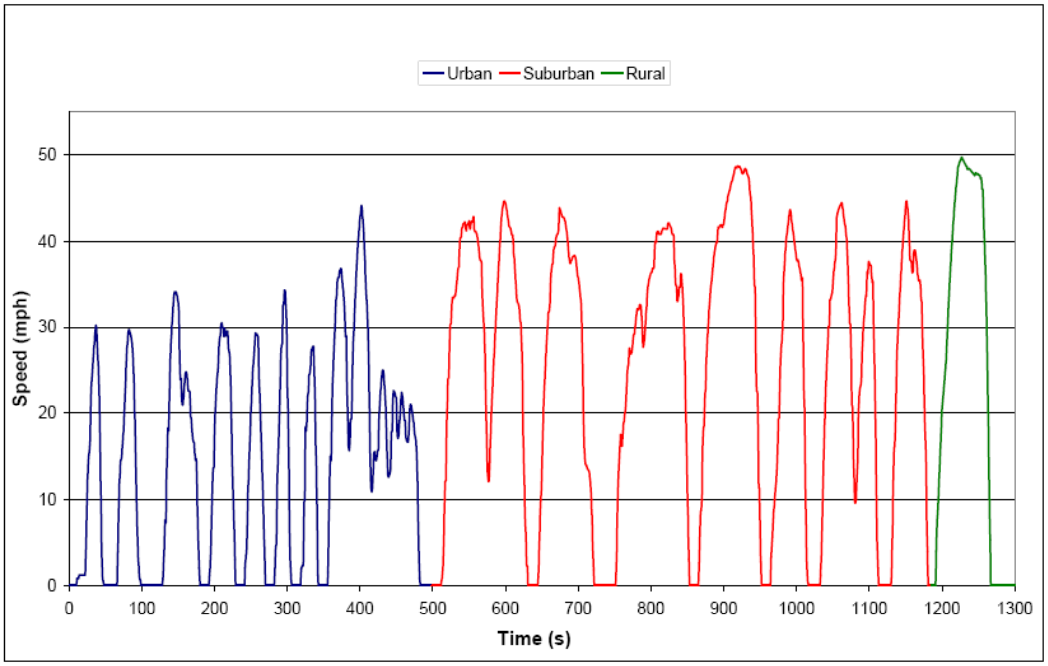

Figure 18: Modified Rowan University Composite School Bus Cycle used for one mile loop.

The RUCSBC was designed for continuous driving which is best done on a test loop or oval track. The original 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. Figure 19 shows the adapted RUCSBC 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 turn arounds. The figure compares the modified cycle (RCSBC-S) in blue and the original RUCSBC in red. In Figure 19 the time between the two cycles was aligned so that the changes made to the original cycle can be visually compared.

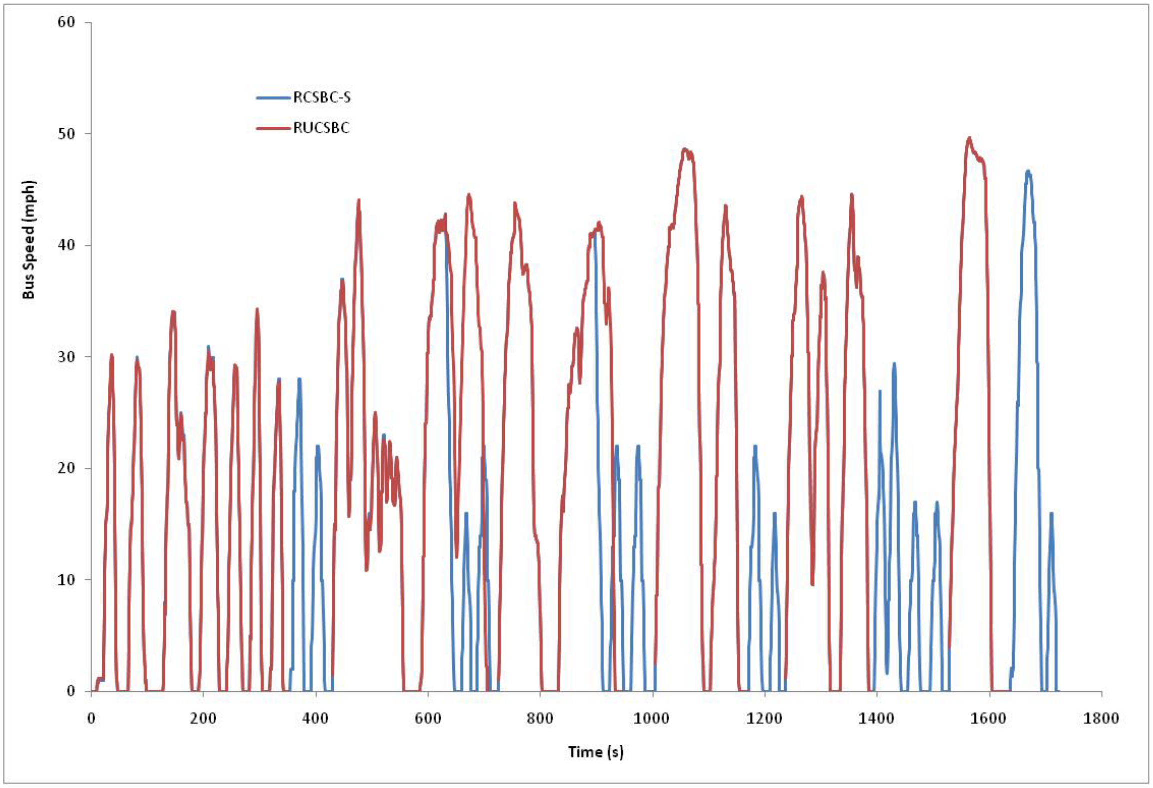

Figure 19: Comparison between RUCSBC and the modified cycle (RCSBC-S) for the dynamometer track at ATC.

In order to have repeatability for the testing conditions, the bus driver followed the RCSBC-S that lasts 28 minutes with 46 seconds by using the real time cycle data provided by the SEMTECH-D software. 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 20 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 20: 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.

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.[44] The fuel used for this study was the Amoco Emission Control Diesel (ECD) Fuel from BP with the following specifications presented in Table 1.

Table 1: 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[45]. 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. Other studies using this fuel are (Sabin L. D. et al., 2005)[23], (Fitz D.R. et al., 2003)[8], (Chatterjee S. et al., 2001)[46], (Chatterjee S. et al., 2001[b])[47], (Lev-On M., et al., 2002)[48], (Le Tavec C., et al., 2002)[49], (Durbin T.D., et al., 2002)[50], (E. Behrentz, 2004)[21], (B.A. Holmén and A Ayala, 2002)[34], (B.A. Holmén, and Yingge Qu, 2004)[51].

The work plan proposed three runs per configuration for windows closed. Table 2 provides the runs completed.

Table 2: Number of runs per configuration and dates performed.

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

There was a previous 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 larger number of windows closed tests were based on initial findings that 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.

For the present study with windows closed condition the following sets of runs were conducted: 3 runs without any retrofit technology (baseline condition), 3 runs using only the crankcase ventilation system (CCVS) without tailpipe retrofit, 3 runs using the diesel particulate filter (DPF) in combination with the CCVS, 3 runs using the DPF alone, 4 runs using the flow through filter (FTF) with the CCVS and 3 runs using only the FTF.

Only three runs using the FTF combined with the CCVS are reported since a leak was detected after Run 13

Calibration Particulate Instrumentation Check

The particulate concentration instruments were analyzed for both their accuracy compared to gravimetric and FRM calibrated instruments and how they tracked together. Prior to this study the DataRAM and P-Trak instruments were calibrated in a controlled room environment in December 2006, 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 an SKC Legacy pump operated at 10 L/min with a $PM_{2.5}$ sampling head was used. Three measurements were made for concentrations of 40 and 80μg/m^3, and one measurement for the 0 and 200μg/m^3 concentration levels.

After this calibration was conducted over 87 school bus tests were run and then the instruments were sent back to the factory for calibration and cleaning as specified in the operating manual. Since the instruments were recalibrated by the factory, then the initial calibration against diesel emissions 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 (<40μg/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.

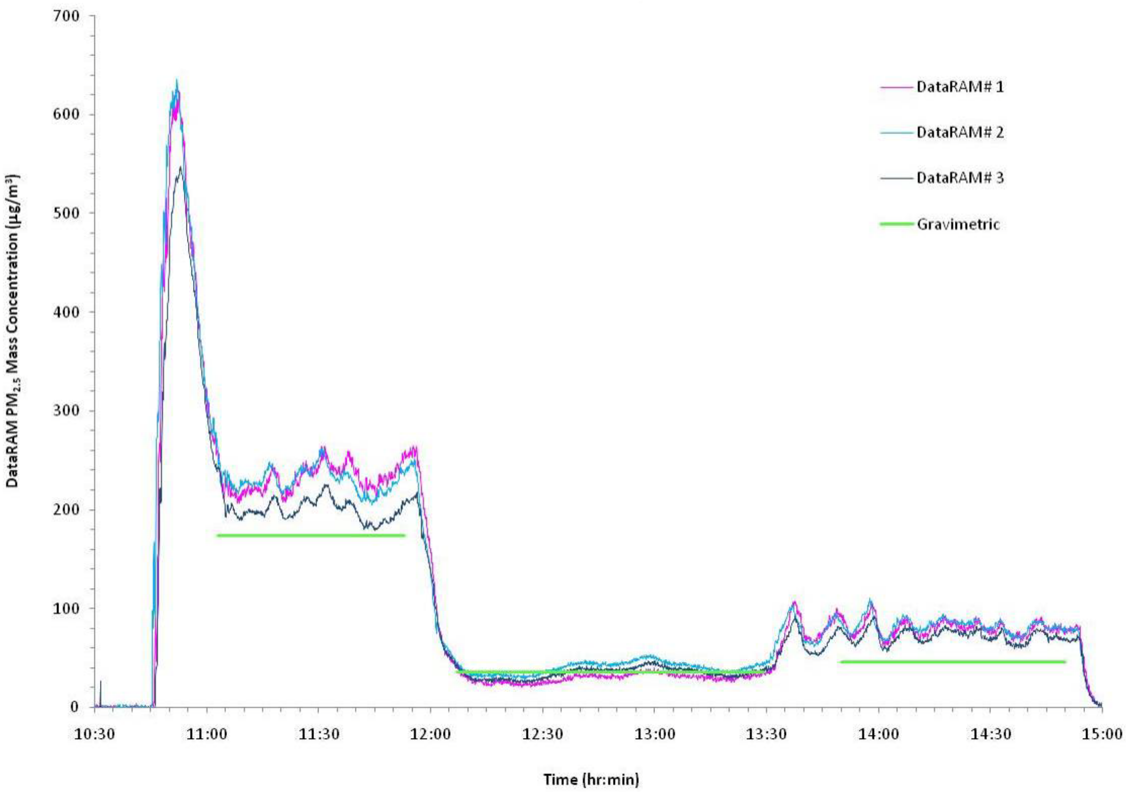

Figure 21: Real time data from the three DataRAM instruments at the EOHSI controlled chamber on December 8, 2006.

Figure 21 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 complementary to the EOHSI controlled chamber test values. 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 values for the low concentrations as seen.

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

TEOM (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 (%)
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 ±1μg/m^3 to ±5μg/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 0.1μg/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 combination of the low concentration values obtained at the NJDEP air monitor site at Camden NJ were combined with the calibration values obtained at EOHSI in order to have a complete calibration 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 calibration 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 together with particulate concentration. However the P-Trak instrument from EOHSI did not show this 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 calibration curves (obtained by the DataRAM #1 with serial number D572) is shown in Figure 22. Additional calibration curves for the DataRAM instruments are given in Appendix A.

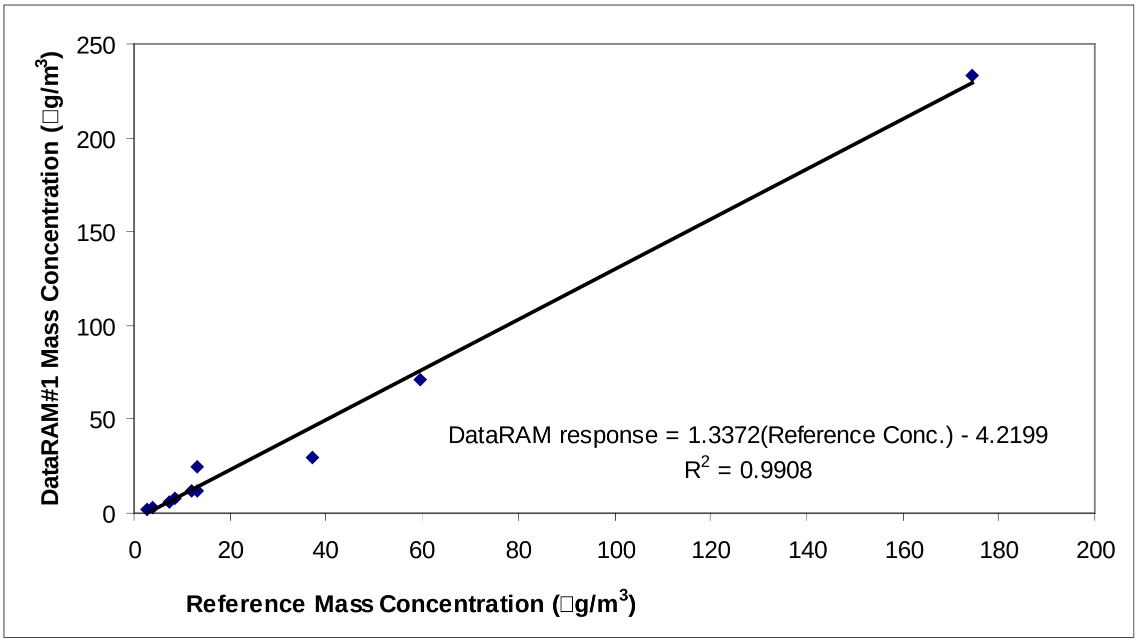

Figure 22: Calibration curve for DataRAM instrument No. 1 with serial number: D572.

As seen in Figure 22, only one measurement was taken at a high concentration level of ~250μg/m^3. Most of the calibration data obtained were at values less than 50μg/m^3 which corresponds to the concentration range that was expected to be measured within the school bus cabin during the runs. These results are similar to that reported for the TSI DustTrak in several previous calibration studies. Yanosky et al[52] 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, were between 5 and 20μg/m^3. Also for 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[7] 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 which was done in this study.

After the instruments were sent back to the factory for maintenance and recalibration on April-9-2008, a check on the calibration with respect to ambient PM2.5 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 23. The sampling manifold used by the TEOM is shown at the middle right of the picture with a conic head and transparent tube.

Figure 23: 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 calibration 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.

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 24 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 calibration, 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.

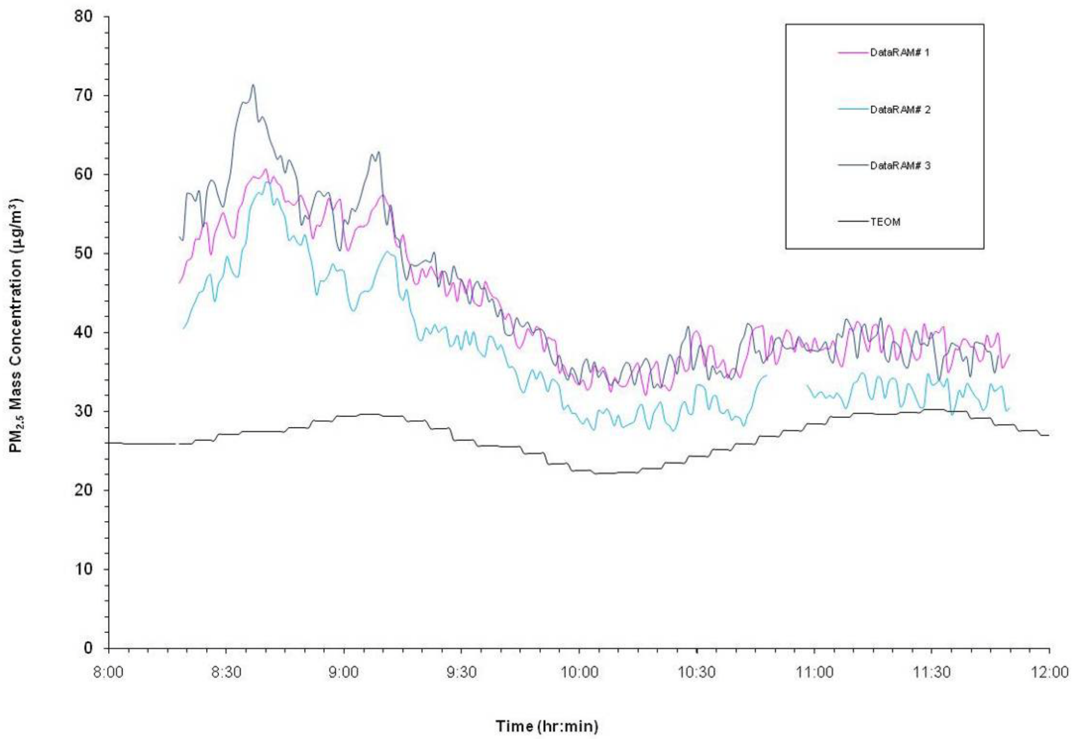

Figure 24: Measurements obtained at Elizabeth NJ, monitor station on May 3, 2008. Values are presented in one minute average for the DataRAM and TEOM instruments.

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 calibration resulting in a coefficient of variation from 2 to 7% for an average concentration range of 2196 to 124139pt#/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.								

6. RESULTS

This 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.

Continuous Sampling Results

This study showed that there is an accumulation of particulate matter within the cabin of a school bus. Figure 25 shows the DataRAM values for a baseline run, Run 3, in which no retrofits were installed on the bus. In Figure 25, 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 DataRAMs (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 3 started at approximately 16:43. The run has 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.

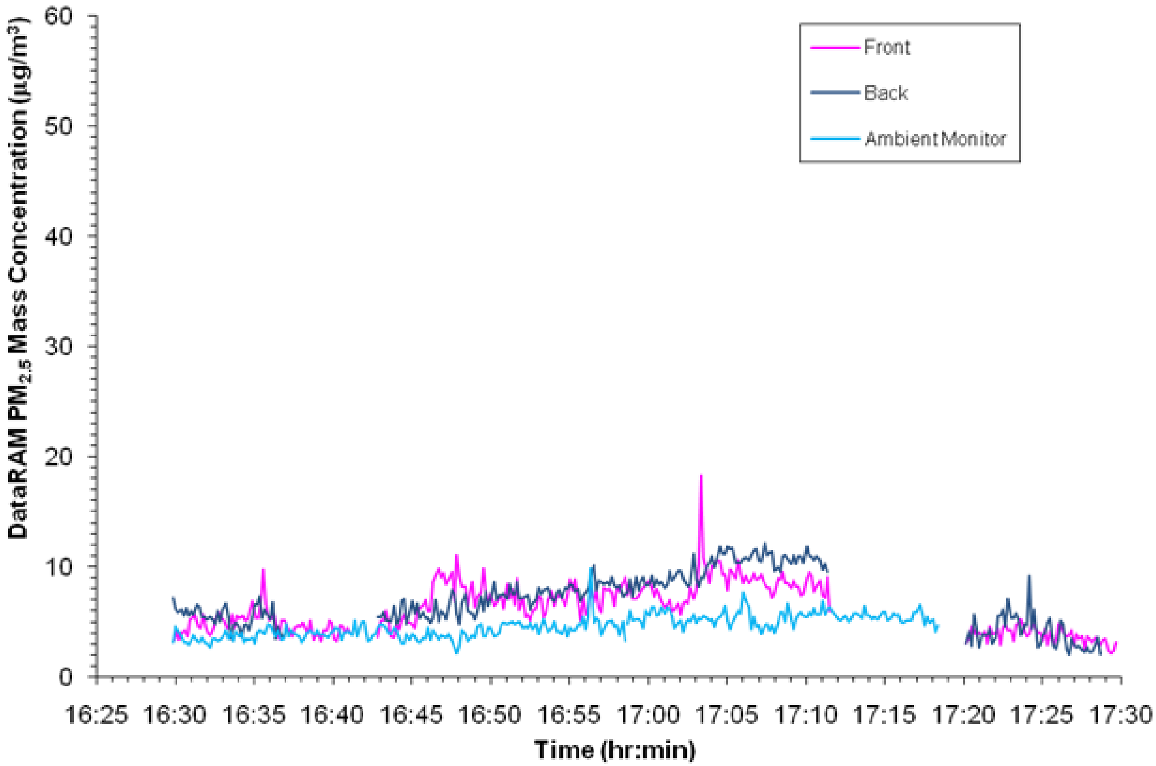

Figure 25: Baseline run #3 baseline condition, DataRAM results with 10 seconds averaging.

This baseline run shows an accumulation of $PM_{2.5}$ concentration inside the bus cabin as the run advances as evidence 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 was 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 average of the pre and post sampling periods was 4.7$\mu g/m^3$ and the run was 8.3$\mu g/m^3$. Again this increased level over the ambient demonstrates that there was an accumulation of particulate matter in the bus.

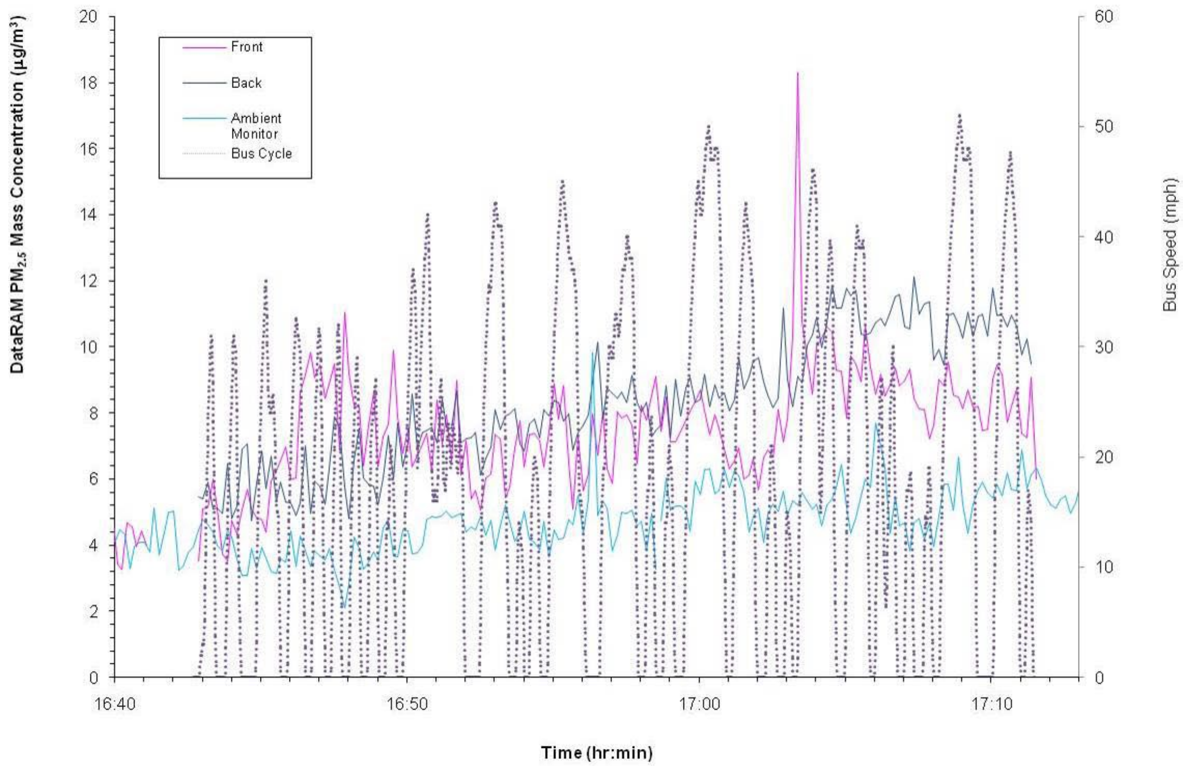

Figure 26: Baseline run #3 baseline condition, DataRAM results with 10 seconds averaging and bus cycle overlapped.

A comparison between RCSBC-S and the DataRAM concentrations is shown in Figure 26 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.

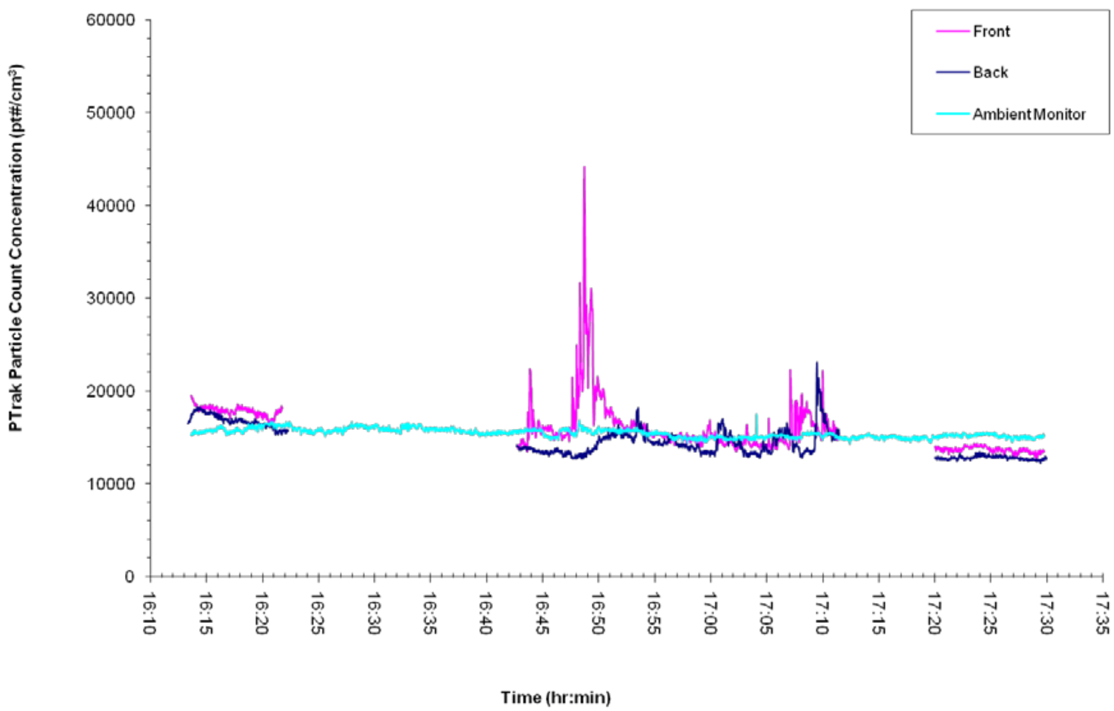

Figure 27: Baseline run #3 baseline condition, P-Trak results.

Figure 27 presents the P-Trak results for particle count concentrations during the baseline run# 3 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.

Using this passage way the particulates will still enter towards the front of the bus, and on the driver's side as shown in Figure 1.

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 3, 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.

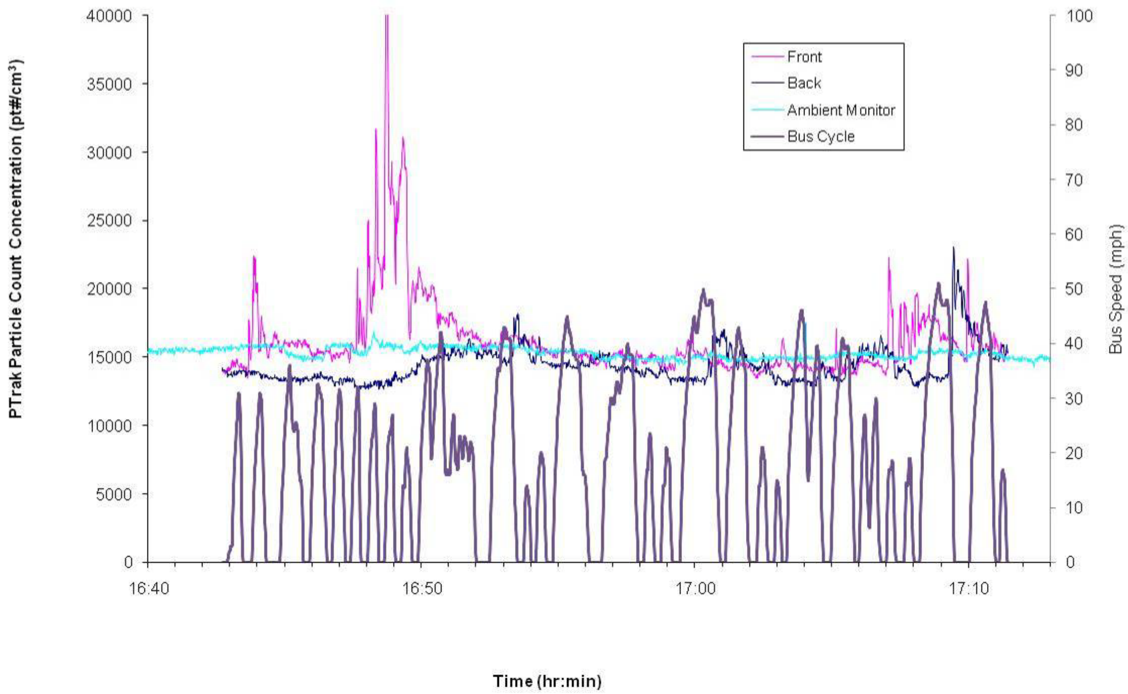

Figure 28: Baseline run #3 baseline condition, P-Trak results with bus cycle.

Figure 28 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 mayor accumulation of particle count concentration resulted from 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 as a result of consecutive small accelerations and stops.

The ability to give the same concentration value between the measurements made with the three DataRAM and the three P-Trak instruments was quantified in terms of the coefficient of variation (C.V) which is a normalized measure of dispersion of a probability distribution and t is defined as the ratio of the standard deviation to the mean. Table 8 presents a comparison of the three DataRAM instruments at one location measuring the same ambient air. These data were obtained from both the NJDEP ambient monitoring station in Elizabeth, N.J. and at the dynamometer track at ATC. The average coefficient of variation was 16% for all the values yielding an average 95% confidence interval of ±5.1μg/m^3 at an 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 8: 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 9 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 3 shown in Figure 27.

Table 9: 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 10 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 8, 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. 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 8. 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 8. 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 10: 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.

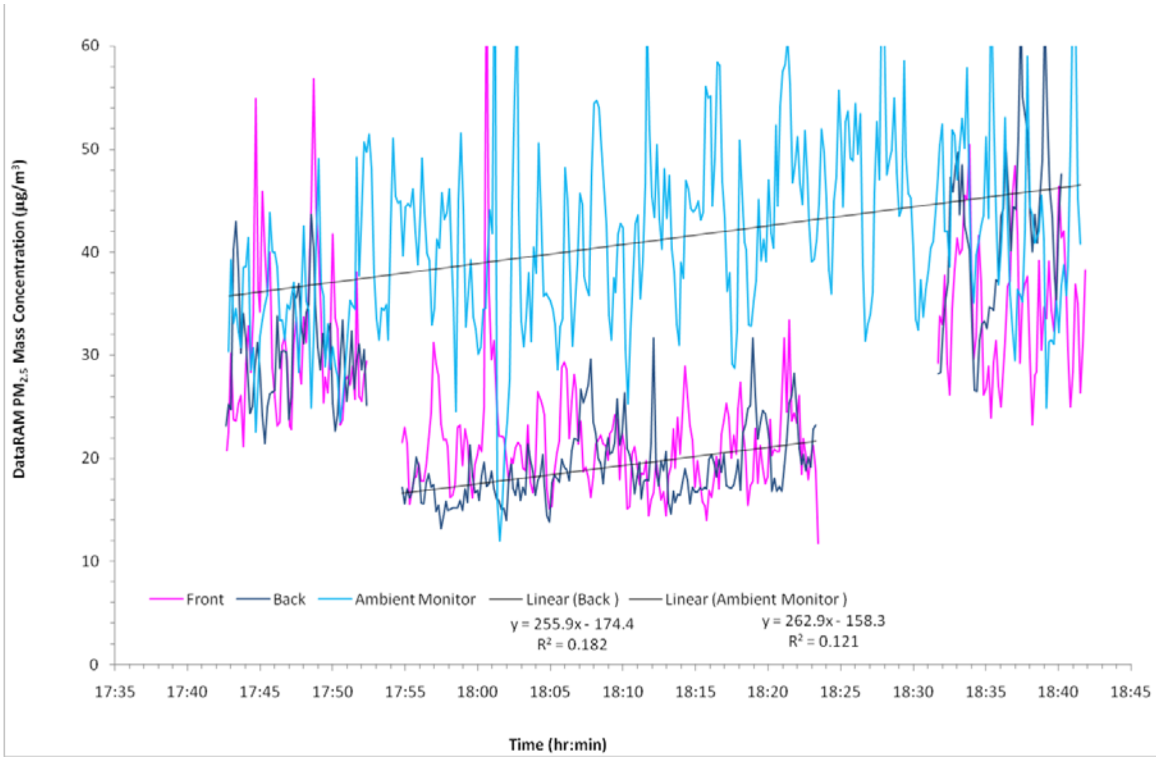

Figure 29: DataRAM results for DPF & CCVS run# 12.

Figure 29 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 sinusoidal 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 29. 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 are 263 and 256µg/m^3/min, respectively. These slopes are within 3% of each other. This shows that the particulate concentrations within the bus are tracking the ambient values and appear to not be related to self pollution from the bus.

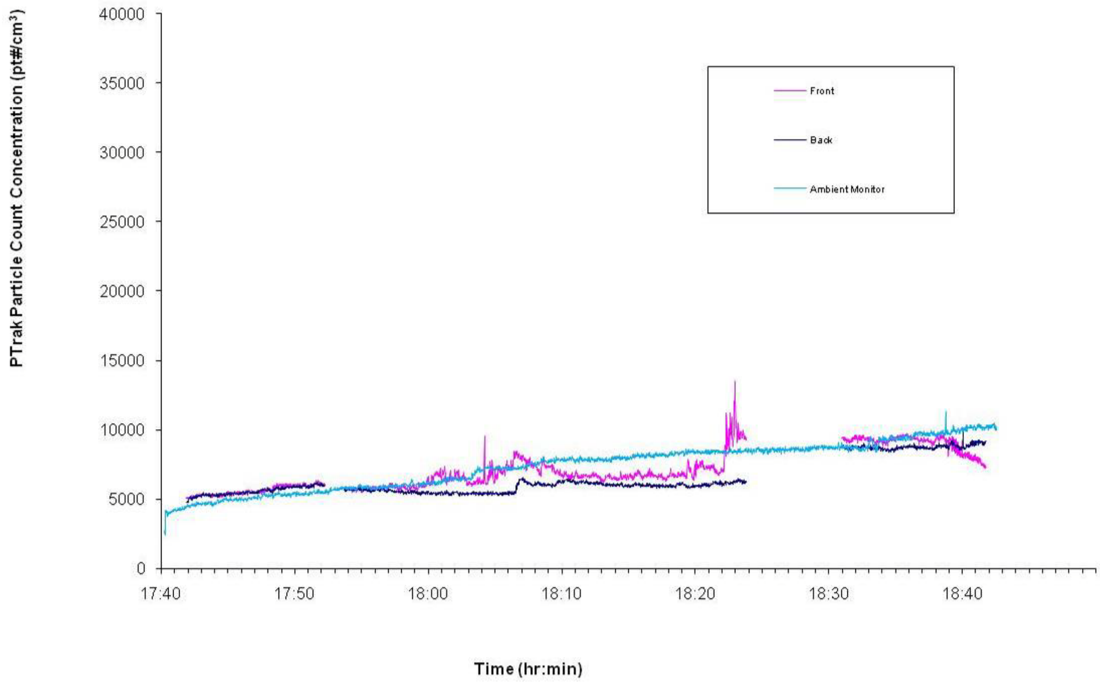

Figure 30: P-Trak results for DPF and CCVS run# 12.

Figure 30 shows the results for the particle count concentration with both the DPF and CCVS retrofits installed on the bus. 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 29 and 30 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.[28] the $PM_{2.5}$ values measured by a Dustrak had average values in the cabin of the bus being 38% higher 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[19] 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 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[12] that net pollutant levels inside a bus cabin are sometimes below outdoor ambient 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 run#3, 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.

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 particles greater than 0.1 microns (99.99% efficiency) from entering the analytical gas detection instrumentation and were replaced after each retrofit configuration. These filters give a visual indication of the efficiency of the retrofit technology.

Figure 31: SEMTECH-D filter after use with three runs with no tailpipe retrofit for baseline condition.

Figure 31 shows the SEMTECH-D filter after being used with no tailpipe retrofit. In comparison Figure 32 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 particulates exiting the tailpipe of the bus. It should be noted that the small amount of black that can be seen in Figure 32 was obtained in the removal of the filter from its housing.

Figure 32: SEMTECH-D filter after use with three runs using the DPF & CCVS retrofits configuration.

Figure 33: SEMTECH-D filter after three runs with the FTF and CCVS configuration.

Figure 33 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 only rated to capture 50% of the particulate matter and it would not be expected to visually see this difference on the outside of a filter. This device reduces PM by means of the catalyzed wire mesh structure as opposed to a DPF that traps particulate matter using a ceramic monolith.

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 variance 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 variance is given in this section. The coefficient of variance 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 variance 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 variance coefficient of 1.28%. This value is well below the 10% acceptance established in the previous QAPP for fuel consumption. The CO_2 average results was 612g/bhp-hr for all the runs, with a standard deviation of 4.63g/bhp-hr and a variance coefficient of 0.76%. This is far below the criteria of less than 8% variance of CO_2 emissions. A visual depiction of these results is presented in

Figure 34. In this figure it can be seen that all of the bars representing CO_2 emissions are essentially have identical vertical height.

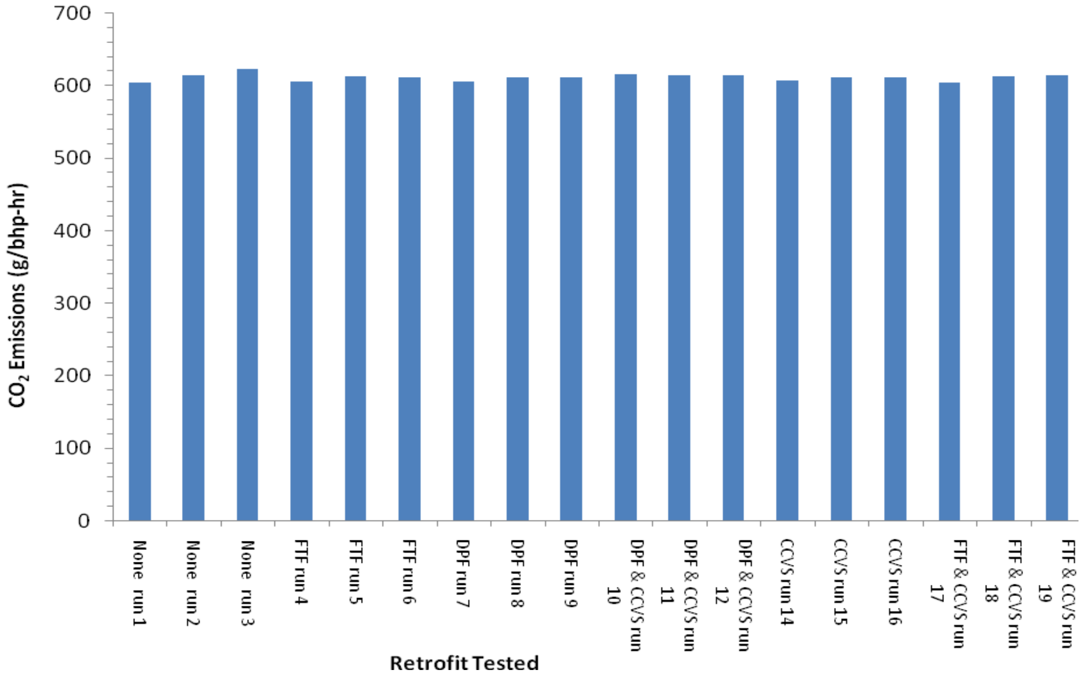

Figure 34: CO_2 emissions for all runs.

Figure 34 shows the CO_2 emissions for all the runs, the lowest value obtained was 604.7g/bhp-hr for run# 17, and the highest was 623g/bhp-hr for run# 3. 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 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 variance coefficient of 0.36%. A comparison of the speed reported by the engine control module (ECM) and the cycle is shown in Figure 35.

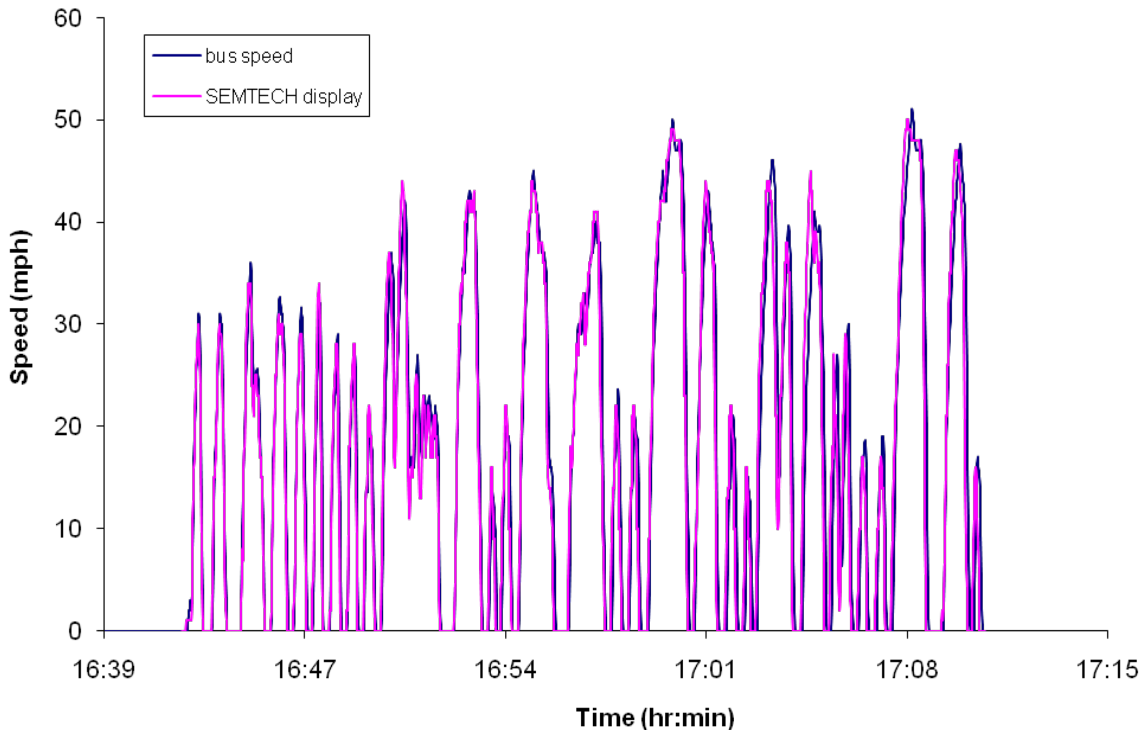

Figure 35: Bus Cycle comparison between the SEMTECH-D cycle display and the actual bus speed for run# 3.

Figure 35 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# 3 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 a single driver was employed for all of the runs.

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 36 only positive values are given, and in Figure 37 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 36, if the net value resulted in a negative value it was graphed as a value of zero and no bar appears on the chart.

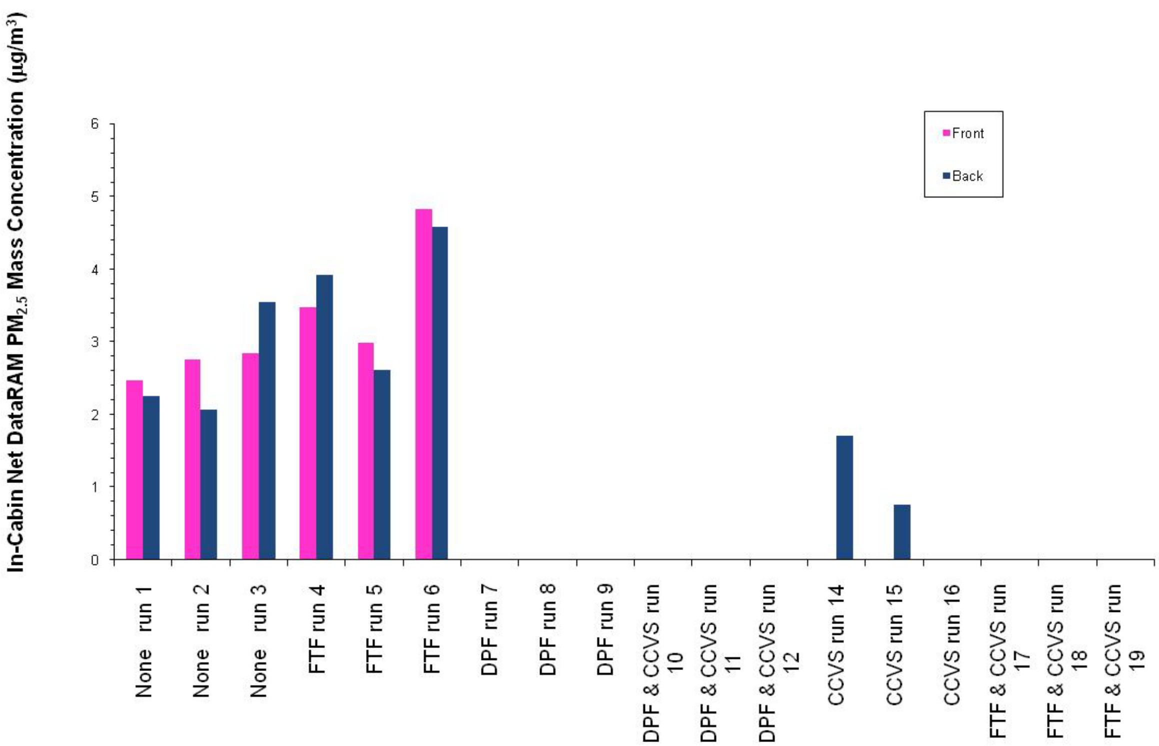

Figure 36: DataRAM results for. Net values are shown with the ambient subtracted from table ambient monitor.

Figure 36shows the DataRAM results with the ambient values subtracted. The results for the baseline runs, runs 1 to 3, have values that are slightly lower than the values from the FTF, runs 4 to 6. 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 ± 1$\mu g/m^3$, 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 7 – 19 and runs 1 – 6.

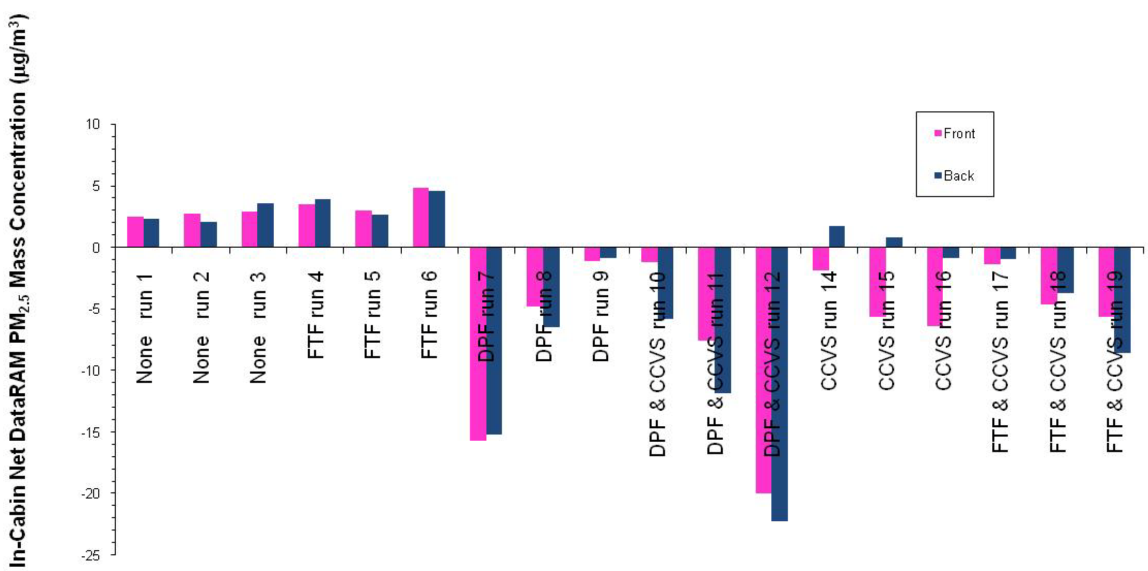

Figure 37: DataRAM net values with ambient subtracted showing the total reduction.

Figure 37 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 7 through 19 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[28] 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[7] DustTrak values of $PM_{2.5}$ for Bus 56 are shown in Table 11. 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[53] has measured exhaust plume concentrations less than the ambient for exhaust temperature less than 250 0176 when a Johnson Matthey CRT or CCRT was used.

Table 11: $PM_{2.5}$ TSI DustTrak Results for Ann Arbor, MI Bus 56[7]

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

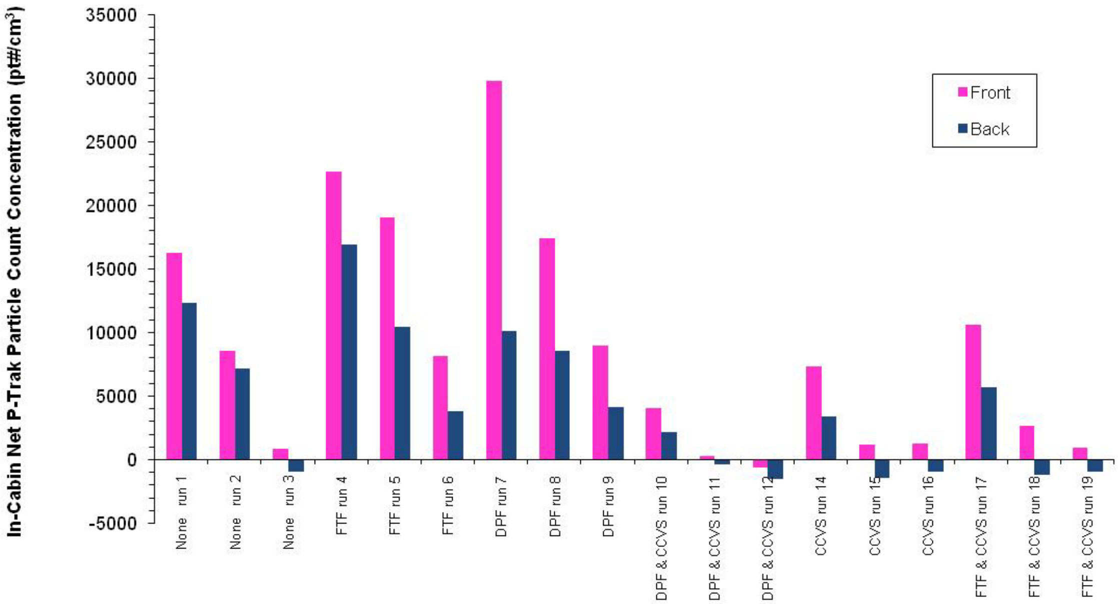

Figure 38: P-Trak net concentration results with ambient subtracted using the ambient monitor outside the bus.

Figure 38 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 1-9) show relatively high particle counts. The runs which employed the CCVS (runs 10-19) 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 between using a retrofit technologies combined with a CCVS compared to 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).[7] In this 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 12. ULSD fuel was used for all DPF retrofits, a CCVS run and a baseline study.

Table 12: Ultrafine TSI P-Trak 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 for the DPF-ULSD-CCVS are comparable to our runs with an average value for the CATF study from -1509pt#/cm^3 to 4078pt#/cm^3 with an average of 1,426 pt#/cm^3. The average value obtained for our base line run of 7,409pt#/cm^3 is much lower than the 43,040 pt#/cm^3. The CATF value for ULSD is comparable to the value for the “low” sulfur fuel baseline runs 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 study using the DPF, which ranged from 4198 to 29797pt#/cm^3.

Hammond[26] 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[27] for conventional transit buses reported values ranging from 20,000 to 450,000 pt#/cm^3 without any aftertreatment 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 treatment technology.

Particulate Matter Concentration Results – Tabular

Table 13 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 13: Net values DataRAM results with ambient monitor subtracted and particle sizes.

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

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/m³ for the back of the bus and 2.7μg/m³ for the front. For the runs using only the CCVS with no tailpipe retrofit there was an average value of 0.5μg/m³ for the back and -4.7μg/m³ for the front. The use of the FTF in combination with the CCVS gave values of -3.9μg/m³ for

[1] Incomplete ambient from table monitor station

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

Table 14: Results for 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)
1	None	28318	16272	24461	12415	12046
2	None	20717	8636	19260	7179	12082
3	None	16208	884	14394	-930	15324
4	FTF	28853	22718	23098	16963	6136
5	FTF	25380	19118	16716	10454	6261
6	FTF	17338	8223	12935	3821	9115
7	DPF	48057	29797	28449	10189	18260
8	DPF	25002	17483	16092	8574	7518
9	DPF	15351	9012	10537	4198	6338
10	DPF & CCVS	14006	4078	12173	2245	9928
11	DPF & CCVS	4745	294	4091	-359	4450
12	DPF & CCVS	6784	-555	5830	-1509	7339
14	CCVS	20220	7359	16295	3434	12861
15	CCVS	15812	1221	13165	-1426	14591
16	CCVS	14871	1317	12666	-888	13554
17	FTF & CCVS	33338	10629	28424	5715	22709
18	FTF & CCVS	20453	2741	16537	-1175	17712
19	FTF & CCVS	13671	961	11813	-896	12709

Table 14 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.

Exhaust gas pollutant emissions

The results obtained for the exhaust gas pollutant emissions measured by the SEMTECH-D gas analyzer are presented in Figure 39. This figure shows the values obtained for each technology configuration.

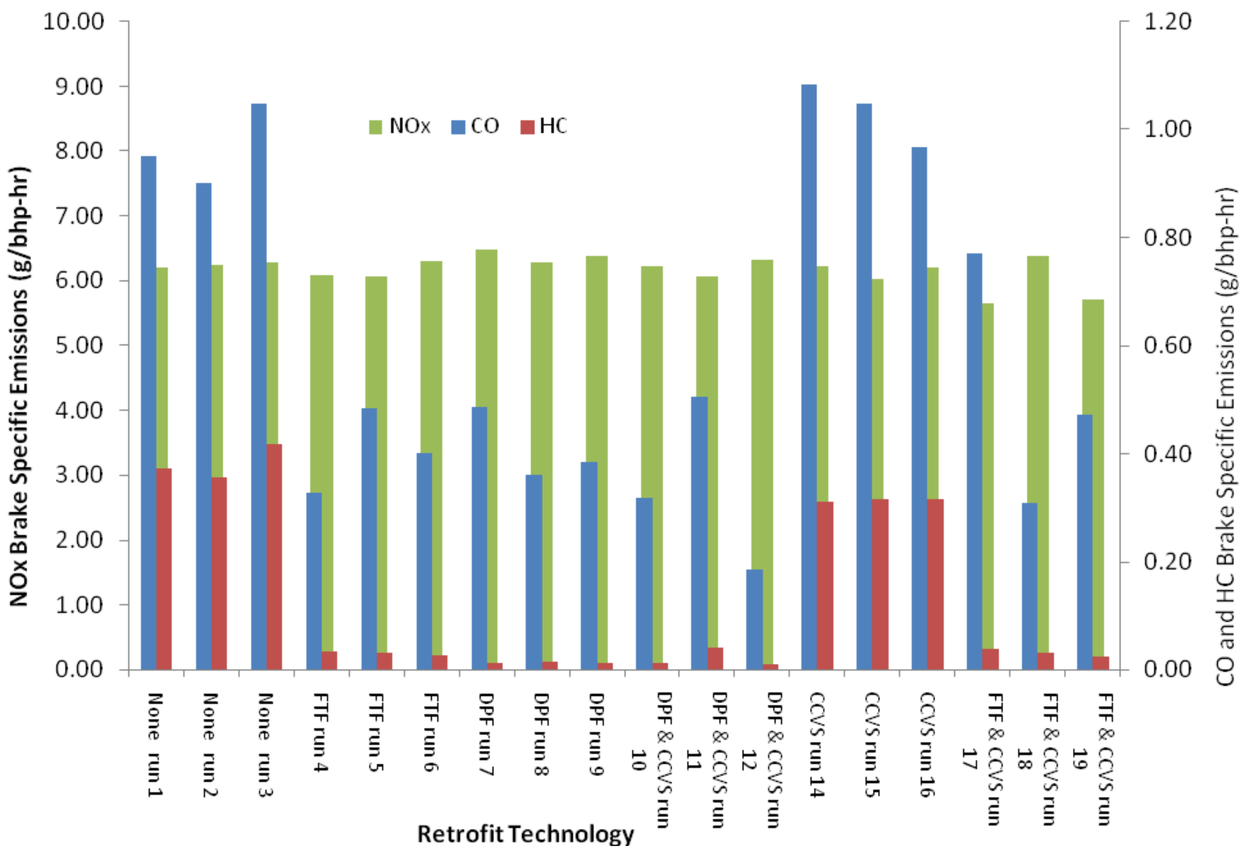

Figure 39: Gas emissions results for NO_x, CO, and HC values.

The results for NO_x are shown as green bars in Figure 39 and their numeric value is shown in the left axis. These values were obtained by adding the total NO and NO_2 measured using the SEMTECH D. From this plot it can be seen that the NO_x mass emission values are nearly identical for all retrofit technologies. This was expected since none of these technologies were designed to remove NO_x. These NO_x values also confirm the proper operation of the DPF which produces NO_2 in the first chamber of the DPF and then consumes NO2 in the second chamber in the oxidation of trapped PM.

The CO and HC values are shown in blue and red respectively and their numeric values are given in the right axis. 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 variance 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.

7. DISCUSSION AND CONCLUSIONS

An analysis of variance for the school bus runs was conducted to determine statistical difference between technologies. The ANOVA statistical tool 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 means of the variables at the 95.0% confidence level. To determine which means are significantly different from other means, 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.

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 34 and the CO and HC results were shown previously in a bar chart shown in Figure 39. All of these values were obtained from the SEMTECH D gas analyzers.

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.

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. As shown in Figure 40 the CCVS and baseline tests belong to one group while the other technologies configuration obtained similar results for CO.

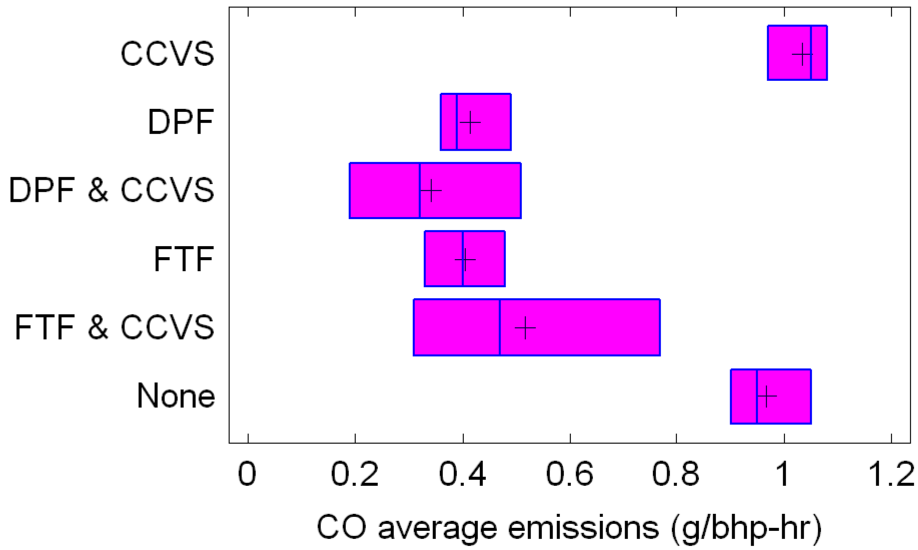

Figure 40: Box and whisker plot of average CO emissions per retrofit technology.

As presented in Table 15, 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 is important. Since the CCVS operates by filtering out large particles and returning the remaining gases and small particles back to the combustion chamber, then there is a possibility that these small particles are not completely burned in the combustion chamber and result in CO production. From these results this is not observed and the use of a CCVS does not increase CO emissions.

Table 15: 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.					

HC Emissions

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 41. 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 41, 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 technology, but not a USEPA verified technology and the hydrocarbon reduction is not reported as a certified technology. The DPF is an USEPA certified retrofit and is rated at a reduction of 95%[54]. It was also interesting to note that the CCVS alone also resulted in a significant reduction 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 gas emissions back into the inlet combustion air of 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.

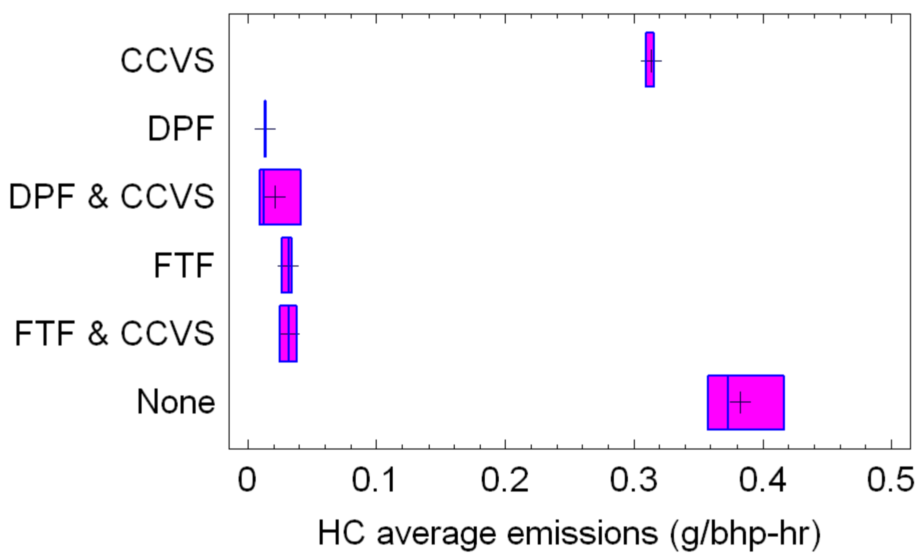

Figure 41: Box and whisker plot for average HC emissions per retrofit configuration.

As shown in Table 15, 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.

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 42. 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.

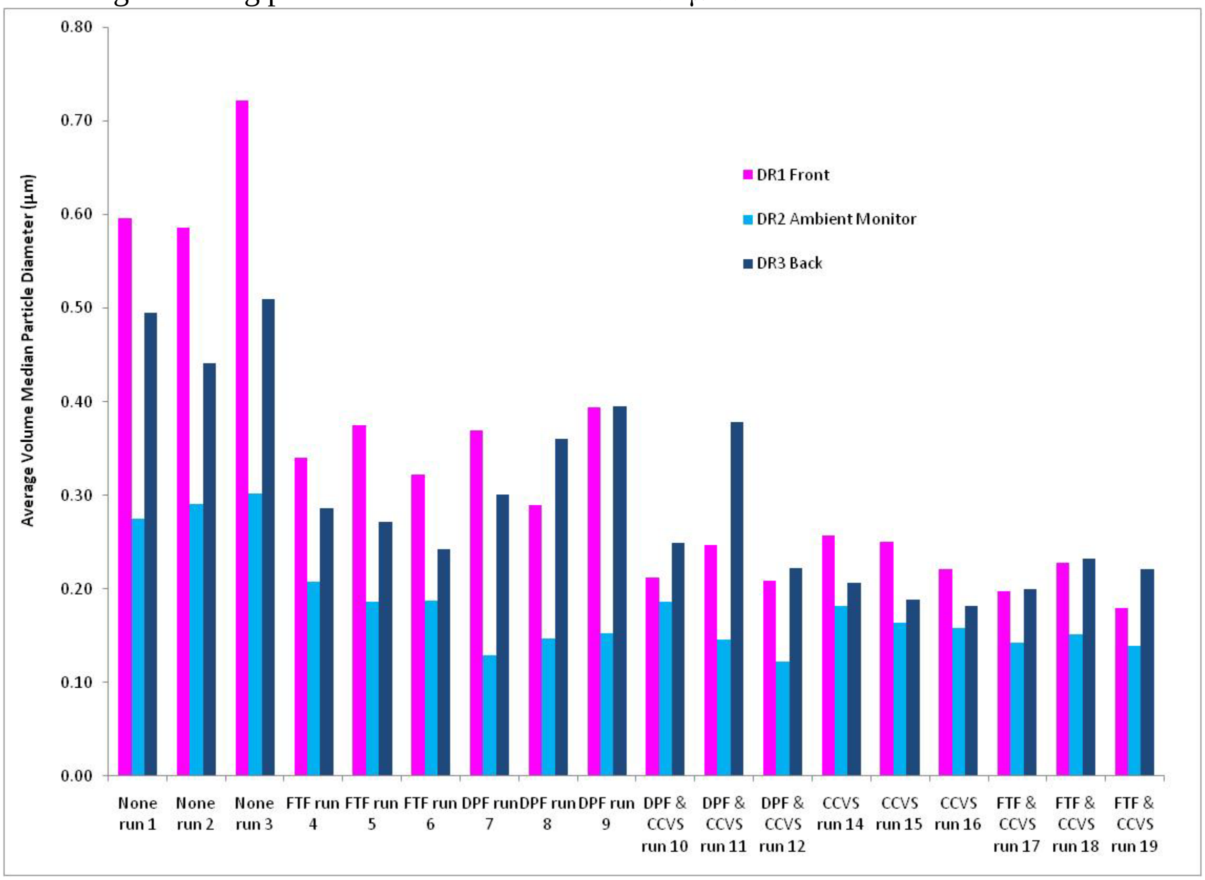

Figure 42: Comparison of average volume median particle diameters with retrofit technologies and ambient measurements.

An ANOVA was performed on this data using the averaged values calculated from instantaneous measurements for each run which are shown in Figure 42. 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.

The box and whisker plot shown in the Figure 45 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. Figure 45, shows the particle size data for the front sampling location. It can be seen that the baseline condition results in the largest particle size of 0.64µm compared to all other conditions at the 95% confidence level. When using the DPF or FTF 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 larger particles come from the crankcase and this appears to be the main source of $PM_{2.5}$.

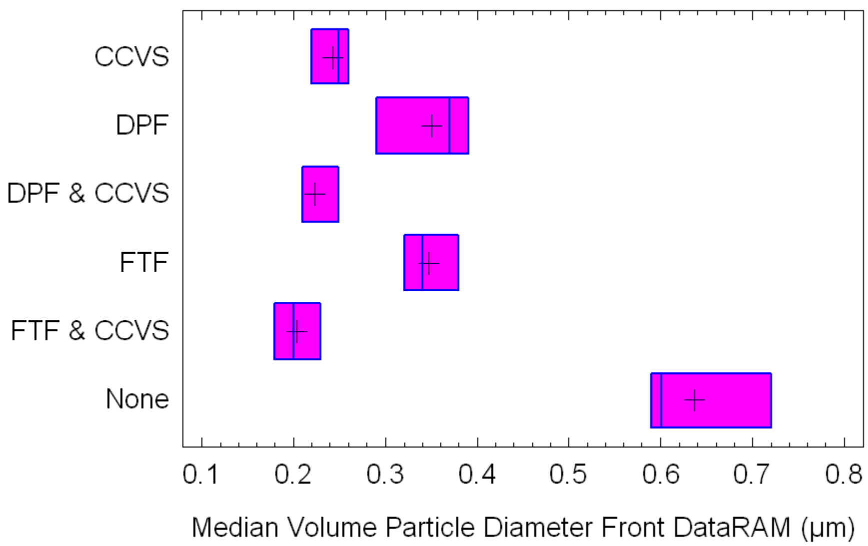

Figure 43: Box and whisker plot for particle size results from the DataRAM located in the front of the bus.

Figure 44 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 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 the figure it can be seen that the CCVS related technologies results in a lower particle size. Since particle size distributions from the crankcase vent have been measured and contain a fraction with larger particles than the exhaust, then it 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 which enter primarily through the front door which is located near the exhaust vent of the crankcase.

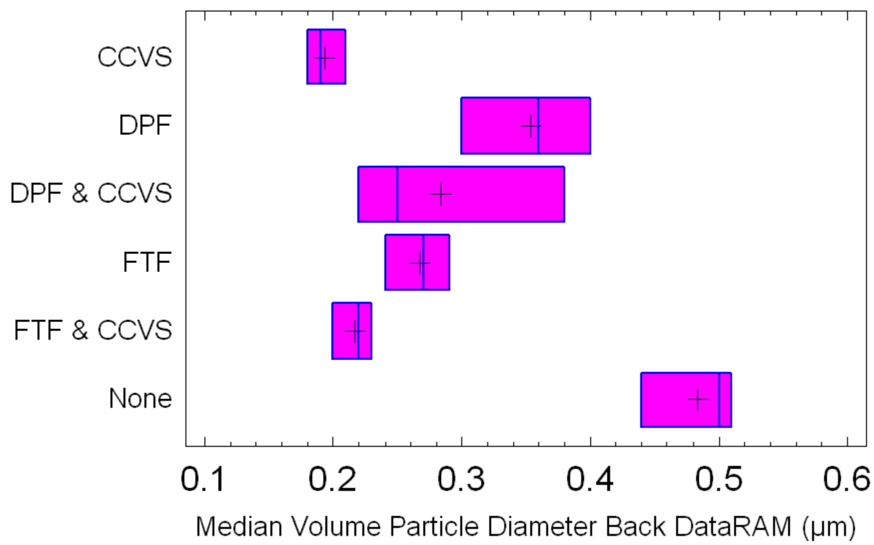

Figure 44: Box and whisker plot for particle size results from the DataRAM located in the back seat.

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

The present experimental procedure was designed for the bus running with windows closed only. This decision was made based on the preliminary 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 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 study found that the average in-cabin particulate concentrations for a bus driving on a school bus route with windows closed was 2.7 $\mu g/m^3$ as shown in Table 16. 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 calibration data presented in the section, "Calibration Particulate Instrumentation Check," this value is 1.3 to 1.8 times higher than the 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[55] 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 other point or moving sources of particulate matter.

Higher in-cabin particulate levels can be produced within a school bus then measured by this study. The mandate of this study was not to examine school bus idling, but from preliminary data it was found 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 study the school bus was idled and then driven until the engine oil temperature reached 200°F before each run.

An analysis of variance was conducted to determine if there was a statistically significant difference between the retrofit technologies and 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 16.

The P-value of the F-test for this ANOVA was less than 0.05 showing that the means of the 6 retrofit technologies contained statistically significant differences at the 95.0% confidence level. This ANOVA was 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 this analysis and the results for the in-cabin net $PM_{2.5}$ concentrations are shown Table 16 and graphically in the box and whisker plot in Figure 45.

Table 16: ANOVA 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		2			257%	48%
CCVS	-2.1		2	3		NSSD	NSSD
Baseline (None)	2.7			3	4	0%	0%
FTF	3.7				4	NSSD	NSSD

NSSD: Not statistically significantly different at the 95% confidence level
FTF: Environmental Solutions Worldwide Particulate Reactor, DPF - Johnson Matthey CRT, CCVS-Donaldson Spiracle Crankcase Ventilation System

This statistical analysis concluded that the difference in the means must be greater than the absolute value of 5.33μg/m^3. Using this value there is no statistical significant difference between the baseline and the FTF or CCVS $PM_{2.5}$ values. This can be seen in Table 16 which shows these retrofit technologies in the homogeneous groups of 3 and 4.

This can also be seen in Figure 45 in which the box and whiskers for the baseline (none) and the FTF have approximately the same average and have overlapping boxes. The box and whisker plot shown in the Figure 45 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.

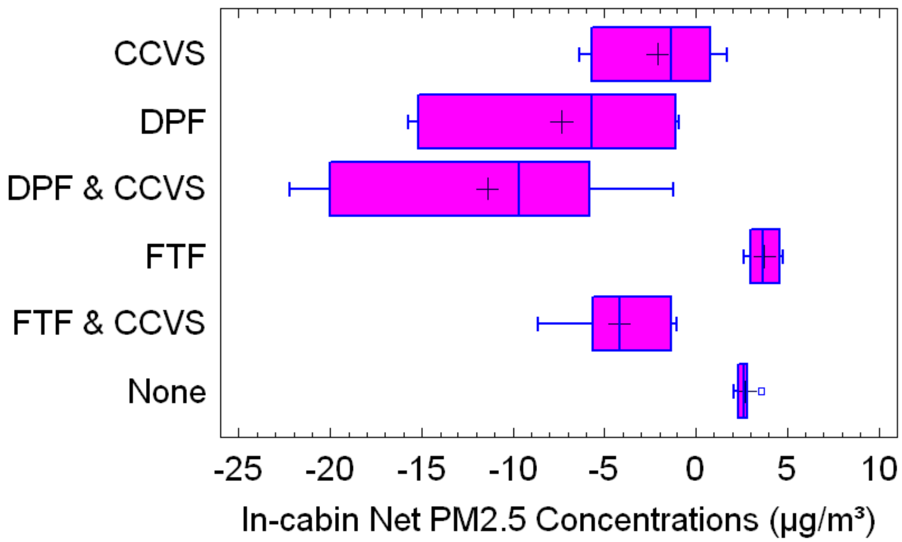

Figure 45: Box and whisker plot for in-cabin net $PM_{2.5}$concentration values.

The relative percent reduction of particulate matter concentration for each retrofit technology compared to the baseline is presented in the Table 16. 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. For the conditions in which there was no statistical significant difference between the retrofit technology and the base line then a numerical value was not presented.

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 not different from the baseline. The combined technology of the DPF and CCVS, the DPF alone and the FTF and CCVS combined.

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 46. The first major conclusion that can be drawn from this data is that the crankcase ventilation system, either alone or combined with the DPF and FTF, appears to be effective in reducing the particle number concentration. 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.

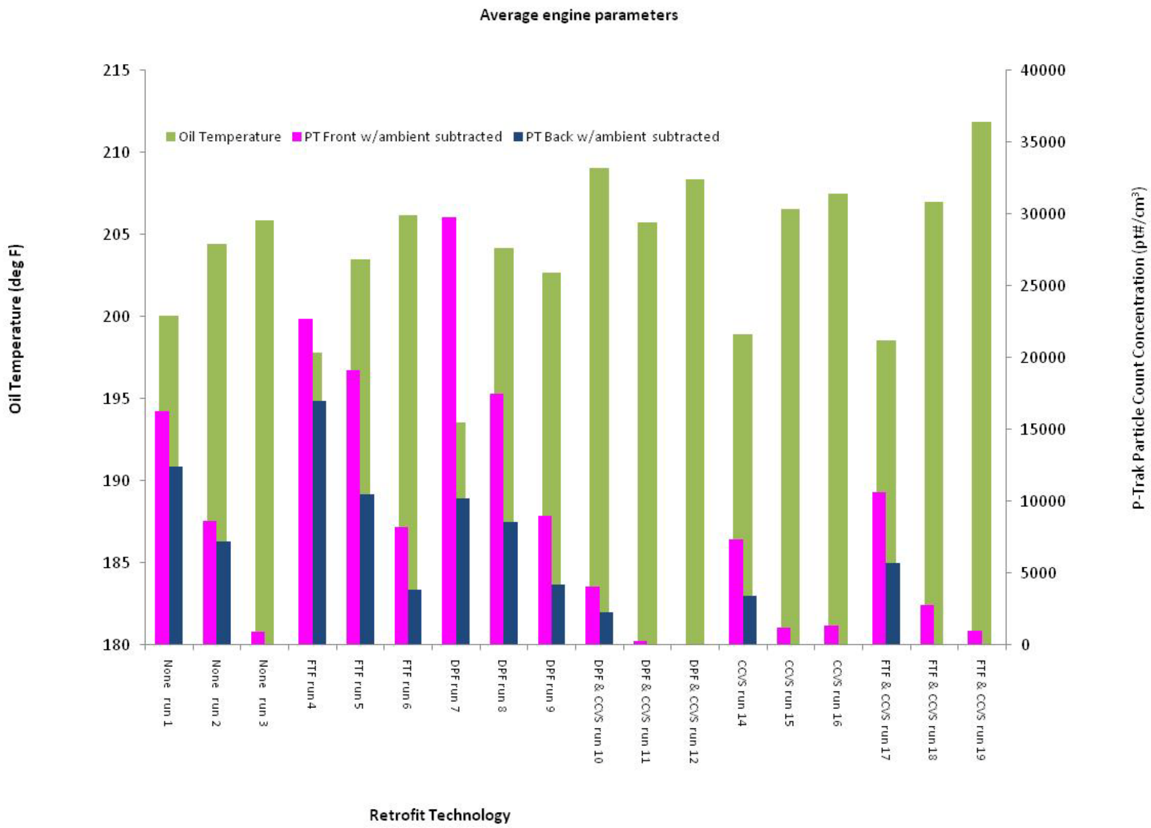

Figure 46: Trend between particle count results and engine oil temperature.

Effect of Oil temperature on Ultrafine Particle Concentration

A trend can be observed in Figure 46 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 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 decreases 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 phenomena is given by Tatli and Clark.[30] In this 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 as the engine oil temperature increases the number of particles emitted through the crankcase vent decrease.

A plot of the in-cabin net particle count concentrations as a function of engine oil temperature is given in Figure 47. 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.

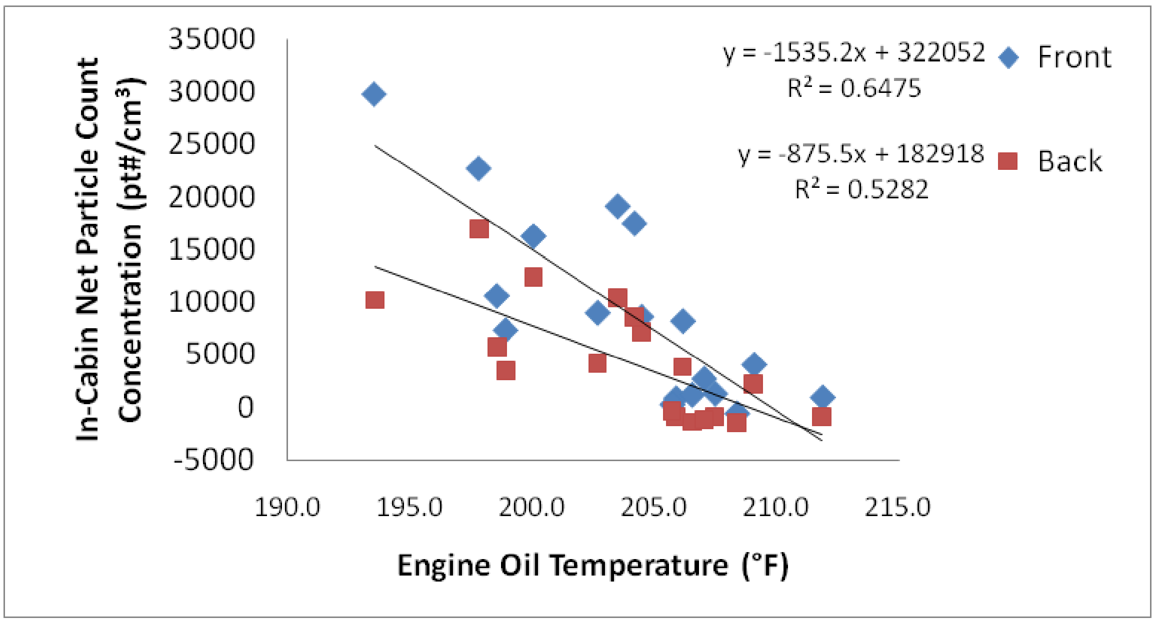

Figure 47: Effect of Engine Oil Temperature on In-Cabin Net Ultrafine Concentrations.

A detailed summary of the in-cabin particle count as a function engine oil temperature for each run is shown in Figure 48 for the front and Figure 49 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.

<u>Ultrafine Particulate Matter Reductions</u>

Unfortunately, a full analysis of the reduction in ultrafines 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 48, 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.

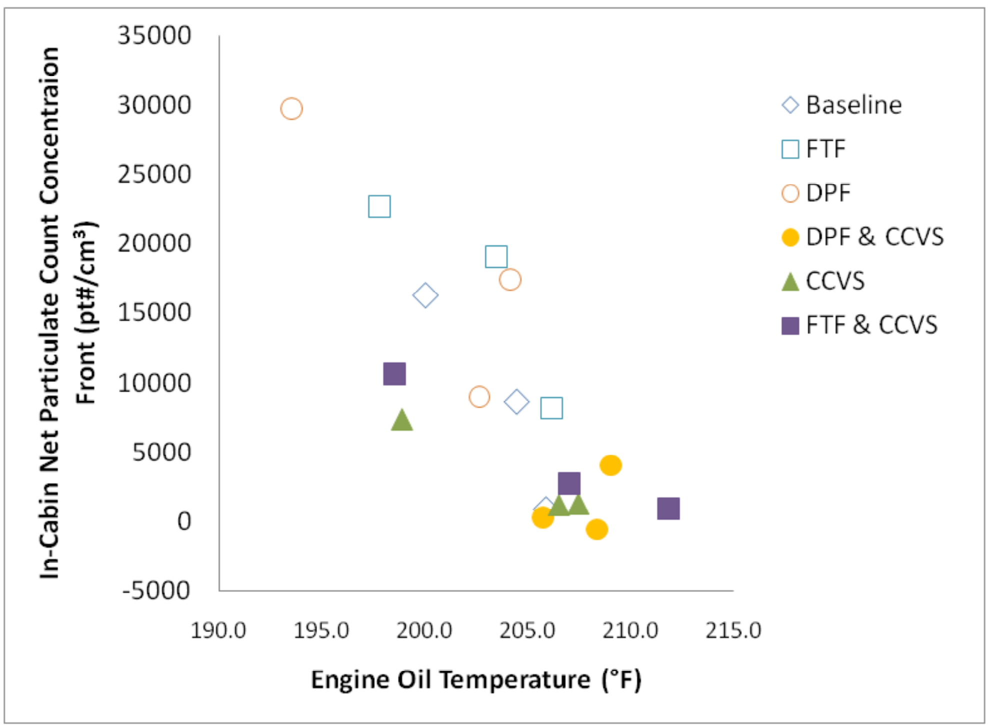

Figure 48: Detailed Summary of In-Cabin Net Particle Count Concentrations for the Front Sampling Location.

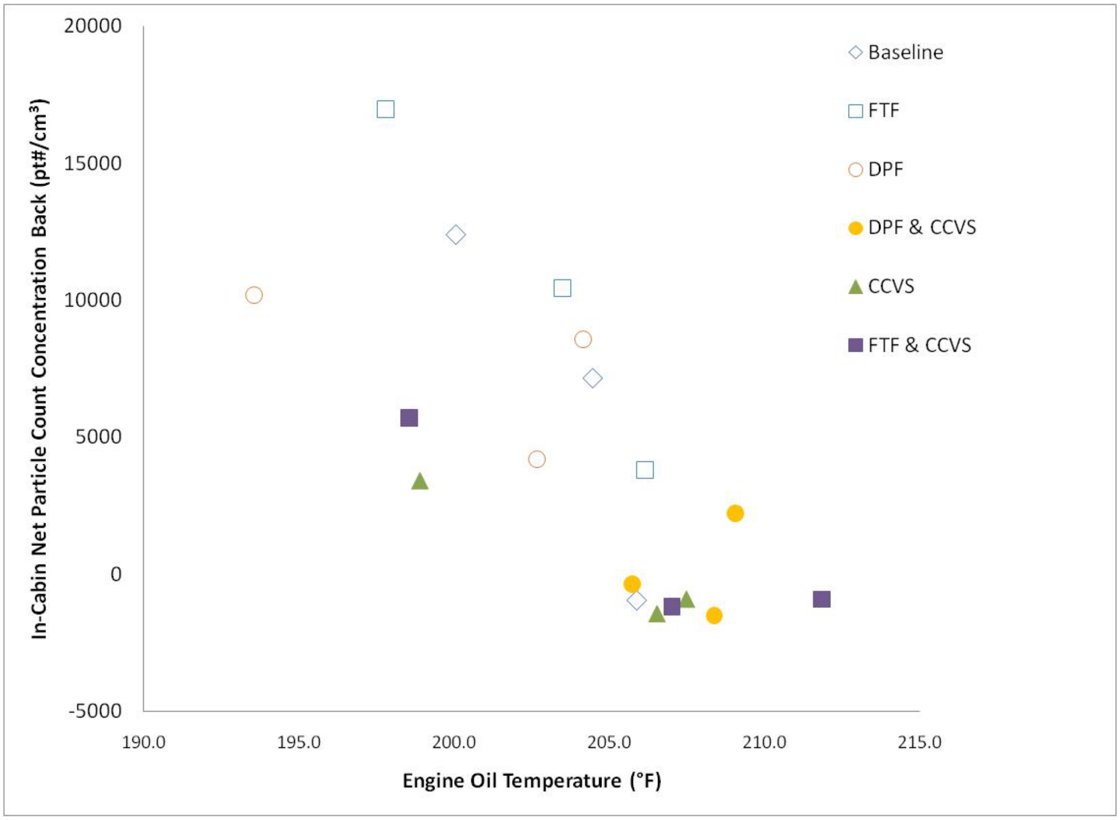

Figure 49: Detailed Summary of In-Cabin Net Particle Count Concentrations for the Back Sampling Location.

In Figure 49 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 17 and 18. 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. This 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 17 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 17: 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 18: 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 19. This was calculated by averaging the overall percent reduction values from both the front and back for a given pair of retrofit technologies.

Table 19: 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. 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 to 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.

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 was 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 was not shown from this data is the cold start emissions values. Again based on the data presented by Tatli and Clark[30] 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.

Conclusions

1. This study was designed using a testing environment and school bus that enabled in-cabin particulate measurements to be made which were free of confounding factors related to extraneous particulate production. These procedures resulted in a test track which was free of diesel pollutant sources on the track and in the near vicinity. The track was also free of road dust source because of the required power washing. The school bus was free of particulates that have 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 emissions met the rigorous state of New Jersey standards.
2. This study found that the average in-cabin particulate concentrations for a bus driving on a school bus route with windows closed was 2.7 $\mu g/m^3$ as shown in Table 16. 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 calibration data presented in the section, "Calibration Particulate Instrumentation Check," this value is 1.3 to 1.8 times higher than the 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 xx 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 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.
3. 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.
4. 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, then it 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 which enter primarily through the front door which is located near the exhaust vent of the crankcase.
5. 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. 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 approximately 50% as effective as the combined DPF-CCVS retrofit technology. It was found for $PM_{2.5}$ neither the CCVS nor the FTF were significantly better than the baseline condition of a standard bus.

6. 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 without the CCVS. The DPF or FTF used without a CCVS did not significantly reduce in-cabin net ultrafines concentrations. From these results it was determined that the use of a CCVS reduces the ultrafine particulate matter by 75% compared to the baseline condition.
7. The use of retrofit technologies resulted in large reductions of gaseous pollutants normally emitted from the tailpipe. For the operating conditions in this study all tailpipe technologies reduced CO from 50-65%. Hydrocarbons were reduced for all tailpipe retrofit technologies from 92 to 97%. This is an added benefit of using tailpipe retrofit technologies to reduce in-cabin particulate concentrations.

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Appendix A - Calibration

After the calibration 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 calibration curve of the DataRAMs.

Table 20: Results from the controlled environment tests at EOHSI.

Gravimetric method (μg/m^3)	DataRAM-4 instrument # 1 Front (μg/m^3)	DataRAM-4 instrument # 2 Ambient Monitor (μg/m^3)	DataRAM-4 instrument # 3 Back (μg/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 21: Results obtained after 6 days of continuous measurement at the ambient monitor station from the NJDEP at Camden New Jersey.

TEOM (μg/m^3)	DataRAM-4 instrument # 1 (μg/m^3)	DataRAM-4 instrument # 2 (μg/m^3)	DataRAM-4 instrument # 3 (μg/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 22: Combination set of EOHSI and NJDEP results.

Source of value	Reference (TEOM or Gravimetric) (μg/m^3)	DataRAM-4 instrument # 1 (μg/m^3)	DataRAM-4 instrument # 2 (μg/m^3)	DataRAM-4 instrument # 3 (μg/m^3)
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 calibration values obtained at EOHSI as shown in Table 22 in order to have a complete calibration 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 calibration is not. For this study most of the measurements fell in the range of the TEOM calibration.

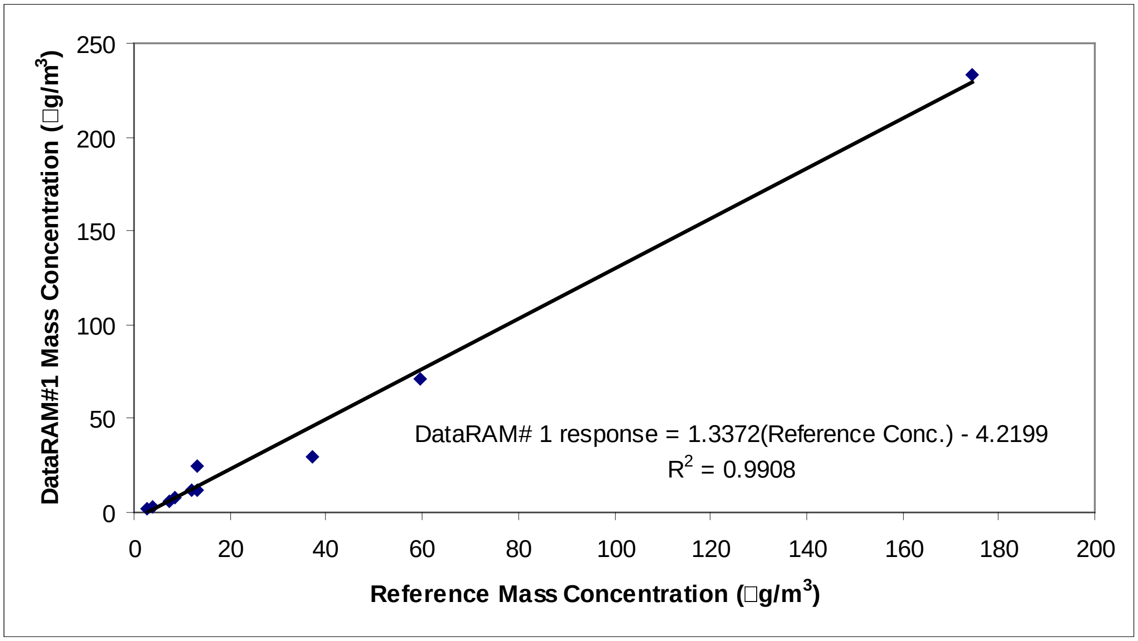


Figure 50: Calibration curve for DataRAM-4 instrument #1 from EOHSI and NJDEP tests.

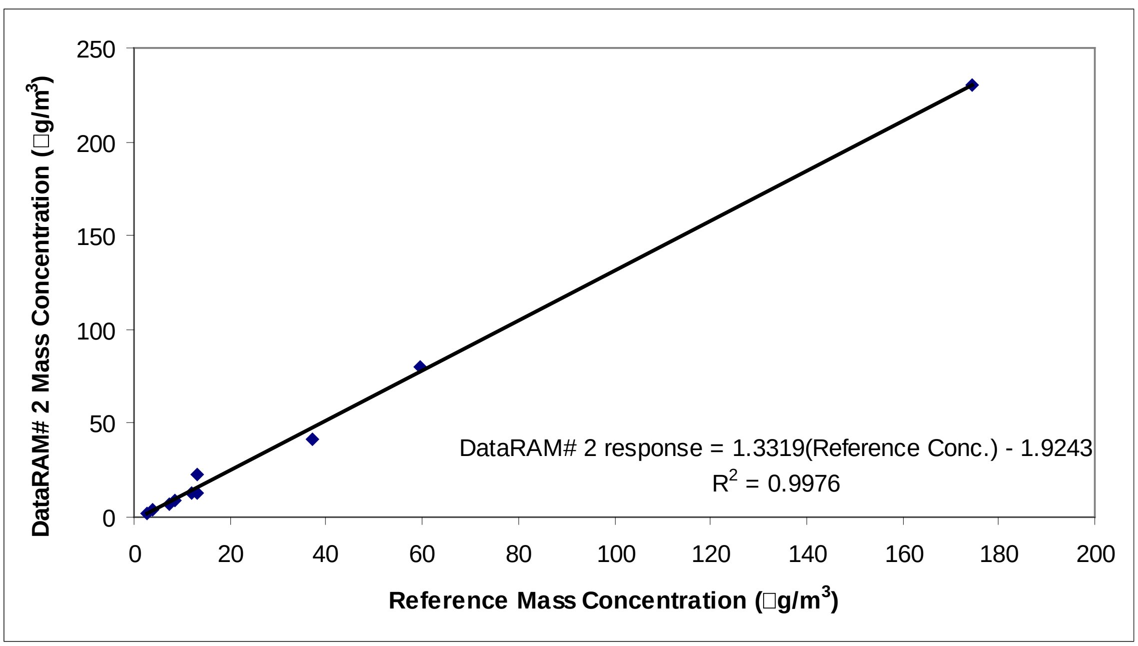


Figure 51: Calibration curve for DataRAM-4 instrument #2 from EOHSI and NJDEP tests.

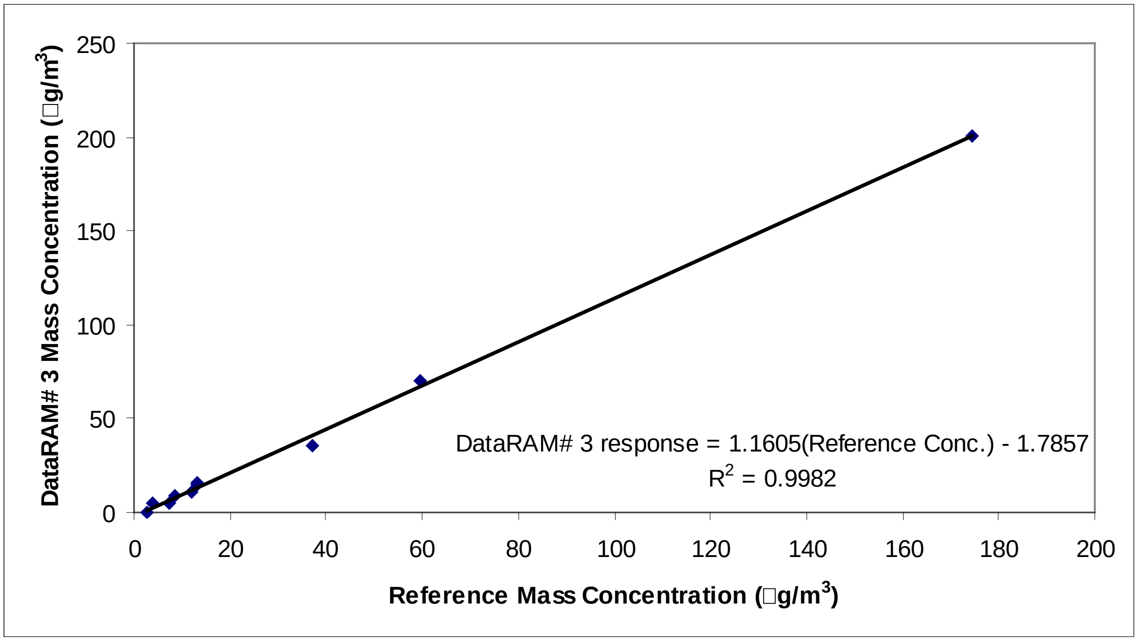


Figure 52: Calibration curve for DataRAM-4 instrument #3 from EOHSI and NJDEP tests.

The P-Trak instrumentation did not have a calibration 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 23: 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

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 ($\mu g/m^3$)	Average $PM_{2.5}$ Mass Concentration ($\mu g/m^3$)	Average $PM_{2.5}$ Mass Concentration ($\mu g/m^3$)
None run 1	5/28/2008	13:23:08	13:51:54	6.4	6.2	4.0[2]
None run 2	5/28/2008	14:21:46	14:50:32	6.9	6.2	4.1[3]
None run 3	5/28/2008	16:42:42	17:11:28	7.6	8.3	4.8
FTF run 4	5/30/2008	13:47:28	14:16:14	15.4	15.9	11.9
FTF run 5	5/30/2008	15:09:06	15:37:52	17.6	17.2	14.6[4]
FTF run 6	5/30/2008	16:23:19	16:52:05	19.1	18.9	14.3[5]
DPF run 7	6/3/2008	12:05:03	12:33:49	20.0	20.5	35.7
DPF run 8	6/3/2008	13:21:31	13:50:17	17.1	15.4	21.9
DPF run 9	6/3/2008	14:53:45	15:22:31	15.3	15.6	16.5
DPF & CCVS run 10	6/17/2008	13:59:39	14:28:25	22.5	17.9	23.7
DPF & CCVS run 11	6/17/2008	17:00:02	17:28:48	14.7	10.5	22.3
DPF & CCVS run 12	6/17/2008	17:54:37	18:23:23	21.3	19.1	41.3
FTF & CCVS run 13	6/18/2008	NA	NA	NA	NA	NA
CCVS run 14	6/19/2008	15:45:34	16:14:20	11.2	14.8	13.1
CCVS run 15	6/19/2008	16:50:10	17:18:56	13.8	20.3	19.5
CCVS run 16	6/19/2008	17:51:44	18:20:30	18.8	24.3	25.2
FTF & CCVS run 17	6/20/2008	13:49:56	14:18:42	18.7	19.1	20.1
FTF & CCVS run 18	6/20/2008	15:44:05	16:12:51	13.9	14.8	18.6
FTF & CCVS run 19	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 C: DataRAM $PM_{2.5}$ Mass Concentration Results pre and post ambient concentrations

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 1	5/28/2008	3.8	3.2
None run 2	5/28/2008	5.0	3.8
None run 3	5/28/2008	4.3	4.7
FTF run 4	5/30/2008	18.2	21.5
FTF run 5	5/30/2008	21.6	25.0
FTF run 6	5/30/2008	24.1	23.9
DPF run 7	6/3/2008	26.7	33.2
DPF run 8	6/3/2008	27.5	31.9
DPF run 9	6/3/2008	21.6	29.9
DPF & CCVS run 10	6/17/2008	27.0	25.8
DPF & CCVS run 11	6/17/2008	24.3	21.5
DPF & CCVS run 12	6/17/2008	32.8	36.1
FTF & CCVS run 13	6/18/2008	NA	NA
CCVS run 14	6/19/2008	13.3	21.9
CCVS run 15	6/19/2008	15.5	36.1
CCVS run 16	6/19/2008	17.5	47.1
FTF & CCVS run 17	6/20/2008	19.5	22.1
FTF & CCVS run 18	6/20/2008	16.0	27.3
FTF & CCVS run 19	6/20/2008	21.5	27.7

Appendix D: P-Trak Particle Count Concentration Results Raw Data

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 1	5/28/2008	13:23:08	13:51:54	28318	24461	12046
None run 2	5/28/2008	14:21:46	14:50:32	20717	19260	12082
None run 3	5/28/2008	16:42:42	17:11:28	16208	14394	15324
FTF run 4	5/30/2008	13:47:28	14:16:14	28853	23098	6136
FTF run 5	5/30/2008	15:09:06	15:37:52	25380	16716	6261
FTF run 6	5/30/2008	16:23:19	16:52:05	17338	12935	9115
DPF run 7	6/3/2008	12:05:03	12:33:49	48057	28449	18260
DPF run 8	6/3/2008	13:21:31	13:50:17	25002	16092	7518
DPF run 9	6/3/2008	14:53:45	15:22:31	15351	10537	6338
DPF & CCVS run 10	6/17/2008	13:59:39	14:28:25	14006	12173	9928
DPF & CCVS run 11	6/17/2008	17:00:02	17:28:48	4745	4091	4450
DPF & CCVS run 12	6/17/2008	17:54:37	18:23:23	6784	5830	7339
FTF & CCVS run 13	6/18/2008	NA	NA	NA	NA	NA
CCVS run 14	6/19/2008	15:45:34	16:14:20	20220	16295	12861
CCVS run 15	6/19/2008	16:50:10	17:18:56	15812	13165	14591
CCVS run 16	6/19/2008	17:51:44	18:20:30	14871	12666	13554
FTF & CCVS run 17	6/20/2008	13:49:56	14:18:42	33338	28424	22709
FTF & CCVS run 18	6/20/2008	15:44:05	16:12:51	20453	16537	17712
FTF & CCVS run 19	6/20/2008	17:14:44	17:43:30	13671	11813	12709

Appendix E: P-Trak Particle Count Concentration Results pre and post ambient concentrations

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 1	5/28/2008	24845	23737
None run 2	5/28/2008	20607	20125
None run 3	5/28/2008	15800	14815
FTF run 4	5/30/2008	7071	6840
FTF run 5	5/30/2008	8552	8194
FTF run 6	5/30/2008	8304	8164
DPF run 7	6/3/2008	13802	13927
DPF run 8	6/3/2008	10832	10758
DPF run 9	6/3/2008	7604	7035
DPF & CCVS run 10	6/17/2008	12241	12940
DPF & CCVS run 11	6/17/2008	4887	4880
DPF & CCVS run 12	6/17/2008	7320	7161
FTF & CCVS run 13	6/18/2008	NA	NA
CCVS run 14	6/19/2008	12419	11297
CCVS run 15	6/19/2008	12871	12006
CCVS run 16	6/19/2008	11249	11264
FTF & CCVS run 17	6/20/2008	30643	28811
FTF & CCVS run 18	6/20/2008	17977	16566
FTF & CCVS run 19	6/20/2008	12047	11052

Appendix F: DataRAM Results for Volume Median Particle Diameter During 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 1	5/28/2008	13:23:08	13:51:54	0.60	0.50	0.28[6]
None run 2	5/28/2008	14:21:46	14:50:32	0.59	0.44	0.29[7]
None run 3	5/28/2008	16:42:42	17:11:28	0.72	0.51	0.30
FTF run 4	5/30/2008	13:47:28	14:16:14	0.34	0.29	0.21
FTF run 5	5/30/2008	15:09:06	15:37:52	0.38	0.27	0.19[8]
FTF run 6	5/30/2008	16:23:19	16:52:05	0.32	0.24	0.19[9]
DPF run 7	6/3/2008	12:05:03	12:33:49	0.37	0.30	0.13
DPF run 8	6/3/2008	13:21:31	13:50:17	0.29	0.36	0.15
DPF run 9	6/3/2008	14:53:45	15:22:31	0.39	0.40	0.15
DPF & CCVS run 10	6/17/2008	13:59:39	14:28:25	0.21	0.25	0.19
DPF & CCVS run 11	6/17/2008	17:00:02	17:28:48	0.25	0.38	0.15
DPF & CCVS run 12	6/17/2008	17:54:37	18:23:23	0.21	0.22	0.12
FTF & CCVS run 13	6/18/2008	NA	NA	NA	NA	NA
CCVS run 14	6/19/2008	15:45:34	16:14:20	0.26	0.21	0.18
CCVS run 15	6/19/2008	16:50:10	17:18:56	0.25	0.19	0.16
CCVS run 16	6/19/2008	17:51:44	18:20:30	0.22	0.18	0.16
FTF & CCVS run 17	6/20/2008	13:49:56	14:18:42	0.20	0.20	0.14
FTF & CCVS run 18	6/20/2008	15:44:05	16:12:51	0.23	0.23	0.15
FTF & CCVS run 19	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 G: SEMTECH-D Gas Emissions Results

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 1	5/28/2008	605.0	0.95	6.20	0.373
None run 2	5/28/2008	615.0	0.90	6.25	0.357
None run 3	5/28/2008	623.0	1.05	6.28	0.417
FTF run 4	5/30/2008	605.6	0.33	6.08	0.034
FTF run 5	5/30/2008	613.3	0.48	6.07	0.032
FTF run 6	5/30/2008	612.0	0.40	6.31	0.026
DPF run 7	6/3/2008	606.5	0.49	6.48	0.013
DPF run 8	6/3/2008	611.8	0.36	6.28	0.014
DPF run 9	6/3/2008	611.1	0.39	6.39	0.013
DPF & CCVS run 10	6/17/2008	615.5	0.32	6.23	0.012
DPF & CCVS run 11	6/17/2008	614.8	0.51	6.07	0.041
DPF & CCVS run 12	6/17/2008	614.8	0.19	6.33	0.009
FTF & CCVS run 13	6/18/2008	NA	NA	NA	NA
CCVS run 14	6/19/2008	607.8	1.08	6.22	0.310
CCVS run 15	6/19/2008	611.4	1.05	6.02	0.316
CCVS run 16	6/19/2008	612.0	0.97	6.21	0.316
FTF & CCVS run 17	6/20/2008	604.7	0.77	5.64	0.038
FTF & CCVS run 18	6/20/2008	613.8	0.31	6.38	0.032
FTF & CCVS run 19	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.

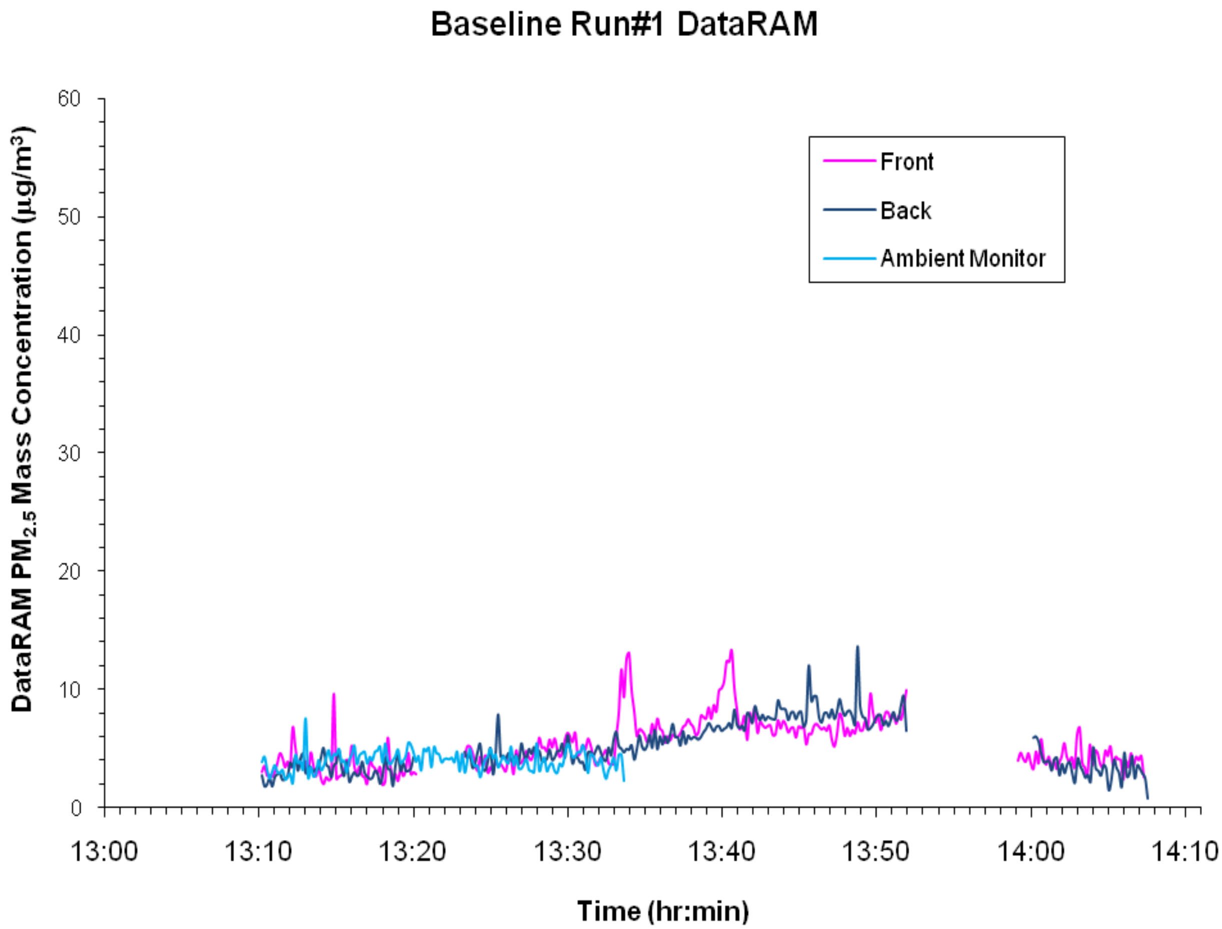
Appendix H: SEMTECH-D Engine Parameter Results

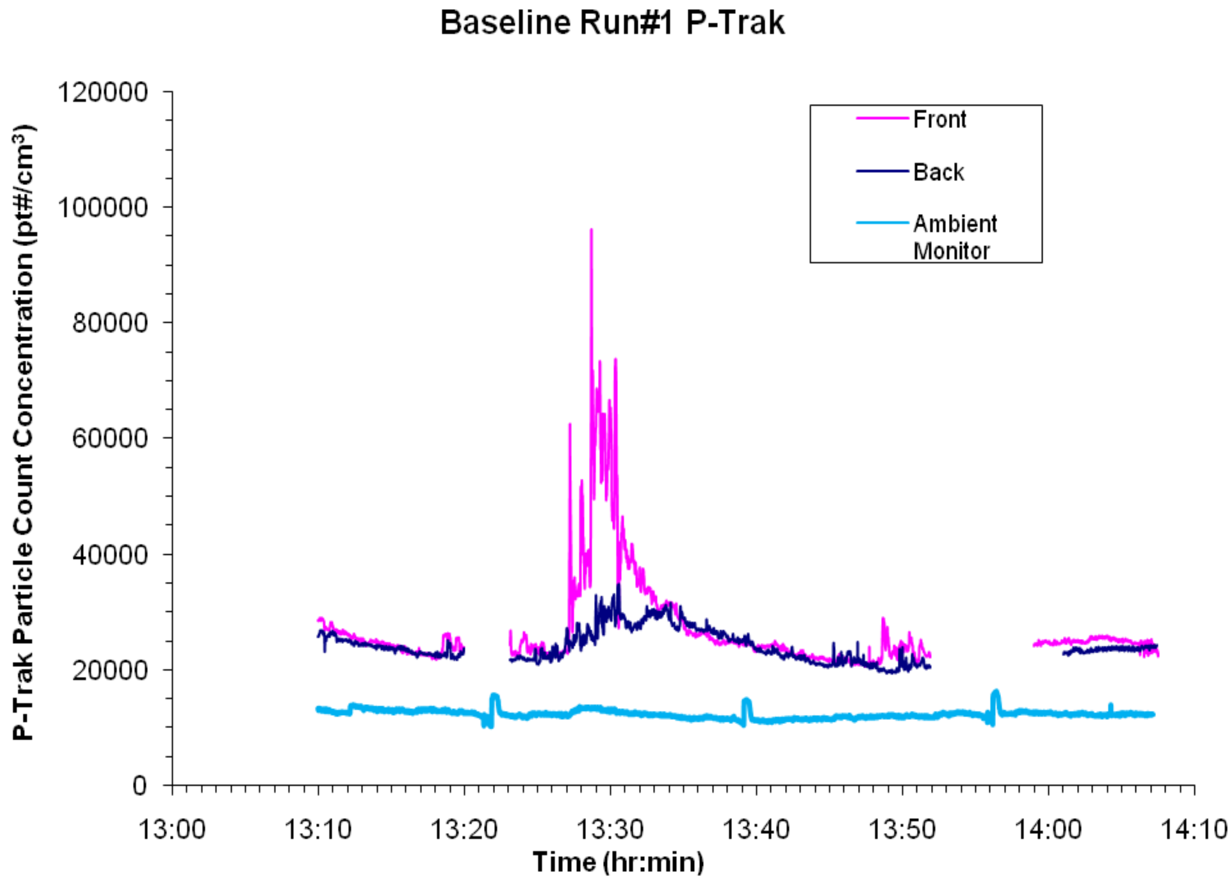
Retrofit	Date	Average oil temperature	Total Cycle Work	Average Oil Pressure	Average Boost Pressure
	mm/dd/yyyy	(ºF)	(bhp-hr)	(kPa)	(kPa)
None run 1	5/28/2008	200.0	35.9	288.8	38.5
None run 2	5/28/2008	204.5	34.7	282.7	37.3
None run 3	5/28/2008	205.9	34.5	282.4	35.9
FTF run 4	5/30/2008	197.8	35.3	298.4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

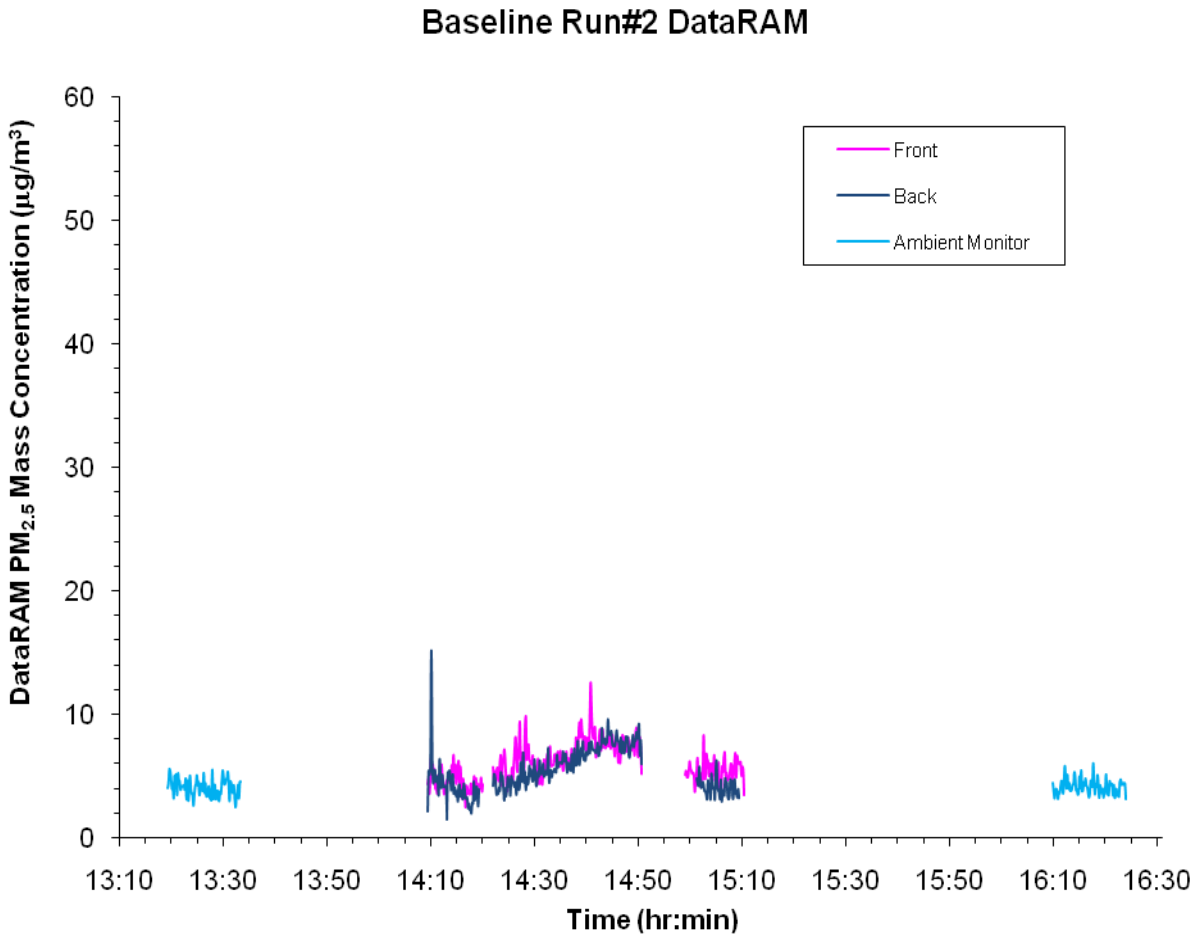
Appendix I: Weather Conditions from Portable Weather Data at the Dynamometer Track

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

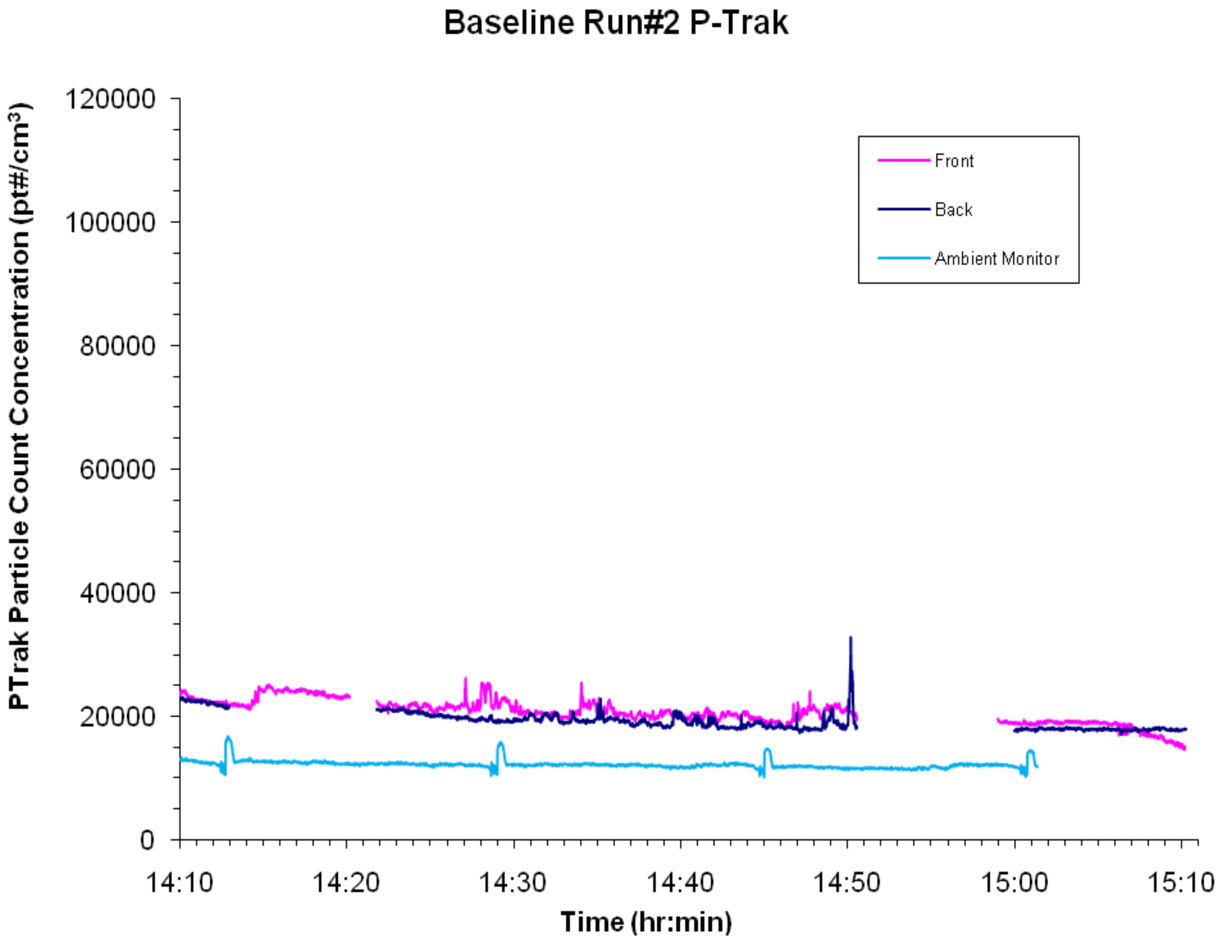
Appendix J: Real Time DataRAM and P-Trak Charts for Runs

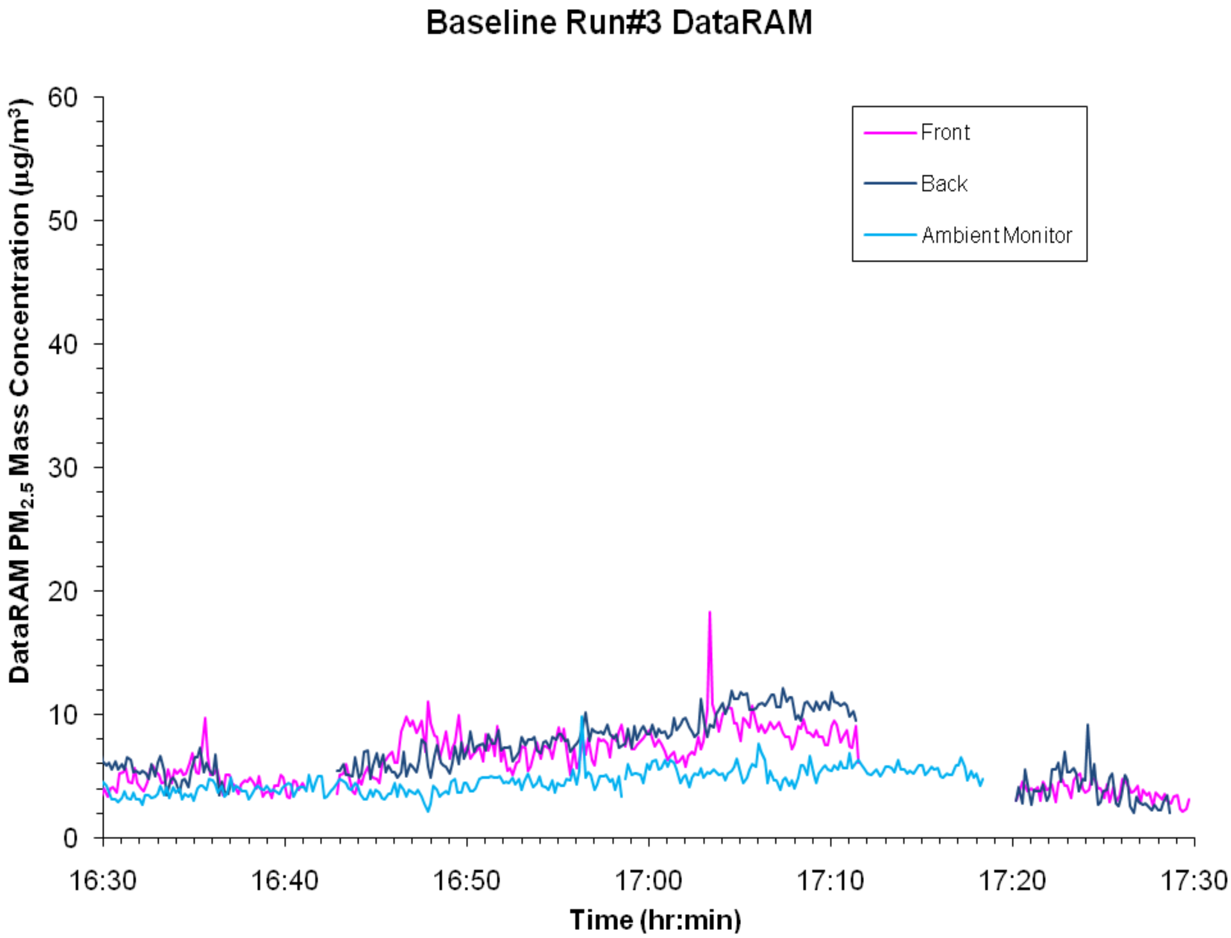


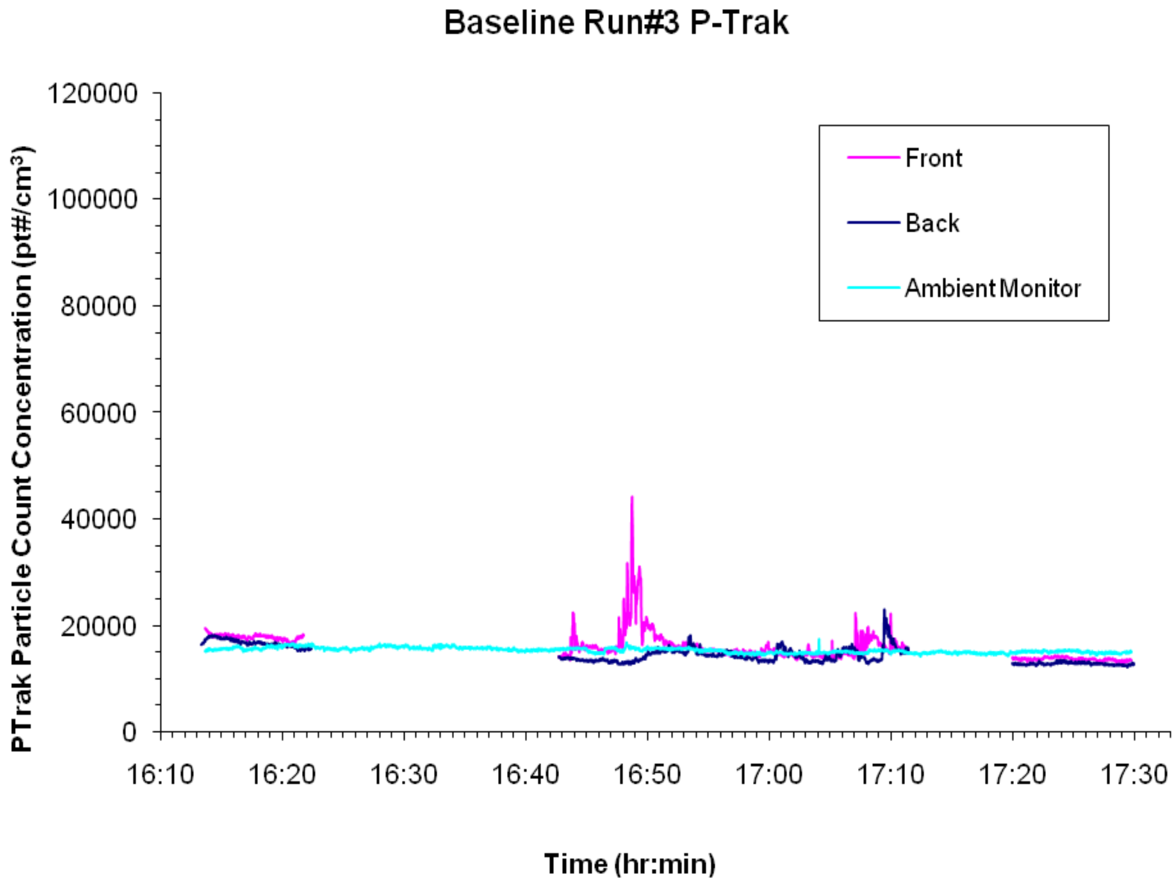

Baseline Run#1 P-Trak
P-Trak Particle Count Concentration (pt#/cm³)
120000
100000
80000
60000
40000
20000
0
13:00
13:10
13:20
13:30
13:40
13:50
14:00
14:10
Time (hr:min)
Front
Back
Ambient Monitor



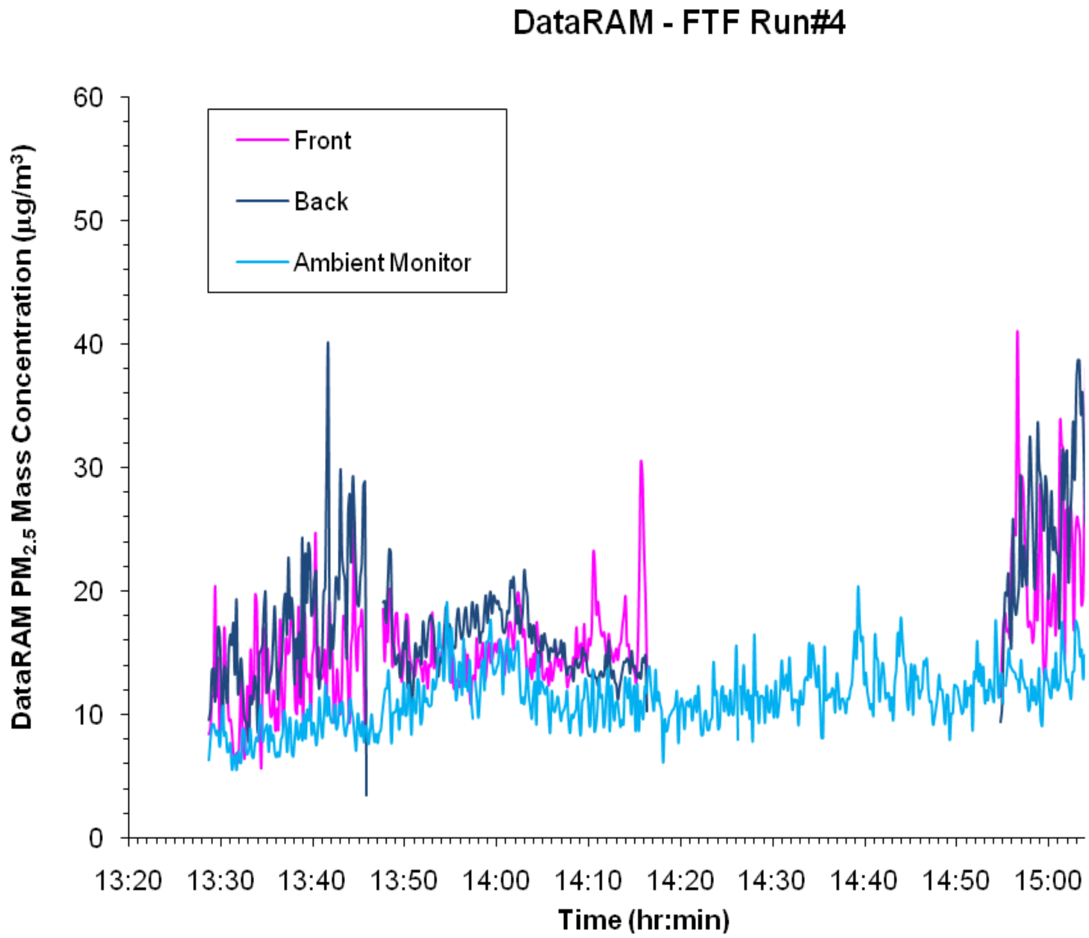
Baseline Run#2 DataRAM
DataRAM PM2.5 Mass Concentration (µg/m3)
0
10
20
30
40
50
60
Front
Back
Ambient Monitor
13:10
13:30
13:50
14:10
14:30
14:50
15:10
15:30
15:50
16:10
16:30
Time (hr:min)

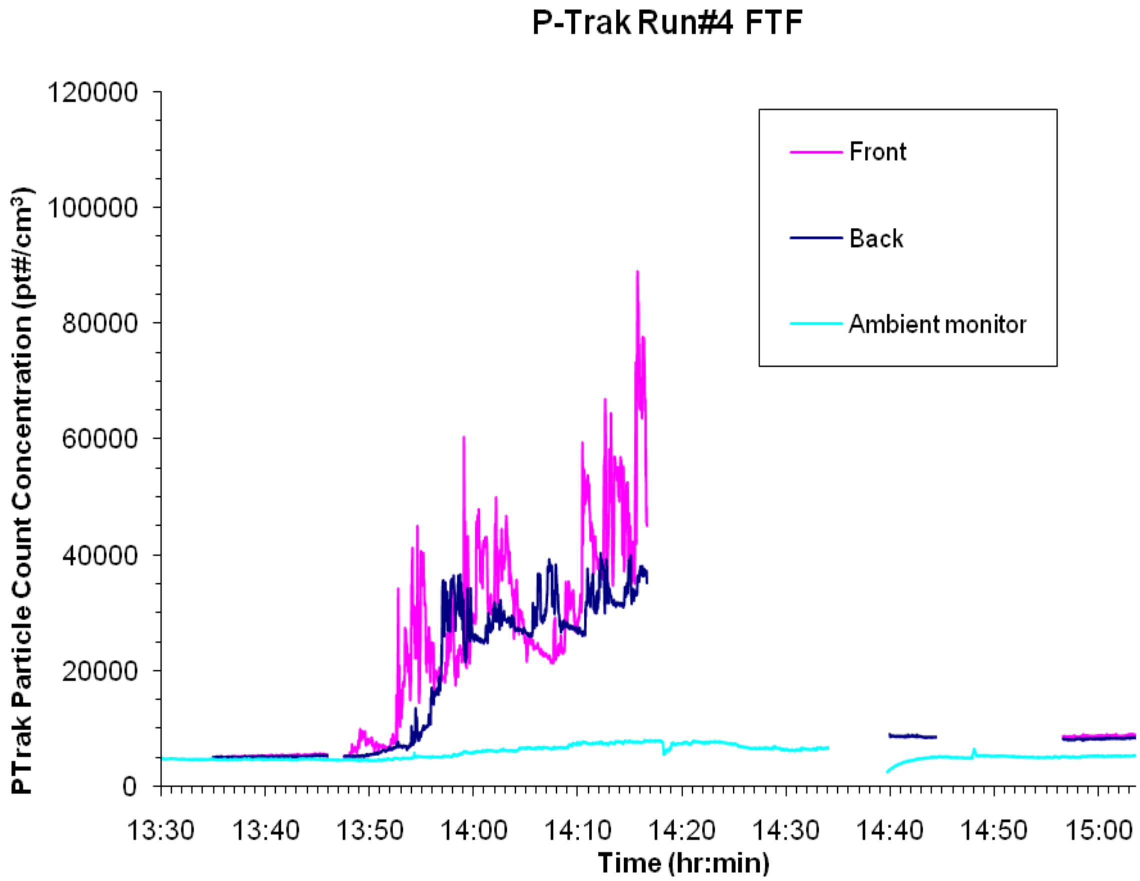

Baseline Run#2 P-Trak
PTrak Particle Count Concentration (pt#/cm³)
120000
100000
80000
60000
40000
20000
0
14:10
14:20
14:30
14:40
14:50
15:00
15:10
Time (hr:min)
Front
Back
Ambient Monitor


Baseline Run#3 DataRAM
DataRAM PM2.5 Mass Concentration (µg/m3)
60
50
40
30
20
10
0
16:30
16:40
16:50
17:00
17:10
17:20
17:30
Time (hr:min)
Front
Back
Ambient Monitor

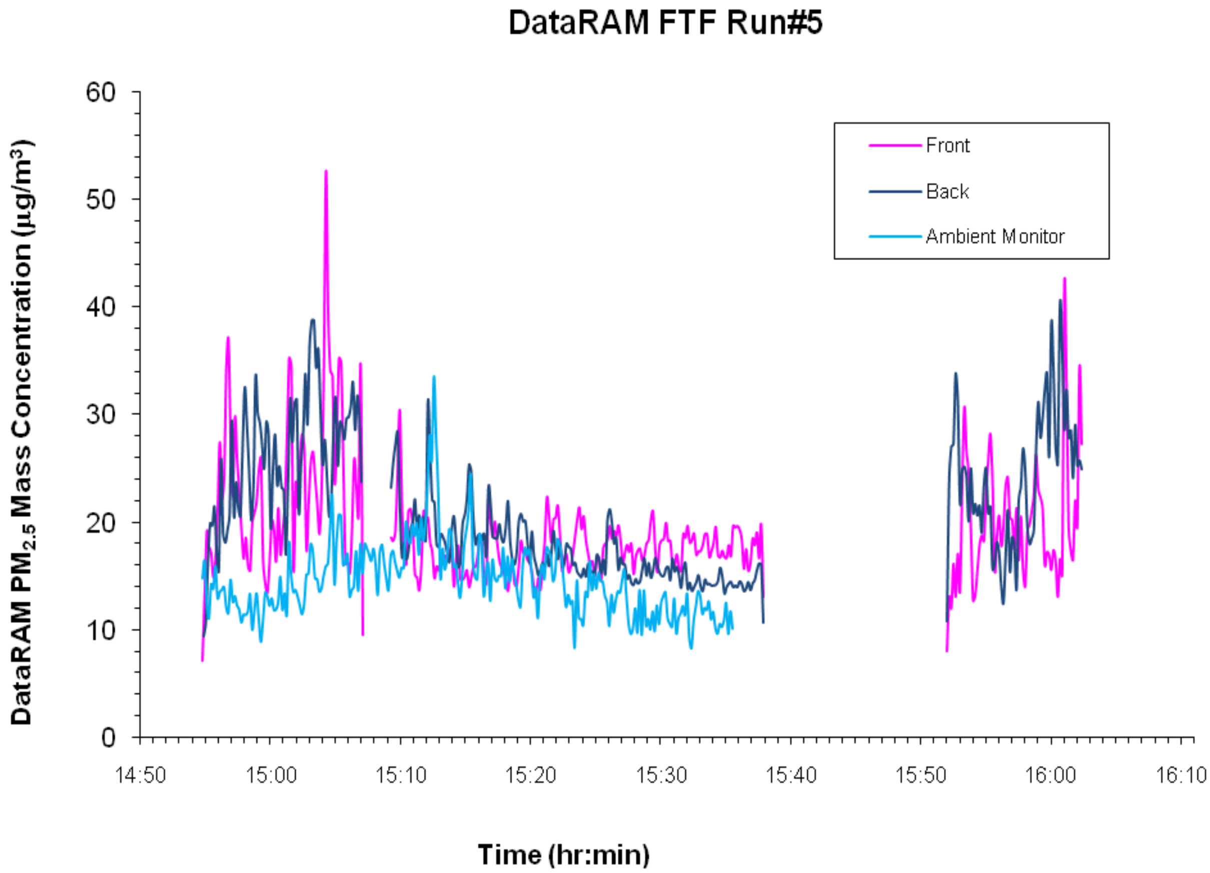


Baseline Run#3 P-Trak
PTrak Particle Count Concentration (pt#/cm³)
120000
100000
80000
60000
40000
20000
0
16:10
16:20
16:30
16:40
16:50
17:00
17:10
17:20
17:30
Time (hr:min)
Front
Back
Ambient Monitor

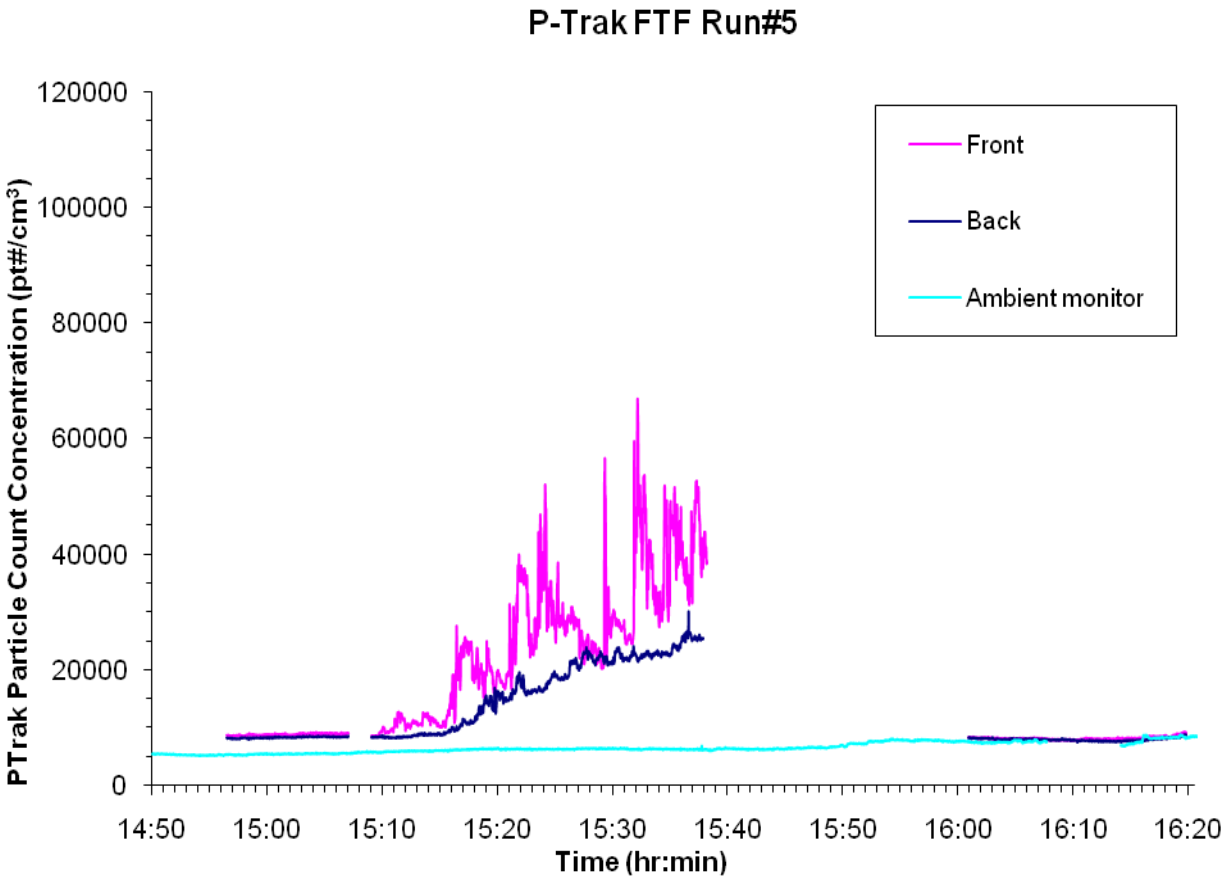

DataRAM - FTF Run#4
Front
Back
Ambient Monitor
DataRAM PM2.5 Mass Concentration (µg/m3)
60
50
40
30
20
10
0
13:20
13:30
13:40
13:50
14:00
14:10
14:20
14:30
14:40
14:50
15:00
Time (hr:min)



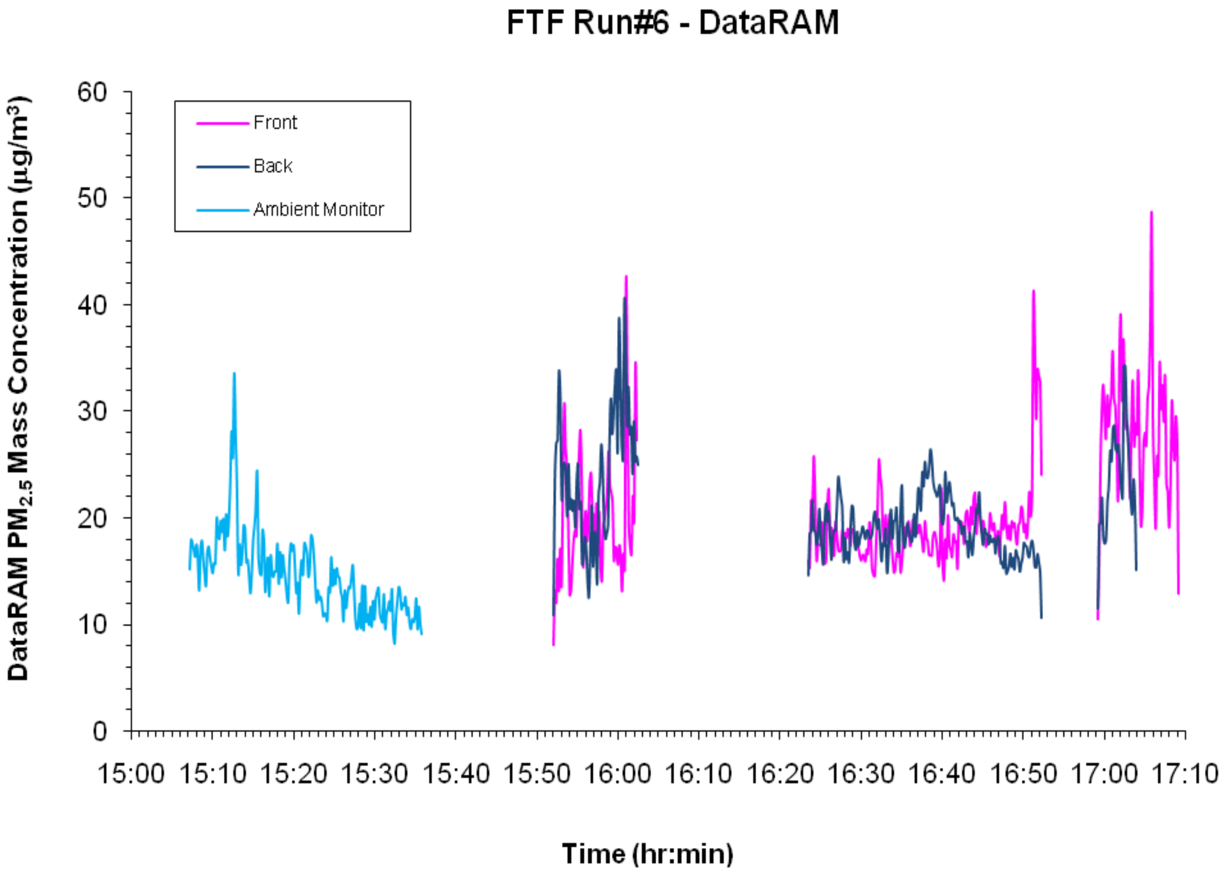
P-Trak Run#4 FTF
PTrak Particle Count Concentration (pt#/cm³)
120000
100000
80000
60000
40000
20000
0
13:30
13:40
13:50
14:00
14:10
14:20
14:30
14:40
14:50
15:00
Time (hr:min)
Front
Back
Ambient monitor



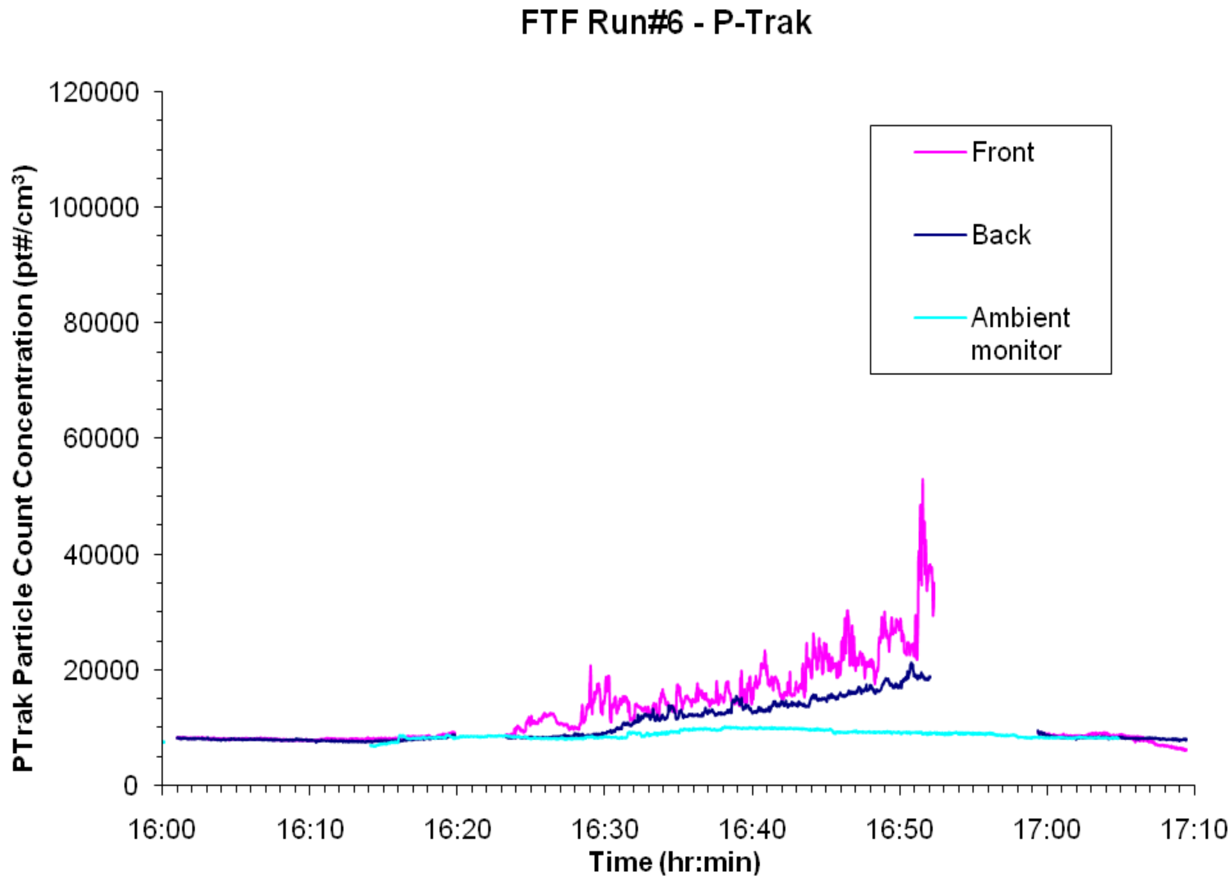
DataRAM FTF Run#5
DataRAM PM$_{2.5}$ Mass Concentration (µg/m^3)
60
50
40
30
20
10
0
14:50
15:00
15:10
15:20
15:30
15:40
15:50
16:00
16:10
Time (hr:min)
Front
Back
Ambient Monitor

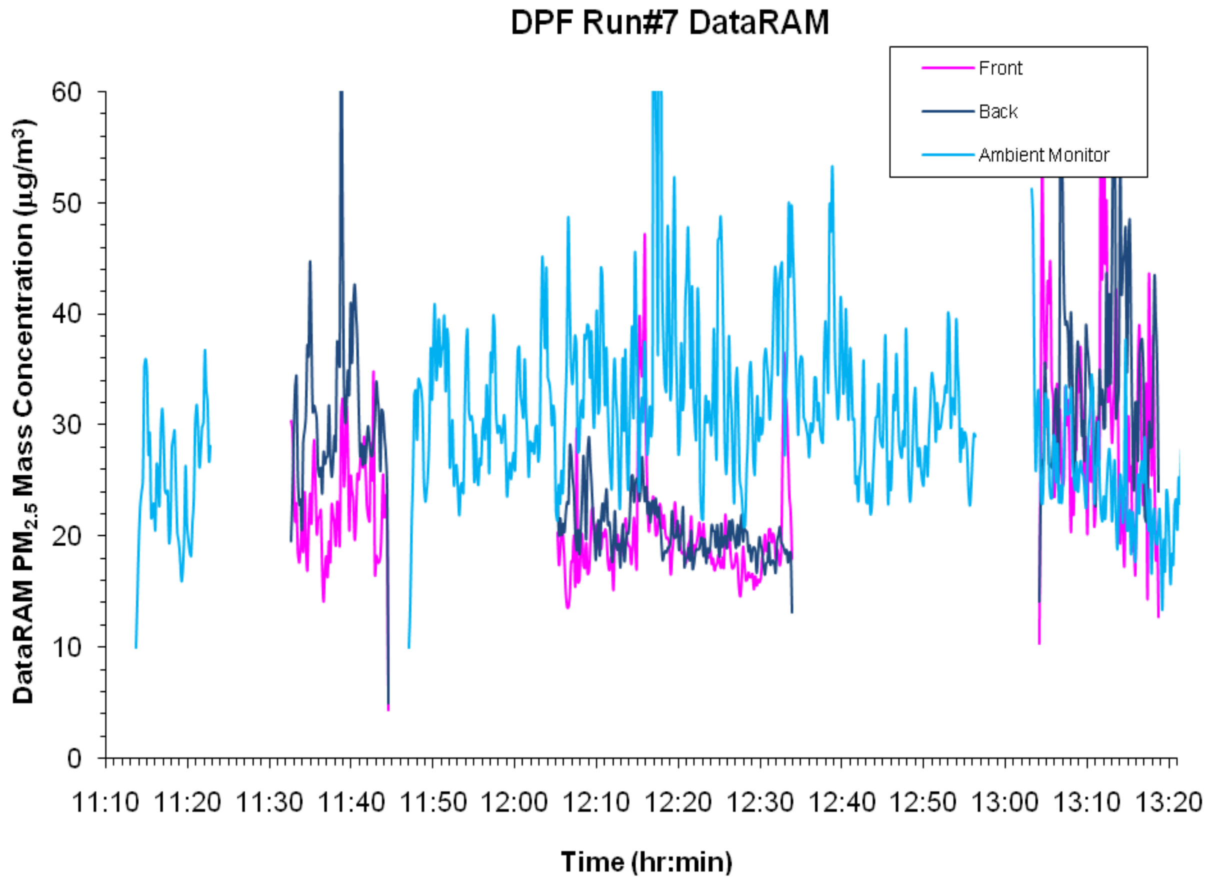


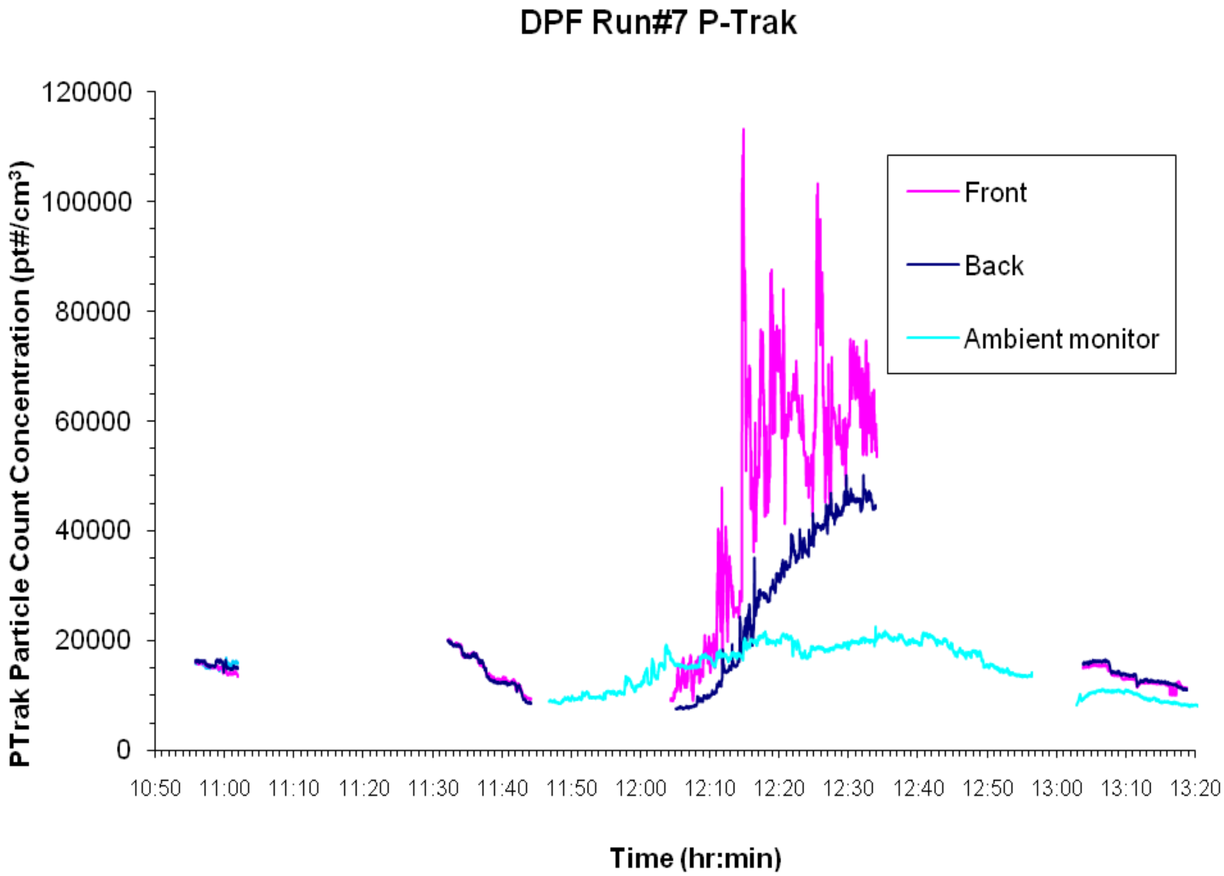
P-Trak FTF Run#5
PTrak Particle Count Concentration (pt#/cm³)
120000
100000
80000
60000
40000
20000
0
14:50
15:00
15:10
15:20
15:30
15:40
15:50
16:00
16:10
16:20
Time (hr:min)
Front
Back
Ambient monitor



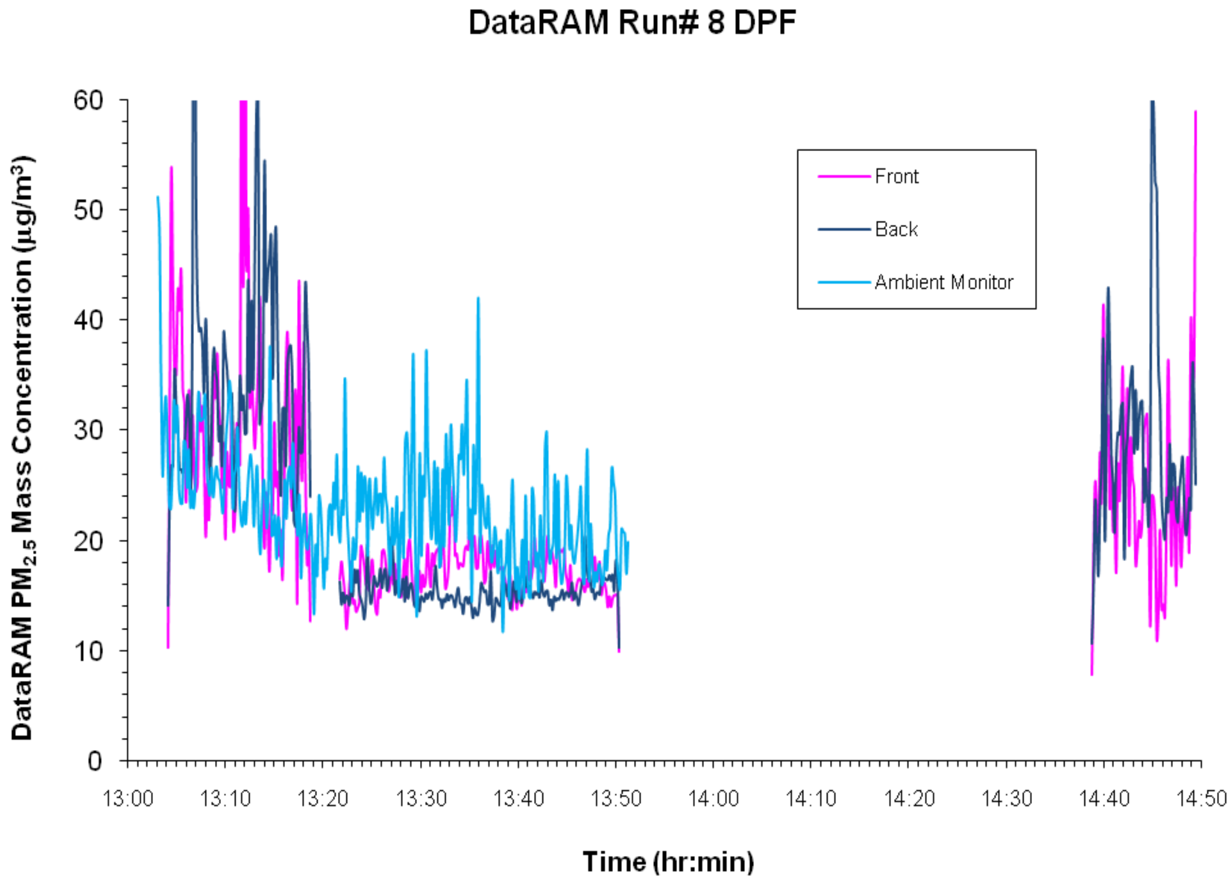
FTF Run#6 - DataRAM
DataRAM PM2.5 Mass Concentration (µg/m³)
Front
Back
Ambient Monitor
0
10
20
30
40
50
60
15:00
15:10
15:20
15:30
15:40
15:50
16:00
16:10
16:20
16:30
16:40
16:50
17:00
17:10
Time (hr:min)

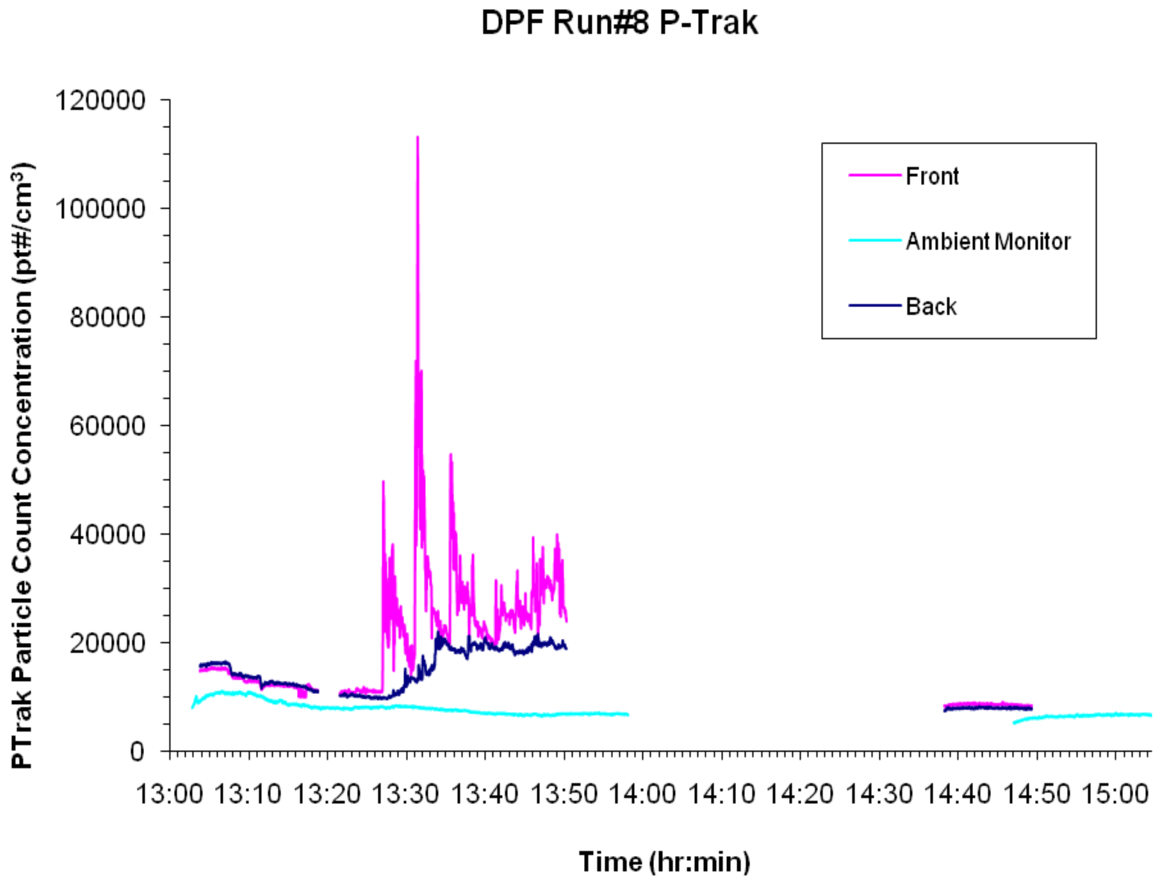

FTF Run#6 - P-Trak
PTrak Particle Count Concentration (pt#/cm³)
120000
100000
80000
60000
40000
20000
0
16:00
16:10
16:20
16:30
16:40
16:50
17:00
17:10
Time (hr:min)
Front
Back
Ambient monitor

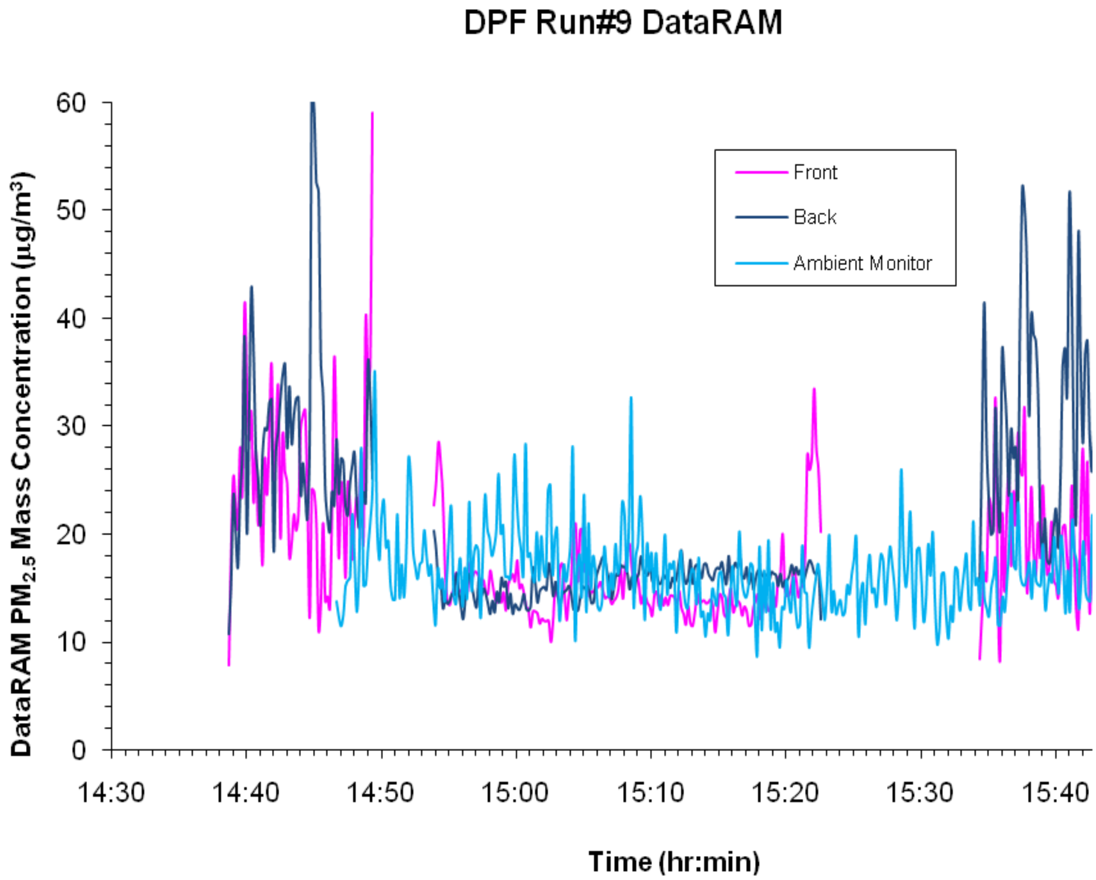

DPF Run#7 DataRAM
Front
Back
Ambient Monitor
DataRAM PM$_{2.5}$ Mass Concentration (μg/m^3)
0
10
20
30
40
50
60
11:10
11:20
11:30
11:40
11:50
12:00
12:10
12:20
12:30
12:40
12:50
13:00
13:10
13:20
Time (hr:min)



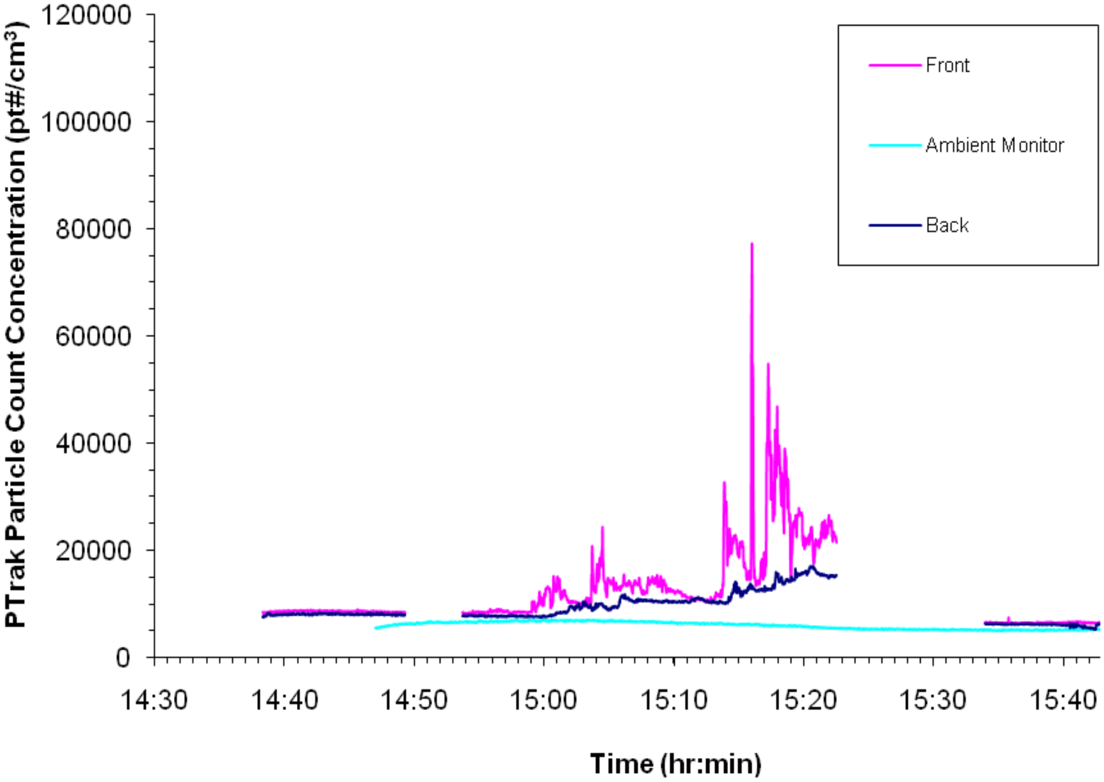
DPF Run#7 P-Trak
PTrak Particle Count Concentration (pt#/cm³)
120000
100000
80000
60000
40000
20000
0
Front
Back
Ambient monitor
10:50
11:00
11:10
11:20
11:30
11:40
11:50
12:00
12:10
12:20
12:30
12:40
12:50
13:00
13:10
13:20
Time (hr:min)

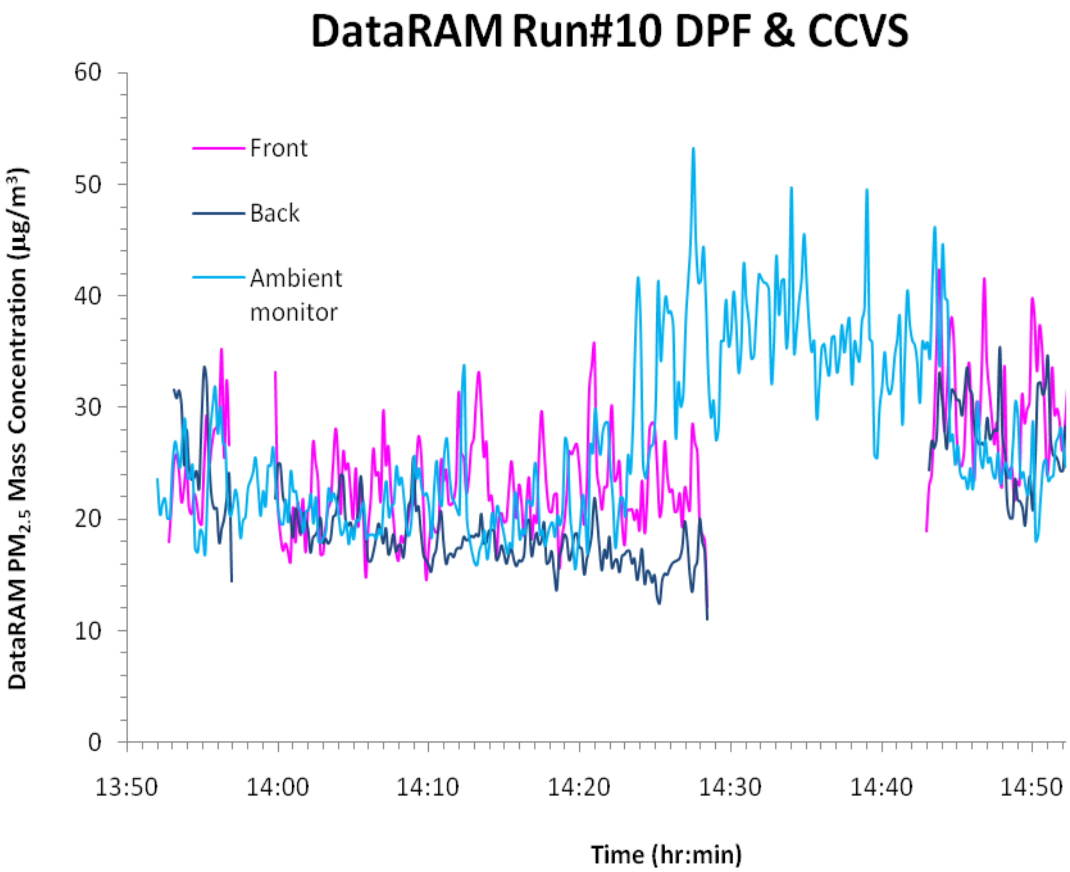

DataRAM Run# 8 DPF
DataRAM $PM_{2.5}$ Mass Concentration (µg/m³)
60
50
40
30
20
10
0
13:00
13:10
13:20
13:30
13:40
13:50
14:00
14:10
14:20
14:30
14:40
14:50
Time (hr:min)
Front
Back
Ambient Monitor

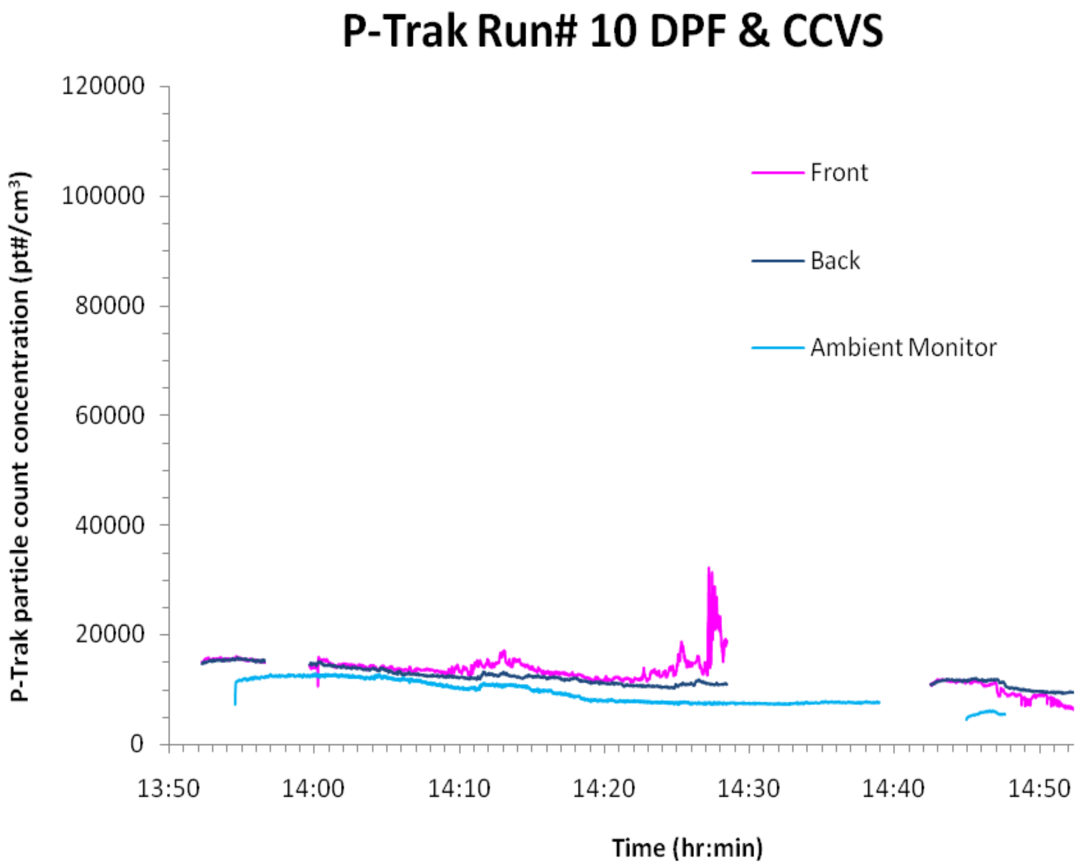

DPF Run#8 P-Trak
PTrak Particle Count Concentration (pt#/cm³)
120000
100000
80000
60000
40000
20000
0
13:00
13:10
13:20
13:30
13:40
13:50
14:00
14:10
14:20
14:30
14:40
14:50
15:00
Time (hr:min)
Front
Ambient Monitor
Back

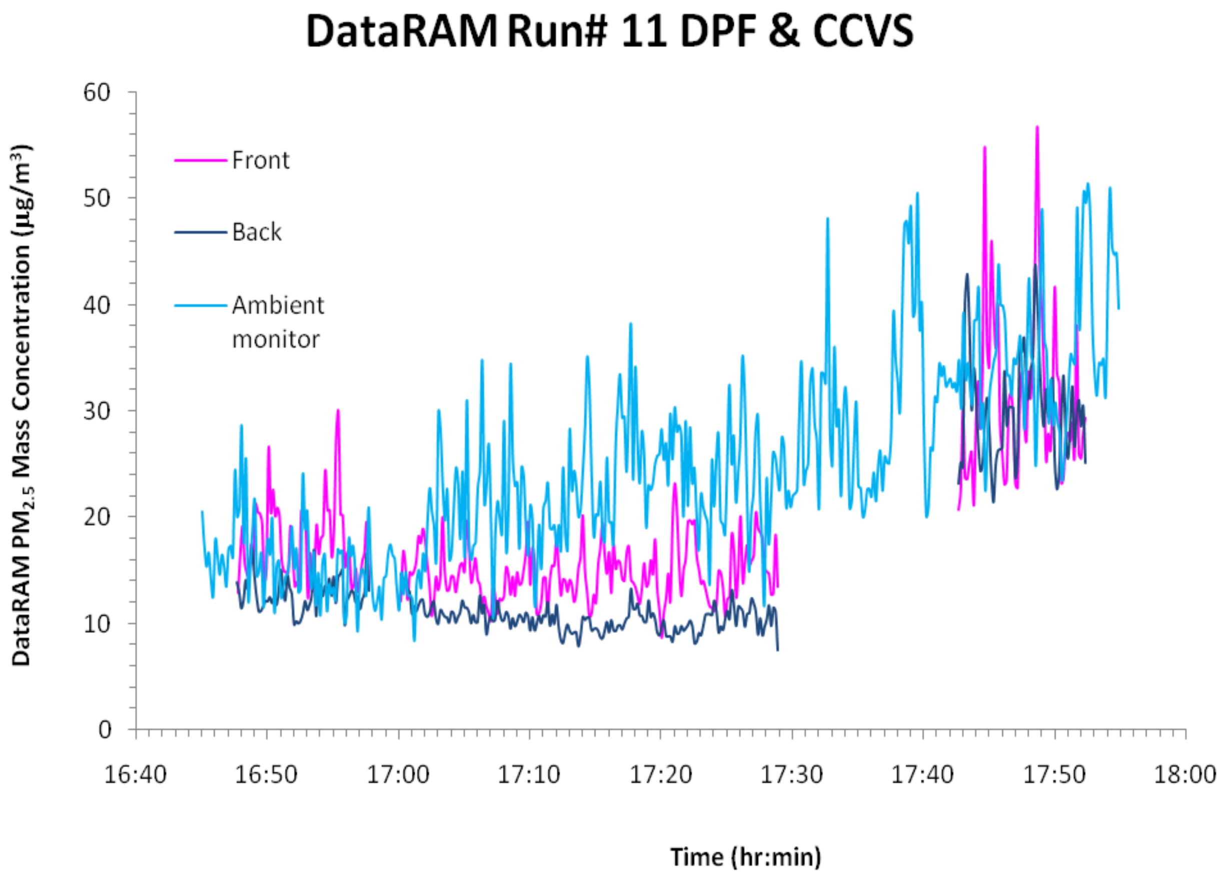

DPF Run#9 DataRAM
DataRAM PM2.5 Mass Concentration (µg/m3)
Time (hr:min)
Front
Back
Ambient Monitor
0
10
20
30
40
50
60
14:30
14:40
14:50
15:00
15:10
15:20
15:30
15:40

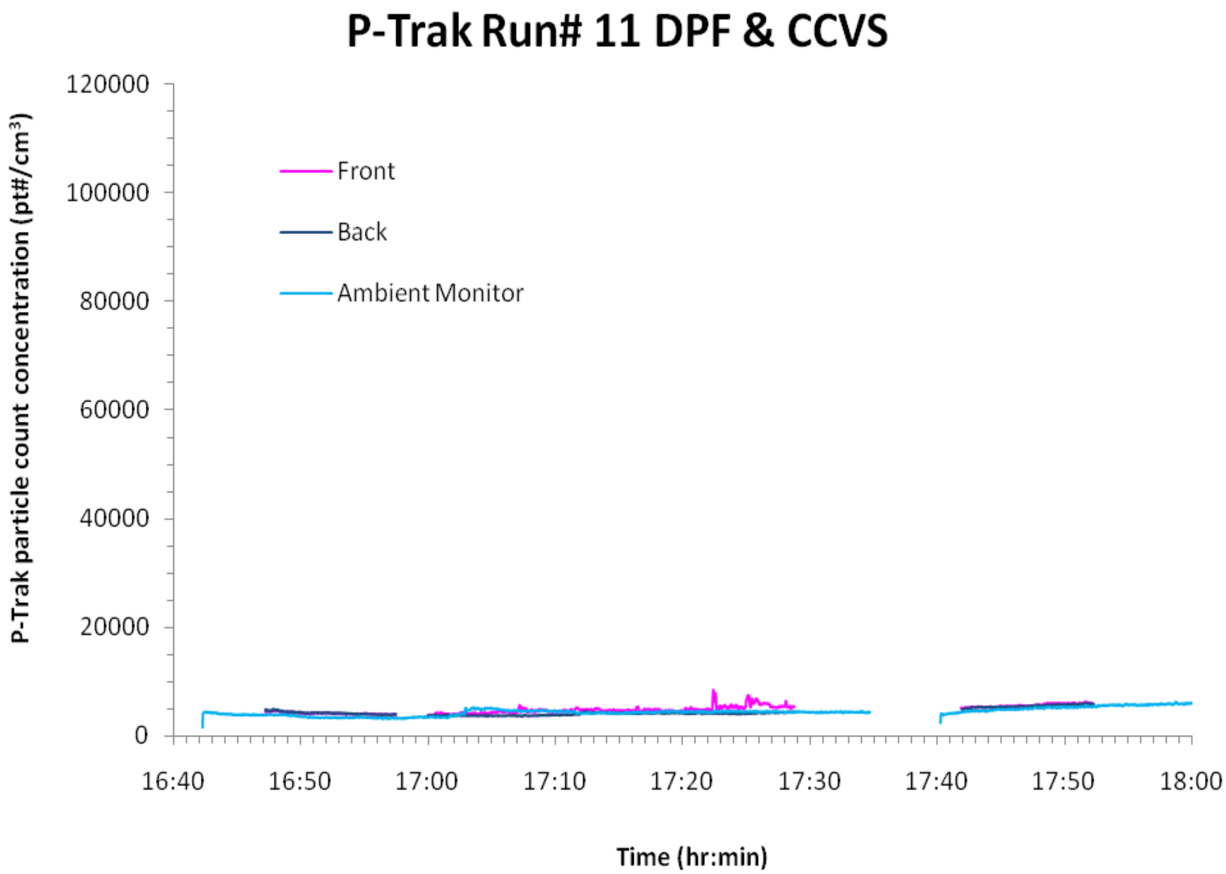
DPF Run#9 P-Trak

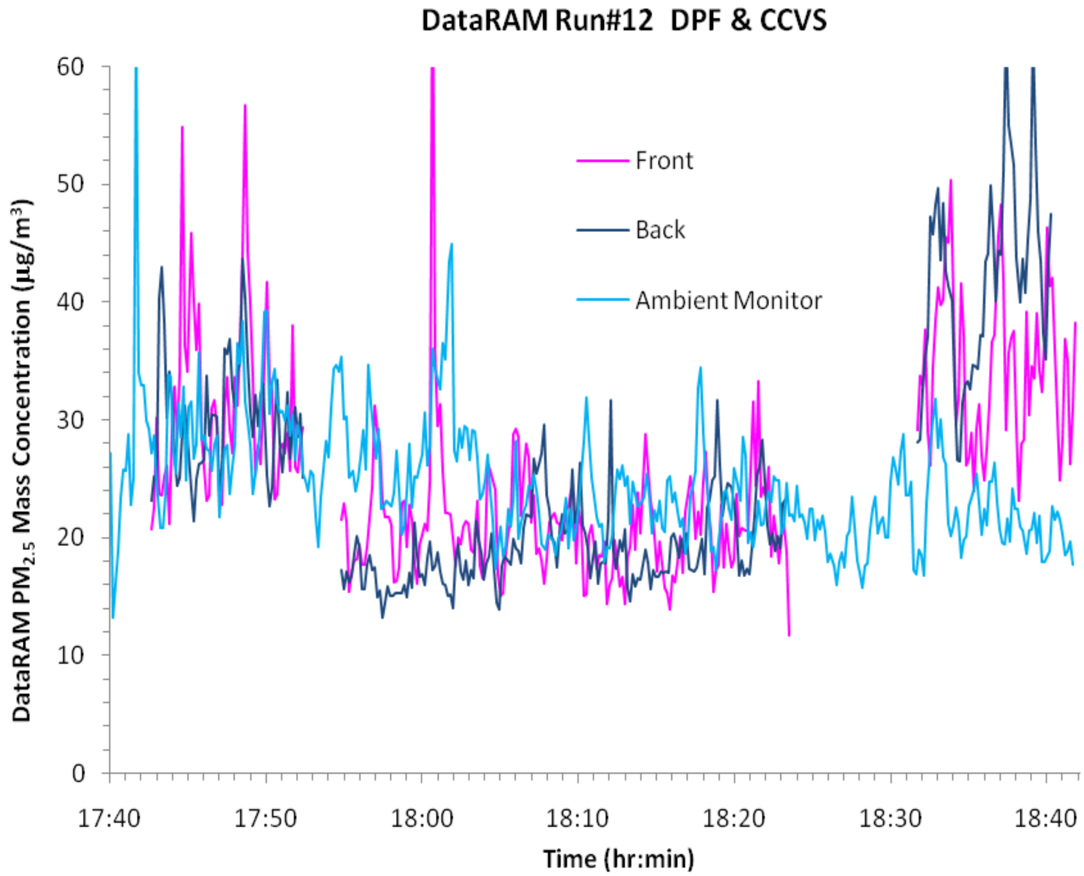


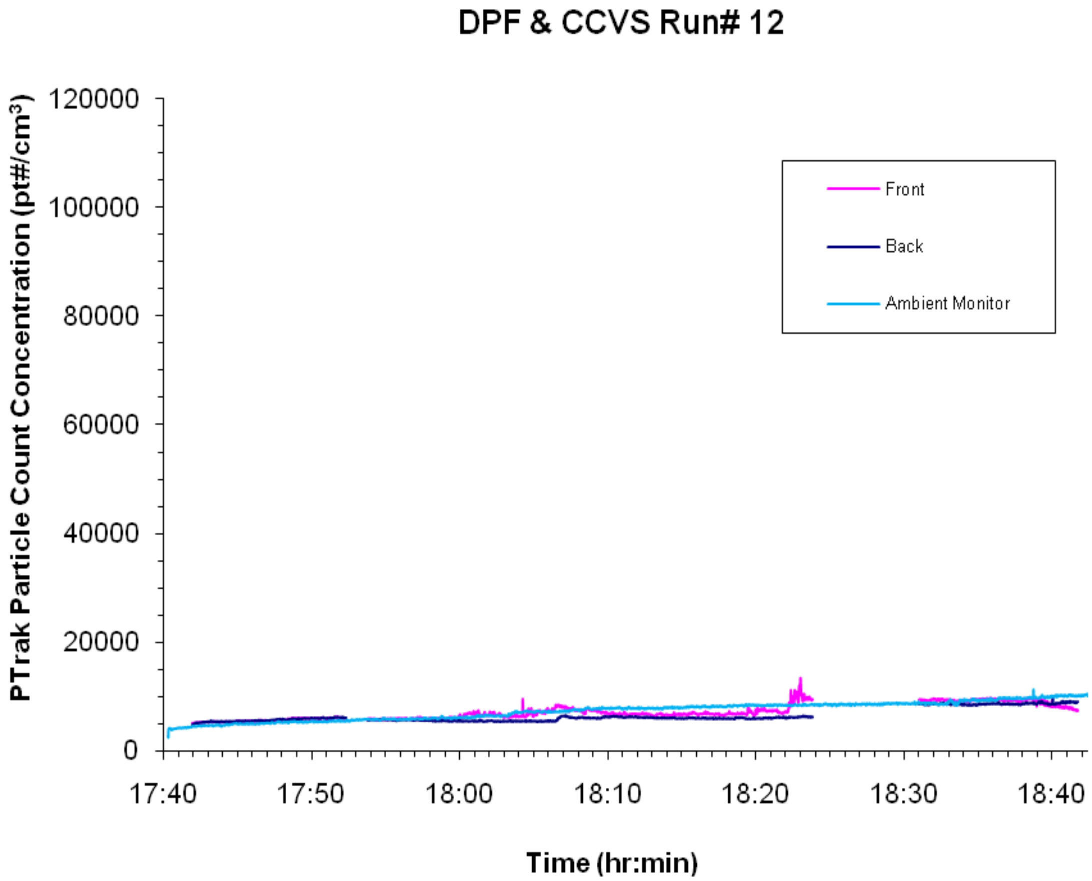

DataRAM Run#10 DPF & CCVS
DataRAM PM2.5 Mass Concentration (µg/m³)
Time (hr:min)
Front
Back
Ambient monitor
0
10
20
30
40
50
60
13:50
14:00
14:10
14:20
14:30
14:40
14:50

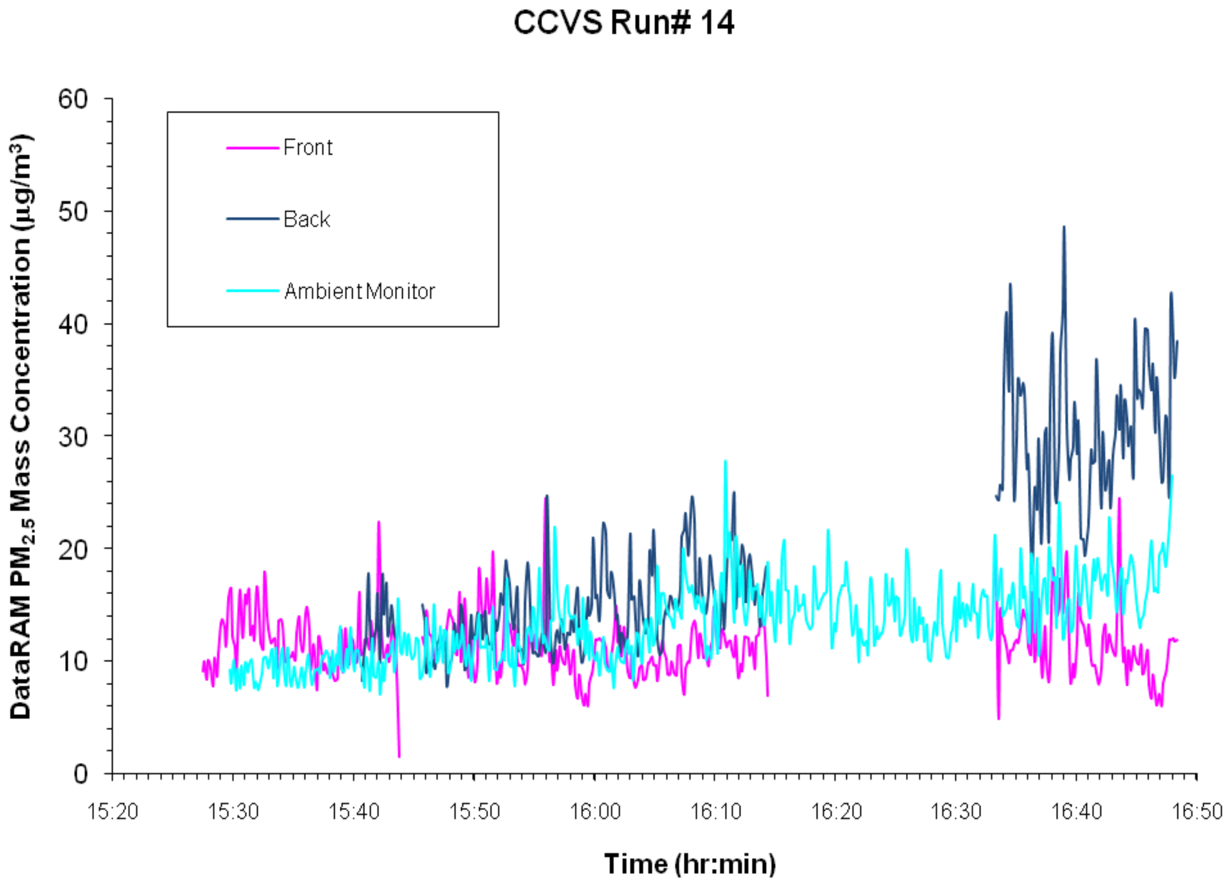

P-Trak Run# 10 DPF & CCVS
P-Trak particle count concentration (pt#/cm³)
120000
100000
80000
60000
40000
20000
0
13:50
14:00
14:10
14:20
14:30
14:40
14:50
Time (hr:min)
Front
Back
Ambient Monitor


DataRAM Run# 11 DPF & CCVS
DataRAM PM2.5 Mass Concentration (µg/m³)
0
10
20
30
40
50
60
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)

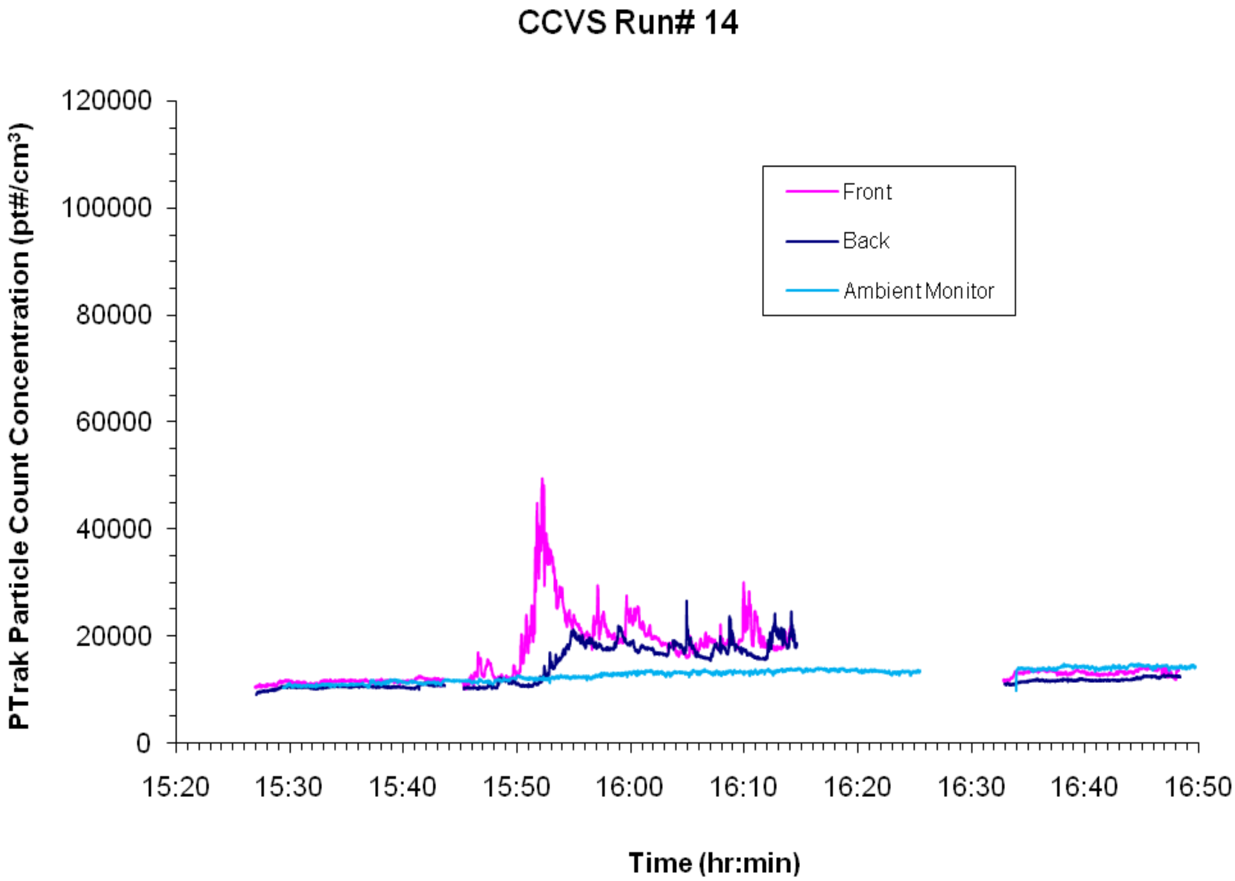

P-Trak Run# 11 DPF & CCVS
P-Trak particle count concentration (pt#/cm³)
120000
100000
80000
60000
40000
20000
0
Front
Back
Ambient Monitor
16:40
16:50
17:00
17:10
17:20
17:30
17:40
17:50
18:00
Time (hr:min)

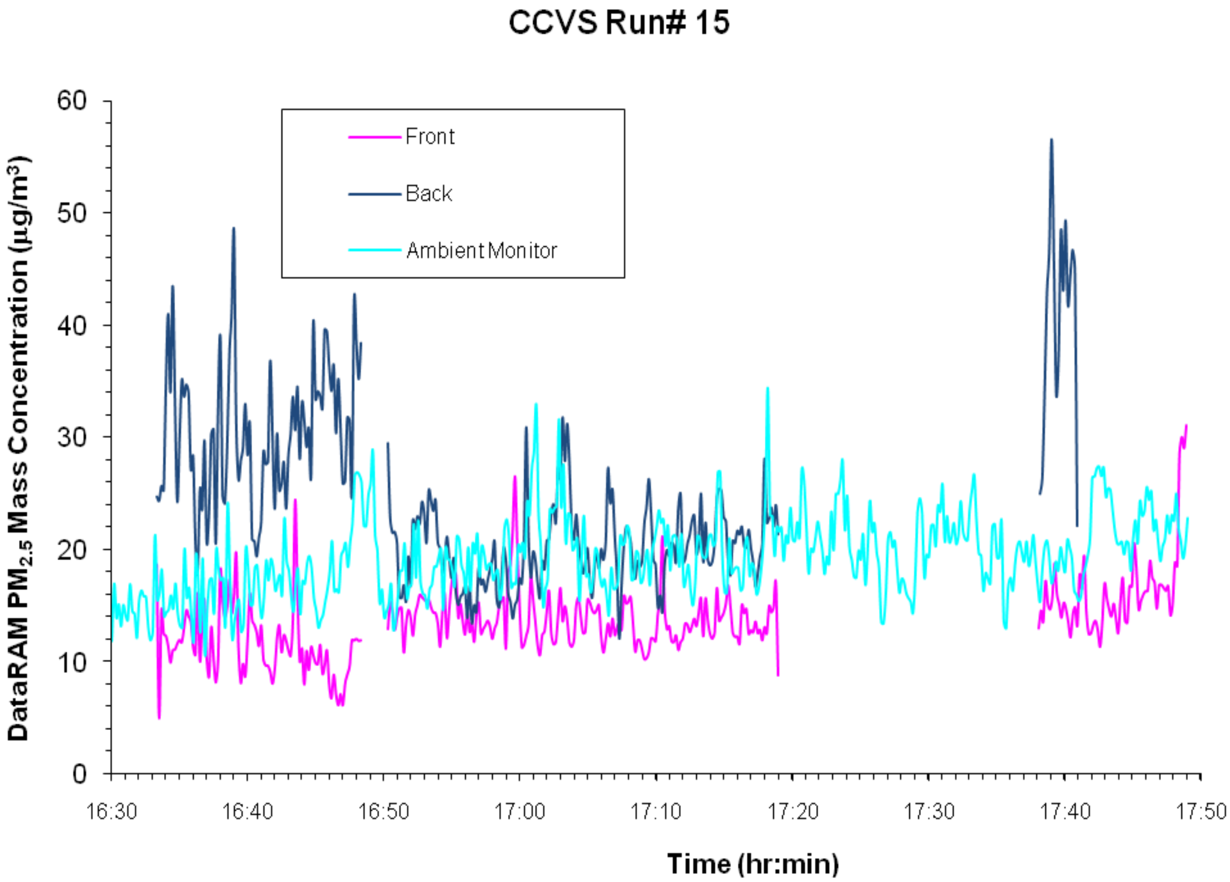

DataRAM Run#12 DPF & CCVS
DataRAM PM2.5 Mass Concentration (µg/m³)
60
50
40
30
20
10
0
17:40
17:50
18:00
18:10
18:20
18:30
18:40
Time (hr:min)
Front
Back
Ambient Monitor

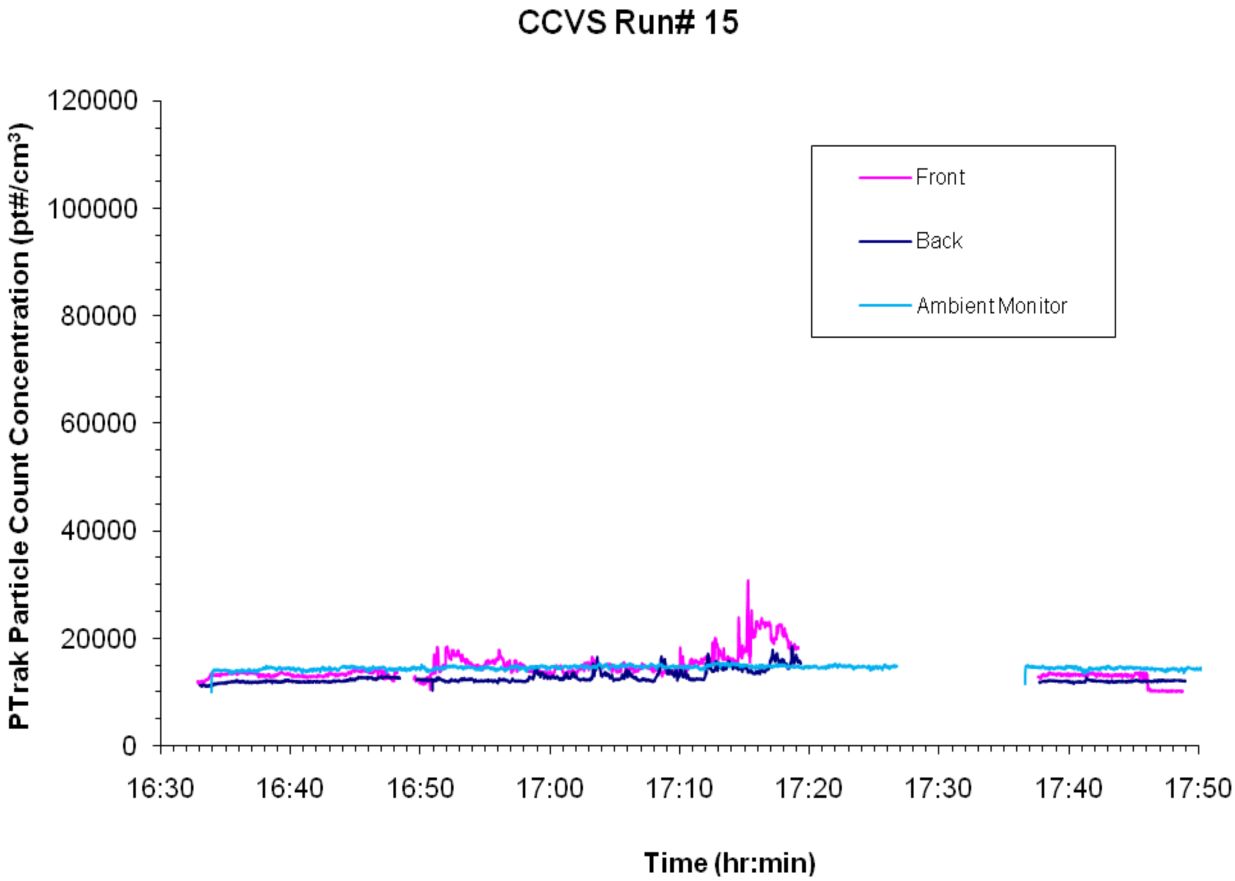

DPF & CCVS Run# 12
PTrak Particle Count Concentration (pt#/cm³)
120000
100000
80000
60000
40000
20000
0
17:40
17:50
18:00
18:10
18:20
18:30
18:40
Time (hr:min)
Front
Back
Ambient Monitor



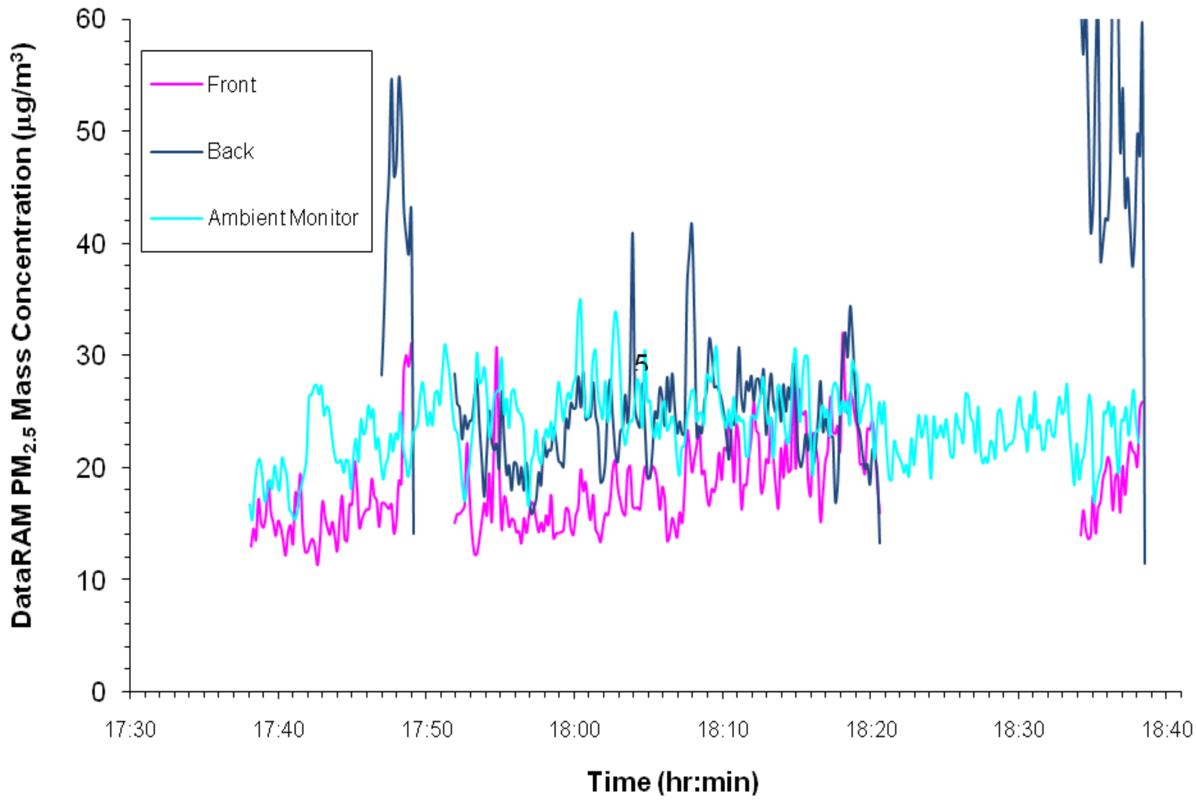
CCVS Run# 14
60
50
40
30
20
10
0
DataRAM PM2.5 Mass Concentration (µg/m³)
Front
Back
Ambient Monitor
15:20
15:30
15:40
15:50
16:00
16:10
16:20
16:30
16:40
16:50
Time (hr:min)


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

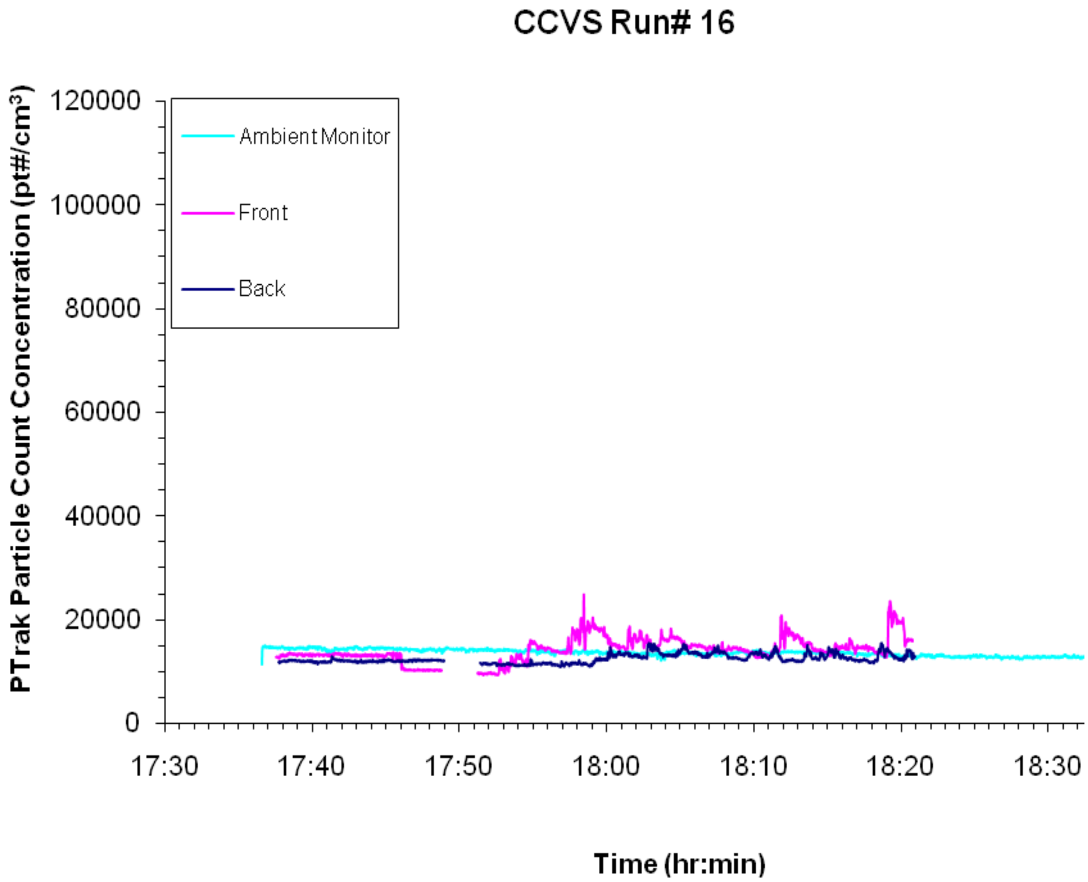

CCVS Run# 15
Front
Back
Ambient Monitor
DataRAM $PM_{2.5}$ Mass Concentration (µg/m³)
0
10
20
30
40
50
60
16:30
16:40
16:50
17:00
17:10
17:20
17:30
17:40
17:50
Time (hr:min)

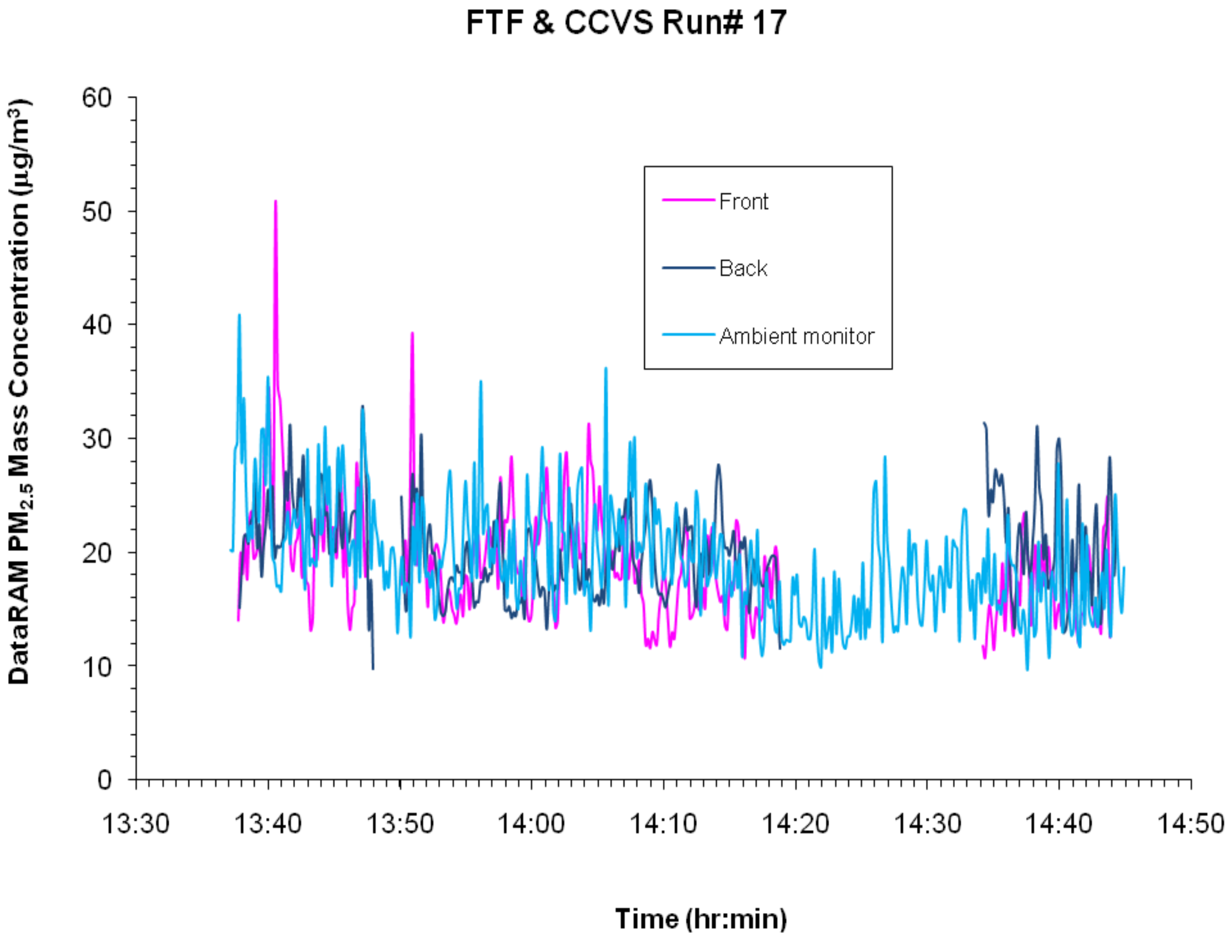

CCVS Run# 15
PTrak Particle Count Concentration (pt#/cm³)
120000
100000
80000
60000
40000
20000
0
16:30
16:40
16:50
17:00
17:10
17:20
17:30
17:40
17:50
Time (hr:min)
Front
Back
Ambient Monitor

CCVS Run# 16

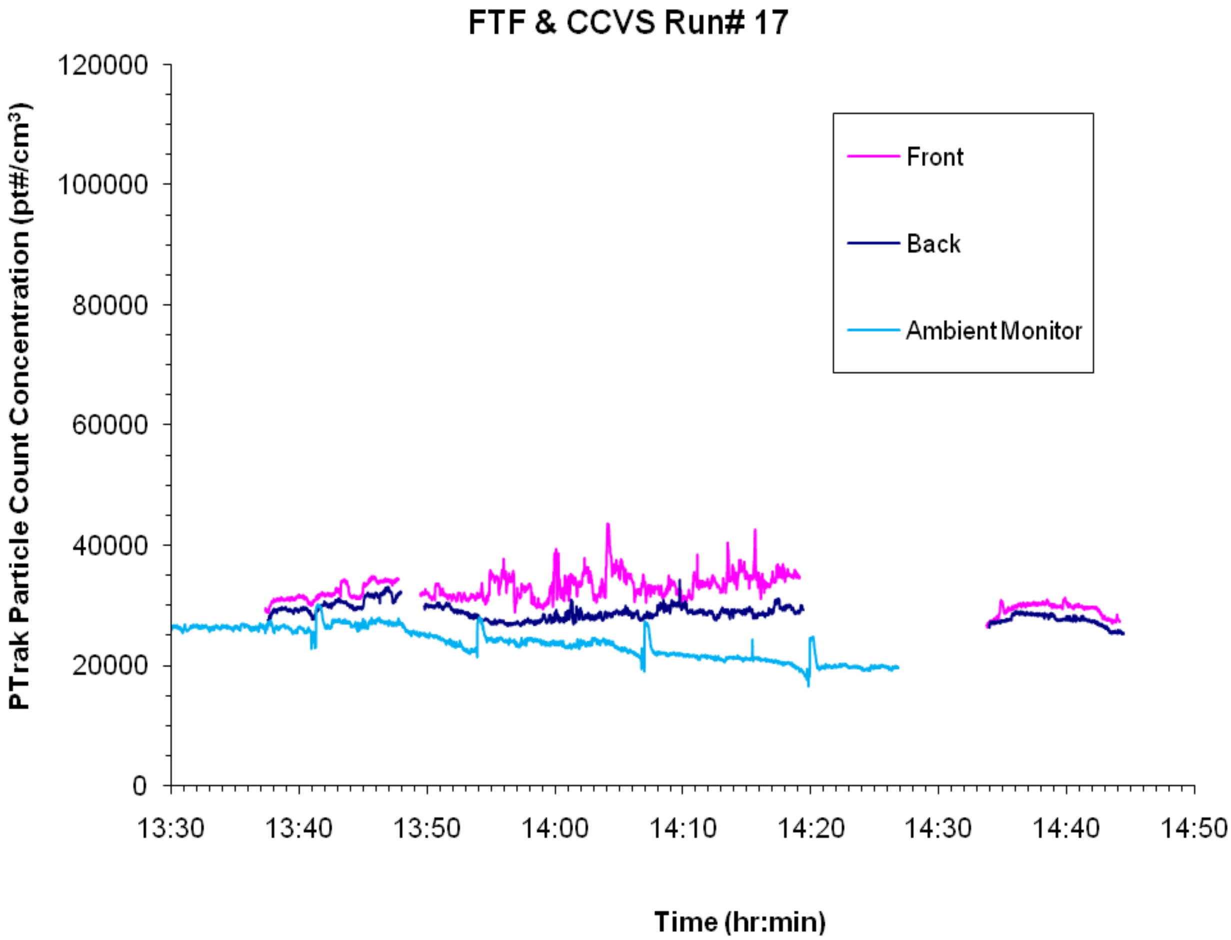


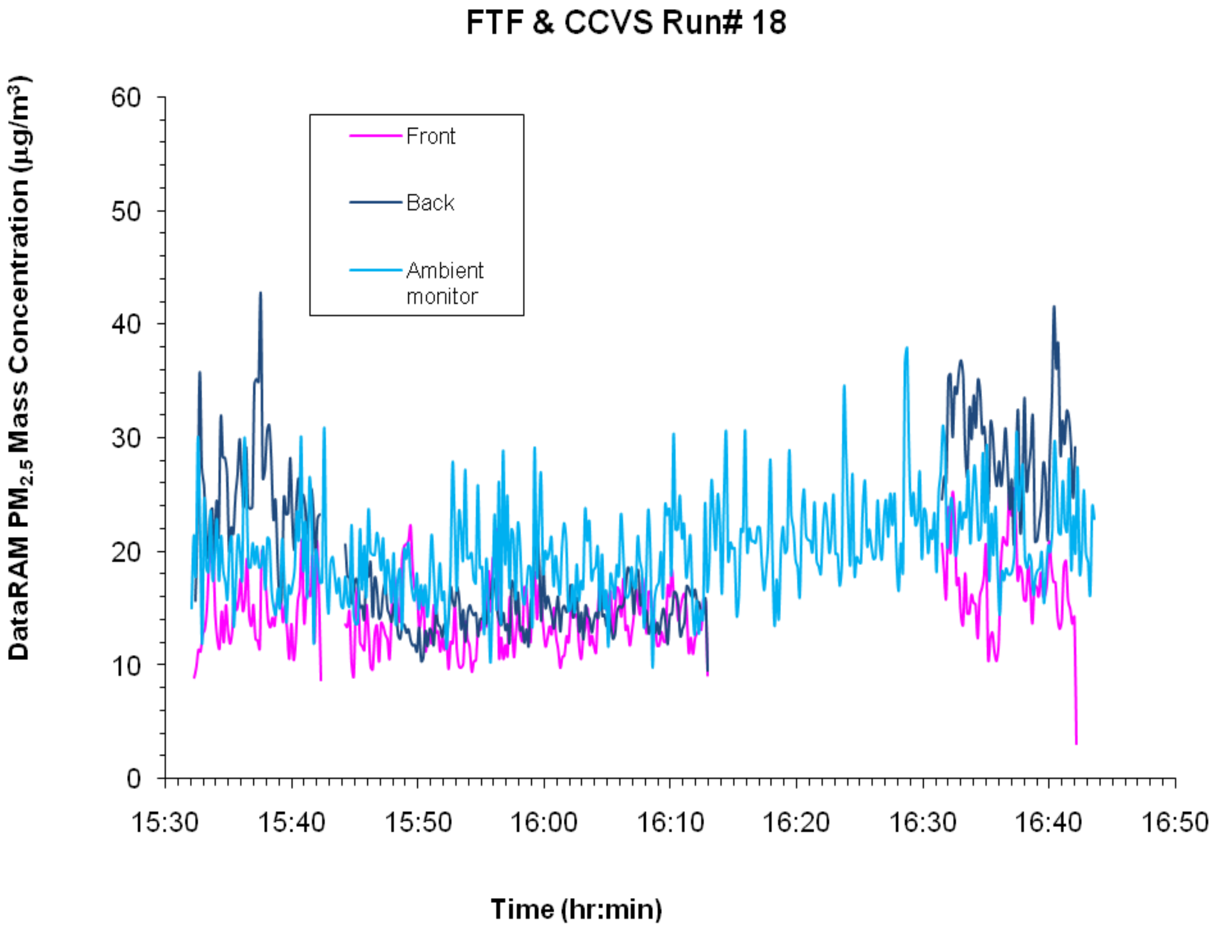
60
50
40
30
20
10
0
Front
Back
Ambient Monitor
5
DataRAM PM2.5 Mass Concentration (µg/m³)
17:30
17:40
17:50
18:00
18:10
18:20
18:30
18:40
Time (hr:min)

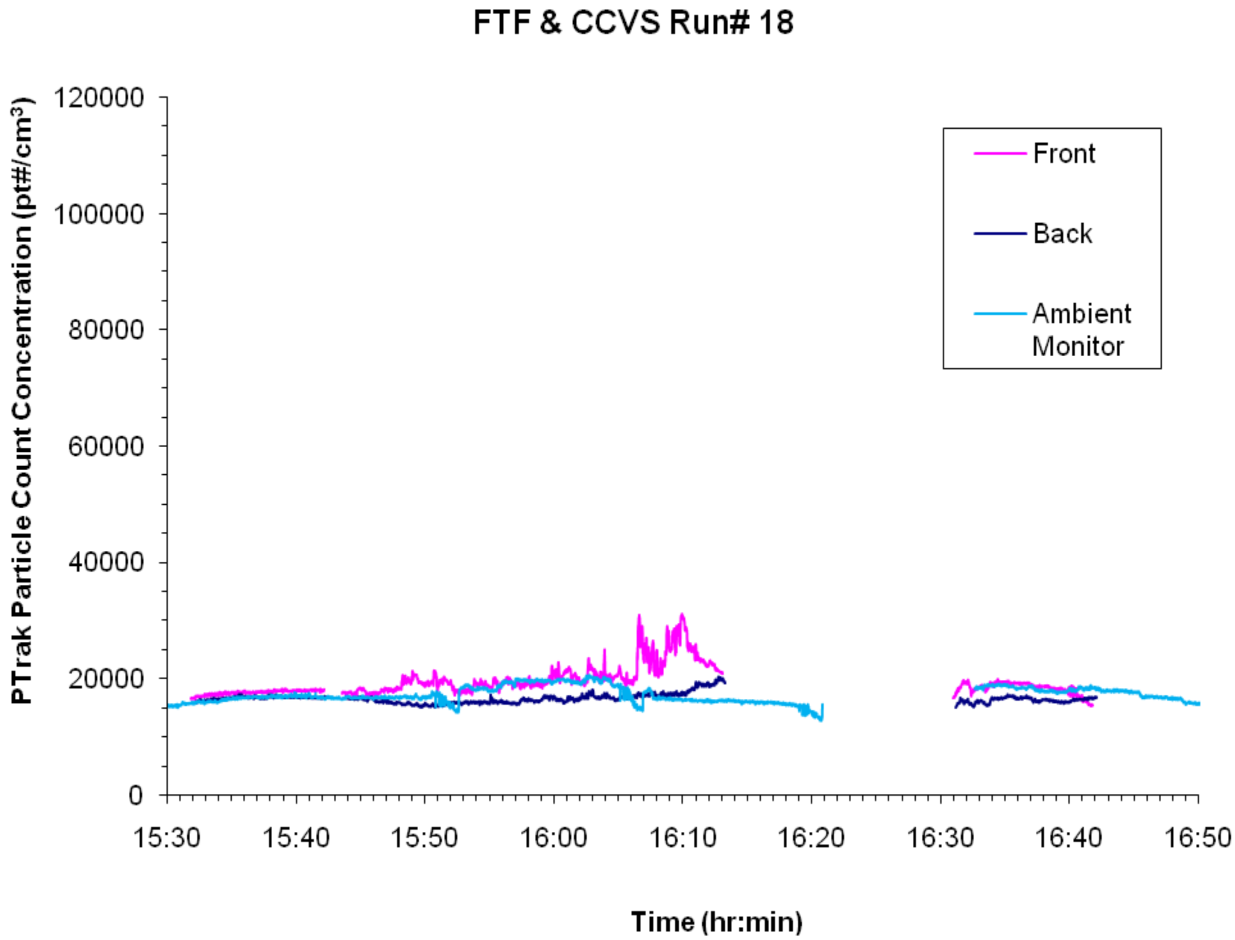

CCVS Run# 16
PTrak Particle Count Concentration (pt#/cm³)
120000
100000
80000
60000
40000
20000
0
Ambient Monitor
Front
Back
17:30
17:40
17:50
18:00
18:10
18:20
18:30
Time (hr:min)

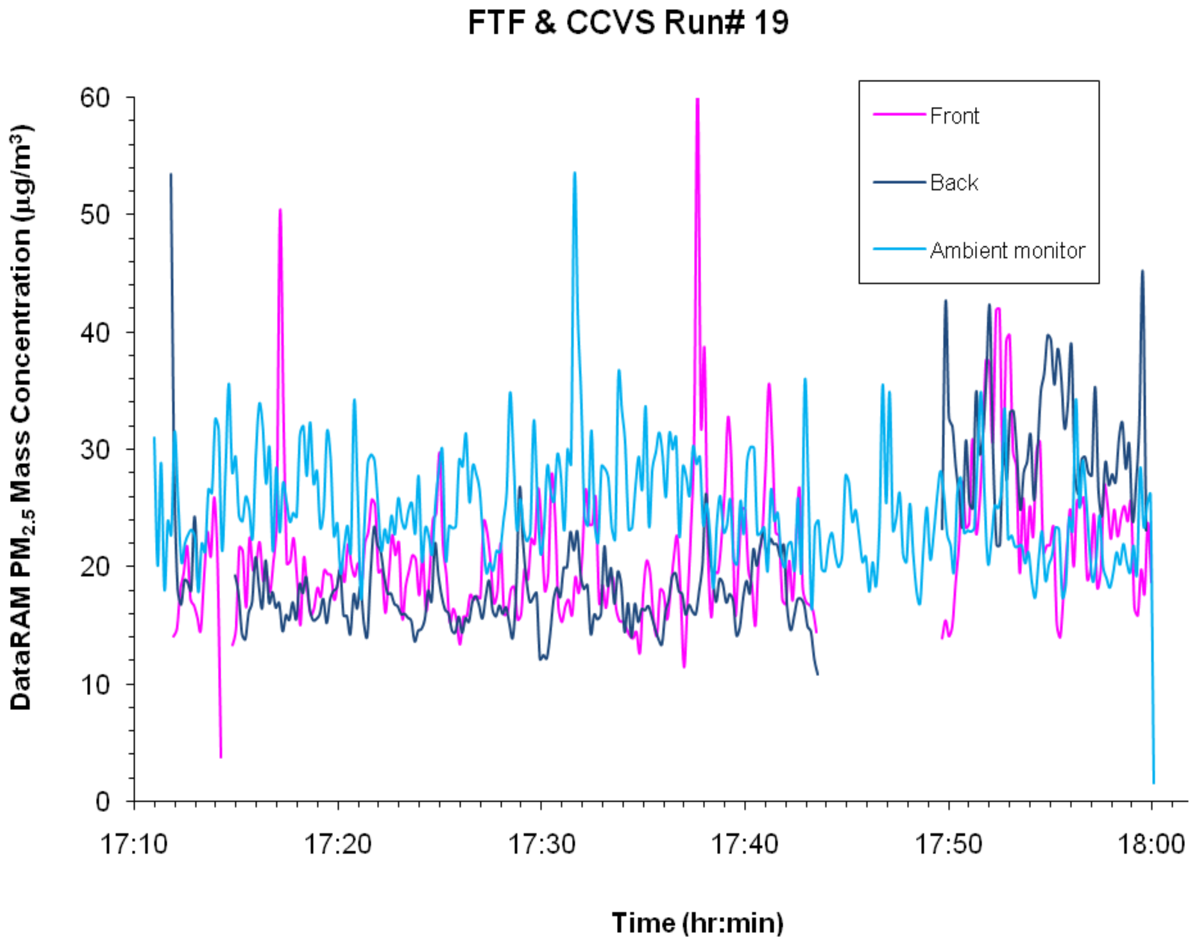


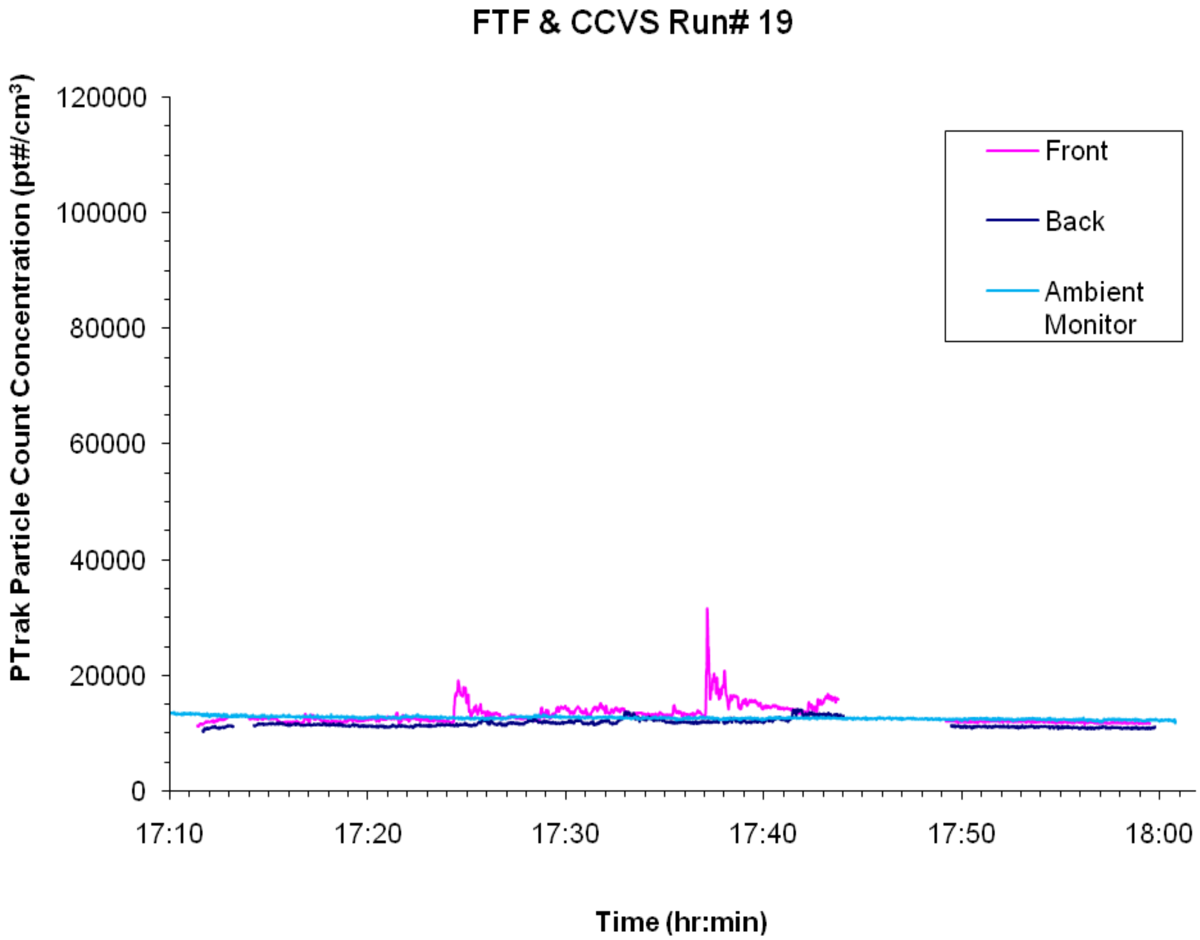
FTF & CCVS Run# 17
DataRAM PM2.5 Mass Concentration (µg/m³)
Time (hr:min)
Front
Back
Ambient monitor
0
10
20
30
40
50
60
13:30
13:40
13:50
14:00
14:10
14:20
14:30
14:40
14:50


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)
60
50
40
30
20
10
0
Front
Back
Ambient monitor
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
Front
Back
Ambient Monitor
17:10
17:20
17:30
17:40
17:50
18:00
Time (hr:min)

Appendix K: 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 mains.
☐	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 DataRAMs 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 and 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 DataRAMs. To perform a zero for the DataRAMs 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 DataRAMs 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 DataRAMs 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 $40\mu g/m^3$ 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 DataRAMs 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 DataRAMs, 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 151 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. DataRAMs
	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 DataRAMs (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 DataRAMs
☐	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 DataRAMs 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 DataRAMs 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 53:

4048 **PT**
CC
MIN 4032 08:32:00
MAX 4950 09:27:00
98 % MEM
LOG MODE 1 ↵ TO STOP

Figure 53: P-Trak display during measurement Log Mode 1
If the P-Trak display is as shown in Figure 54 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 54: P-Trak display during main menu

- The **DataRAMs** should appear as shown in Figure 55

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

Figure 55: 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 56: Run operation display 1

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

Figure 57: Run operation display 2

```
SCATR PARAMETERS
PAR SCAT RATIO     0.5133
ANGSTROM COEF:     2.336
PARTIC. DIA:       0.454 um
```

Figure 58: Run operation display 3

If the DataRAM has stopped recording then the display will return to the main menu as shown Figure 59

```
        EDIT MENU

> LOGGING PARAMETERS
> SETUP PARAMETERS
```

Figure 59: 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 60. This indicates that the run is being recorded.

Figure 60: Session Manager window from the SENSOR Tech-PC application