Measurement of Selected Diesel-Associated Air Pollutants in School Bus Cabins Prior to and Following the Installation of Retrofit Technologies

FINAL REPORT

Submitted to
The Texas Environmental Research Consortium

by

Elena McDonald-Buller[a] (Principal Investigator), Jeffrey Siegel[a] (Co-Principal Investigator), Jarett Spinhirne[a], Donghyun Rim[a], Alba Webb[a], Yosuke Kimura[a], and Gabriel Beko[b], and David Allen[a]

[a]The Center for Energy and Environmental Resources, The University of Texas at Austin

[b]Technical University of Denmark

December 2006

Acknowledgments

The authors would like to express their deepest appreciation to Hazel Barbour of the Central Texas Adopt-A-School Bus Program, and Dan Roberts, Director of Transportation for the Round Rock Independent School District (RRISD), whose tremendous efforts and support made the study possible. We thank Ron Seres, the driver for all of the tests to date, as well as Dennis Thompson, Lester, and the bus maintenance staff of RRISD who provided in-kind support for the installation of the retrofits and whose efforts were instrumental in resolving issues in the field. We would also like to express our appreciation to the Donaldson Company, Inc. for expediting production and shipment of the retrofit kits so that tests could be conducted prior to the start of the school year. Finally, we wish to thank David Hitchcock, Project Manager, of the Houston Advanced Research Center (HARC), Ramon Alvarez of Environmental Defense, the Texas Environmental Research Consortium (TERC) Science Advisory Committee, and the Texas Commission on Environmental Quality (TCEQ) for their insights during the development of the study and their insightful comments on drafts of the final report.

TABLE OF CONTENTS

EXECUTIVE SUMMARY

The percentage of time that children spend in school and/or day care has continued to increase since the early 1980's. Consequently, children's exposure to diesel exhaust may be highly influenced by their time on-board or within the vicinity of school buses. Previous studies that have specifically focused on the impacts of retrofits on in-cabin concentrations of diesel-associated pollutants have been limited, and sample sizes have been small making it difficult to draw conclusions about the impacts of retrofits on in-cabin concentrations. The objectives of this project were to determine NOx, CO, CO_2, TVOC, $PM_{2.5}$ mass, and ultrafine (0.02 – 1 μm) PM number concentrations in school bus cabins prior to and following the installation of the following emission control technologies manufactured by the Donaldson Company, Inc.: a.) a Spiracle, and b) a Diesel Oxidation Catalyst (DOC) in combination with a Spiracle. The Spiracle and DOC target emissions from the crankcase and the tailpipe, respectively.

The study was conducted within the Round Rock Independent School District in Central Texas. Five buses with International T444E engines with model years ranging from 1996-2001 were included, along with one bus with a 1985 model year International 6.9L engine. Ultra Low Sulfur Diesel is currently used as the standard fuel in the district. The test program, conducted during July and early August of 2006, consisted of three phases:

1. Before retrofits (six buses; in addition repetitions were conducted on two buses)
2. After installation of a Spiracle (three buses)
3. After installation of a DOC and Spiracle (same three buses as Phase 2)

Two of the six buses had air conditioning systems and were included in all phases of testing. A typical suburban route was driven exactly as usual, simulating pick-up of children near their homes and drop-off and idling in school yards. It was not possible within the framework of this testing program to determine if the air surrounding the bus where outdoor samples were collected was influenced by bus self-pollution or whether the placement of sampling lines on one side of the bus versus the other would have led to different results. Windows remained closed for all tests. Air exchange rates were measured by decay of sulfur hexafluoride (SF_6).

For the selected route, cruising represented the most significant mode of operation for the buses, followed by bus stops, and then idling with either the front door open or closed. The results for all pollutants indicated substantial variability (by as much as or more than a factor of 2) in mean and median in-cabin concentrations both across the bus test population, and, in some cases, between buses with similar characteristics such as age, mileage, and engine type. Median NOx, $PM_{2.5}$ mass, and ultrafine PM number concentrations prior to retrofits ranged from 67 ppb-143 ppb, 9 $\mu g/m^3$-15 $\mu g/m^3$, and 4413 particles/cc-30,450 particles/cc, respectively. Mean NOx, $PM_{2.5}$ mass, and ultrafine PM number concentrations prior to retrofits ranged from 64 ppb-148 ppb, 9 $\mu g/m^3$-20 $\mu g/m^3$, and 6054 particles/cc-32,272 particles/cc, respectively. These results reinforce the need for future testing programs with large sample sizes.

For both $PM_{2.5}$ and ultrafine PM, in-cabin mean concentrations were generally, but not exclusively, slightly lower than outdoor concentrations. However, median in-cabin concentrations were generally higher (ultrafine PM) or showed no pattern ($PM_{2.5}$).

Median and mean outdoor NO_x and NO concentrations were generally lower than in-cabin concentrations, but intra-test variability was also high. NOx and NO were the only pollutants that showed pronounced differences between operation modes for some buses with relatively larger mean and median in-cabin concentrations for periods with frequent stops and door openings versus cruising.

CO concentrations were both very low and very close to the resolution of the instrument. The TVOC data exhibited differences of approximately a factor of two in mean/median concentrations between the highest and lowest test values. Future testing with canister samples or other techniques that would allow for VOC speciation would likely provide additional relevant detail.

The Spiracle resulted in statistically significant decreases of mean in-cabin concentrations of NOx on all three buses, and decreases of NO on two buses. Small additional benefits or slight disbenefits resulted from the addition of the DOC. Results for in-cabin NO_2 concentrations were similar, with disbenefits following the addition of the DOC. In some cases for which data were available, outdoor NO_x, NO, and NO_2 concentrations following the installation of retrofits were lower than outdoor concentrations prior to retrofits. The U.S. EPA has not certified a level of NOx exhaust emissions reductions for the Donaldson Spiracle/DOC package. The impacts of retrofits on emissions of nitrogen oxides from the crankcase should continue to be investigated.

The TVOC results showed a very similar pattern to that of the NO_x pollutants. The Spiracle and Spiracle/DOC, respectively, resulted in relatively larger reductions of in-cabin $PM_{2.5}$ and ultrafine PM for one bus, but had smaller or essentially no impact on the other two buses. No clear benefit or disbenefit of the DOC was seen for PM as it was for NO_x pollutants. $PM_{2.5}$ concentrations may be affected by differing levels of particle resuspension as well as by variations in the outdoor concentrations. The ultrafine PM concentrations are similarly affected by outdoor levels. A comparison of repetitions (i.e. same bus, same retrofit condition) was conducted for two buses. These data suggested that the results for $PM_{2.5}$ and ultrafine PM were within the range of variation that was seen for the repetitions, suggesting that the results cannot be conclusively linked to the retrofits. Testing on additional buses, as well as testing in a cleaner and more consistent outdoor environment may facilitate assessment of the value of these retrofits for achieving reductions in PM emissions.

Measurement of Selected Diesel-Associated Air Pollutants in School Bus Cabins Prior to and Following the Installation of Retrofit Technologies

1. BACKGROUND

The percentage of time that children spend in school and/or day care has continued to increase since the early 1980's and represents the majority of their weekly schedule (Hofferth, 1998; Hofferth and Sandberg, 2001). Consequently, in many cases, a child's exposure to diesel exhaust may be highly influenced by their time on-board or within the vicinity of school buses. Children, who have high-volumetric inhalation rates and immature immune systems, are particularly susceptible to adverse respiratory system impacts associated with exposure to diesel exhaust and other pollutants (Northbridge et al., 1999; Brunekreef et al., 1997; U.S. EPA, 2002). Asthma is currently one of the leading causes of school absenteeism in Central Texas and is the leading cause of hospitalization of school children in Travis County which includes the city of Austin (Barbour, 2006).

Diesel engines are significant sources of gaseous and particulate pollutants. In contrast to spark ignition engines, which intake a mixture of gas and air, compress and then ignite the mixture with a spark, diesel engines intake air, compress it and then inject fuel into the compressed air; the fuel evaporates and ignites as compression-heated air mixes with the fuel spray (Flagan and Seinfeld, 1988). Direct fuel injection used in diesel engines results in greater fuel efficiency and lower exhaust concentrations of carbon monoxide (CO) and hydrocarbons (THC), but higher PM concentrations than from spark ignition engines. Fuel-lean conditions (characterized by high air-to-fuel ratios) also provide an environment conducive to forming nitrogen oxides (NOx) through the thermal fixation of atmospheric nitrogen in the combustion process (Flagan and Seinfeld, 1988).

Among the gaseous components of regulatory and public concern in diesel exhaust are nitrogen oxides (NOx), sulfur compounds, and hydrocarbons, including formaldehyde, acrolein, benzene, 1,3 butadiene, and polycyclic aromatic hydrocarbons (PAHs) (U.S. EPA, 2002). Diesel particulate matter (DPM) is composed of fine particles, with organic components generally comprising 20%-40% of the particle weight (U.S. EPA, 2002). In addition to their small size which facilitates deposition deep in the lung, many of the organic components of DPM including PAHs are recognized as having carcinogenic properties (U.S. EPA, 2002).

Several studies have been conducted to measure concentrations of diesel-associated air pollutants in school bus cabins, although the overall body of research is limited. Two of the largest efforts that focused on in-cabin measurements of air pollutants included a Los Angeles–based study sponsored by the California Air Resources Board (CARB) and a multi-city study conducted by the Clean Air Task Force (CATF). These studies along with others are described below in order to provide a context for the study conducted under this effort.

1.1 Los Angeles Study

The University of California, Riverside and the University of California, Los Angeles completed a study for the CARB in 2003 characterizing the range of children's exposures during school bus commutes (Fitz et al., 2003; Behrentz et al., 2004; Sabin et al., 2005).

This study was the first comprehensive examination of children's pollutant exposures during commutes to and from school in California and included measurements on-board and within the vicinity of school buses at loading/unloading areas and bus stops. Los Angeles was selected as the geographic focal point of the study because previous research by Rodes et al. (1998) indicated that measured concentrations of PM_{10}, $PM_{2.5}$, VOCs, CO, and black carbon (BC) in passenger cars indicated that in-vehicle pollutant concentrations were higher in Los Angeles than in Sacramento; VOC and CO concentrations inside the vehicle were four to ten times higher than at ambient network or roadside monitors, and, although $PM_{2.5}$ concentrations inside the vehicle were generally lower than just outside of the vehicle or near the roadway, all of these locations had higher concentrations than monitors in the ambient network (Rodes et al., 1998; Fitz et al, 2003).

Six different school buses in the Los Angeles Unified School District including conventional diesel buses (1975, 1985, 1993, and 1998 model years), a 1998 diesel bus with a particle trap, and a 2002 compressed natural gas (CNG) bus were included in the study. The study was conducted during a typical urban bus commute from South Central Los Angeles to west Los Angeles with additional runs on another urban route with less time on congested freeways, a suburban/rural route, and with varying window positions. Behrentz et al. (2004) applied sulfur hexafluoride (SF_6) as a tracer gas in the exhaust system of buses in the Los Angeles Unified School District to examine self-pollution or the percentage of a bus's own exhaust that is measured in the cabin. SF_6 as well as black carbon (BC), $PM_{2.5}$, fine particulate matter counts in the 0.3 and 0.5 μm size range, particle-bound PAHs, and formaldehyde and benzene were measured.

Bus age, bus type, and window position were all found to be important variables affecting self-pollution (Behrentz et al., 2004; Sabin et al., 2005). Regardless of bus age, self-pollution was higher when windows were closed rather than open. The presence of a diesel vehicle in front of the bus was the dominant dynamic variable that influenced high bus cabin pollutant concentrations when bus windows were open; when bus windows were closed, the type of test bus (i.e., self pollution) was the most important variable, especially during idling at bus stops. Up to 0.3% of the air inside the cabin of older buses (circa 1975) with the windows closed was found to be due to self-pollution (Behrentz et al., 2004). This value was approximately an order of magnitude less for newer buses, including the 1998 model year bus with the particulate trap (0.03%-0.04%).

Concentrations during bus commutes were generally more significant than at bus stops or at loading/unloading zones in Los Angeles. The Los Angeles study (Behrentz et al., 2005), along with a Detroit–based study conducted by Batterman et al. (2001), both indicated that pollutant concentrations during bus commutes were substantially higher than measured ambient concentrations. Batterman et al (2001) found that VOC concentrations along bus routes and in buses exceeded concentrations at ambient regulatory monitoring sites by a factor of 2-4. Mean concentrations in the Los Angeles study (Behrentz et al, 2005) inside buses were 2-9 times higher than at loading/unloading zones and 1.5-3 times higher than mean concentrations at bus stops.

Mean in-cabin concentrations in the Los Angeles study were 0.9-19 $\mu g/m^3$ for black carbon (BC), 23 to 400 ng/m^3 for particle-bound polycyclic aromatic hydrocarbons (PB-PAH), 64 to 220 $\mu g/m^3$ for NO_2, 0.1 to 11 $\mu g/m^3$ for benzene, and 0.3 to 5 $\mu g/m^3$ for formaldehyde. In contrast to black carbon, fine particulate matter ($PM_{2.5}$) concentrations were weakly correlated with bus exhaust emissions (Behrentz et al., 2004) and were sensitive to the bus route (Sabin et al., 2005), which suggested the significance of regional background concentrations and secondary formation. Formaldehyde was the only pollutant that had higher concentrations in the compressed natural gas bus than in conventional buses. In general, concentrations of pollutants on the bus equipped with the particle trap fell between the range of values reported for the conventional buses and the CNG bus.

1.2 Clean Air Task Force Multi-City Study

The Clean Air Task Force conducted school bus studies in Chicago, Illinois and Atlanta, Georgia in 2003, Ann Arbor, Michigan in 2004, and Houston, Texas in 2006 for the purposes of determining the relative impacts of crankcase emissions and exhaust/tailpipe emissions on in-cabin air quality and examining the benefits of different retrofit technologies (Hill et al., 2005). Bus routes were primarily located in suburban residential areas with few other sources of diesel emissions. Buses included in the multi-year study were generally of similar age (1998-2001), mileage (45,000-70,000), and manufacturer (International). One bus was used in the Ann Arbor study, three buses were used in the Chicago study, and two buses were used in the Atlanta study. Bus windows were closed during the duration of the tests. In contrast, a lead car equipped with identical instrumentation was driven with windows remaining down during the tests. With the exception of the Houston test that was conducted in May 2006, tests in other cities were conducted in late fall or early spring during relatively cooler temperatures with some rainy days.

The CATF study included conventional buses and retrofitted buses with various combinations of technologies, including a diesel particulate filter (DPF) alone or in combination with a Donaldson Spiracle and/or ultra-low sulfur diesel fuel (ULSD); a diesel oxidation catalyst (DOC) alone or in combination with a Spiracle; a Spiracle alone; and a CNG bus (Hill et al., 2005). The catalyst-based DPF and the DOC target removal of PM and CO from the engine exhaust. The Spiracle Crankcase Filtration System targets removal of PM emissions from the crankcase by eliminating blow-by emissions that originate from combustion chamber leakage past the piston rings and effectively closing off the open crankcase vent (http://www.donaldson.com). It is important to note that all retrofit combinations were tested on a single bus both before and after installation in Ann Arbor. The Chicago study included three buses (two conventional; one retrofitted) but the retrofit was installed on a different bus not on either of the two conventional buses included in the testing program. The Atlanta study included two conventional buses, one of which was tested before and after the installation of a retrofit.

Measurements of $PM_{2.5}$ mass concentration, ultrafine PM number concentration, BC, and particle-bound PAH were made during idling, a 3-bus queue (only conventional buses), and a typical bus route. CATF found that emissions primarily enter the cabin while buses were idling with the front door open at loading/unloading areas. Although the techniques for measuring wind direction and speed were not reported (Hill et al., 2005), CATF describes that emissions were highly dependent not only on the strength of the sources (crankcase, tailpipe, other roadways diesel sources), but also on the prevailing wind direction. CATF found that tailpipe emissions were responsible for emissions of ultrafine particles, BC, and PAH in the cabin when the prevailing wind was from the rear of the bus. Emissions of $PM_{2.5}$ originated from the crankcase and were the dominant emission source when the prevailing wind was from the front of the bus. A clear gradient in concentrations existed from the front to the middle of the bus, with passage of diesel smoke through the front door dominating other pathways.

Mean ultrafine PM number concentrations in Ann Arbor for a conventional bus ranged from 28,145-50,724 particles/cc (Hill et al., 2005). Mean ultrafine PM concentrations on the same bus retrofitted with a DOC ranged from 38,091 particles/cc-40,782 particles/cc in Ann Arbor (buses with this retrofit were not tested in Chicago or Atlanta). The mean ultrafine PM concentration on the same bus retrofitted with a Spiracle was 26,927 particles/cc in Ann Arbor (buses with this retrofit were not tested in Chicago or Atlanta). Mean ultrafine PM concentrations on the same bus retrofitted with a DOC and Spiracle in Ann Arbor ranged from 30,969-38,139 particles/cc. In contrast, the same bus retrofitted with a DPF and Spiracle in Ann Arbor (using ULSD) ranged from 9,823 -13,029 particles/cc. The retrofit (DPF alone using ULSD) in Chicago was conducted on a different bus but ultrafine PM ranged from 29,868-30,808 particles/cc in contrast to 68,565-74,466 particles/cc for the conventional bus. The retrofit (DPF with a vent tube extension using ULSD) in Atlanta was conducted on the same bus and ultrafine PM concentrations ranged from 7,381-10,375 particles/cc in contrast to 47,994-50,230 particles/cc for the conventional bus.

Mean $PM_{2.5}$ mass concentrations in Ann Arbor for a conventional bus ranged from 47-50 $\mu g/m^3$, respectively (Hill et al., 2005). Mean $PM_{2.5}$ concentrations on the same bus in Ann Arbor retrofitted with a DOC were 52-65 $\mu g/m^3$. Mean $PM_{2.5}$ on the same bus in Ann Arbor retrofitted with a DOC and Spiracle were 22-25 $\mu g/m^3$. The mean $PM_{2.5}$ concentration on the same bus in Ann Arbor retrofitted with a Spiracle alone was 36 $\mu g/m^3$. Mean $PM_{2.5}$ concentrations on the same bus in Ann Arbor retrofitted with a DPF alone (using ULSD) were 45-47 $\mu g/m^3$. Mean $PM_{2.5}$ concentrations on the same bus retrofitted with a DPF and a Spiracle (using ULSD) were 31-43 $\mu g/m^3$. The retrofit (DPF alone using ULSD) in Chicago was conducted on a different bus but $PM_{2.5}$ ranged from 77-163 $\mu g/m^3$ in contrast to 40-92 $\mu g/m^3$ for the conventional bus. The retrofit (DPF with a vent tube extension using ULSD) in Atlanta was conducted on the same bus and $PM_{2.5}$ concentrations ranged from 23-37 $\mu g/m^3$ in contrast to 75-77 $\mu g/m^3$ for the conventional bus.

The only retrofit combination that CATF found effectively reduced all sources of the pollutants measured was the DPF in combination with a Spiracle and ULSD (Hill et al., 2005). These two technologies address different sources of emissions (i.e., DPF addresses tailpipe emissions whereas a Spiracle is a closed crankcase filtration device). The DOC was found to have minimal or no benefit for reducing in-cabin concentrations of pollutants measured in this study. The DOC in combination with a Spiracle reduced $PM_{2.5}$ mass, which CATF attributed to the impacts of the Spiracle alone on $PM_{2.5}$ emissions originating from the crankcase (Hill et al., 2005). Similar to the Los Angeles study, $PM_{2.5}$ concentrations were poorly correlated with black carbon mass, as well as PAH and ultrafine particles (Hill et al., 2005).

2. OBJECTIVES

The Los Angeles and CATF studies, among others, have suggested that children's exposures to diesel exhaust are enhanced by school bus commutes and proximity to roadways, and that window position, route, length of commute, bus age, meteorological conditions, and the presence or absence of emission control technologies are among the variables that influence the magnitude and duration of exposures. The Los Angeles-based studies suggested that in-cabin $PM_{2.5}$ concentrations and concentrations of other pollutants with significant secondary sources are weakly correlated with exhaust emissions. Although the Los Angeles-based studies did compare the range of emissions among buses of different ages, the study included only a single CNG bus and a single bus that had a particle trap making it difficult to draw conclusions about the impacts of retrofits on in-cabin concentrations. The CATF studies indicated that in-cabin concentrations of $PM_{2.5}$ and ultrafine particles originate from different sources (crankcase versus tailpipe), and consequently are responsive to different retrofit technologies. However, the sample size of the CATF studies was small, in some cases with retrofits being conducted before and after on only a single bus (Ann Arbor and Atlanta) or on different buses (Chicago). The results for Houston were not publicly available at the time of this report. However, the studies in Ann Arbor, Chicago, and Atlanta by the CATF were conducted under meteorological conditions that are likely to be quite different than those encountered in Eastern Texas.

The primary purpose of the current project is to assess in-cabin concentrations of selected diesel-associated air pollutants prior to and following the installation of selected emission controls on school buses in Central Texas. The specific objective of the project is to determine NOx, CO, CO_2, TVOC, $PM_{2.5}$ mass, and ultrafine (0.02 – 1 μm) PM number concentrations in cabin air prior to and following the installation of the following emission control technologies on selected buses within a Central Texas school district: a.) Spiracle, and b) a DOC in combination with a Spiracle. Although the resources for the study were limited and needed to be tightly focused, this study expands the number of buses examined before and after retrofits in the United States, addresses in-cabin NO, NO_2, NOx concentrations as well as $PM_{2.5}$ and ultrafine PM, examines the impacts of retrofits on buses with and without operating air conditioning systems, and is conducted under meteorological conditions specific to Central Texas.

3. METHODOLOGY

3.1 School District Selection

The selection of a school district considered the following factors:

1. Geographic location
2. Presence of potentially confounding sources of emissions
3. Length of commute for children
4. Age and maintenance history of the bus fleet
5. Relationship with the Clean Air Force's Adopt-a-School Bus Program and willingness to work with the research team

In reality, the geographic location and the willingness of the district to work with the research team and to provide in-kind support for retrofit installation and for the driver's time became the dominant factors in the selection process. Round Rock Independent School District (RRISD) expressed early interest in the study and quickly volunteered in-kind support of an experienced driver and its bus maintenance crew for retrofit installation. The capital costs for the retrofits were funded under this study.

The City of Round Rock, Texas, has a population of 86,902 and is located 15 miles north of Austin in the Central Texas (http://www.roundrocktexas.gov/about/).

Figure 1. Map showing the location of the City of Round Rock, Texas. Source: http://www.roundrocktexas.gov/about/).

Major employers in the area include Dell, Farmers Insurance Group and Cypress Semiconductor. The RRISD has 42 total campuses: 27 elementary schools, 8 middle schools, 4 high schools and one 9th grade center, and 2 alternative centers (http://www.roundrockisd.org/home/index.asp?page=1731). The RRISD transportation department is recognized for its excellence, receiving the 2004 Larson Award for Quality School Transportation from the National Association for Pupil Transportation (NAPT) in 2004 (http://www.roundrockisd.org/home/index.asp?page=1272).

3.2 Bus Selection

The RRISD fleet included 220 buses at the time of project implementation, 90 of which have air conditioning; 28 of 68 recent model year (MY) buses have DPF’s, which will continue to be included with new buses added to the fleet (Roberts, 2006). New buses were not purchased between 1990 and 1995. A few buses in the fleet have gasoline engines, but most are diesel engines (engines of buses purchased in the 1990’s and later were primarily manufactured by International). ULSD is currently used as the standard fuel.

Buses were selected for the study through a semi-random process. Dan Roberts, RRISD Transportation Director, provided the research team with a list of all buses in the fleet. After eliminating all buses that did not meet basic criteria (i.e. gasoline engines, specialty use designation, presence of a DPF, pre-1991 MY buses which were not eligible for the DOC retrofit, smaller than typical size), a total of 10 buses were randomly selected using the random number generator in MS Excel. The research team selected the five buses shown in Table 1 and Figure 2 from that list in order to achieve a sample with a range a model years and good retrofit compatibility, and to include two buses with fully operational air conditioning systems. A sixth bus MY 1985 bus was later selected for testing. This bus was not eligible for retrofits, but provided an interesting case for comparison with later MY buses.

Table 1. Summary of characteristics of buses included in the current study (source: Roberts, 2006). All buses had engines manufactured by International and located in the front of the bus with exhausts located on the right.

Bus ID#	RRISD ID#	Bus Make	Bus Model	Bus Year	Engine Year	Engine Model	Mileage (at the time of selection)	Air Conditioning
1	13	Bluebird	3800	2001	2001	T444E	98,804	No
2	16	Bluebird	3800	2001	2001	T444E	88,555	No
3	120	Bluebird	3800	2000	2000	T444E	109,083	No
4	114	Thomas	3800	1996	1996	T444E	122,191	Yes
5	79	Wayne	1753	1985	1985	6.9L	264,452	No
6	113	Thomas	3800	1996	1996	T444E	NA	Yes

Figure 2. Illustration of the school bus type used in the current study (source: Roberts, 2006). All buses have a gross vehicle weight rating (GVWR) of more than 10,000 lbs (Type C).

3.3 Personnel and Bus Route During the Tests

Testing occurred during July and early August of 2006. During these summer months, bus crews work 10 hours per day (0630-1730) on Mondays-Thursdays. Only research team members and the driver, no school children, were on-board buses during the tests. The driver (Ron Seres) was the same for all of the tests.

Children in the RRISD are on-board buses for a maximum of 45 minutes on regular routes (Roberts, 2006). Bus drivers typically have three routes for elementary, middle, and high school students, respectively, for approximately 2.5 hours in transit during morning pick-up or afternoon drop-off each day. Special needs routes require longer distances and time on-board buses, with drivers in transit nearly 8 hours per day (Roberts, 2006).

The research team asked RRISD Transportation Director, Dan Roberts, to select the bus route for the study because of his knowledge of the area and bus fleet. The team asked that a typical suburban route be selected. Given the economic growth and expansion of roads and freeways in Round Rock, the team recognized that it was likely not possible to avoid all confounding sources but a route was selected with the goal of minimizing sources such as construction areas. The route was to be conducted exactly as usual, simulating pick-up of children near their homes and drop-off and idling in school yards. The route shown in Figure 3 was selected and used for all test runs.

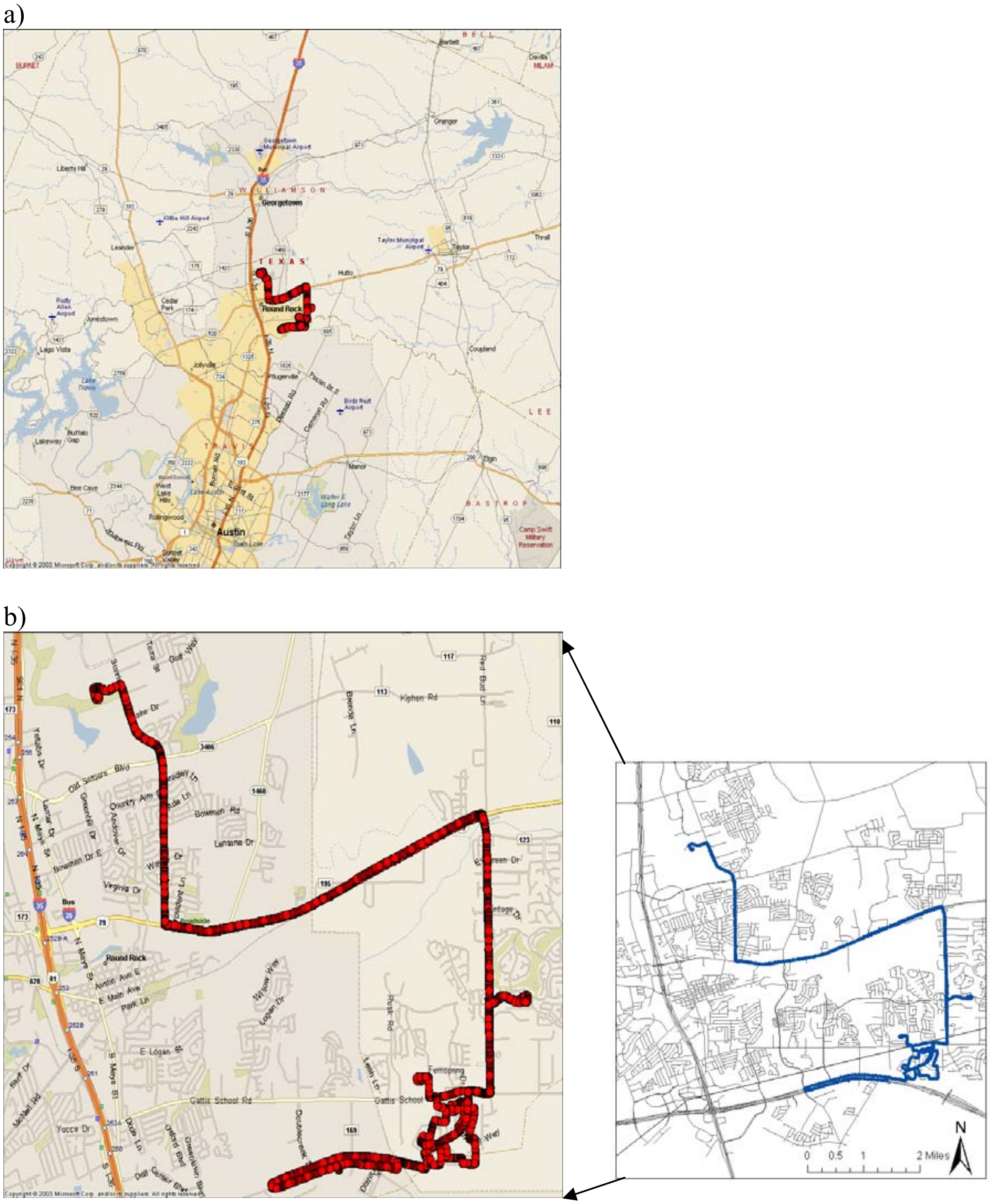


Figure 3. Maps showing the location and distance for bus route. The same route was driven for all tests. The route was 26.5 miles in length and required approximately 1.5 hours to complete.

3.4 Test Phases and Retrofit Package

The project was consisted of three phases of testing:

1. Before retrofits (all 6 buses listed in Table 1)
2. After installation of a Spiracle (3 buses: 3, 4, and 6)
3. After installation of a DOC and Spiracle (3 buses:3, 4, and 6)

A total of 15 tests were conducted: the 12 described above along with three additional tests that were repetitions for Bus 1 (2 tests) and Bus 2 (1 test) before retrofits.

A priority for the study was to examine a retrofit package with the largest sample size allowed by the available resources. Given that costs for a single DPF are approximately \$7000-\$8,000 versus approximately \$1575 for the a Spiracle/DOC kit, the team felt that resources were better utilized focusing on a more cost effective package and testing the greatest number of buses possible before and after installation of this package, rather than testing a single bus with a DPF. The Donaldson Spiracle Crankcase Filtration System (CFS) is verified by both the U.S. EPA and the CARB when combined with a DOC. Percent reductions of verified or test levels recognized by the U.S. EPA for the Series 6000 DOC and Spiracle are 25%-33% for PM, 13-23% for CO, and 50%-52% for HC, and for the Series 6100 DOC and Spiracle are 28%-32% for PM, 31%-34% for CO, and 42% for HC (http://www.epa.gov/otaq/retrofit/retroverifiedlist.htm). Further information regarding the installation and operation of the Spiracle CFS and DOC is available from Donaldson (http://www.donaldson.com).

3.5 Instrumentation and Activity Logs

A summary of the instruments used in the study and their characteristics is provided in Table 2.

Table 2. Instruments used in the study and their characteristics.

Measurement	**Dimension**	**Instrument**	**Brand**	**Model #**	**Detection Limit**
Nitrogen Oxide (NO)	Ppb	Chemiluminescence analyzer	Thermo Electron Corp. (TECO)	42C Trace Level	0.05 ppb (120 sec. averaging time)
Nitrogen Dioxide (NO_2)	Ppb	Chemiluminescence analyzer	Thermo Electron Corp. (TECO)	42C Trace Level	0.05 ppb (120 sec averaging time)
Total Oxides of Nitrogen (NOx)	Ppb	Chemiluminescence analyzer	Thermo Electron Corp. (TECO)	42C Trace Level	0.05 ppb (120 sec averaging time)
Carbon Monoxide	Ppm	Nondispersive Infrared (NDIR)	TSI	Q-Trak 8551	1 ppm
Carbon Dioxide (CO_2)	Ppm	NDIR NDIR	Tellaire TSI	7001 Q-Trak 8551	1 ppm 1 ppm
$PM_{2.5}$ Continuous	$\mu g/m^3$	Handheld Nephalometer	TSI	AM510 SidePak & 8520 DustTrak	1 $\mu g/m^3$
Ultrafine PM	#/cc	Condensation Particle Counter (CPC)	TSI	8525 PTrak	$1/cm^3$
Total VOC	Ppb	Photoionization Detector (PID)	Rae Systems	PPB plus	1 ppb
Sulfur Hexafluoride	Ppb	Electron Capture Detector/Gas Chromatograph	Lagus	Autotrac ATGM	0.05 ppb (linear)
Temperature	°C	Thermistor Thermistor	Onset TSI	Hobo U10/U12 Q-Trak 8551	-20 °C
Relative Humidity	%	Resistance Resistance	Onset TSI	Hobo U10/U12 Q-Trak 8551	25%

Instrument calibration protocols and frequencies are discussed below.

3.5.1 TECO NO-NO_2-NOx Analyzer

Calibration of the instrument was performed prior to the start of the sampling season. Span checks were performed prior to and after bus test runs. The instrument responses along with reference values for all calibrations and span checks were recorded in the operator's logbook along with an electronic copy of data (1-minute averaging time).

A Tanabyte Model 300 automatic calibration system was used to generate gas mixtures of known composition and concentration for use in calibrating the TECO NO-NO_2-NOx analyzer. The calibrator relies on the operation of flow controllers to maintain a source gas flow and a dilution air flow at each test level. Standardization of the calibrator involves measurement of system parameters needed to calculate pollutant concentrations generated during a multi-point calibration or span check. Calibration gases were derived from the Environmental Protection Agency (EPA) Protocol National Institute of Standards and Technology (NIST) traceable secondary gas standards that are blended with zero air to produce the concentrations needed for calibration. These secondary standards are certified by the vendor following vendor established procedures.

The standard used to calibrate the NO analyzer contained 49.5 ppm NO in a balance of dry nitrogen. A multipoint calibration of at least five NO calibration gas mixtures that correspond to approximately 0%, 5%-15%, 20%-30%, 50%-60%, and 75%-90% of the sampling range of interest (0 ppbv - 150 ppbv) was introduced automatically into the inlet of the analyzer by the calibrator. The level of the span check gas was approximately 80% of the sampling range of interest.

NO_2 calibration gas mixtures were derived from the reaction of NO with controlled amounts of ozone generated within the Tanabyte calibrator. Similar to the NO calibration, a multipoint calibration of at least five calibration gas mixtures of NO_2 corresponding to approximately 0%, 5%-15%, 20%-30%, 50%-60%, and 75%-90% of the sampling range of interest (0 ppbv-50 ppbv) was introduced automatically into the inlet of the analyzer. The level of the Span check gas was approximately 80% of the monitoring range of interest.

3.5.2 Carbon Monoxide

The TSI Q-Trak was calibrated before testing began with a two-point calibration (0, 40 ppm) according to the procedure specified in the Q-Trak manual. Given the low CO concentrations seen during this investigation and the low resolution of the instrument, the CO values should be interpreted carefully.

3.5.3 Carbon Dioxide

The TSI Q-Trak was calibrated before testing began with a two-point calibration (0, 400 ppm) according to the procedure specified in the Q-Trak manual. The Tellaire 7001 was not calibrated but was periodically collocated with the Q-Trak and was found to read similarly.

3.5.4 Continuous $PM_{2.5}$

The TSI SidePak and DustTrak were calibrated with a multi-step procedure. Before each day of testing, these instruments were cleaned, oiled, and zero-calibrated according to the procedure in the manual. Both instruments were calibrated within the past year with Arizona Road Dust with the manufacturer. Because both of these instruments are significantly sensitive to the morphology and index of refraction of the aerosol that they are measuring (Jenkins *et al.*, 2004), these instruments were also calibrated with gravimetric samples. The procedure for calibration involved collocating both $PM_{2.5}$ instruments with an SKC761-203B personal exposure monitor (PEM) badge connected to a 10 L/min pump. The PEM has a 37 mm filter in it and a collection plate to remove particles larger than 2.5 μm. By weighing the filter before and after exposure to air, the total mass collected on the filter can be compared to the integrated measurements from the continuous monitors. A blank filter (no airflow) was also collocated to account for any changes in filter weight due to air humidity. Our original protocol called for filter samples to be collected on each bus. In initial runs, even with a 5-digit balance and the high-flow PEM, we were unable to collect a large enough mass for filter calibration. Instead, 24-hour tests were conducted at our lab during and after the test and these values were used to correct the readings from the two $PM_{2.5}$ monitors. Ideally, this calibration should have been done with the same aerosols that were measured during the investigation. Given that it could not be done, this calibration should be interpreted with caution. A third part of the calibration procedure involved collocating the two $PM_{2.5}$ monitors in both in-cabin and ambient environments and comparing their readings (after correction based on the filter samples as described above). Four collocation events were completed during the field experiments and the team found that the instruments agreed within 10% of each other with no bias (i.e. neither instrument read consistently higher during testing) and therefore took 10% to be the approximate accuracy of these instruments.

3.5.5 Ultrafine PM

The TSI P-Traks were calibrated by the manufacturer within the year prior to the testing. Both units were zero-calibrated each day before testing. Further, the two P-Traks were collocated both inside and outside of the bus and the results compared to each other. Four collocation events were completed during the field experiments and the instruments agreed within 10% of each other with no bias. The team, therefore, took 10% to be the approximate accuracy of these instruments.

3.5.6 TVOCs, SF_6, Temperature, Relative Humidity

Without prior knowledge of the entire range and concentrations of VOCs of interest, it is impossible to conduct calibrations for the instrument. Given that this measurement was added to this study for no cost, no calibration procedures were conducted. The minimal importance of the temperature and relative humidity measurements to the study outcomes also limited the value of calibrating these instruments and thus they were not calibrated during the study. The SF_6 monitor was also not calibrated because the error from the regression (see methodology) was deemed to be much larger than the instrument error.

3.5.7 Global Positioning System

A Vehicle-Tracking, Incorporated LandAirSea Tracking Key was used to track the route, elevation, and ground speed of the test bus.

3.5.8 Video and Activity Recording

A video camera was positioned in the first row of passenger seats to record bus activity. One research team member was designated as the event recorder during each run and maintained a written log of bus activity, nearby traffic or potentially confounding sources, and instrument operations.

3.6 In-Cabin Instrument Configuration and Study Design

With the exception of the NO-NO_2-NOx monitor, which required an external power source, instruments were placed in the center of the bus and secured to the seats with 3M Scotch blue painters tape. Figure 4a shows the instruments secured in the center of the bus with the sampling lines in the configuration used for in-cabin monitoring. Figure 4b shows the sampling lines routed and secured through a window on the opposite side of the bus from the indoor lines. There were no alternations of the internal physical configuration of the buses, such as removal of seats or floorboards. Windows remained closed for all tests and tightly sealed to the extent possible around sampling lines. The research team attempted to minimize their movements to the extent possible inside of the buses during the testing.

The NO-NO_2-NOx monitor was placed in the first seat behind the driver such that it was in close proximity to access panels in the front of the bus that contained access to the power source. This instrument was powered by the 12 volt alternator of each bus via a 1000 Watt DC to AC converter. A battery was secured in parallel with the bus power to provide approximately 20 minutes of backup power in the event that connection or supply of power from the bus was interrupted. Two sampling lines were connected to the instrument via a 3-way valve to allow for selection of outdoor air or cabin air by manual manipulation of the valve. The sample lines were both ¼” x 25’ FEP (0.16 ID) tubing assembled with stainless steel compression fittings at the 3-way valve and at the back of the instrument. The terminal end of the indoor sampling line was collocated with other monitors in the center of the bus as shown in Figure 4a. The outdoor line was placed just outside the window on the opposite side of the bus from the indoor sampling lines as shown in Figures 4a and 4b. The instrument dump line was placed outside of a window behind the driver to avoid contamination of the outdoor sampling line. A laptop computer was used for data collection and monitoring of instrument operations. Real-time one-minute averaged data was collected via the RS323 protocol and TEI for MS Windows software package. After each test, the instrument was either moved to the next bus for another test, or it was moved to an air conditioned trailer for final span checks. After the final span checks were completed, the instrument was allowed to run overnight in the trailer to maintain it in a state of readiness for the next day of sampling.

Air exchange rate was measured by decay of sulfur hexafluoride (SF_6). At the beginning of the bus run, approximately 3 L of 0.01 % SF_6 was released on the bus. An attempt was made to evenly disperse the SF_6 by conducting the release while walking up and down the aisle. After 15 minutes of mixing, a sample of bus air was taken and stored in a sealed and purged Tedlar bag. Samples were taken approximately every 10 minutes thereafter. The bags were later analyzed with GC/ECD and the air exchange rate was assessed as the best fit slope to a plot of the natural log of the ratio of concentration of SF_6 to the initial concentration vs. the time of the sample. This method, based on a mass-balance on SF_6 assumes several conditions including that the air in the bus was well-mixed and that the air exchange rate was constant. Given that mixing was imperfect, particularly early in each bus run, the standard error in the slope from the regression was taken as the uncertainty in the air exchange rate.

All other instruments were configured according to their manuals. The TSI Dust-Trak ($PM_{2.5}$) and one TSI P-Trak (Ultrafine PM) were set to sample outside of the bus through short (approx 15 cm) lengths of tubing though an open and taped window.

A summary of instrument operations for the NO_x, ultrafine PM, TVOC, and GPS for each test is provided in Table 3. During several initial tests, problems related to overheating due to the intense heat inside of the buses (at times exceeding 100°F) and fluctuations in power due to unstable connections resulted in loss of data from the NO-NO_2-NOx instrument. These problems were quickly remedied by working with the RRISD bus crew to devise new approaches for securing the power connections and by staging the testing such that a bus without air conditioning was tested early in the morning (around 0600) followed by a second test on an air conditioned bus. Working within the constraints of the intense heat and humidity inside of the buses also became a serious consideration for the health of the research team and driver. Staging the tests in this manner preserved both the operations of the instruments and the team. Tests in which NO-NO_2-NOx data was lost were repeated in totality. Although the NO-NO2-NOx data were lost from several tests, these tests, nonetheless, provided a good opportunity to conduct inter-comparisons of the $PM_{2.5}$ and ultrafine PM data for repeated tests on the same bus. The GPS receiver did fail during two of tests for undetermined reasons, perhaps due to the jostling experienced on at least one these buses (e.g., Bus 5, the 1985 MY bus, did not have the same type of suspension system as more recent MY buses, and the ride was markedly less comfortable). The team felt that this was not critical because the same route was driven for each test. The excessive heat also caused problems with one of the TSI P-Trak ultrafine PM instruments. These devices work by evaporating isopropyl alcohol onto the sample particle stream to aid the optical counting of the device. These devices are not designed for the high temperatures encountered in this study and one of the units stopped functioning early during test 3CC0726. All of the subsequent tests had only one P-Trak operating and this unit was periodically switched to measure outside concentrations.

As described above, the bus route for each test was conducted exactly as usual with the driver simulating the number of stops, along with the typical duration for the opening and closing of the front door. The route consisted of 21 stops; 17 were in suburban residential neighborhoods, one was along a more congested multi-lane roadway, one was at an apartment complex, and two were at an elementary school and a middle school, respectively. At the elementary and middle schools, the driver simulated unloading of children with the front door open near the entrance of the school, as well as pulling forward and idling with the front door closed as he would in a bus queue.

Table 3. Instrument operations during each test for instruments with missing data.

Test ID	NOx	Ultrafine PM (Number of P-Traks in Operation)	TVOC	GPS
1NONE0711	N	2	N	Y
1NONE0713	N	2	Y	Y
1NONE0802	Y	1	Y	Y
2NONE0713	N	2	Y	Y
2NONE0720	Y	2	Y	Y
3CC0726	Y	1	Y	Y
3CCDOC0727	Y	1	Y	Y
3NONE0717	Y	2	Y	Y
4CC0727	Y	1	Y	N
4CCDOC0802	Y	1	Y	Y
4NONE0717	Y	2	Y	Y
5NONE0718	Y	2	Y	N
6CC0731	Y	1	Y	Y
6CCDOC0803	Y	1	Y	Y
6NONE0718	Y	2	Y	N

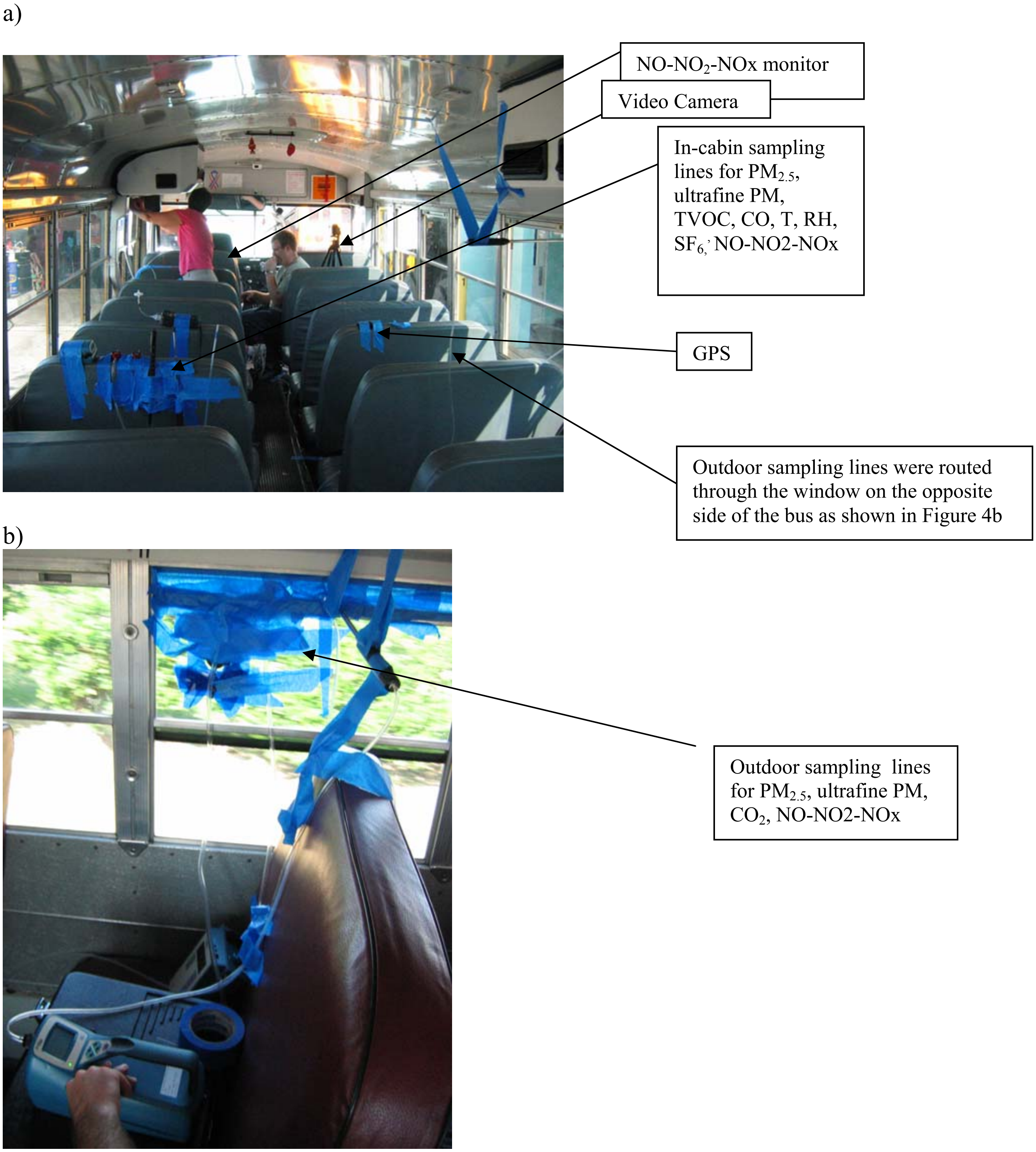


Figure 4. Instrument configuration on-board the school buses.

Table 4 lists the conditions for each test. The tests were typically completed between 0600 and 1200 on the days of testing. Outdoor temperatures were typically between 25 and 40°C. The very hot outside temperatures for three tests (2NONE0713, 4NONE0717, 6NONE0718) likely represent periods of time where the outdoor temperature sensor was in direct sunlight, and, thus, these results should be interpreted with caution. Outdoor relative humidities (RH) ranged from 33% to 77%. RH is a strong function of temperature, so the very low RH for the three tests with very hot temperatures are likely incorrect. The strong dependence of RH on temperature limits the value of presenting the standard deviation in RH, therefore it was not included in the presentation of the results.

Each test typically had 4 or 5 occupants on the bus (1 driver and 3 or 4 researchers). However, early tests had more occupants as the test protocol was undergoing refinement. The number of occupants is important when interpreting $PM_{2.5}$ data. $PM_{2.5}$ can be resuspended by human activities, and therefore would be expected to be higher on bus runs with higher number of occupants and with more activity. Number of occupants, as well as air exchange rate and outdoor CO_2 levels are expected to affect indoor CO_2 concentrations as well. The air exchange rate was calculated by decay of SF_6 as described above. The air exchange rates were remarkably consistent across buses and tests, although much more variation was expected by the team due to differences in between in-cabin and outdoor temperatures, in wind speed and direction, in bus speed, as well as in leaks between the outdoors and the bus cabin. The standard error for the air exchange rate shown in Table 4 is from the decay test, as described in Section 3.6. It should be noted that although air exchange rates are 3 – 10 times larger than rates for typical buildings, the amount of air flow represented by these values is small because of the small volume of the cabin. However, the large air exchange rates suggest that any pollutant emitted inside of the buses will be quickly removed and that any pollutant present in close proximity to the bus will quickly enter the cabin. Quantitatively, if ambient concentrations and indoor emissions remain constant, and the air on the bus is well-mixed, a pollutant will take approximately 45 minutes to reach a steady-state concentration on most of the buses. A specific reason for the low air exchange rate for test 3NONE0717 could not be ascertained. Air conditioning may have increased the air exchange rate for Bus 4 (it is higher than for the other buses), but Bus 6 had a similar air exchange rate to the non air-conditioned buses. Air conditioning would be expected to increase the air exchange rate if the fresh air intake was open (it was closed for all tests in this study) or if it did not seal properly. Air conditioning may also change the flow and pressure differences in the bus which may lead to changes in the air exchange rate.

Table 4. Test conditions.

Test ID	Bus ID	Retrofit Status*	Date	Time of Test	# Occupants (incl. driver)	AC Oper**	Air Exchange Rate (# of exch/hr)	Outdoor Conditions		
								Temp. Mean (SD) (°C)	**Mean RH (%)**	**CO_2 Mean (SD) (ppm)**
1NONE0711	1	NONE	7/11/2006	8:34-10:22	7	N	3.93 ± 0.03	30.5 (1.8)	63	340 (10)
1NONE0713	1	NONE	7/13/2006	6:40-8:31	6	N	3.75 ± 0.15	27.8 (1.5)	72	344 (7)
1NONE0802	1	NONE	8/2/2006	6:39-8:24	4	N	3.24 ± 0.09	27.5 (0.2)	77	327 (5)
2NONE0713	2	NONE	7/13/2006	10:06-11:51	7	N	3.85 ± 0.07	40.5 (2.2)	33	364 (10)
2NONE0720	2	NONE	7/20/2006	6:24-8:22	5	N	3.36 ± 0.07	28.4 (0.2)	69	354 (9)
3CC0726	3	CC	7/26/2006	6:19-8:04	5	N	3.18 ± 0.17	25.7 (0.3)	81	341 (12)
3CCDOC0727	3	CCDOC	7/27/2006	6:12-7:52	5	N	3.55 ± 0.15	26.3 (0.5)	73	353 (8)
3NONE0717	3	NONE	7/17/2006	6:42-8:23	5	N	2.6 ± 0.09	28.3 (0.4)	68	360 (6)
4CC0727	4	CC	7/27/2006	8:45-10:33	5	Y	4.45 ± 0.13	28.7 (0.6)	68	342 (9)
4CCDOC0802	4	CCDOC	8/2/2006	9:19-11:06	4	Y	4.55 ± 0.1	30.9 (1.0)	61	338 (9)
4NONE0717	4	NONE	7/17/2006	9:00-10:42	5	Y	4.22 ± 0.14	41.4 (4.0)	33	384 (7)
5NONE0718	5	NONE	7/18/2006	6:43-8:25	5	N	3.91 ± 0.26	29.9 (1.4)	57	375 (11)
6CC0731	6	CC	7/31/2006	6:18-8:04	4	Y	3.78 ± 0.06	27.3 (0.3)	75	326 (7)
6CCDOC0803	6	CCDOC	8/3/2006	7:05-8:53	4	Y	3.06 ± 0.25	28.1 (0.9)	74	338 (11)
6NONE0718	6	NONE	7/18/2006	9:14-11:17	5	Y	3.59 ± 0.04	39.6 (1.9)	33	385 (11)

*****CC=Spiracle only; CCDOC=Spiracle and DOC

**AC=Air conditioning

3.7 Data Reduction and Analysis

The research team developed macros in STATA and SAS to process and time synchronize the data for all of the instruments and for the activity logs, to examine the percent time in mode during each test, and to produce statistical summaries for each pollutant (i.e., NO, NO_2, NOx, $PM_{2.5}$, ultrafine PM, TVOC) including mean concentrations, population standard deviation, median, minimum, and maximum concentrations in cabin air and outdoors during each test, as well as during different modes of operation.

Data and event logs were reviewed to identify problems/sources of error and data reduction strategies. Each NO-NO_2-NOx data record was flagged with the following four codes:

Status Code:
1=Not on-board bus
2=Outdoor
3=In-cabin
4=Erroneous sampling location/sampling from incorrect line
5=Zero
6=Span

Power-Date-Time Code:
0=No power to instrument or incorrect date/time stamp
1=Power to instrument and correct date/time stamp

NO Data Code:
0=Out-of-range (<-15ppb, >180 ppb)
1=In-range
2=Negative concentrations reported as zeros (0 ppb>$C_{NO} \geq$-15 ppb)
3=Within 5 minute instrument response period between outdoor and in-cabin sampling (or vice versa)

NO_2 Data Code:
0=Out-of-range (<-5ppb, >60 ppb)
1=In-range
2=Negative concentrations reported as zeros (0 ppb>$C_{NO2} \geq$-5 ppb)
3=Within 5 minute instrument response period between outdoor and in-cabin sampling (or vice versa).

Because the NO-NO_2-NOx analyzer was either moved to another bus if two tests were performed on a given day or moved to an air conditioned trailer at the end of each day with continued operation through the night, it was important to flag any records in the test data files associated with another sampling location (i.e., the trailer), zero air, or span checks if these records were not written to separate files during the field work. A power-date-time code of 0 was usually associated with transitions prior to the start of a test between the power source in the trailer and the source on the bus (12 volt alternator), which resulted in a momentary loss of power and required resetting of the date/time stamp. As described above, the NO and NO_2 calibration ranges were 0 ppbv-150 ppbv and 0 ppv-50 ppbv. Measurements that fell within a lower limit of 10% below the calibrated range and an upper limit of 20% above the calibrated range, based on TECO guidance, were flagged as in-range. The five- minute transition time between outdoor and in-cabin sampling or vice versa was determined empirically through observations after manual switching of the 3-way valve. Only buses records with the following combination of codes were used in the NO, NO_2, and NOx statistical analyses:

In-cabin - (STATUS=3, POWER-DATE-TIME=1, NO=1, NO_2=1)
Outdoor - (STATUS=2, POWER-DATE-TIME=1, NO=1, NO_2=1)

A similar set of codes was used for the ultrafine PM instruments. Only one instrument was in operation after July 26th; a code was developed to determine whether the P-Trak was measuring in-cabin or outside air. Additionally, the P-Trak was sensitive to its orientation because the wick needs to stay continuously submerged in alcohol. Therefore, turns and bumps during the bus rides would occasionally cause the instrument to tilt and require restarting. The excessive heat also caused the P-Traks to run out of alcohol, particularly on early runs. Only P-Trak data from when the unit was operating properly were included in the dataset.

All other instruments operated without problems or interruptions. The percent times in mode (idling door closed, idling door open, cruise, bus stop, and other) for each minute of the bus run was determined from the activity logs.

The primary objective of this study was to evaluate the impact of retrofits on in-cabin concentrations of relevant pollutants. In all cases, the team compared in-cabin concentrations with and without retrofits. To assess the statistical significance of the results, the data were analyzed with standard parametric statistics. Variances were not assumed to be equal, and therefore the Sattherthwaite approximation was used to correct the degrees of freedom. These statistical analyses were conducted over an entire test on a given bus and for different modes of operation (frequent stops and door openings, cruise with occasional stops) during a test.

It should be noted that all of the variables considered in this study are positive-definite and skewed, and therefore the statistical analysis may not be directly appropriate. The application of non-parametric statistics was considered, but was ultimately rejected because of time constraints. It is critically important to note that the relatively large sample sizes provide a large amount of statistical power and therefore the absolute value, and not just statistical significance, of the differences in concentrations with and without a retrofit should also be considered.

4 RESULTS AND DISCUSSION

The results from the study to date, which includes twelve tests (i.e., retrofits on three of five buses) as well as three repetitions are presented in this section.

4.1 Percent Time in Mode

Table 5 shows the percent time in mode for each for each test. Five modes of operation, including "idling door closed", "idling door open", "cruising", "bus stops", and "other" were identified from the test activity logs. The "other" category was almost always due to idling in the bus yard at the beginning of the test with no record of the door position. Because the same route was driven, the durations of the tests were relatively consistent ranging from approximately 102-110 minutes. It is important to note that two tests, 2NONE0720 and 6NONE0718, were 118 and 123 minutes in duration, respectively, and for at least Bus 6, the tests with the retrofits on this same bus were shorter in duration. Both 2NONE0720 and 6NONE0718 had relatively longer periods of idling in the bus yard at the beginning of the test during which the NO-NO_2-NOx analyzer was collecting in-cabin data, but data collection with the other instruments had not yet begun. This was largely due to the timing of the transition between the power source in the trailer for the NO-NO_2-NOx analyzer and the power source on the bus. In all tests, cruising represented the most significant mode of operation for the buses, followed by bus stops, and then idling with either the front door open or closed. The percent time in mode will obviously vary with the type of route, distance, and number of bus stops and these factors should be investigated in future studies.

Table 5. Percent time in mode and duration (minutes) of tests.

Test ID	Idling, Door Closed (%)	Idling, Door Open (%)	Cruise (%)	Bus Stop (%)	Other (%)	Test Duration (Min)
1NONE0711	15	7	53	18	7	108
1NONE0713	8	13	62	17	.	111
1NONE0802	9	8	66	18	.	105
2NONE0713	10	9	64	18	.	105
2NONE0720	5	5	58	16	15	118
3CC0726	5	10	67	18	.	105
3CCDOC0727	5	7	69	18	1	100
3NONE0717	6	7	68	19	.	101
4CC0727	10	8	64	18	.	108
4CCDOC0802	4	14	64	18	.	107
4NONE0717	10	7	65	19	.	102
5NONE0718	6	6	70	17	2	102
6CC0731	4	7	72	18	.	106
6CCDOC0803	4	8	70	18	.	108
6NONE0718	3	5	59	15	17	123

4.2 $PM_{2.5}$ Mass Concentrations

Table 6 shows the in-cabin and outdoor measurements of $PM_{2.5}$ mass concentrations during the tests. Several features of the dataset are notable including the large variation in outdoor concentrations most likely caused when the school bus was close to $PM_{2.5}$ sources (traffic, construction sites, etc.). The large spikes in the outdoor data are clearly visible in the figures in Appendix A. Also, given that the $PM_{2.5}$ outdoor measurements were made on one side of the bus, typically on the same side that had the door, they should not be interpreted as an average outdoor concentration. In-cabin maximums may be related to the outdoor concentration spikes, but are generally much smaller. In-cabin spikes may also be caused by resuspension of particles, as mentioned above. In-cabin mean $PM_{2.5}$ concentrations were generally, but not exclusively, lower than outdoor concentrations. Median concentrations did not exhibit the same pattern with approximately half the tests having larger indoor than outdoor $PM_{2.5}$ mass concentrations. Test 6NONE0718 had a more frequent measurement interval (5 seconds vs. 10 seconds for the other tests) for the outdoor $PM_{2.5}$ measurements, and hence a larger number of data points.

Two other studies reported $PM_{2.5}$ concentrations, the Los Angeles Study (Behrentz et al., 2005; Sabin et al., 2005) and the CATF study. Both studies used similar instrumentation for $PM_{2.5}$, but tested different buses in different locations with different engines and engine retrofits, and under different test conditions. Behrentz et al., (2005) report $PM_{2.5}$ concentrations of 21 – 62 $\mu g/m^3$, higher than the 7 – 20 $\mu g/m^3$ reported for our study. Both our investigation and Behrentz et al. (2005) had similar background (i.e. ambient) concentrations. Mean $PM_{2.5}$ concentrations for all buses tested in the three cities for the CATF study ranged from 21 – 163 ug/m^3, which was considerably higher, on average, than our results. However, ambient concentrations for the CATF study, particularly for buses tested in Chicago and Atlanta, were on average much higher than for our study.

Table 6. Analyses of in-cabin and outdoor $PM_{2.5}$ mass concentrations ($\mu g/m^3$) over entire tests.

RunID	# of In-Cabin Meas.	In-Cabin Mean	In-Cabin Std Dev.	In-Cabin Min	In-Cabin Max	In-Cabin Median	# of Outdoor Meas.	Outdoor Mean	Outdoor Std Dev.	Outdoor Min	Outdoor Max	Outdoor Median
1NONE0711	648	16	6	8	51	15	648	19	14	8	166	16
1NONE0713	657	20	5	12	48	19	575	25	20	12	196	18
1NONE0802	627	20	5	12	42	19	630	28	13	18	118	24
2NONE0713	631	16	6	8	39	15	630	19	12	12	90	14
2NONE0720	601	18	8	7	51	15	586	12	11	4	98	8
3CC0726	607	7	2	3	16	7	581	7	9	2	120	6
3CCDOC0727	600	10	2	6	32	9	600	11	5	6	88	10
3NONE0717	606	19	9	6	46	19	606	27	67	6	680	10
4CC0727	648	8	2	4	28	7	639	17	13	6	142	14
4CCDOC0802	597	8	2	4	16	7	590	21	8	12	92	18
4NONE0717	602	11	4	4	24	10	595	14	16	6	188	8
5NONE0718	612	9	2	6	19	9	607	10	10	6	180	8
6CC0731	636	9	4	2	28	9	609	16	16	4	86	8
6CCDOC0803	639	14	5	6	70	14	641	33	17	16	144	28
6NONE0718	614	13	5	6	37	11	1212	14	20	4	238	7

4.3 Ultrafine PM Number Concentrations

The ultrafine PM number concentrations appear in Table 7. For tests prior to July 26th, two TSI P-Trak devices were operational during the testing, and the numbers of indoor and outdoor measurements were similar. For tests after that date, the P-trak was periodically switched to measure outdoor concentrations, which resulted in a lower number of outdoor measurement points (typically around 100, instead of 600 sample points when both P-Traks were operational). The outdoor data from July 26th were clearly erroneous and were excluded from the dataset. Outdoor ultrafine PM number concentrations showed very large variations, much smaller than variations inside of the bus cabin. One exception to this is a very large spike in in-cabin ultrafine particle concentrations during test 1NONE0713 – this spike is unexplained, but may be due to a tube constriction or other erroneous measurement issue. In-cabin mean concentrations were generally, but not exclusively, slightly lower (8% on average) than their outdoor counterparts. However, median in-cabin concentrations were generally higher (28% on average) with a few exceptions.

The CATF study reported ultrafine PM concentrations using similar instrumentation, but tested different buses in different locations with different engines and engine retrofits, and under different test conditions. Hill et al. (2005) reported ultrafine PM number concentrations of 7,381 – 74,466 particles/cc, higher (on average) than the 6,054 – 32,272 particles/cc found in this study. Both our investigation and Hill et al., (2005) had similar ambient concentrations, on average, as well as similar extremely high maximum concentrations (i.e. bus 1NONE0713 discussed above).

Table 7. Analyses of in-cabin and outdoor ultrafine PM number concentrations (particles/cc) over entire tests.

RunID	# of In-Cabin Meas.	In-Cabin Mean	In-Cabin Std Dev.	In-Cabin Min	In-Cabin Max	In-Cabin Median	# of Outdoor Meas.	Outdoor Mean	Outdoor Std Dev.	Outdoor Min	Outdoor Max	Outdoor Median
1NONE0711	477	6286	2278	2042	21550	5901	366	15136	18936	922	114000	5600
1NONE0713	639	15008	26332	1662	266200	5580	641	8888	2082	4416	16680	8772
1NONE0802	466	6911	2688	2060	37370	6748	101	8771	7477	2153	48970	5964
2NONE0713	452	6054	3933	1194	24370	4413	326	7425	9227	1835	66266	4050
2NONE0720	582	15908	5142	6289	28340	15170	580	17224	21274	2795	139750	8750
3CC0726	573	13770	5409	3150	30550	13150	.	.	.	.	.	.
3CCDOC0727	510	8739	3537	2786	23919	8942	82	9204	1977	5802	13010	9163
3NONE0717	597	24117	11615	4783	49130	22790	602	25191	34958	4511	280000	10804
4CC0727	546	8059	2999	3195	16670	7604	102	8336	5328	2787	35923	6730
4CCDOC0802	460	6176	1444	2128	12264	5902	120	7242	6728	1623	44190	4829
4NONE0717	583	13052	3668	6074	26580	12240	591	15045	17551	3833	143620	8727
5NONE0718	588	32272	13443	9837	77170	30450	607	24415	31671	4074	295230	12390
6CC0731	486	8739	4566	2270	20690	8214	108	8634	6103	2523	45460	6625
6CCDOC0803	528	10020	4893	2585	74020	9319	108	15893	16488	4381	123580	9648
6NONE0718	603	9359	2258	4125	17010	9128	611	15764	19467	4702	151800	8734

4.4 NO-NO_2-NO_x Concentrations

In-cabin NO_x, NO, and NO_2 data are shown in Figures 8, 9, and 10, respectively. The U.S. EPA has not certified a level of NOx emissions reductions for the Donaldson Spiracle/DOC package. A preliminary examination of the data from this study suggests that future studies should continue the investigation and quantification of NOx emissions before and after the installation of retrofits.

Mean and median in-cabin NO_x, NO, and NO_2 concentrations across the test population without retrofits in some cases varied by more than a factor of 2 (e.g., Bus1:1NONE0802 and Bus 4:4NONE0717). Mean and median in-cabin NO_x , NO, and NO_2 concentrations for Bus 13 and Bus 16 which both have MY 2001 International T444E engines with similar mileage, 98,804 and 88,555, respectively, also varied as much as a factor 2 (1NONE0802 and 2NONE0720). Thus, the results suggested substantial variability in mean and median in-cabin concentrations both across the bus test population, and, in some cases, between buses with similar characteristics such as age, mileage, and engine type. These results reinforce the need for future testing programs with large sample sizes. In-cabin NOx and NO concentrations during a given test also varied substantially with minimum and maximum concentrations differing by as much as an order of magnitude.

The outdoor data present a complex and ambiguous picture. The sampling framework was not ideal, given the need to manually switch the sampling between in-cabin and outdoor air. Ideally, a separate NO-NO_2-NO_x analyzer should be available to sample outdoor air. Emphasis was placed on the collection of in-cabin data, but this strategy resulted in a very small number of outdoor measurements when the time period for the instrument response was considered. Median and mean outdoor NO_x and NO concentrations were generally lower than in-cabin concentrations, but intra-test variability was also high. It is not possible within the framework of this testing program to determine if the air surrounding the bus where outdoor samples were collected was influenced by bus self-pollution or whether the placement of sampling lines on one side of the bus versus the other would have lead to different results. However, it is important to recognize that in some cases for which data were available, outdoor NO_x, NO, and NO_2 concentrations following the installation of retrofits were lower than outdoor concentrations prior to retrofits. Both in-cabin and outdoor concentrations have the potential to be influenced by confounding sources such as other diesel vehicles and equipment; although large segments of the route were on suburban, residential streets, sources such as construction equipment and on-road heavy-duty diesel engines were occasionally encountered on segments of the route where the bus was cruising with few stops.

The only other study to report NO_x concentrations was the Los Angeles Study (Behrentz et al., 2005; Sabin et al., 2005), where NO_2 concentrations were reported. Behrentz et al. (2005) report NO_2 concentrations of 34 – 110 ppb, with a mean of 73 ppb for all six buses tested and for all test conditions. These values were considerably higher than those reported here (10.3 – 30.8 ppb, mean of 20.2 ppb) although there are substantial differences in test conditions, bus engines, engine retrofits, and background concentrations (average of 49.1 ppb in the LA study, 15.0 ppb here).

Table 8. Analyses of in-cabin and outdoor NOx concentrations (ppb) over entire tests.

RunID	# of In-Cabin Meas.	In-Cabin Mean	In-Cabin Std Dev.	In-Cabin Min	In-Cabin Max	In-Cabin Median	# of Outdoor Meas.	Outdoor Mean	Outdoor Std Dev.	Outdoor Min	Outdoor Max	Outdoor Median
1NONE0711	0	.	.	.	.	.	0	.	.	.	.	.
1NONE0713	0	.	.	.	.	.	0	.	.	.	.	.
1NONE0802	69	64.1	23.3	19.8	111.3	66.9	6	17.5	12.9	4.2	39.6	15.4
2NONE0713	0	.	.	.	.	.	0	.	.	.	.	.
2NONE0720	93	118.5	38.9	46.5	191.7	119.4	5	79.4	28.4	37.5	110.2	80.3
3CC0726	71	47.8	16.3	15.7	86.6	43.9	1	12.3	.	12.3	12.3	12.3
3CCDOC0727	52	44.7	27.1	15.1	120.6	48	10	39.4	13	24.9	69.8	37
3NONE0717	70	75.7	31.1	23.2	132.8	87	1	43.6	.	43.6	43.6	43.6
4CC0727	72	95.9	40.6	15.9	192.3	96.1	3	12.4	7.7	6.6	21.2	9.3
4CCDOC0802	69	99.9	19.6	57.3	135.2	100	9	29.1	27.4	6.5	81.6	18.3
4NONE0717	54	147.8	36.2	96.1	215.5	142.6	0	.	.	.	.	.
5NONE0718	55	133.1	22.9	96	187.7	132	18	82.5	47.7	30.9	181	68.4
6CC0731	60	95.4	42.2	13.7	173.3	80.5	6	22.2	16.2	6.2	49.2	17
6CCDOC0803	79	93.6	37.4	13.7	164	96.2	9	25.4	17.2	9	63.8	22.4
6NONE0718	99	125	35.3	82.2	207.4	111.3	3	67.4	81.7	10.9	161.1	30.1

Table 9. Analyses of in-cabin and outdoor NO concentrations (ppb) over entire tests.

RunID	# of In-Cabin Meas.	In-Cabin Mean	In-Cabin Std Dev.	In-Cabin Min	In-Cabin Max	In-Cabin Median	# of Outdoor Meas.	Outdoor Mean	Outdoor Std Dev.	Outdoor Min	Outdoor Max	Outdoor Median
1NONE0711	0	.	.	.	.	.	0	.	.	.	.	.
1NONE0713	0	.	.	.	.	.	0	.	.	.	.	.
1NONE0802	69	49.1	21.2	8	95.6	51.5	6	12.8	14.1	1.1	36.1	7.4
2NONE0713	0	.	.	.	.	.	0	.	.	.	.	.
2NONE0720	93	93.8	36.3	28.2	172.8	95.8	5	57.8	26	26.4	81.4	68.5
3CC0726	71	33.4	15.6	3.2	70.3	29.4	1	6.9	.	6.9	6.9	6.9
3CCDOC0727	52	27.2	24.8	0.5	102	29	10	21.3	7.2	13	36.3	19.1
3NONE0717	70	53.3	29	4.8	107	63.9	1	21.6	.	21.6	21.6	21.6
4CC0727	72	81.7	41.4	4.8	177.1	82.8	3	4.3	3.6	2.2	8.4	2.3
4CCDOC0802	69	77.8	14.8	46.6	106.7	77.5	9	15.3	16.5	1.1	47.5	6.2
4NONE0717	54	116.9	35	59.1	178.3	114.1	0	.	.	.	.	.
5NONE0718	55	111.9	22.9	71.8	160.7	108.3	18	59.5	44.1	11.9	141.2	51.3
6CC0731	60	85.1	40.9	7.6	162.1	70	6	13	11.5	3.8	29.1	7
6CCDOC0803	79	73.1	31.7	3.1	132.5	74.8	9	12.2	8.6	3.9	30	10.2
6NONE0718	99	95.5	33.6	46.5	167.3	84.3	3	40.6	61.2	4.5	111.3	6.1

Table 10. Analyses of in-cabin and outdoor NO_2 concentrations (ppb) over entire tests.

RunID	# of In-Cabin Meas.	In-Cabin Mean	In-Cabin Std Dev.	In-Cabin Min	In-Cabin Max	In-Cabin Median	# of Outdoor Meas.	Outdoor Mean	Outdoor Std Dev.	Outdoor Min	Outdoor Max	Outdoor Median
1NONE0711	0	.	.	.	.	.	0	.	.	.	.	.
1NONE0713	0	.	.	.	.	.	0	.	.	.	.	.
1NONE0802	69	15	2.9	7.6	19.3	15.6	6	4.7	5	0.7	14.3	3.1
2NONE0713	0	.	.	.	.	.	0	.	.	.	.	.
2NONE0720	93	24.7	5.1	14.9	34.2	23	5	21.5	14.8	0.9	35.3	28.8
3CC0726	71	14.5	1.7	10.2	19.6	14.4	1	5.4	.	5.4	5.4	5.4
3CCDOC0727	52	17.5	3.9	11.8	29.4	16.8	10	18.1	7.6	7.8	37.5	17.7
3NONE0717	70	22.4	2.8	17.8	32.4	22.8	1	21.9	.	21.9	21.9	21.9
4CC0727	72	14.2	2.7	7.3	21.8	13.7	3	8	4.2	4.4	12.7	7
4CCDOC0802	69	22.1	5.6	10.7	33.7	23.3	9	13.8	13.2	0.3	34.7	7.8
4NONE0717	54	30.8	5	13.4	40.5	31.9	0	.	.	.	.	.
5NONE0718	55	21.2	5.9	7.1	35.6	21.7	18	23	13	9.7	57.3	18.6
6CC0731	60	10.3	3	4.9	23.3	10.1	6	9.2	7.4	2.4	22.8	7.2
6CCDOC0803	79	20.5	6.3	10.7	34.4	19.5	9	13.2	10.8	0.1	33.8	12.3
6NONE0718	99	29.4	5.7	18.3	41.6	28.9	3	26.7	22.5	4.8	49.8	25.6

4.5 Temperature, Relative Humidity, TVOC, and CO

In-cabin temperature and relative humidity during each test are presented in Table 11. With the exceptions of Bus 4 and Bus 6, the buses did not have air conditioning and were operated with the windows closed or tightly sealed. Mean in-cabin temperatures in non-air-conditioned buses (Buses 2, 3, and 5) during the tests ranged from 27.6°C (82°F) to 36°C (96.8°F). Mean in-cabin temperatures in Bus 4 showed little variability between tests at approximately 24.5°C (76°F). Mean in-cabin temperatures in Bus 6 ranged from 19.4°C (67°F) to 23.6°C (74.5°F). Recorded outdoor temperatures in Table 4 during the twelve tests ranged from 25.7°C (78.3°F) to 41.4°C (106.5°F) with the highest readings recorded when the Hobo was likely in direct sunlight. Mean in-cabin and outdoor temperatures during this study likely were substantially higher than during tests conducted in other cities such as Chicago and Ann Arbor. As described above, the intense heat led to operational difficulties with the NO-NO_2-NOx monitor (overheating of the photomultiplier) and loss of one P-trak partially through the testing program. The issues with the NO NO_2-NOx monitor were resolved by staging the testing such that buses without air conditioning were tested very early in the morning followed by testing of buses with operating air conditioning systems. In all cases, tests in which NO-NO_2-NOx data were lost or suspect were not considered in the statistical analyses and were repeated in totality. No other direct problems with other instrumentation were attributed to the heat. As expected, in-cabin relative humidity was a strong function of temperature and the operation of air conditioning.

Table 12 lists the carbon monoxide (CO) and total volatile organic compound (TVOC) in-cabin concentrations. These contaminants were not measured outside. The sampling interval for both instruments was 10 seconds with the exception of two tests (4NONE0717 and 4NONE0717) where the sampling interval for the TSI Q-Trak was inadvertently set to one minute. CO concentrations were both very low and very close to the resolution of the instrument, and thus should be interpreted with extreme caution. No statistical tests on these data were performed for this reason. The TVOC instrument measures all VOCs with different levels of sensitivity and was included in the testing for completeness. Testing with canister samples or other techniques that would allow for VOC speciation (but were not feasible given the resources for this project) would likely provide additional relevant detail. The data show differences of approximately a factor of two in mean/median concentrations between the highest and lowest test values. A stronger correlation between the number of TSI P-Trak ultrafine particle counters operating (see Table 4) and the TVOC concentration was expected by the team because these devices emit isopropyl alcohol, but we saw no such obvious evidence of a correlation. All pre-retrofit tests on buses that eventually had retrofits (Buses 3, 4, and 6) were tested with two P-Trak units, while the post-retrofit tests were completed with one P-Trak. This is because the pre-retrofit tests were largely completed when both P-Traks were operational (i.e. prior to July 26th). It was not appropriate to compare TVOC measurements from this study with those from other studies (i.e. Batterman *et al.*, 2002), as our study measured TVOCs rather than specific VOCs. We know of no other similar study that reports CO data.

Table 11. Analyses of in-cabin temperature (°C) and relative humidity (%) over entire tests.

RunID	# of Temp Meas.	Temp Mean	Temp Std Dev.	Temp Min	Temp Max	Temp Median	# of RH Meas.	RH Mean	RH Std Dev.	RH Min	RH Max	RH Median
1NONE0711	649	33.8	1.4	30.8	35.4	34.6	649	61	8	38	72	62
1NONE0713	666	29.6	1.1	27.2	31.4	29.6	666	70	5	57	76	71
1NONE0802	630	28.3	1.1	26.2	30.1	28.5	630	75	3	69	82	75
2NONE0713	630	36	1.5	32.8	38.1	36.4	630	55	3	49	59	55
2NONE0720	602	29.2	0.9	27.6	30.4	29.3	602	69	2	65	73	68
3CC0726	612	28.4	0.8	26.9	29.5	28.8	612	68	1	65	70	68
3CCDOC0727	600	27.6	1	25.9	29.4	27.7	600	71	2	67	74	71
3NONE0717	606	29.3	1.2	27.6	31.9	28.9	606	71	2	64	74	72
4CC0727	108	24.3	1.4	23.2	29.4	23.9	108	41	4	36	62	41
4CCDOC0802	590	24.8	0.6	23.9	27	24.7	590	41	2	38	46	41
4NONE0717	100	24.5	0.8	23.3	25.9	24.5	100	42	2	37	48	42
5NONE0718	612	31.2	2.4	27.5	35.3	31.4	612	57	6	46	67	57
6CC0731	636	19.4	1.8	17.5	26.5	18.6	636	50	6	42	78	48
6CCDOC0803	638	20.1	1.5	18.5	26	19.6	638	47	5	38	72	46
6NONE0718	613	23.6	1.1	21.6	25.6	23.4	613	39	3	34	46	39

Table 12. Analyses of in-cabin CO (ppm) and TVOC concentrations (ppb) over entire tests.

RunID	# of CO Meas.	CO Mean	CO Std Dev.	CO Min	CO Max	CO Median	# of TVOC Meas.	TVOC Mean	TVOC Std Dev.	TVOC Min	TVOC Max	TVOC Median
1NONE0711	649	2.5	0.6	1	4	3	.	.	.	.	.	.
1NONE0713	666	1.7	0.6	0	3	2	631	677	161	123	1149	707
1NONE0802	630	0.9	0.5	0	2	1	604	382	96	193	989	369
2NONE0713	630	1.5	0.7	0	2	2	631	718	130	80	1063	739
2NONE0720	602	1.8	0.8	0	3	2	602	713	98	341	1047	735
3CC0726	612	1.8	0.6	0	4	2	601	499	84	326	790	484
3CCDOC0727	600	1.2	0.4	1	2	1	603	621	225	370	2881	533
3NONE0717	606	2.3	0.8	0	3	2	607	872	122	524	1292	887
4CC0727	108	0	0	0	0	0	649	458	46	252	583	459
4CCDOC0802	590	0	0	0	0	0	587	365	43	195	476	375
4NONE0717	100	0.7	0.5	0	1	1	601	715	81	438	911	729
5NONE0718	612	1.9	0.4	1	3	2	606	676	132	297	1199	691
6CC0731	636	0	0	0	0	0	637	436	99	78	623	457
6CCDOC0803	638	0	0	0	0	0	635	413	51	190	598	414
6NONE0718	613	0.3	0.4	0	1	0	614	801	68	533	937	816

4.5 Investigations of the Statistical Significance of Differences in Pollutant Concentrations Before and After Retrofits

The testing program was designed as a phased installation of the Spiracle followed by the addition of the DOC. Differences in mean pollutant concentrations ($C_{\text{Spiracle or Spiracle/DOC}} - C_{\text{Prior to retrofit}}$) are shown in Tables 13 and 14 for each retrofit package when the results were statistically significant as described in Section 3.7. Therefore, negative results indicate lower indoor concentrations when the retrofit is installed. Results are specified as "n.s." when differences were not statistically significant.

The Spiracle resulted in statistically significant decreases of mean in-cabin concentrations of NOx on all three buses, and decreases in NO on Bus 3 and Bus 4, but not on Bus 6. Small additional benefits or slight disbenefits resulted from the addition of the DOC. These small changes from the addition of the DOC were of the same order of magnitude as the uncertainty of the instrument. Results for in-cabin NO_2 concentrations were similar, with disbenefits following the addition of the DOC. Additional tables showing differences between cases with the Spiracle only and cases with the Spiracle and the DOC appear in Appendix B. The impacts of retrofits on emissions of nitrogen oxides from the crankcase should continue to be investigated.

The Spiracle and Spiracle/DOC, respectively, resulted in relatively larger reductions of in-cabin $PM_{2.5}$ and ultrafine PM for Bus 3, but had a smaller impact on Bus 4, and essentially no impact on Bus 6. No clear benefit or disbenefit of the DOC was seen for $PM_{2.5}$ as it was for NO_x pollutants. There may be an additional ultrafine PM reduction benefit for the DOC, but it appears to be much smaller than the reduction due to the Spiracle. $PM_{2.5}$ concentrations may be affected by differing levels of particle resuspension (as described earlier) as well as by variations in the outdoor concentrations. The ultrafine PM concentrations are similarly affected by outdoor levels.

Of the other studies described in Section 1, only the CATF study reports before/after retrofit values for PM. For the only comparable case to ours (CATF's Bus 56 in Ann Arbor), ultrafine PM shows no benefit from the retrofits with values of 28,145 and 50,724 num/cc on two runs before the retrofit and 30,969 and 38,139 num/cc after the installation of a DOC and a Spiracle (our CCDOC cases). The CATF $PM_{2.5}$ results are unambiguous and show an approximate factor of two reduction in $PM_{2.5}$ concentrations after the retrofit on the same bus (essentially all due to the Spiracle portion of the retrofit). These are very similar to our results for Bus 3, stronger than our results for Bus 4, and very different from our results for Bus 6. The reason for the difference for Bus 6 is not clear, but there may be issues with the retrofit installation, engine combustion conditions, or other unmeasured parameters. We also feel strongly that $PM_{2.5}$ should be interpreted with caution because of the many possible $PM_{2.5}$ sources (test personal resuspension, outdoor ambient sources, etc.). It was not clear why our $PM_{2.5}$ and ultrafine reductions are consistent for each bus, and the CATF results do not show this pattern. However, our findings and those of the CATF are in agreement that of the two test retrofit technologies, the Spiracle appears to be responsible for any $PM_{2.5}$ reduction.

One important issue is the comparison of repetitions (i.e. same bus, same retrofit condition) done for Buses 1 and 2. Appendix C includes tables that show statistical comparisons of these cases. The data in Appendix C suggests that the results for $PM_{2.5}$ and ultrafine PM for both Bus 4 and Bus 6 are within the range of variation that was seen for the repetitions, suggesting that these results cannot be conclusively linked to the retrofits. In future studies, testing on additional buses, as well as testing in a cleaner and more consistent outdoor environment would facilitate assessment of the value of these retrofits for PM emission reductions.

TVOC results showed a very similar pattern to that of the NO_x pollutants, but should be interpreted with caution because of the lack of measurements of outdoor TVOCs, the difference in the number of operating P-Traks, and the general nature of the instrument used to measure TVOC concentrations.

Table 13. Impact of the Spiracle on pollutant concentrations based on the Satterthwaite method. Differences in the test means are shown if the impacts of the Spiracle were statistically significant (n.s.=difference not statistical significant).

Bus ID	Test 1	Test 2	NO_x (ppb)	NO (ppb)	NO_2 (ppb)	$PM_{2.5}$ ($\mu g/m^3$)	Ultrafine PM (num/cc)	TVOC (ppb)
6	6CC0731	6NONE0718	-29.6	n.s.	-19.1	-4	-620	-365
3	3CC0726	3NONE0717	-27.9	-19.9	-8	-12	-10347	-373
4	4CC0727	4NONE0717	-51.8	-35.2	-16.6	-3	-4993	-257

Table 14. Impact of the Spiracle and DOC on pollutant concentrations based on the Satterthwaite method. Differences in the test means are shown if the impacts of the Spiracle and DOC were statistically significant (n.s.=difference not statistical significant).

Bus ID	Test 1	Test 2	NOx (ppb)	NO (ppb)	NO_2 (ppb)	$PM_{2.5}$ ($\mu g/m^3$)	Ultrafine PM (num/cc)	TVOC (ppb)
6	6CCDOC0803	6NONE0718	-31.4	-22.4	-9	1	661	-387
3	3CCDOC0727	3NONE0717	-31.1	-26.1	-5	-10	-15378	-250
4	4CCDOC0802	4NONE0717	-47.9	-39.1	-8.7	-3	-6876	-350

It is interesting to note that of the three buses with retrofits, only Bus 3 did not have air conditioning, and it also tended to show the largest reductions in PM due to the retrofits. One possible explanation is the fact that buses with HVAC systems have cabin air filters or other particle loss in the ducts and other HVAC components. This effect may serve to diminish the effect of ambient particle concentrations as well as any self-pollution.

4.6 In-Cabin Concentrations for Two Different Bus Operation Modes

The results were repeated by temporally clustering the data for two different bus operation modes: frequent stops and door openings and cruising with occasional stops. The route consisted of two periods with frequent stops and door openings in primarily suburban, residential areas or near the elementary or middle schools, and three periods of cruising with few stops to and from the bus yard and between neighborhoods. Tables 15 -21 show the results for all pollutants when the buses were in the two operation modes.

NOx and NO were the only pollutants that showed pronounced differences between the two modes for some buses with relatively larger mean and median in-cabin concentrations for periods with frequent stops and door openings versus cruising.

Tables 22-25 show the results of similar statistical analysis as was presented in Tables 13 and 14. Tables 22-25 apply the results for the two bus operation modes described above. This clustering of data reinforces the discussions associated with Tables 13 and 14.

Table 15. Analyses of in-cabin $PM_{2.5}$ mass concentrations ($\mu g/m^3$) for two different bus operation modes: frequent stops and door openings, and cruising with occasional stops.

RunID	Frequent Stops and Door Openings				Cruise with Occasional Stops			
	# of Obs.	Mean	Std. Dev.	Median	# of Obs.	Mean	Std. Dev.	Median
1NONE0711	174	15	3	14	222	19	7	17
1NONE0713	222	17	3	16	246	22	6	21
1NONE0802	222	19	4	19	246	21	6	20
2NONE0713	198	15	3	15	253	17	6	15
2NONE0720	229	13	4	12	242	20	8	18
3CC0726	222	9	2	8	252	6	2	7
3CCDOC0727	228	10	2	9	240	9	3	9
3NONE0717	228	20	7	20	240	17	8	16
4CC0727	222	8	2	8	246	7	3	7
4CCDOC0802	222	8	1	8	246	7	1	6
4NONE0717	216	9	3	9	235	10	3	9
5NONE0718	192	9	2	9	288	9	1	8
6CC0731	234	9	3	8	276	8	4	9
6CCDOC0803	242	14	4	15	273	12	6	12
6NONE0718	234	11	3	10	258	13	5	12

Table 16. Analyses of in-cabin ultrafine PM number concentrations (particles/cc) for two different bus operation modes: frequent stops and door openings, and cruising with occasional stops.

RunID	Frequent Stops and Door Openings				Cruise with Occasional Stops			
	# of Obs.	Mean	Std. Dev.	Median	# of Obs.	Mean	Std. Dev.	Median
1NONE0711	114	6035	819	6314	191	6428	2186	5802
1NONE0713	222	10080	13039	4357	243	8542	16712	4391
1NONE0802	167	7028	1845	6946	200	7487	3224	7832
2NONE0713	146	6949	3016	5727	173	4590	2989	3645
2NONE0720	228	12835	4693	12410	229	17724	3527	17120
3CC0726	221	16281	5921	15300	233	11704	4781	11810
3CCDOC0727	211	9089	2226	9533	181	8292	4321	7954
3NONE0717	226	27236	11120	22935	236	20112	9310	21745
4CC0727	198	8780	2138	8031	192	7561	2705	7205
4CCDOC0802	174	6235	1109	5978	165	6011	1849	5763
4NONE0717	214	11934	3315	11965	226	13345	2953	12335
5NONE0718	189	34506	7674	32390	272	33109	15485	28445
6CC0731	197	8568	4481	7337	188	7241	3620	8133
6CCDOC0803	216	10681	2920	9542	197	9518	7104	8486
6NONE0718	234	9037	3128	7779	255	9185	951	9237

Table 17. Analyses of in-cabin NOx concentrations (ppb) for two different bus operation modes: frequent stops and door openings, and cruising with occasional stops.

RunID	Frequent Stops and Door Openings				Cruise with Occasional Stops			
	# of Obs.	Mean	Std. Dev.	Median	# of Obs.	Mean	Std. Dev.	Median
1NONE0711	0	.	.	.	0	.	.	.
1NONE0713	0	.	.	.	0	.	.	.
1NONE0802	31	61	19.2	63.4	26	71.4	22.4	71.4
2NONE0713	0	.	.	.	0	.	.	.
2NONE0720	37	97	41.6	87.6	22	133	31.7	126.4
3CC0726	31	56.1	19.8	61.4	27	41.4	8	42.2
3CCDOC0727	28	47.1	18.6	52.6	15	44.7	41.7	22.5
3NONE0717	31	80.6	25.9	88.2	28	55.7	26.1	57.7
4CC0727	33	119.1	36.5	115.2	23	81.2	23	89.2
4CCDOC0802	35	99.2	18.3	100	16	102.9	20	98.6
4NONE0717	23	153.1	37.7	169.3	18	146	35.3	150.6
5NONE0718	33	135	24.2	135.2	11	128.2	26.5	125.7
6CC0731	30	94.4	34.4	86.5	19	85	50	75.7
6CCDOC0803	29	109.8	35.2	117.3	33	80.7	26.5	90.5
6NONE0718	35	129	40.4	99.8	32	116.1	28.9	108.9

Table 18. Analyses of in-cabin NO concentrations (ppb) for two different bus operation modes: frequent stops and door openings, and cruising with occasional stops.

RunID	Frequent Stops and Door Openings				Cruise with Occasional Stops			
	# of Obs.	Mean	Std. Dev.	Median	# of Obs.	Mean	Std. Dev.	Median
1NONE0711	0	.	.	.	0	.	.	.
1NONE0713	0	.	.	.	0	.	.	.
1NONE0802	31	47.3	17.2	49.4	26	55	21.1	54.9
2NONE0713	0	.	.	.	0	.	.	.
2NONE0720	37	75.8	40.5	65.4	22	108.9	28.6	103.5
3CC0726	31	41.1	19	48	27	27.4	7.6	28.5
3CCDOC0727	28	28.7	15	32.3	15	29.4	40.2	8.5
3NONE0717	31	57.9	24.1	65.3	28	34.2	23.6	36.5
4CC0727	33	106	35.8	102.5	23	66.5	25.7	75.7
4CCDOC0802	35	76.9	14.2	77.5	16	81.1	15.3	75.3
4NONE0717	23	124.3	34.2	140.3	18	115.6	34.6	121.7
5NONE0718	33	113.7	21.4	115.6	11	109.6	32.6	101.4
6CC0731	30	84.5	33.7	77.4	19	75.2	47.7	66.3
6CCDOC0803	29	87	28.3	93.4	33	62.8	23.5	71.1
6NONE0718	35	101.4	34.2	79.2	32	87	28.4	83.8

Table 19. Analyses of in-cabin NO_2 concentrations (ppb) for two different bus operation modes: frequent stops and door openings, and cruising with occasional stops.

RunID	Frequent Stops and Door Openings				Cruise with Occasional Stops			
	# of Obs.	Mean	Std. Dev.	Median	# of Obs.	Mean	Std. Dev.	Median
1NONE0711	0	.	.	.	0	.	.	.
1NONE0713	0	.	.	.	0	.	.	.
1NONE0802	31	13.8	2.9	14.4	26	16.4	2	16.7
2NONE0713	0	.	.	.	0	.	.	.
2NONE0720	37	21.2	2.4	20.9	22	24	3.9	22.9
3CC0726	31	15.1	2.1	15	27	14	1	14.1
3CCDOC0727	28	18.4	4.4	18.6	15	15.3	1.8	14.4
3NONE0717	31	22.8	3.1	22.8	28	21.5	2.6	22
4CC0727	33	13.2	2.1	13.1	23	14.7	3	13.7
4CCDOC0802	35	22.3	4.9	22.6	16	21.8	5.8	24.3
4NONE0717	23	28.8	4.7	29	18	30.4	5	31.7
5NONE0718	33	21.3	5.7	21.1	11	18.6	7.5	21.2
6CC0731	30	9.9	3.3	9.1	19	9.8	2.8	9.6
6CCDOC0803	29	22.8	7.4	24.3	33	17.9	3.4	18.3
6NONE0718	35	27.6	6.5	25.1	32	29	4	29.8

Table 20. Analyses of in-cabin CO concentrations (ppm) for two different bus operation modes: frequent stops and door openings, and cruising with occasional stops.

RunID	Frequent Stops and Door Openings				Cruise with Occasional Stops			
	# of Obs.	Mean	Std. Dev.	Median	# of Obs.	Mean	Std. Dev.	Median
1NONE0711	176	2.1	0.6	2	225	2.6	0.5	3
1NONE0713	222	2.1	0.3	2	246	1.5	0.6	2
1NONE0802	222	1	0	1	246	1	0.5	1
2NONE0713	198	1.8	0.4	2	252	1.3	0.6	1
2NONE0720	228	1.5	0.5	2	240	2	0.9	2
3CC0726	222	2	0	2	252	1.7	0.6	2
3CCDOC0727	228	1	0	1	240	1.4	0.5	1
3NONE0717	228	2.4	0.5	2	240	2.2	0.9	3
4CC0727	37	0	0	0	41	0	0	0
4CCDOC0802	222	0	0	0	246	0	0	0
4NONE0717	36	0.7	0.5	1	39	0.6	0.5	1
5NONE0718	192	2	0.1	2	288	1.9	0.5	2
6CC0731	234	0	0	0	276	0	0	0
6CCDOC0803	241	0	0	0	270	0	0	0
6NONE0718	234	0.1	0.3	0	258	0.4	0.5	0

Table 21. Analyses of in-cabin TVOC concentrations (ppb) for two different bus operation modes: frequent stops and door openings, and cruising with occasional stops.

RunID	Frequent Stops and Door Openings				Cruise with Occasional Stops			
1NONE0711	0	.	.	.	0	.	.	.
1NONE0713	224	687.9	82.1	689.5	249	703.5	164	729
1NONE0802	222	370.1	70.6	357	246	412.9	101.2	397
2NONE0713	200	742.1	58.6	738	255	729.5	105.7	736
2NONE0720	230	712.7	65	719.5	243	733	88.9	748
3CC0726	224	521.7	94.5	499.5	255	490.9	75.8	478
3CCDOC0727	231	502.7	79.2	485	244	730.5	254.2	712
3NONE0717	230	902.1	80.6	897.5	243	880.7	141.2	908
4CC0727	224	471.8	35.8	469.5	249	460.4	29.3	456
4CCDOC0802	224	368.2	24.4	375.5	249	368.5	48.3	375
4NONE0717	218	734.3	45.6	728.5	237	722.3	64.3	731
5NONE0718	194	724.4	94	716.5	291	658.5	147.7	670
6CC0731	236	478	56.6	487	279	434.6	85.6	439
6CCDOC0803	242	407.5	49.8	403.5	274	433.4	37.6	430
6NONE0718	236	811.5	31.9	813.5	261	805	80.5	844

Table 22. Impact of the Spiracle on pollutant concentrations during frequent stops and door openings. Differences in the test means are shown if the impacts of the Spiracle were statistically significant based on the Satterthwaite method (n.s.=difference not statistical significant).

Bus ID	Test 1	Test 2	NOx (ppb)	NO (ppb)	NO_2 (ppb)	$PM_{2.5}$ ($\mu g/m^3$)	Ultrafine PM (num/cc)	TVOC (ppb)
4	4CC0727	4NONE0717	-34	n.s.	-15.6	-2	-3154	-263
6	6CC0731	6NONE0718	-34.6	-16.9	-17.7	-1	n.s.	-333
3	3CC0726	3NONE0717	-24.5	-16.8	-7.7	-11	-10955	-380

Table 23. Impact of the Spiracle on pollutant concentrations during cruising with occasional stops. Differences in the test means are shown if the impacts of the Spiracle were statistically significant based on the Satterthwaite method (n.s.=difference not statistical significant).

Bus ID	Test 1	Test 2	NOx (ppb)	NO (ppb)	NO_2 (ppb)	$PM_{2.5}$ ($\mu g/m^3$)	Ultrafine PM (num/cc)	TVOC (ppb)
4	4CC0727	4NONE0717	-64.8	-49.1	-15.8	-2	-5784	-262
6	6CC0731	6NONE0718	-31	n.s.	-19.2	-5	-1943	-370
3	3CC0726	3NONE0717	-14.3	n.s.	-7.5	-11	-8408	-390

Table 24. Impact of the Spiracle and DOC on pollutant concentrations during frequent stops and door openings. Differences in the test means are shown if the impacts of the Spiracle and DOC were statistically significant based on the Satterthwaite method (n.s.=difference not statistical significant).

Bus ID	Test 1	Test 2	NOx (ppb)	NO (ppb)	NO_2 (ppb)	$PM_{2.5}$ ($\mu g/m^3$)	Ultrafine PM (num/cc)	TVOC (ppb)
3	3CCDOC0727	3NONE0717	-33.6	-29.2	-4.4	-10	-18147	-399
6	6CCDOC0803	6NONE0718	-19.2	n.s.	-4.8	4	1645	-404
4	4CCDOC0802	4NONE0717	-54	-47.4	-6.6	-1	-5699	-366

Table 25. Impact of the Spiracle and DOC on pollutant concentrations during cruising with occasional stops. Differences in the test means are shown if the impacts of the Spiracle and DOC were statistically significant based on the Satterthwaite method (n.s.=difference not statistical significant).

Bus ID	Test 1	Test 2	NOx (ppb)	NO (ppb)	NO_2 (ppb)	$PM_{2.5}$ ($\mu g/m^3$)	Ultrafine PM (num/cc)	TVOC (ppb)
3	3CCDOC0727	3NONE0717	n.s.	n.s.	-6.2	-8	-11820	-150
6	6CCDOC0803	6NONE0718	-35.4	-24.2	-11.2	-1	n.s.	-372
4	4CCDOC0802	4NONE0717	-43.1	-34.5	-8.6	-3	-7334	-354

5. CONCLUSIONS

A total of fifteen tests were completed, including three repetitions. Key findings are listed below:

1) It is not possible within the framework of this testing program to determine if the air surrounding the bus where outdoor samples were collected was influenced by bus self-pollution or whether the placement of sampling lines on one side of the bus versus the other would have led to different results. It is expected that outdoor concentrations of all pollutants would influence indoor concentrations.

2) The results for all pollutants indicated substantial variability in mean and median in-cabin concentrations across the bus test population. Median NOx, $PM_{2.5}$ mass, and ultrafine PM number concentrations prior to retrofits ranged from 67 ppb-143 ppb, 9 $\mu g/m^3$-15 $\mu g/m^3$, and 4,413 particles/cc-30,450 particles/cc, respectively. Mean NOx, $PM_{2.5}$ mass, and ultrafine PM number concentrations prior to retrofits ranged from 64 ppb-148 ppb, 9 $\mu g/m^3$-20 $\mu g/m^3$, and 6,054 particles/cc-32,272 particles/cc, respectively.

3) The results also indicated substantial variability in pollutant concentrations between buses with similar characteristics such as age, mileage, and engine type. For example, Bus 1 and Bus 2 were both 2001 International T444E engines with mileage of 98,804 and 88,555, respectively. The median in-cabin NOx concentration prior to retrofits for Bus 1 (67 ppb) was approximately a factor of two less than the median concentration for Bus 2 (119 ppb). Median ultrafine PM

number concentrations prior to retrofits ranged between 5,580-6,748 particles/cc for Bus 1 and between 4,413-15,170 particles/cc for Bus 2.

4) For both $PM_{2.5}$ and ultrafine PM, in-cabin mean concentrations were generally, but not exclusively, slightly lower than their outdoor counterparts. However, median in-cabin concentrations were either generally higher (ultrafine PM) or showed no pattern ($PM_{2.5}$).

5) The Spiracle resulted in statistically significant decreases (ranging from 27.9 ppb to 51.8 ppb) of mean in-cabin concentrations of NOx on all three buses, and statistically significant decreases in NO on Bus 3 (by 19.9 ppb) and Bus 4 (by 35.2 ppb), but not on Bus 6. The impacts of retrofits on emissions of nitrogen oxides from the crankcase should continue to be investigated.

6) Small additional NO_x, NO, and NO_2 benefits or disbenefits resulted from the addition of the DOC. However, these small changes from the addition of the DOC were of the same order of magnitude as the uncertainty of the instrument. Similar patterns were seen for TVOCs.

7) The Spiracle and Spiracle/DOC, respectively, resulted in relatively large reductions of in-cabin $PM_{2.5}$ and ultrafine PM for Bus 3 (i.e. a 50% or greater reduction of pre-retrofit concentrations), but had a smaller impact on Bus 4, and essentially no impact on Bus 6. No clear benefit or disbenefit of the DOC was seen for $PM_{2.5}$. The $PM_{2.5}$ results for Bus 3 were consistent with those for one bus tested as part of the Clean Air Task Force study (Hill et al., 2005), as well as the fact that the Spiracle appeared to be responsible for most of the $PM_{2.5}$ reduction.

8) The data from repetitions (multiple tests done on the same bus at the same retrofit condition) suggest that the retrofit results for $PM_{2.5}$ and ultrafine PM for both Bus 4 and Bus 6 are within the range of variation seen for the repetitions, suggesting that these results cannot be conclusively linked to the retrofits for these two buses.

REFERENCES

Barbour, H., personal communication with S. Conti (2006) of the Austin Asthma Coalition.

Batterman, S.A., C. Peng, and J. Braun (2002) "Levels and composition of volatile organic compounds on commuting routes in Detroit, Michigan," *Atmospheric Environment* 36:6015-6030.

Behrentz, E., D.R. Fitz, D.V. Pankratz, L.D. Sabin, S.D. Colome, S.A. Fruin, and A.M. Winer (2004) "Measuring self-pollution in school buses using a tracer gas technique," *Atmospheric Environment*, 38:3735-3746.

Behrentz, E., L.D. Sabin, A.M. Winer, S. Jeong, D.R. Fitz, D.V. Pankratz, S.D. Colome, and S.A. Fruin, (2005) "Relative importance of school bus-related microenvironments to children's pollutant exposure," *Journal of the Air and Waste Management Association* 55:1418-1430.

Brunekreef B, Jansses N, de Hartog J, Harssema H, Knape M, van Vliet P. (1997) "Air pollution from truck traffic and lung function in children living near motorways," *Epidemiology* 8:298-303.

Fitz, D.R., A.M. Winer, S. Colome, E. Behrentz, L.D. Sabin, S. Jeong, K. Wong, K. Kozawa (2003) *Characterizing the Range of Children's Pollutant Exposure During School Bus Commutes*, final report submitted to the California Air Resources Board.

Flagan, R.C. and J.H. Seinfeld (1988), *Fundamentals of Air Pollution Engineering*, Prentice-Hall, Englewood Cliffs, NJ.

Hill, L. B., N. B. Zimmerman, and J. Gooch (2005), A Multi-City Investigation of the Effectiveness of Retrofit Emissions Controls in Reducing Exposures to Particulate Matter in School Buses, developed by the Clean Air Task Force.

Hofferth, S.L. (1998) *Healthy Environments, Healthy Children: Children in Families*, Ann Arbor, MI: University of Michigan, 1997 Panel Study of Income Dynamics, Child Development Supplement.

Hofferth, S.L. and J.F. Sandberg (2001) "How American children use their time", *Journal of Marriage and the Family* 63(2).

Jenkins RA, Ilgner RH, Tomkins BA and Peters DW. (2004), "Development and application of protocols for the determination of response of real-time particle monitors to common indoor aerosols", *Journal of the Air & Waste Management Association*. 54(2): 229-241.

Northbridge M, Yankura J, Kinney P, Santella R, Shepard P, Riojas Y, et al (1999), "Diesel exhaust exposure among adolescents in Harlem: a community-driven study," *American Journal of Public Health* 89:998-1002.

Rodes, C et al (1998) *Measuring Concentrations of Selected Pollutants Inside California Vehicles* , final report submitted to the California Air Resources Board.

Roberts, D, personal communication, May 12, 2006.

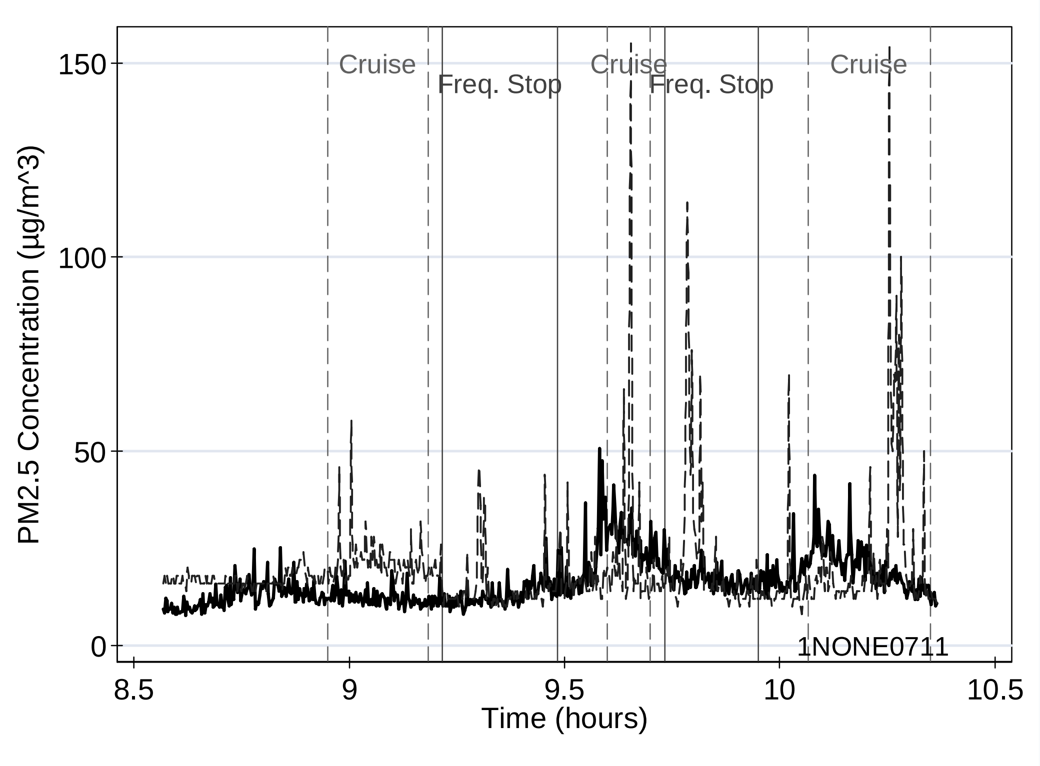
Sabin, L.D., E. Behrentz, A.M. Winer, S. Jeong, D.R. Fitz, D.V. Pankratz, S.D. Colome, and S.A. Fruin, (2005) "Characterizing the range of children's air pollutant exposure during school bus commutes," *Journal of Exposure Analysis and Environmental Epidemiology* 15:377-387.

Sabin, L.D., K. Kozawa, E. Behrentz, A.M. Winer, D.R. Fitz, D.V. Pankratz, S.D. Colome, and S.A. Fruin, (2005) "Analysis of real-time variables affecting cildren's exposure to diesel-related pollutants during school bus commutes in Los Angeles," *Atmospheric Environment* 39:5423-5254.

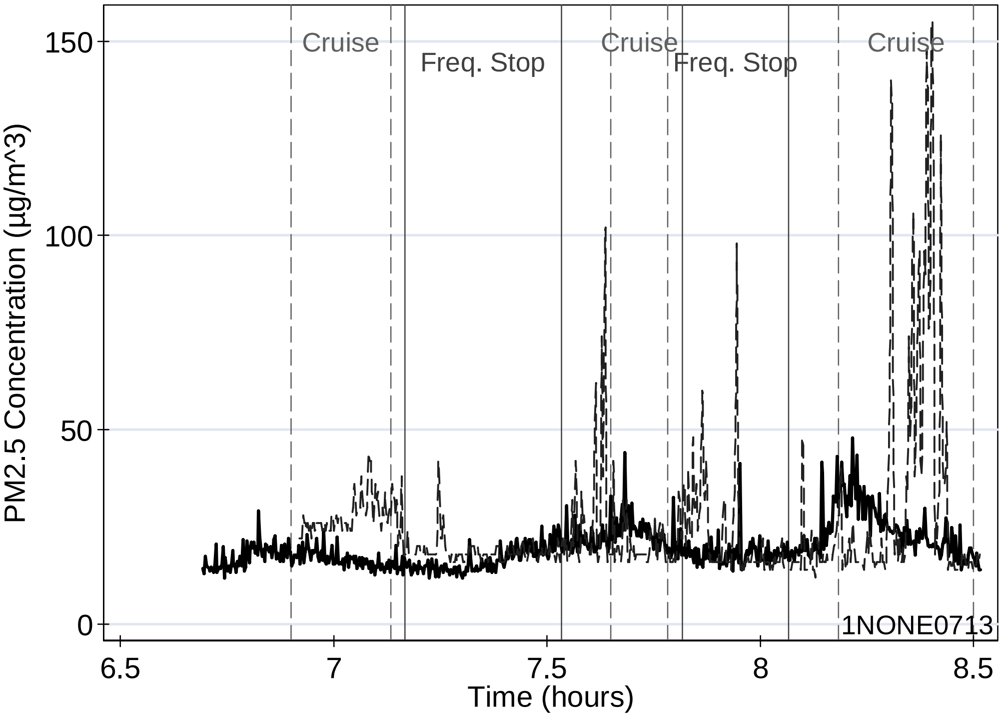
United States Environmental Protection Agency (2002), *Health Assessment Document for Diesel Engine Exhaus*t, EPA/600/8-90/057F, National Center for Environmental Assessment, Washington D.C.

Appendix A: Time Series of Pollutant Concentrations

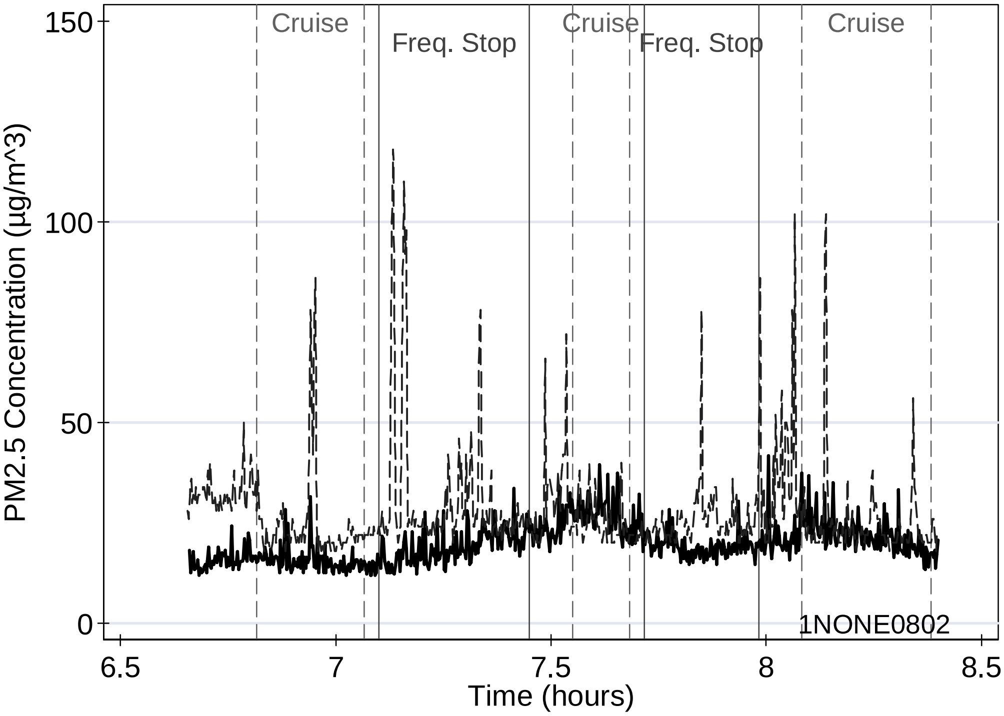
$PM_{2.5}$ concentrations versus time for all 15 tests. Outdoor concentrations shows with a dashed line. In-cabin concentrations shown with a solid line. Two bus operations modes are delineated with vertical lines: cruising with occasional stops (dashed vertical) and frequent stops with door openings (solid vertical). The Bus ID number is indicated on each plot as well as in the captions.



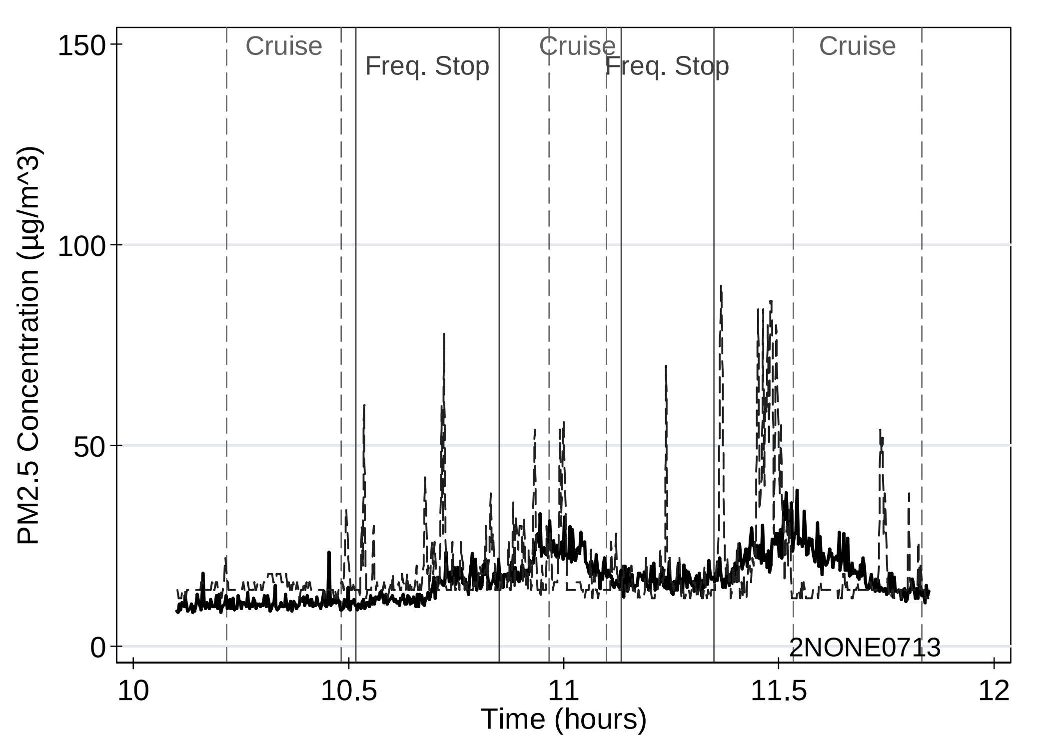
PM2.5 Concentrations - 1NONE0711



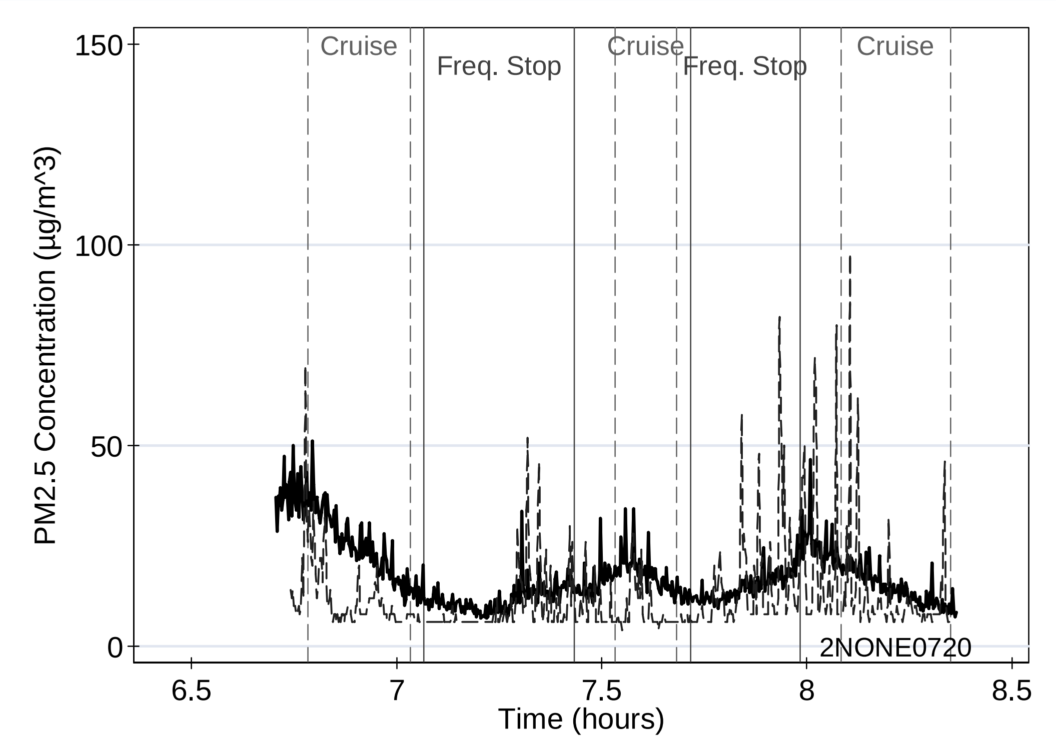
PM2.5 Concentrations - 1NONE0713



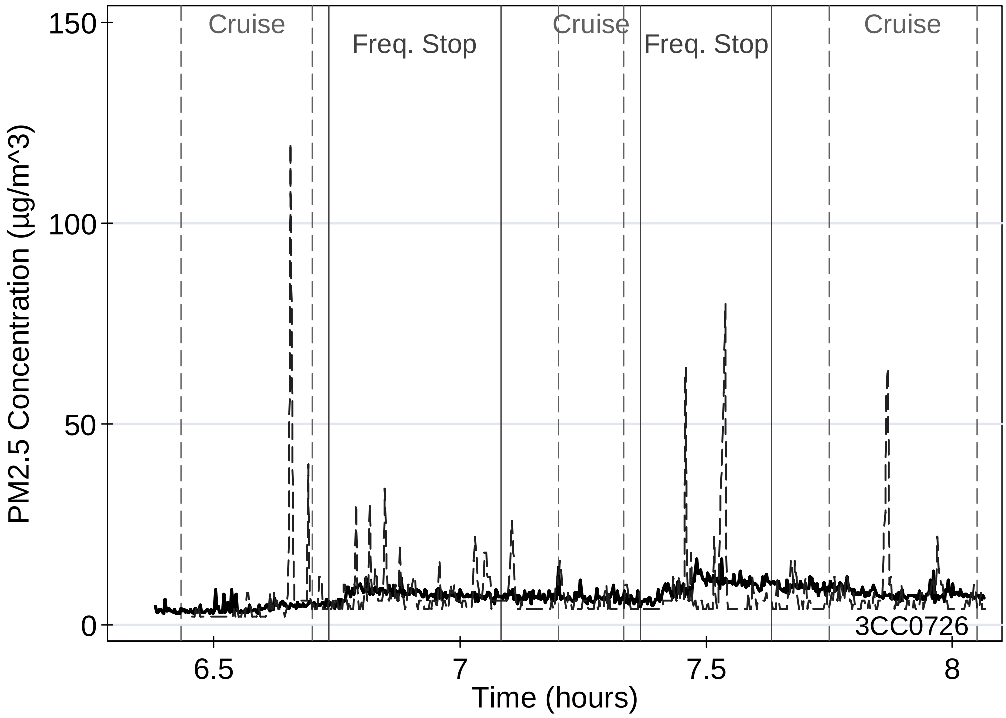
PM2.5 Concentrations - 1NONE0802



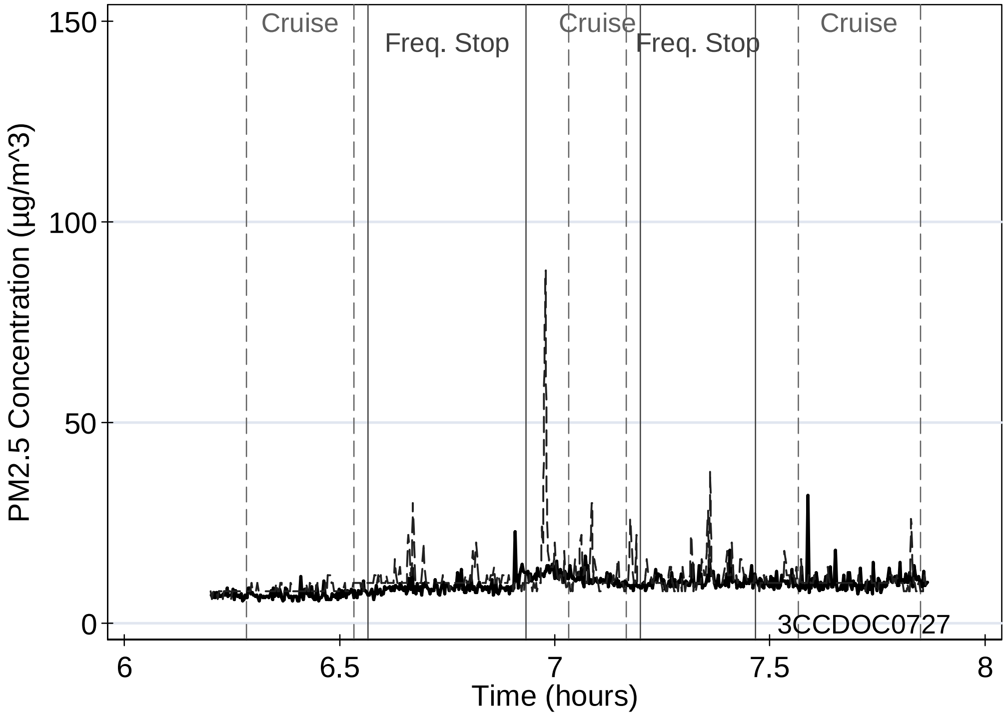
PM2.5 Concentrations - 2NONE0713



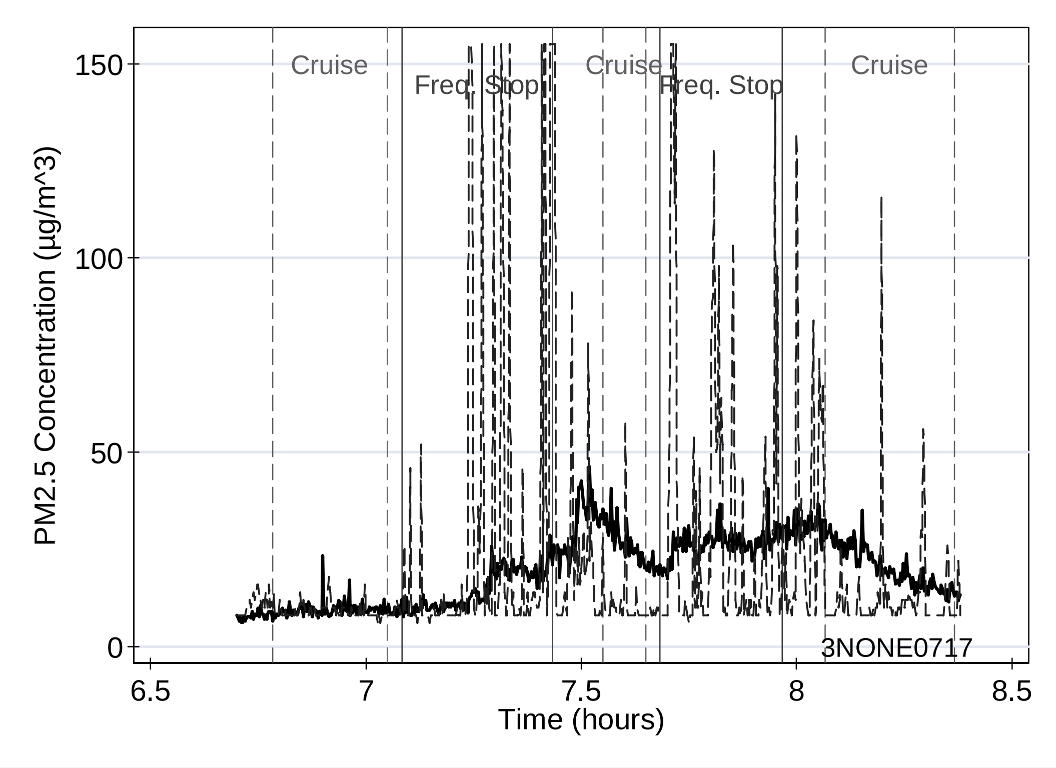
PM2.5 Concentrations - 2NONE0720



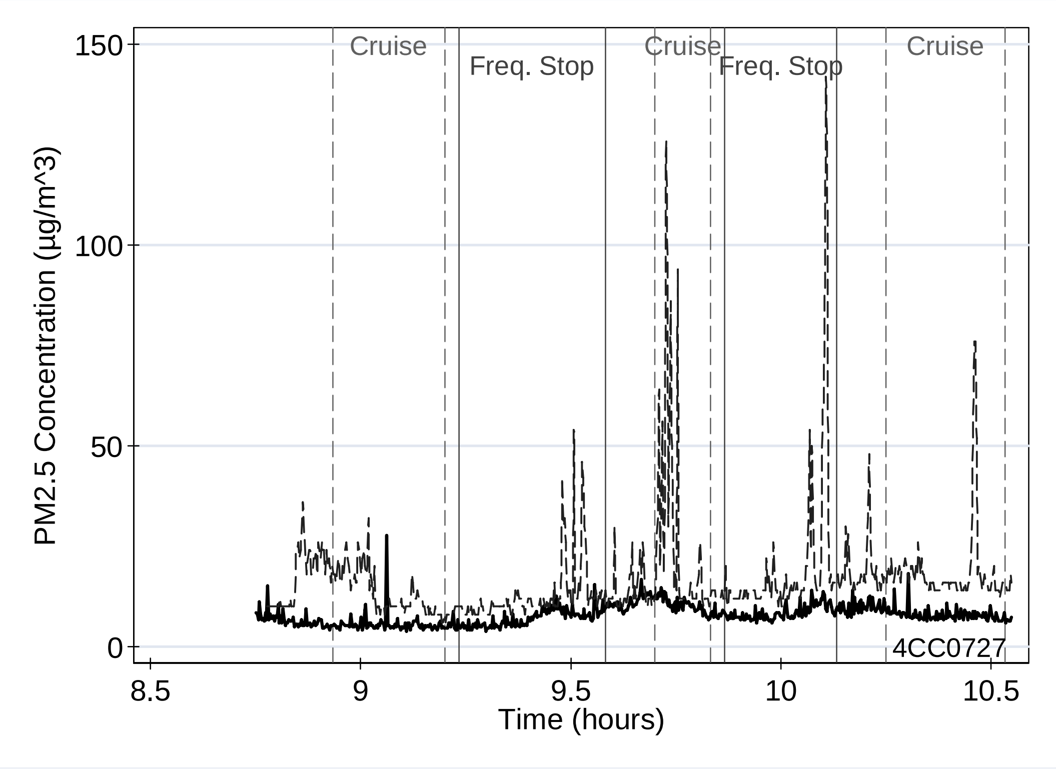
PM2.5 Concentrations – 3CC0726



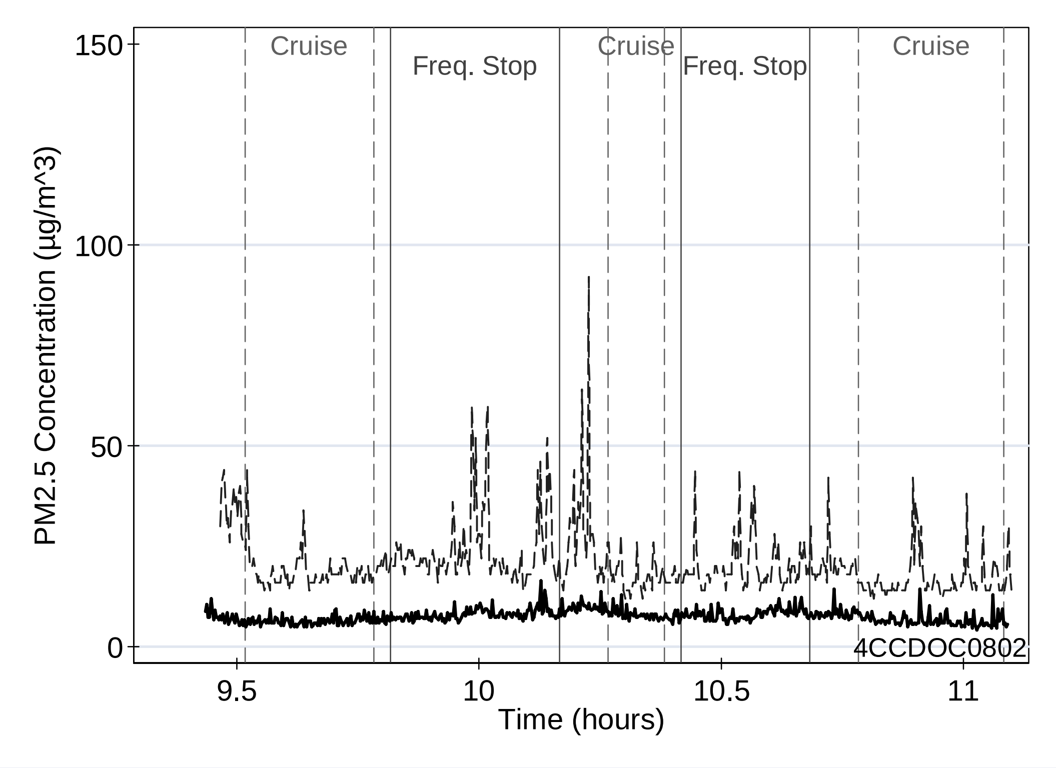
PM2.5 Concentrations – 3CCDOC0727



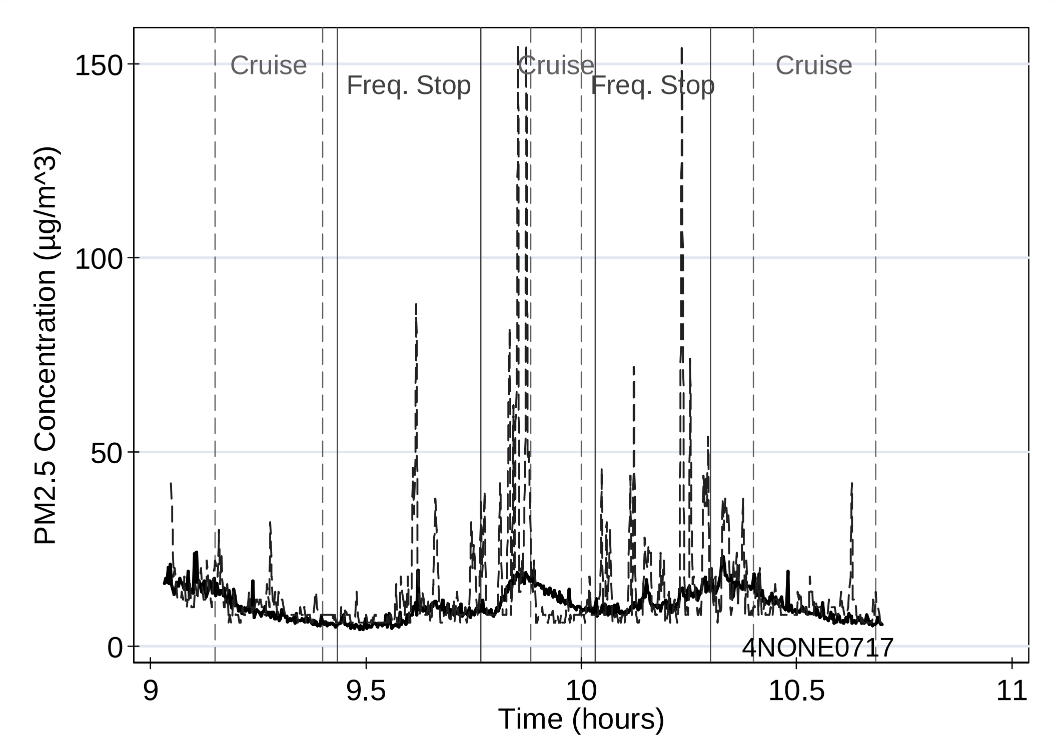
PM2.5 Concentrations – 3NONE0717



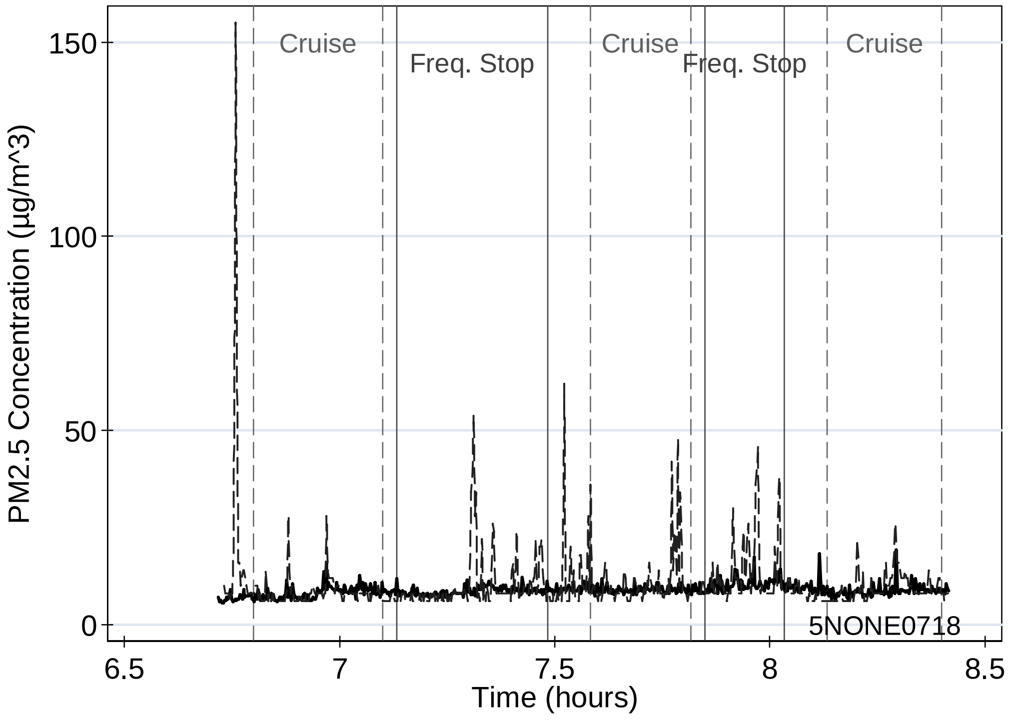
PM2.5 Concentrations – 4CC0727



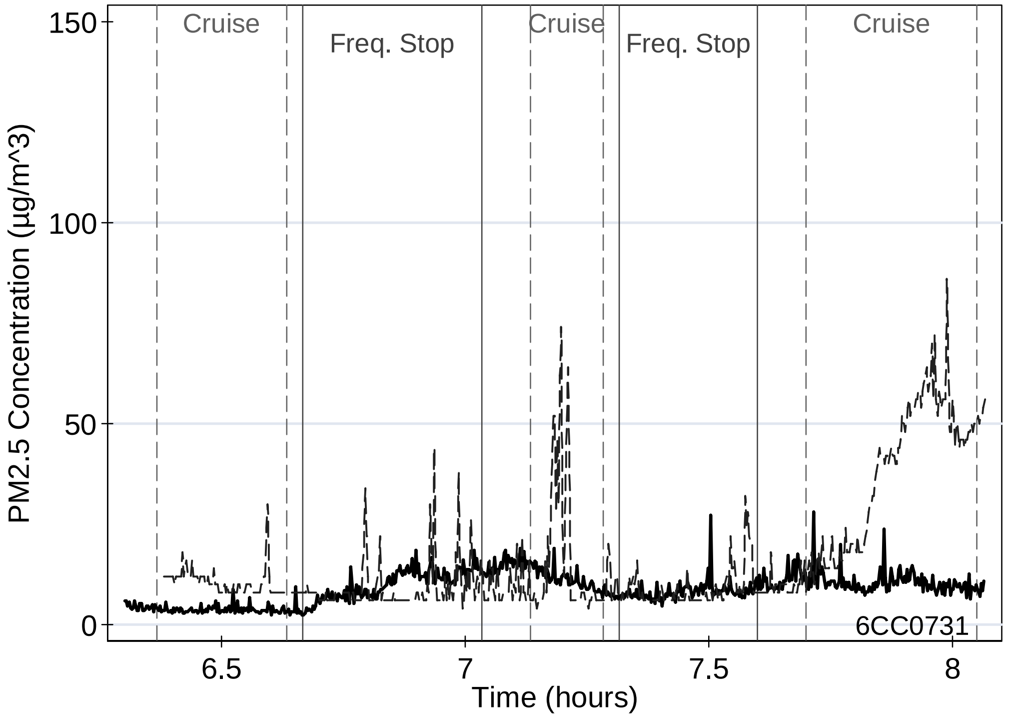
PM2.5 Concentrations – 4CCDOC0802



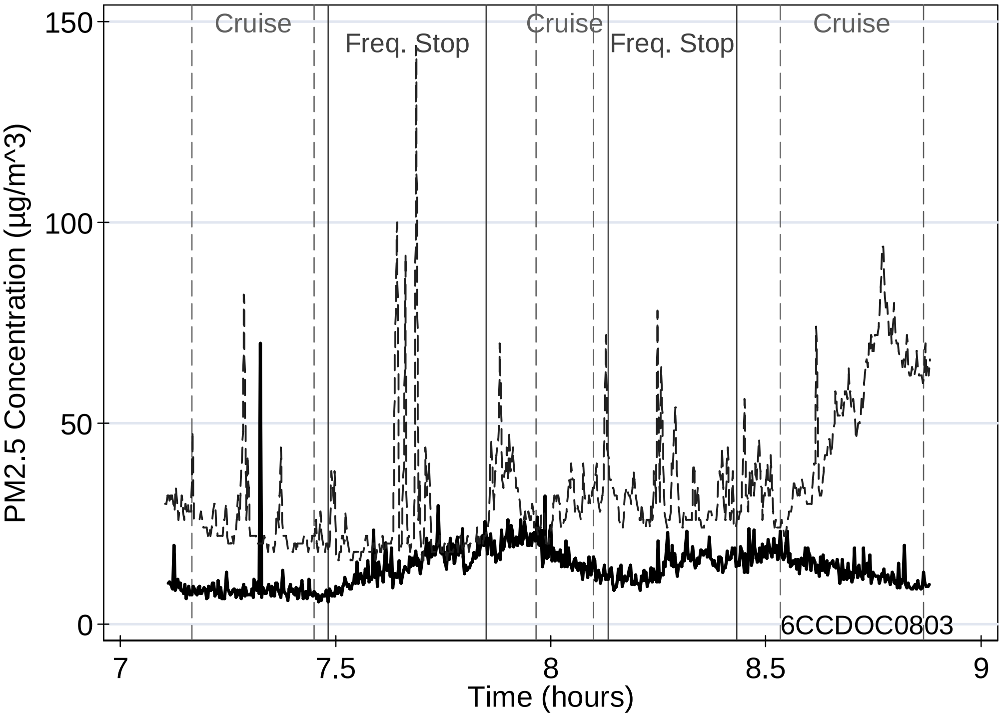
PM2.5 Concentrations – 4NONE0717



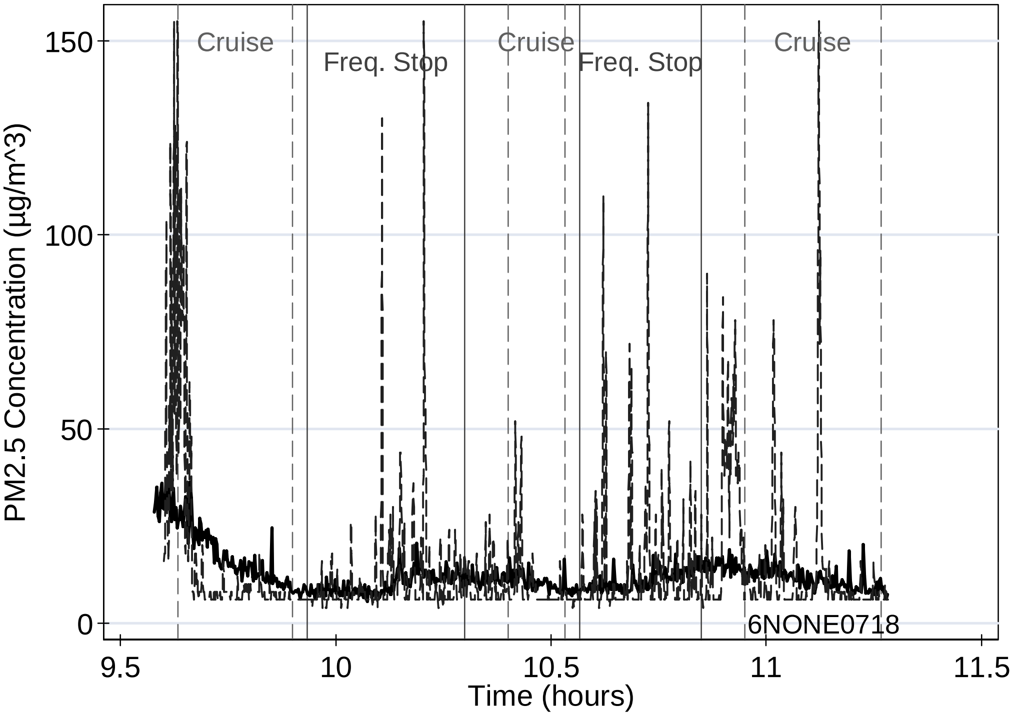
PM2.5 Concentrations – 5NONE0718



PM2.5 Concentrations – 6CC0731

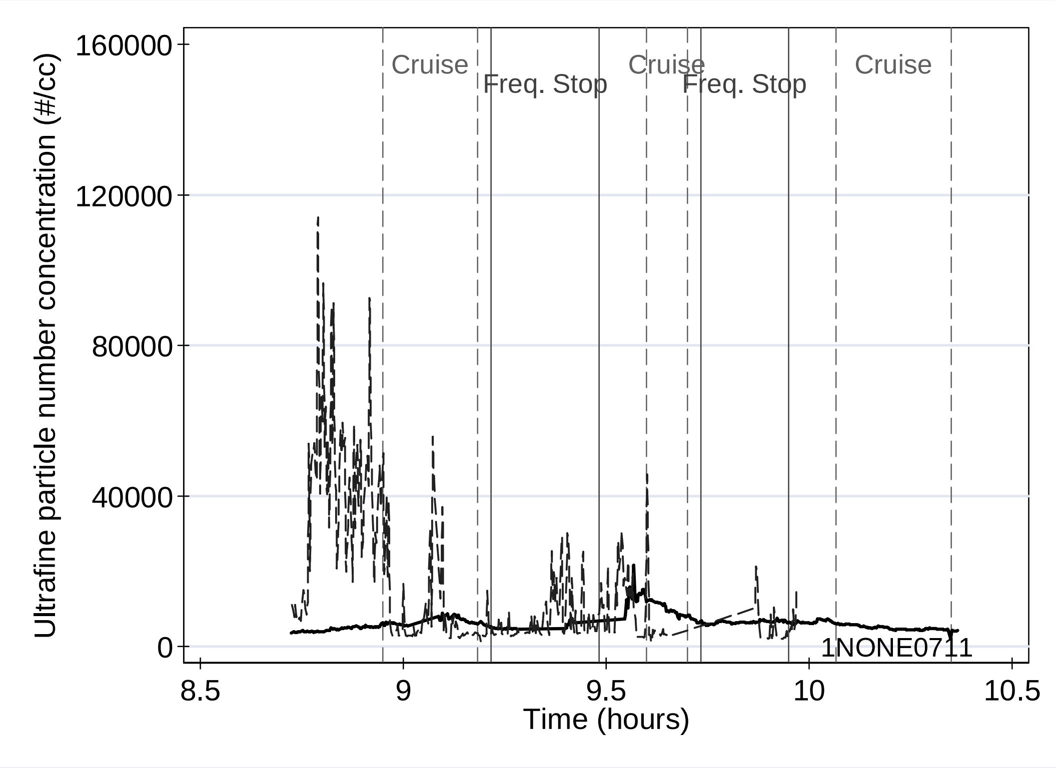


PM2.5 Concentrations – 6CCDOC0803

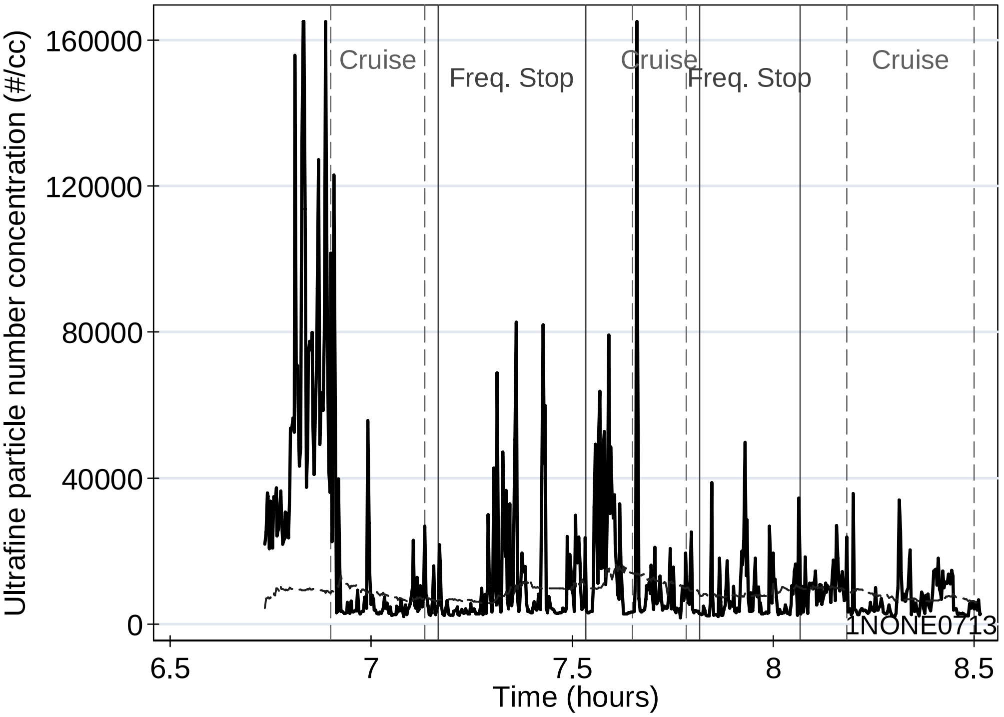


PM2.5 Concentrations – 6NONE0718

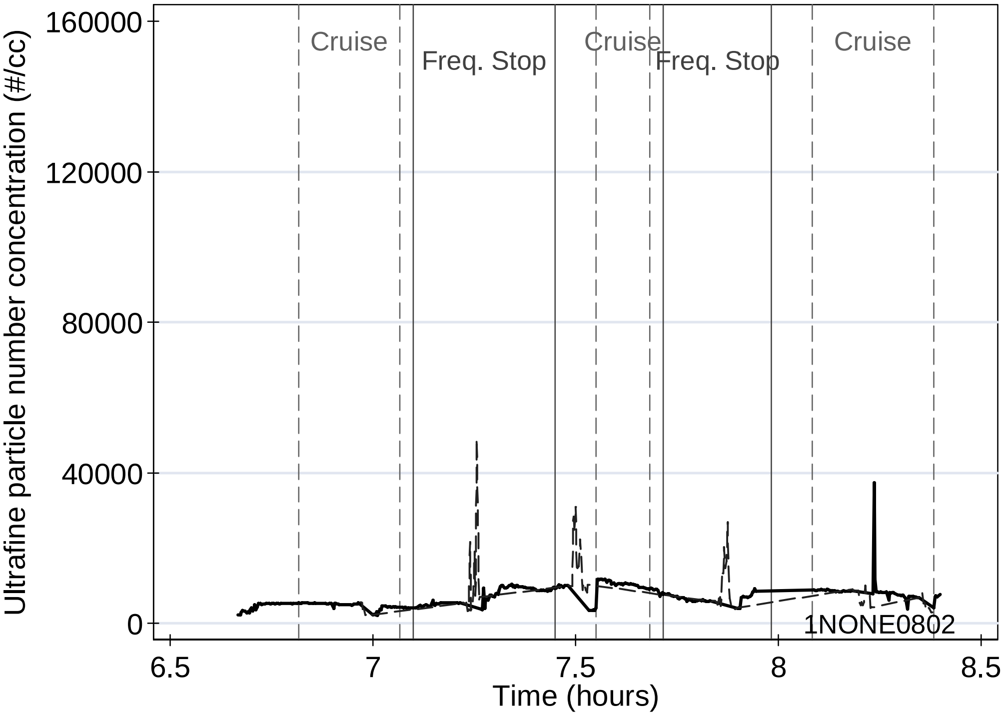
Ultrafine particle number concentrations vs. time for all 15 tests. Outdoor concentrations shows with a dashed line – note that outdoor measurements were discontinuous for all tests after July 26th.. See discussion surrounding Table 7 for more details. In-cabin concentrations shown with a solid line. Two bus operations modes are delineated with vertical lines: cruising with occasional stops (dashed vertical) and frequent stops with door openings (solid vertical).



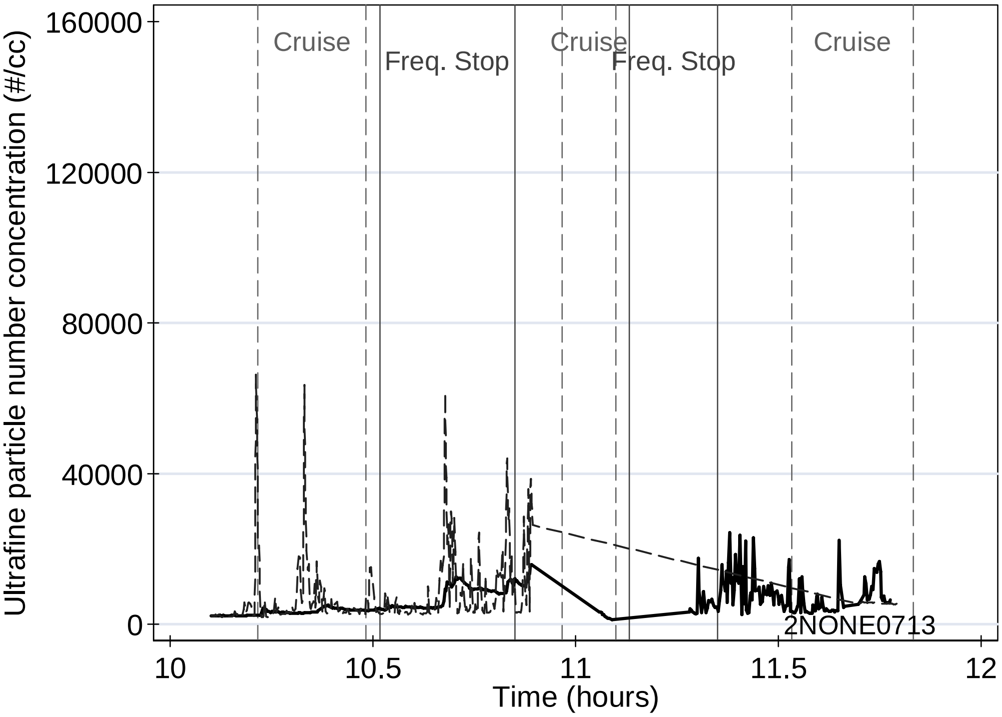
Ultrafine PM Concentrations – 1NONE0711



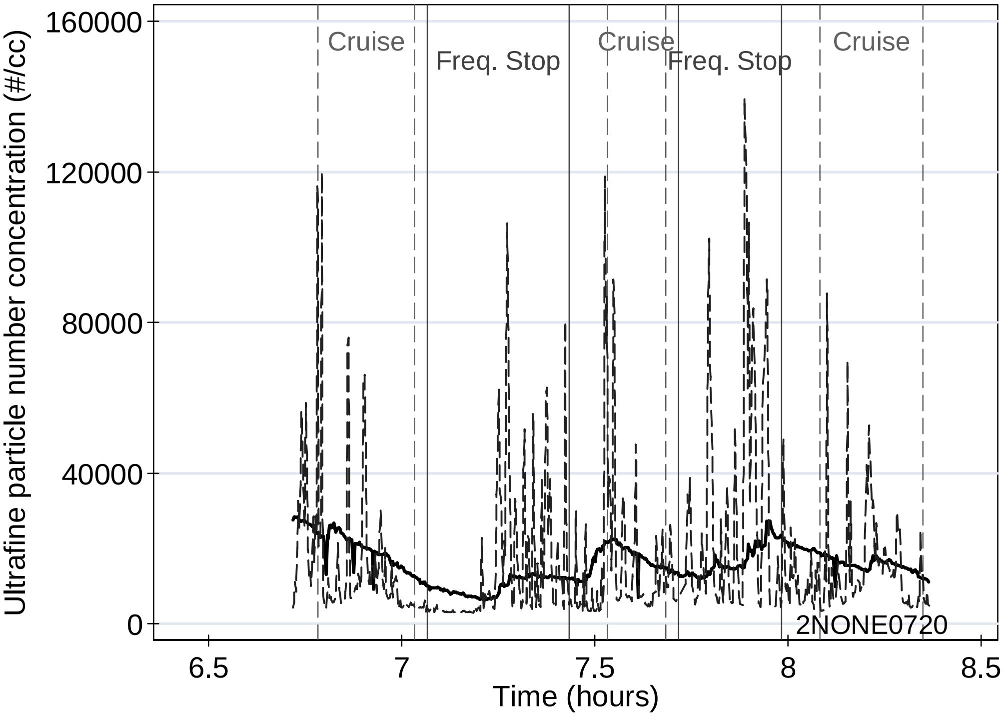
Ultrafine PM Concentrations – 1NONE0713



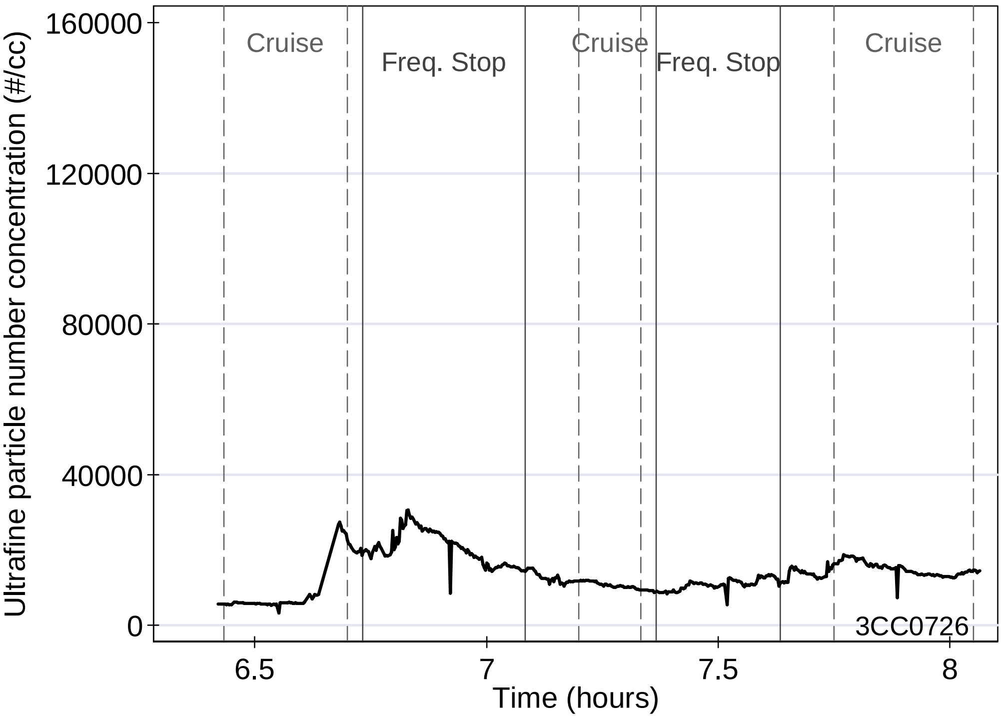
Ultrafine PM Concentrations – 1NONE0802



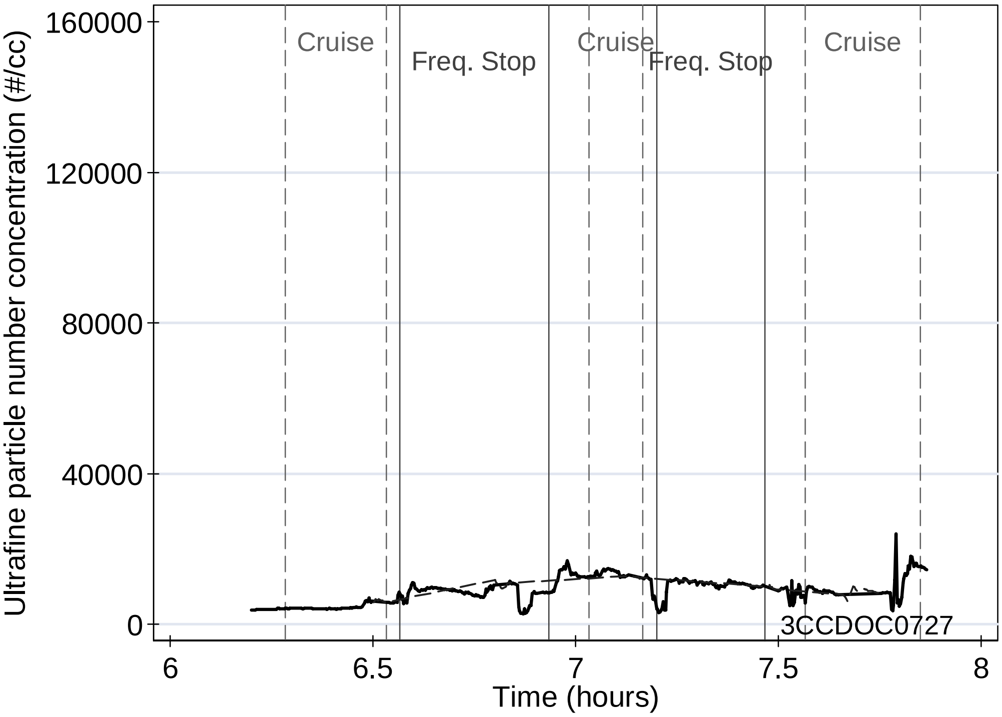
Ultrafine PM Concentrations – 2NONE0713



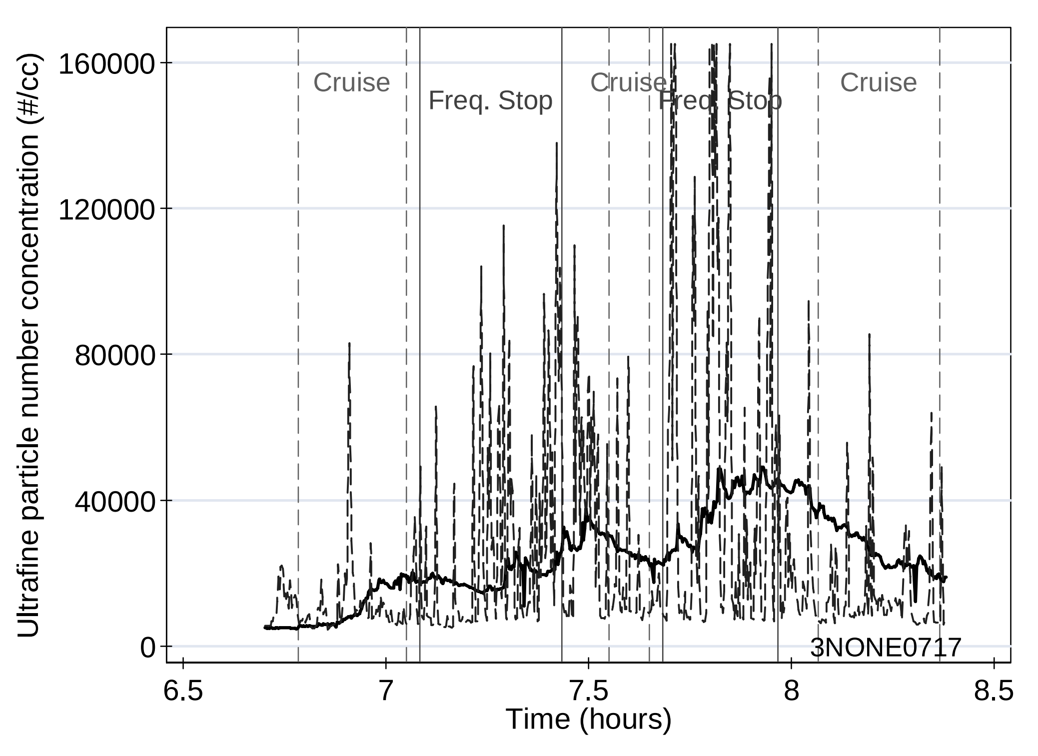
Ultrafine PM Concentrations – 2NONE0720



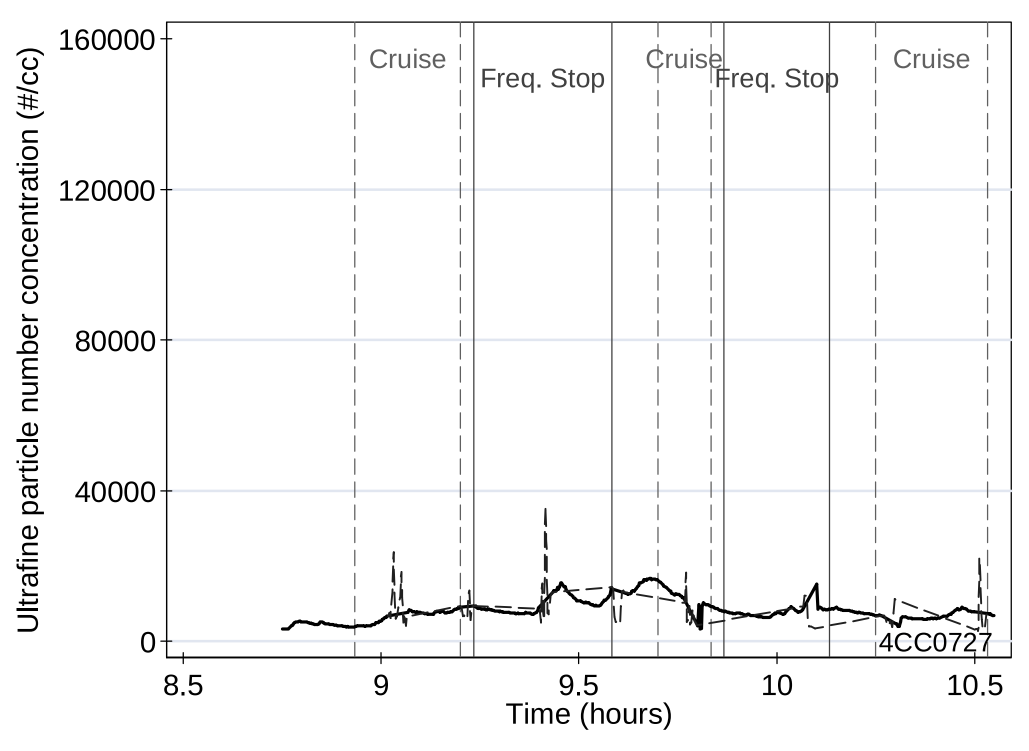
Ultrafine PM Concentrations – 3CC0726



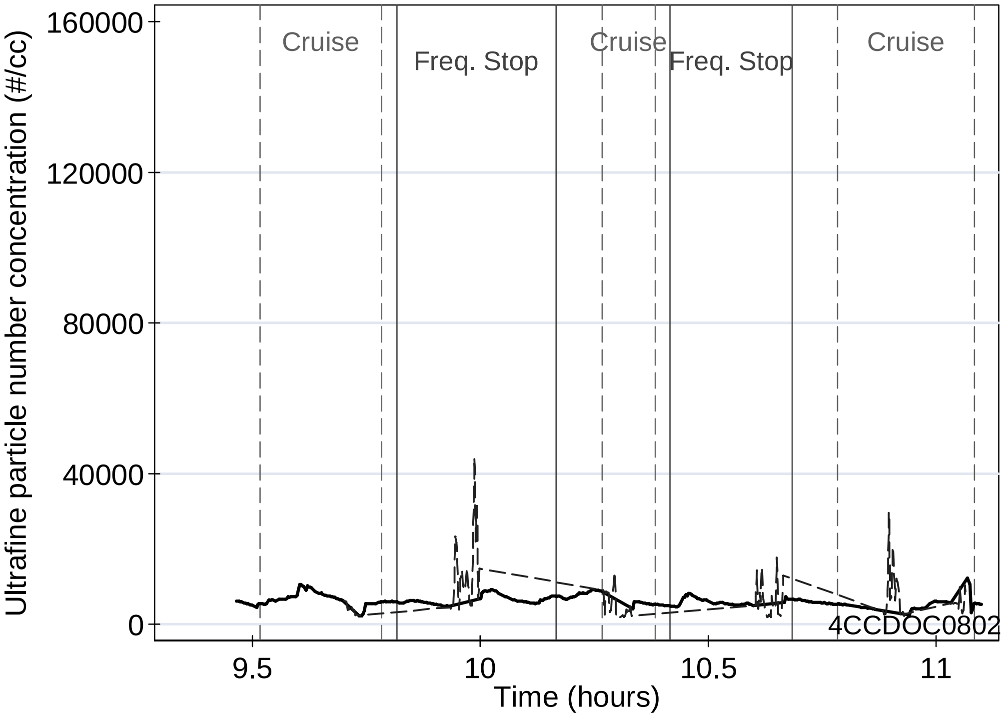
Ultrafine PM Concentrations – 3CCDOC0727



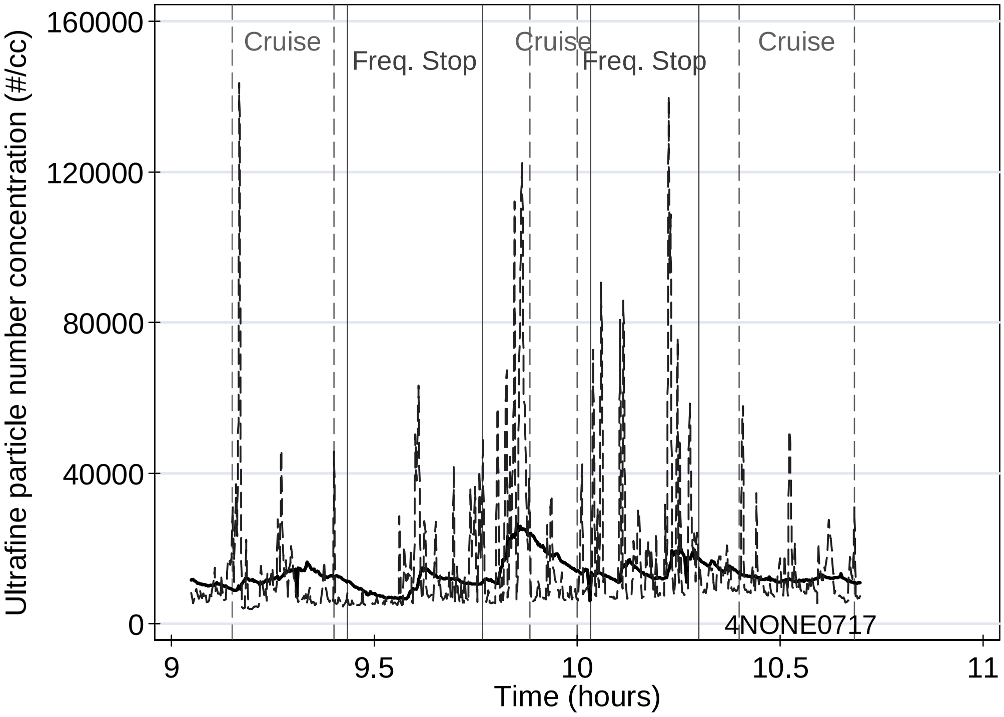
Ultrafine PM Concentrations – 3NONE717



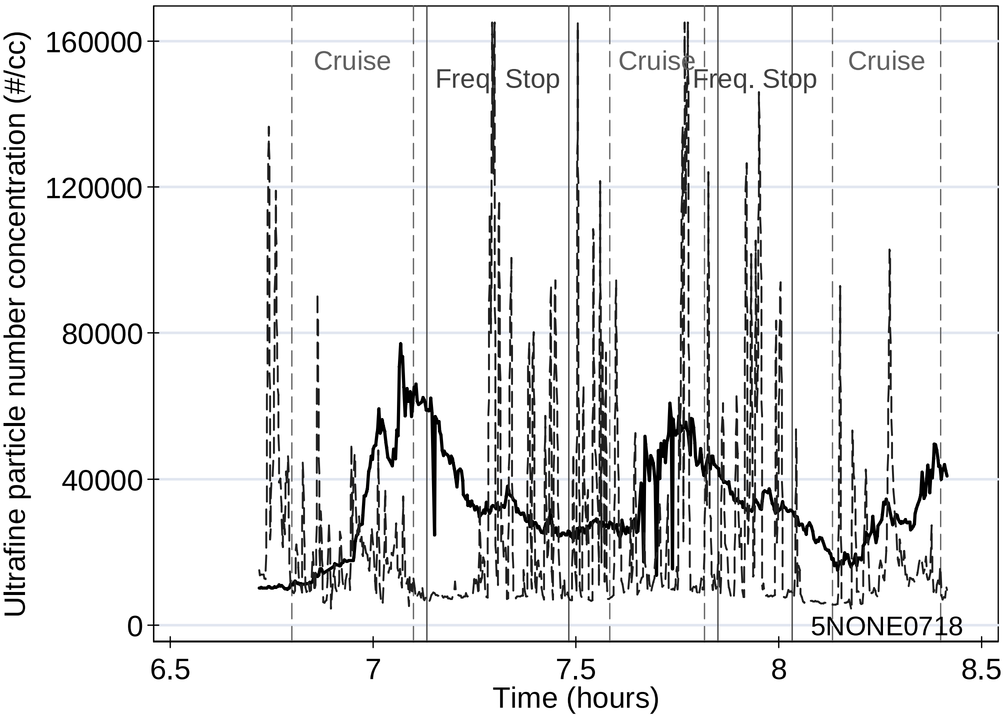
Ultrafine PM Concentrations – 4CC0727



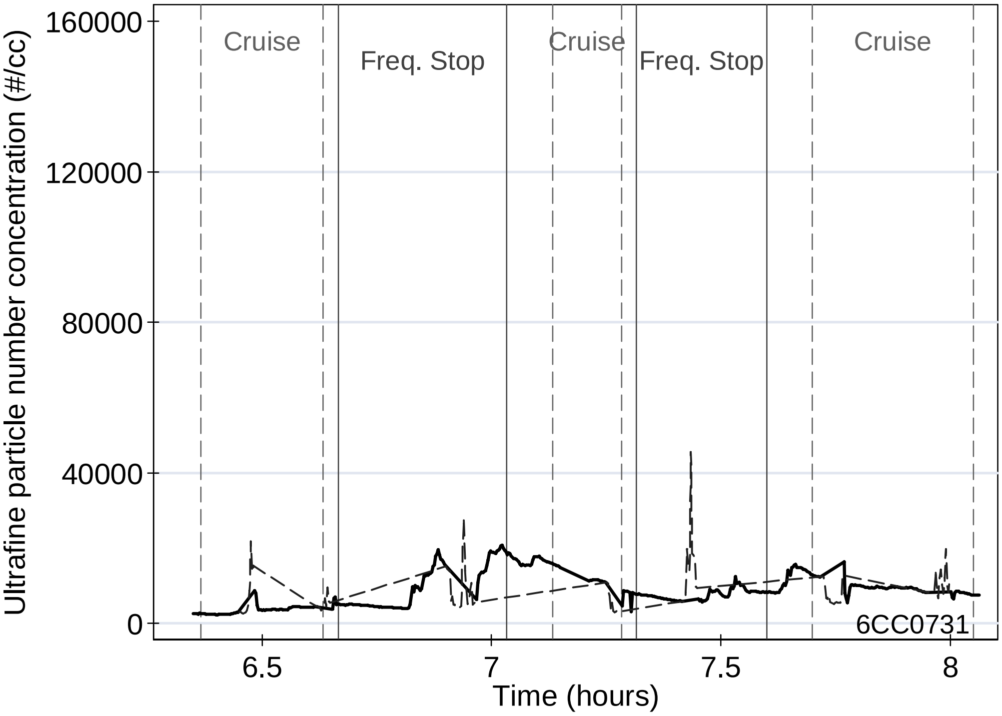
Ultrafine PM Concentrations – 4CCDOC0802



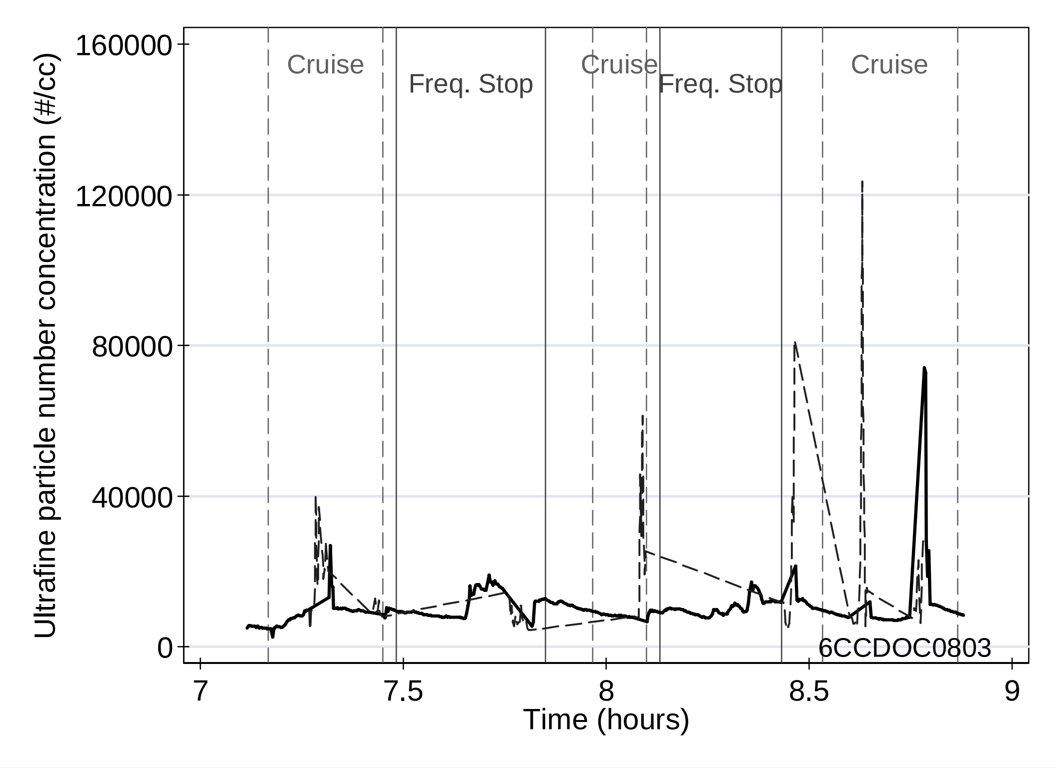
Ultrafine PM Concentrations – 4NONE0717



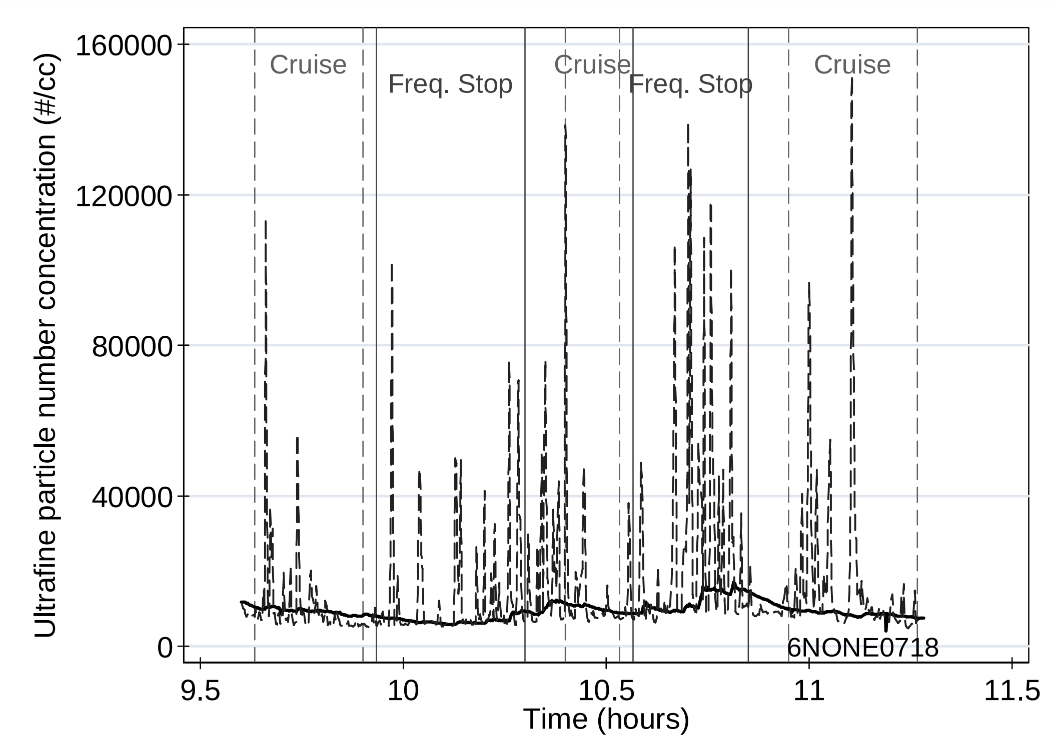
Ultrafine PM Concentrations – 5NONE0718



Ultrafine PM Concentrations – 6CC0731

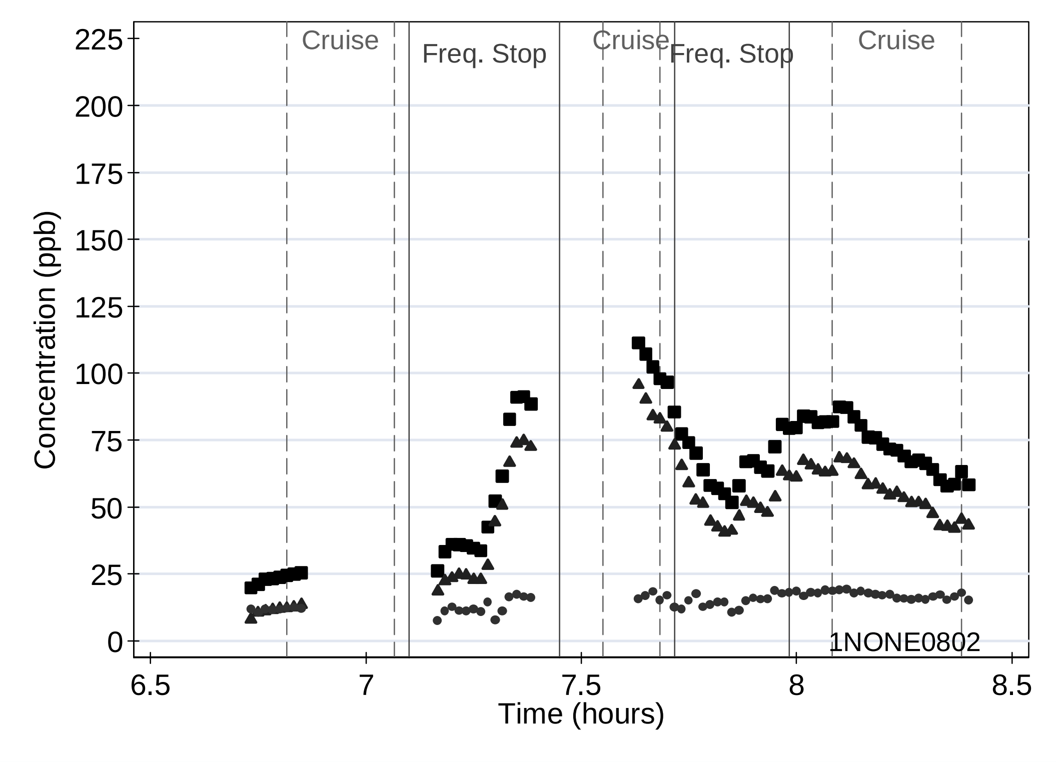


Ultrafine PM Concentrations – 6CCDOC0803

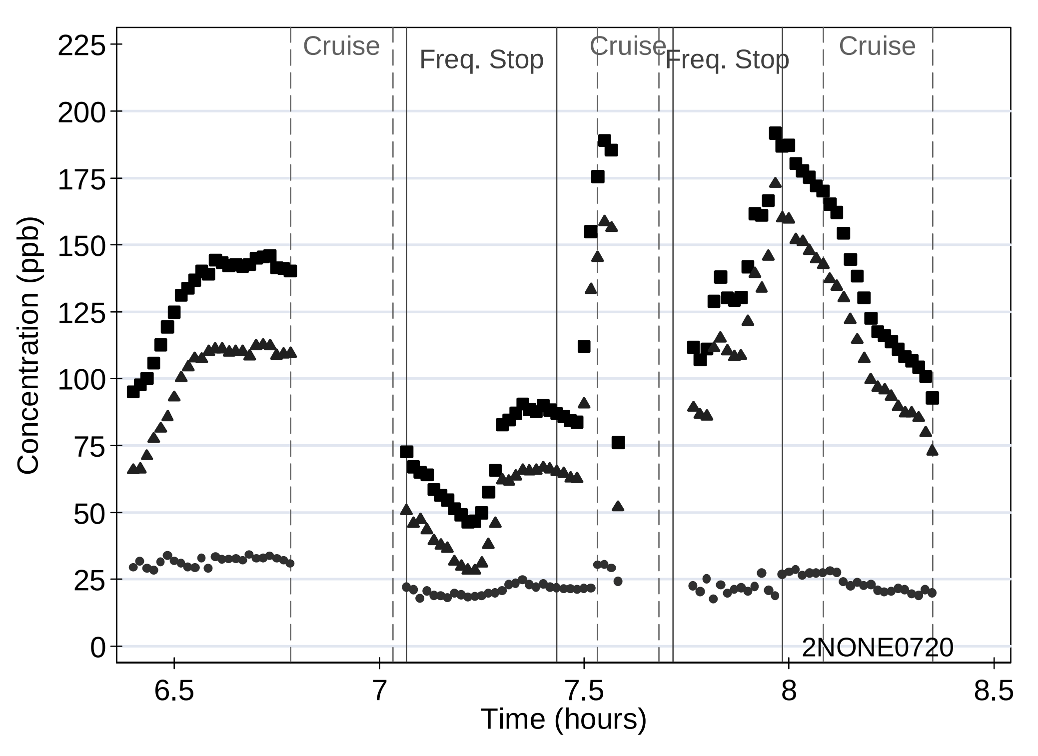


Ultrafine PM Concentrations – 6NONE0718

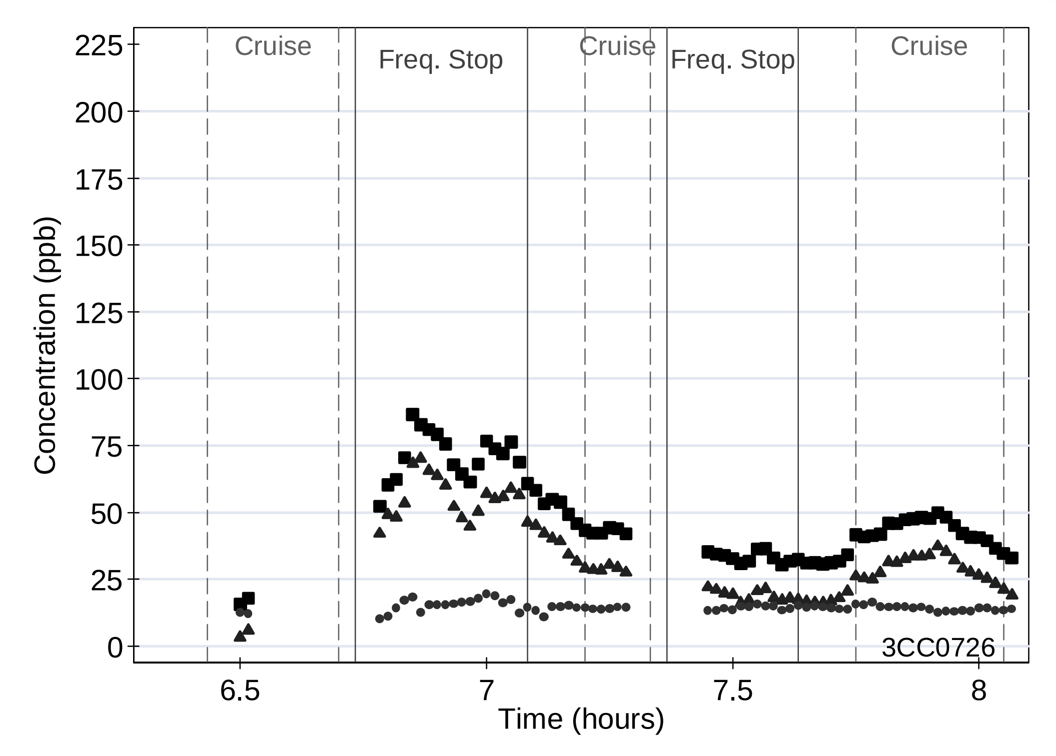
NO_x (square), NO (triangle), and NO_2 (circle) for 13 tests where NO_x instrumentation was operational.



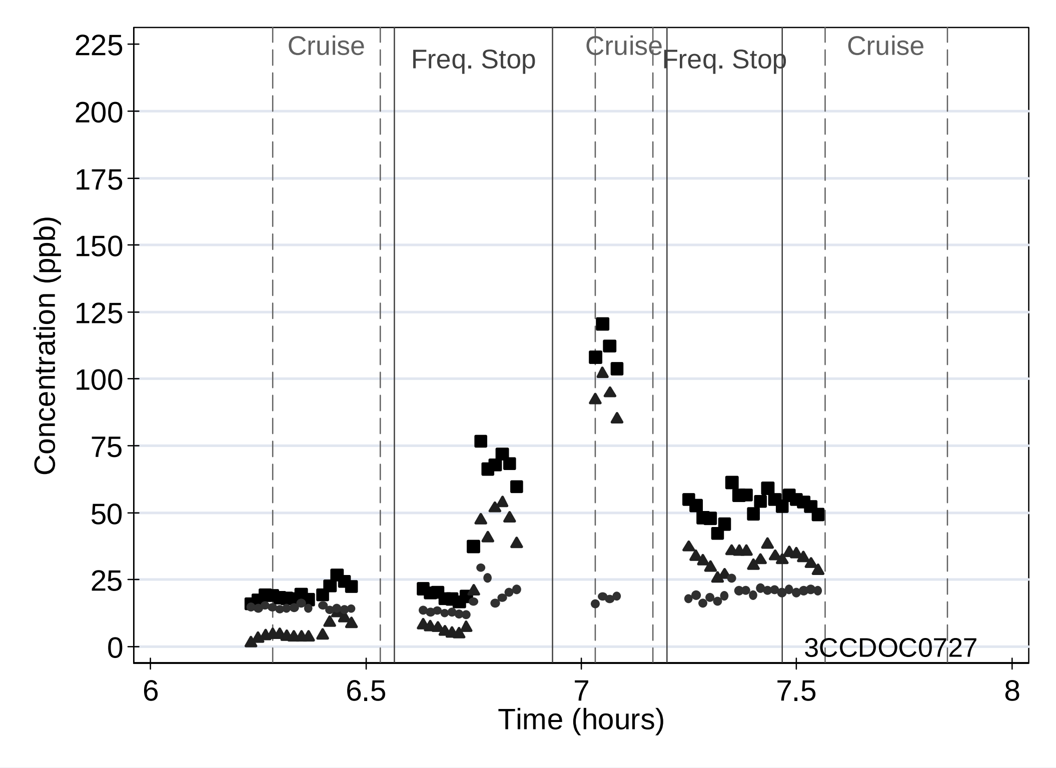
NO_x (square), NO (triangle) and NO_2 (circle) Concentrations – 1NONE0802



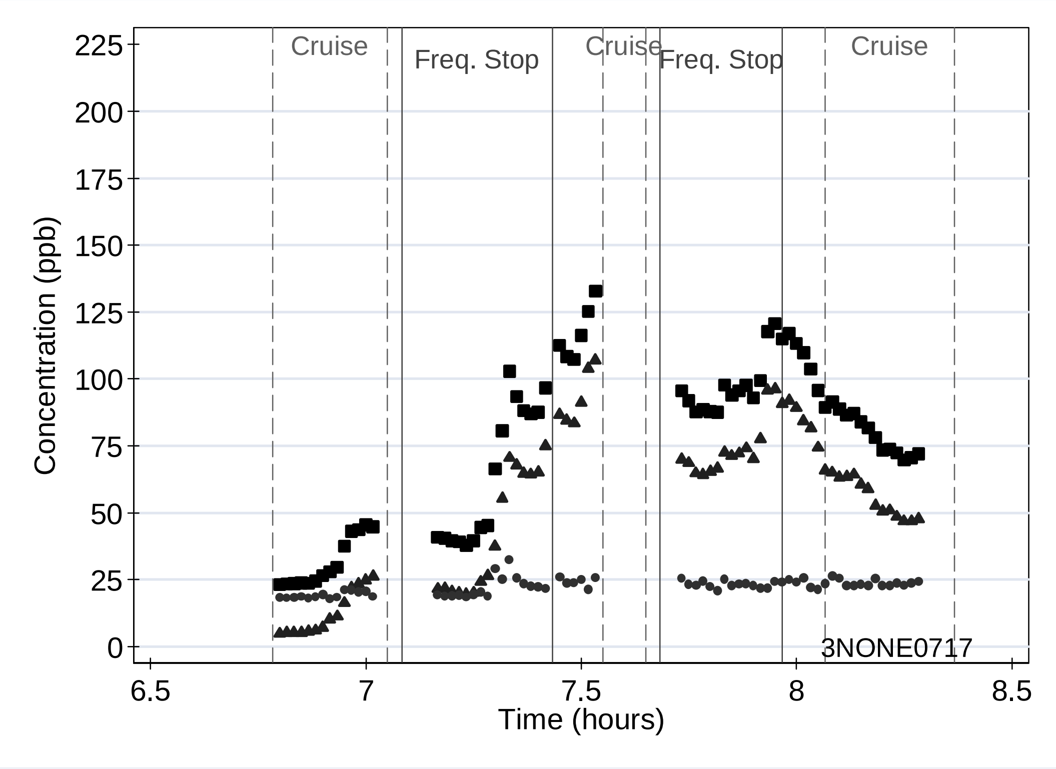
NO_x (square), NO (triangle) and NO_2 (circle) Concentrations – 2NONE0720



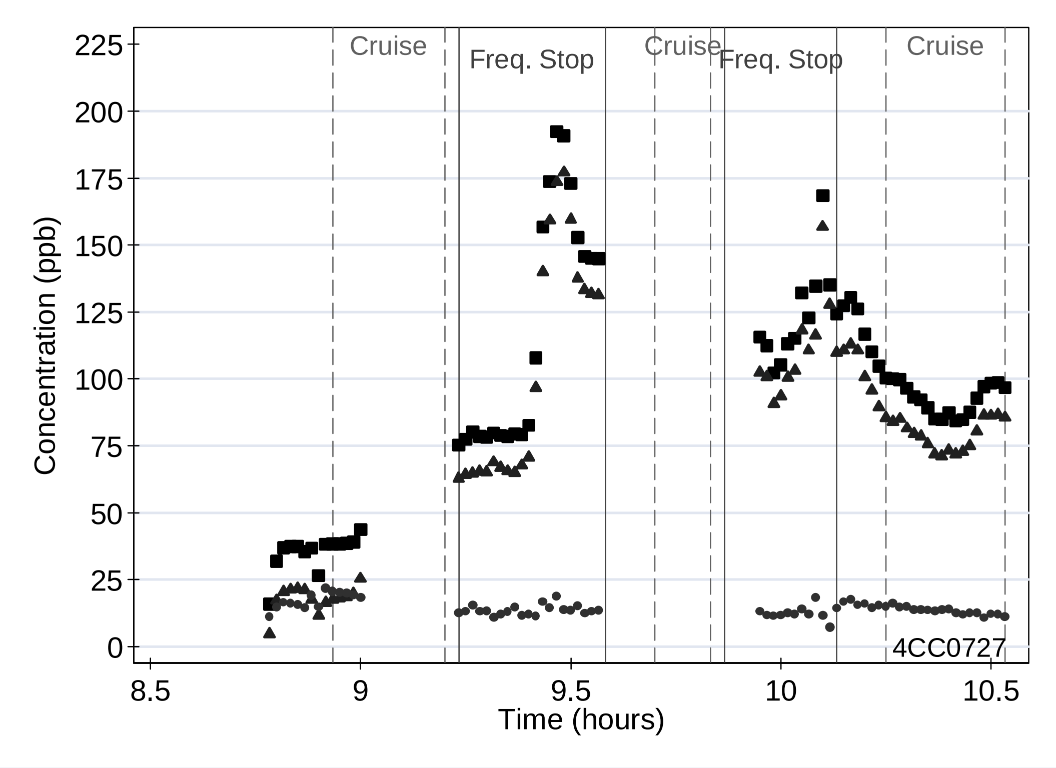
NO_x (square), NO (triangle) and NO_2 (circle) Concentrations – 3CC0726



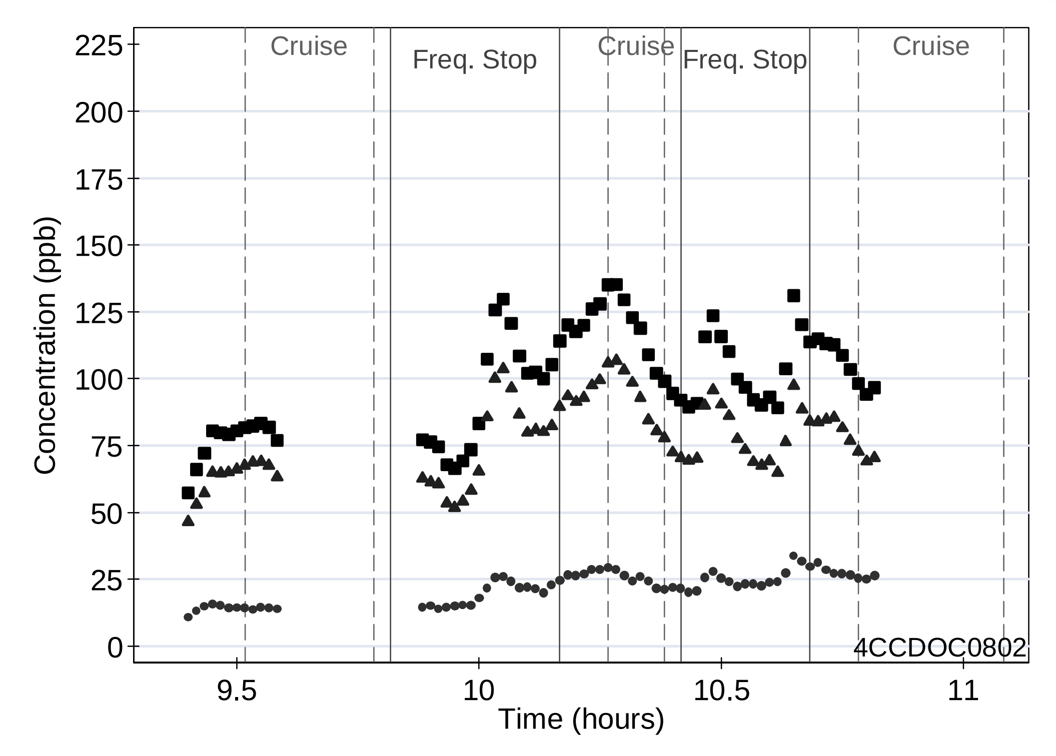
NO$_x$ (square), NO (triangle) and NO$_2$ (circle) Concentrations – 3CCDOC0727



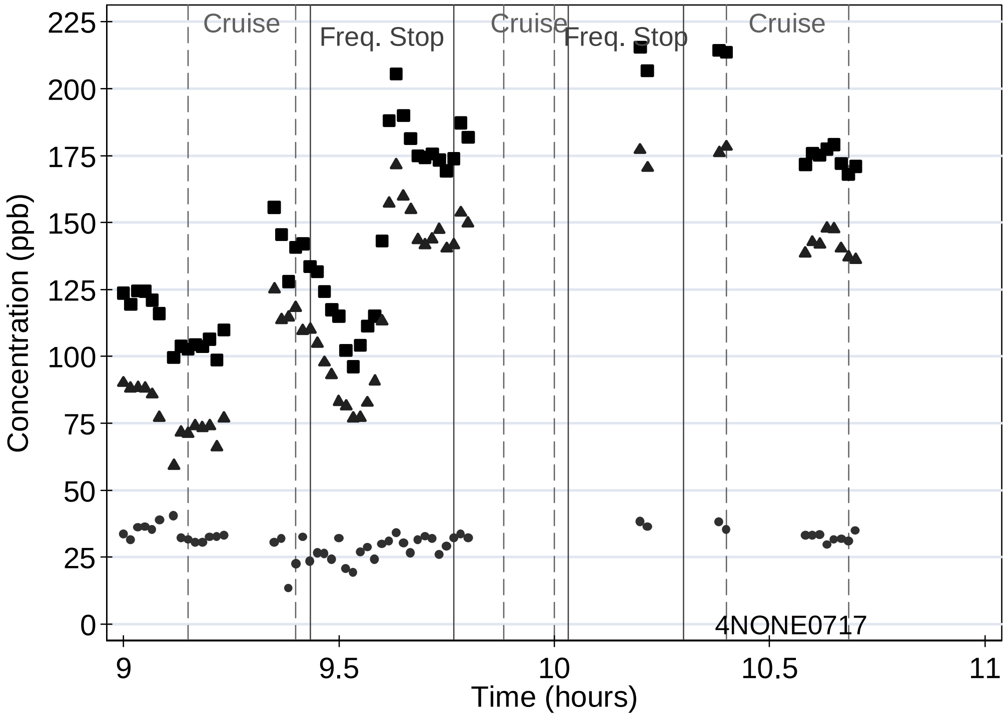
NO$_x$ (square), NO (triangle) and NO$_2$ (circle) Concentrations – 3NONE0717



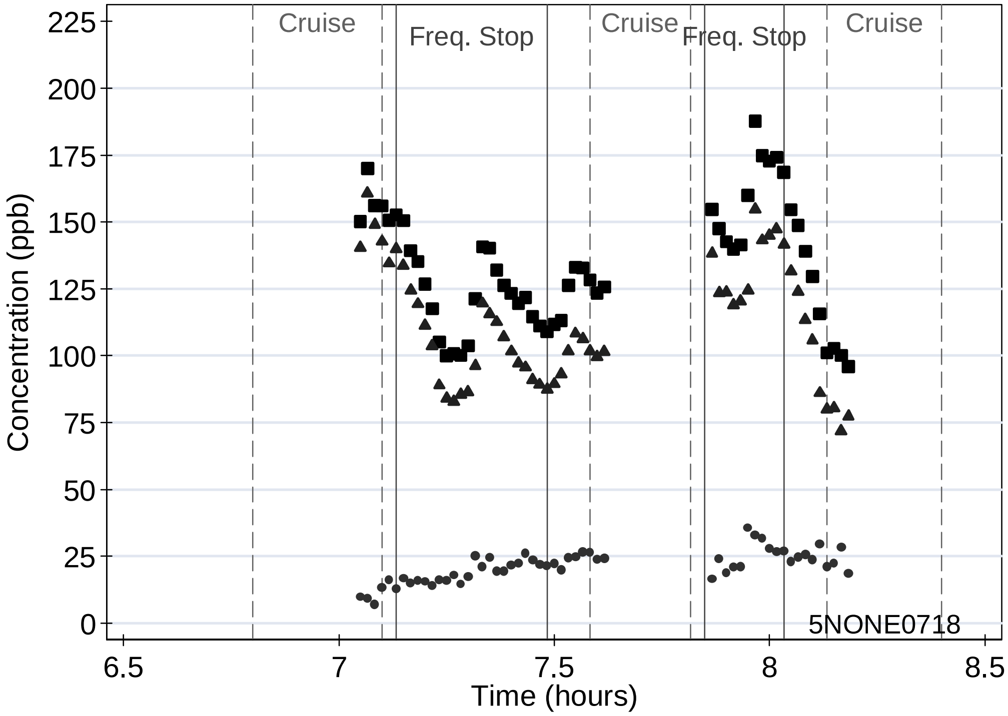
NO_x (square), NO (triangle) and NO_2 (circle) Concentrations – 4CC0727



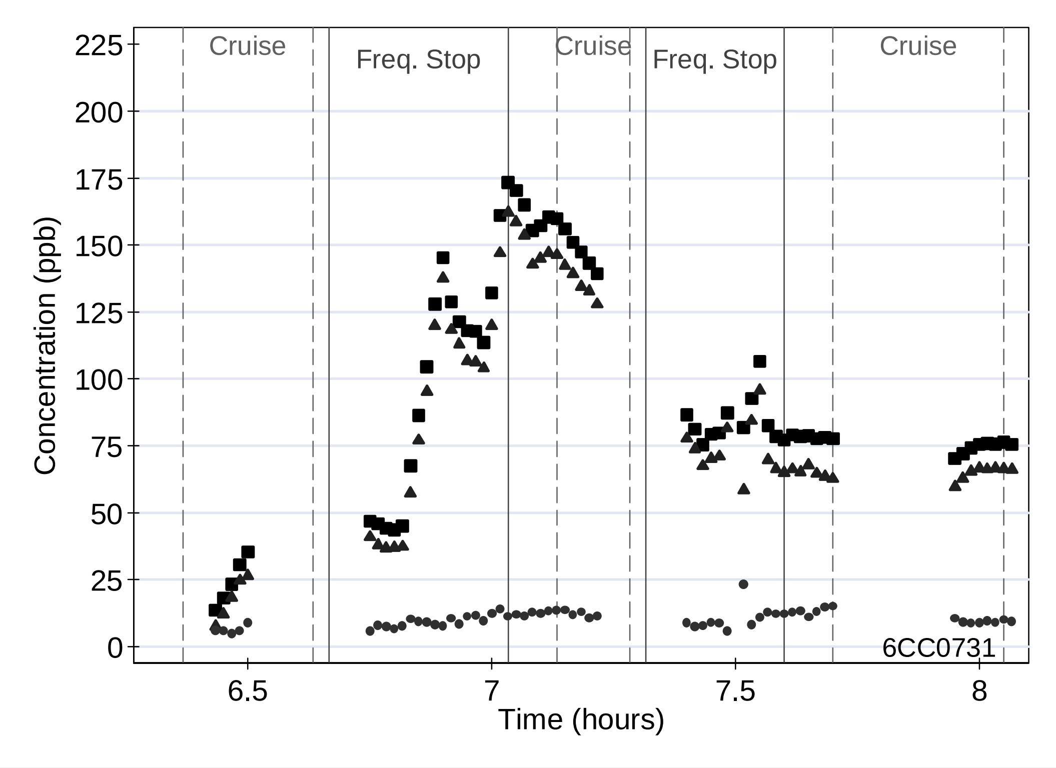
NO_x (square), NO (triangle) and NO_2 (circle) Concentrations – 4CCDOC0802



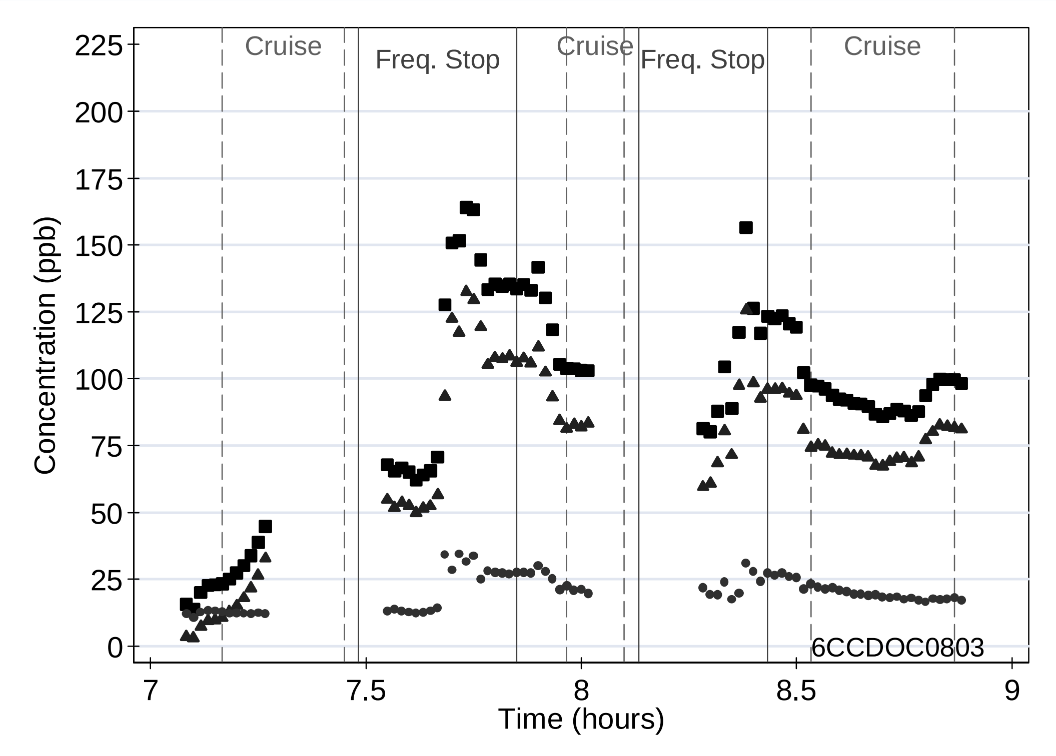
NO$_x$ (square), NO (triangle) and NO$_2$ (circle) Concentrations – 4NONE0717



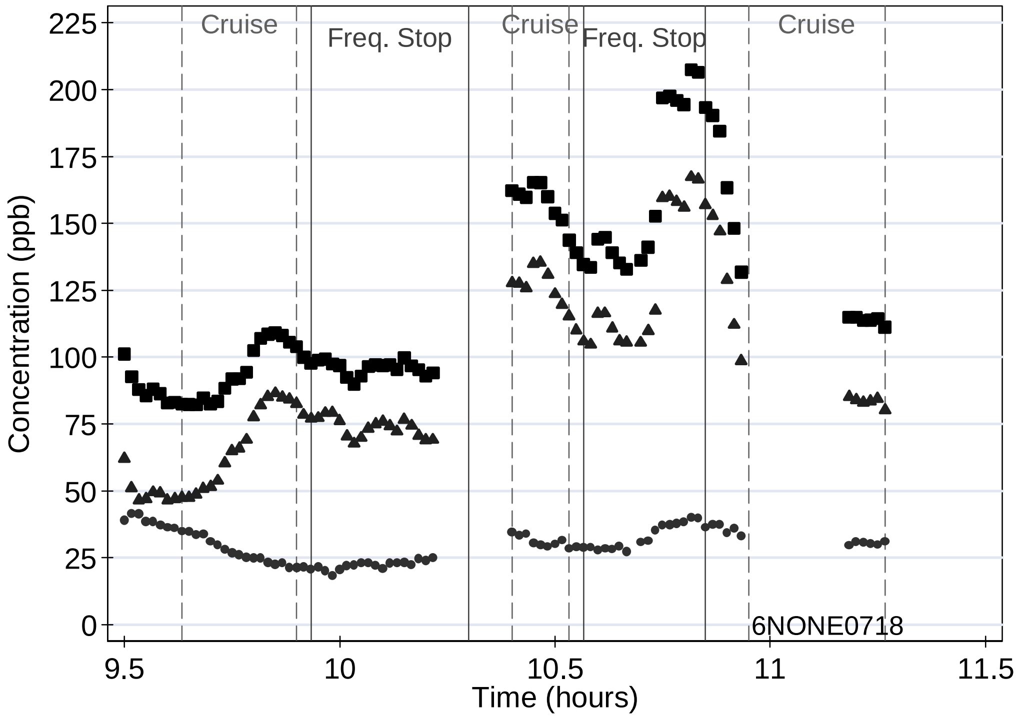
NO$_x$ (square), NO (triangle) and NO$_2$ (circle) Concentrations – 5NONE0718



NO$_x$ (square), NO (triangle) and NO$_2$ (circle) Concentrations – 6CC0731



NO$_x$ (square), NO (triangle) and NO$_2$ (circle) Concentrations – 6CCDOC0803



NO_x (square), NO (triangle) and NO_2 (circle) Concentrations – 6NONE0718

Appendix B. Investigations of the Statistical Significance of Differences in Pollutant Concentrations after Installation of the Spiracle Alone and After Installation of Both the Spiracle and the DOC

Differences in mean concentrations ($C_{\text{Spiracle and DOC}}$- C_{Spiracle}) are shown for statistically significant results; n.s. = not statistically significant

Over entire test

Bus ID	Test 1	Test 2	NO_x (ppb)	NO (ppb)	NO_2 (ppb)	$PM_{2.5}$ ($\mu g/m^3$)	Ultrafine PM (num/cc)	TVOC (ppb)
4	4CC0727	4CCDOC0802	n.s.	n.s.	7.9	0	-1883	-93
3	3CC0726	3CCDOC0727	n.s.	n.s.	3	2	-5031	122
6	6CC0731	6CCDOC0803	n.s.	n.s.	10.1	5	1281	-23

During frequent stops and door openings

Bus ID	Test 1	Test 2	NO_x (ppb)	NO (ppb)	NO_2 (ppb)	$PM_{2.5}$ ($\mu g/m^3$)	Ultrafine PM (num/cc)	TVOC (ppb)
4	4CC0727	4CCDOC0802	-20	-29	9.1	0	-2545	-104
3	3CC0726	3CCDOC0727	n.s.	-12.4	3.3	1	-7192	-19
6	6CC0731	6CCDOC0803	n.s.	n.s.	12.9	5	2113	-70

During cruising with occasional stops

Bus ID	Test 1	Test 2	NO_x (ppb)	NO (ppb)	NO_2 (ppb)	$PM_{2.5}$ ($\mu g/m^3$)	Ultrafine PM (num/cc)	TVOC (ppb)
4	4CC0727	4CCDOC0802	-21.7	-14.6	-7.1	1	1551	92
3	3CC0726	3CCDOC0727	n.s.	n.s.	-1.3	-3	3412	-240
6	6CC0731	6CCDOC0803	n.s.	n.s.	-8	-4	-2277	n.s.

Appendix C. Investigations of the Statistical Significance of Differences in Pollutant Concentrations for Tests with Repetitions (Buses 1 and 2 no retrofit)

n.s. = not statistically significant, n.a. = data not available.

Over entire test

Bus ID	Test 1	Test 2	$PM_{2.5}$ (µg/m^3)	Ultrafine PM (num/cc)	TVOC (ppb)
1	1NONE0711	1NONE0713	3	8722	n.a.
1	1NONE0711	1NONE0802	4	625	n.a.
1	1NONE0713	1NONE0802	n.s.	-8097	-295
2	2NONE0713	2NONE0720	1	9854	n.s.

During frequent stops and door openings

Bus ID	Test 1	Test 2	$PM_{2.5}$ (µg/m^3)	Ultrafine PM (num/cc)	TVOC (ppb)
1	1NONE0711	1NONE0713	2	4045	n.a.
1	1NONE0711	1NONE0802	4	993	n.a.
1	1NONE0713	1NONE0802	2	-3052	-318
2	2NONE0713	2NONE0720	-2	5886	-29

During cruising with occasional stops

Bus ID	Test 1	Test 2	$PM_{2.5}$ (µg/m^3)	Ultrafine PM (num/cc)	TVOC (ppb)
1	1NONE0711	1NONE0713	4	n.s.	n.a.
1	1NONE0711	1NONE0802	2	1059	n.a.
1	1NONE0713	1NONE0802	-1	n.s.	-291
2	2NONE0713	2NONE0720	3	13134	n.s.