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Josue Rene Hernandez Pedroza
University of Colorado at Boulder, josue61290@gmail.com

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A Study of the Impact of Diesel Buses on Downtown Boulder

By

Josue Rene Hernandez Pedroza

B.S., Mechanical Engineering

Technological University of Panama, Panama City, 2014

A thesis submitted to the Faculty of the

Graduate School of the University of Colorado

in partial fulfillment of the requirement

for the degree of

Master of Science

Department of Mechanical Engineering

2017

This thesis entitled:

A Study of the Impact of Diesel Buses on Downtown Boulder

Written by Josue Rene Hernandez Pedroza

has been approved for the Department of Mechanical Engineering

Dr. Shelly L. Miller

Dr. Michael Hannigan

Dr. Darin Toohey

Date____________________

The final copy of this thesis has been examined by the signatories, and we find that both the content and the form meet acceptable presentation standards of scholarly work in the above-mentioned discipline.

Abstract

Hernandez Pedroza, Josue Rene

Master of Science, Department of Mechanical Engineering

A Study of the Impact of Diesel Buses on Downtown Boulder

Thesis directed by Professor Shelly L. Miller

Many studies have reported the adverse health effects of diesel combustion engine emissions; diesel exhaust is considered carcinogenic to humans. This research examined the major pollutants produced by diesel-powered engines within the city of Boulder, Colorado: particulate matter, black carbon, and nitrogen oxides. Ozone was also studied due to its secondary formation from nitrogen oxides. Summer and Winter measurements were taken next to the Boulder Downtown Bus Station, for one week in each season. It was not possible to estimate bus emissions due to variability in the number of vehicles and buses traveling in the study corridor. Results showed limited association between pollutant levels and traffic patterns, and followed regional pollution and seasonal trends. Only Winter particle number and nitrogen oxides followed traffic trends. NOx was elevated in Winter, and Black carbon contributed 12-34% of the total fine particulate matter.

Bicycle rides were carried out to capture fresh emissions on-road. Black carbon concentration peaked when chasing certain buses, while emissions from other buses were low. Passenger vehicle emissions were not reflected in the black carbon levels. Bicycle ride pollutant averages were lower than averages from stationary measurements, while bicycle ride peak values were higher than peak values in stationary measurements for black carbon and particulate matter. Ozone was always higher on-road.

With the use of MOVES and R-Line, the impact of buses on the concentration of pollutants was analyzed. Emission rates were estimated with MOVES in Summer and Winter by running simulations with and without buses. The R-Line dispersion model was used to estimate the concentration of pollutants at the Boulder Downtown Bus Station and the street right in front of the station. Results showed the fraction of NOx and PM that could be attributable to buses was between 24-40% and 16-45%, respectively. These values would have been lower if traffic-related emissions from additional surrounding streets would have been included. Bus emissions due to the idling period represented a significant part of pollutants emitted. Therefore, the bus station contributed significantly to the total traffic emissions in Boulder Downtown.

Dedication

This thesis is dedicated to God for giving me the strength and faith to complete my studies. I also dedicate this research to my parents, sister, and little nephew for their support and encouragement to pursue graduate studies.

Acknowledgements

I would like to thank my advisor Dr. Shelly Miller for giving me her support, guidance, and also the opportunity to develop this research. I thank Dr. Darin Toohey for his time and help throughout the project. I acknowledge the help and advice of the students of the Miller Air Quality Research Group. I express my gratitude to all the people that made this project possible: Preston Padden and the Boulder residents who funded this study, and provided a site to carry out the measurement campaigns; the staff of 2B Technologies who provided a black carbon and ozone monitor in Summer and Winter; the Colorado Department of Public Health and Environment (CDPHE) for providing access to the measurement station at Globeville to calibrate an instrument. And finally, many thanks to the Fulbright-Ifarhu-Senacyt scholarship for believing in me and sponsoring my graduate education.

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Chapter I: Introduction

Background

Freshly emitted air pollutants downwind from major roadways include elevated levels of particulate matter, black carbon, and nitrogen oxides. People living within 200 m of highways are exposed to these pollutants more so than persons living farther away. Health studies show high risk from exposure to traffic-related air pollutants for cardio and pulmonary mortality (Andersen et al. 2011), high blood pressure (Zhong et al. 2015), lung cancer (Beelen et al. 2008), childhood asthma (Clark et al. 2010) and behavioral problems in school children (Forns et al. 2016). These air pollutants are generated by combustion engines, including gasoline and diesel-powered engines.

Emissions produced by diesel combustion engines contain a considerable amount of particulate matter (PM), ranging from very small particles with sizes under 100 nm (ultrafine particles) to fine particles with diameters < 2.5 μm (PM2.5) (Park et al. 2011). The inhalation of PM is a big concern for human health. Ultrafine and fine particles can travel deep into the respiratory system, and they have been related to illnesses and mortality, since they can affect blood vessels, lungs, and the heart (Fruin et al. 2008). It has been shown that a decrease in the levels of PM2.5 by 10 $\mu g/m^3$ reduces the risk of heart disease deaths by 15% (CDC 2016a). Current state-of-the-art science shows that the concentration of PM2.5 has a strong relationship with human mortality, while coarse PM (particles with diameters between 2.5 and 10 microns) does not show a direct connection with mortality; coarse PM is associated with short-term health effects such as hospital admissions and asthma cases (Clements et al. 2016). PM2.5 is linked with some fraction of hospitalizations and deaths (Kloog et al. 2013). The exposure of any type of PM increases the risk of illnesses in newborn babies, breathing problems, decreased lung growth, and early deaths (CDC 2016b).

Other pollutants of concern related to diesel engine emissions are nitrogen oxides and ozone. In Beijing, China, diesel vehicles are responsible for a high percentage of nitrogen oxides (NOx) emitted in the environment, and diesel trucks are the biggest contributors, since the number of trucks is high in Beijing (Huo et al. 2012). NOx emissions produced by trucks in urban areas accounted for up to 60% of the total NOx emissions.

Nitrogen oxides are associated with respiratory diseases and hospital admissions, where long exposure to NOx augments the risk of suffering asthma. NOx also impacts the environment, contributing to acid rain in the western US, visibility reduction, and coastal waters nutrient pollution (US EPA 2016a). NOx emitted in the atmosphere takes part in the chemistry responsible for the secondary formation of both ozone and PM2.5.

Ozone (O_3) degrades the function of lungs and increases chronic respiratory illnesses, including bronchitis, pneumonia, and lung and throat irritation (CDC 2016c). Some studies have analyzed the co-exposure effects of ozone and diesel exhaust particles (DEP). Jang et al. (2005) concluded that DEP and ozone increase the airway hyper-responsiveness, and this mix may worsen the health of people with asthma. Madden et al. (2000) examined the increase of the bioactivity of PM exposed to ozone by using rats to test lung injury. Their experiments suggested that ozone can augment the potency of the PM bioactivity. The ozonized PM generates more injuries and lung inflammation issues compared to non-ozonized PM.

Black carbon (BC) emitted by diesel vehicles represents around 93% of all the BC mobile source emissions (US EPA 2017b). After carbon dioxide (CO_2), it is considered the second most important anthropogenic emitted pollutant (Zheng et al. 2015). The relative risk of mortality was correlated with increasing PM2.5 concentrations and BC (Kim et al. 2015). For an inter-quartile increase of 4.55 $\mu g/m^3$ of PM2.5, the relative risk was 1.012, and for an increase of 0.33 $\mu g/m^3$ of BC was 1.024; in both cases with a 95% confidence interval. These results show that a major contributor to mortality is the BC within PM2.5.

Black carbon has been designated as a Group 2B carcinogen (possibly carcinogenic to humans) by the Interagency for Research on Cancer (IARC) with the evidence showing respiratory cancer in rats (Baan et al. 2006). Note that diesel exhaust has been classified as a Group 1 carcinogen (carcinogenic to humans) by IARC, in the same category as asbestos and ultraviolet (UVA and UVB) radiation (IARC 2016).

The US Environmental Protection Agency (EPA) regulates PM, as well as NO_2 and ozone. The National Ambient Air Quality Standards (NAAQS) are based on adverse health effects for sensitive populations and reflect the current best understanding of what levels of air pollution are reasonable to be exposed without degrading health (US EPA 2016d). The standards are: 53 ppb (parts per billion) annual mean and 100 ppb 1-h mean for NO_2, 70 ppb 8-h mean for O_3, 12 $\mu g/m^3$ annual mean and 35 $\mu g/m^3$ 24-h mean for PM2.5, and 150 $\mu g/m^3$ 24-h mean for PM10. Note the Denver Metro area is in compliance with all NAAQS except for ozone (CDPHE 2017).

Study Objectives

Traffic-related air pollution, and specifically emissions from diesel engines, is responsible for many of the most dangerous contaminants for human being welfare and health. A high density of diesel vehicles in operation represents a serious hazard for people living or spending several hours within the surrounding areas. In Colorado, the Boulder Downtown Bus Station is located in the middle of a residential and commercial district, with a high density of people living, working and visiting the downtown area. A high concentration of diesel buses traveling in Downtown Boulder may present a significant concern for air quality and health. The objective of this research was to provide data about the effects of diesel buses on the air quality level in the downtown region of Boulder, Colorado. In this study, measurements were taken in Summer and Winter over the course of a week in each season to understand different seasonal emission patterns. Bicycle rides were carried out to measure pollutants on-road, in which buses and vehicles were chased to capture fresh emissions. Computational modeling was used to characterize the effects of buses to the total traffic-related emissions on Boulder Downtown.

Chapter II: Methodology

Instruments Description

A suite of instruments was deployed to measure air pollutant levels, in real-time. Some of the fundamental technologies that the instruments were based on consist of light absorption, chemiluminescence, condensation, optical scattering, and acceleration. Traffic-related contaminants were our research focus. For this reason, measurements of Black Carbon (BC), Ozone (O_3), Nitrogen Oxides (NOx), and Particulate Matter (PM) were carried out throughout the study. Six instruments were used for the experiments: Aethalometer for BC, Ozone Personal Monitor for O_3, NOx analyzer for NO and NO_2, Condensation Particle Counter for nanoparticles, Ultra-High Sensitivity Aerosol Spectrometer for ultrafine PM, and Aerodynamic Particle Sizer for PM2.5 and PM10. A description of these instruments is presented below.

Aethalometer

The Aethlabs MicroAeth AE51 kindly provided by 2BTechnologies, Inc. is a light-absorption-based portable instrument to measure Black Carbon (BC) (Aethlabs 2017). Light transmission is measured by a LED light source of 880 nm and a photodiode detector. A Teflon coated borosilicate glass fiber filter is used to measure the attenuation of light. The accumulation of optically absorbing particles in the filter causes an increment in the optical attenuation between readings. Then, the attenuation of light is correlated to the mass concentration of BC by the change in the light transmission level from the previous reading. A time resolution of 10 seconds and the default sample rate of 100 ml/min were employed. Figure 1 shows the MicroAeth used in this study.

Figure 1. Aethlabs MicroAeth AE51

Ozone Monitor

The Personal Ozone Monitor (POM) generously provided by 2BTechnologies, Inc. is a UV light-based absorption instrument to measure O_3 concentration (2BTech 2017). O_3 concentration is measured by the attenuation of light passing along a 15-cm tube length fitted with quartz windows. One side of the tube has a low-pressure mercury lamp that produces an emission wavelength of 254 nm, which is the O_3 maximum absorption wavelength. The other side has a photodiode with an incorporated interference filter centered on 254 nm. One drawback of the POM is that its battery lasts up to 6 hours; if an extended measurement period is required a replacement battery must be used. The resolution was set to 10 seconds. Figure 2 shows the utilized POM.

Figure 2. Personal Ozone Monitor (POM)

Chemiluminescence NOx Analyzer

The Thermo Fisher NO-NO_2-NOx Low Source Analyzer (Thermo 42i) is a chemiluminescence-based nitrogen oxides measurement device (ThermoFisher 2017). The principle of operation consists of a luminescence linear proportionality to NO concentration, when NO is reacted with O_3. Once an ambient air sample of 25 cm^3/min is drawn into the instrument, a solenoid valve routes the sample straight to a reaction chamber to measure NO, or to a 625 °C heated stainless NO_2-to-NO converter and then to the reaction chamber. The latter way measures NOx; NO_2 is based on the difference between NOx and NO. Dry air is required in the ozonator to produce the O_3 needed in the reaction chamber. Luminescence produced in the reaction chamber is detected by a photomultiplier tube contained in a thermoelectric cooler. Besides the luminescence, NO_2 and O_2 are produced, as well. The time resolution was set to the minimum possible value of 1 minute. Figure 3 shows a Thermo 42i.

Figure 3. Thermo Fisher 42i NO-NO2-NOx Low Source Analyzer (ThermoFisher 2017)

Condensation Particle Counter

The TSI Condensation Particle Counter (CPC 3007) is a portable particle counter that uses the principle of condensation to count particles within the size range 10nm-1µm (TSI 2017b). The instrument does not measure the size distribution; it only allows the determination of the total particle number concentration. Another drawback of this device is the measurement length period. It has a maximum continuous working period of 6 hours, since the alcohol dries out after this time; therefore, it must be replenished to keep it working. The CPC draws a laminar flow aerosol sample of 100 cm^3/min into a heated saturator, in which alcohol is evaporated and mixed into the sample flow. Then, the mix is cooled down by passing it through a cooling condenser, where the alcohol steam reaches a supersaturated condition. The particles in the flow become the condensation site for the alcohol steam. The condensation makes particles grow into larger alcohol droplets that pass through a laser light source and an optical detector to measure the particle number concentration. A time resolution of 1 second was used. Figure 4 shows one of the two CPCs used during this study.

Figure 4. TSI Condensation Particle Counter (CPC 3007)

Ultra-High Sensitivity Aerosol Spectrometer

The Droplet Measurement Technology (DMT) Ultra-High Sensitivity Aerosol Spectrometer (UHSAS) is a laser-based, optical-scattering aerosol particle spectrometer instrument for continuous sizing of particles within a diameter range from 55 nm to 1 µm (DMT 2017). This device provides the option to specify up to 100 bins, allowing the user to control the sizes of interest, in detail. The laser is a semiconductor-diode-pumped $Nd^{3+}:YLF_4$ solid-state laser. The particulate flow moves perpendicular to the standing-wave laser mode. Additionally, particle scatter collection takes place perpendicular to the flow of particles and the laser. Two pairs of Mangin collection optics are employed in the detection system. When the laser intersects the sample flow, light is scattered onto the detection system. One pair of collection optics images onto an avalanche photodiode for detecting particles in the lower size range. The other pair of collection optics images onto a low-gain PIN photodiode for detecting particles in the upper size range. In this study, the time resolution was set to 10 seconds. Though our interest was focused on the total count within 55-1000 nm, the bins were set to have higher resolution for particles of smaller size. The flow rate was set to 50 sccm (standard cubic centimeter per minute). Figure 5 shows an UHSAS.

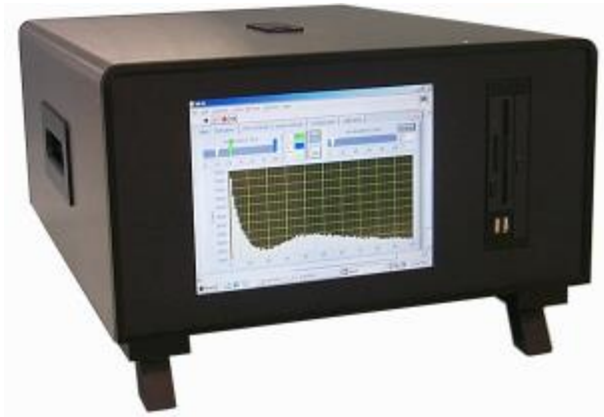

Figure 5. DMT Ultra-High Sensitivity Aerosol Spectrometer (UHSAS) (DMT 2017)

Aerodynamic Particle Sizer

The TSI Aerodynamic Particle Sizer (APS 3321) is a particle spectrometer that measures aerodynamic diameter and light-scattering intensity. The instrument counts particles within 0.5-20 µm and detects light-scattering intensity within 0.3-20 µm. However, this device has been mainly developed to do aerodynamic size measurements (TSI 2017a). The APS is based on the principle of time-of-flight; it measures the acceleration of aerosol particles due to the acceleration of the total flow through a nozzle. The mix of the aerosol flow (1 L/min) and sheath flow (4 L/min) is passed through the nozzle. The rate of acceleration depends on particle size, where smaller particles accelerate faster due to their lower inertia. The APS uses two laser beams to determine the aerodynamic particle diameter. Once particles leave the nozzle, the time of flight between the two beams is recorded and the calibration curve of the APS correlates the time of flight to particle diameter. When a particle passes through the beams, a beam profile with two peaks is produced, allowing the determination of the time interval between lasers. Side-scattered light is captured by an elliptical mirror that focuses the captured light onto a solid-state photodetector that transforms light to electrical pulses. Particle size is distributed in 52 logarithmic scale channels. In this study, the time resolution was set to 30 seconds. Results can be expressed in terms of number, surface area, and mass concentration. Our main purpose was to determine PM2.5 and PM10, thus 10 µm was the maximum size of interest and mass concentration was employed for the analysis. On the other hand, a minimum size of 542 µm was used, since diameters below this number tend to produce an erroneous outcome (Peters and Leith 2003). Figure 6 shows the APS employed during this study.

Figure 6. TSI Aerodynamic Particle Sizer (APS 3321)

Stationary Measurements

Measurement campaigns were carried out in Summer and Winter during the week of July 25^{th} to 31^{st}, 2016, and January 16^{th} to 22^{nd}, 2017, respectively. The aim of the study was to measure the concentration of traffic-related air pollutants, describe the air quality in Downtown Boulder, and obtain seasonal variations of pollutants' levels. In addition, the concentration readings were compared to the Regional Transportation District - Denver (RTD) bus count per hour and routes next to the measurement location to explore their relationship. The testing site was the balcony of an apartment complex next to the Boulder Downtown Bus Station (BDS). Table 1 shows the streets taken by each bus route surrounding the measurements' location and BDS. Figure 7 shows the measurements' location and the street number code employed in Table 1.

Table 1. Bus routes of the Boulder Downtown Station surrounding streets

Street	1	2	3	4	5	6	7	8	9	10	11
Route	AB	AB	205	205	205	205	205	205	205	AB	205
	225	225	Jump	AB	Jump	AB	Jump	Jump	Bolt	Bolt	AB
	Dash	Dash	225	225	225	Jump	Bolt	Bolt	204	FF	Bolt
	Skip	Hop	Dash	Dash	N	Bolt	Hop	204		GS	FF
	FF	FF	Bolt	FF		Hop	204			Y	GS
	GS	GS	208	GS		FF				N	Y
	208	208	N	208		GS					N
	Y	Y	204	Y		Y					204
	204	204		N		N					
				204		204					

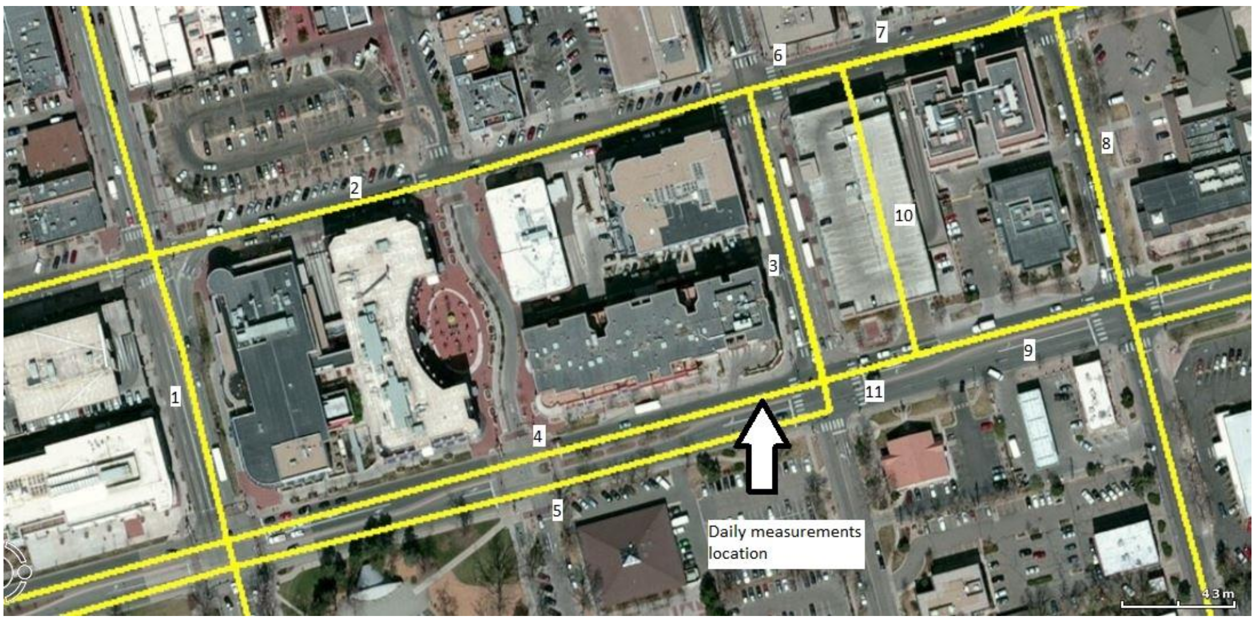

Figure 7. Measurements' location and bus routes traveling the streets around the Boulder Downtown Bus Station

This place provided an optimum location to analyze the concentration that people are exposed to when living close to a zone with a high volume of diesel buses. Comparisons between measurements collected on weekdays and weekends were made to study their relationship to bus count and vehicle traffic. A neighbor living in the apartment complex (Mr. Preston Padden) kindly arranged for access to two condo units in Summer and one in Winter. The daily Summer measurement period was between 12-6 pm, since some instruments could not work indefinitely and to avoid disturbing the condo unit owners. The first testing site was located on the second floor in front of Canyon Boulevard, where tests were performed as planned until July 27th. The second condo unit was located on the third floor in front of BDS and lateral to Canyon Boulevard to see possible differences due to location, and a main Boulder street, and a street only composed of buses. This location was employed until July 31st. Nevertheless, the owner did not want to provide daily access. Thus only the equipment that works continuously was used. For this reason, the CPC, MicroAeth and POM measurements were not collected on these days. The entire Winter campaign was conducted in the same location as the first testing site used in the beginning of the Summer campaign. Daily measurements started between 7-8 am and were performed until 6 pm. Night measurements were not taken due to the freezing Winter temperatures. Daily alcohol refilling of the CPC, and battery change of the POM were carried out to keep the instruments working.

Experimental Set-Up

In deciding the best possible place to set up the equipment for the stationary measurements, only condo units facing Canyon Boulevard and BDS were considered as options to carry out the campaigns. Condo units with roof cover were selected for the measurement campaigns to protect the equipment from adverse weather conditions. A shelving unit was employed to set up all the instruments. Figure 8 shows the instrument set-up on the shelving unit. The balconies had multiple electricity outlets that were used to distribute the electricity demand and avoid the risk of having a short circuit. The condo unit facing Canyon Boulevard was about 15 m away from the closest street lane. On the other hand, the condo unit facing BDS was around 6 m away from the closest street lane.

Figure 8. Stationary measurement campaigns set-up

Bus Count

Initially, a video camera was employed to manually count the number of buses that passed by the apartment complex. These recordings were compared to the schedule provided by the Regional Transportation District - Denver (RTD). Three randomly selected routes were compared between the observations from the video recordings and the RTD Summer schedule. The routes selected were the 204, 208 and Dash. The analysis was done for the recording performed on July 27th. The video and the schedule showed the same amount of the buses leaving from BDS. The route 204 showed the same number of buses leaving from gate K (19 buses), but none of the buses leaving from gate J were registered by the video camera. The route 208 also coincided with the recording, having 12 buses leaving. The route Dash had the same number of buses leaving from the station compared to the video, 20 buses. However, on two occasions there was an extra bus leaving and in two other times the bus did not leave; therefore, the count was still the same. After checking the veracity of the schedule, it was decided to follow the RTD schedule to compare the number of buses to the concentration of pollutants in Summer and Winter. Table 2 contains the total bus count per hour. It must be noted that in Winter the RTD fleet operated more buses.

Table 2. RTD bus trips per hour in Summer and Winter

	Summer buses trips per hour			Winter buses trips per hour		
Time	Weekdays	Weekends	Sundays	Weekdays	Weekends	Sundays
00:00-1:00	8	5	3	8	8	5
1:00-2:00	3	3	1	4	5	1
2:00-3:00	2	2	1	2	2	1
3:00-4:00	1	2	1	1	2	1
4:00-5:00	5	2	2	5	2	2
5:00-6:00	21	2	1	23	2	1
6:00-7:00	57	8	6	56	10	6
7:00-8:00	76	18	14	82	19	15
8:00-9:00	72	29	17	81	29	17
9:00-10:00	56	31	20	64	31	20
10:00-11:00	47	33	21	55	33	20
11:00-12:00	44	33	24	52	33	24
12:00-13:00	45	33	25	53	33	25
13:00-14:00	44	33	25	52	33	25
14:00-15:00	48	33	25	56	33	25
15:00-16:00	64	34	26	70	34	26
16:00-17:00	75	34	26	80	34	26
17:00-18:00	77	33	25	82	33	25
18:00-19:00	70	31	25	71	31	25
19:00-20:00	47	23	21	49	23	22
20:00-21:00	34	21	20	35	21	19
21:00-22:00	22	18	14	22	18	24
22:00-23:00	18	16	7	18	16	8
23:00-00:00	13	13	4	12	13	6
Total	949	490	354	1033	498	369

Stationary Measurements and CAMP Comparison

Results of the stationary measurement campaigns were compared to the hourly data reported by the Colorado Department of Public Health and Environment (CDPHE) at their CAMP monitoring station, in Denver. This station was chosen because it experiences similar traffic patterns to Canyon Boulevard. CDPHE reports the concentration of ozone, nitric oxide, nitrogen dioxide, PM2.5 and PM10. Therefore, we were able to compare only three out of six instruments. Figure 9 shows the CAMP monitoring station in Denver.

Figure 9. CDPHE CAMP monitoring station

Bicycle Rides

Bicycle rides were performed to study pollutants at street-level and determine the effects of following buses by bicycle commuters. Thus, buses were chased at some instances, only cars in other periods, and streets without any vehicles were also part of the experiments. The bicycle that was used was an electric one so that it could follow at speeds similar to the vehicles of interest. Portable measurement devices (CPC, MicroAeth, and POM) were set in a frontal bicycle basket to carry out the tests. The POM has an incorporated GPS that allowed us to keep track of the entire trip for subsequent analysis, and it works in conjunction with the MicroAeth. A typical map of a trip with the concentration readings of these instruments is shown in Figure 10, in which yellow dots represent BC and red dots O_3; the height of the dots is related to the concentration of the pollutant. CPC and POM results of the rides were averaged daily.

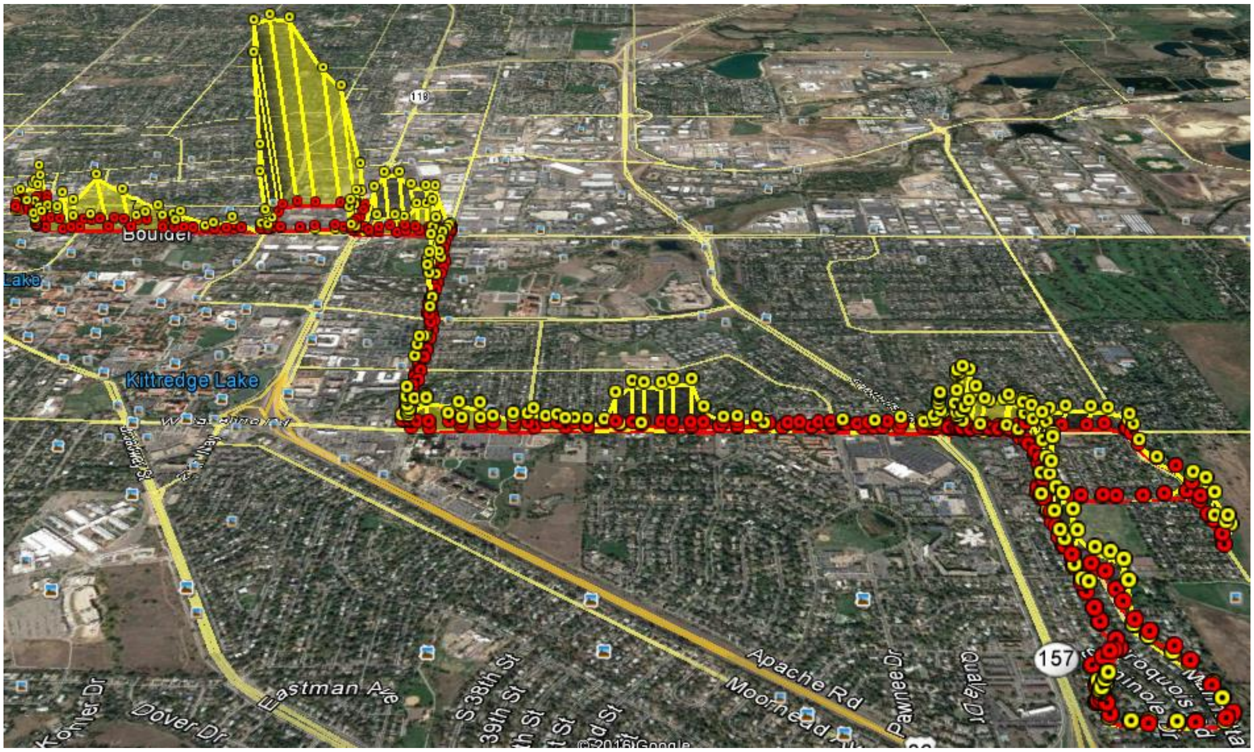

Figure 10. Example of a bicycle ride

Data Processing and Analysis

All the collected stationary data was averaged to 5 minutes for visualization and descriptive purposes, and to reduce the noise level of the original readings. It must be noted, however, that the statistical information presented for each instrument is based on the original data. BC data from bicycle rides were averaged to one minute for visualization and descriptive purposes, since a higher resolution had an excessive amount of noise. However, similar to the stationary analysis, the statistical data are based on the original time resolution.

Post-processing analysis was performed for three of the instruments: APS, MicroAeth, and POM. A description of the employed techniques is described below.

The Optimized Noise-Reduction Averaging Algorithm (ONA) was used to smooth the MicroAeth data and decrease the frequency of negative values to almost zero while keeping the data trends. EPA has developed a MATLAB-based ONA program that was employed for processing our data. One of the biggest problems of BC filtering measurement techniques is the sensitivity when measuring low concentrations or at a very high time resolution. The optical and electrical noise produced during these periods could lead to a light attenuation (ATN) constant value or even a drop in ATN (Hagler 2011). Since the BC concentration is based on successive increments of ATN, the aforementioned circumstance can produce erroneous negative values. A minimum ATN change (ΔATN_{min}) must be specified by the user. The noise level of aethalometers asymptotes to almost zero when establishing a ΔATN=0.05 (Hagler 2011), providing a balance between noise reduction and keeping the data series trends. Therefore, ΔATN=0.05 was chosen for this study. The ONA method averages the raw BC concentration until ΔATN is reached, and it must be its last occurrence in the data series.

Loading of light absorbing particles on the filter tends to reduce the actual BC concentration. ΔATN of 20, 40, 60, 80, 100, or 125 underestimate BC concentration approximately by 16%, 31%, 42%, 51%, 59%, and 69%, respectively (Good et al. 2016b). Our maximum observed ΔATN was 42. When ΔATN is excessively high, data must be eliminated. Our maximum change value is considerably lower than the recommended maximum ΔATN of 75 (Dons et al. 2012). Several correction equations have been reported to fix the filtering loading underestimation problem. The Kirchstetter equation shows a very similar trend compared to the actual fractional MicroAeth reduction and ΔATN (Good et al. 2016b); therefore, it was selected for the analysis. The Kirchstetter equation is presented below.

$$R = a_1 e^{-\Delta ATN/100} + a_2 \qquad (1)$$

Where R: fractional reduction, ΔATN: light attenuation from the first ATN value, a_1: 0.88 and a_2: 0.12.

To find the corrected BC concentration the following equation is used:

$$BC_{corrected} = \frac{BC_{ONA}}{R} \quad (2)$$

Where BC_{ONA} is the smoothed BC concentration.

The original POM data was checked for possible negative values and outliers. Similar to the ozone study developed by Sofen et al. (2016), negatives values and extreme outliers (three standard deviations or more) were eliminated from the data series. In Summer, most of the eliminated values were below the lower outer limit (LOF). On the other hand, Winter eliminated data were mostly composed of negative values, since lower O_3 concentrations were seen during this period of the year.

Since the APS employed was not calibrated, a one-week collocation at the Colorado Department of Public Health and Environment (CDPHE) Globeville monitoring station was carried out (Figure 11). A 5-foot long, 3/4" diameter conductive silicone tubing was used during this test to sample PM, since the APS was placed inside the station shelter. An experiment was performed to estimate the line losses as a function of particle size. During 100 minutes, measurements were taken by attaching and removing the sampling line from the instrument's inlet every 5 minutes. Since the process of attaching and removing the sampling line took a few seconds, it could have altered the results. So, the first minute was eliminated from the data and the concentration for each bin size was averaged with the 4-minute readings left. The average of the ten subsets is presented in Figure 12. It can be noted that as the particle size increases, a bigger mass loss was observed when sampling with the line.

Figure 11.CDPHE Globeville measurement station

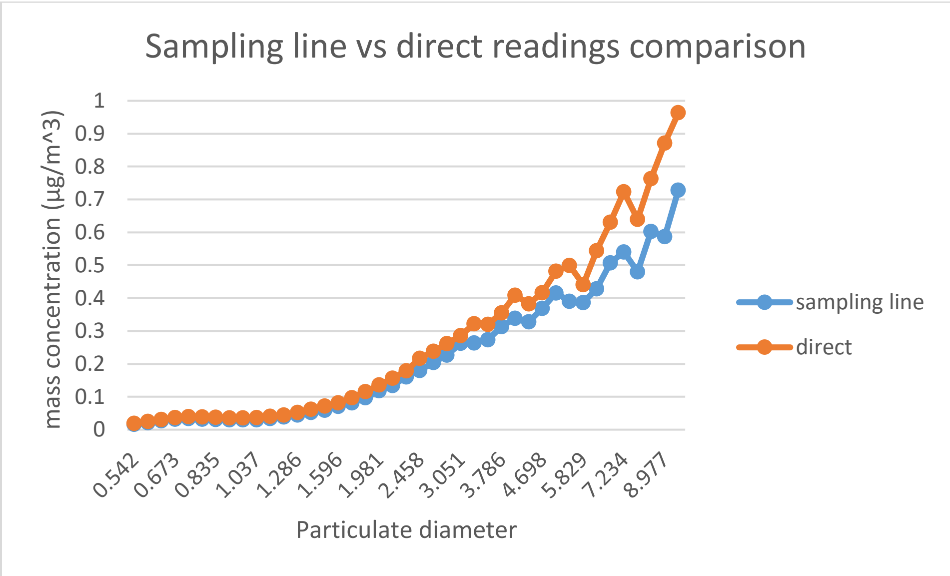

Figure 12. Sampling line and direct APS average measurements comparison

The average fractional losses and their standard deviations are presented in Figure 13. Average losses between 10-20% are observed up to a particle size of around 5µm; after this size particle losses reach a maximum of 33%. As particle size increases the fractional losses and standard deviations also increase. Large particles have a smaller number concentration; therefore, even a small change in their number can lead to a big change in the results. The mean losses for PM2.5 and PM10 were 14.8% and 16.2%, respectively. The standard deviations based on the mean for each APS bin were 2.1% and 4.7% for PM2.5 and PM10.

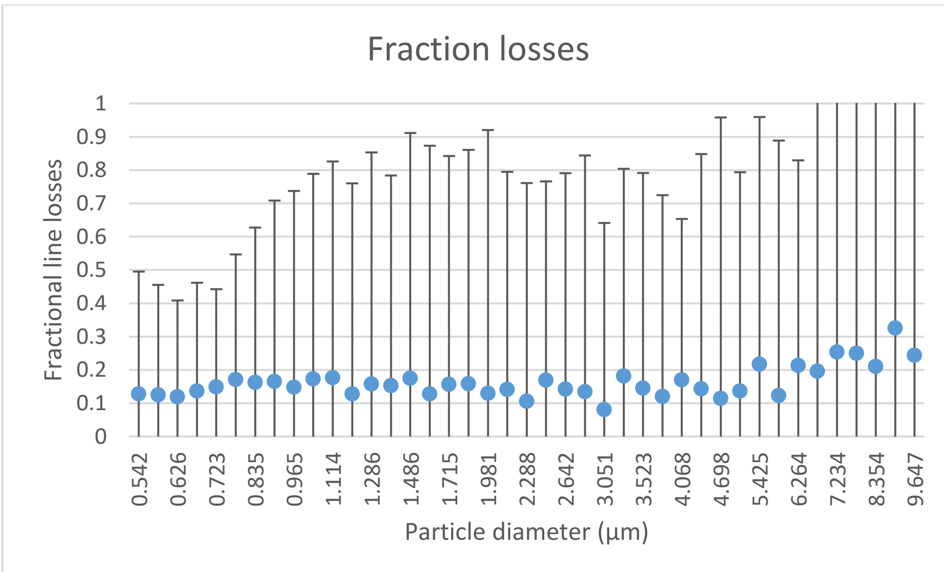

Figure 13. Sampling line losses and standard deviations

The APS measurements were compared to the Globeville hourly PM2.5 and PM10 concentration reports. Both pollutants show a similar trend; however, PM2.5 had a slightly higher fraction loss than PM10. The average fraction loss of the entire week was 67.25 ± 8.69% and 60.95 ± 9.76% for PM2.5 and PM10, respectively. Daily fraction losses for PM2.5 and PM10 are presented in the Appendix A. Globeville and APS measurements had a linear relationship. Figure 14 and Figure 15 show the PM2.5 and PM10 linear regression fits. The regression equations were employed to correct the data collected in Summer. Plots comparing Globeville and the APS, before and after correcting the data are presented in the Appendix A. Very good agreement was found once the correction equations were applied to the APS raw data.

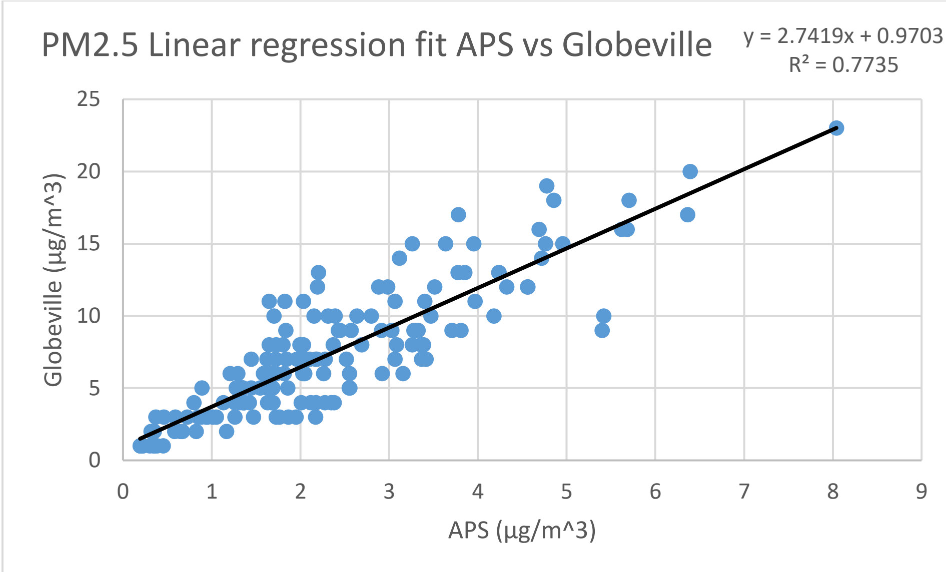

Figure 14. APS and Globeville PM2.5 linear regression fit

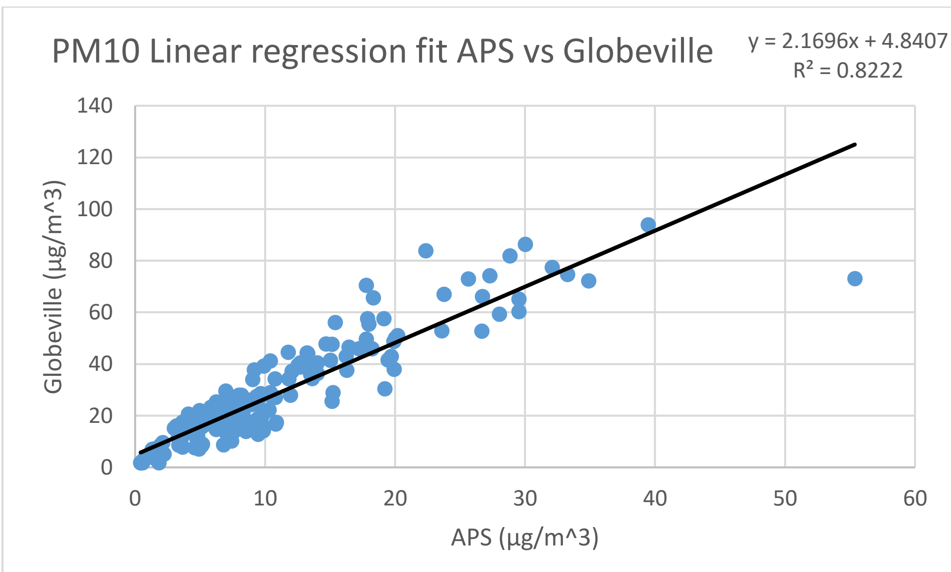

Figure 15. APS and Globeville PM10 linear regression fit

Computational Modeling

The software MOVES (Motor Vehicle Emission Simulator) was used to estimate pollutant mass emission rates in Canyon Boulevard and the Boulder Downtown Bus Station (BDS). MOVES was developed by the EPA (US Environmental Protection Agency) to estimate air pollution emissions from mobile sources. MOVES is based on millions of emission experiments, and it can estimate exhaust emissions, and brake and tire wear emissions from any kind of on-road vehicle (US EPA 2017c). A project-scale approach simulates average emissions for input links, that represent driving conditions. Initially, an off-network link would be used to simulate BDS, since its function is to analyze start and idling periods. However, it only currently works for long-haul diesel trucks. Therefore, two regular links were used at Canyon and BDS.

The first step to generate a simulation is to set a RunSpec. A RunSpec has the specifications of the entire simulation. A project-scale model was employed to simulate traffic conditions observed at Canyon and BDS, using the MOVES inventory of Boulder emissions. The model can only estimate emissions for one selected hour of the year, month, and weekdays or weekend specified by the user. In our case, emissions were estimated in July and January for weekdays, using two periods of time, 12:00-12:59 pm (noon) and 4:00-4:59 pm (afternoon). Diesel, electricity, Ethanol (E-85), and gasoline were selected as fuel types. Passenger cars, passenger trucks, transit buses, single unit long-haul and short-haul trucks, and combination long-haul and short-haul trucks were used as vehicle types. An urban unrestricted road type was also employed. A critical part of the set-up is the characterization of pollutants and processes. To make the simulations more realistic, all the possible vehicle sources of emissions were selected: running exhaust, start exhaust, crankcase running exhaust, crankcase start exhaust, crankcase extended idle exhaust, extended idle exhaust, and auxiliary power exhaust. These options were chosen for NO, NO_2, PM2.5 exhaust, and PM10 exhaust. Additionally, PM2.5 and PM10 brake-wear and tire-wear were included. Figure 16 shows the RunSpec menu.

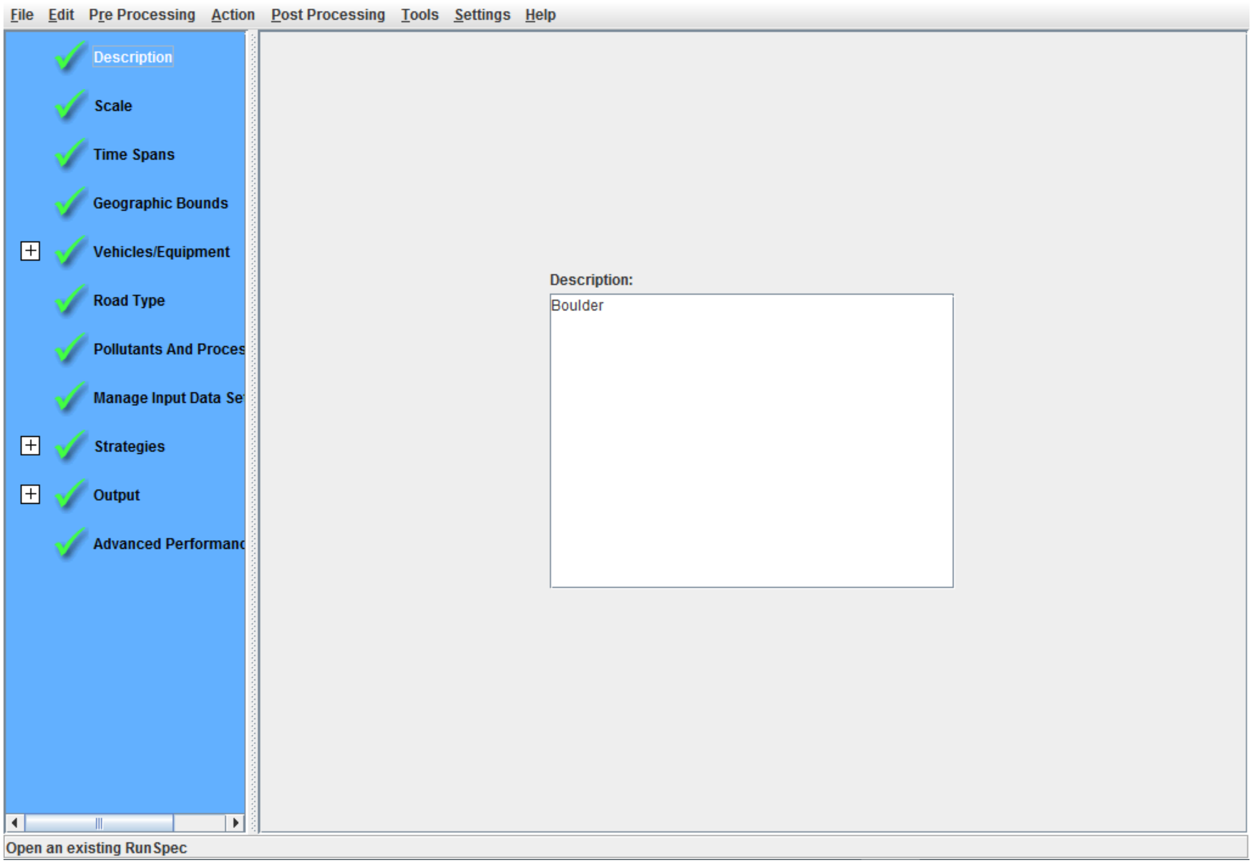

Figure 16. MOVES RunSpec

The second step is to set the project data manager, in which all the traffic and vehicle inputs must be introduced. Links must have data about street length, number of vehicles, and speed; vehicles within a link must have a similar driving behavior. A link with driving schedule was used to represent driving patterns at Canyon Boulevard. The Appendix B contains the employed driving schedule. To estimate the emissions of idling buses in BDS, a four-minute period of 0 mile/h per bus at the station was used to simulate hoteling of buses between arrival and departure. The vehicle type fraction must be inserted in source type and vehicle age fraction must be entered in age distribution. The information on the number of vehicles at Canyon was obtained from the Online Transportation Information System (OTIS). The Regional Transportation District-Denver (RTD) provided details of the number of buses per hour and the usual idling period of their buses at the station; their rule is not to idle a bus for more than three minutes unless it is actively loading. The Appendix B contains the fraction and number of vehicles per hour, and the RTD Summer and Winter buses per hour.

The Colorado Department of Motor Vehicles (DMV) generously provided a spreadsheet with the Boulder age distribution and fuel type of vehicles. The temperature and relative humidity from the Boulder Reservoir measurement station were used in the meteorology conditions. The fuel MOVES inventory was used to characterize fuel supply, in which gasoline, diesel, E-85, and electricity were considered. The Appendix B contains the vehicle age distribution, number of vehicles per fuel type in Boulder, temperature, and relative humidity. After this process, the software was ready to estimate the mass emission rate of each pollutant. Figure 17 shows the project data manager menu.

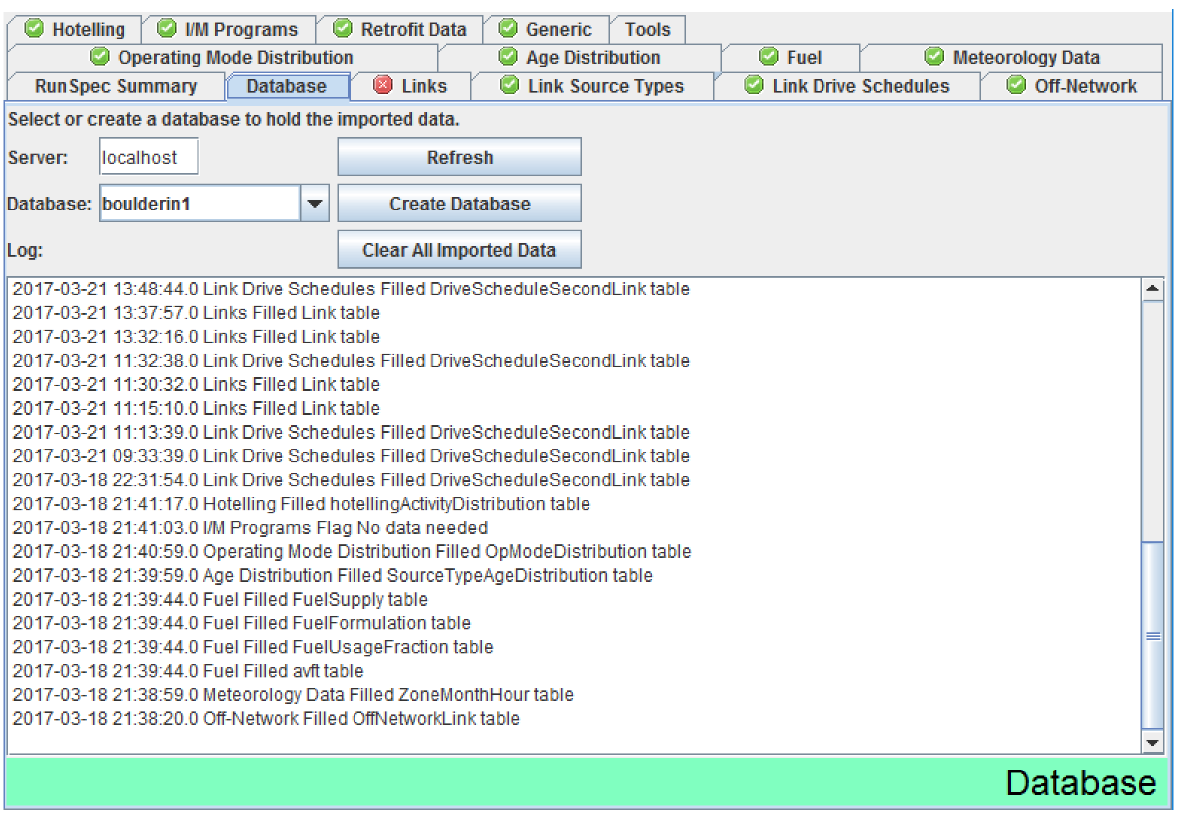

Figure 17. MOVES Project Data Manager

The MOVES outputs were used as source inputs in R-Line. R-Line is a steady-state Gaussian formulation model developed by EPA to simulate near-surface line source emissions, such as mobile sources along roadways (CMAS 2017). Figure 18 shows the domain size used for the simulations.

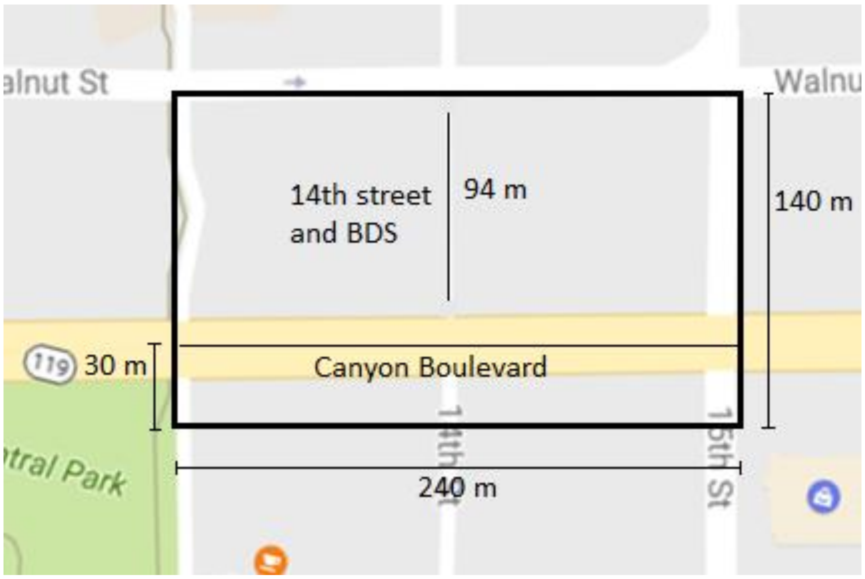

Figure 18. Canyon Boulevard and BDS computational domain

Detailed information about the R-Line model formulation can be found in (Snyder et al. 2013). The program requires four input files: line source, source, receptor, and surface meteorology. The line source file requires to specify a convergence error limit. The EPA recommended limit of 0.001 was used in all the simulations (CMAS 2017). Since most of the buildings in the surrounding area have four floors, around 12 m height, a medium height urban surface form was used (Grimmond and Oke 1999). For this form, the displacement height (d) and surface roughness length (z_0) oscillate between 3.5-8.0 m and 0.7-1.5 m, respectively. A factor of displacement height to roughness length (f) of 5 was calculated from the following equation (CMAS 2017).

$$d = f\, z_0 \tag{3}$$

A concentration output based on the combination of the direct plume and low wind speed meander was selected to improve the dispersion behavior. The analytical solution was used instead of the numerical solution. It has the advantage that it is considerably faster, but the accuracy is slightly reduced. The R-Line user guide shows simulation results using both approaches. The outcomes were quite similar for most of the cases (CMAS 2017). Therefore, it was decided to use the analytical solution.

In the source file, the length of the streets must be set. The Canyon Boulevard section from 13^{th} to 15^{th} street was used in the discretized simulation model. It was represented as a straight single lane having the combined traffic emissions. BDS was also simulated as a single lane with the length of the distance from Canyon to Walnut. A initial vertical dispersion (σ_{z0}) of 1.42 m was calculated based on EPA recommended equation (CMAS 2017).

$$\sigma_{z0} = average\ vehicle\ height\ x\, \frac{1.7}{2.15} \tag{4}$$

R-Line automatically calculates the initial horizontal dispersion based on the lane width of 3.5 m. For simplicity, a simulation with no road barriers was employed. Therefore, surrounding building do not block the emissions dispersion. R-Line road barriers are still in beta and our simulation goal was to see differences with buses and without buses. For these reasons, it was decided to run the simulations without the barriers option.

The receptor file contains the points were R-Line calculates the concentration of pollutants. The computational domain has a length of 240 m from west to east, and a length of 140 m from south to north. Points with an interval of 10 m were used in both directions, producing a total of 375 spatial locations. The simulations work differently than standard finite element or fluid dynamics simulations, in the sense that boundary conditions are not required and the mesh resolution does not affect the results on the chosen points. However, the resolution affects the contour areas without receptor points. All the measurements were calculated at an altitude of 2 m.

The surface meteorology file must be generated with AERMET. R-Line takes from the surface file the surface friction velocity, convection velocity scale, heights of boundary layers produced convectively and mechanically, Monin-Obhukov length, surface roughness length, wind speed and direction at a reference height (CMAS 2017). All of this is required to generate the dispersion model.

Before using AERMET, the programs AERSURFACE and AERMINUTE must be used to generate surface characteristics and wind data, respectively. AERSURFACE estimates surface characteristics from the Geological Survey National Land Cover Data 1992 archive (AERMOD 2017). The National Land Characteristics data were obtained from the Multi-Resolution Land Characteristics Consortium (MRLC). The Geotiff generated file is then used in AERSURFACE to produce three surface characteristics by season: surface roughness length (z_0), albedo, and Bowen ratio. The surface roughness length is the height above a surface where the mean horizontal speed is zero based on a logarithmic wind profile. Albedo is the fraction of solar radiation that is reflected back to space. Bowen ratio, which measures surface moisture, is defined as the ratio of sensible heat flux to latent heat flux. It must be noted that surface characteristics are based on a meteorological station (AERMOD 2017). The Denver Airport Station was used in our study. The output data report the characteristics for the four seasons of the year. AERMINUTE uses Automated Surface Observing System (ASOS) 1-minute data to calculate the hourly averaged wind speed and direction. The data were obtained from the National Climatic Data Center (NCDC). The output data consist of the hourly wind speed and direction. The International Civil

Aviation Organization airport code (ICAO) is required to find the ASOS 1-minute data. In the case of the Denver Airport it is KDEN.

AERMET also requires hourly surface and upper air sounding data. To obtain the hourly surface data, the USAF (US Air Force catalog station number) and WBAN (Weather Bureau Army Navy ID number) are required. Denver Airport USAF and WBAN are 725650 and 03017, respectively. The hourly surface data were obtained from NCDC. Surface data consist of physical parameters such as wind speed and direction, cloud cover and layers, temperature, dew point, ceiling height, precipitation, and visibility (US EPA 2017e). The upper air sounding data were obtained from the NOAA/ESRL Radiosonde Database (Earth System Research Laboratory of the National Oceanic Atmospheric Administration). Upper air data from the Denver Airport were not available. In Colorado, this information was only available at the Grand Junction Airport, so it was used for the study. Grand Junction WBAN ID is 23066. Hourly surface and upper air data do not require pre-processing as the land cover and 1-minute wind data. Upper air data usually consist of wind speed and direction, temperature, humidity, height, and atmospheric pressure (NCDC 2017).

AERMET generates the surface meteorological data required by R-Line using information from the land cover, upper air, hourly surface, and 1-minute data. Eight different cases were run using MOVES and R-Line: Summer noon with buses and without buses, Summer afternoon with and without buses, Winter noon with and without buses, and Winter afternoon with and without buses. Figure 19 shows a conceptual map of the modeling steps required to run R-Line.

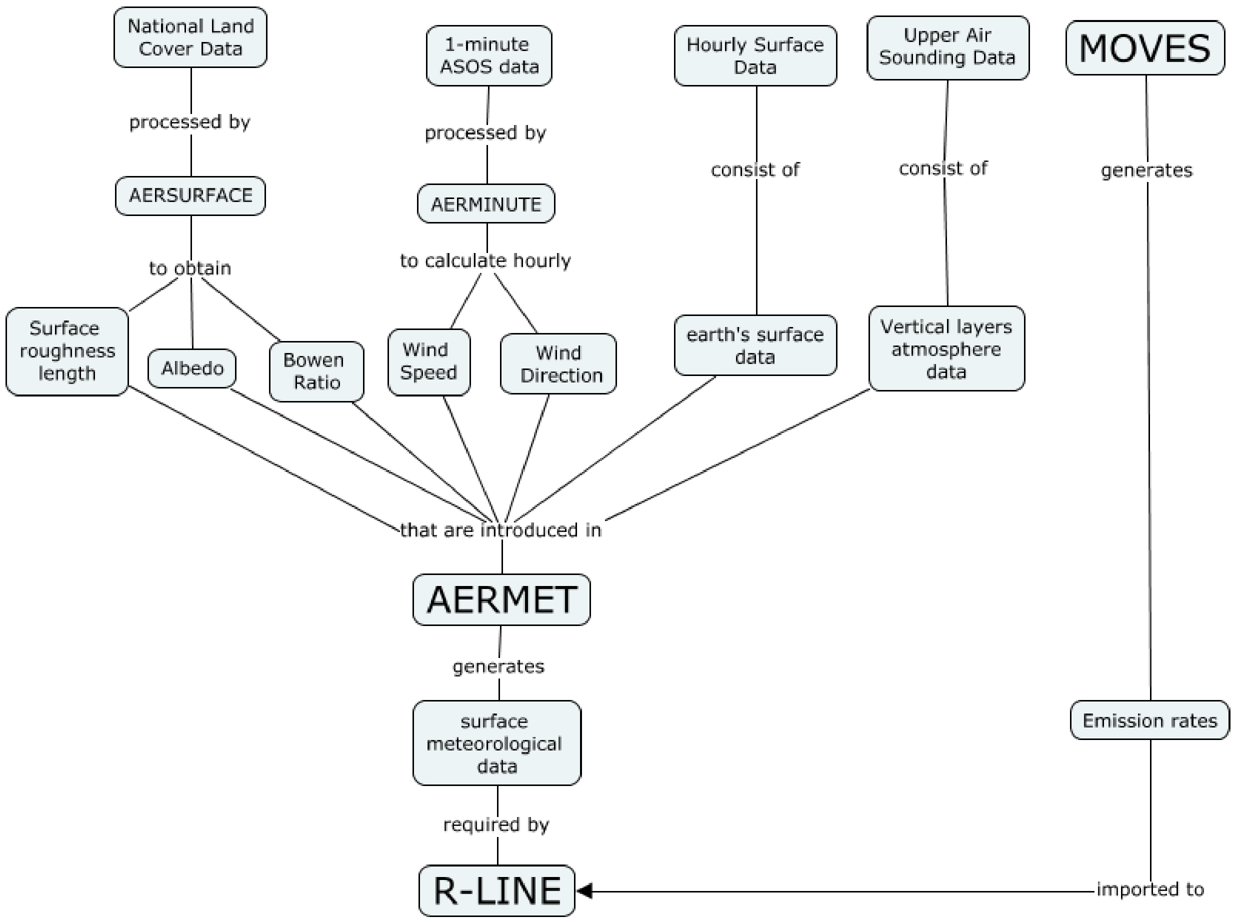

Figure 19. Conceptual map of modeling steps

Chapter III: Results and Discussion

Stationary Measurements

Stationary measurements provided limited evidence to link RTD buses to pollution levels in Boulder Downtown. Only Winter NO_x and particle number measurements were weakly associated with the traffic volume trends. It was difficult to directly estimate the pollutant levels due to the number of RTD buses (i.e., observing that the concentration increased when the bus count/traffic density increased), since the periods of time with many buses also had high traffic volume of other vehicles. Even the total traffic volume did not generally resemble the measurements collected. The observations appeared to follow seasonal and regional pollution trends and strongly driven by meteorology. It must be noted that the concentrations of all the pollutants were below the National Ambient Air Quality Standards (NAAQS). A detailed explanation of each pollutant is presented below. Appendices C, D, E, F show the daily measurement results for Black Carbon, Ozone, Nitrogen Oxides, and Particulate Matter, respectively.

Black Carbon (BC)

BC was measured with an aethalometer. The results of the measurements showed that only 2 out of the 11 days of tests had similar behavior to the bus count and vehicle traffic density. On several occasions, BC levels did not increase when there were more buses. A general description of each day of measurement is presented below.

On July 25th there was a slight continuous increase in the BC concentration, from 1000 to 4000 ng/m^3, from 12 pm until 3:50 pm. The highest concentrations and peak numbers were observed between 3-3:50 pm. Note that there was a small increase in the number of buses between 12-3 pm, and at 3 pm it started to increase more. The period with the highest number of buses and other vehicles occurred from 4 to 6 pm, but the concentration readings did not increase during this time. The last 2 hours of measurements did not show any association between BC levels and traffic volume.

The concentrations on July 26th were relatively constant during the first and the last hour of measurements. A decline in the BC levels was seen during the interval between 1-4:30 pm. The highest peak, around 8500 ng/m^3, occurred close to 1 pm, but the time between 12-1 pm did not have a high volume of traffic. Therefore, there was no clear connection with the bus count.

The July 27th measurements showed the smallest average from 12 to 1 pm, around 1000 ng/m^3. The rest of the day had a highly constant tendency with two high peaks, one between 2-3 pm (7442 ng/m^3) and the other one (6684 ng/m^3) almost at the end of the day, close to 6 pm. No direct connection was found with the traffic conditions.

The July 28th readings had a constant average of around 1000 ng/m^3 throughout the entire period of measurements and no peaks were found. Analogous to the previous days of the Summer campaign, the outcome of this day did not present a relationship with the vehicle traffic and bus count.

The January 16th test presented the smallest concentration of BC from 8 to 10 am, about 1000 ng/m^3, while the morning period with the highest number of buses occurred from 7 to 10 am. At around 11 am, the highest morning peak (5229 ng/m^3) was observed. At this time, the average concentration (approximately 1500 ng/m^3) was higher than at any other time of the morning; nonetheless, in this period there was a smaller bus count than at other times of the day. After this, a small decrease in BC was seen and it remained constant until close to 5 pm, when the highest peak of the day (5722 ng/m^3) and average concentrations (more than 2000 ng/m^3) were presented. The rise of the number of buses after 3 pm did not increase the BC levels. No connection was found between the bus count and BC concentration.

The January 17th result showed the smallest readings from the beginning of the measurements at 7:40 am until 11:00 am, on average below 2000 ng/m^3. A slight constant increase took place between 8-11 am, from 204 ng/m^3 to about 3000 ng/m^3. The readings between 11 am-3 pm were highly constant, ranging from 2000 to 4000 ng/m^3. At 3 pm, a very high peak of 18123 ng/m^3 was observed, and after this instant the concentration was higher than the rest of the day, having a range between 2000-8000 ng/m^3. The only period that appeared to have some connection with the bus count was the interval from 3 to 6 pm. The morning period with the highest number of buses had the smallest concentration of BC.

The January 18th outcome had the highest readings of the day from 7:50 to 11:00 am, on average around 3500 ng/m^3. The interval between 11 am-3:30 pm had the smallest concentration, about 2500 ng/m^3. After 3:30 pm, an increment to 3200 ng/m^3 was seen, but the concentration was not as high compared to the morning. The highest morning peaks and concentration were found from 9:30 to 11 am. However, the vehicle traffic and number of buses started to decrease at 9 am. After 5 pm, the BC concentration went down but the bus count was still high at this time.

The January 19th measurements showed the highest peak (22567 ng/m^3) and BC concentration average (approximately 10000 ng/m^3) was from 7:25 to 9 am. This was the first morning occasion that presented a connection between BC and the bus count. After 9 am, the readings were quite constant until 4 pm, on average about 3000 ng/m^3. A high concentration, around 5000 ng/m^3, and peaks were found from 4 to 5 pm. The biggest peak in this interval was close to 11000 ng/m^3. The period from 5 to 6 pm did not show high peaks but the concentration was still higher than most of the day, around 4500 ng/m^3. The entire day showed a similar tendency with the number of buses.

The January 20th test had a similar response to the previous day. The highest average concentration, about 7000 ng/m^3, occurred from 8 to 9 am. A drop took place between 9-10 am, from around 4000 to 2000 ng/m^3. After this, BC levels remained rather constant until 3 pm. Starting at 3 pm, a constant increase was seen. After 5 pm, this increment was even higher, since the concentration increased to an average of 6000 ng/m^3, but the BC levels were not as high compared to the morning biggest level. This day also produced an association between the BC concentration and the number of buses.

The January 21st (Saturday) measurement day brought the opportunity of analyzing BC levels with a virtually constant number of buses throughout the day. Only the period from 7 to 8 am had a smaller number of buses. From 7:30 to 9 am, the highest average of the morning readings was presented, approximately 2000 ng/m^3. The interval between 9 and 10 am showed a sharp decrease to about 100 ng/m^3. Between 10-11 am, the biggest peak of the day occurred (10200 ng/m^3), but the average was not as high compared to the early morning. From 4 to 6 pm, a constant increment took place, from around 1000 to 2500 ng/m^3. The variations of BC during this day did not have a link with the highly constant number of buses per hour.

The January 22nd outcome showed a constant concentration from 8 to 9 am, 32 ng/m^3. This effect occurred since the change in the light intensity attenuation was very small; indicating that a small BC concentration was presented at the moment of taking measurements. At 9 am, an increment to about 1500 ng/m^3 was observed, but it almost immediately went down to 200 ng/m^3. The moment in the morning with the highest BC levels happened between 11 am-12 pm, having an approximate average of 1000 ng/m^3. At 12 pm, the readings dropped to below 500 ng/m^3, and remained highly constant until 4:30 pm. At this time, the concentration increased to an average of 2500 ng/m^3, which represented the highest values of the day. The bus count was quite similar throughout the day, but the BC concentration did not show a constant behavior, and no connection was found with the number of buses.

Comparison between Summer and Winter, and Weekdays and Weekend

Black Carbon during Summer was collected for only four days of the week, the same days were used in this comparison. It must be noted that the period of the day in which measurements were taken in Summer and Winter differs. Winter readings had different behavior depending on the day; on some occasions morning BC levels were higher than the afternoon, and on other days the opposite situation occurred. Figure 20 shows a plot of the average concentration in Summer and Winter. The Summer results generally showed a lower concentration. Monday was the only Winter day with a lower BC average. Winter presented more variations between days, while the interval of values in Summer was quite constant. Only one test in Summer presented a mean far from the rest of the measurements; it was the one carried out in the condo unit on the third floor. Table 3 and Table 4 show the statistical data for every day of measurement in Summer and Winter, respectively.

Weekend data were only collected in Winter. The Saturday outcome was lower than any weekday, which was expected due to the lower traffic volume. The Sunday result was around half of the one obtained on Saturday. Though the number of buses was lower on Sunday than Saturday, it was not as large as the difference in the BC concentration.

A significant difference was found in the number of buses between weekdays and weekends. However, the Saturday average was close to the Monday average. Apparently, the BC levels were more connected to the traffic volume than the bus count.

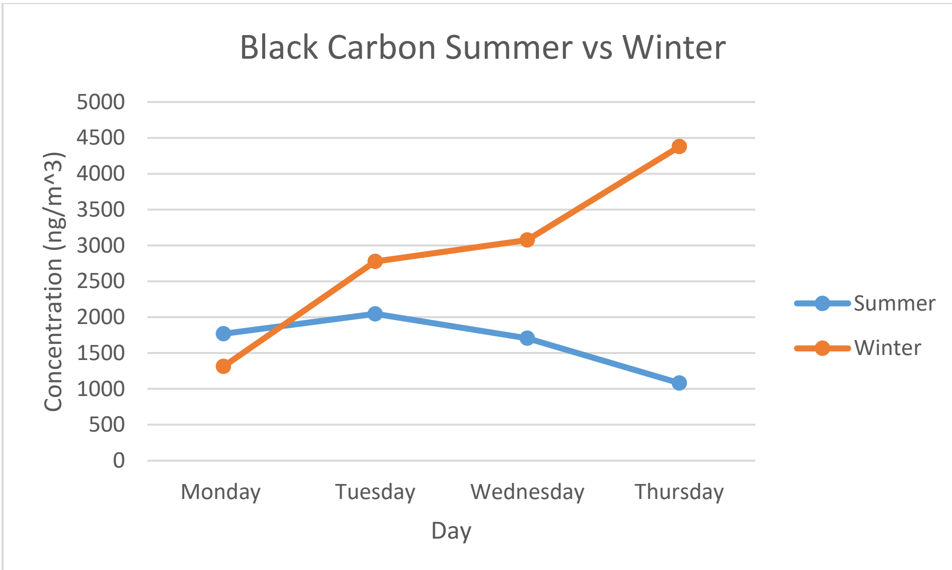

Figure 20. Summer and Winter Black Carbon daily average

Table 3. Black Carbon (ng/m^3) Summer Statistics

Day	Monday	Tuesday	Wednesday	Thursday
Monitor Period	12-6 pm (7/25/16)	12-6 pm (7/26/16)	12-6 pm (7/27/16)	12-6:05 pm (7/28/16)
Location	Canyon Apt. 1	Canyon Apt. 1	Canyon Apt. 1	Canyon Apt. 2
Mean	1771	2047	1705	1082
Median	1552	1709	1281	1038
Standard Deviation	729	1913	1641	276
Range	4307	33160	17644	2193
Minimum	790	583	306	583
Maximum	5097	34193	17950	2776
Number of data points	2161	2169	2162	2205

Table 4. Black Carbon (ng/m^3) Winter Statistics

Day	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
Monitor Period	8am-6:15pm (1/16/17)	7:40am-6:10pm (1/17/17)	7:50am-6:05pm (1/18/17)	7:25am-6:15pm (1/19/17)	7:30am-6:10pm (1/20/17)	7:30am-6:20pm (1/21/17)	8am-6:20pm (1/22/17)
Location	Canyon Apt. 1	Canyon Apt. 1	Canyon Apt. 1	Canyon Apt. 1	Canyon Apt. 1	Canyon Apt. 1	Canyon Apt. 1
Mean	1312	2777	3076	4377	2829	1260	637
Median	1107	2590	2780	3293	2216	1074	344
Standard Deviation	886	2393	1266	3549	2208	1566	797
Range	9783	56354	16041	25372	14631	46450	4995
Minimum	412	205	1394	933	375	77	32
Maximum	10195	56559	17435	26305	15007	46450	5027
Number of data points	3703	3781	3719	3907	3847	3922	3722

Ozone (O_3)

The Ozone measurements taken with a POM did not show a link with the bus count. Typically, in Summer, an increase of O_3 was observed with a constant number of buses between 12-3 pm, and a constant value or reduction of O_3 was presented with the rise of the bus count, after 3 pm. Winter measurements had an increment of O_3 after the morning rush hour, but the readings were low. On Winter afternoons, the concentration of O_3 did not increase when the traffic volume went up in the afternoons. Ozone seemed to have an opposite behavior to the traffic volume. A detailed description of each measurement day is presented below.

The July 25th result showed an increase of O_3 between 12-3 pm, from around 20 to 70 ppb. The concentration of O_3 remained virtually constant until almost 6 pm. During the last five minutes of the day O_3 dropped to around half of the previous level. The O_3 concentration did not reflect a connection with the number of buses, since the bus count was virtually constant between 12-3 pm and the O_3 levels increased. After 3 pm, the bus count grew but the concentration of O_3 remained constant.

The July 26th outcome had an increase of O_3 between 12-1 pm, from 20 to 45 ppb. An almost constant O_3 magnitude was seen from 1 to 3 pm. After this time, a continuous decrease to a value of around 10 ppb took place until the end of the day at 6 pm. The period between 1-3 pm had an almost constant number of buses and O_3 concentration, after 3 pm, the bus count increased while the O_3 levels decreased.

The July 27th O_3 test presented a continuous increment of O_3 between 12-3 pm, from around 40 to 60 ppb. After 3 pm, O_3 levels remained rather constant, on average, until 5:30 pm. The last 30 minutes of the day showed a drop of O_3; the concentration was analogous to the beginning of the day. The bus count remained constant while O_3 increased from 12 to 3 pm, and when the number of buses increased during the second half of the day the concentration did not increase.

The July 28th measurements had an almost constant O_3 level throughout the day. A slight constant increase, from around 55 to 65 ppb, took place between 3-6 pm. This was the first day that appeared to have a similar trend of number of buses and O_3 levels. The period between 12-3 pm had a constant of bus count and O_3 concentration, and an increment of both the number of buses and O_3 concentration was presented in the second half of the day.

Wintertime ozone was very low during our study. The January 16th outcome had the smallest readings between 8-9 am, slightly above 2 ppb, when there was heavy bus and vehicle traffic. The period between 9-11 am had the highest O_3 levels, ranging between 4-8 ppb. From 11 am-6 pm, readings were rather constant, showing an average of around 4 ppb. The O_3 increment occurred an hour after the period with the highest traffic in the morning; however, the afternoon traffic rise was not reflected in the O_3 concentration.

The January 17th test showed a systematic increase of O_3 between 8-11 am, from 2 to 14 ppb. After 11 am, the O_3 levels went down until 2 pm, from 14 ppb to 2 ppb. An increment of the concentration of O_3 was observed between 2-3 pm to an average of 7 ppb. The rest of the day had an average of around 4 ppb. The O_3 concentration grew when there was a low traffic volume. One decrease happened at noon with a low traffic density, but another O_3 drop occurred when the traffic volume was high in the last part of our measurement period.

The January 18th result had O_3 levels around 3 ppb, from 8 to 10 am. After this time, an increment of O_3 took place; the rise lasted until 1 pm having a maximum value of approximately 13 ppb. At 1 pm, a concentration drop was presented; the concentration between 1-6 pm was similar to the interval between 8-10 am. The period with the highest O_3 concentration was the one with the lowest traffic volume.

The January 19th test experienced some problems with logging data and the battery ran out in the last 15 minutes of the day. Measurements were taken from 1:30 to 5:45 pm. The average O_3 concentration increased from 2 to 3 ppb, between 1:30-2:30 pm. The O_3 levels remained constant until almost 5 pm. After this, O_3 remained between 4 and 6 ppb, which was the period with the highest concentrations. The O_3 trend had similar tendency to the bus count and traffic volume.

The January 20th test also had problems in logging data. Measurements were taken from 7:30 am to 12:55 pm. The readings until close to 11 am were highly constant, on average, having a value of around 4 ppb. An increase was seen after this instant, giving as a result an average of about 6 ppb. The periods with the highest traffic volume presented the smallest O_3 concentration, while periods with lower traffic density had a higher O_3 concentration.

The January 21st test did not record all of the data. Data were logged from 7:30 to 11:45 am. The O_3 concentration had the highest magnitude of 10 ppb at 7:30 am, going down to below 2 ppb at 9 am. Then, the O_3 levels started to grow until 11:45 am to a value of around 6 ppb. The number of buses increased after 8 am and remained constant for the rest of the day. However, the highest O_3 values occurred before the bus count increment. When the bus density was constant a slight increase of O_3 was observed.

The January 22nd outcome showed a virtually constant average of about 4 ppb in the morning, with two peaks; one of 11 ppb a few minutes after 8 am, and the other one of 14 ppb at around 10:30 am. Between 12-1 pm, the average rose to 6 ppb and it dropped to 4 ppb at 1 pm; this last value lasted until 2 pm. Some minutes after 2 pm, the O_3 levels increased to around 12 ppb; this concentration went systematically down to 4 ppb during the 2-4 pm interval. After 4 pm, a high continuous increment happened until 6 pm, having a maximum value close to 30 ppb. The early morning had a lower number of buses compared to the rest of the day, but the difference was small. The concentration of O_3 throughout the day was highly constant. Only after 4 pm the O_3 level rose considerably but the number of buses remained constant.

Comparison between Summer and Winter, and Weekdays and Weekend

Since the Ozone data from Summer were only comprised of four days of the week, the same days were used in this comparison. It must be noted that only the measurements collected on Thursday, in Summer and Winter, were taken at similar time. Summer measurements typically peaked between 3-5 pm. Winter readings showed on average higher values during the mornings than afternoons. The highest values usually occurred between 9 am-12 pm. Figure 21 shows a plot of the O_3 average concentration in Summer and Winter, respectively. The differences in concentration were large. Though Summer measurements were taken only in the afternoon, the readings presented at least 6 times and up to 18 times higher concentrations than Winter measurements. Summer changes between days were minimal; on the other hand, Winter had more variations each day. The readings taken in the third-floor condo had similar values to the second-floor condo measurements. Table 5 and Table 6 present the statistical data for every day of measurement in Summer and Winter, in that order. Weekend data were only taken in Winter. The Saturday result was similar to weekdays, which was not expected due to the different traffic volume. The Sunday result was higher than any other Winter measurement day. The maximum peak value also occurred on Sunday. Paradoxically, the lower traffic volume on Sunday caused a higher O_3 concentration, since a lower degradation of roadside O_3 took place (Geng et al. 2008).

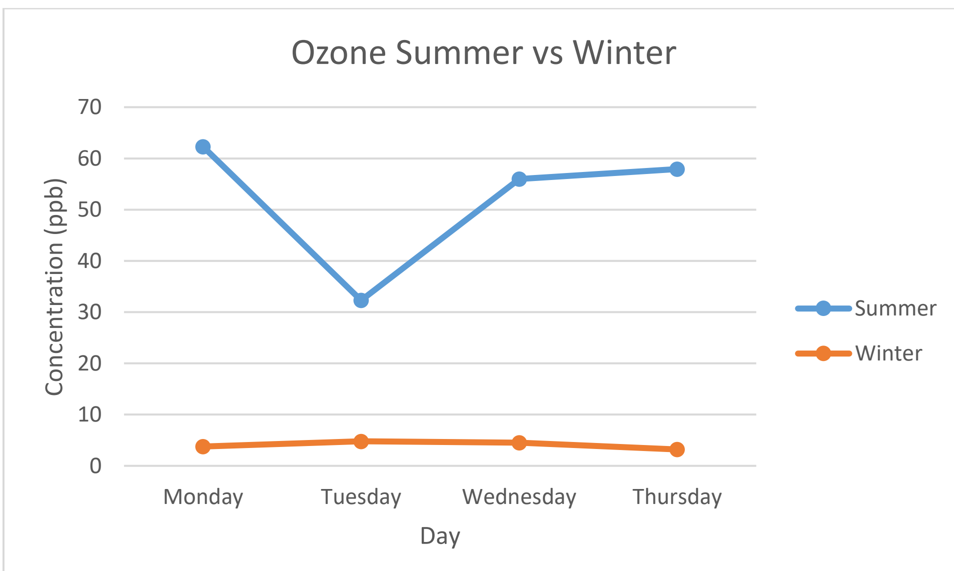

Figure 21. Summer and Winter Ozone daily average

Table 5. Ozone (ppb) Summer Statistics

Day	Monday	Tuesday	Wednesday	Thursday
Monitor Period	12-6 pm (7/25/16)	12-6 pm (7/26/16)	12-6 pm (7/27/16)	12-6 pm (7/28/16)
Location	Canyon Apt. 1	Canyon Apt. 1	Canyon Apt. 1	Canyon Apt. 2
Mean	62.3	32.3	56.0	57.9
Median	63.4	33.6	56.5	57.3
Standard Deviation	13.5	13.1	10.0	5.1
Range	77.5	55.4	63.1	36.0
Minimum	11.9	0.4	18.1	36.8
Maximum	89.4	55.8	81.2	72.8
Number of data points	2155 out of 2158	2132 out of 2161	2156 out of 2156	2160 out of 2161

Table 6. Ozone (ppb) Winter Statistics

Day	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
Monitor Period	8am-6:15pm (1/16/17)	8am-6:05pm (1/17/17)	8am-6:05pm (1/18/17)	1:30-5:45pm (1/19/17)	7:30am-12:55pm (1/20/17)	7:30am-6:20pm (1/21/17)	8am-6:20pm (1/22/17)
Location	Canyon Apt. 1	Canyon Apt. 1	Canyon Apt. 1	Canyon Apt. 1	Canyon Apt. 1	Canyon Apt. 1	Canyon Apt. 1
Mean	3.8	4.8	4.5	3.2	4.6	4.3	6.1
Median	3.2	3.7	3.2	2.9	4.2	3.6	4.6
Standard Deviation	2.9	4.1	4.2	2.2	3.3	3.4	5.5
Range	17.7	23.4	21.3	14.5	20.0	17.8	29.1
Minimum	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Maximum	17.7	23.4	21.3	14.5	20.0	17.8	29.1
Number of data points	2673 out of 3700	2433 out of 3658	2173 out of 3655	1203 out of 1545	1266 out of 1952	980 out of 1531	2390 out of 3726

Outliers

Outliers were deleted from the data to eliminate erroneous values caused by the noise of the POM. Figure 22 shows an example of a box plot and outliers (black dots) for the January 19th measurements. In the Summer campaign, only 0.37% of the total data were outliers. All the values deleted were under the lower outer fence (LOF) and only one day had some negative readings. On the other hand, the Winter campaign presented a larger number of outliers, almost all of them under the LOF and just a few over the upper outer fence (UOF). A total percentage of 33.6% of the collected data was eliminated. Practically, all the outliers were negative values, showing that the POM had more problems measuring ozone at low concentrations, such what was observed during the Winter campaign. Box plots and outliers for each measurement day are shown in the Appendix G.

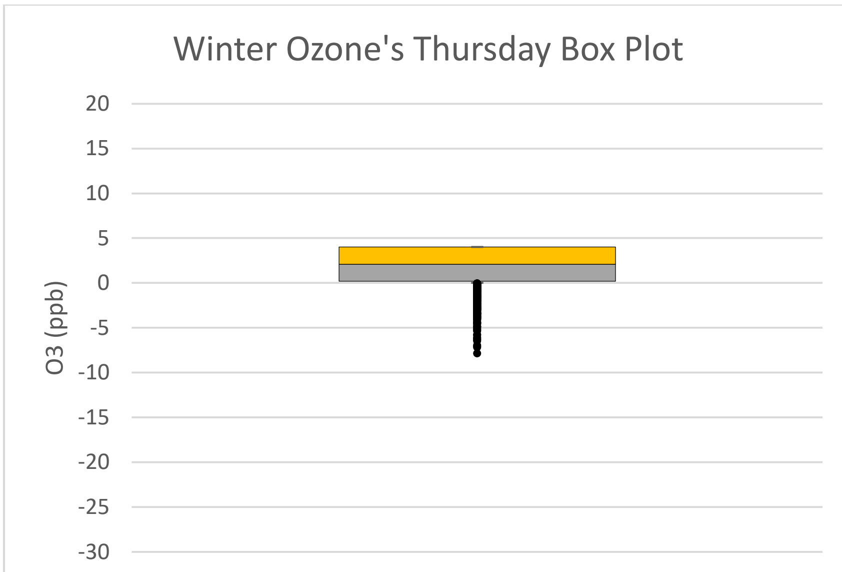

Figure 22. January 19th outliers (black dots) box plot

Comparison of Boulder and CAMP

The Ozone concentration at CAMP was higher than the concentration measured in Boulder. Only the Summer measurements taken on Thursday were slightly smaller than at CAMP. The test performed this day took place in the third-floor condo. The daily Summer average values are shown in Figure 23. The mean values in Boulder were around 11 ppb lower than at CAMP. The Summer averages were 52.1 ppb and 63.4 ppb in Boulder and at CAMP, respectively. Similar behavior was observed in both measurements' locations. The daily Winter average values are shown in Figure 24. Winter averages were 4.5 ppb and 19.7 ppb in Boulder and CAMP, in that order. Boulder showed almost no changes between days; nevertheless, CAMP had variations between days. The Winter average value at CAMP was about 4 times higher.

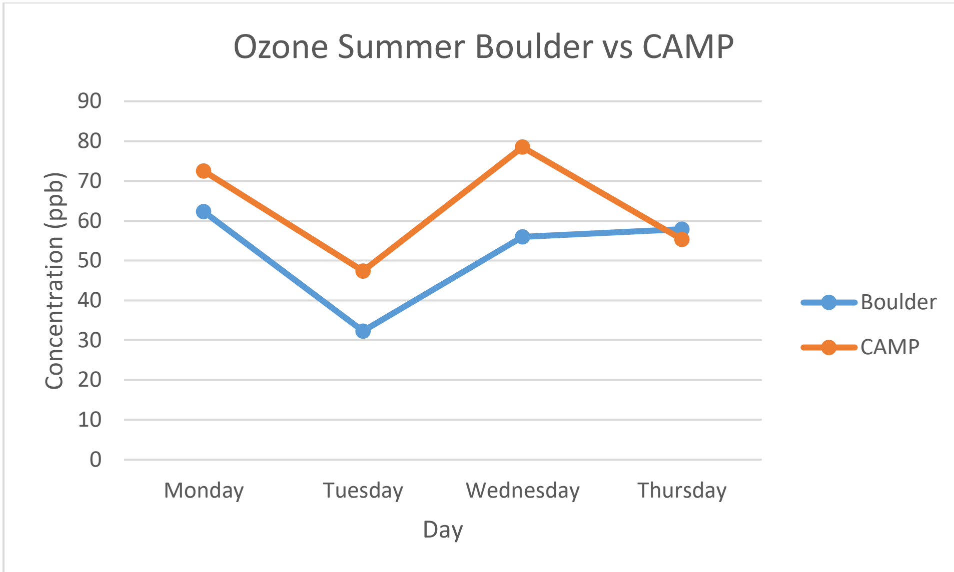

Figure 23. Boulder and CAMP Ozone daily Summer average

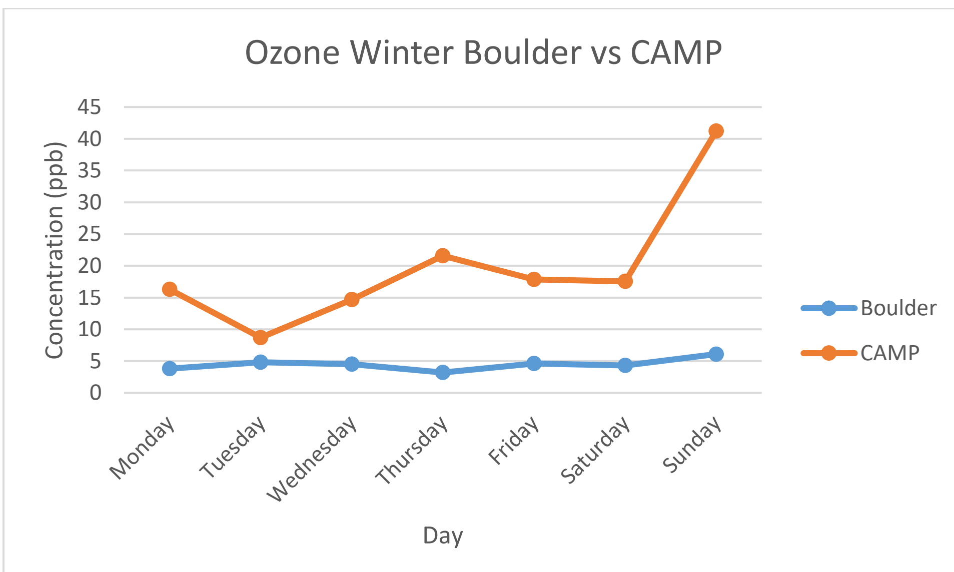

Figure 24. Boulder and CAMP Ozone daily Winter average

Nitrogen Oxides (NOx)

The Summer NOx concentrations showed a relationship with the bus and vehicle density, on some occasions, especially during the afternoons. However, some days presented an increase of the readings a few hours before the rise in the bus count. Mornings did not show an increment in the readings when the number of buses went up, where the concentration was quite constant. One day had high readings in the night for unknown reasons most likely from the decreased mixing height. Winter NOx had more connection with the bus count and traffic density, showing high levels in the early morning, having a drop after the rush hour. Late afternoons showed an increase of the readings with the rise of the number of buses. A detailed description of each measurement day is presented below. Unfortunately, measurements were not taken on Monday and Tuesday in Summer, since the NOx analyzer did not arrive on time.

The July 27th test showed an almost constant NO concentration between 5-10 ppb, from 12 to 6 pm. The NO_2 concentration had a linear increment from an average value of around 15 ppb at 12 pm to about 35 ppb in the last hour of this day. The maximum value of NO_2 was close to 50 ppb, it took place between 5-6 pm. NO_2 behaved similar to the bus count, having the largest increment between 4-6 pm.

The July 28th test was performed from 12 pm to 12 am. The interval between 1:30-6:00 pm had the highest peak, 18 ppb for NO and 27 ppb for NO_2. The average concentration in this interval was also the highest, around 8 ppb and 15 ppb for NO and NO_2, respectively. The highest values occurred at 3 pm, which is the moment when the bus density increased. However, the NOx concentration had a small decrease from 3 to 5:30 pm. This is the period when the traffic volume went up; nonetheless, it was not reflected in the NOx concentration. From 6 to 8 pm, a drop was observed. Then, a rise was seen between 8-11 pm having values slightly lower than the 1:30-6 pm interval.

The July 29th test took place between 12 am-12 am. NO and NO_2 had the same tendency throughout the day. The period from 12 to 6 am had the lowest concentrations; below 4 ppb for NO and 8 ppb for NO_2. At 6 am, NOx had a sudden rise, up to 10 ppb and 17 ppb for NO and NO_2, respectively. From 12 to 6 pm, several peaks occurred, most of them between 3-5 pm. The maximum peaks were around 28 ppb for NO and 46 ppb for NO_2. The period between 5-7:30 pm was similar to the morning. After 7:30 pm, the concentration dropped to values lower than the daytime but higher than the interval before 6 am. The bus count started to increase at 6 am but the sunrise occurred almost at the same time. The morning had an almost constant NOx concentration that did not change with the variation of the number of buses. The interval between 3-5 pm had a high traffic volume and number of buses that appeared to have a connection to the observed peaks.

The July 30th measurements took place between 12 am-12 am, as well. Once again, NO and NO_2 had similar behavior throughout the day. The period from 12 to 5:30 am was quite constant, having values below 5 ppb and 12 ppb for NO and NO_2, respectively. After this time, NOx had a small rise, with the highest morning readings from 8 to 10 am. The afternoon showed higher values than the morning. The highest afternoon values happened from 12 to 3 pm. At around 7 pm, the magnitude of NOx presented a considerable increase with peaks of 20 ppb and 40 ppb for NO and NO_2, in that order. The concentration average between 7-9 pm was the highest this day. The highest NO peak (45 ppb) happened at 10 pm. It must be noted that NO_2 did not increase considerably at that moment. The bus count from 8 am to 7 pm was virtually constant, but the NOx concentration was not constant during this interval. However, the period between 12-3 pm had a very high traffic volume; more vehicles were observed than any weekday. The reason for the NOx rise appears to be the high number of vehicles. The highest readings happened after 7 pm, most likely happened due to meteorology and a lowering of the mixing height.

The July 31st measurements were taken from 12 to 11 am. The readings between 12-8 am were lower than the last three hours. One peak was observed in this time interval a few minutes before 2 am, 8 and 15 ppb for NO and NO_2, respectively. A 7 am slight increment of NOx was followed by the largest peak of the day at 8 am, around 18 ppb for NO and 24 ppb for NO_2. Another large peak occurred at 9 am, but the concentration went down quickly after it. Then, a new constant increase happened until 11 am. The bus count started to increase at 7 am, exactly when the NOx increment began. The period with the highest NOx level occurred between 8 am and a few minutes after 9 am, and the bus count was slowly increasing between 8-11 am, showing some similarities between bus count and NOx concentration.

The January 16th test had a highly constant average of NO between 8 am-2 pm, about 15 ppb. After this time, NO slowly decreased until 5 pm to an approximate value of 5 ppb. NO_2 showed a quite constant value of around 25 ppb until 5 pm. At 5 pm, NOx presented a rise, having the highest average and peak of the day. The NO peak of 40 ppb was higher than any NO_2 value of the day. The average from 5 to 6 pm was about 20 and 30 ppb for NO and NO_2, respectively. An elevated number of buses was observed from 7-10 am. After this moment, the count decreased but NOx did not drop after this time, only NO started to decrease at 2 pm. The afternoon increment of the bus count occurred after 3 pm, which lasted until the end of the measurements. A rise of NOx began at 5 pm. The readings on this day appeared to have a delay with respect to the changes in the number of buses.

The January 17th outcome showed a slightly higher NO average than NO_2. Large variations were found in NO. The measurements began with high values for both pollutants, almost 60 ppb for NO and slightly above 40 ppb for NO_2. Close to 9 am NOx was also high, but smaller than at the beginning. During 9-10 am, the values dropped to around 15 ppb for both pollutants. Then, the interval between 10-11 am showed an increase of NO to around 40 ppb and NO_2 to 25 ppb. NO had a slight constant decrease to a value of about 20 ppb at 3 pm; however, NO_2 remained constant in this interval. After 3 pm, NO showed an increment and several peaks; the biggest one of 70 ppb, between 3-4 pm. NO_2 rose to an average of 30 ppb, but did not have peaks. The morning NOx behavior did not seem to be related to the traffic density. Only the peak close to 9 am could have been related to it. The drop after 9 am might indicate a reduction in the number of vehicles, but the increment of NOx at 10 am did not support this assumption. The afternoon seemed to have a pattern similar to the bus count, since the increase and peaks of NO occurred when the number of buses increased.

The January 18th test began at 8:15 am, with NOx concentrations around 20 and 30 ppb for NO and NO_2, respectively. The 9-10 am interval showed the highest values of the day. NO reached a value above 80 ppb, and NO_2 around 50 ppb. The period between 10 am-12 pm had a decrease of NOx to values of about 10 and 18 ppb for NO and NO_2, in that order. The NOx levels remained relatively constant until 3 pm. After this time, NOx increased, showing higher average for NO_2, but NO had bigger peaks. NO seemed to be on average below 30 ppb and NO_2 above 30 ppb. The morning increase of the NOx concentration occurred when there was still a high amount of buses, just after the rush hour. After this time, the readings went down. At 3 pm, both the readings of NOx and the bus count increased. This day seemed to have a strong association between the number of vehicles, buses, and the NOx concentration.

The January 19th outcome had the highest concentration at the beginning of the day from 7:45 to 9 am. Initially, NO reached a value about 130 ppb and NO_2 presented values up to 60 ppb. The NOx levels had a decreasing tendency until 9 am. During 9 am-3 pm, average values of 15 and 20 ppb were seen for NO and NO_2, respectively. After 3 pm, the NOx concentration increased but the values were lower than the early morning. NO grew up to 70 ppb and NO_2 increased to 40 ppb. NOx maximum values occurred during the period with more buses and vehicles. After 9 am, the bus count started to decrease, having a constant number of buses until 3 pm. NOx presented low values between 9-10 am, even though the traffic volume was still high again most likely showing the strong impact that meteorology can play on pollutant concentrations. The last portion of the day had an increment of NOx similar to the increase in the number of buses and traffic density.

The January 20th test showed the highest NOx values during 7:50-9 am. NO presented a concentration up to 100 ppb and NO_2 up to 40 ppb. These readings had a drop to 15 ppb for NO and 25 ppb for NO_2 at 9 am. Another rise of NOx occurred from 9 am to 10 am; NO showed a maximum of 50 ppb and NO_2 40 ppb. After 10 am, NO had average readings above 5 and 10 ppb for NO and NO_2, which lasted until 3 pm. The period between 3-6 pm had a rise of NOx, where the maximum readings in this portion of the day were seen during 5-6 pm; NO reached a value of 55 ppb and NO_2 40 ppb. The early morning had a decreasing concentration until 10 am resembling the bus count pattern. The 10 am-3 pm interval had the lowest NOx concentration this day; having a link with the low number of buses and traffic. The last three hours of measurements showed an increment parallel to the increase of buses and traffic.

The January 21st measurements had the highest readings during 8-9 am. NO reached a maximum of 80 ppb, while NO_2 had a maximum slightly above 40 ppb. The period between 9 am-2 pm showed a highly constant tendency, around 5 ppb for NO and 10 ppb for NO_2. A continuous increment was shown after 2 pm until 6 pm, when the average during the last hour was about 15 and 25 ppb for NO and NO_2, respectively. The bus count started increasing at 7 am, reaching a value that remains virtually constant after 8 am for the rest of the day. Therefore, it would be expected to have an NOx concentration constant throughout the day if the meteorology was consistent. However, NO_x averaged 40 ppb from 8 to 9 am, and then it decreased substantially between 9 am-2 pm. After 2 pm, a rise of NOx was observed, similar to weekdays; however, the traffic patterns did not change.

The January 22nd measurements started at 8:20 am. The average was low until 5 pm for NO, about 2 ppb. The last hour showed an increment of NO to an average of 20 ppb. NO_2 averaged around 6 ppb until 3 pm. Between 3 and 4 pm NO_2 had a drop to 3 ppb. Then, a rise occurred from 4 to 5 pm to around 30 ppb, which was kept until 6 pm. The bus count throughout the day was rather constant, where only the period from 8 to 11 am had a smaller number of buses, but the difference was minimal. NOx was constant until the last portion of the day, reflecting a similar number of buses.

Comparison between Summer and Winter, and Weekdays and Weekend

The Thermo 42i NOx analyzer employed during Summer did not arrive on time for the start of the measurement campaign. For this reason, measurements were not taken on Monday and Tuesday. The interval of Wednesday-Sunday was used for the Summer-Winter comparison. It must be noted that in Summer only the Wednesday test was performed in the second-floor condo; the rest were taken in the third-floor condo. NOx typically presented high peaks in Winter. The NO peaks surpassed the NO_2 levels indicating not much oxidation of NO to NO_2. In Summer, however, NO_2 was always higher than NO indicating more oxidation as expected. In Winter, the highest values of NOx were seen in the early morning and the late afternoon, and having a drop between these periods, most likely due to the decrease in mixing height as the sun diminishes. Summer mornings had low readings, which regularly increased in the early afternoons. The means of NO and NO_2 during Summer and Winter are shown in Figure 25. Summer presented lower levels of both pollutants, NO and NO_2. The concentration of NO was between 2 and 5 times higher in Winter, except for Sunday which presented virtually the same average. NO_2 also had higher readings in Winter, but it was almost twice the Summer level. Table 7 and Table 8 have the Summer statistical information for NO and NO_2, and Table 9 and Table 10 show the statistics in Winter. NO did not change on the Saturday during Summer, and Sunday in the Summer had only a slight decrease compared to weekdays. On the hand, Winter NO had a big drop on the weekend, having around half of the weekdays mean on Saturday, and 4 times lower concentration on Sunday. Summer NO_2 had similar behavior to Summer NO. Saturday resembled weekdays, and Sunday had a small decline. Winter NO_2 had a drop of about 1.5 times weekdays mean on Saturday, and around 3 times on Sunday. In summary, NOx was elevated in Winter, dominated by NO and showed strong influence of mixing height and traffic patterns. NOx was lower in Summer dominated by NO_2, showing influence of the sun on NO-to-NO_2 oxidation and atmospheric mixing.

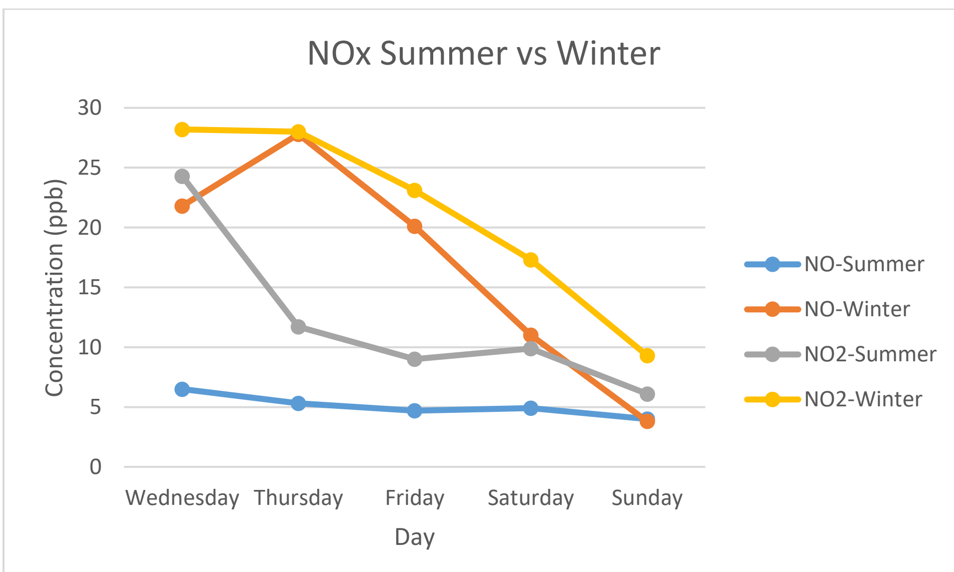

Figure 25. Summer and Winter NOx daily average

Table 7. Nitrogen Monoxide (ppb) Summer Statistics

Day	Wednesday	Thursday	Friday	Saturday	Sunday
Monitor Period	12-6:20 pm (7/27/16)	12:20pm-12am (7/28/16)	12am-12am (7/29/16)	12am-12am (7/30/16)	12am-11am (7/31/16)
Location	Canyon Apt. 1	Canyon Apt. 2	Canyon Apt. 2	Canyon Apt. 2	Canyon Apt. 2
Mean	6.5	5.3	4.7	4.9	4.0
Median	6.1	4.3	4.0	4.4	3.0
Standard Deviation	1.8	3.7	4.3	4.8	3.2
Range	14.6	40.6	86.6	135.7	48.0
Minimum	4.2	2.3	1.4	1.5	1.2
Maximum	18.9	42.9	88.0	137.2	49.2
Number of data points	383	700	1440	1440	661

Table 8. Nitrogen Dioxide (ppb) Summer Statistics

Day	Wednesday	Thursday	Friday	Saturday	Sunday
Monitor Period	12-6:20 pm (7/27/16)	12:20pm-12am (7/28/16)	12am-12am (7/29/16)	12am-12am (7/30/16)	12am-11am (7/31/16)
Location	Canyon Apt. 1	Canyon Apt. 2	Canyon Apt. 2	Canyon Apt. 2	Canyon Apt. 2
Mean	24.3	11.7	9.0	9.9	6.1
Median	22.0	10.2	7.2	7.4	4.7
Standard Deviation	9.0	5.9	6.6	7.4	4.6
Range	47.7	52.7	63.2	71.2	53.5
Minimum	10.7	4.8	2.7	2.6	1.4
Maximum	58.4	57.4	65.9	73.7	54.9
Number of data points	383	700	1440	1440	661

Table 9. Nitrogen Monoxide (ppb) Winter Statistics

Day	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
Monitor Period	8am-6:20pm (1/16/17)	7:55am-6:30pm (1/17/17)	8:15am-6:10pm (1/18/17)	7:45am-6:15pm (1/19/17)	7:50am-6:10pm (1/20/17)	7:50am-6:25pm (1/21/17)	8:20am-6:25pm (1/22/17)
Location	Canyon Apt. 1	Canyon Apt. 1	Canyon Apt. 1	Canyon Apt. 1	Canyon Apt. 1	Canyon Apt. 1	Canyon Apt. 1
Mean	13.2	26.9	21.8	27.8	20.1	11.0	3.8
Median	11.9	22.9	17.1	18.6	10.5	5.6	1.9
Standard Deviation	7.8	14.0	15.8	24.7	22.2	13.6	6.2
Range	54.7	85.0	86.9	152.7	122.0	94.0	52.8
Minimum	1.5	5.3	3.3	4.0	1.5	1.1	0.1
Maximum	56.3	90.3	90.1	156.7	123.4	95.1	52.9
Number of data points	622	639	598	632	624	638	607

Table 10. Nitrogen Dioxide (ppb) Winter Statistics

Day	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
Monitor Period	8am-6:20pm (1/16/17)	7:55am-6:30pm (1/17/17)	8:15am-6:10pm (1/18/17)	7:45am-6:15pm (1/19/17)	7:50am-6:10pm (1/20/17)	7:50am-6:25pm (1/21/17)	8:20am-6:25pm (1/22/17)
Location	Canyon Apt. 1	Canyon Apt. 1	Canyon Apt. 1	Canyon Apt. 1	Canyon Apt. 1	Canyon Apt. 1	Canyon Apt. 1
Mean	24.7	26.7	28.2	28.0	23.1	17.3	9.3
Median	24.2	26.2	28.9	26.5	23.1	13.7	5.9
Standard Deviation	4.6	6.0	9.0	9.7	10.5	9.8	8.7
Range	32.2	41.5	57.0	55.3	44.8	44.4	38.2
Minimum	13.5	8.3	10.5	9.3	7.2	3.0	0.6
Maximum	45.7	49.8	67.5	64.6	52.0	47.4	38.9
Number of data points	622	639	598	632	624	638	607

Comparison of Boulder and CAMP

Summer NO averages were low, but higher in Boulder than at CAMP every day of the study. The averages in Summer in Boulder and at CAMP were 5.1 and 2.9 ppb, respectively. However, Winter NO was generally higher at CAMP, more than twice the Boulder average on some days. Only one day had a lower average at CAMP, and another day showed the same concentration in both locations. The averages were 17.8 ppb in Boulder and 32.9 ppb at CAMP.

In the case of Summer NO_2, the averages were more similar in Boulder and at CAMP. This was demonstrated by comparing the mean based on all the days of the study: 12.2 ppb in Boulder and 12.0 ppb at CAMP. Winter NO_2 levels were higher every day at CAMP, and similar trends were observed in both places. The average values were 22.5 ppb in Boulder and 31.2 ppb at CAMP. Figure 26 and Figure 27 show the daily NOx average in Boulder and at CAMP for every day of measurement in Summer and Winter, respectively.

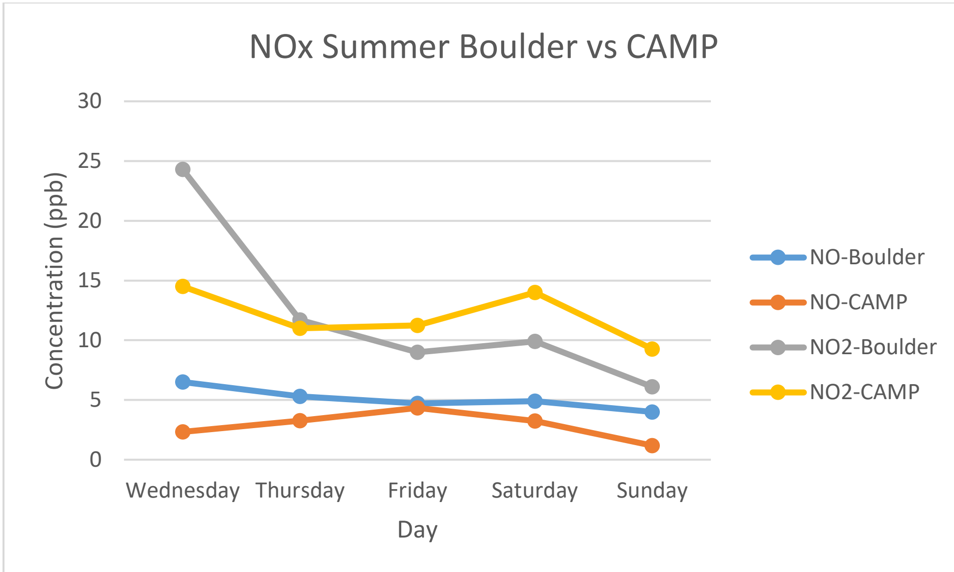

Figure 26. Boulder and CAMP NOx daily Summer average

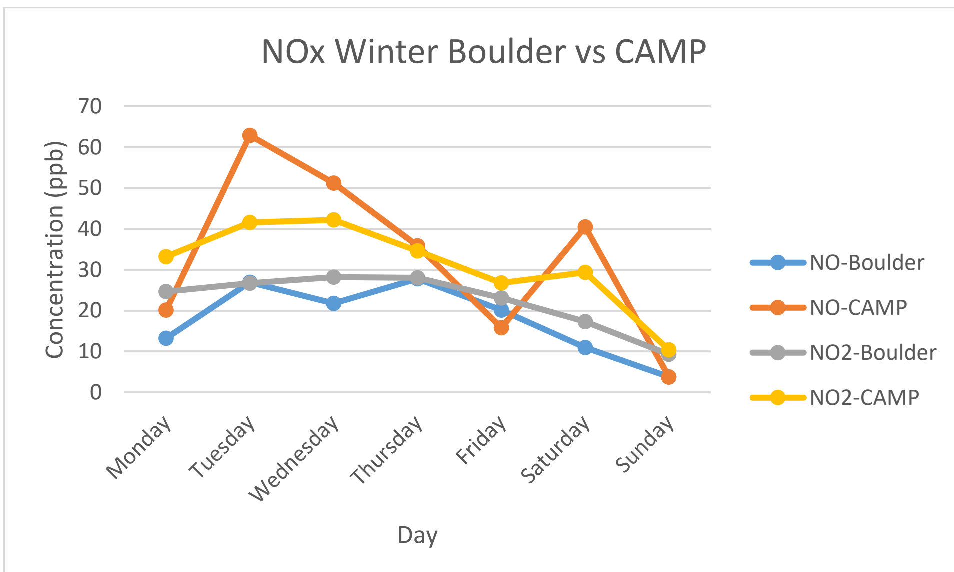

Figure 27. Boulder and CAMP NOx daily Winter average

Particulate Matter (PM)

The study of particulate matter (PM) was comprised of number concentration and mass concentration analysis. Both analyses did not generally show a relationship between the bus count and PM levels. Only the Winter CPC and UHSAS readings showed some connection to the bus count and traffic density. The concentration of PM appeared to be more strongly connected to seasonal trends and regional sources as has been shown in the literature. For the number concentration study two instruments were employed. A Condensation Particle Counter (CPC), which measures particles down to 10 nm (nanoparticles), and an Ultra-High Sensitivity Aerosol Spectrometer (UHSAS), which measures particles down to 55 nm (ultrafine PM). CPC number concentrations were always higher than the UHSAS because the CPC measures smaller particle diameters than the UHSAS and number counts increase with decreasing particle diameter. For the mass concentration study, an Aerodynamic Particle Sizer (APS) was used to measure PM2.5 and PM10. Mass concentrations increase with increasing particle diameter. The following sections contain the results of these studies.

Number Concentration

Only the Winter PM number concentration readings of the CPC and UHSAS generally followed the bus count and traffic volume. The CPC Summer measurements usually presented high readings at noon, which was a period of the day with a low number of buses compared to peak hours. The UHSAS had low readings in the morning and high readings in the night, while the bus count was high in the morning and low in the night. Since the CPC measurements were not taken in the night, it is unknown whether PM below 55 nm had the same pattern or not. Gani, Messier, and Apte (2016) found that Summer mid-days have high nanoparticles formation, while this effect is not observed in Winter mid-days. Condensation of organic compounds into nanoparticles, such as low-volatility products of photochemical reactions, causes secondary aerosol formation (Singh et al. 2005). Summer behavior seems to be more related to seasonal urban pollution patterns. The CPC and UHSAS Winter characteristics generally followed the bus count and traffic volume pattern. Mornings showed the highest readings and afternoons had a rise in the

PM concentration, but lower than in the mornings. At noon, the PM levels were usually to lowest of the day. The CPC readings tended to be an order of magnitude higher than the UHSAS.

On July 25th from 12 to 1:30 pm, the CPC had readings up to 120000 $\#/cm^3$ that went down to slightly above 10000 $\#/cm^3$. A few minutes after 1:30 pm, the CPC readings suddenly increased to a concentration below 20000 $\#/cm^3$ that lasted until the end of the day at 6 pm. On the other hand, the UHSAS readings were virtually constant throughout the day; readings around 3000 $\#/cm^3$ were seen. The CPC did not resemble the bus count, since the highest concentration occurred when there was a low number of buses and the rise in the traffic volume did not increase the readings, they remained constant. The UHSAS did not present any variation with traffic changes.

The July 26th outcome showed CPC initial values up to 22000 $\#/cm^3$ between 12-1 pm. After 1 pm, readings decreased to about 4000 $\#/cm^3$ at 2:30 pm. Then, an increment to an average of 10000 $\#/cm^3$ occurred until 4 pm. After this time, the CPC readings increased to a maximum of 23000 $\#/cm^3$ at 5 pm. The readings stayed above 15000 $\#/cm^3$ until 5:45 pm, where a drop to 5000 $\#/cm^3$ occurred in the last 15 minutes. The UHSAS had values above 2000 ppb the first hour of measurement. At 1 pm a constant drop began; it took place until 3 pm. A slight increment took place at 3 pm, where the last three hours had concentrations between 1000 and 2000 $\#/cm^3$. In terms of a pattern, the CPC and UHSAS showed similar characteristics. It is not clear why the beginning of the test had high values, since traffic volume was low but most likely it was due to a lower mixing height and regional PM source impacts. A rise of PM was observed in the late afternoon, showing a behavior comparable to the bus count and traffic density.

The July 27th test for the CPC started before 12 pm to see whether or not the high initial readings were due to a warm-up problem. The measurements began at 11:10 am, showing values of about 13000 $\#/cm^3$ until 12 pm. Immediately, at 12 pm, a sudden increment to 80000 $\#/cm^3$

took place. The rest of the day showed a decreasing pattern until 6 pm to around 10000 #/cm^3. The UHSAS readings had a constant average of 1500 #/cm^3 between 12-3 pm. At 3 pm, readings increased until 4 pm to about 20000 #/cm^3. This level remained constant until 6 pm. The increment of the CPC readings at 12 pm did not show any connection to the traffic conditions, and the concentration reduction in the late afternoon was opposite to the buses and traffic increase. The UHSAS readings looked very similar to the number of buses; constant readings until 3 pm were observed. Then, readings increased between 3-4 pm, and steady values were seen until 6 pm.

The July 28th outcome showed highly constant readings of the CPC of about 7000 #/cm^3 during the measurements taken during 12-6 pm. The UHSAS readings had values of around 1500 #/cm^3 from the beginning at 12 pm until 9:40 pm. Then, an average of 2500 #/cm^3 was kept until 10:10 pm. After this moment, a reduction to 1000 #/cm^3 was seen until 12 am. The CPC did not show the increasing characteristics of the traffic density and bus count. The same case occurred for the UHSAS; the reasons for the high readings after 9:40 pm were probably due to the lowering of the mixing height at night.

The July 29th test only had UHSAS measurements. The period between 12-6 am showed a constant value of 1000 #/cm^3. Between 6-9 am, the readings increased to around 2000 #/cm^3. At 9 am, a reduction to 1000 #/cm^3 was presented. Then, the concentration continuously increased until 12 pm, again to 2000 #/cm^3. This number remained constant until 4 pm, where a decrease occurred between 4-6:30 pm. A sudden increment to 4500 #/cm^3 happened at 6:30 pm, having a slow reduction until 12 am to 1000 #/cm^3. The particle number concentration did not seem similar to the number of buses. The first increase at 6 am occurred when the number of buses began to increase. However, at 9 am the bus count started to decrease, but the concentration had a new increment. The late afternoon concentration dropped when the bus count increased. The highest readings happened after 6:30 pm when the traffic began to go down.

The July 30th measurements with the CPC were taken between 12:45-6 pm. The readings started at around 10000 #/cm^3, but a few minutes after 1 pm the concentration rose to 70000 #/cm^3, where it remained until 2:45 pm. Then, a continuous decline took place until 4 pm to 10000 #/cm^3. This concentration lasted until 6 pm. For the UHSAS, the 12 am-3 pm interval had values between 1000 and 2000 #/cm^3. At 3 pm, the concentration increased to an average of 2500 #/cm^3 until 6:30 pm, having a reduction between this time and 7:30 pm to about 1500 #/cm^3. Then, the highest average of the day from the UHSAS occurred, approximately 3500 #/cm^3. The rest of the night had a reduction until 12 am, to readings slightly below 2000 #/cm^3. The CPC readings seemed similar to the traffic volume but not to the number of buses. The period between 12-3 pm had a large amount of the vehicles, higher than any weekday, that appeared to be related to the elevated particle number concentration in this interval. The UHSAS did not reflect the high number of vehicles in the readings. The increase in the concentration in the late afternoon occurred when the traffic volume was low, and the same case can be said for the increment of the readings in the night.

The UHSAS was the only instrument deployed for particle number concentrations on July 31st from 12 to 11 am. The average values remained between 1000 and 2000 #/cm^3. A peak of 4000 #/cm^3 was observed between 9-10 am. The readings did not increase with the rise of the bus count. Conversely, the readings remained constant almost all the time, except for the peak that took place for a few minutes.

The January 16th outcome of the CPC had a constant average of about 20000 #/cm^3 from 7:45 am to 3 pm, having one peak of 60000 #/cm^3 at 8 am. After 3 pm, the average dropped to

15000 #/cm^3 until 6 pm. The UHSAS showed a constant mean of 2000 #/cm^3 throughout the day, with two peaks. The first one of 7000 #/cm^3 at 8 am and the second one of 6000 #/cm^3 at 12 pm. The pattern of the CPC and UHSAS readings did not show variations corresponding to the changes of the bus count and traffic volume.

The January 17th CPC result showed the highest concentration from 7:30 to 9 am with an average around 40000 #/cm^3 and a maximum of 70000 #/cm^3 at 8 am. After 9 am, the average was 25000 #/cm^3 until 5 pm when a peak of 60000 #/cm^3 was seen. This value went down to 20000 #/cm^3 at 6 pm. The UHSAS readings had an average value of 2000 #/cm^3 between 7:30-10 am. After 10 am, an increment to 7500 #/cm^3 at 11 am was presented. The tendency after this instant was a drop of the concentration to a minimum of 2000 #/cm^3 at 6 pm. The CPC readings resembled the buses activity and traffic behavior in the morning; however, the afternoon concentration remained constant, while buses and traffic increased. The UHSAS presented the opposite behavior to the bus and traffic volume; low concentration in moments with more traffic and high concentration with less vehicles.

The January 18th test showed CPC readings averaging 40000 #/cm^3 from 7:35 to 10 am. After 10 am, the readings went continuously down to 10000 #/cm^3 at 3 pm. Then, the concentration had a mean of 25000 #/cm^3 until 6 pm. The readings of the UHSAS showed values between 1000 and 2000 ppb from 7:45 to 9 am. After 9 am, the concentration rose to 8000 #/cm^3 at 10 am. This value decreased to a level below 1000 #/cm^3 at 11:30 am. The average had an increment to 2000 #/cm^3 at 12 pm, which remained constant until 3 pm. An increase in the average to 2500 #/cm^3 was presented in the last 3 hours. The CPC early measurements were high, resembling the traffic volume. Then, a drop occurred and it continued even when the traffic remained constant. After 3 pm the bus count increased and the same situation was seen for the CPC readings. The rise of the

UHSAS readings in the morning happened after the heavy traffic period. The interval with similar number of buses showed a constant concentration, but the increment of buses in the late afternoon had only a small increment of the particle number concentration.

The January 19th result had the highest CPC readings in the early morning, having an average of around 70000 #/cm^3 from 7:15 to 9 am. Between 9 am-6 pm, an approximate mean of 20000 #/cm^3 was observed, since the concentration dropped in the 8:30-9 am interval. The UHSAS highest values also occurred from 7:15 to 9 am, with an average of about 3500 #/cm^3. A constant value of 2000 #/cm^3 was observed from 9 am to 4 pm. Then, the readings increased to about 3000 #/cm^3. The CPC early morning readings resembled the traffic and buses pattern, but the afternoon concentration remained constant when the number of buses increased. The UHSAS readings showed characteristics of the bus count, higher values in the early morning and late afternoon.

The January 20th measurements showed the highest CPC readings in the early morning. Starting at 7:30 am with 35000 #/cm^3, having an increment to 60000 #/cm^3 until 8:30 am. After this time, the readings continuously decreased until 11 am to 10000 #/cm^3, which remained constant until 3:30 pm, where a rise in the concentration was observed until 6 pm. At this time, the concentration was about 20000 #/cm^3. The UHSAS measurements started at 7:20 am, having readings between 2000 and 5000 #/cm^3 until 10:45 am. After this instant, the UHSAS readings remained, generally, below 2000 #/cm^3 until 4 pm. Then, the last 2 hours showed an increment to about 3000 #/cm^3. The CPC morning readings had similar characteristics to the bus count and traffic volume. However, the drop of the concentration began before the end of the rush hour. Then, the period between 11 am-3 pm, which has a low traffic density, presented a low steady concentration. The late afternoon had just a small rise in the readings with the increment of the traffic volume. For the UHSAS, the entire day resembled the bus count characteristics. The early morning presented high concentrations, that had a decline after the reduction of the number of buses and vehicles. Then, the readings were constant until the rise of the number of buses and traffic density in the afternoon.

The January 21st CPC test had values between 10000 and 20000 $\#/cm^3$ from 7:20 to 8 am. At 8 am, a sudden increase was observed, having an average of around 55000 $\#/cm^3$ until 9 am, where a sudden decrease to 10000 $\#/cm^3$ took place. An average of 10000 $\#/cm^3$ remained until 4:30 pm, where an increase of the mean to 20000 $\#/cm^3$ was kept until the end of the measurements. The UHSAS showed an increase from 1000 to almost 5000 $\#/cm^3$ between 7:20-9 am. Then, the readings slowly decreased until 1 pm to 1000 $\#/cm^3$. After this time, a rise took place until 5 pm to about 3000 $\#/cm^3$. The last hour had a drop of the readings to 2000 $\#/cm^3$. The CPC readings did not resemble the bus pattern. The period from 8 to 9 am had readings up to 8 times higher than noon, even though the bus count is slightly lower in this interval. The late afternoon presented a low increment in the particle number concentration, but buses remained constant. The UHSAS behavior was similar to the CPC; the interval between 8-9 am had a rise in the readings, and the period around noon showed a drop of the concentration, in spite of the steady number of buses. A rise of the UHSAS readings took place in the afternoon, although the bus count was constant.

The January 22nd CPC measurements began at 7:50 am, having readings of about 10000 $\#/cm^3$, which slowly decreased until 12 pm to 3000 $\#/cm^3$. Then, the CPC readings presented a small rise during the afternoon until 4 pm to around 5000 $\#/cm^3$. A new increment occurred between 4-5 pm, to a maximum of 30000 $\#/cm^3$, which was the highest number of the day. Finally, a mean of 20000 $\#/cm^3$ lasted until the end. The UHSAS readings had a constant average of 500 $\#/cm^3$ from 7:45 am to 2 pm, where two peaks of around 1300 $\#/cm^3$ happened between 2-3 pm. After 3 pm, an increase in the readings was observed until 6 pm, having a maximum value of about

3300 #/cm^3. The CPC did not show characteristics that resembled the bus count. When the count was constant a drop and a rise were observed, and a big increment took place at the end of the day. The UHSAS resembled the bus count until 2 pm, with constant readings. After this time, peaks were presented and a considerable increment in the concentration was seen.

Comparison between Summer and Winter, and Weekdays and Weekend

Two instruments were employed for the analysis of particle number concentration, the CPC and the UHSAS. On two days of the Summer campaign it was not possible to use the CPC. Also, the Summer analysis had only data from the afternoons, while the Winter data were collected during the mornings and afternoons. Three out of the five Summer days had CPC readings with a very high concentration during the first hours of the afternoon, which went down during the later afternoon. Two days had an almost constant behavior throughout the afternoon. A test was done to investigate if the reason for the initial high values was the instrument warm-up period. However, this test showed that this was not the case. The Winter CPC outcome had the highest readings in the early morning; then, the readings had a drop during the later morning. The noon-time typically had the lowest concentration of the day. Conversely, the late afternoon had an increase in the readings, while Summer had a constant or decreasing tendency, at this time. Figure 28 shows the CPC daily averages in Summer and Winter. The averages were similar between Summer (23929 #/cm^3) and Winter (24581 #/cm^3). Summer showed more variability between days, having days with high and low concentrations. Winter did not present this behavior. Table 11 and Table 12 have the CPC statistical information in Summer and Winter, respectively. The Summer Saturday had a concentration similar to weekdays, showing a high concentration. It was not possible to analyze Sunday, since the information is not available. On the other hand, the Winter CPC outcome showed lower concentrations on the weekend, where Saturday had a mean slightly below the minimum average of any weekday. Sunday presented around half of the Saturday level.

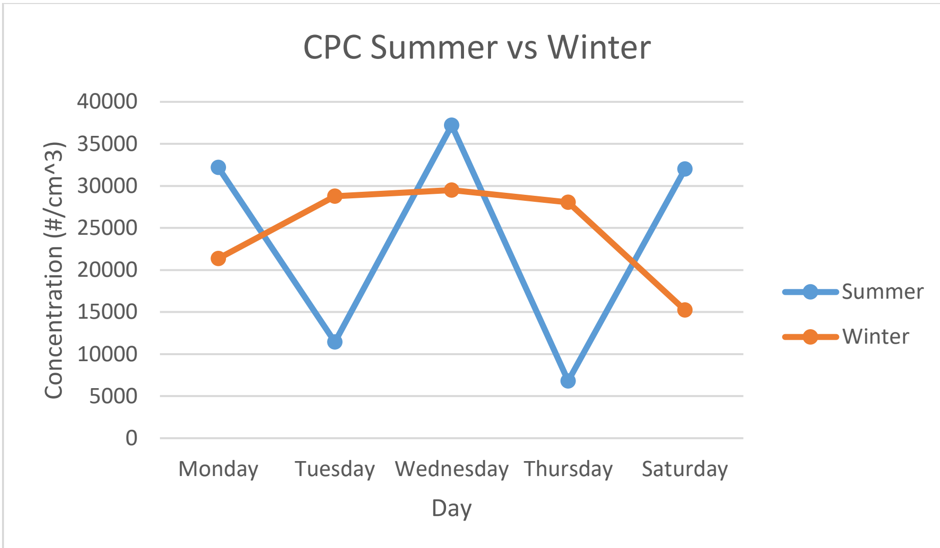

Figure 28. Summer and Winter CPC daily average

Table 11. CPC (#/cm^3) Summer Statistics

Day	Monday	Tuesday	Wednesday	Thursday	Saturday
Monitor Period	12-6 pm (7/25/16)	12-6 pm (7/26/16)	11:10am-6pm (7/27/16)	12-6 pm (7/28/16)	12:45-6 pm (7/30/16)
Location	Canyon Apt. 1	Canyon Apt. 1	Canyon Apt. 1	Canyon Apt. 2	Canyon Apt. 1
Mean	32190	11436	37200	6808	32012
Median	17338	10709	34171	5760	14233
Standard Deviation	32125	5341	23558	4329	26872
Range	126883	43785	91235	90847	79604
Minimum	8844	2989	3315	2073	5033
Maximum	135727	46774	94550	92920	84637
Number of data points	21466	21404	24580	21513	18825

Table 12. CPC (#/cm^3) Winter Statistics

Day	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
Monitor Period	7:45am-6:05pm (1/16/17)	7:30am-6:05pm (1/17/17)	7:35am-6:10pm (1/18/17)	7:15am-6:15pm (1/19/17)	7:30am-6:15pm (1/20/17)	7:20am-6:25pm (1/21/17)	7:50am-6:20pm (1/22/17)
Location	Canyon Apt. 1	Canyon Apt. 1	Canyon Apt. 1	Canyon Apt. 1	Canyon Apt. 1	Canyon Apt. 1	Canyon Apt. 1
Mean	21347	28768	29503	28060	17998	15227	7894
Median	19082	24650	28611	19330	12222	10078	5720
Standard Deviation	9867	13789	12902	22570	14482	14346	6335
Range	101792	152056	124109	176796	127779	144584	46803
Minimum	5309	8798	6391	5403	3287	2638	809
Maximum	107101	160854	130500	182199	131066	147222	47612
Number of data points	37023	37764	37945	39269	38452	39929	37671

The Summer UHSAS measurements showed the lowest concentration during the mornings. At noon, the readings showed an increase. An interesting pattern was the early night behavior, which had the highest Summer concentrations. During Winter, four out of seven days showed the lowest concentration at noon. The highest readings were mostly observed in the morning and the late afternoon; typically, afternoon increments were not as high as in the morning. Only one day had high values at noon. Figure 29 shows the UHSAS daily Summer and Winter averages. The weekly average was higher in Winter, having a concentration of 2339 #/cm^3, while in Summer it was 1867 #/cm^3. In terms of the range of the concentration, Winter had smaller and bigger values, as well.

Table 13 and Table 14 have the UHSAS statistical information in Summer and Winter, respectively. Summer and Winter Saturdays presented similar averages compared to weekdays. The Summer Sunday had an average slightly below the weekday with the minimum value. However, this test took place until 11 am. We should recall that the Summer UHSAS readings were low in the morning. Therefore, there were no apparent differences between Summer weekdays and the weekend. On the other hand, the Winter Sunday had a mean at least 4 times smaller than weekdays.

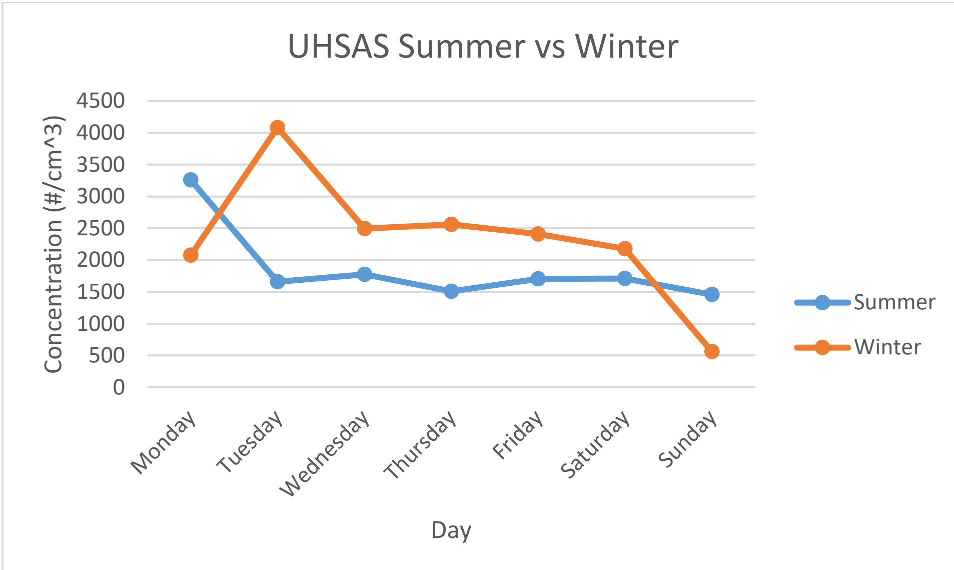

Figure 29. Summer and Winter UHSAS daily average

Table 13. UHSAS (#/cm^3) Summer Statistics

Day	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
Monitor Period	12-6 pm (7/25/16)	12-6 pm (7/26/16)	12-6 pm (7/27/16)	12pm-12 am (7/28/16)	12am-12am (7/29/16)	12am-12am (7/30/16)	12am-11am (7/31/16)
Location	Canyon Apt. 1	Canyon Apt. 1	Canyon Apt. 1	Canyon Apt. 2	Canyon Apt. 2	Canyon Apt. 2	Canyon Apt. 2
Mean	3259	1658	1773	1506	1706	1708	1457
Median	3227	1585	1722	1301	1435	1549	1457
Standard Deviation	387	603	395	601	965	745	543
Range	2514	3750	2525	6023	6863	11655	11526
Minimum	2198	653	1001	798	802	905	832
Maximum	4713	4403	3526	6821	7665	12560	12357
Number of data points	2161	2159	2162	4315	8640	8640	3998

Table 14. UHSAS (#/cm^3) Winter Statistics

Day	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
Monitor Period	7:40am-6:10pm (1/16/17)	7:30am-6:10pm (1/17/17)	7:45am-6:05pm (1/18/17)	7:15am-6:10pm (1/19/17)	7:20am-6:05pm (1/20/17)	7:20am-6:20pm (1/21/17)	7:45am-6:20pm (1/22/17)
Location	Canyon Apt. 1	Canyon Apt. 1	Canyon Apt. 1	Canyon Apt. 1	Canyon Apt. 1	Canyon Apt. 1	Canyon Apt. 1
Mean	2079	4083	2495	2562	2410	2180	562
Median	1877	4372	2043	2451	2195	2045	363
Standard Deviation	1024	1674	1533	861	882	874	520
Range	11853	11446	8675	6689	6355	7041	5091
Minimum	1009	608	299	796	1240	555	86
Maximum	12862	12054	8974	7485	7595	7597	5177
Number of data points	3798	3847	3765	3961	3904	4010	3824

Comparison between CPC and UHSAS

Since the CPC and the UHSAS use different measurement technologies and the resolution differs, pattern differences are discussed in this section. The CPC measures particle number concentration down to 10 nm, while the UHSAS down to 55 nm. This range difference results in the CPC measuring a particle number concentration about 10 times higher than the UHSAS, in both seasons. The Summer outcome had similar characteristics between days for both instruments. When the CPC average readings dropped, the UHSAS readings also decreased. The CPC exhibited more variability than the UHSAS, showing that the smaller particles have the largest change in Summer. Figure 30 shows Summer CPC and UHSAS daily averages. In the case of Winter, the UHSAS showed more variability than the CPC. Figure 31 presents the Winter daily average of the CPC and UHSAS readings.

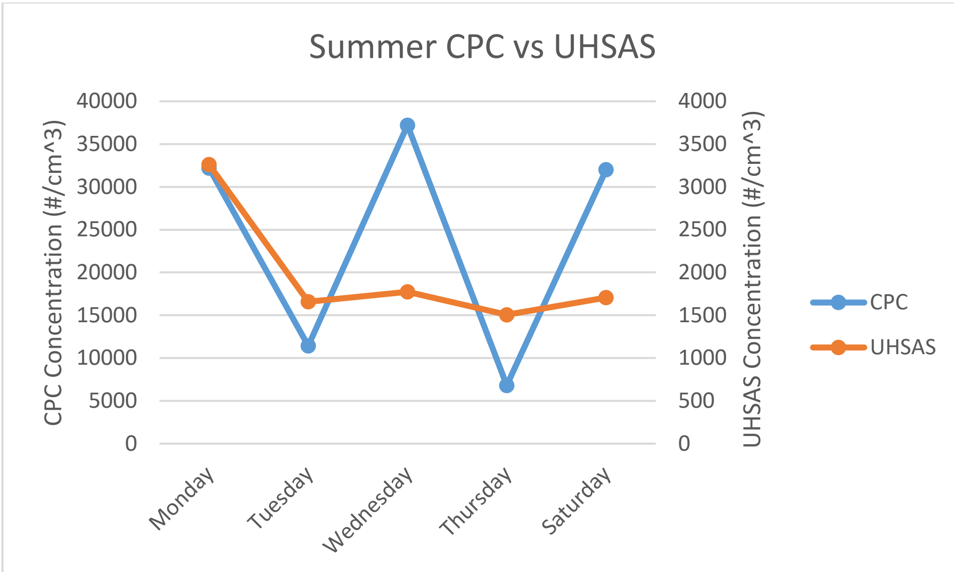

Figure 30. Summer CPC and UHSAS daily average (note difference in y axes).

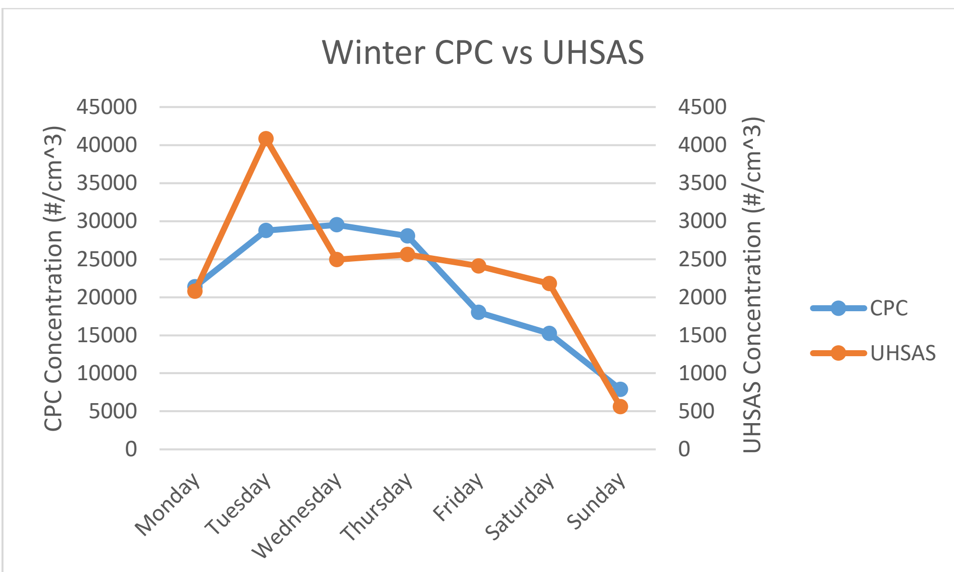

Figure 31. Winter CPC and UHSAS daily average (note difference in y axes)

Measurement-Location Effects

Since two CPCs were available, a verification performance test was carried out on July 25th. Each CPC was placed next to the other one to check if they were comparable. Figure 32 shows the measurements taken by each device; the CPCs had high agreement. A slight difference was noted; the reason for this might be an initial disparity after the factory calibration that virtually disappeared after the first hour. The Appendix H contains the regression fit of the instruments.

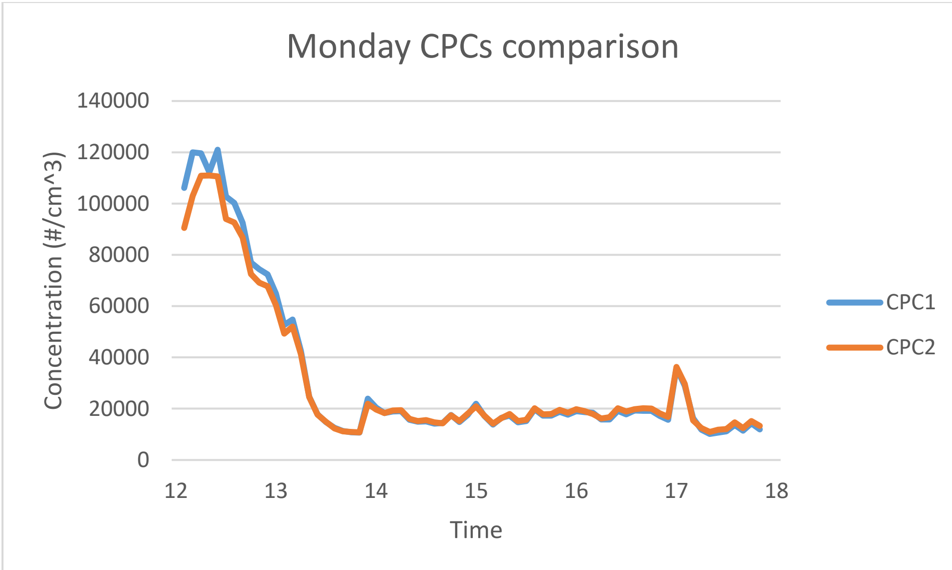

Figure 32. Summer CPCs performance comparison

After checking that both CPCs produced virtually the same readings, one device was placed in the second-floor condo and the other one on the third floor on July 28th. This test was performed to analyze the effects of the location difference on the measurements. Figure 33 shows the outcome of the measurements. The PM levels were higher at almost any time in the second-floor condo. The Appendix H contains the regression fit of the experiment.

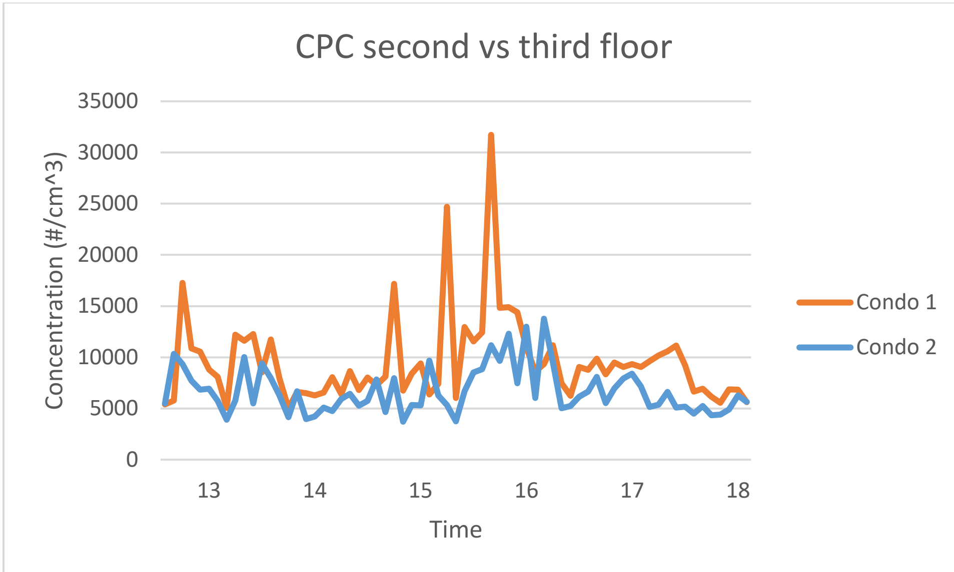

Figure 33. PM Concentration due to Elevation Differences (condo 1: second floor Canyon Boulevard, condo 2: third floor, 14th street)

From the Summer results, it was thought that the location of the measurements produced a considerable difference in the concentration of PM. The same procedure applied in Summer was used in Winter. The CPCs were placed together and measurements were taken on January 17th. Figure 34 shows the outcome of this experiment. A slightly higher value was seen in the secondary CPC, but a similar trend was observed throughout the day. The Appendix H shows the regression fit of the test.

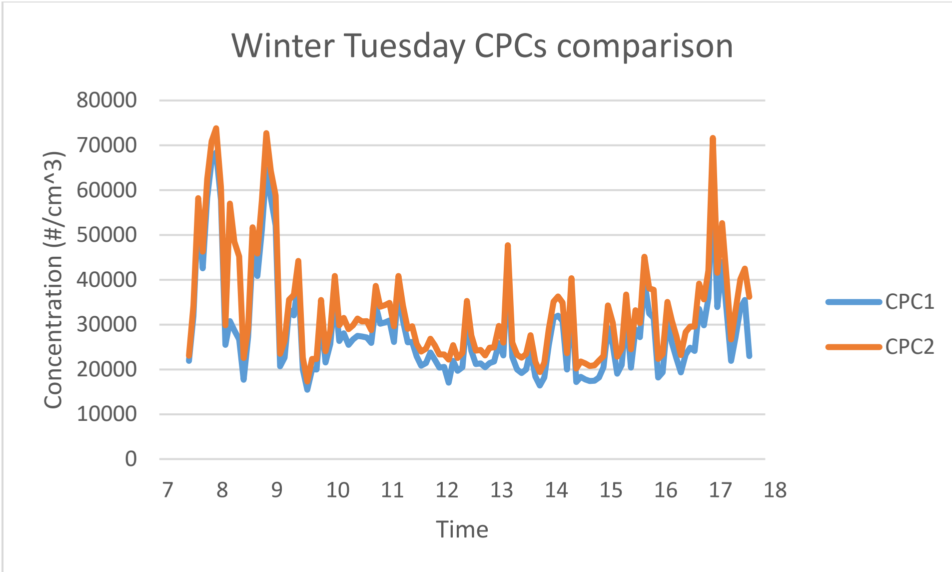

Figure 34. Winter CPCs performance comparison

The Summer comparisons were made in condo units facing different streets. The second-floor condo was facing Canyon Boulevard and the third-floor condo was facing BDS on 14th street. Therefore, it was decided to compare the CPSs on both floors, but facing Canyon Boulevard. The experiment was carried out on January 18th. Figure 35 shows the result of the test. The outcome was slightly higher on the third floor. After looking at the concentrations, the difference was virtually the same compared to the test performed on the previous day (placing both instruments together). Again, the readings' change seemed to be linked to the street facing the measurements' location. The Appendix H contains the regression fit for this test.

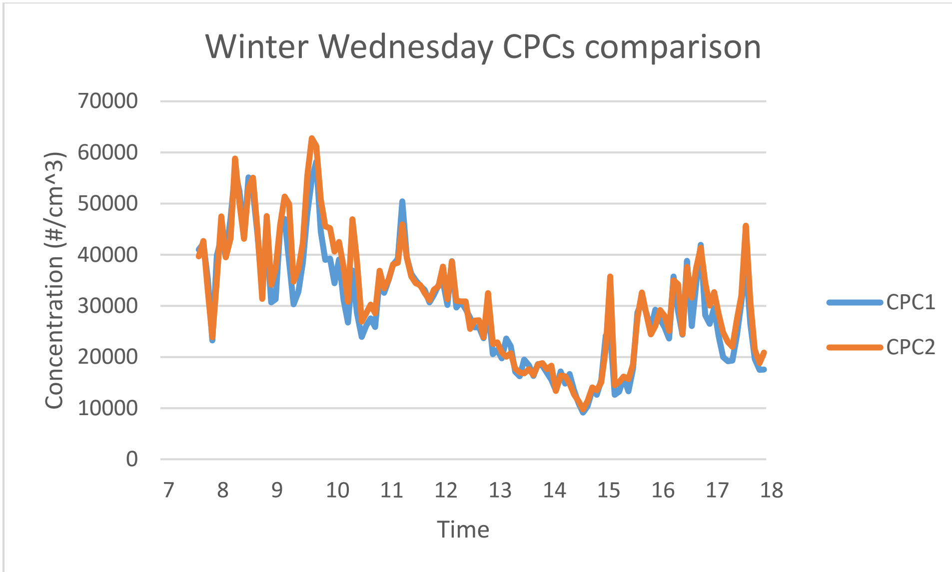

Figure 35. PM Concentration due to Elevation Differences (condo 1: second floor, condo 2: third floor)

Mass Concentration

Only the mass concentration Summer data taken with the APS 3321 are analyzed in this section. The equipment could not collect data in Winter due to the very cold temperatures. PM2.5 and PM10 did not generally have a pattern related to the number of buses and traffic volume. Only one weekday test presents morning data, which had a considerable increment of PM2.5 in the period of a high number of buses; PM10 had only a small increment. Besides this occurrence, PM did not show the similarities to traffic trends. The afternoons' concentration remained constant or had a decrease when the number of buses and vehicles increased, and there were high readings in the night, when the bus count went down. Again, these results are similar to the number concentration results in that the meteorology and regional sources had a great impact on concentrations than local emissions. A description of each day of measurement is presented below.

The July 25th test showed a similar pattern of PM2.5 and PM10. At the beginning, before 12:30 pm, higher readings were observed: almost 8 μg/m^3 for PM2.5 and about 40 μg/m^3 for

PM10. The rest of the time a nearly constant pattern was shown between 12:30-6 pm. The averages were around 6 and 22 $\mu g/m^3$ for PM2.5 and PM10, respectively. In the last minutes before 6 pm, PM10 had a peak slightly below 35 $\mu g/m^3$. The readings did not show a relationship with the bus count and traffic density, since traffic increment was not reflected in the concentration of PM.

The July 26th outcome had the highest PM2.5 reading of almost 10 $\mu g/m^3$ at 12 pm; PM10 also had an elevated concentration (30 $\mu g/m^3$) at this time. PM2.5 and PM10 had a drop until a few minutes past 3 pm, to around 5 and 15 $\mu g/m^3$, in that order. Between 3-4 pm high concentrations were presented, 9 $\mu g/m^3$ for PM2.5 and 35 $\mu g/m^3$ for PM10. These numbers went down to 4 and 10 $\mu g/m^3$ at 4 pm. Then, the concentration had a new increase to 8 $\mu g/m^3$ for PM2.5 and 35 $\mu g/m^3$ for PM10, at 5 pm. The last hour had a decline to 4 and 15 $\mu g/m^3$. The readings had a drop when the number of buses was constant, but a rise in the concentration was seen with the bus count increase. However, the reasons for the two declines, one at 4 pm and the other at 6 pm, are not clear.

The July 27th test had rather constant PM2.5 readings throughout the day. The highest PM2.5 values were seen between 12-1 pm, with a maximum of 9 $\mu g/m^3$. After this time until a few minutes before 6 pm, the PM2.5 concentration remained between 6 and 7 $\mu g/m^3$. A decline to 4 $\mu g/m^3$ took place before 6 pm. PM10 was highly constant throughout the day, having an average of around 25 $\mu g/m^3$. The bus count did not present any similarity to the PM concentration pattern, where there was no rise of the readings with the number of buses and traffic volume increment.

The July 28th test took place from 12 pm to 12 am. PM2.5 levels showed a decreasing tendency from the beginning until the end of the day, from about 13 to 6 $\mu g/m^3$. PM10 concentrations were between 20 and 25 $\mu g/m^3$ until 5 pm. A decline to 15 $\mu g/m^3$ was observed during 5-8:30 pm. Then, PM10 levels oscillated between 15 and 35 $\mu g/m^3$. No connection was found between the PM levels, bus count, and traffic volume. PM 2.5 had a drop when the number of buses increased, while PM10 remained constant.

The July 29th test took place over 24 hours. The measurements showed an increment of PM2.5 between 3-8 am from 6 to 16 µg/m^3, which was the maximum average of the day. After this time, PM2.5 had a continuous reduction until 6 pm, to a value of 4 µg/m^3. The period between 6 pm-12 am had a rise to 8 µg/m^3. PM10 showed a level between 15 and 30 µg/m^3 from 12 am to 4 pm, where the readings dropped to 10 µg/m^3 between 4-6 pm. Then, the 6 pm-12 am interval presented a range between 15 and 35 µg/m^3, which was the portion of the day with the highest PM10 concentration. PM did not resemble the number of buses and traffic density. PM2.5 had an increment starting several hours before the increase of the bus count, and the late afternoon showed a decline of the concentration when the traffic increases. PM10 remained constant while the number of buses increased or decreased.

The July 30th PM2.5 outcome showed values between 7 and 12 µg/m^3 in the 12-9 am interval. After this, readings of PM2.5 decreased to about 6-8 µg/m^3 until 6 pm, where the PM2.5 level increased to a magnitude between 8 and 10 µg/m^3 that was kept until 12 am. PM10 had an approximate average of 20 µg/m^3 from 12 am to 8 am, where the readings presented a continuous decline to 15 µg/m^3 at 12 pm. The readings oscillated between 15-20 µg/m^3 during 12-3 pm. The period between 3-6 pm had an average of 13 µg/m^3. The 6-7 pm interval showed a sudden increment to about 25 µg/m^3, which lasted until 9 pm. Then, a continuous decline to around 17 µg/m^3 took place until 12 am. PM was completely different compared to the bus count and traffic density. The time before the sunrise and the night had the highest concentrations. The periods with high traffic volume and bus count showed low concentrations.

The July 31st test was developed from 12 am to 11 am. The result showed a decreasing tendency of PM2.5 between 12-6 am, from 8 to 6 μg/m^3. Between 6-7 am a sudden decrease to 4 μg/m^3 was observed; this value remained constant until 8 am, where PM2.5 increased to 8 μg/m^3. Between 9-10 am a peak of 11 μg/m^3 was presented. Then, the readings had a continuous decline to 4 μg/m^3 at 11 am. PM 10 oscillated between 10 and 20 μg/m^3 during the measurement period. Nonetheless, only at one moment PM10 surpassed 20 μg/m^3. This event occurred between 9-10 am, where a peak of almost 70 μg/m^3 was observed. There were no clear reasons for this behavior. PM did not show a connection with the bus count, because the increment in the number of buses did not increase the PM concentration.

Comparison between PM2.5 and PM10, and Weekdays and Weekend

PM2.5 and PM10 had similar behavior, where typically the increase of one was accompanied with the rise of the other one. The same trend was also observed for the concentration drops. Many times, this is expected since the PM10 measurement includes PM2.5, if the particulate air pollution is derived mostly from combustion sources, and atmospheric processing and not mechanical processes. On some occasions PM2.5 had a higher rise than PM10, such as the case presented on Friday morning. Conversely, Friday evening had a higher increase of PM10 than PM2.5. Figure 36 shows the daily average of PM2.5 and PM10. On two occasions PM2.5 had a rise in the mean from the previous day, while PM10 had a decline. Table 15 and Table 16 show the statistical information of PM2.5 and PM10, respectively. The PM2.5 averages on the weekend resembled the readings of weekdays. On the other hand, PM10 was slightly lower on the weekend, especially on Sunday.

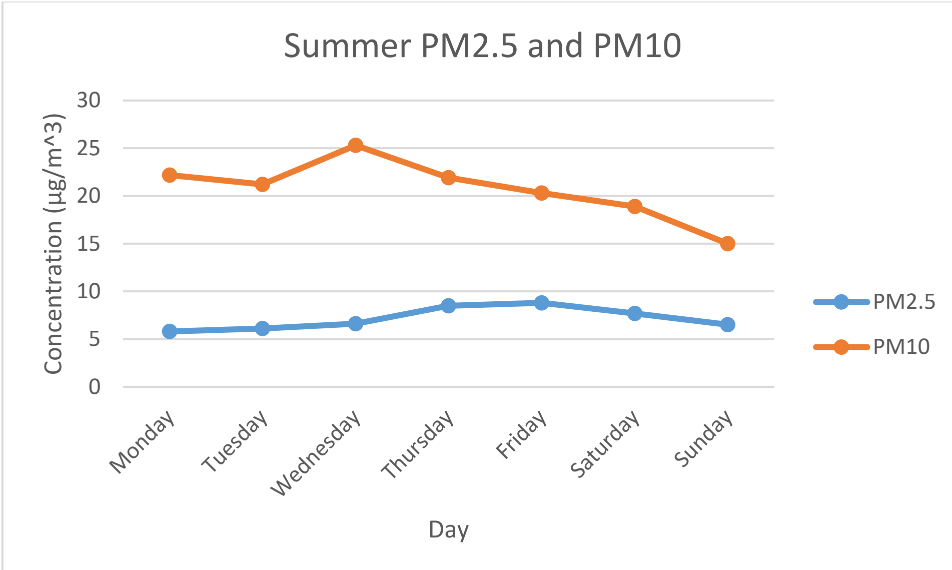

Figure 36. PM2.5 and PM10 daily average

Table 15. PM2.5 (µg/m^3) Summer Statistics

Day	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
Monitor Period	12-6 pm (7/25/16)	12-6 pm (7/26/16)	12-6 pm (7/27/16)	12pm-12 am (7/28/16)	12am-12am (7/29/16)	12am-12am (7/30/16)	12am-11am (7/31/16)
Location	Canyon Apt. 1	Canyon Apt. 1	Canyon Apt. 1	Canyon Apt. 2	Canyon Apt. 2	Canyon Apt. 2	Canyon Apt. 2
Mean	5.8	6.1	6.6	8.5	8.8	7.7	6.5
Median	5.7	5.6	6.6	8.1	7.7	7.9	6.4
Standard Deviation	0.7	1.6	0.9	1.8	3.3	1.4	1.9
Range	4.6	9.1	11.1	13.0	23.9	26.6	29.7
Minimum	4.4	3.1	3.1	5.7	3.5	5.0	3.4
Maximum	9.0	12.2	14.2	18.7	27.3	31.6	33.1
Number of data points	720	720	720	1442	2880	2880	1319

Table 16. PM10 (μg/m^3) Summer Statistics

Day	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
Monitor Period	12-6 pm (7/25/16)	12-6 pm (7/26/16)	12-6 pm (7/27/16)	12pm-12 am (7/28/16)	12am-12am (7/29/16)	12am-12am (7/30/16)	12am-11am (7/31/16)
Location	Canyon Apt. 1	Canyon Apt. 1	Canyon Apt. 1	Canyon Apt. 2	Canyon Apt. 2	Canyon Apt. 2	Canyon Apt. 2
Mean	22.2	21.2	25.3	21.9	20.3	18.9	15.0
Median	21.1	19.2	24.8	21.4	19.3	18.5	14.0
Standard Deviation	5.8	8.3	4.9	4.8	5.8	4.6	10.0
Range	51.3	47.4	32.4	35.2	41.0	41.3	273.1
Minimum	10.8	8.7	10.5	11.8	8.2	9.9	8.1
Maximum	62.0	56.1	42.9	47.1	49.2	51.2	281.2
Number of data points	720	720	720	1442	2880	2880	1319

Comparison of Boulder and CAMP

Six out of seven days had a slightly higher average PM2.5 concentration at CAMP compared to Boulder. Nonetheless, the difference was small, having two days with virtually the same PM2.5 levels. Boulder and CAMP PM2.5 averages of the week were 7.6 and 8.3 μg/m^3, respectively. In the case of PM10, CAMP had more changes between days. In 2 out of 7 days, the Boulder daily mean was higher than the CAMP mean. Boulder and CAMP PM10 averages of the week were 20.0 and 23.0 μg/m^3, respectively. Figure 37 shows the daily average of PM2.5 and PM10 in Boulder and at CAMP.

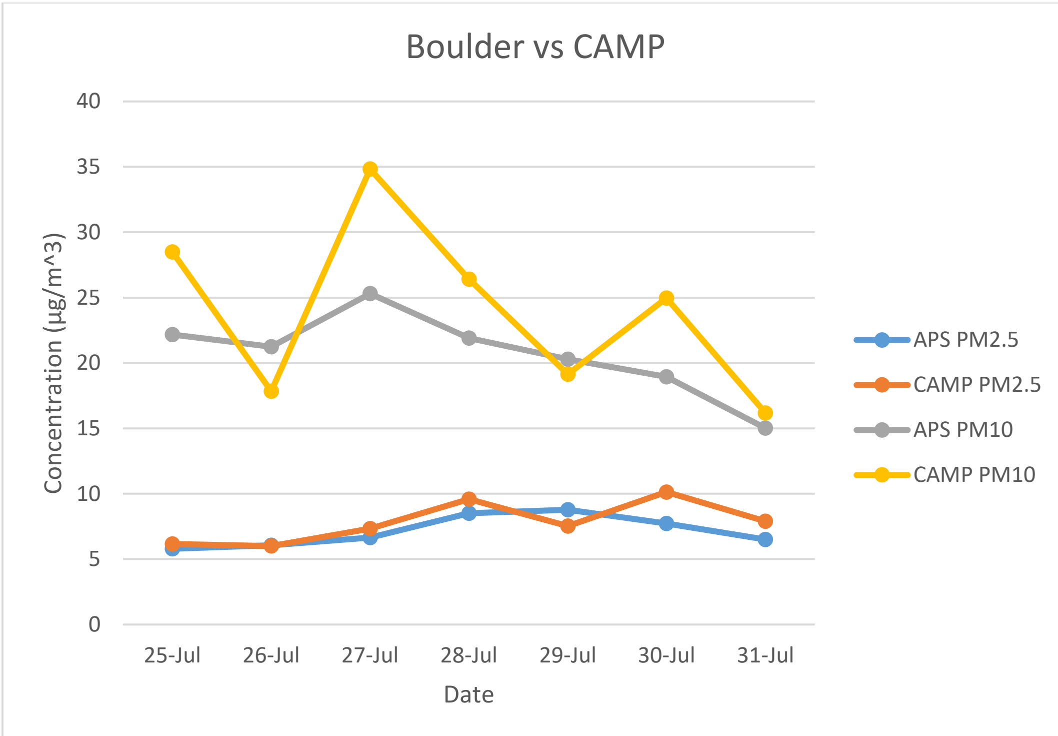

Figure 37. Boulder and CAMP PM2.5 and PM10 daily Summer average

Bicycle Rides

Five bicycle rides were taken to capture fresh emissions of RTD buses. Three instruments were employed: a portable aethalometer (microaeth AE51), a CPC 3007, and an ozone personal monitor (POM). Black carbon (BC) showed an increase in its concentration during the chase of some buses. The emission rates appeared to be related to specific bus routes. All the buses on the HOP route that were chased had the maximum BC levels of day, showing values of around 16000 ng/m^3. JUMP buses also caused a rise in the aethalometer readings during the chases, and there was only one occasion when the readings did not increase. The Bound, 206, and 225 also caused increments in the BC readings but at a lower magnitude. Other routes, such as Stampede, 205 and 209 did not reflect an increase in the BC readings. It must be noted that one day had its maximum reading while chasing a truck, and some peaks were found when the number of vehicles was low. Compared to a study done in Fort Collins, Colorado (Good et al. 2016a), the frequency of BC concentration between 0-2000 ng/m^3 was similar. However, differences were found within 2000-6000 ng/m^3, having more observations within this range in Fort Collins than in Boulder, but readings above 6000 ng/m^3 were more frequent in Boulder. The Fort Collins study was carried out during the morning and evening commutes. On the other hand, our rides were taken around noon, during a period of the day with less traffic, causing lower observations of the intermediate concentration of BC. Nevertheless, higher values were observed in Boulder since the purpose of the measurements was to chase buses. A description of the bicycle rides is presented below. The Appendix I shows the results for BC on every bicycle ride.

The December 16th trip began at 11:11 am on Canyon and 14th Street, next to the Boulder Downtown Station. At 11:17 am, a peak of about 13000 ng/m^3 took place when crossing Arapahoe and Broadway. After this, two small peaks were seen at 11:24 and 11:26 am on Arapahoe and 30th Street. The first bus chase was carried out from Arapahoe and 30th Street to Arapahoe and Folsom, between 11:32-11:34 am, but small BC readings were observed, having an average of 3000 ng/m^3 with no peaks. During 11:39-11:42 am, a second bus chase took place at 15th Street, then turning left onto Arapahoe, finishing at 20th Street. It had a peak slightly above 13000 ng/m^3. In both cases JUMP buses were chased. The highest peak was observed at 11:45 am when entering on Canyon. The concentration of BC surpassed 50000 ng/m^3. Nevertheless, there were only a few vehicles at that moment. A continuous reading of 14000 ng/m^3 happened between 11:48-11:50 am from Canyon and 26th to 22nd Street, and similar to the previous peak, only a few vehicles were observed. Unfortunately, the CPC data is not available since some issues were presented while logging the information. O_3 had an average of 13.2 ppb during the measurement period. The test was continued until 12:05 pm.

The December 23rd ride started at 12:06 pm at Cherokee Way. A 206 bus chase took place along Manhattan Drive from 12:11 to 12:14 pm, where a peak above 4000 ng/m^3 occurred. The highest peak of the day, above 8000 ng/m^3, happened when chasing a truck at Baseline and Foothills. A peak slightly above 3500 ng/m^3 was seen when riding on the CU Boulder Campus; however, no vehicles were observed. A Stampede bus was chased between 12:38:20-12:41:51 pm from 18th Street throughout Colorado Avenue, but the readings remained below 1000 ng/m^3. When riding down Folsom at 12:55 pm, a peak of around 4500 ng/m^3 was seen, but no vehicles were observed. Then, a Bound bus chase was carried out from 1:00:50 to 1:01:20 pm showing a peak of 4000 ng/m^3. After this, a peak of 4500 ng/m^3 was found at 1:07 pm on 30th Street and Arapahoe. A reading of 3000 ng/m^3 was shown when approaching the Boulder Downtown Station at 1:17 pm. However, it decreased when riding around the station. Concentrations up to 4000 ng/m^3 occurred when chasing a JUMP bus between 1:34:40-1:36:20 pm, from Arapahoe and 28th Street to Arapahoe and 30th Street. The CPC readings had a particle number mean of 8544 #/cm^3 during the measurement period. On the other hand, O_3 had an average of 21.1 ng/m^3. The test took place until 2:00 pm.

The December 24th trip began at 12:28 pm having extremely low concentrations until 12:58 pm, about 100 ng/m^3. Three buses were chased during this period but the aethalometer showed no variations on the readings. It is not clear whether the instrument had a filtering malfunction or not. A HOP bus was chased going down Folsom and turning right at Canyon between 1:00:00-1:02:30 pm; during this chase the highest reading of the day was observed, above 15000 ng/m^3. Then, a JUMP bus was chased through 15th Street and Arapahoe from 1:09:35 to 1:12:36 pm, showing a peak of around 4500 ng/m^3. A small peak of almost 4000 ng/m^3 was observed when turning onto

30th Street from Arapahoe at 1:16 pm. The CPC readings showed a mean of 19281 #/cm^3, while O_3 had an average of 6.8 ppb. The test was carried out until 1:37 pm.

The December 26th trip, starting at 1:31 pm, generally had low readings. A 225 bus was chased between 1:41-1:44:20 pm in Manhattan, then turning at Tenino and finally on 55th Street, having an increment from around 350 ng/m^3 to above 1000 ng/m^3. When riding along 30th Street the readings increased to around 2000 ng/m^3, but no vehicles were chased. A 205 bus was followed from 2:09:40 to 2:10:20 pm on Walnut and then turning right at 15th Street. The readings did not increase during this chase. After this, a JUMP bus was chased between 2:11:50-2:13:20 pm on Arapahoe, showing an increment to above 2500 ng/m^3. The last chase of the day was a HOP bus, on Folsom and turning right at Canyon, between 2:14:40-2:15:40 pm, showing the highest readings of the day, approximately 17000 ng/m^3. The rest of the time low readings were observed. During the trip, the CPC readings showed an average of 5141 #/cm^3, while the O_3 mean concentration was 5.5 ppb. The test finished at 2:34 pm.

The December 28th trip began at 11:27 am. A 209 bus was chased on Mohawk between 11:30-11:32:30 am, but no changes were observed in the BC readings. A peak of 2500 ng/m^3 occurred when approaching Arapahoe and 28th Street. At 11:52 am, a peak of almost 3000 ng/m^3 took place when crossing Arapahoe and Broadway, but similar to previous peak, no vehicles were chased at this moment. The maximum value of the day occurred when finishing the ride at 11:59 am next to the bus station. The CPC readings had an average of 5911 #/cm^3 and O_3 showed a mean of 19.9 ppb.

Statistical Analysis

The statistical information did not show a pattern that connects the concentration level of BC, nanoparticles and O_3. The aethalometer showed readings between 1000-1500 ng/m^3 on 4 out of 5 days. The other day had a mean of 5454 ng/m^3, which is completely out of this range. CPC nanoparticle measurements presented more variations than BC, having 2 out of 4 days with averages between 5000-6000 #/cm^3, while the two other days were considerably higher. Additionally, there were days in which nanoparticle concentrations were low and high, while BC was similar. O_3 also varied depending on the day, where two days had an average of 5-7 ppb, two days had 19-22 ppb, and the fifth day showed an intermediate point, 13.2 ppb. On some days, O_3 had low and high averages, while BC did not change between days. Table 17, Table 18, and Table 19 show the entire statistical information for BC, CPC particle number concentration, and O_3, respectively.

Table 17. Black Carbon (ng/m^3) Bicycle Ride Statistics

Day	Friday	Friday	Saturday	Monday	Wednesday
Monitor Period	11:11am-12:05pm (12/16/16)	12:06-2 pm (12/23/16)	12:28-1:37 pm (12/24/16)	1:31-2:34 pm (12/26/16)	11:27-11:59 am (12/28/16)
Location	Bicycle ride	Bicycle ride	Bicycle ride	Bicycle ride	Bicycle ride
Mean	5454	1347	1280	1099	1417
Median	2338	938	410	714	1315
Standard Deviation	13257	1616	2917	3197	766
Range	106801	26956	23927	54886	4139
Minimum	74	300	99	352	684
Maximum	106875	27256	24026	55273	4822
Number of data points	302	686	417	379	194

Table 18. CPC nanoparticles (#/cm^3) Bicycle Ride Statistics

Day	Friday	Friday	Saturday	Monday	Wednesday
Monitor Period	11:11am-12:05pm (12/16/16)	12:06-2 pm (12/23/16)	12:28-1:37 pm (12/24/16)	1:31-2:34 pm (12/26/16)	11:27-11:59 am (12/28/16)
Location	Bicycle ride	Bicycle ride	Bicycle ride	Bicycle ride	Bicycle ride
Mean	N/A	8544	19281	5141	5911
Median	N/A	4818	17534	2472	2878
Standard Deviation	N/A	14955	8367	10172	14032
Range	N/A	204711	143422	147576	169927
Minimum	N/A	446	10531	878	816
Maximum	N/A	205157	153953	148454	170743
Number of data points	N/A	6888	4173	3371	2316

Table 19. Ozone (ppb) Bicycle Ride Statistics

Day	Friday	Friday	Saturday	Monday	Wednesday
Monitor Period	11:11am-12:05pm (12/16/16)	12:06-2 pm (12/23/16)	12:28-1:37 pm (12/24/16)	1:31-2:34 pm (12/26/16)	11:27-11:59 am (12/28/16)
Location	Bicycle ride	Bicycle ride	Bicycle ride	Bicycle ride	Bicycle ride
Mean	13.2	21.1	6.8	5.5	19.9
Median	12.0	20.5	6.0	4.4	10.2
Standard Deviation	8.7	14.4	5.0	4.0	20.5
Range	57.5	96.1	30.5	20.6	91.1
Minimum	0	0	0	0	0
Maximum	57.5	96.1	30.5	20.6	91.1
Number of data points	248	549	340	328	191

Stationary and Bicycle Ride Measurements

Bicycle rides were carried out in Winter, so the BC, CPC and O_3 data from the Winter campaign were utilized for this analysis. Stationary measurements had a higher BC average than the bicycle rides, but the difference was not large. The stationary measurements average was 2324 ng/m^3, while bicycle rides had a mean of 2119 ng/m^3. Conversely, bicycle rides showed higher maximum values, where the difference between the highest bicycle ride peak and stationary measurement peak was about 50000 ng/m^3 (based on the 10-second data). These characteristics seem correct, since the stationary measurements were taken continuously at a location with high traffic volume. Bicycle rides were comprised of a mix of conditions with polluted and non-polluted places, and higher peaks were expected due to the proximity while chasing buses and vehicles. Particle number concentrations from the stationary measurements showed more than twice the mean of the bicycle rides, where the mean was 21257 and 9719 #/cm^3 for stationary and bicycle ride measurements, respectively. It must be noted that bicycle rides were carried out during the December Christmas break, when there were less vehicles on the roads. The peak values were higher on bicycle rides, which was expected due to the closer distance to vehicles and buses' exhaust. O_3 was considerable higher on bicycle rides, having an average of 13.3 ppb, while stationary measurements had a mean of 4.5 ppb. The maximum values were around 4-5 times higher during bicycle rides (based on the 10-second data). This situation probably occurred due to the low traffic density during the bicycle rides, having lower fresh NO production from vehicles' exhaust to degrade O_3.

Computational Modeling

The mass emission rates on Canyon Boulevard and the Boulder Downtown Bus Station (BDS) were estimated using the Motor Vehicle Emission Simulator (MOVES). In addition, simulations without buses and BDS were performed to quantify emissions due to the RTD fleet. Table 20 contains the emission rates found during eight study cases for NO, NO_2, PM10 and PM2.5. Several trends were found from the MOVES outputs. Buses emit a higher mass of NOx in Winter, while PM from buses is virtually the same in Summer and Winter. Vehicles produce less NOx in Winter, but more PM in Winter than in Summer. Since the traffic on Canyon is mostly composed of vehicles, a high number of vehicles relative to buses would produce more NOx and less PM in Summer, and the opposite case would be observed in Winter. The simulations with buses on Canyon showed higher NOx and PM in Winter than in Summer, at noon-time. It must be noted that there are more buses in Winter than in Summer, particularly at noon-time. Summer afternoons had higher NOx and lower PM than Winter afternoons.

Table 20. MOVES NO, NO2, PM10, and PM2.5 emission rates

Study case	Locations	NO (g/(mile*h))	NO_2 (g/(mile*h))	PM10 (g/(mile*h))	PM2.5 (g/(mile*h))
1	Canyon Summer noon with buses	2782	400	318	92
	BDS Summer noon	970	125	38	35
2	Canyon Winter noon with buses	2838	414	350	118
	BDS Winter noon	1142	148	39	36
3	Canyon Summer noon without buses	2168	321	272	66
4	Canyon Winter noon without buses	1986	304	295	86
5	Canyon Summer afternoon with buses	3470	490	366	113
	BDS Summer afternoon	1980	256	75	69
6	Canyon Winter afternoon with buses	3394	487	394	136
	BDS Winter afternoon	2285	296	78	71
7	Canyon Summer afternoon without buses	2425	355	288	70
8	Canyon Winter afternoon without buses	2108	320	310	89

MOVES outputs were used in R-Line to simulate the dispersion and concentration of pollutants. The main purpose of the analysis was to compare traffic-related pollutant concentrations with and without RTD buses and BDS. Figure 38 and Figure 39 show the noon and afternoon maximum values of ratios of no-buses and buses. NOx had lower ratios in Winter, indicating a Winter NOx increase from buses and a reduction from vehicles. PM had higher ratios in Winter, since vehicles PM increases in Winter. Noon presented higher ratios than afternoons for all the pollutants; indicating a higher bus contribution, during the afternoons, to the maximum concentration found within the computational domain.

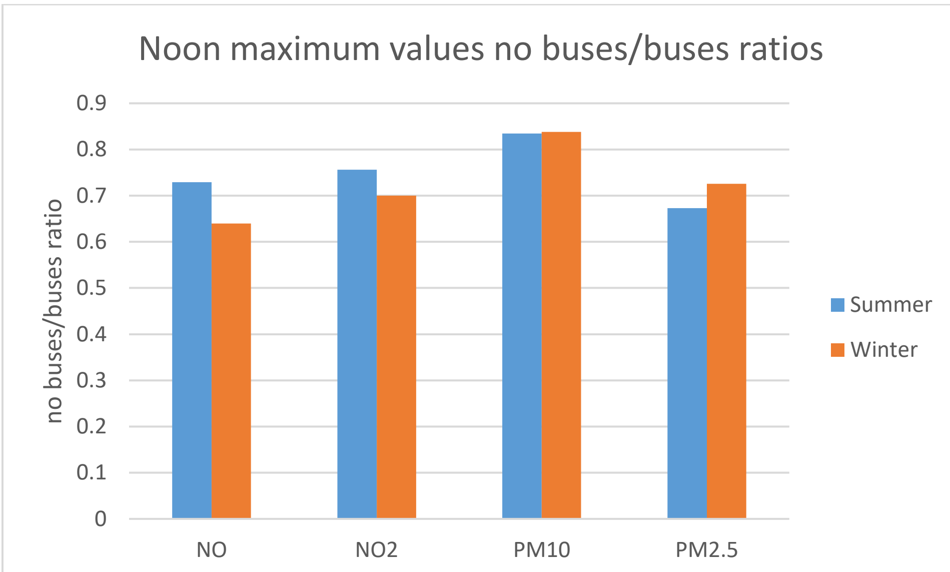

Figure 38. Ratios of maximum pollutant concentration values of no buses and buses

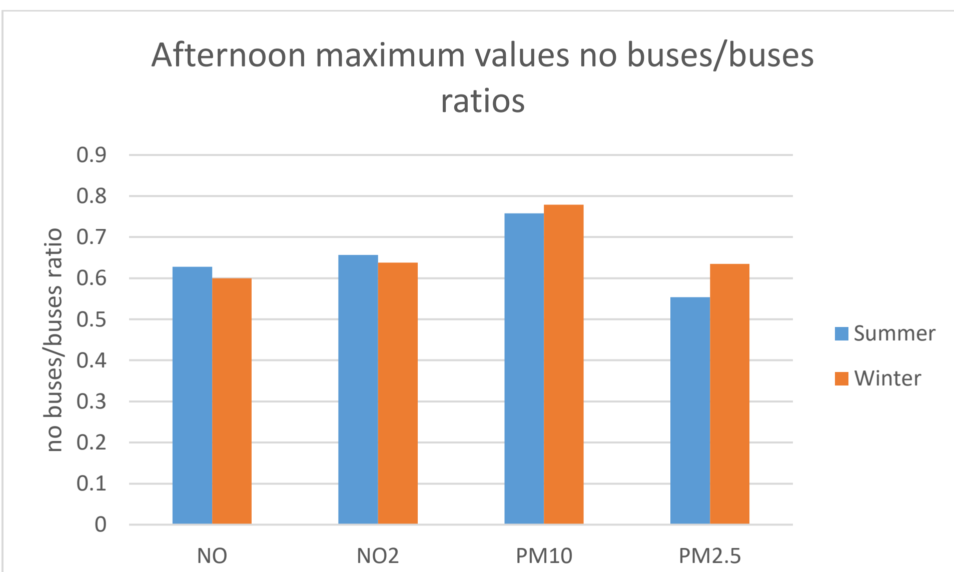

Figure 39. Ratios of maximum pollutant concentration values of no buses and buses

Figure 40, Figure 41, and Figure 42 show plots of the computational domain with the concentration of pollutants in the Summer afternoon for NO, NO_2, and PM10, respectively. The concentrations were taken at an elevation of 2 m. R-Line only analyzes physical dispersion processes; chemical atmospheric processes are not performed by the model (Zhai et al. 2016). Therefore, high NO and low NO_2 concentration were observed since NO does not react to produce NO_2. In the model, fresh emissions from vehicles do not have any interaction with the surrounding pollutants. In the case of PM, concentrations were lower compared to the measurement campaigns, since R-Line only estimates traffic-related concentration. Therefore, other sources of PM are not observed in the model. Based on these results, the concentration of NOx in Boulder Downtown is highly traffic-related, but traffic-related PM is a small contribution to the total PM level. Our results seemed similar to a study developed in Atlanta (Zhai et al. 2016). The concentration in their study was between 50-100 ppb for NOx and 0.5-2 μg/m^3 for PM2.5 in most of the streets.

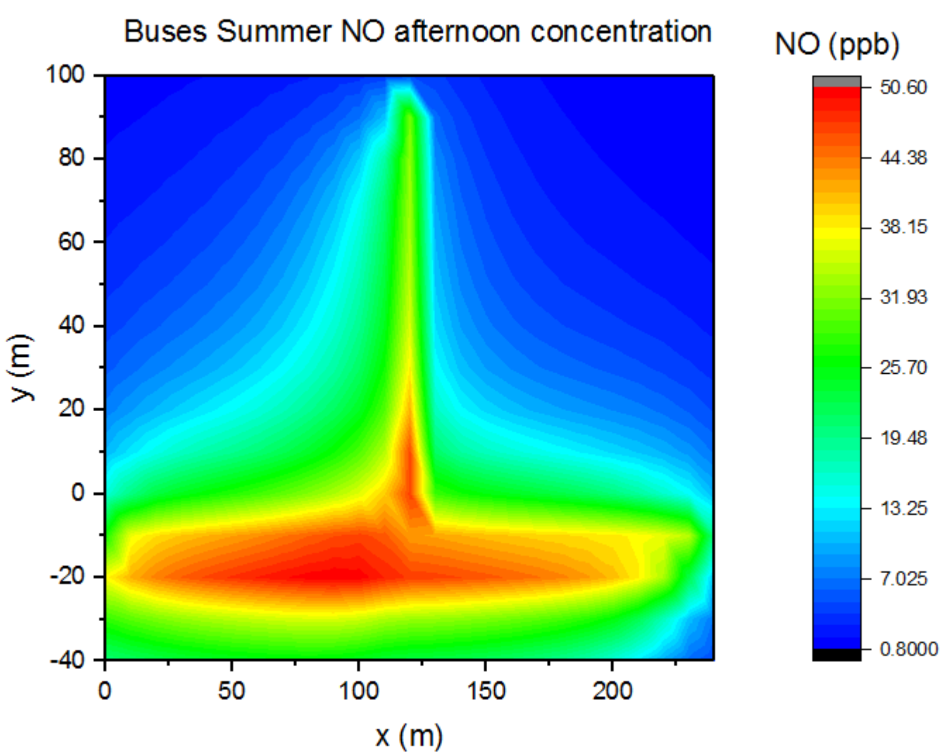

Figure 40. Summer NO afternoon concentration with buses

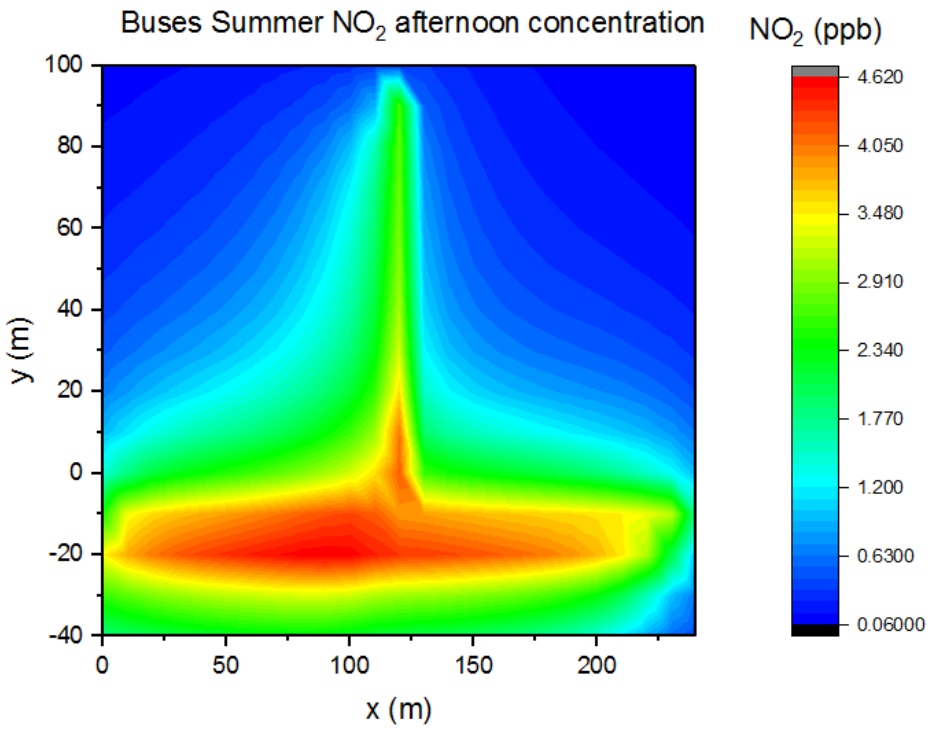

Figure 41. Summer NO_2 afternoon concentration with buses

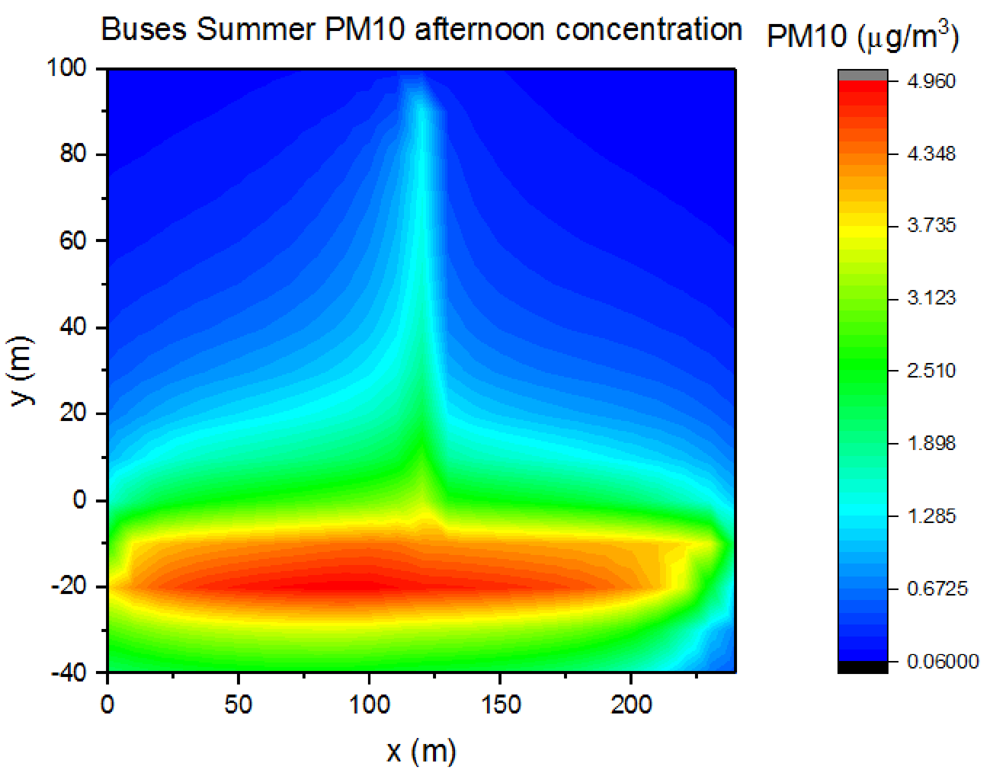

Figure 42. Summer PM10 afternoon concentration with buses

As an example of the difference in concentration with and without buses, Figure 43 and Figure 44 show the PM2.5 concentration with buses and BDS, and without buses and BDS, respectively. The maximum value with buses was about 1.8 times higher than the model without buses. It must be noted that the model has only a portion of Canyon Boulevard and all the surrounding streets are not included. Therefore, a smaller difference would be expected when considering all the surrounding streets. R-Line contour plots are presented in the Appendix J.

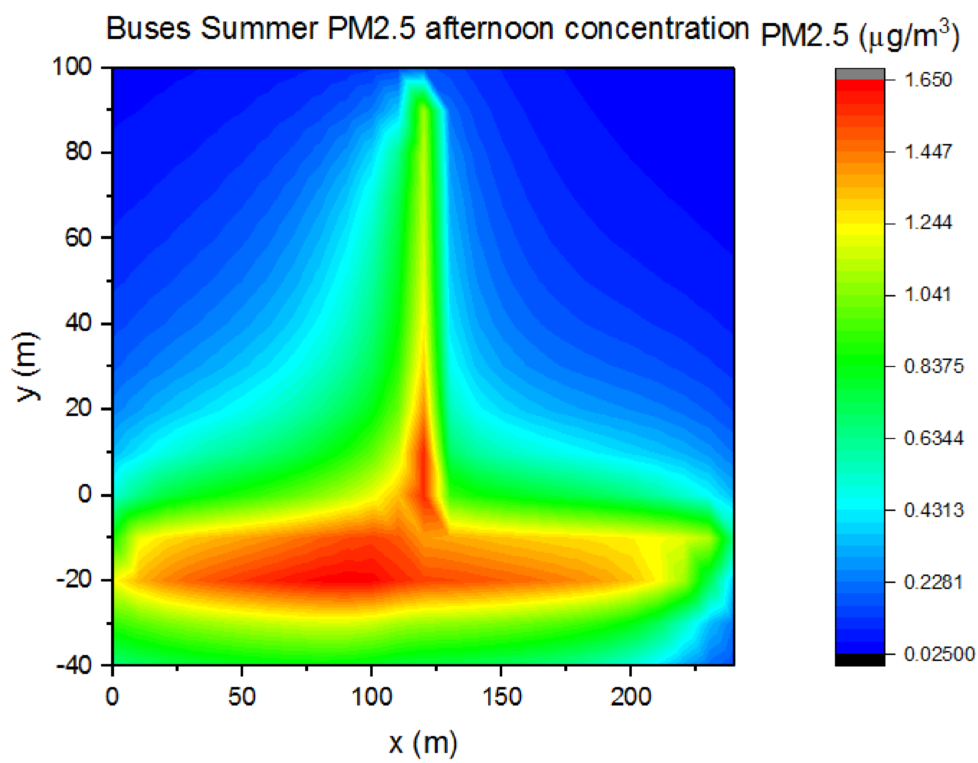

Figure 43. Summer PM2.5 afternoon concentration with buses

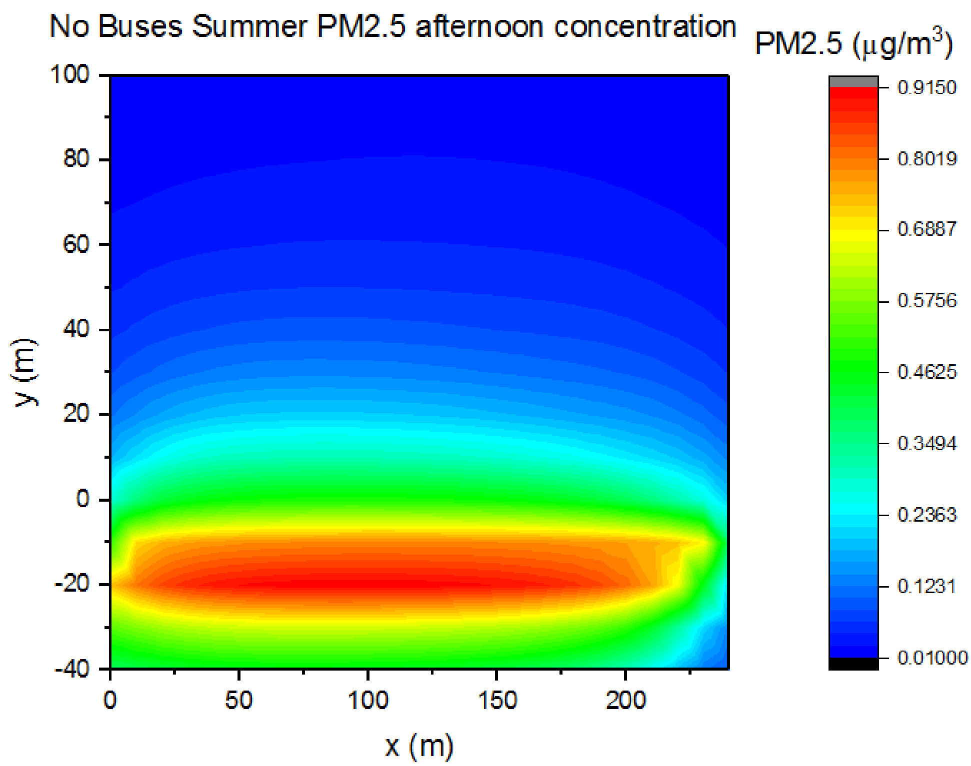

Figure 44. Summer PM2.5 afternoon concentration without buses

Pollutant Relationships

In this section, the relationship of pollutants is analyzed to obtain possible connections between pollutants to traffic-related emissions. Summer and Winter stationary measurement results are studied, as well as the data collected during the bicycle rides.

The daily BC/PM2.5 ratios in Summer averaged between 0.12 and 0.34, indicating that BC represented up to one-third of the total PM2.5 concentrations. According to Medina, Mancilla, and Mendoza (2016), BC/PM2.5 emission ratios of diesel vehicles range between 0.1 and 0.4. Our results show high agreement to this statement. Unfortunately, it was not possible to analyze the BC/PM2.5 ratios in Winter, since PM2.5 data were not collected. Figure 45 shows the daily BC/PM2.5 ratios of the stationary measurements.

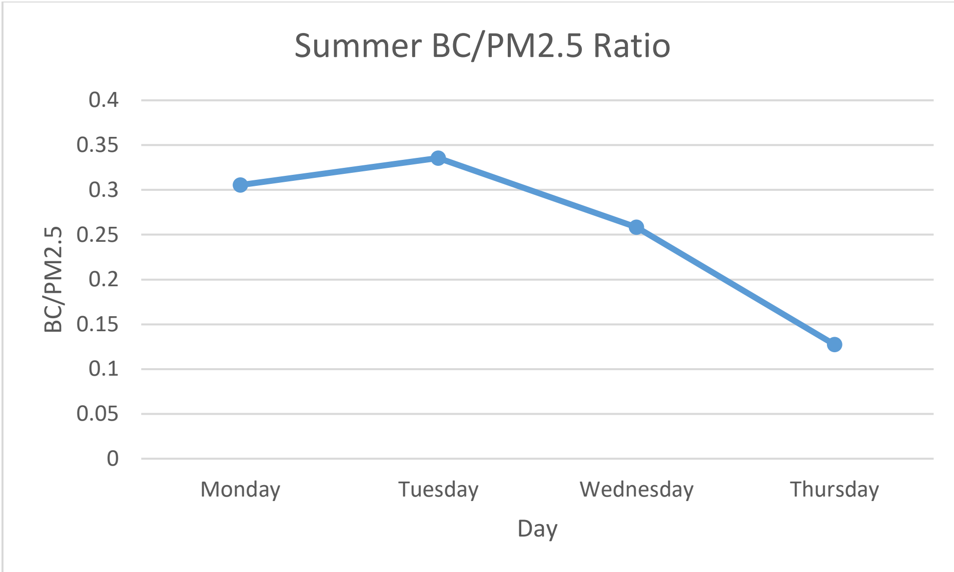

Figure 45. BC/PM2.5 daily Summer ratios

NO and BC were studied the find possible signs of diesel vehicle emissions. NO and BC are both emitted by diesel engines; however, NO reacts quickly with ozone to become NO_2. In addition, other sources of NO and BC can be independent. Therefore, sometimes it is difficult to see a relationship between NO and BC. Figure 46 and Figure 47 show scatter plots of NO and BC concentration in Summer and Winter, respectively. The outcome observed in Winter showed a higher agreement. The reason for this is probably the higher concentrations of NO in the Winter, and also low concentrations of ozone in Winter.

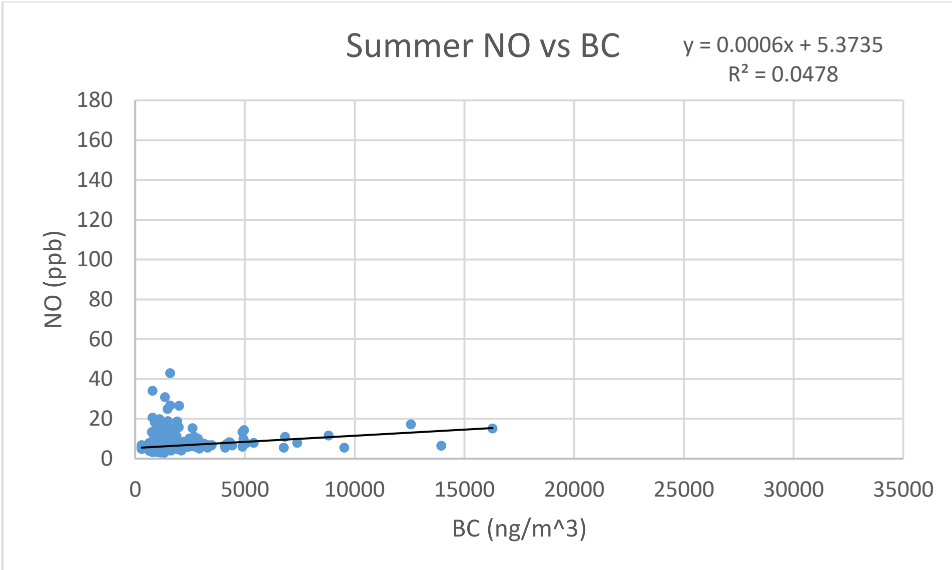

Figure 46. NO and Black Carbon concentration in Summer

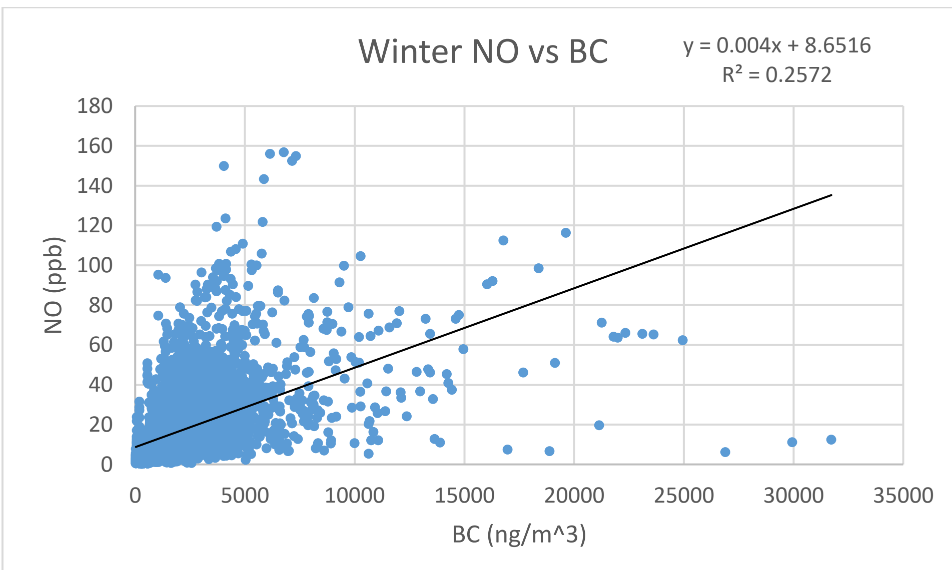

Figure 47. NO and Black Carbon concentration in Winter

NOx and BC were also studied to include the effects of NO_2, since it is a product of the reaction of NO with ozone. Figure 48 and Figure 49 show scatter plots of NOx and BC in Winter and Summer, respectively. The trends of NOx and BC, and NO and BC were similar. In Winter, pollutant levels were higher, and the plots show a better agreement.

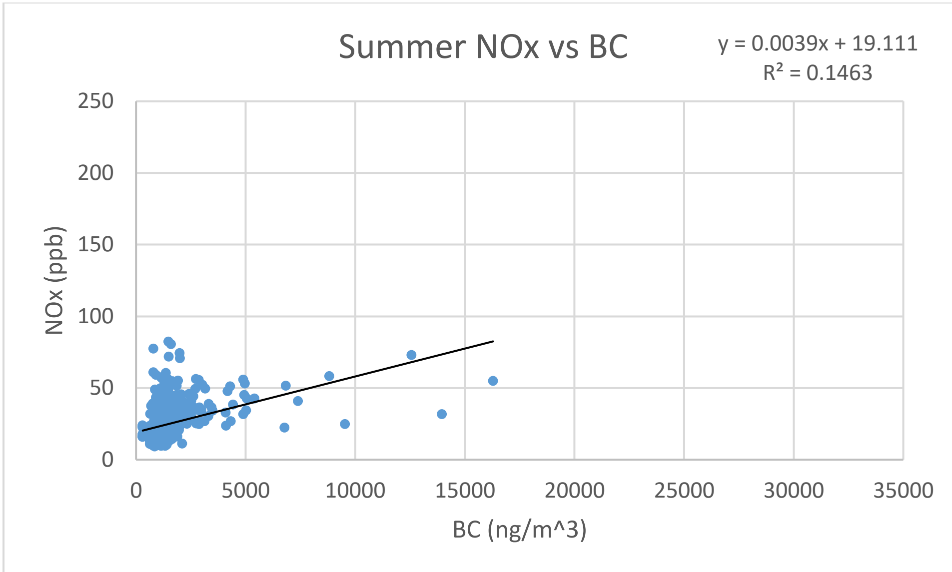

Figure 48. NOx and Black Carbon concentration in Summer

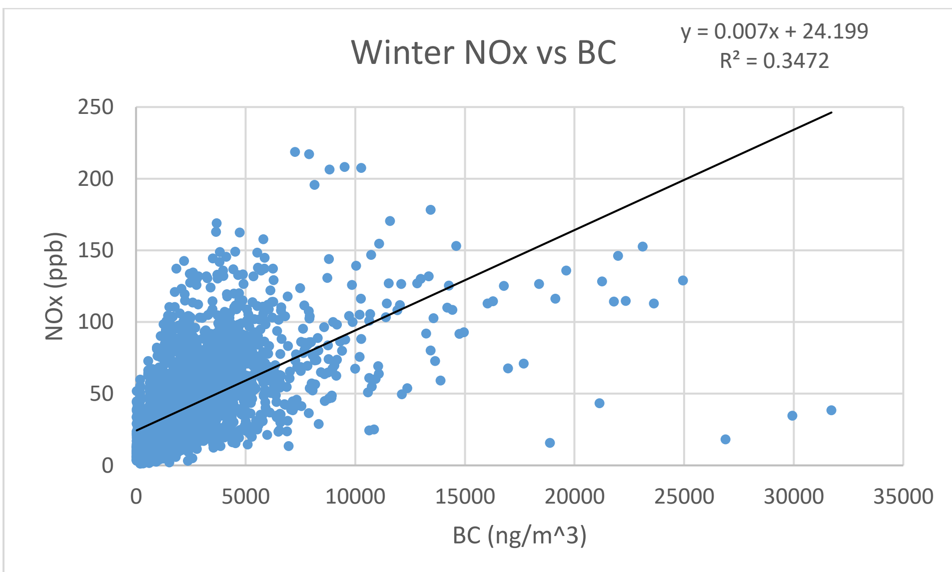

Figure 49. NOx and Black Carbon concentration in Winter

Fresh emissions of NO were compared to NO_2 to understand seasonal variations. Figure 50 and Figure 51 show scatter plots of NO and NO_2 in Summer and Winter, in that order. The result in Summer showed that NO is lower than NO_2 at almost any concentration. The outcome in Winter presented a different trend. As the concentration of NO_2 becomes higher NO increases rapidly, surpassing the levels of NO_2. An exponential pattern was observed in the Winter season, while Summer had a linear trend.

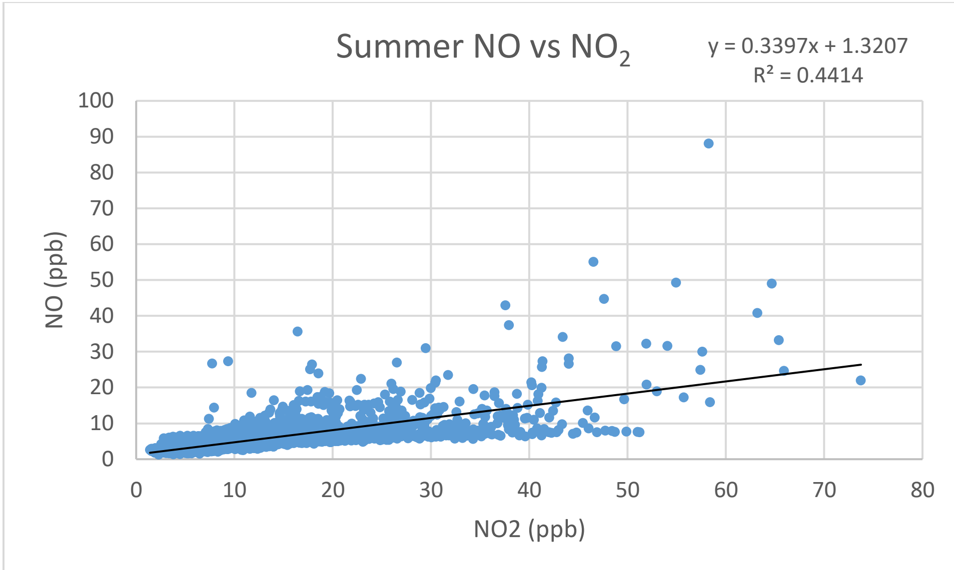

Figure 50. NO and NO_2 Summer concentration

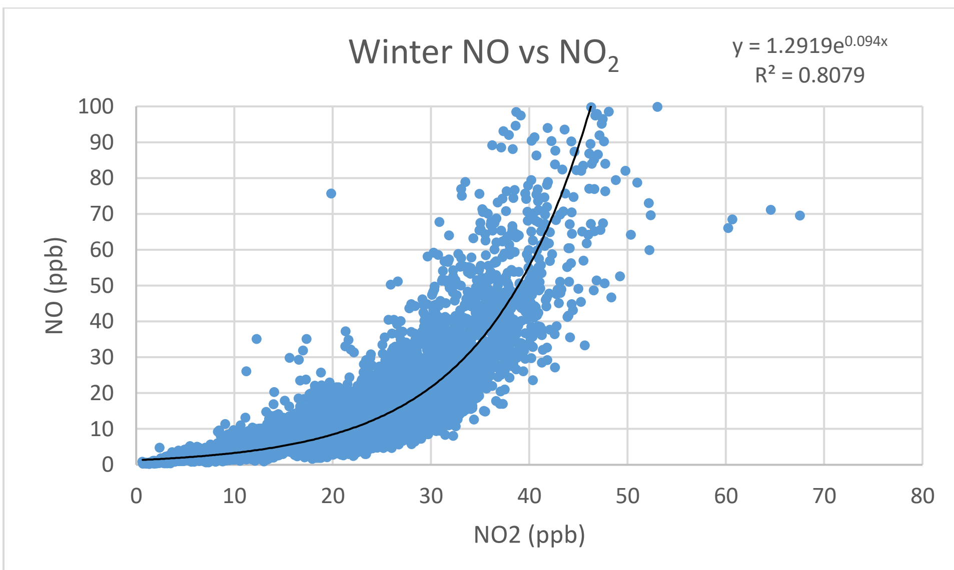

Figure 51. NO and NO_2 Winter concentration

The data collected during the bicycle rides provided useful information about the frequency that a concentration of BC was observed, compared to its frequency based on stationary measurements. Figure 52 show the cumulative BC fraction of all the collected data during the stationary measurements (blue line), entire bicycle trips (orange line), and only moments where buses were chased (gray line). Surprisingly, the bicycle trips had a bigger portion of the cumulative fraction than the stationary measurements until a concentration of 8.2 μg/m^3. After this value, the cumulative fraction of BC in bicycle trips is lower than in stationary measurements; indicating a higher frequency at bigger concentrations. In the case of moments were buses were chased, the cumulative fraction is always lower, as expected; since higher BC levels were observed.

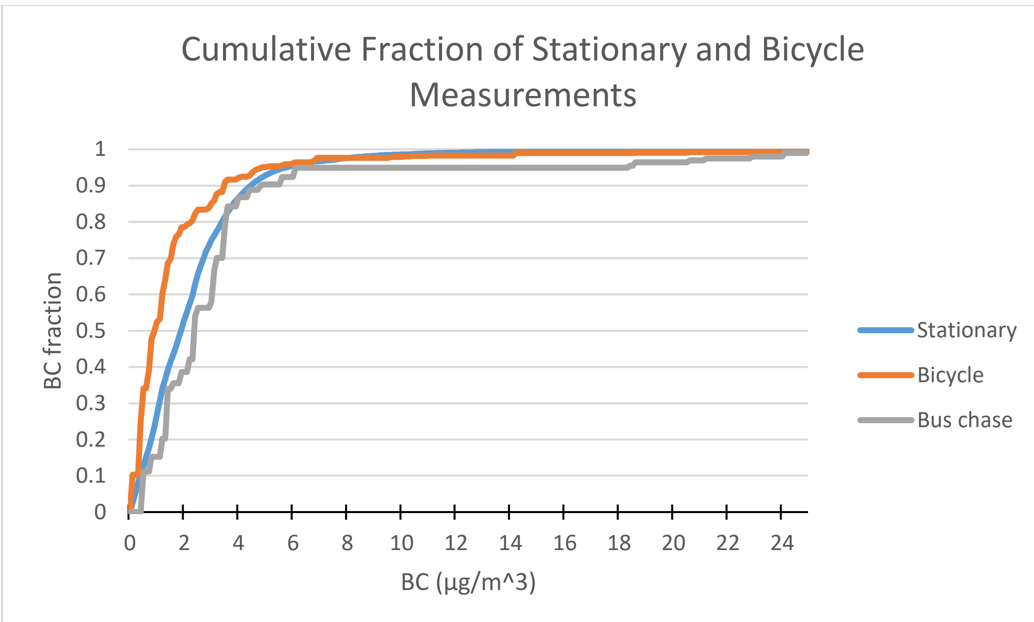

Figure 52. Black Carbon cumulative fraction

Chapter IV: Conclusions and Future Research

Conclusions

This study was carried out to estimate the impact of diesel buses on Downtown Boulder's air quality. The focus was Black Carbon (BC), Ozone (O_3), Nitrogen Oxides (NOx), and Particulate Matter (PM). Measurement campaigns were conducted in Summer and Winter for a period of one week in each season to have a better understanding of the seasonal and traffic-related pollution. An apartment complex next to the Boulder Downtown Bus Station (BDS) was the stationary measurement site. BC mass concentration was measured with an aethalometer. Ozone was measured using an ozone personal monitor (POM). NO and NO_2 were measured with a chemiluminescence NOx analyzer. Using a condensation particle counter (CPC), ultra-high sensitivity aerosol spectrometer (UHSAS), and aerodynamic particle sizer (APS), the nanoparticle number, ultrafine PM number, and PM2.5 and PM10 mass concentrations were measured.

Stationary measurements did not have a pattern related to the bus count. Time periods with a high bus count also had a high traffic volume. The concentration of pollutants seemed to be more related to seasonal pollution trends and dominated by regional sources and meteorology. Only NOx and particle number concentration experiments in Winter looked similar to the traffic volume. On many occasions, BC did not increase when the traffic density had an increase; Winter showed a higher daily mean than Summer for BC. O_3 usually had a reduction when the traffic increased and increased when the traffic decreased. This is expected since fresh emissions of NO scavenges ozone and so roadway measurements usually show depressed ozone. As expected, Summer O_3 was at least six times higher than Winter O_3. Summer NOx only had similar behavior to the traffic increment in the late afternoon. As mentioned before Winter NOx increased with the traffic rise and decreased with the reduction of the traffic. Additionally, Winter NOx was higher than NOx in

Summer. Nanoparticles and ultrafine PM did not follow traffic patterns in Summer. However, Winter concentration had a similar trend. Nanoparticles had about 10 times higher number concentration than ultrafine PM. Particle number concentration was usually higher in Winter than in Summer, especially ultrafine PM, which is consistent with previous studies of PM seasonal trends in the front range. PM mass concentration in Summer had a constant or decreasing tendency when the number of buses increased in the afternoon. Unfortunately, PM mass measurements in Winter were not taken due to the low temperatures. All measurements of ozone, NO_2, PM2.5 and PM10 mass concentration were below the NAAQS.

Five bicycle rides were carried out to measure fresh emissions of buses and vehicles on-road. The purpose of the experiments was to chase buses and vehicles as close as possible to capture emissions from the exhaust. A portable aethalometer, CPC, and POM were used during the bicycle rides. Since measurements also included zones with a few number of vehicles, the daily mean values for BC and PM were higher during the stationary measurements. However, higher peaks and maximum values were observed in bicycle rides. Emissions from vehicles did not cause a considerable rise in the BC levels. In the case of buses, emissions seemed to be route dependent. Some routes always had high BC concentrations and the highest peaks of the day. On the other hand, other routes did not show any effect on the readings. The aethalometer had some problems measuring BC, since the light attenuation system, on occasions, did not increase between measurement intervals. This effect usually occurred during periods with low BC levels. The O_3 mean and maximum values were lower in stationary measurements.

The Motor Vehicle Emission Simulator (MOVES) and R-Line dispersion model were used to model emissions at noon and afternoon; in both cases in Summer and Winter. In addition, for these cases two scenarios were modeled. One experiment consisted of a simulation on Canyon

Boulevard and at the Boulder Downtown Bus Station (BDS). In the second experiment, buses on Canyon and BDS were excluded from the simulation. The goal was to quantify the effects of diesel buses in the total pollution level on Downtown Boulder. MOVES was employed to estimate the mass emission rates of NO, NO_2, PM10 and PM2.5. Buses emitted more NOx in Winter than Summer, while PM was virtually the same. MOVES also showed that the Canyon general traffic produced more NOx and less PM production in Summer, while Winter showed less NOx and more PM. The R-Line dispersion model was used to estimate the concentration of pollutants in BDS and a portion of Canyon. The MOVES emission outputs were used as source inputs in R-Line. The ratios of concentration without buses, and with buses and BDS ranged between 0.55-0.84. This result indicates that 16-45% of the pollutant concentrations are attributable to buses. The afternoon simulations had the lowest ratios, which can be attributed to a higher number of buses. The NOx ratios were higher in Summer, while the PM ratios were higher in Winter.

Future Research

The use of a stationary location such as a condo balcony as a monitoring station did not provide data to directly relate all the pollutants to the traffic patterns. Some alternatives can be used to measure emissions directly on the road. Remote sensing technologies can measure emissions from every vehicle passing through. In this way, emissions of diesel buses and other vehicles could be studied, in detail. These kinds of systems have been used to estimate emission factors of several pollutants (Chan and Ning 2005; Moosmüller et al. 2003). The systems are usually composed of ultraviolet and infrared detecting lights that determine vehicle emissions, and can also measure vehicle speed; measurements are taken in real time. Other methods that could be used are on-board systems that are connected to the vehicle exhaust. On-board equipment can be installed in diesel buses to measure their emissions from the exhaust of the tailpipe. Barrios et al. (2011) reported great results using this technique.

A problem with the chasing technique by using a bicycle was that it was not always possible to keep up with the bus and vehicle speeds even on an electric bicycle. Additionally, in some streets the traffic flow was very fast; therefore, on some occasions it was necessary to ride on the sidewalk. The use of a mobile emission laboratory would allow the capture of fresh emissions from any vehicle and the ability to remain close to vehicles for a longer time. Fruin et al. (2008) carried out a study using a mobile monitoring vehicle, in which several pollutants were successfully measured in freeways, arterials, and residential zones.

A four-season study is recommended for an understanding of the general trend of pollutants in Downtown Boulder throughout the year. This research consisted of only one week of measurements per season, and there might be variations every week that were not observed in the study, especially due to weather patterns. A longer campaign of measurements is also recommended.

The modeling analysis only constituted of one street in Downtown Boulder and the bus station. Traffic information for every downtown street most be obtained to simulate a larger scale model representative of the entire area. Implementation of methods that incorporate the effects of chemical processes and atmospheric pollution would increase the accuracy of the computational solution.

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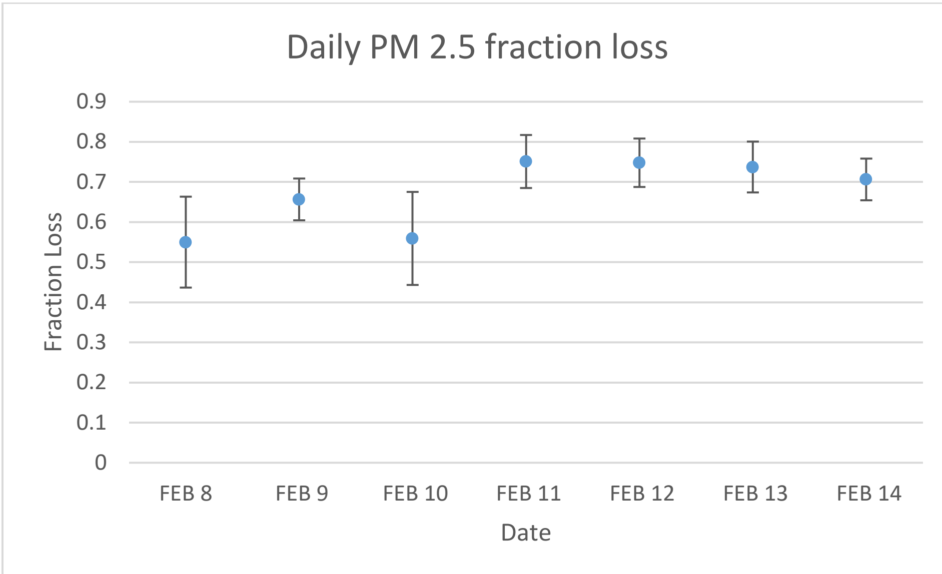
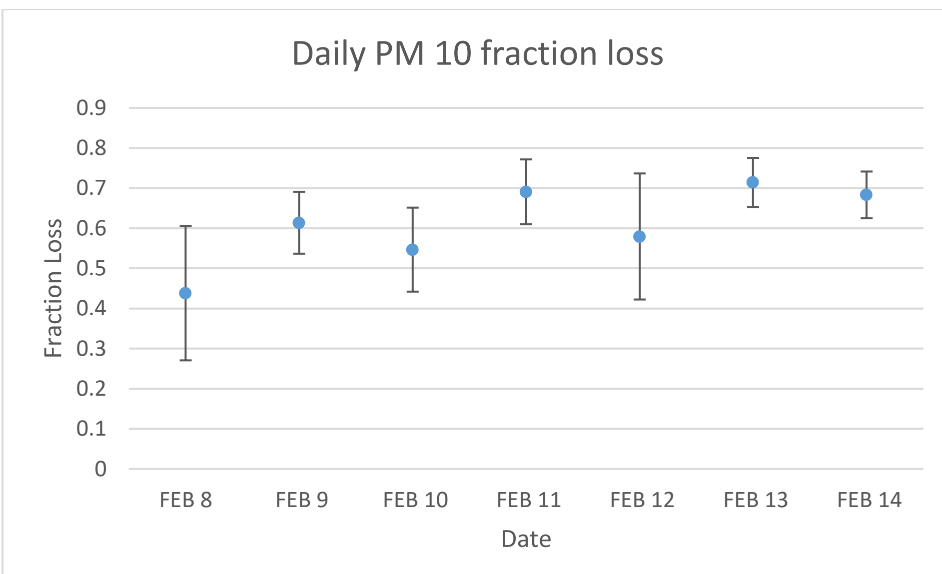
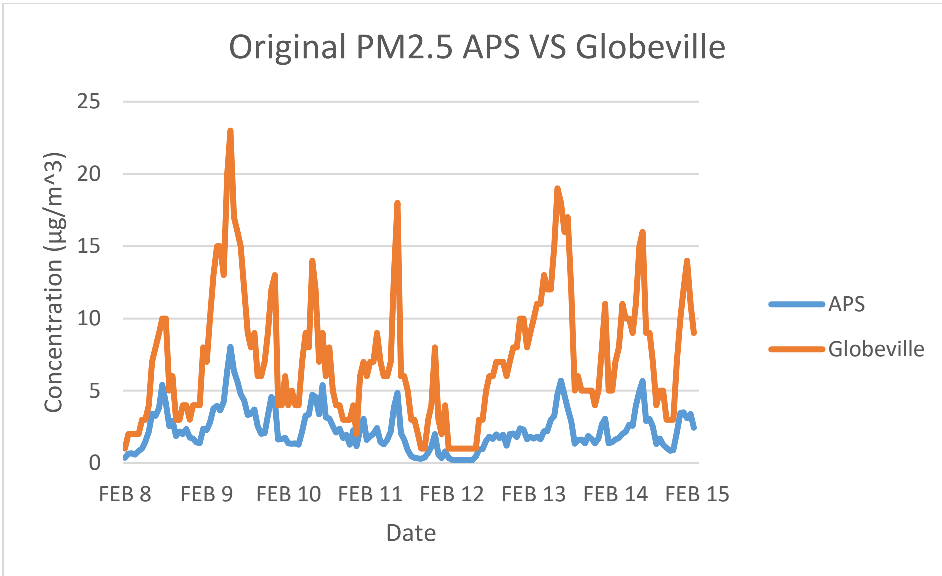
Appendix A: Globeville APS Collocation Plots



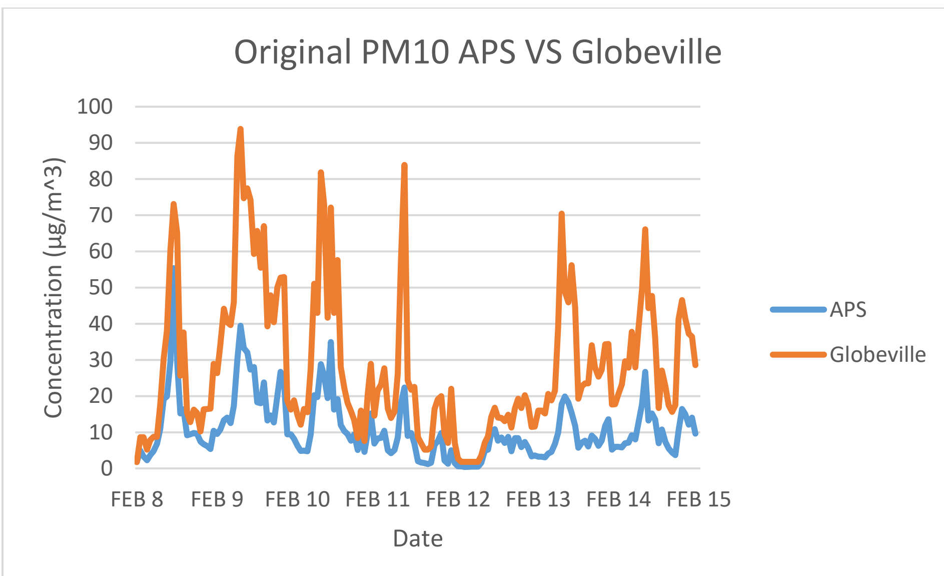
Daily PM2.5 fraction losses



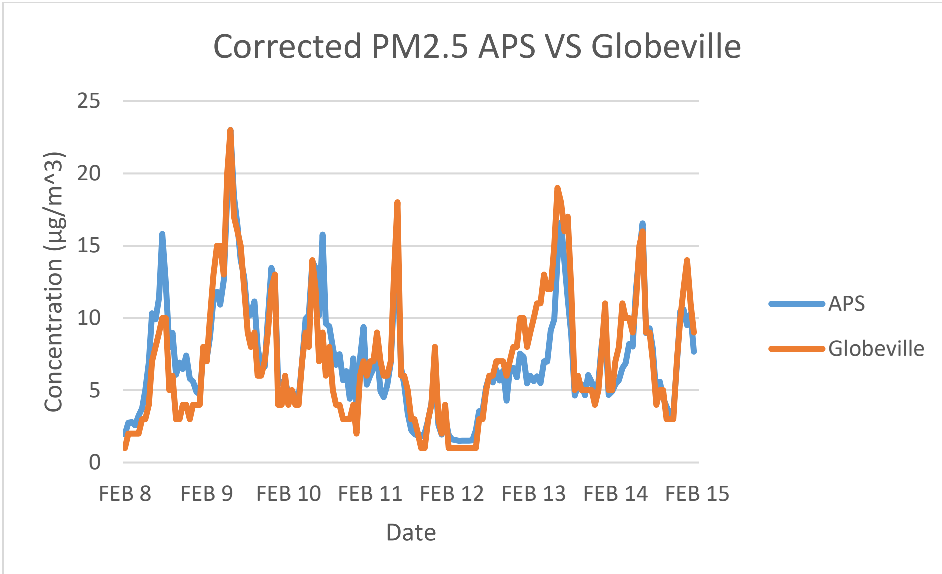
Daily PM10 fraction losses



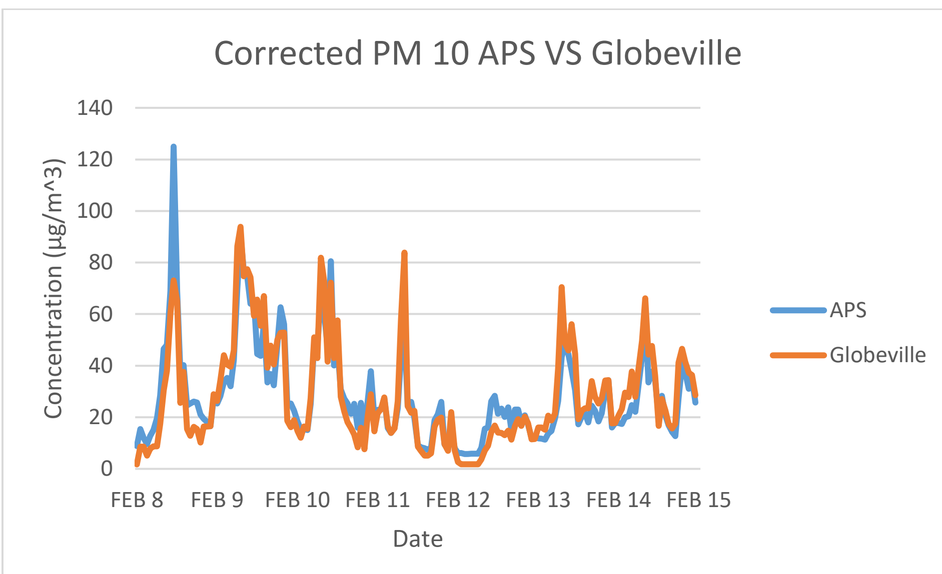
Original APS and Globeville PM2.5 concentration



Original APS and Globeville PM10 concentration

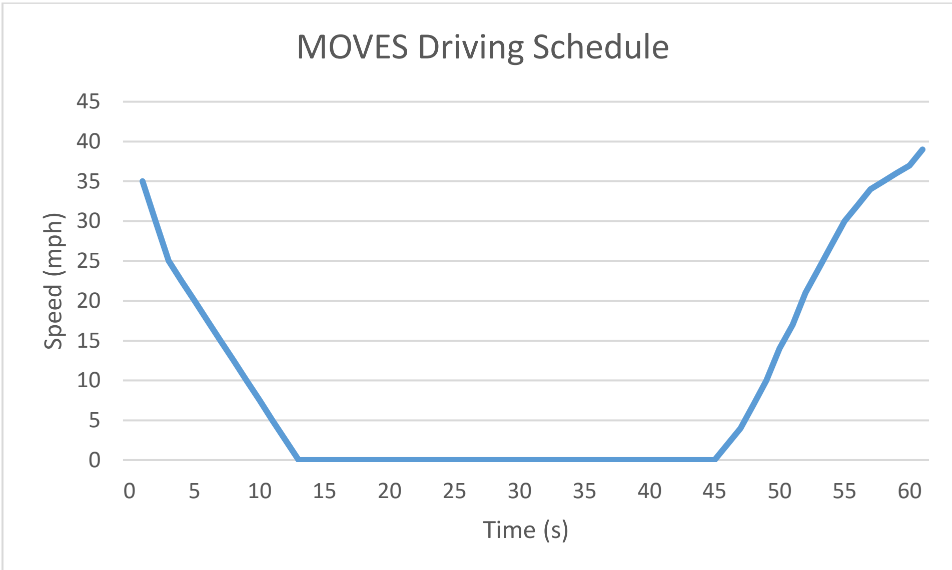


Corrected APS and Globeville PM2.5 concentration



Corrected APS and Globeville PM10 concentration

Appendix B: MOVES Vehicle Information and Weather Condition



MOVES Canyon Boulevard Driving Schedule

Vehicle number and fraction used to estimate mass emission rates

	Summer Vehicles Noon		Summer Vehicles Afternoon		Winter Vehicles Noon		Winter Vehicles Afternoon	
Vehicle type	Number	Fraction	Number	Fraction	Number	Fraction	Number	Fraction
Single unit haul trucks	27.9	0.0141	27.9	0.0130	27.9	0.0140	27.9	0.0130
Combination haul trucks	17.1	0.0086	17.1	0.0080	17.1	0.0086	17.1	0.0080
Buses	45.0	0.0227	75.0	0.0350	53.0	0.0267	80.0	0.0373
Passenger cars	1829.5	0.9240	1956.3	0.9137	1829.5	0.9203	1956.3	0.9116
Passenger trucks	60.5	0.0305	64.7	0.0302	60.5	0.0304	64.7	0.0301

Number of vehicles per year in Boulder

Year	Number of Vehicles
1900	3
1907	1
1919	1
1922	1
1923	4
1924	1
1925	3
1926	1
1928	6
1929	12
1930	11
1931	8
1932	10
1933	4
1934	3
1935	14
1936	13
1937	3
1938	2
1939	8
1940	6
1941	15
1942	3
1944	2
1945	4
1946	31
1947	15
1948	15
1949	24
1950	19
1951	25
1952	18
1953	33
1954	31
1955	37
1956	39
1957	71
1958	27
1959	71

1960	75
1961	51
1962	62
1963	64
1964	95
1965	168
1966	185
1967	175
1968	192
1969	192
1970	274
1971	285
1972	320
1973	343
1974	295
1975	190
1976	294
1977	328
1978	461
1979	404
1980	376
1981	373
1982	563
1983	563
1984	865
1985	965
1986	1261
1987	1491
1988	1512
1989	1801
1990	2149
1991	2830
1992	3049
1993	3603
1994	4311
1995	6112
1996	6854
1997	9310
1998	11009
1999	12828
2000	15272

2001	16458
2002	17955
2003	18198
2004	19756
2005	20476
2006	20567
2007	21338
2008	20467
2009	13063
2010	14190
2011	14697
2012	16531
2013	18126
2014	16398
2015	13668
2016	6021
2017	771
Total	363437

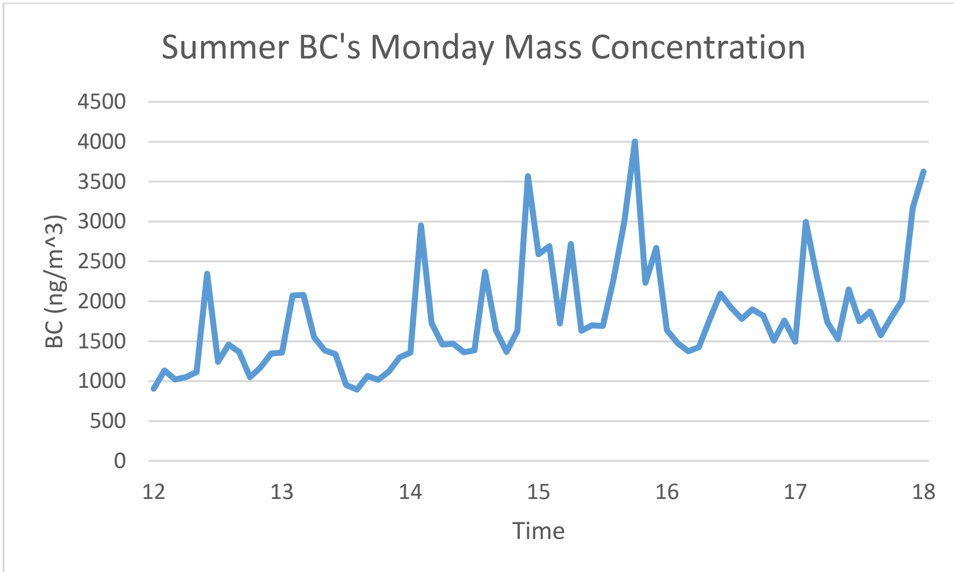
Vehicle fuel type and number in Boulder

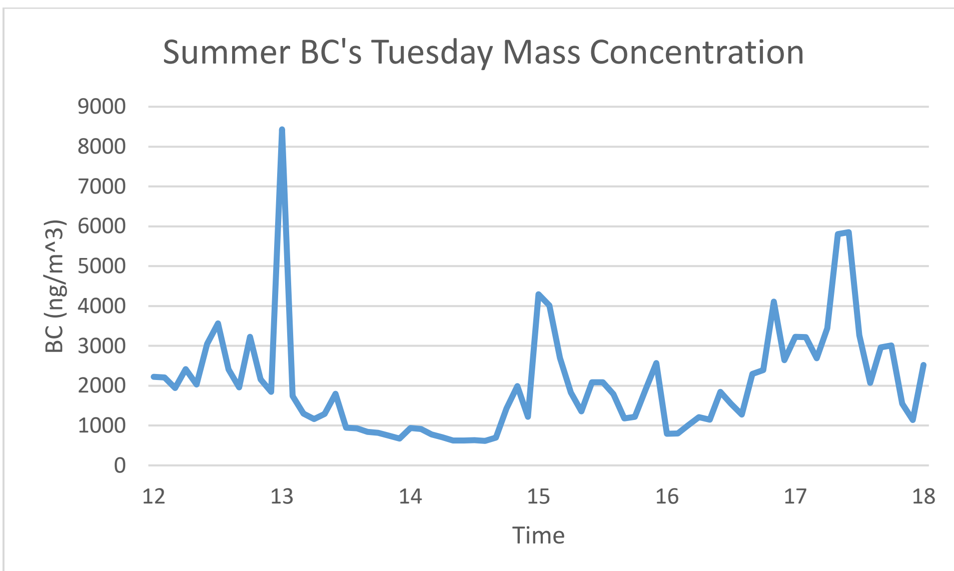
Vehicle type	**Number of vehicles**
Diesel	10348
Electric	1424
Gasoline	304596
Natural Gas	135
Other	13
Propane	61
Propane/Gasoline	11
Natural Gas/Gasoline	34
Methanol/Gasoline	2
Ethanol	13
Ethanol/Gasoline	843
Natural Gas/Diesel	1
Electric/Natural Gas	4
Electric/Diesel	9
Electric/Gasoline	13583

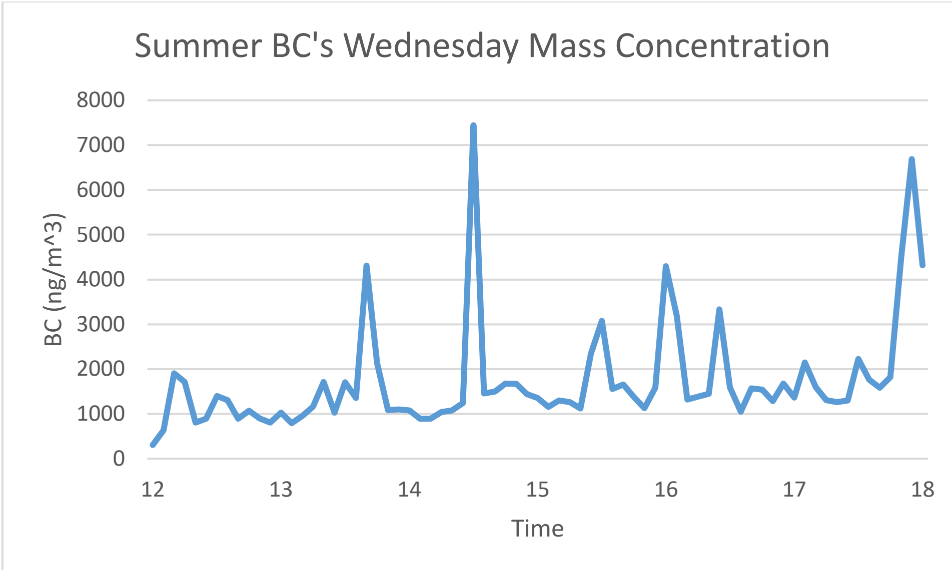
Temperature and relative humidity used in MOVES

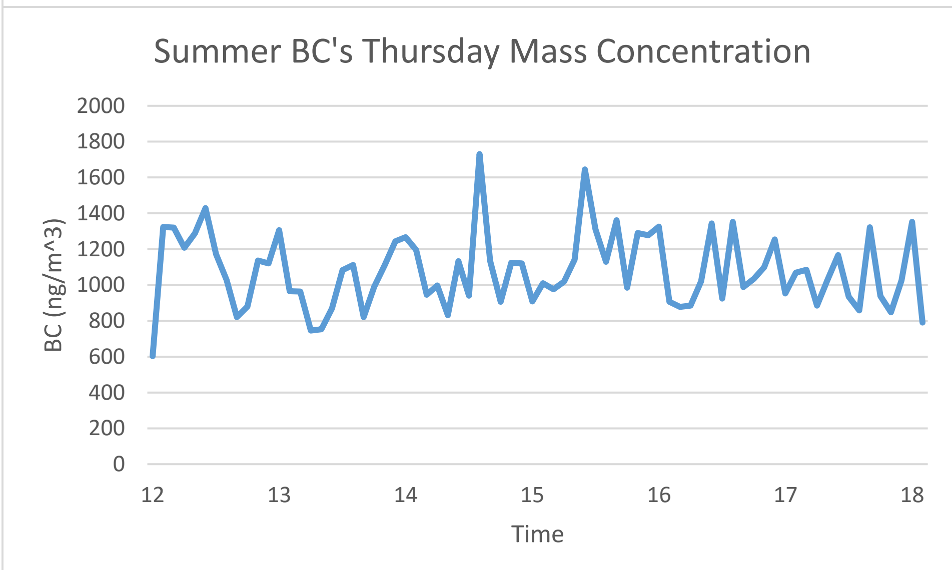
	Summer noon	Summer afternoon	Winter noon	Winter afternoon
Temperature (°F)	82	85	47	49
Relative Humidity (%)	43.5	36.2	38	35

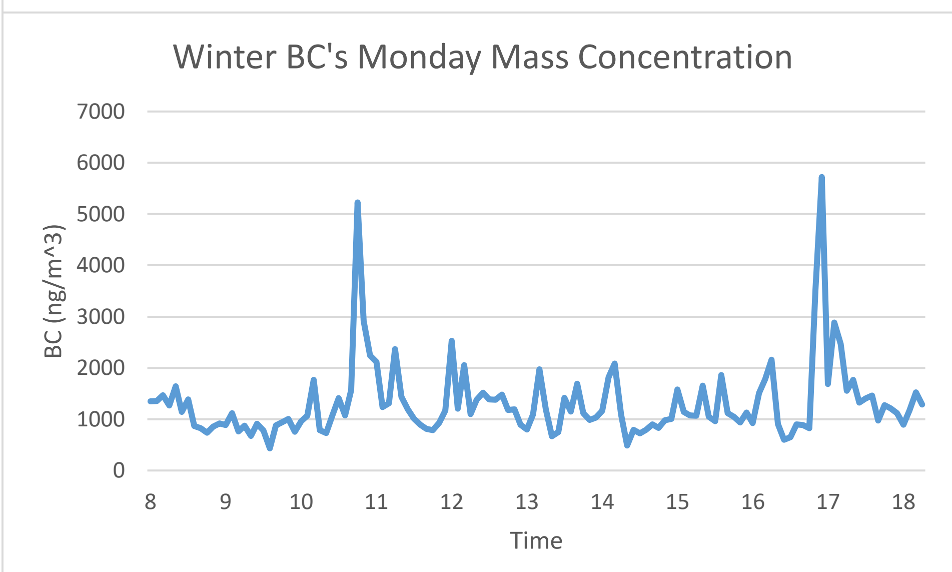
Appendix C: Black Carbon Concentration Plots

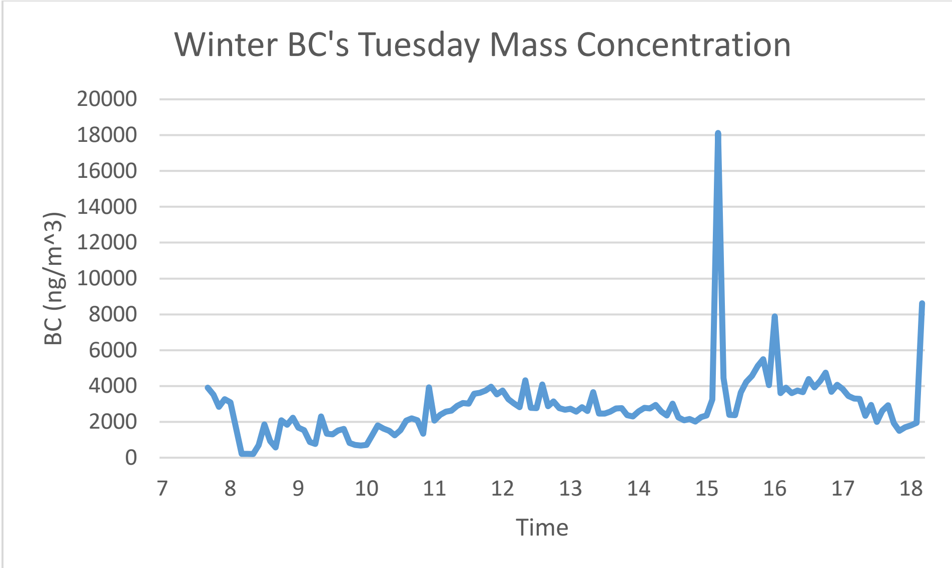




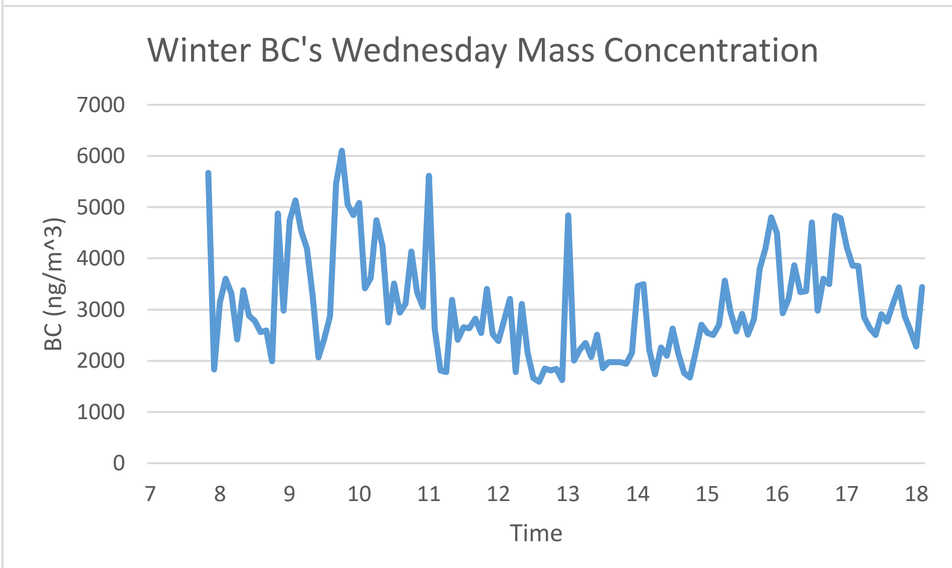

Summer BC's Wednesday Mass Concentration
8000
7000
6000
5000
4000
3000
2000
1000
0
BC (ng/m^3)
12
13
14
15
16
17
18
Time


Summer BC's Thursday Mass Concentration
2000
1800
1600
1400
1200
1000
800
600
400
200
0
BC (ng/m^3)
12
13
14
15
16
17
18
Time

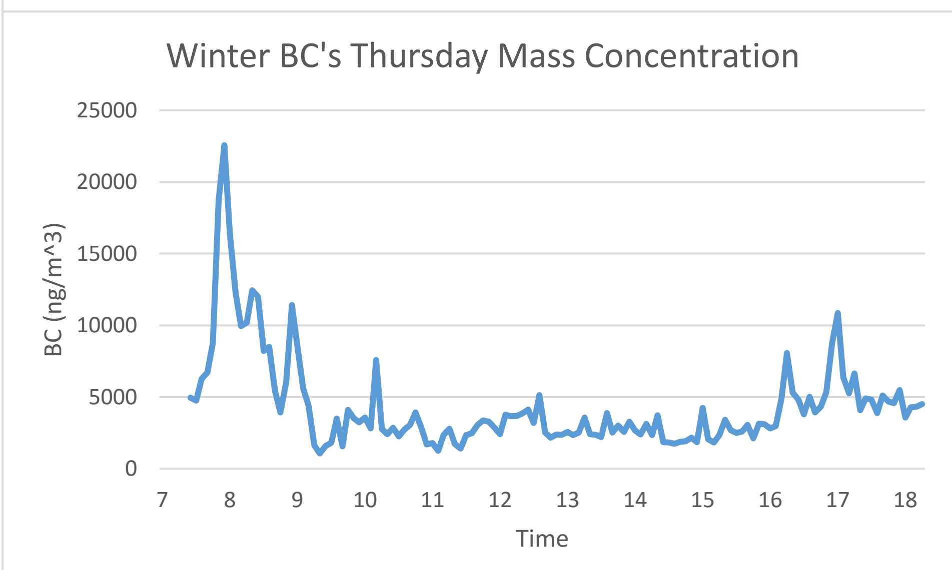

Winter BC's Monday Mass Concentration
7000
6000
5000
4000
3000
2000
1000
0
BC (ng/m^3)
8
9
10
11
12
13
14
15
16
17
18
Time



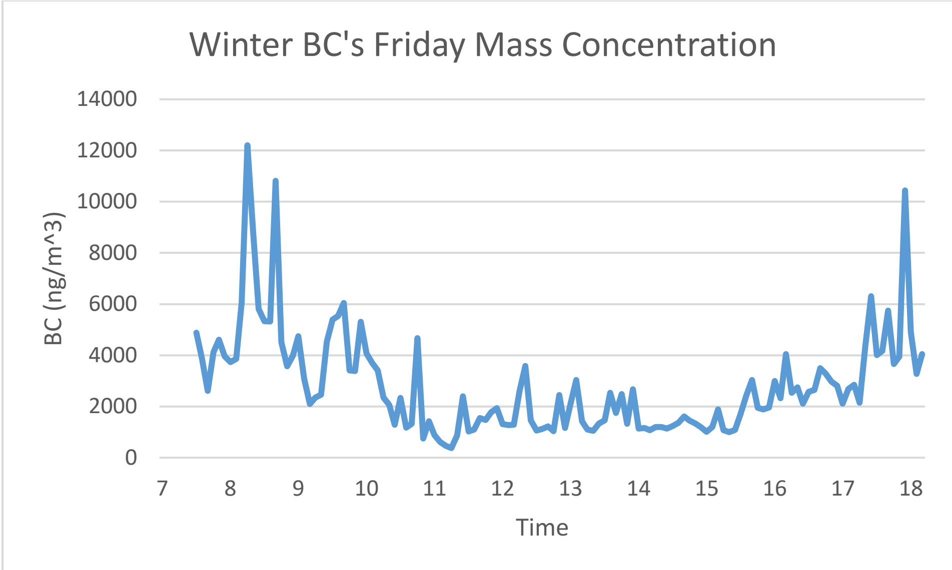
Winter BC's Tuesday Mass Concentration
BC (ng/m^3)
20000
18000
16000
14000
12000
10000
8000
6000
4000
2000
0
7 8 9 10 11 12 13 14 15 16 17 18
Time

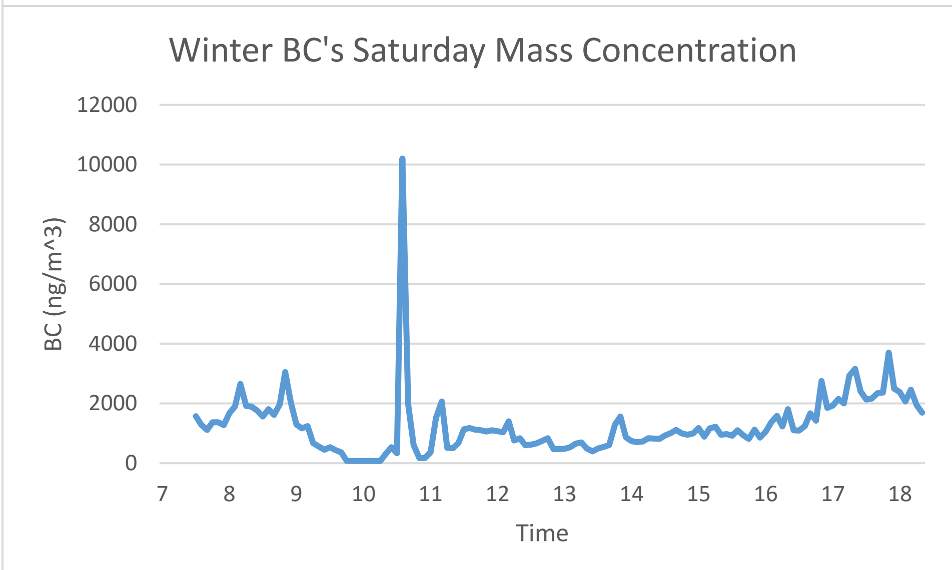


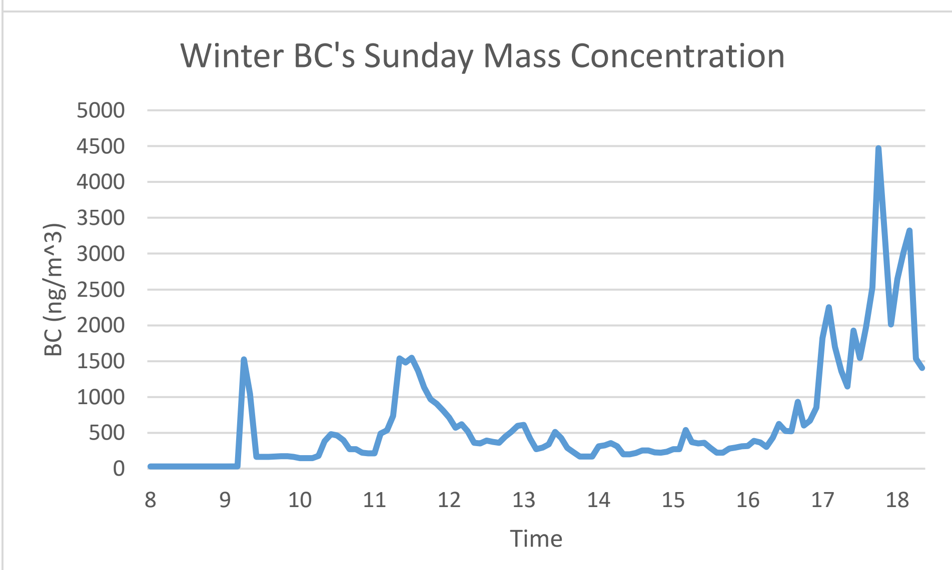
Winter BC's Wednesday Mass Concentration
BC (ng/m^3)
7000
6000
5000
4000
3000
2000
1000
0
7 8 9 10 11 12 13 14 15 16 17 18
Time



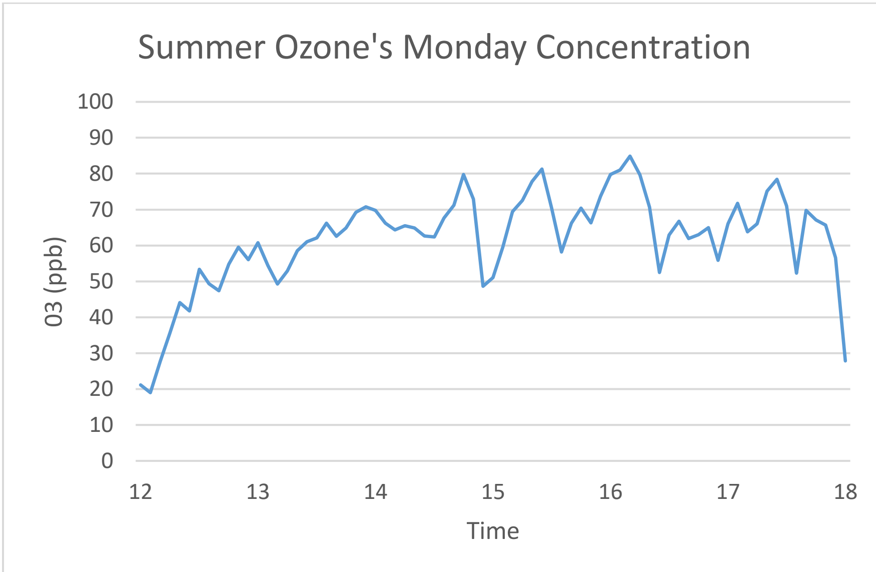
Winter BC's Thursday Mass Concentration
BC (ng/m^3)
25000
20000
15000
10000
5000
0
7 8 9 10 11 12 13 14 15 16 17 18
Time

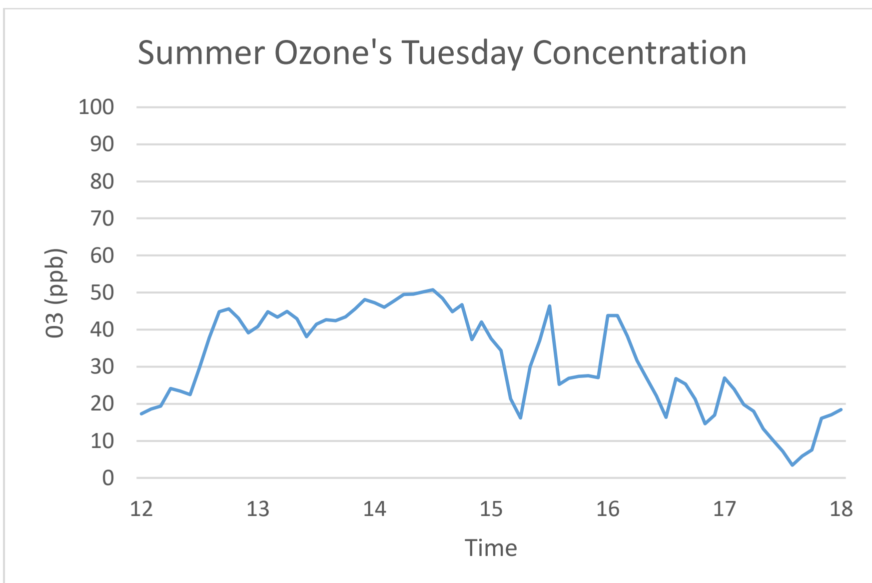

Winter BC's Friday Mass Concentration
BC (ng/m^3)
0
2000
4000
6000
8000
10000
12000
14000
7
8
9
10
11
12
13
14
15
16
17
18
Time

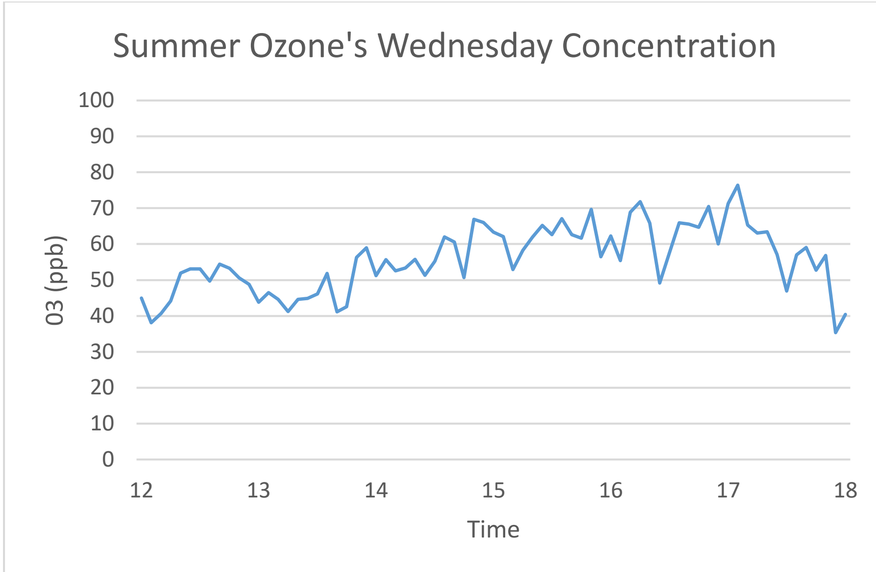

Winter BC's Saturday Mass Concentration
BC (ng/m^3)
0
2000
4000
6000
8000
10000
12000
7
8
9
10
11
12
13
14
15
16
17
18
Time

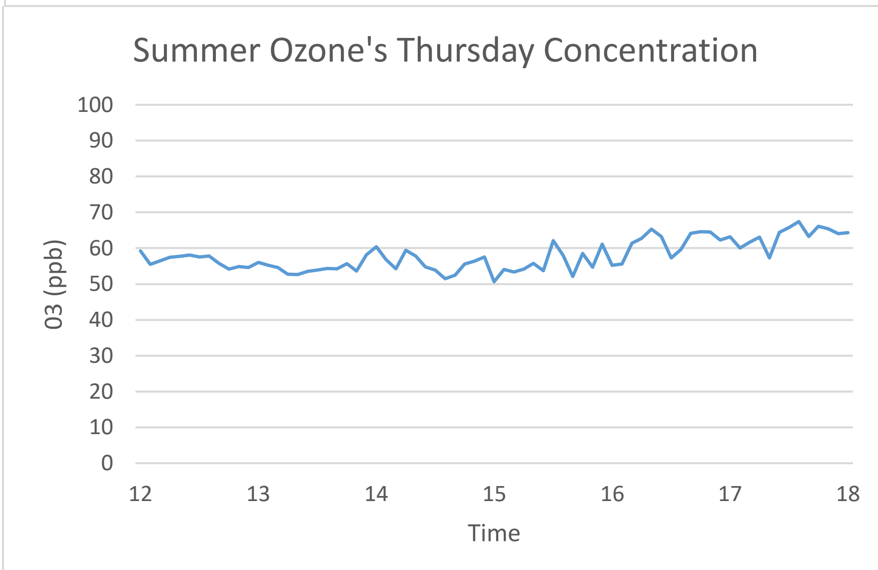

Winter BC's Sunday Mass Concentration
BC (ng/m^3)
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
8
9
10
11
12
13
14
15
16
17
18
Time

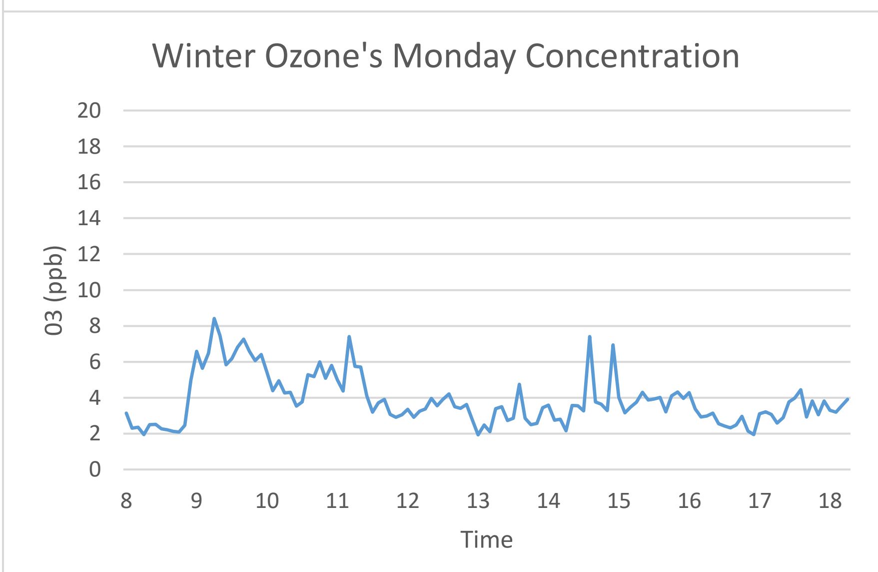
Appendix D: Ozone Concentration Plots

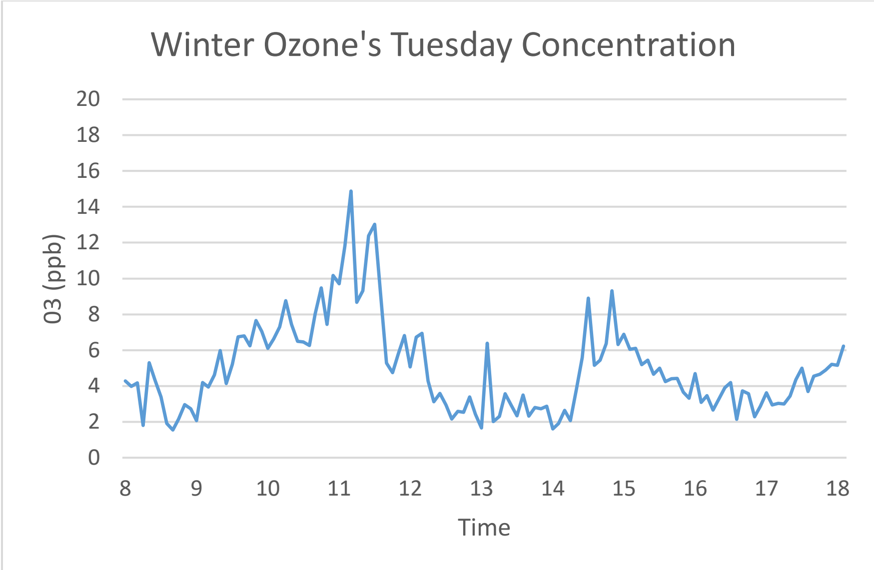


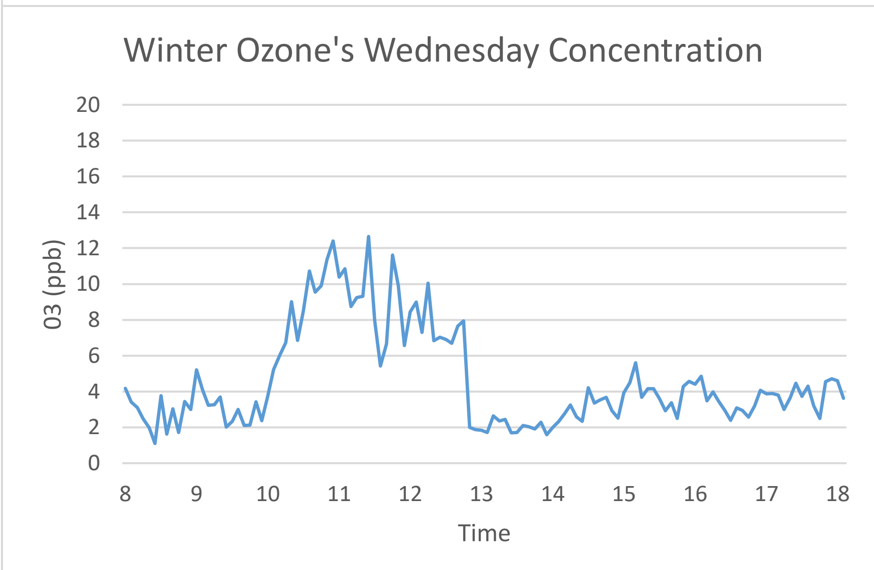


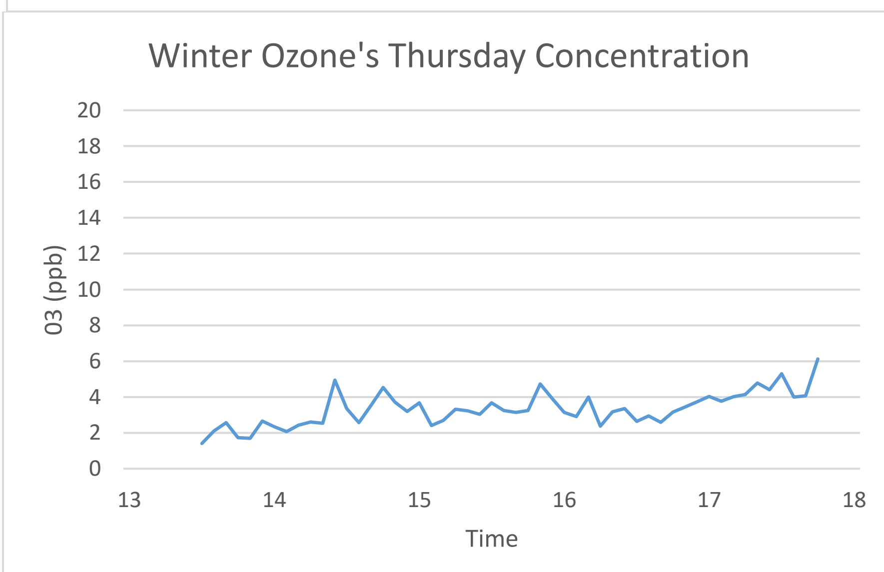

Summer Ozone's Wednesday Concentration
100
90
80
70
60
50
40
30
20
10
0
03 (ppb)
12
13
14
15
16
17
18
Time

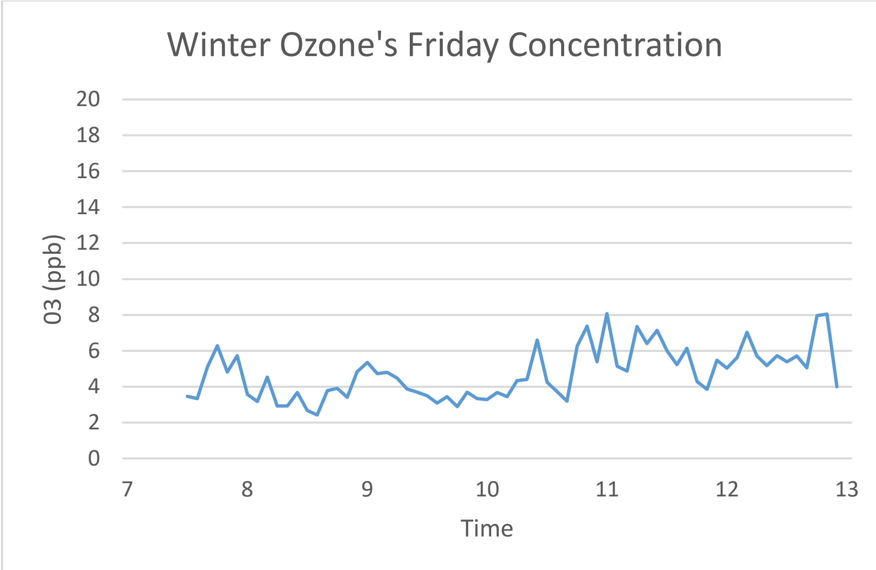

Summer Ozone's Thursday Concentration
100
90
80
70
60
50
40
30
20
10
0
03 (ppb)
12
13
14
15
16
17
18
Time

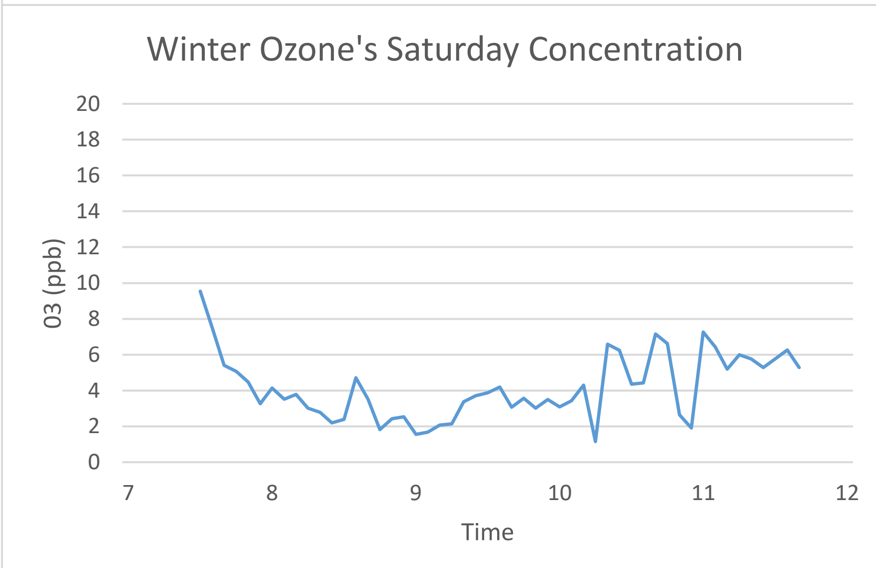

Winter Ozone's Monday Concentration
20
18
16
14
12
10
8
6
4
2
0
03 (ppb)
8
9
10
11
12
13
14
15
16
17
18
Time

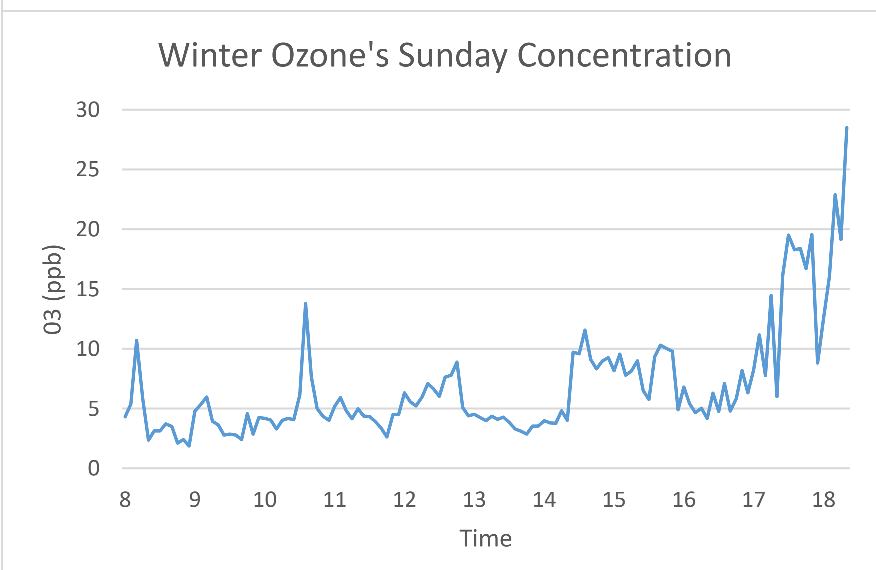

Winter Ozone's Tuesday Concentration
03 (ppb)
20
18
16
14
12
10
8
6
4
2
0
8
9
10
11
12
13
14
15
16
17
18
Time


Winter Ozone's Wednesday Concentration
03 (ppb)
20
18
16
14
12
10
8
6
4
2
0
8
9
10
11
12
13
14
15
16
17
18
Time

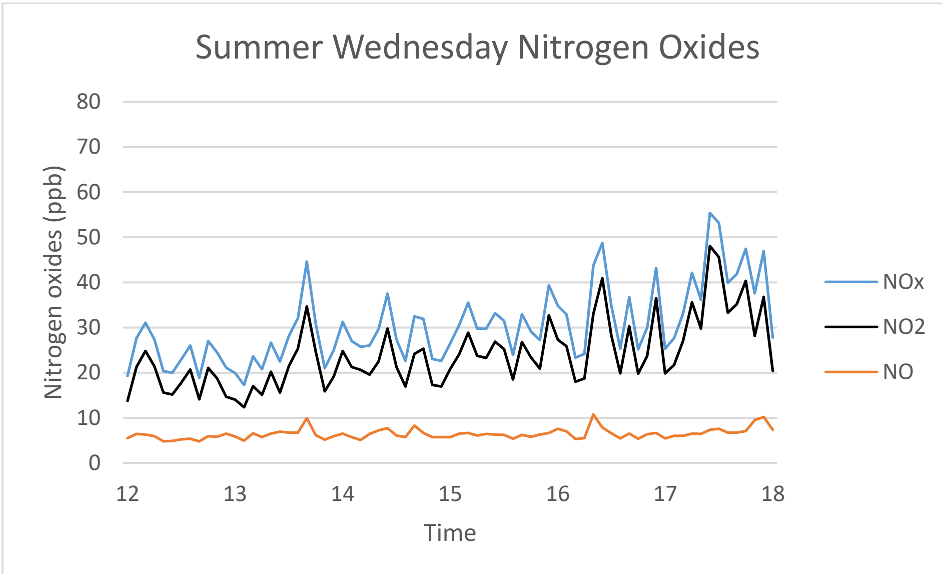

Winter Ozone's Thursday Concentration
03 (ppb)
20
18
16
14
12
10
8
6
4
2
0
13
14
15
16
17
18
Time

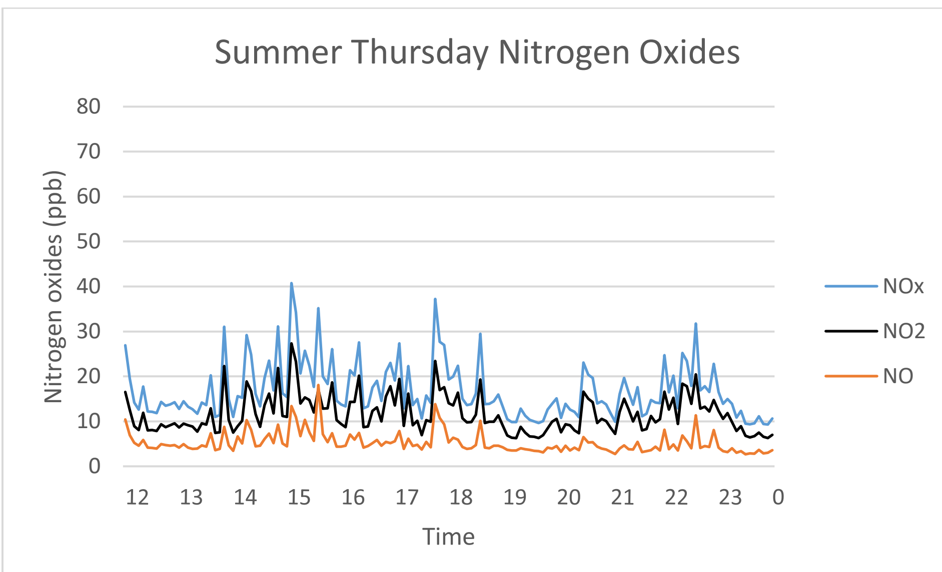

Winter Ozone's Friday Concentration
03 (ppb)
20
18
16
14
12
10
8
6
4
2
0
7
8
9
10
11
12
13
Time

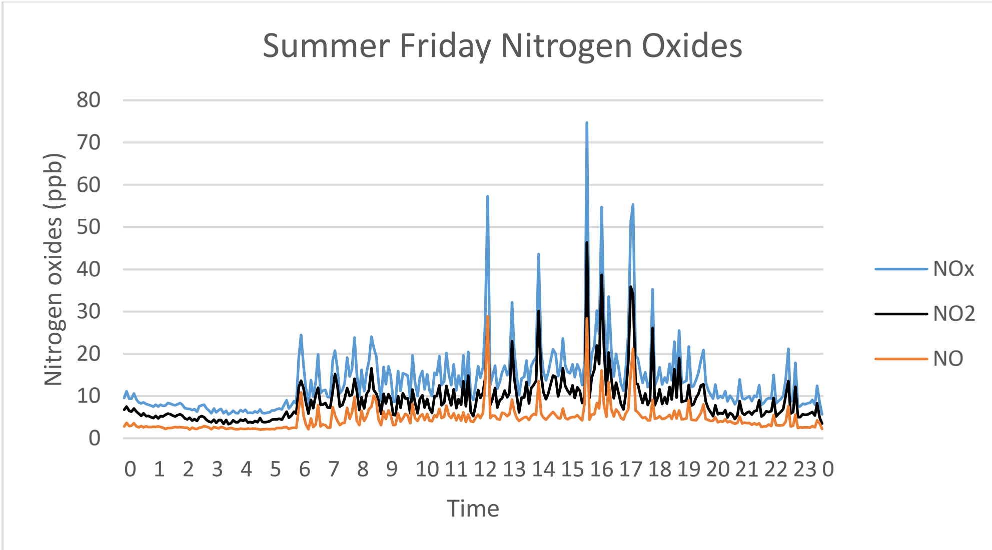

Winter Ozone's Saturday Concentration
03 (ppb)
20
18
16
14
12
10
8
6
4
2
0
7
8
9
10
11
12
Time

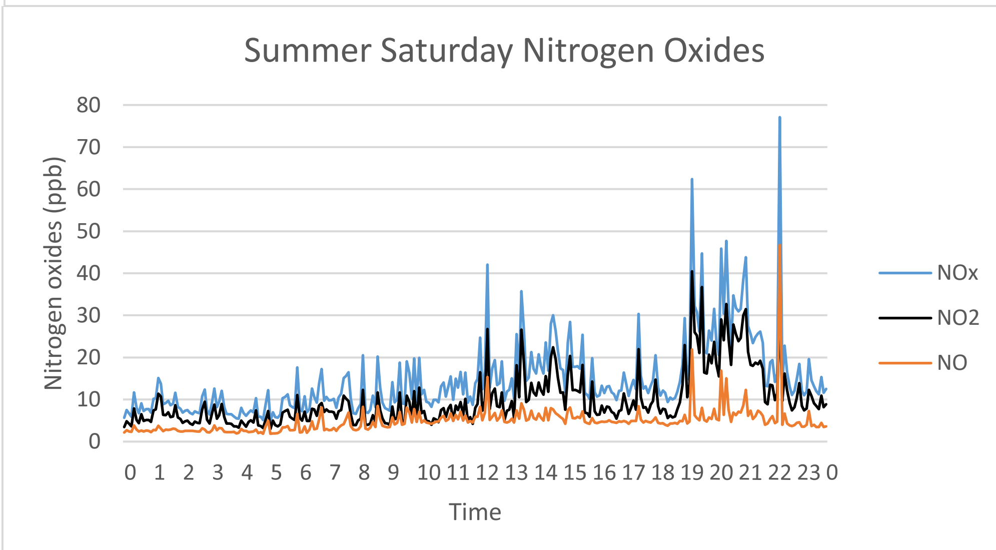

Winter Ozone's Sunday Concentration
03 (ppb)
30
25
20
15
10
5
0
8
9
10
11
12
13
14
15
16
17
18
Time

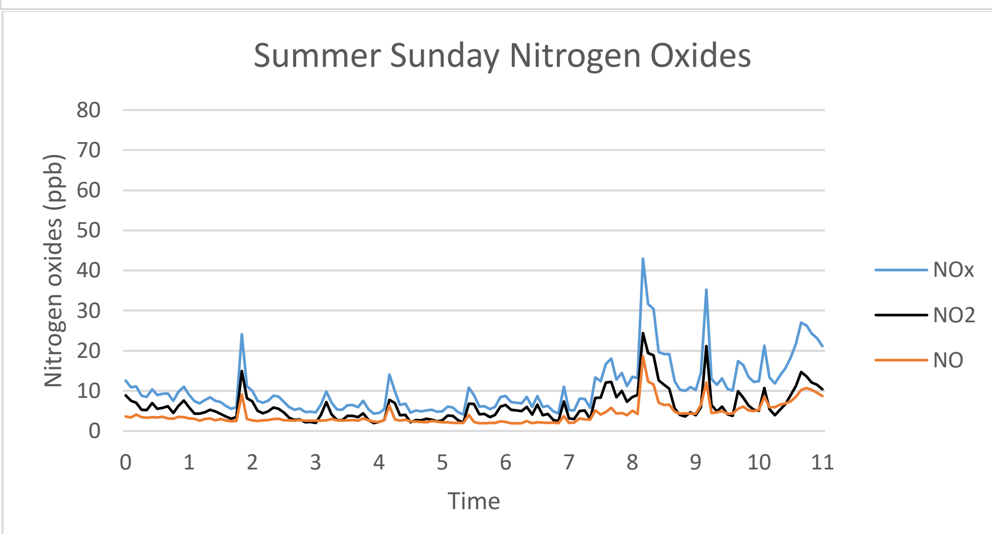
Appendix E: Nitrogen Oxides Concentration Plots

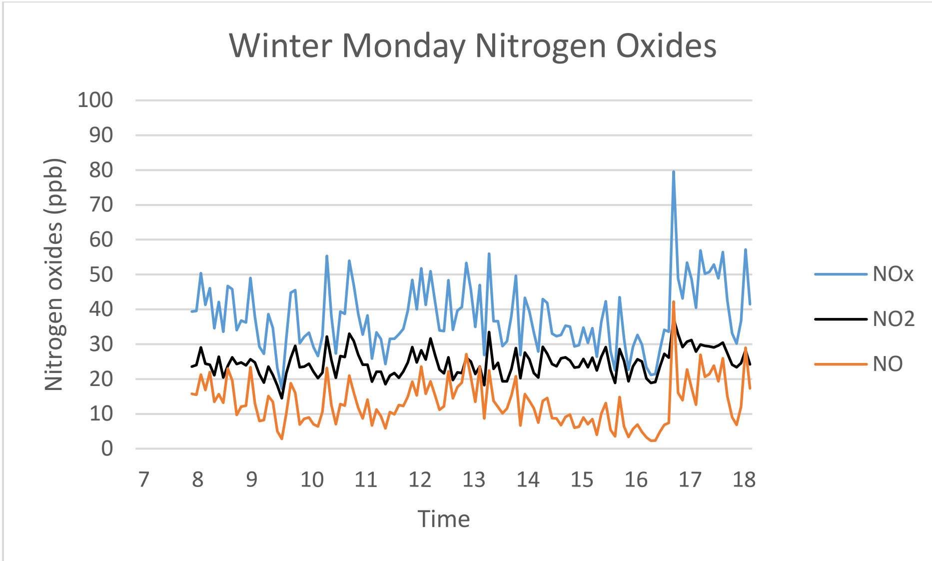


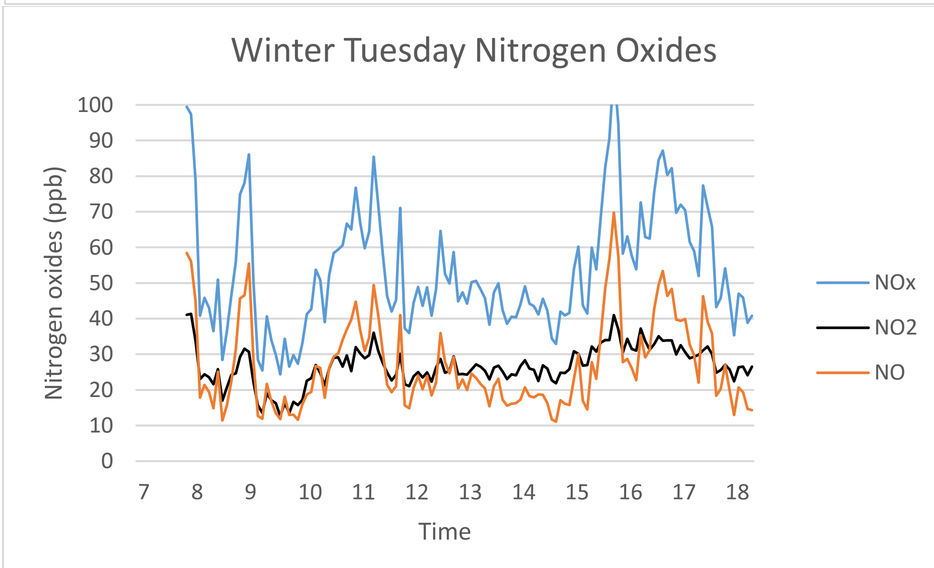


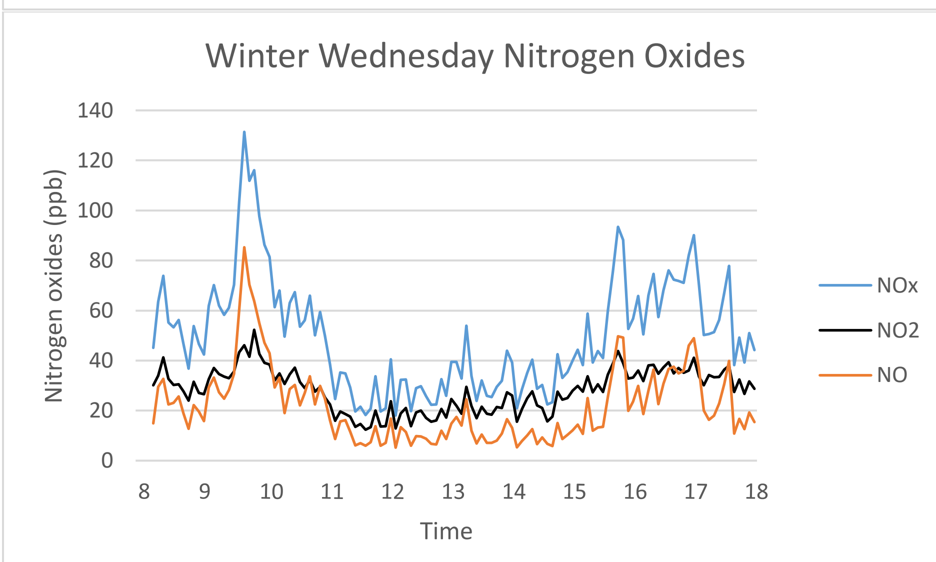

Summer Friday Nitrogen Oxides
Nitrogen oxides (ppb)
0
10
20
30
40
50
60
70
80
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 0
Time
NOx
NO2
NO

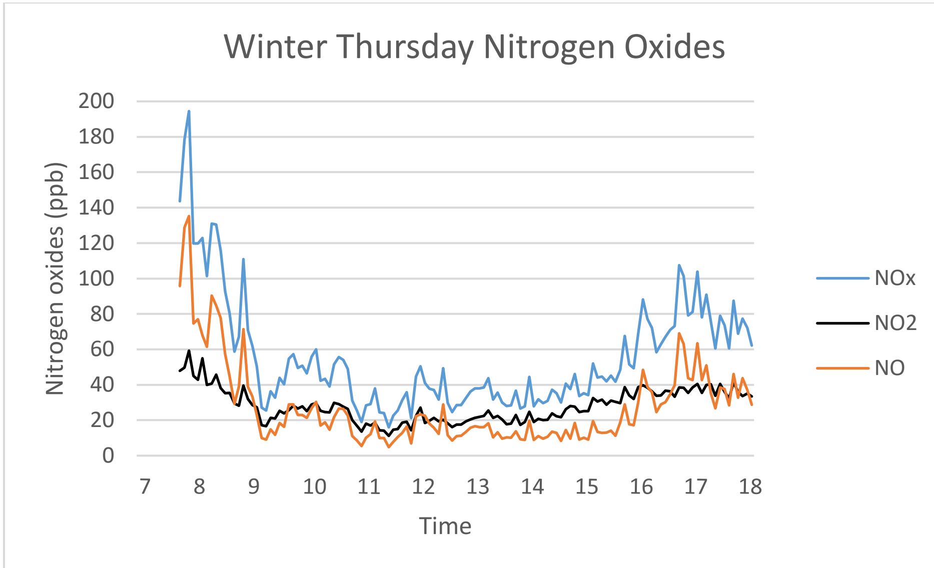

Summer Saturday Nitrogen Oxides
Nitrogen oxides (ppb)
0
10
20
30
40
50
60
70
80
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 0
Time
NOx
NO2
NO

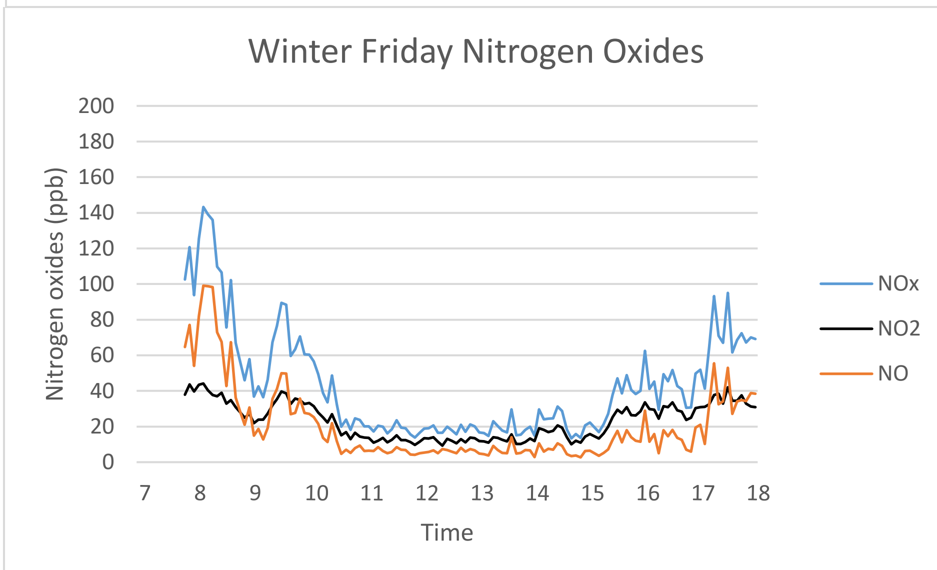

Summer Sunday Nitrogen Oxides
Nitrogen oxides (ppb)
0
10
20
30
40
50
60
70
80
0 1 2 3 4 5 6 7 8 9 10 11
Time
NOx
NO2
NO

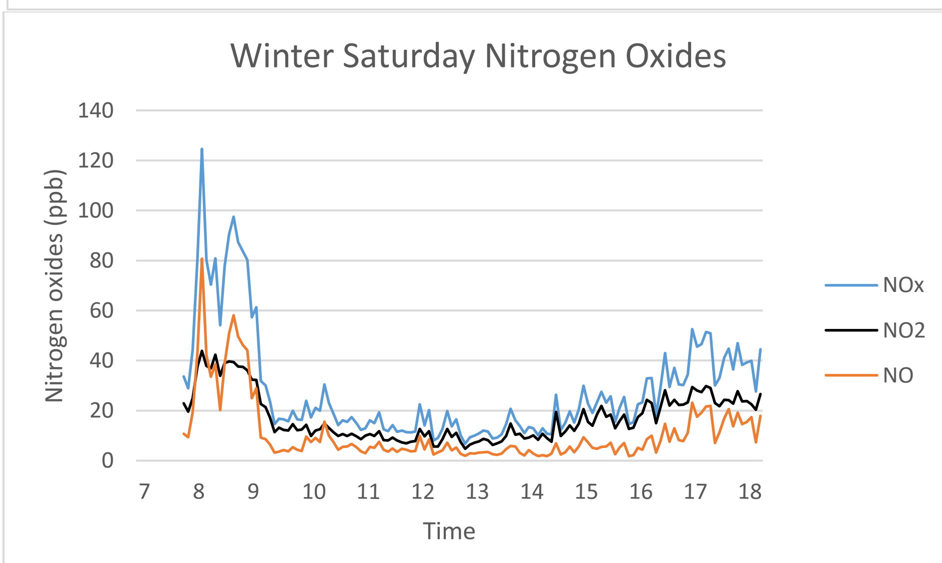

Winter Monday Nitrogen Oxides
100
90
80
70
60
50
40
30
20
10
0
Nitrogen oxides (ppb)
7
8
9
10
11
12
13
14
15
16
17
18
Time
NOx
NO2
NO

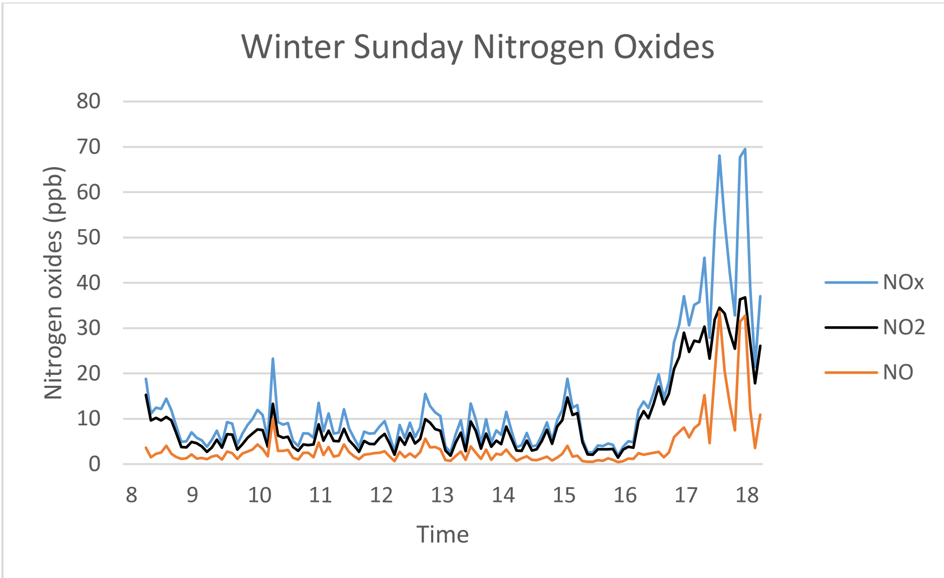

Winter Tuesday Nitrogen Oxides
100
90
80
70
60
50
40
30
20
10
0
Nitrogen oxides (ppb)
7
8
9
10
11
12
13
14
15
16
17
18
Time
NOx
NO2
NO


Winter Wednesday Nitrogen Oxides
140
120
100
80
60
40
20
0
Nitrogen oxides (ppb)
8
9
10
11
12
13
14
15
16
17
18
Time
NOx
NO2
NO


Winter Thursday Nitrogen Oxides
200
180
160
140
120
100
80
60
40
20
0
Nitrogen oxides (ppb)
7
8
9
10
11
12
13
14
15
16
17
18
Time
NOx
NO2
NO

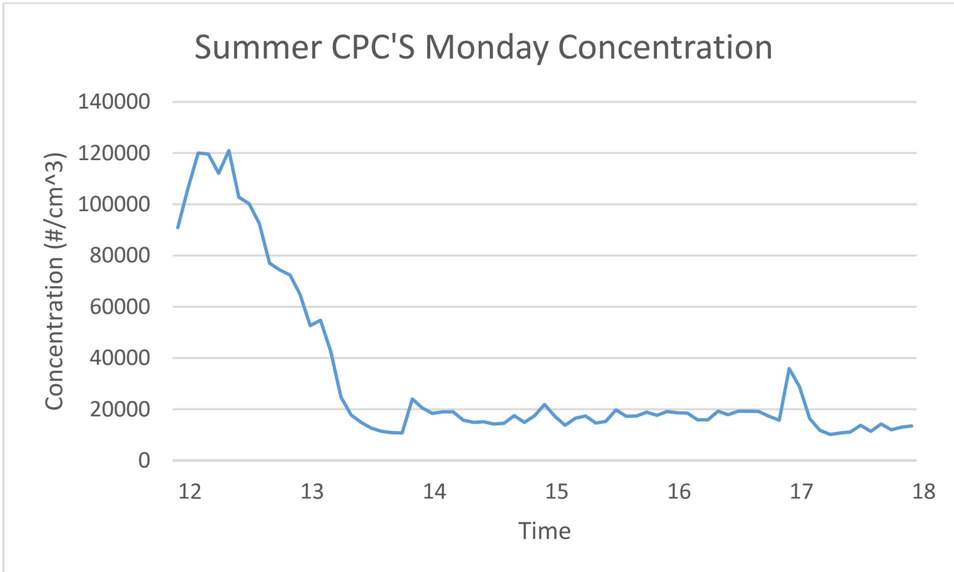

Winter Friday Nitrogen Oxides
200
180
160
140
120
100
80
60
40
20
0
Nitrogen oxides (ppb)
7
8
9
10
11
12
13
14
15
16
17
18
Time
NOx
NO2
NO

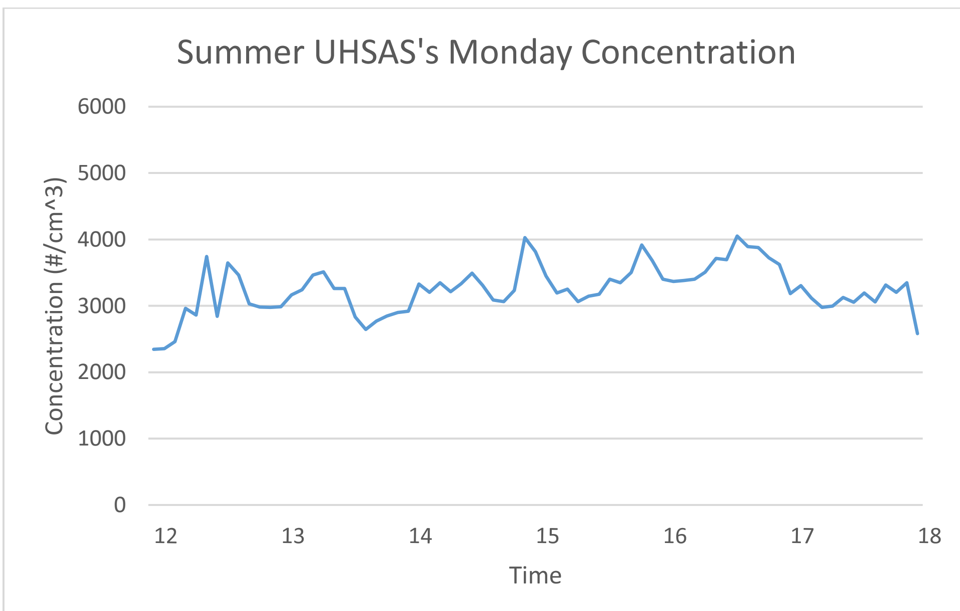

Winter Saturday Nitrogen Oxides
140
120
100
80
60
40
20
0
Nitrogen oxides (ppb)
7
8
9
10
11
12
13
14
15
16
17
18
Time
NOx
NO2
NO

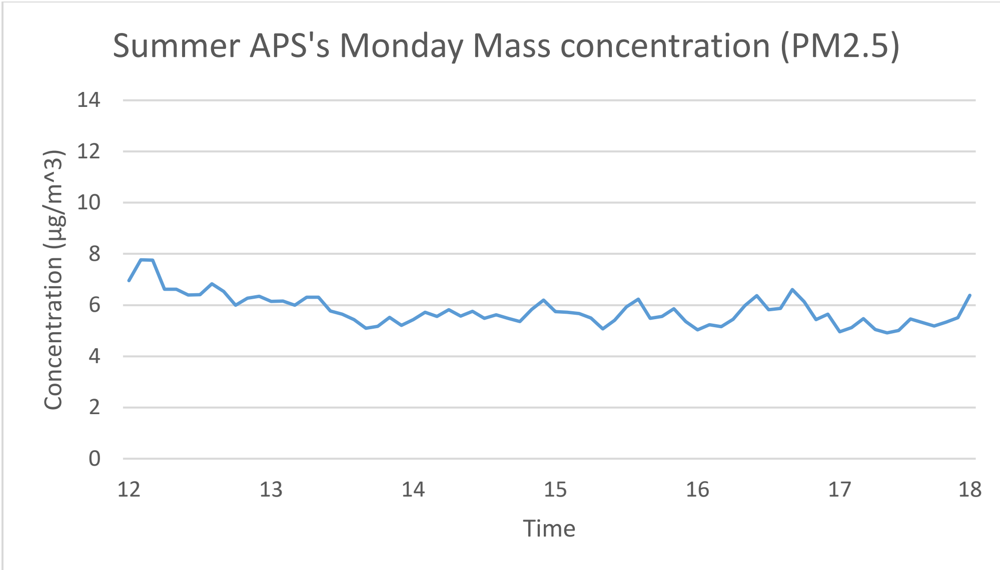


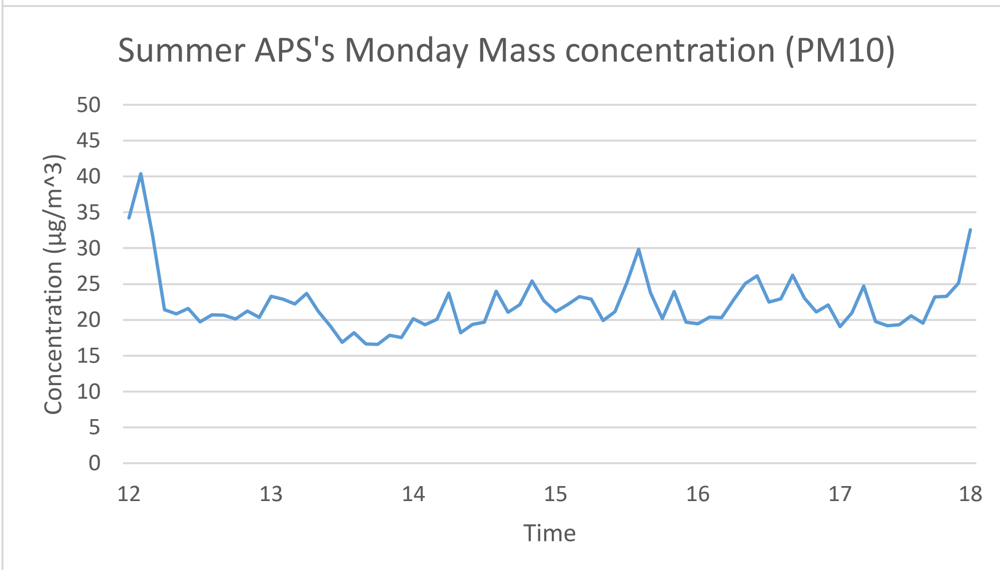
Winter Sunday Nitrogen Oxides
80
70
60
50
40
30
20
10
0
Nitrogen oxides (ppb)
8
9
10
11
12
13
14
15
16
17
18
Time
NOx
NO2
NO

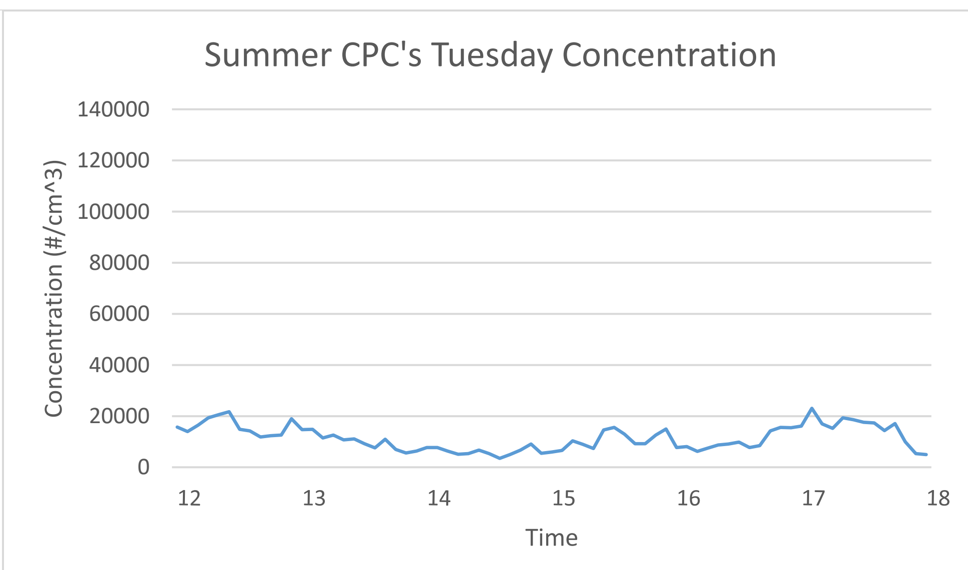
Appendix F: Particulate Matter Concentration Plots

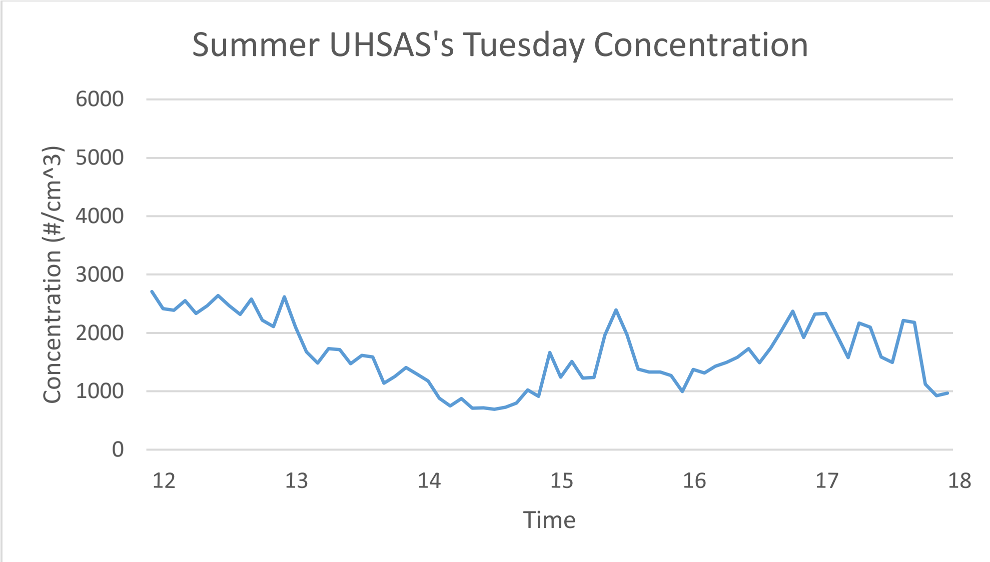


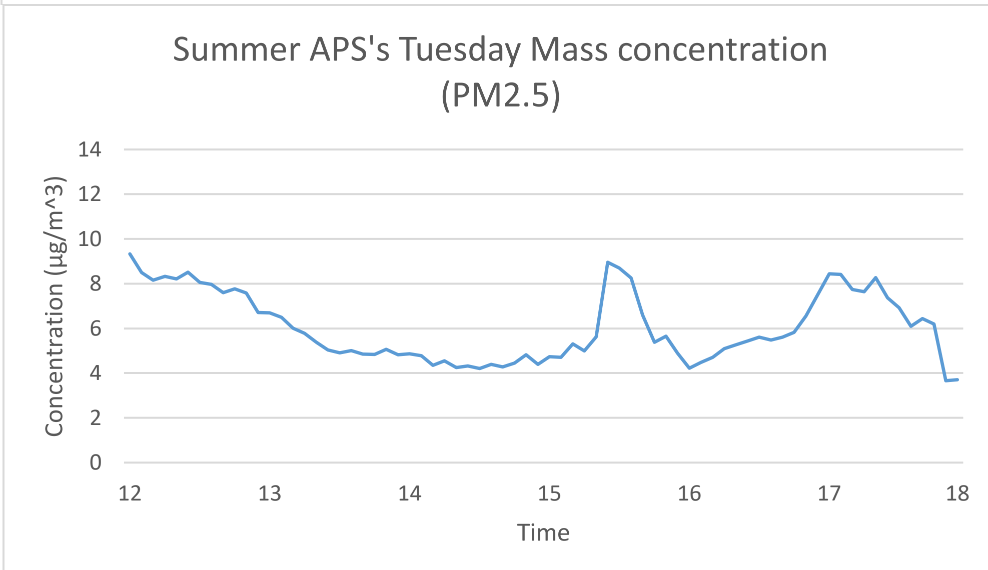


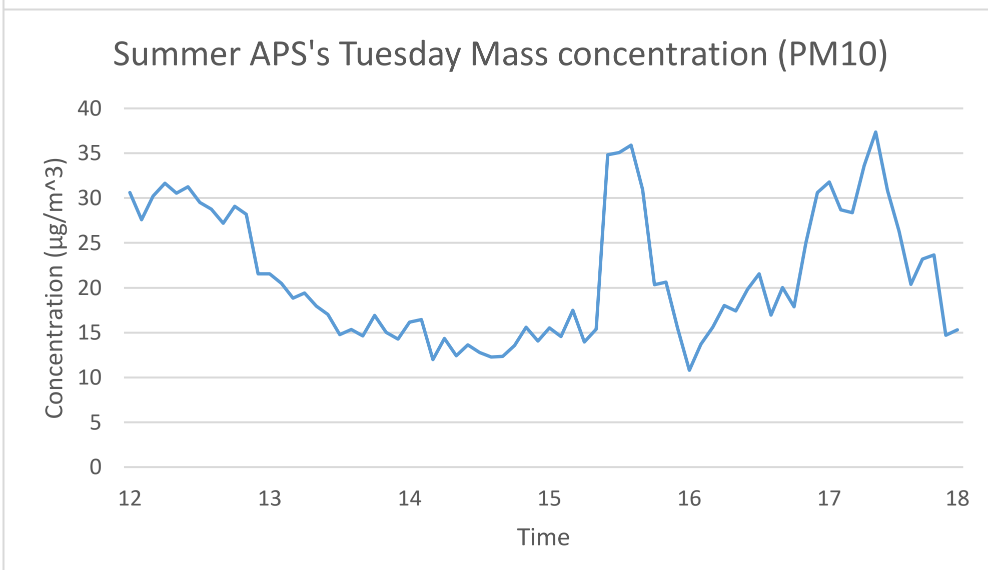

Summer APS's Monday Mass concentration (PM2.5)
Concentration (µg/m^3)
0
2
4
6
8
10
12
14
12
13
14
15
16
17
18
Time

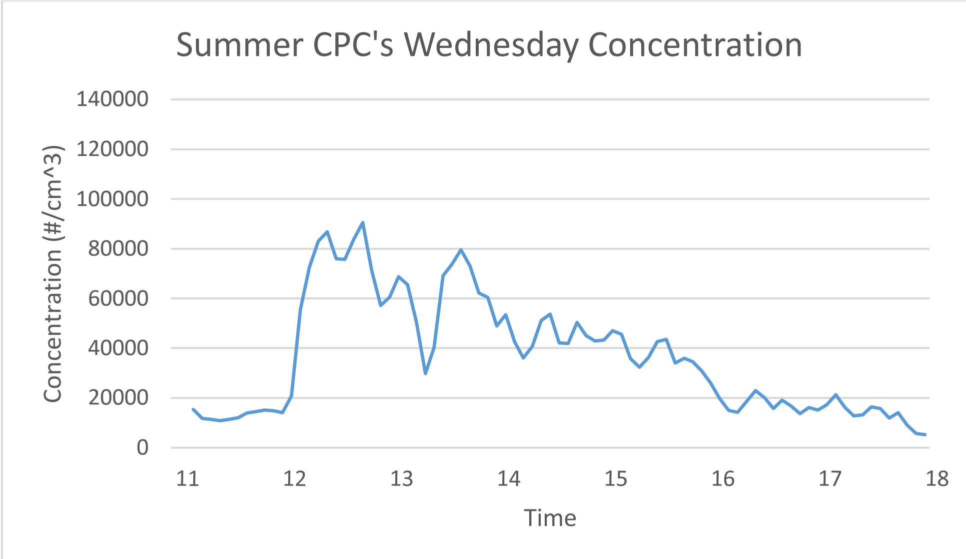

Summer APS's Monday Mass concentration (PM10)
Concentration (µg/m^3)
0
5
10
15
20
25
30
35
40
45
50
12
13
14
15
16
17
18
Time

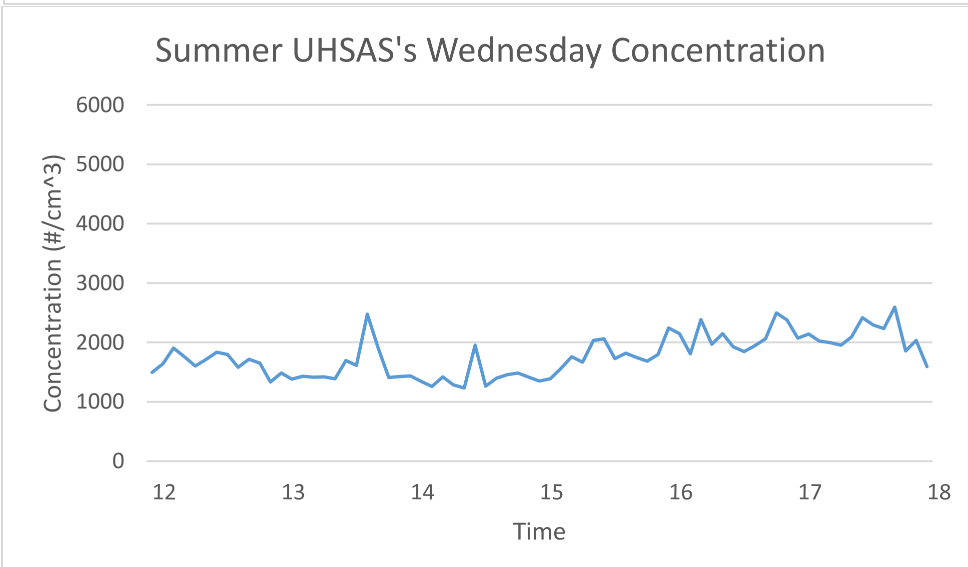

Summer CPC's Tuesday Concentration
Concentration (#/cm^3)
0
20000
40000
60000
80000
100000
120000
140000
12
13
14
15
16
17
18
Time

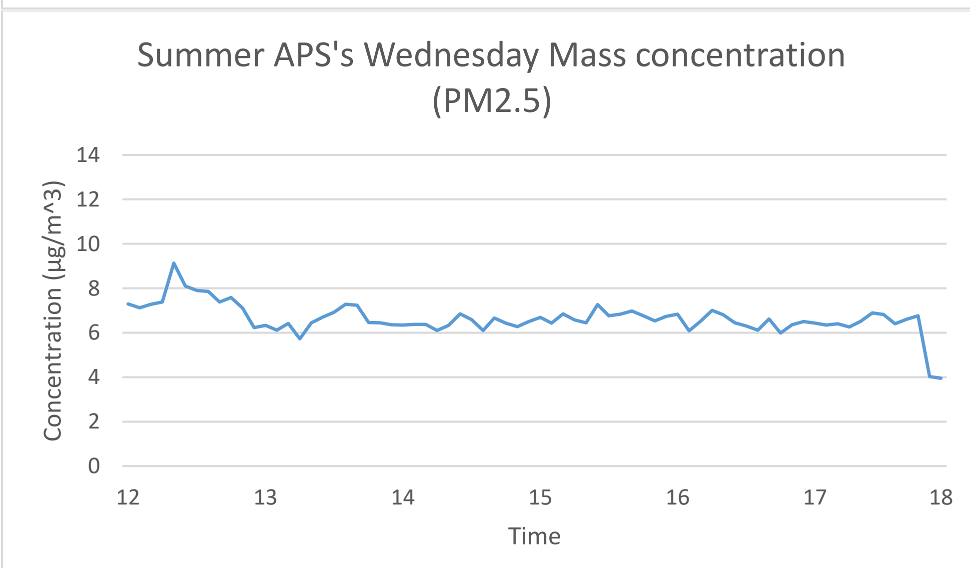

Summer UHSAS's Tuesday Concentration
Concentration (#/cm^3)
6000
5000
4000
3000
2000
1000
0
12
13
14
15
16
17
18
Time

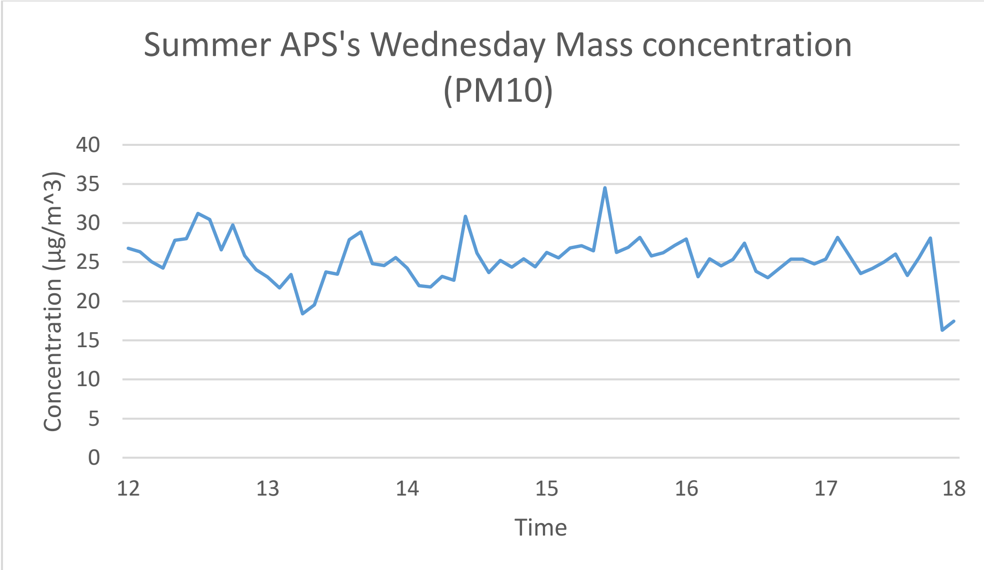

Summer APS's Tuesday Mass concentration (PM2.5)
Concentration (µg/m^3)
14
12
10
8
6
4
2
0
12
13
14
15
16
17
18
Time


Summer APS's Tuesday Mass concentration (PM10)
Concentration (µg/m^3)
40
35
30
25
20
15
10
5
0
12
13
14
15
16
17
18
Time

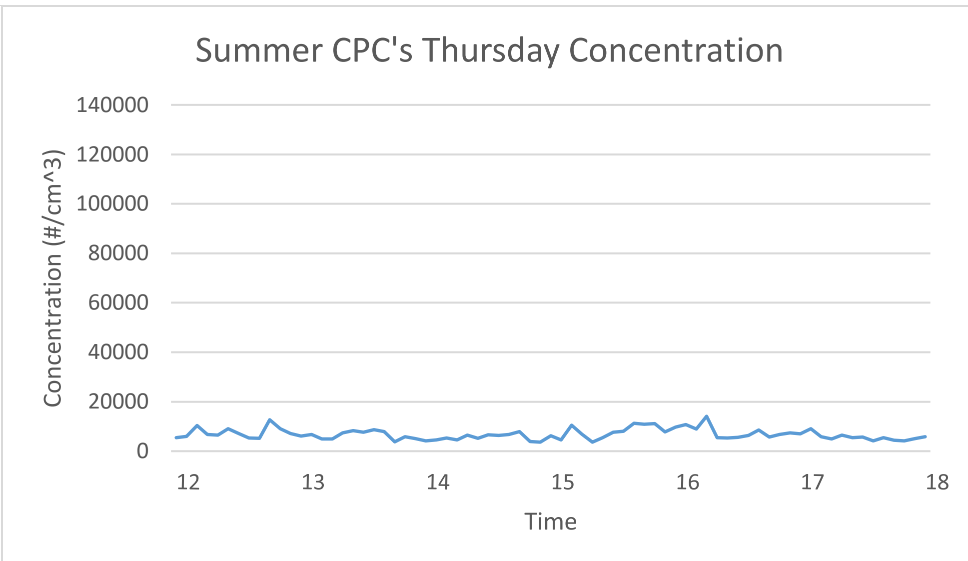

Summer CPC's Wednesday Concentration
Concentration (#/cm^3)
140000
120000
100000
80000
60000
40000
20000
0
11
12
13
14
15
16
17
18
Time


Summer UHSAS's Wednesday Concentration
Concentration (#/cm^3)
6000
5000
4000
3000
2000
1000
0
12
13
14
15
16
17
18
Time

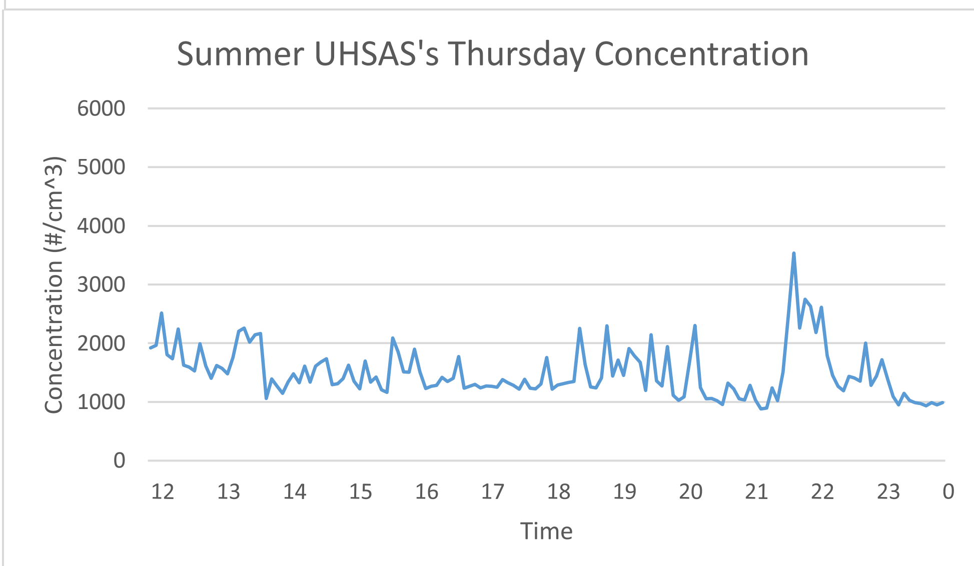

Summer APS's Wednesday Mass concentration (PM2.5)
Concentration (µg/m^3)
14
12
10
8
6
4
2
0
12
13
14
15
16
17
18
Time



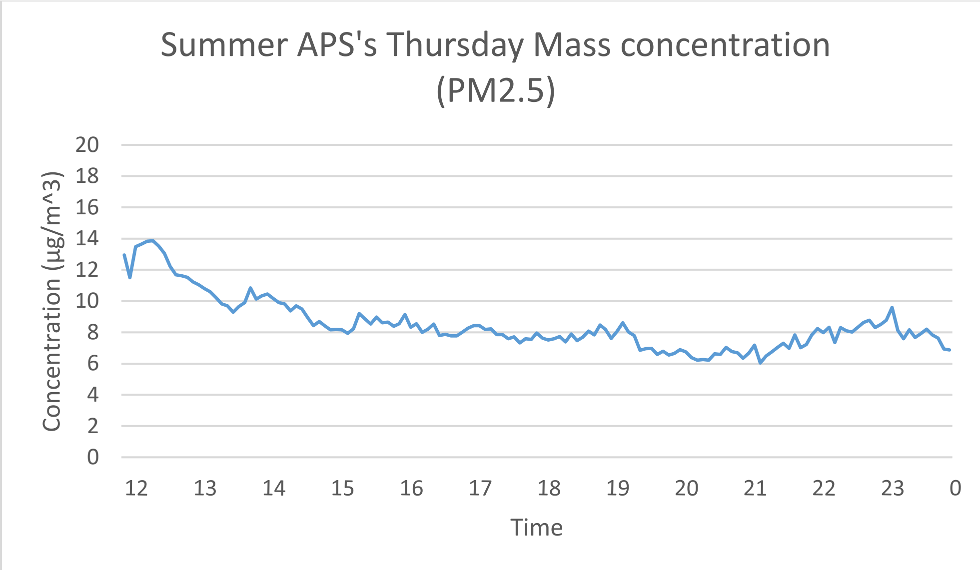
Summer APS's Wednesday Mass concentration (PM10)
Concentration (µg/m^3)
40
35
30
25
20
15
10
5
0
12
13
14
15
16
17
18
Time

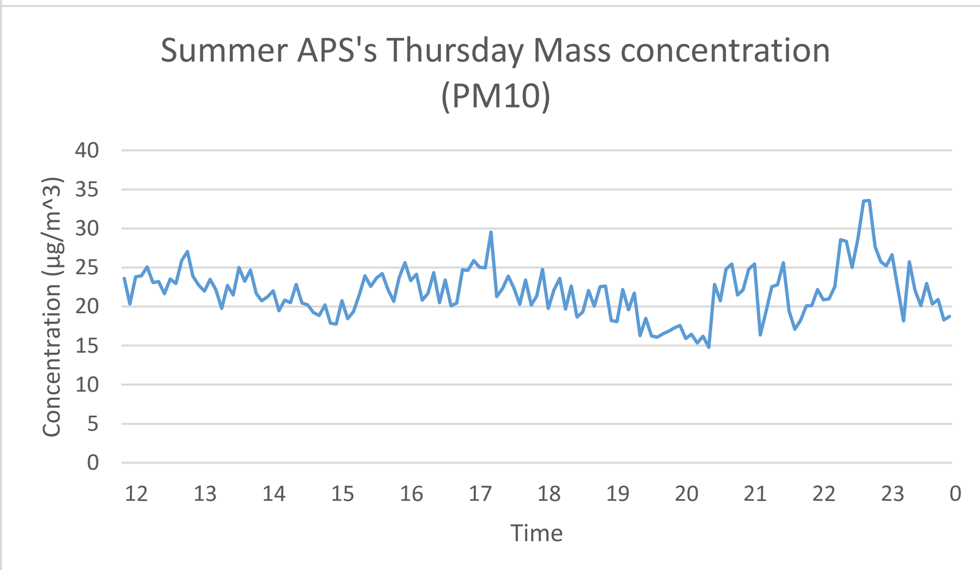


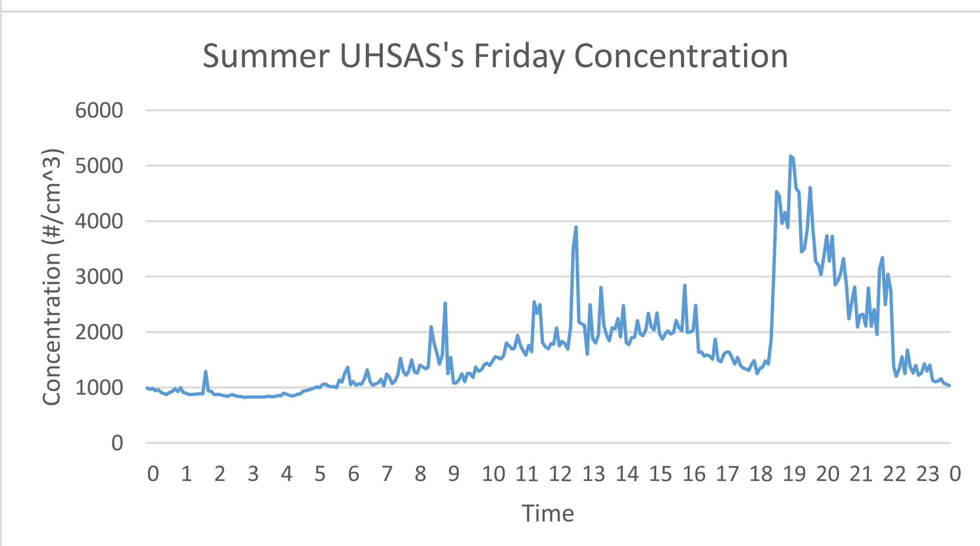
Summer CPC's Thursday Concentration
Concentration (#/cm^3)
140000
120000
100000
80000
60000
40000
20000
0
12
13
14
15
16
17
18
Time

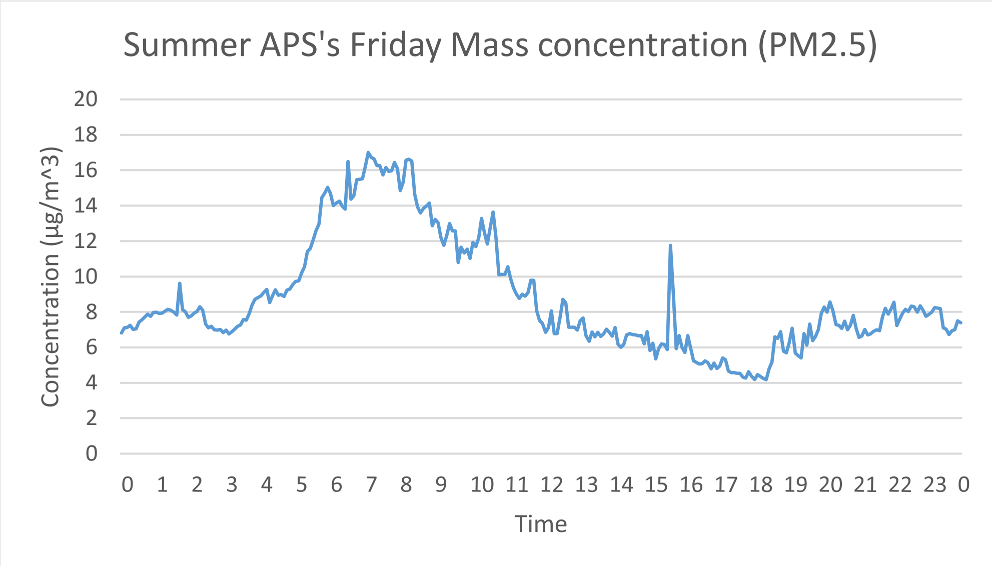


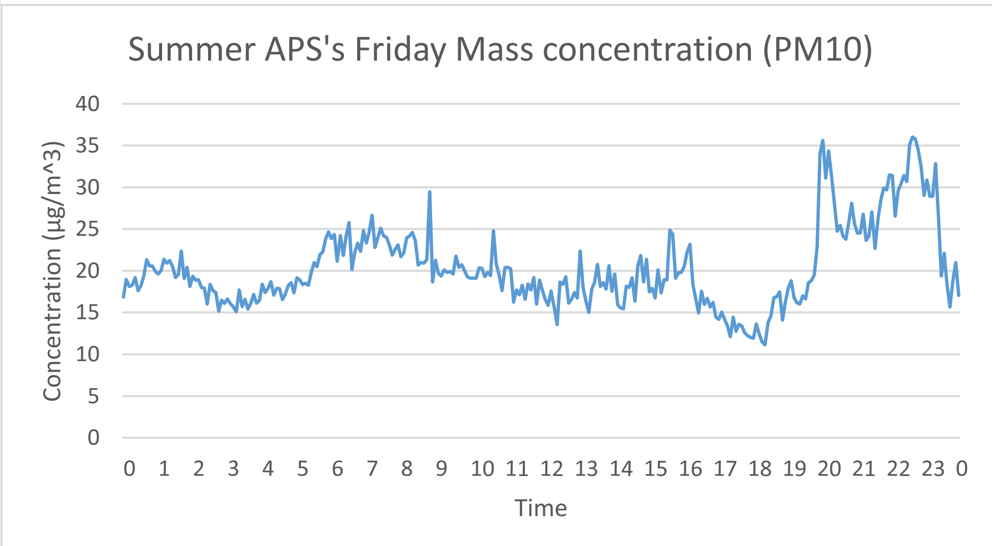
Summer UHSAS's Thursday Concentration
Concentration (#/cm^3)
6000
5000
4000
3000
2000
1000
0
12
13
14
15
16
17
18
19
20
21
22
23
0
Time

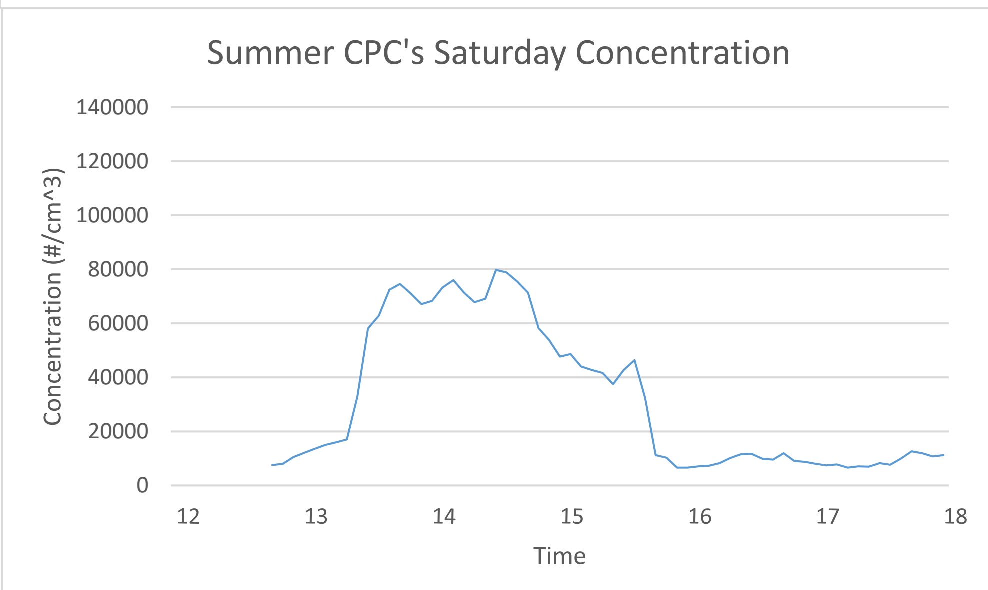

Summer APS's Thursday Mass concentration (PM2.5)
Concentration (µg/m^3)
20
18
16
14
12
10
8
6
4
2
0
12 13 14 15 16 17 18 19 20 21 22 23 0
Time

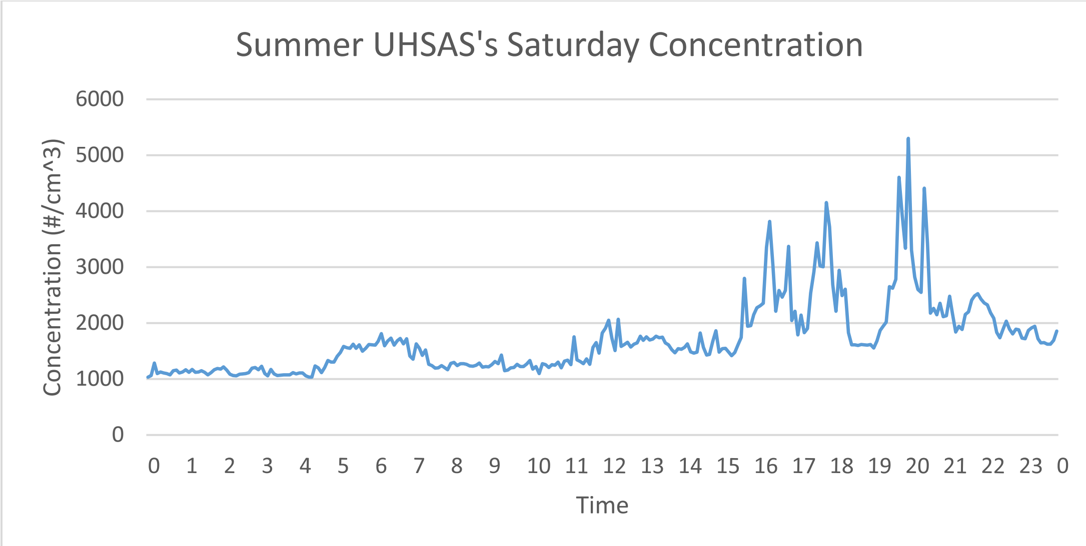

Summer APS's Thursday Mass concentration (PM10)
Concentration (µg/m^3)
40
35
30
25
20
15
10
5
0
12 13 14 15 16 17 18 19 20 21 22 23 0
Time

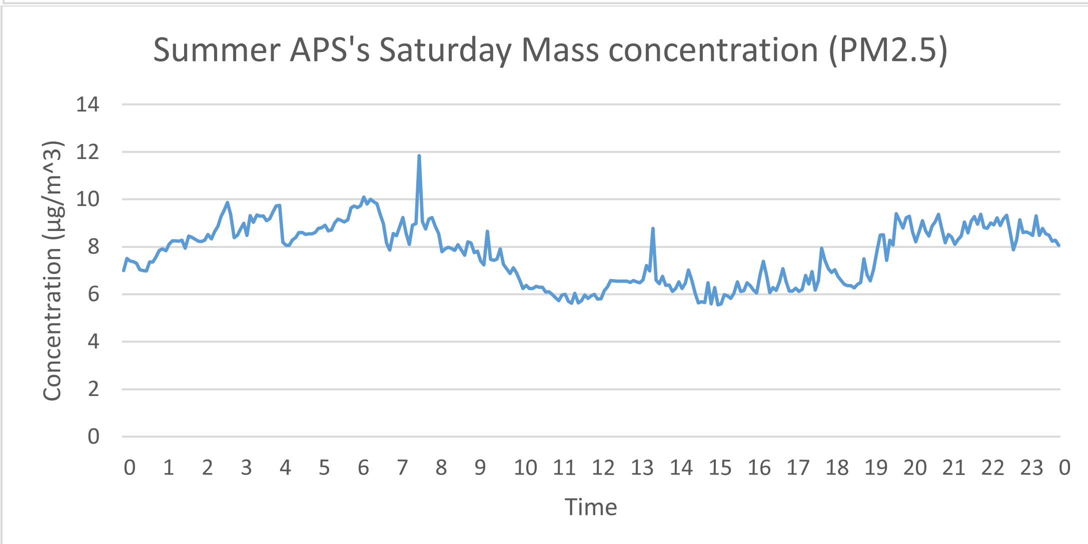

Summer UHSAS's Friday Concentration
Concentration (#/cm^3)
6000
5000
4000
3000
2000
1000
0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 0
Time

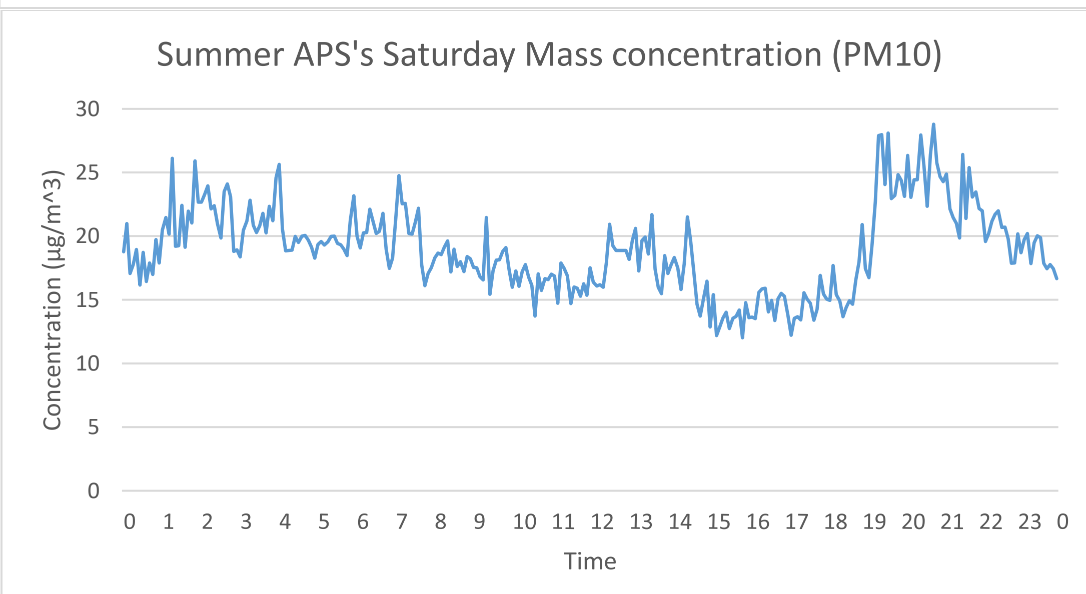

Summer APS's Friday Mass concentration (PM2.5)
Concentration (µg/m^3)
20
18
16
14
12
10
8
6
4
2
0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 0
Time

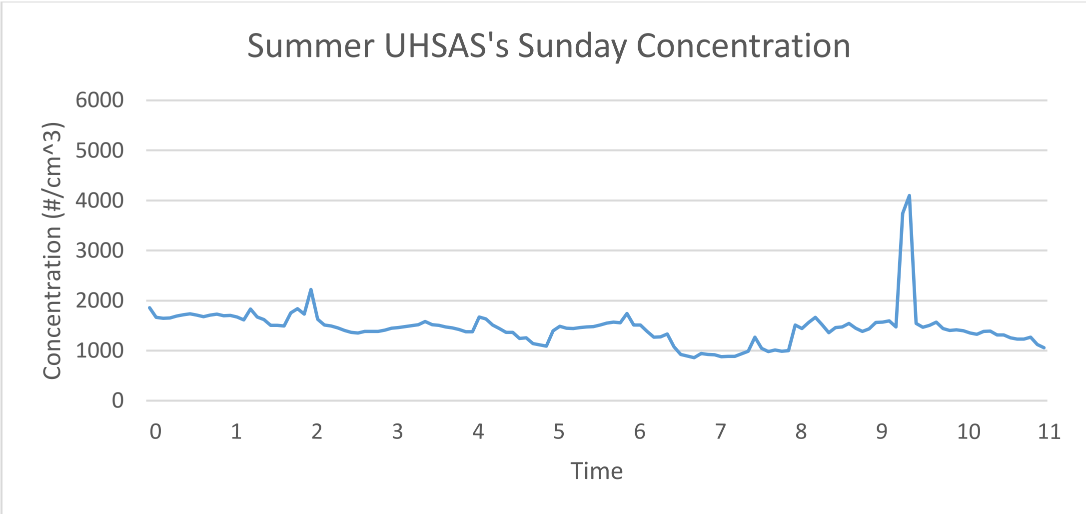

Summer APS's Friday Mass concentration (PM10)
Concentration (µg/m^3)
40
35
30
25
20
15
10
5
0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 0
Time

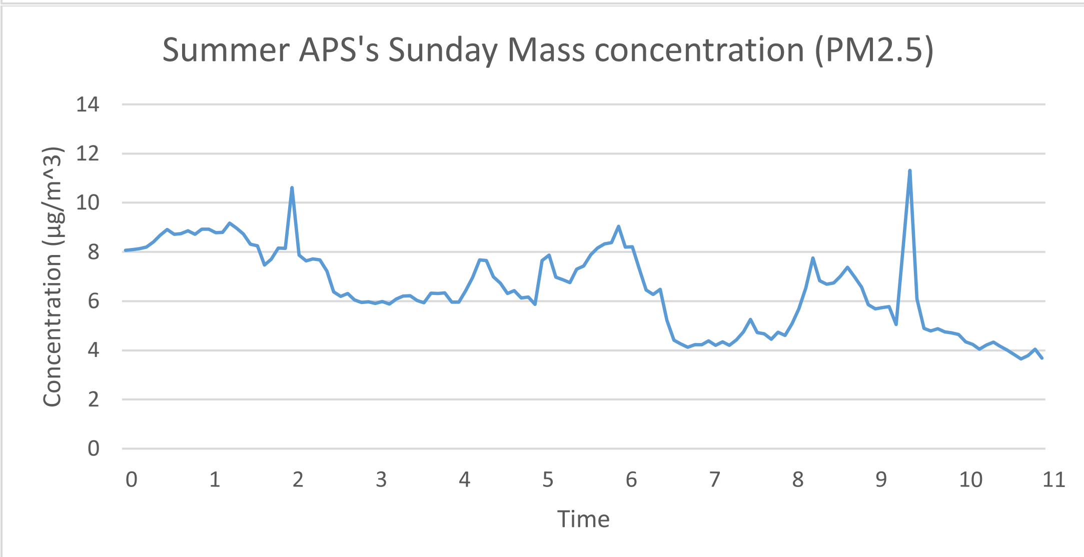

Summer CPC's Saturday Concentration
Concentration (#/cm^3)
140000
120000
100000
80000
60000
40000
20000
0
12
13
14
15
16
17
18
Time

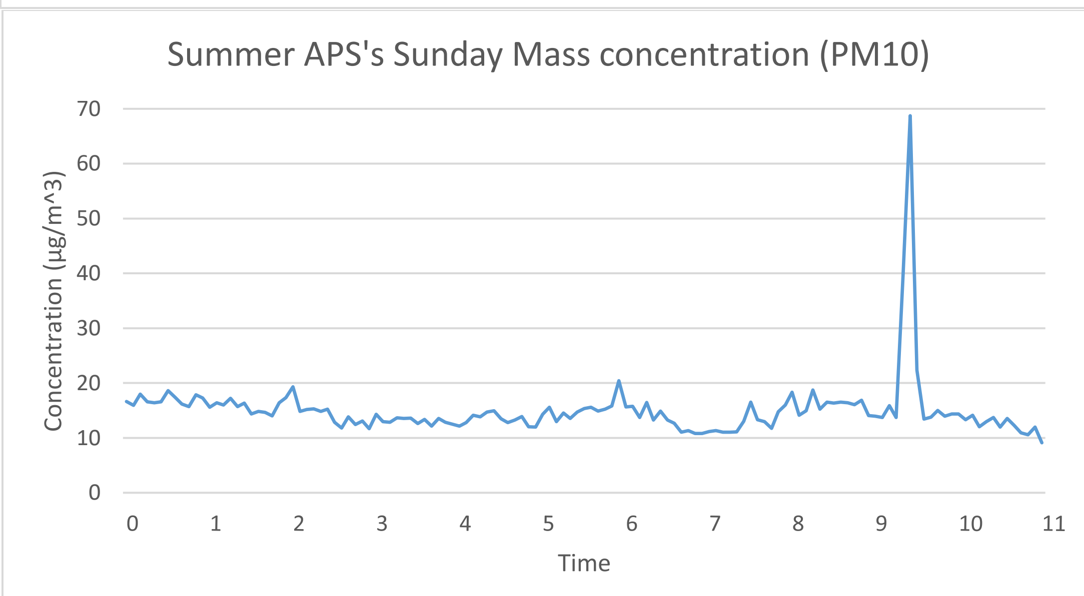

Summer UHSAS's Saturday Concentration
Concentration (#/cm^3)
6000
5000
4000
3000
2000
1000
0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 0
Time

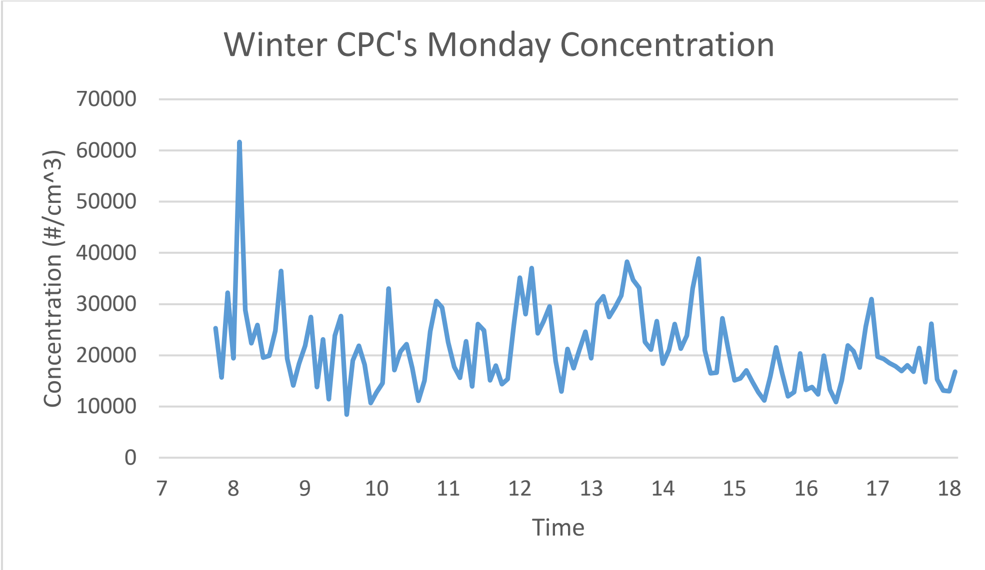

Summer APS's Saturday Mass concentration (PM2.5)
Concentration (µg/m^3)
14
12
10
8
6
4
2
0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 0
Time

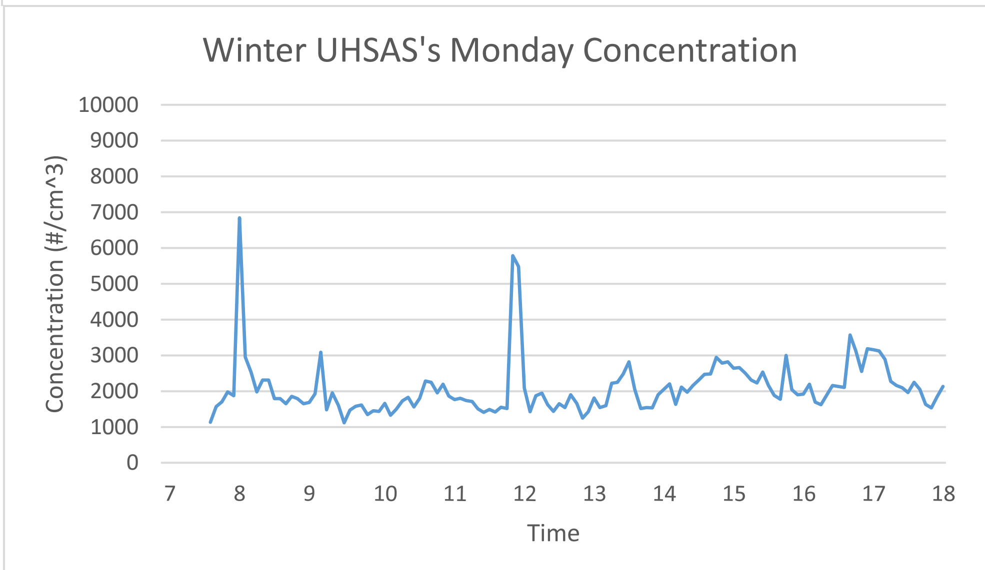

Summer APS's Saturday Mass concentration (PM10)
Concentration (µg/m^3)
30
25
20
15
10
5
0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 0
Time

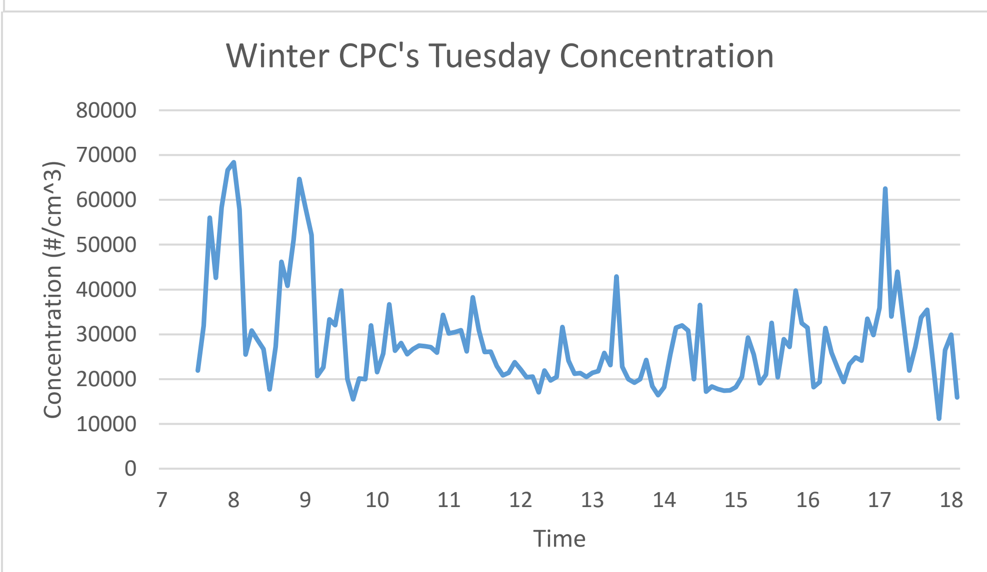

Summer UHSAS's Sunday Concentration
Concentration (#/cm^3)
6000
5000
4000
3000
2000
1000
0
0
1
2
3
4
5
6
7
8
9
10
11
Time

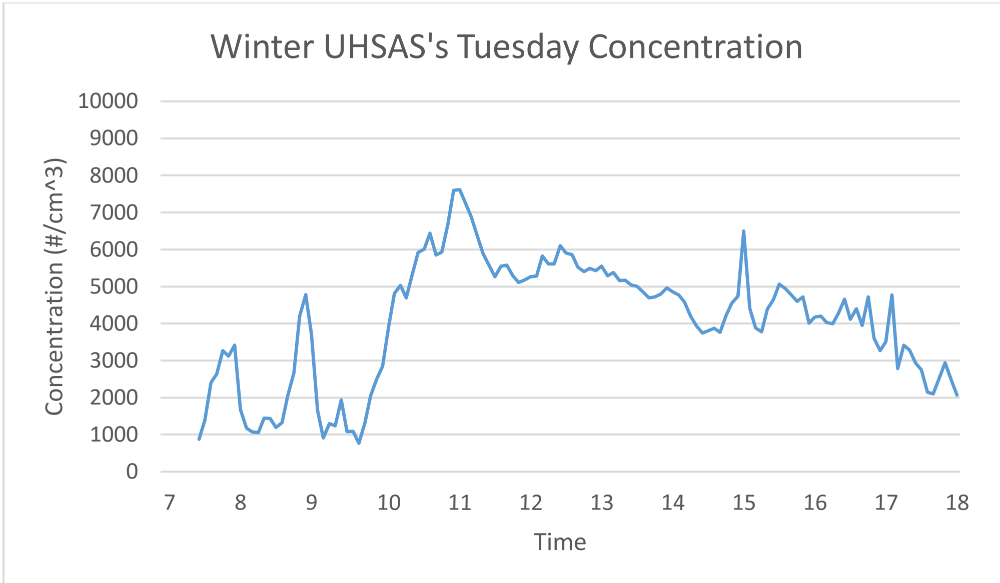

Summer APS's Sunday Mass concentration (PM2.5)
Concentration (µg/m^3)
14
12
10
8
6
4
2
0
0
1
2
3
4
5
6
7
8
9
10
11
Time

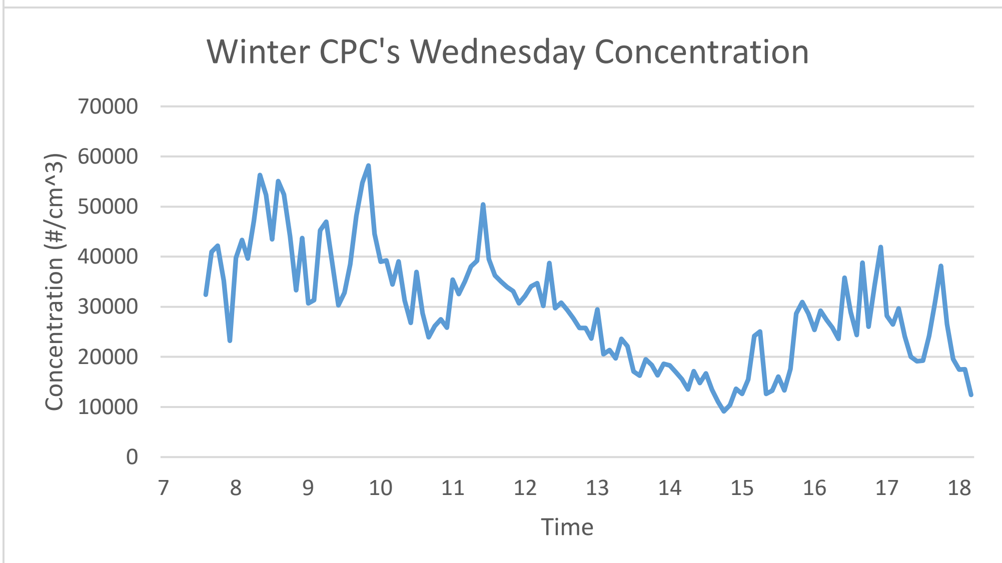

Summer APS's Sunday Mass concentration (PM10)
Concentration (µg/m^3)
70
60
50
40
30
20
10
0
0
1
2
3
4
5
6
7
8
9
10
11
Time

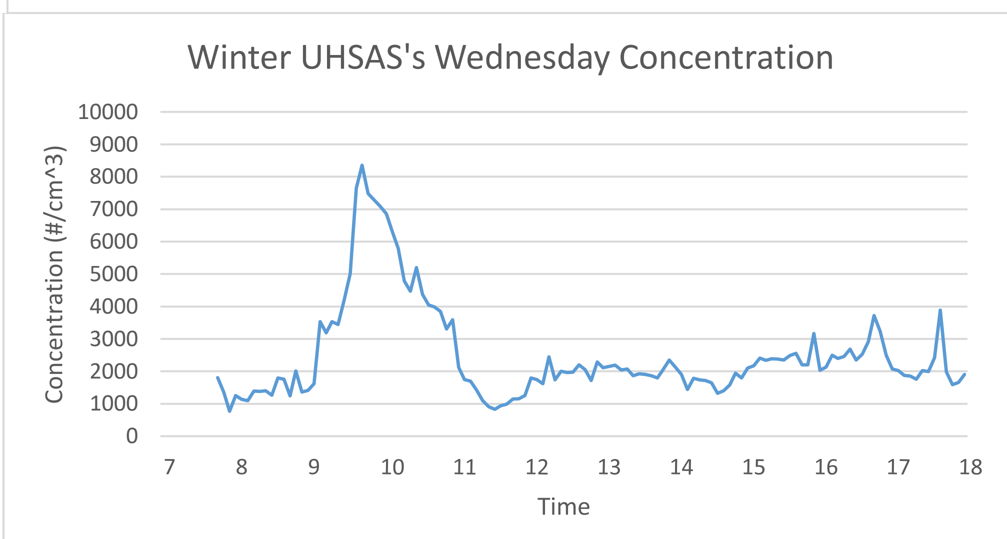

Winter CPC's Monday Concentration
Concentration (#/cm^3)
70000
60000
50000
40000
30000
20000
10000
0
7
8
9
10
11
12
13
14
15
16
17
18
Time

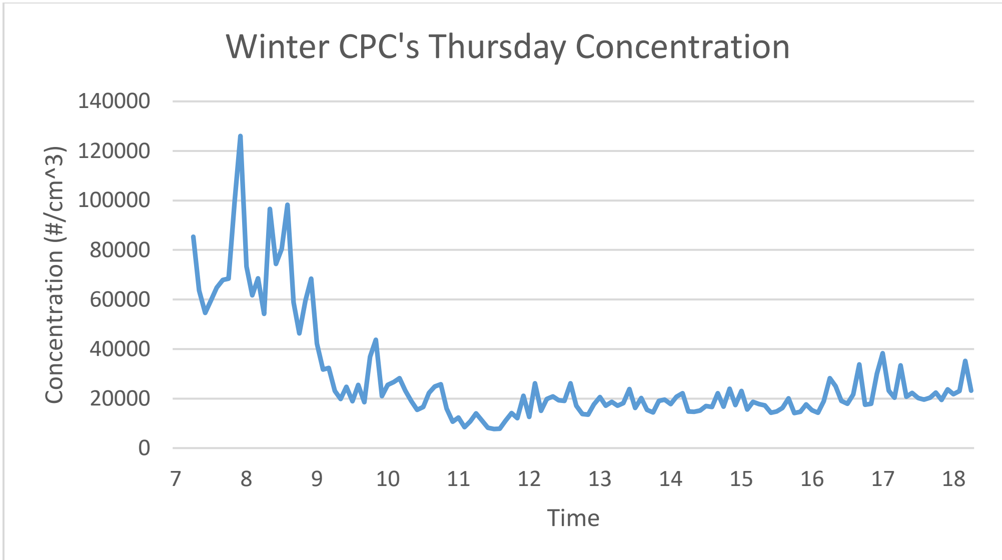

Winter UHSAS's Monday Concentration
Concentration (#/cm^3)
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
7
8
9
10
11
12
13
14
15
16
17
18
Time

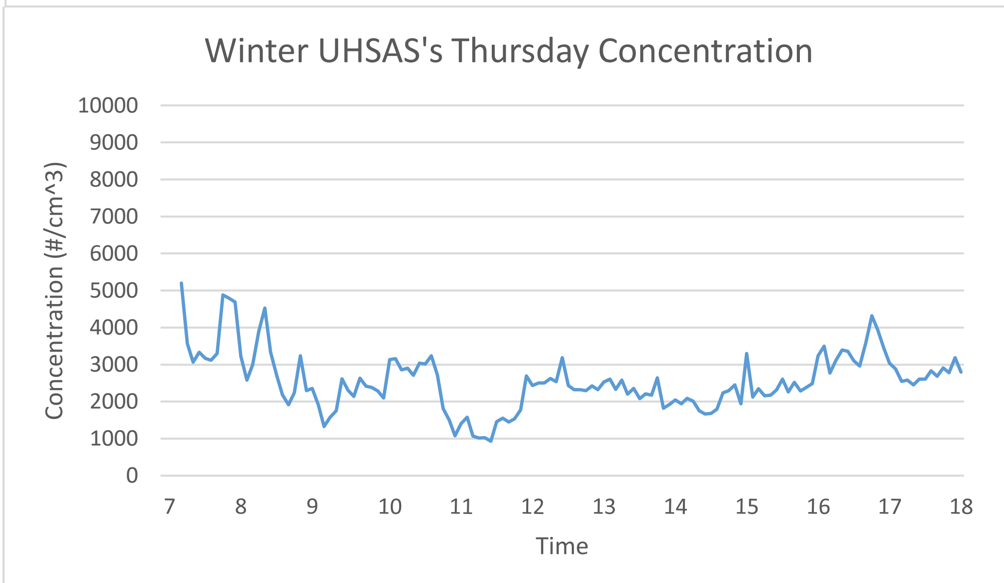

Winter CPC's Tuesday Concentration
Concentration (#/cm^3)
80000
70000
60000
50000
40000
30000
20000
10000
0
7
8
9
10
11
12
13
14
15
16
17
18
Time

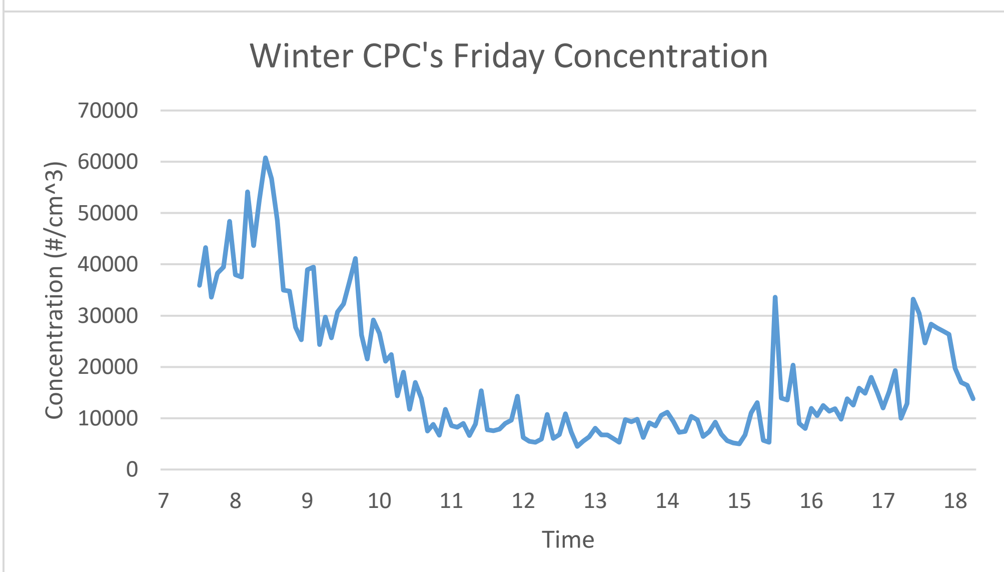

Winter UHSAS's Tuesday Concentration
Concentration (#/cm^3)
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
7
8
9
10
11
12
13
14
15
16
17
18
Time

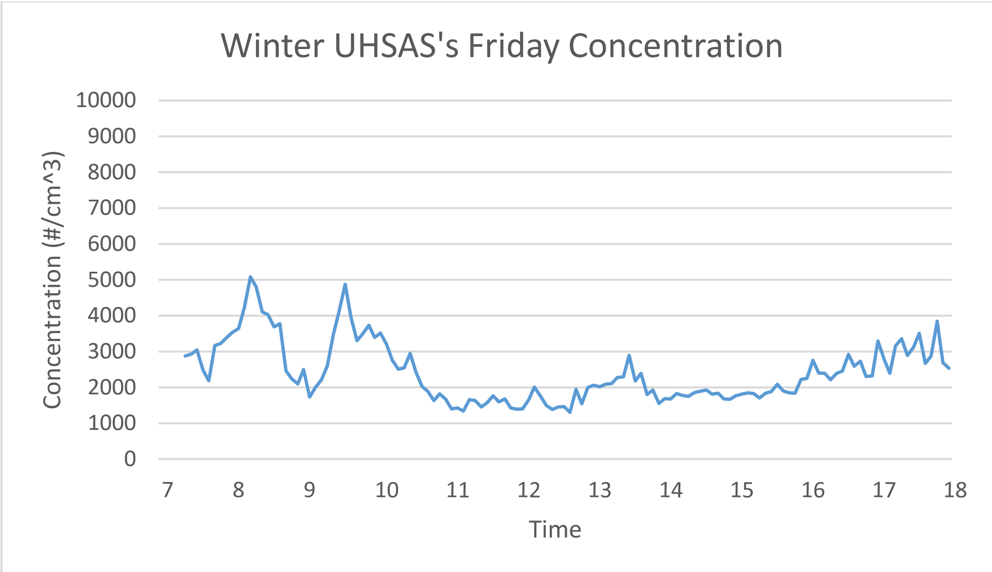

Winter CPC's Wednesday Concentration
Concentration (#/cm^3)
70000
60000
50000
40000
30000
20000
10000
0
7
8
9
10
11
12
13
14
15
16
17
18
Time

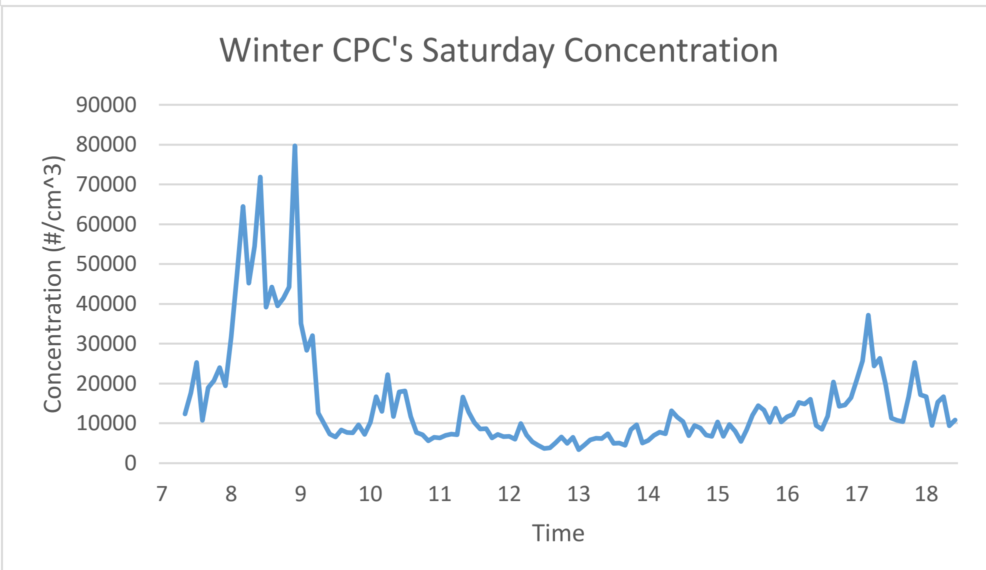

Winter UHSAS's Wednesday Concentration
Concentration (#/cm^3)
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
7
8
9
10
11
12
13
14
15
16
17
18
Time

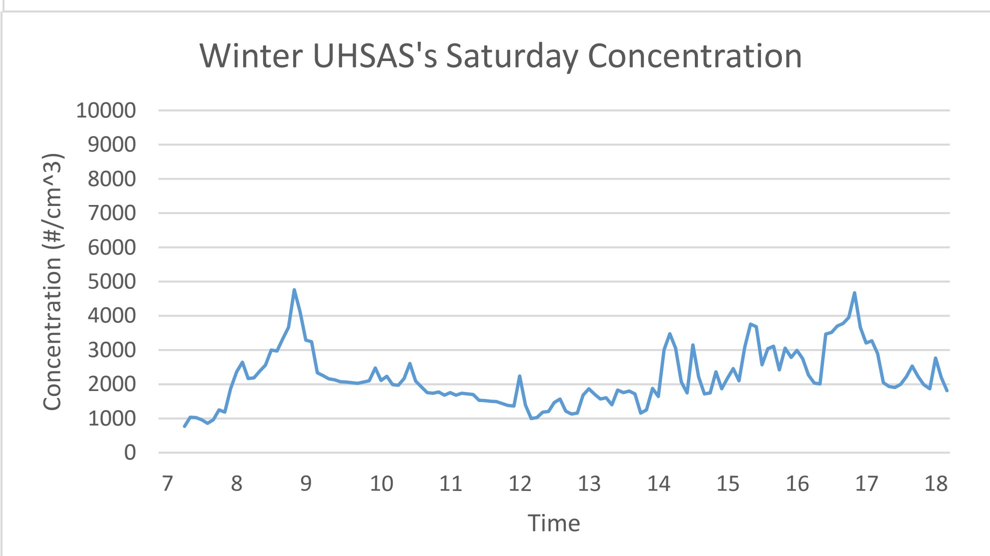

Winter CPC's Thursday Concentration
Concentration (#/cm^3)
140000
120000
100000
80000
60000
40000
20000
0
7 8 9 10 11 12 13 14 15 16 17 18
Time

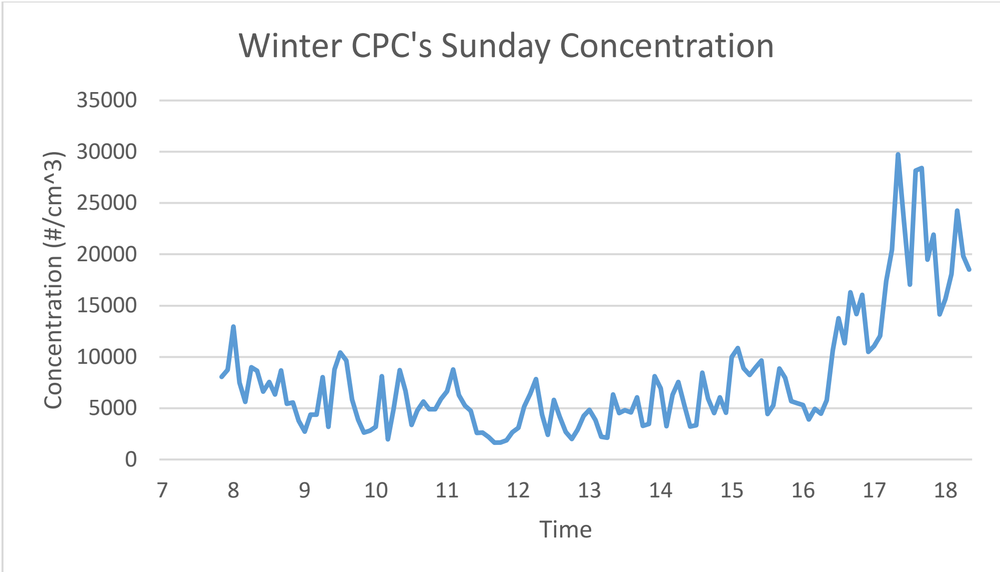

Winter UHSAS's Thursday Concentration
Concentration (#/cm^3)
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
7 8 9 10 11 12 13 14 15 16 17 18
Time

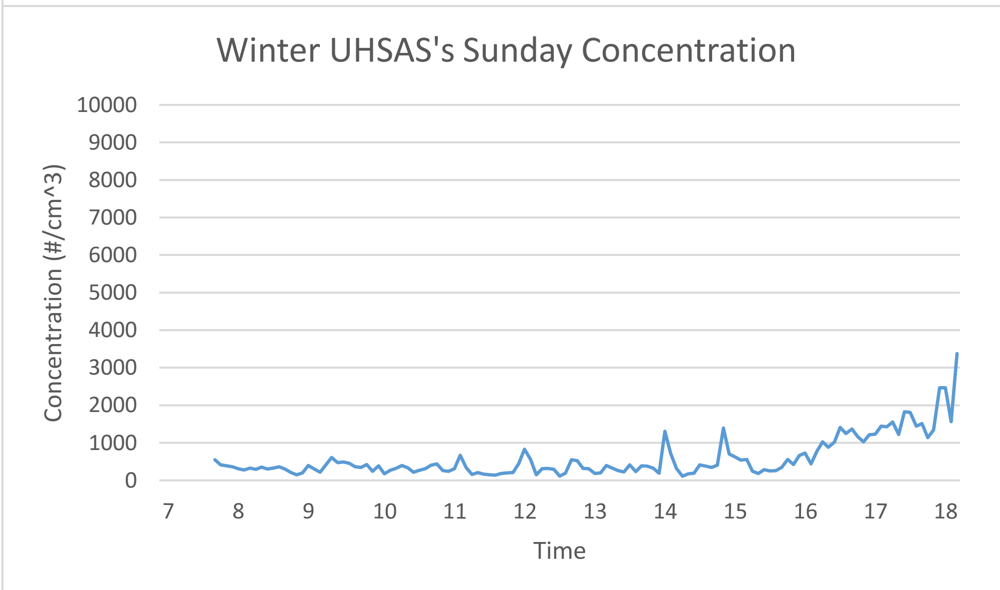

Winter CPC's Friday Concentration
Concentration (#/cm^3)
70000
60000
50000
40000
30000
20000
10000
0
7 8 9 10 11 12 13 14 15 16 17 18
Time


Winter UHSAS's Friday Concentration
Concentration (#/cm^3)
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
7
8
9
10
11
12
13
14
15
16
17
18
Time

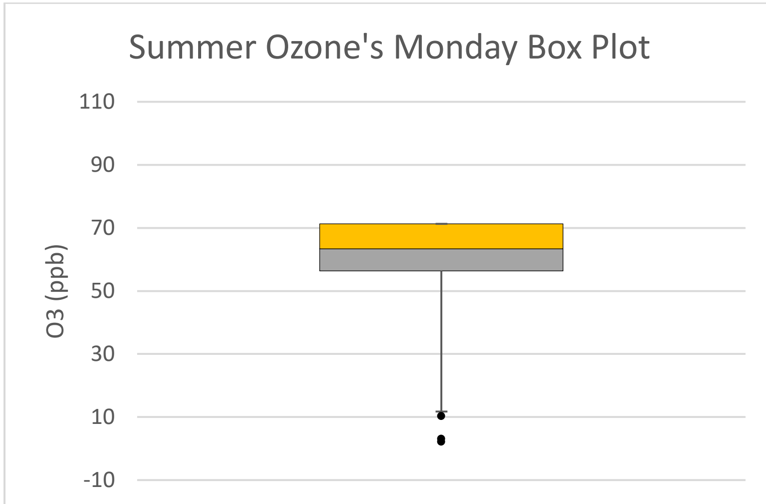

Winter CPC's Saturday Concentration
Concentration (#/cm^3)
90000
80000
70000
60000
50000
40000
30000
20000
10000
0
7
8
9
10
11
12
13
14
15
16
17
18
Time

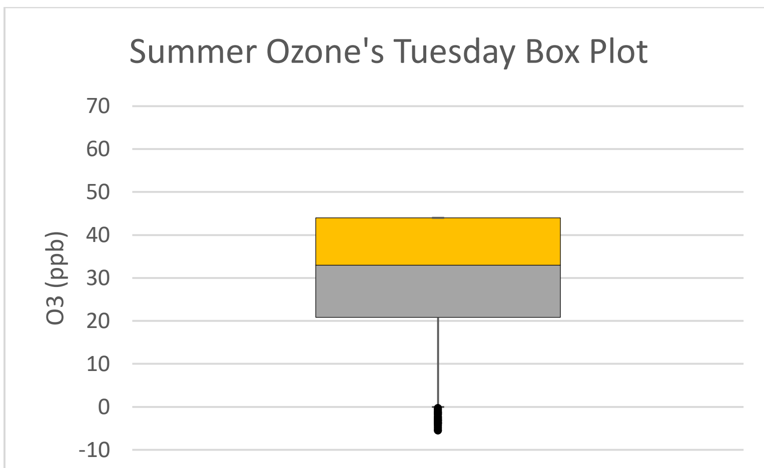

Winter UHSAS's Saturday Concentration
Concentration (#/cm^3)
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
7
8
9
10
11
12
13
14
15
16
17
18
Time

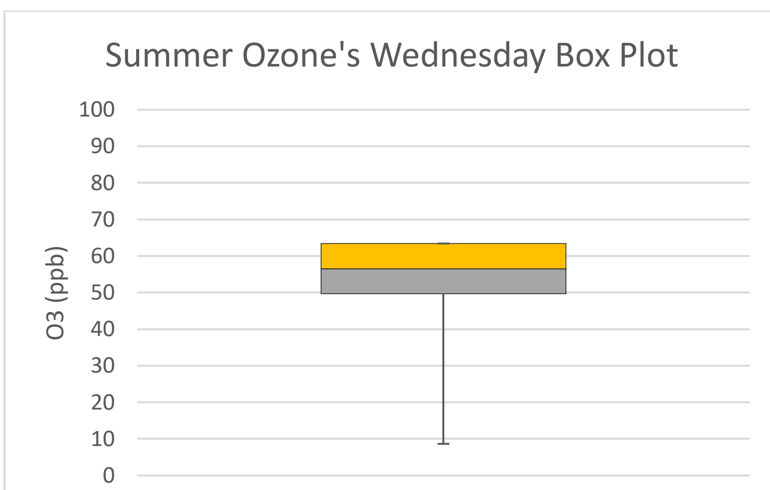

Winter CPC's Sunday Concentration
Concentration (#/cm^3)
35000
30000
25000
20000
15000
10000
5000
0
7
8
9
10
11
12
13
14
15
16
17
18
Time

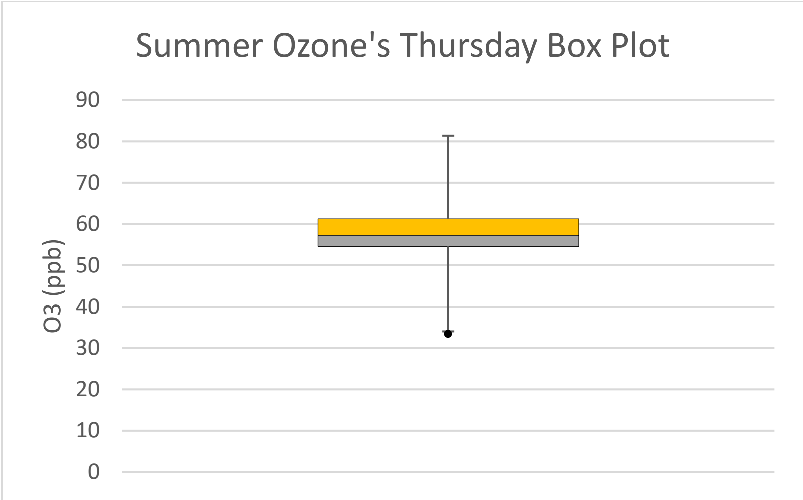

Winter UHSAS's Sunday Concentration
Concentration (#/cm^3)
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
7
8
9
10
11
12
13
14
15
16
17
18
Time

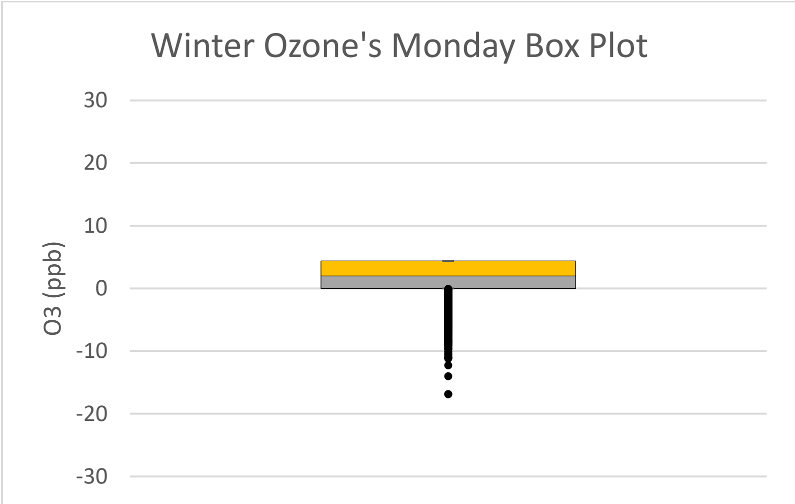
Appendix G: Ozone Box Plots and Outliers

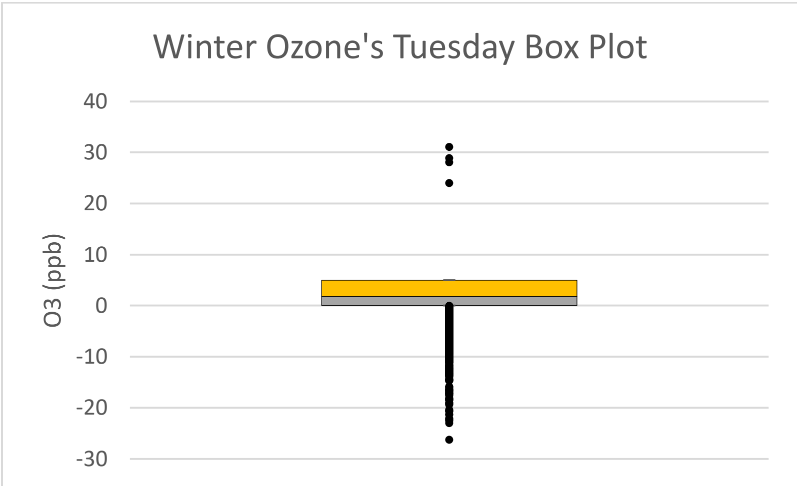


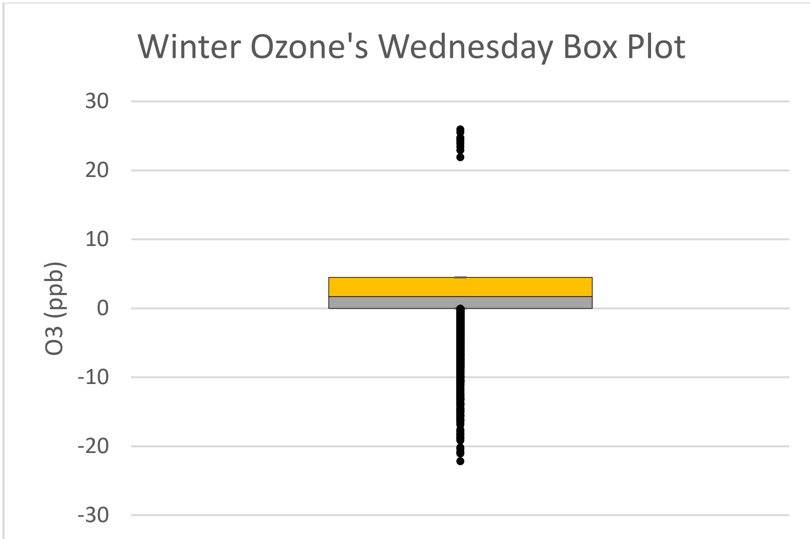


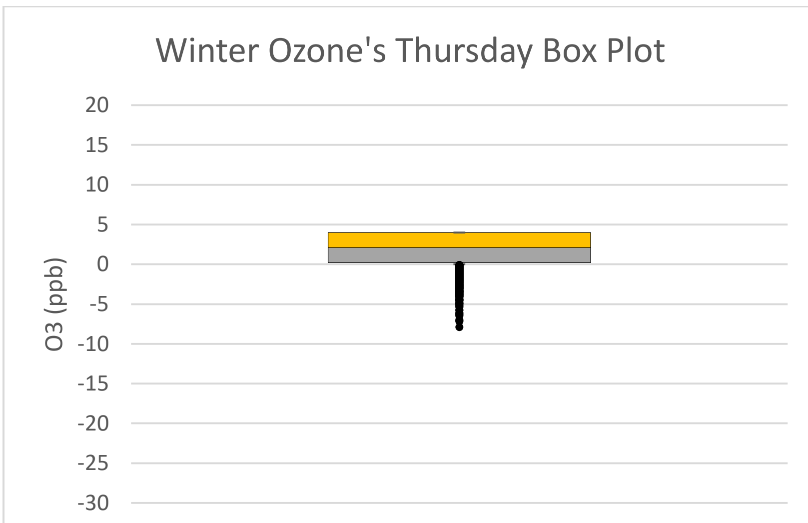


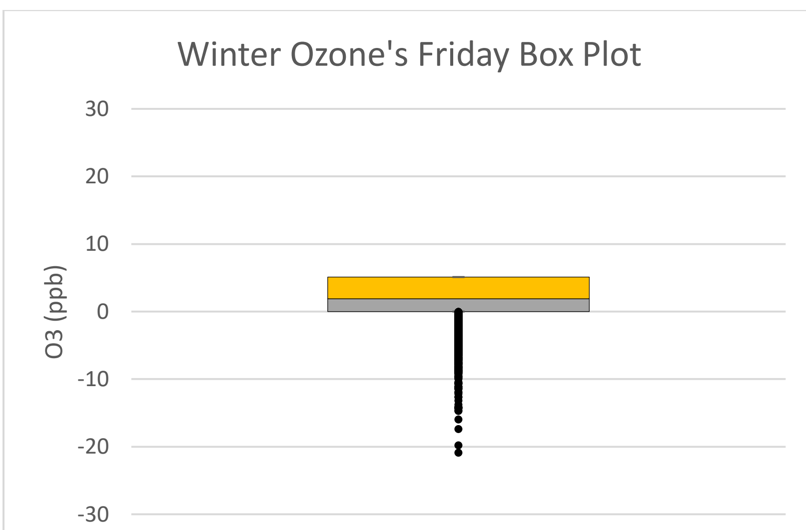

Summer Ozone's Thursday Box Plot
O3 (ppb)
90
80
70
60
50
40
30
20
10
0

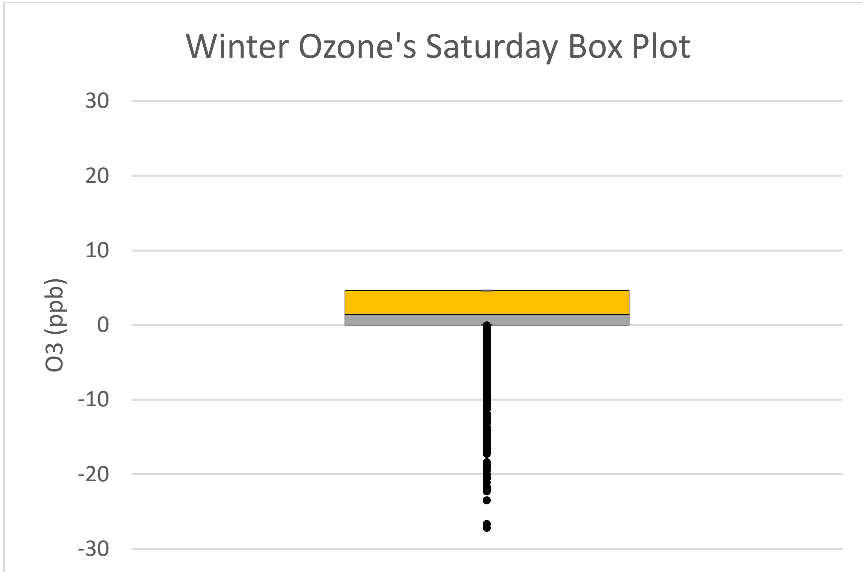

Winter Ozone's Monday Box Plot
O3 (ppb)
30
20
10
0
-10
-20
-30

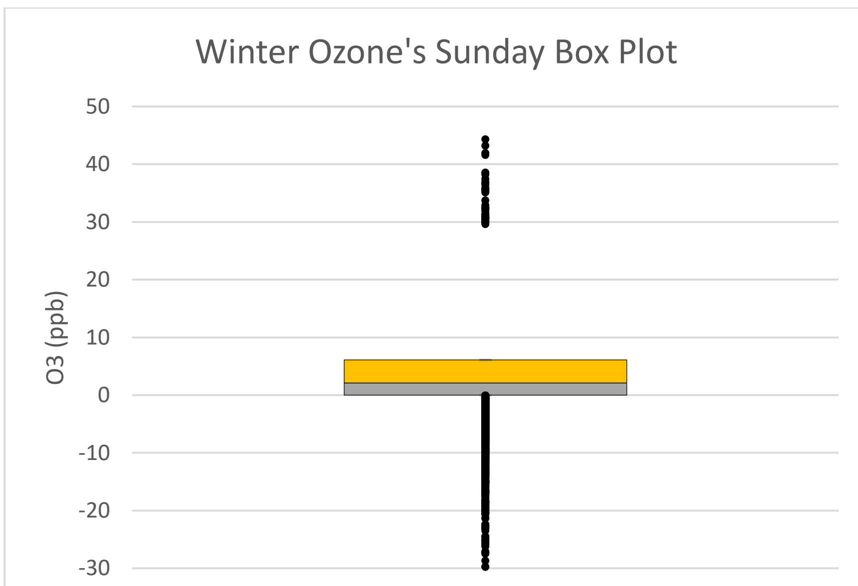

Winter Ozone's Tuesday Box Plot
O3 (ppb)
40
30
20
10
0
-10
-20
-30


Winter Ozone's Wednesday Box Plot
30
20
10
0
-10
-20
-30
O3 (ppb)

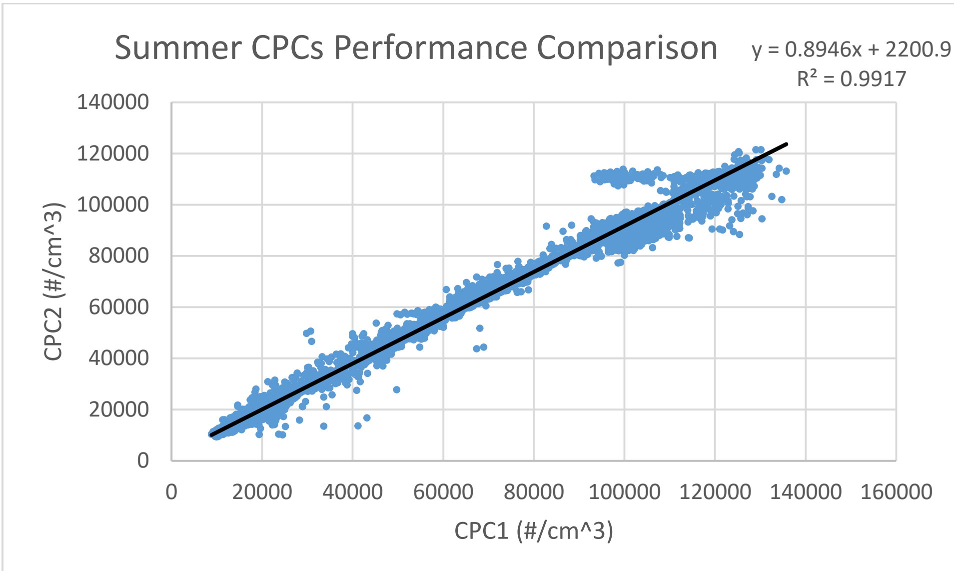

Winter Ozone's Thursday Box Plot
20
15
10
5
0
-5
-10
-15
-20
-25
-30
O3 (ppb)

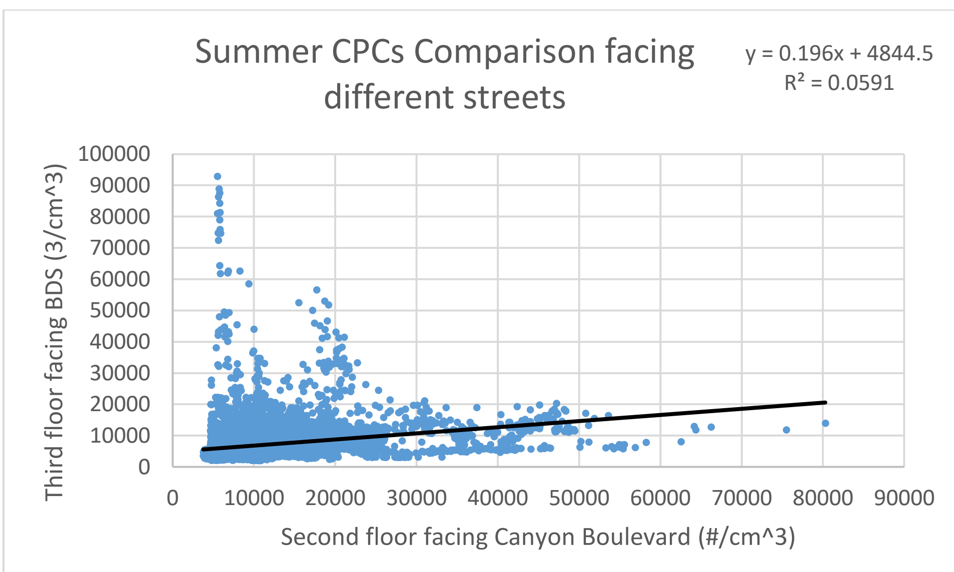

Winter Ozone's Friday Box Plot
30
20
10
0
-10
-20
-30
O3 (ppb)

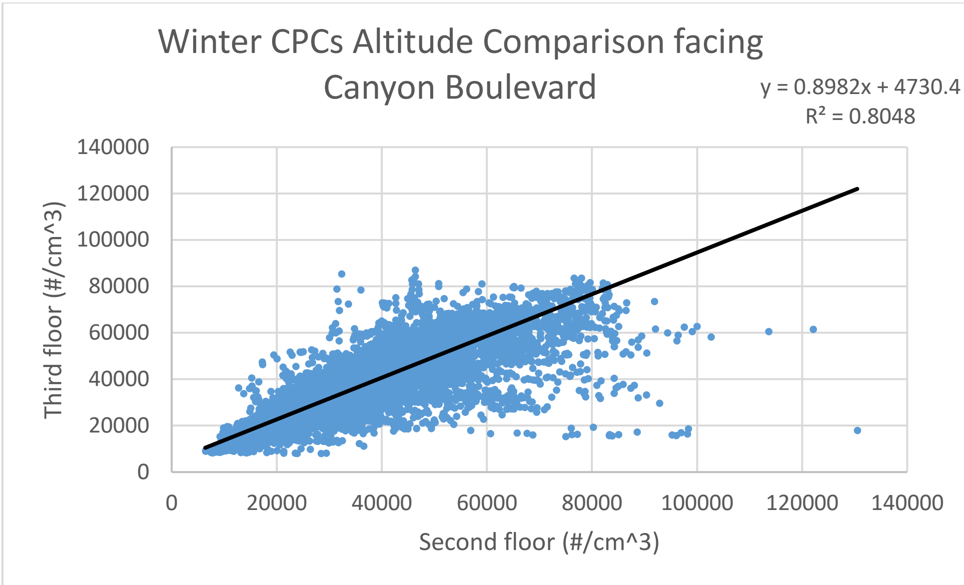

Winter Ozone's Saturday Box Plot
30
20
10
0
-10
-20
-30
O3 (ppb)

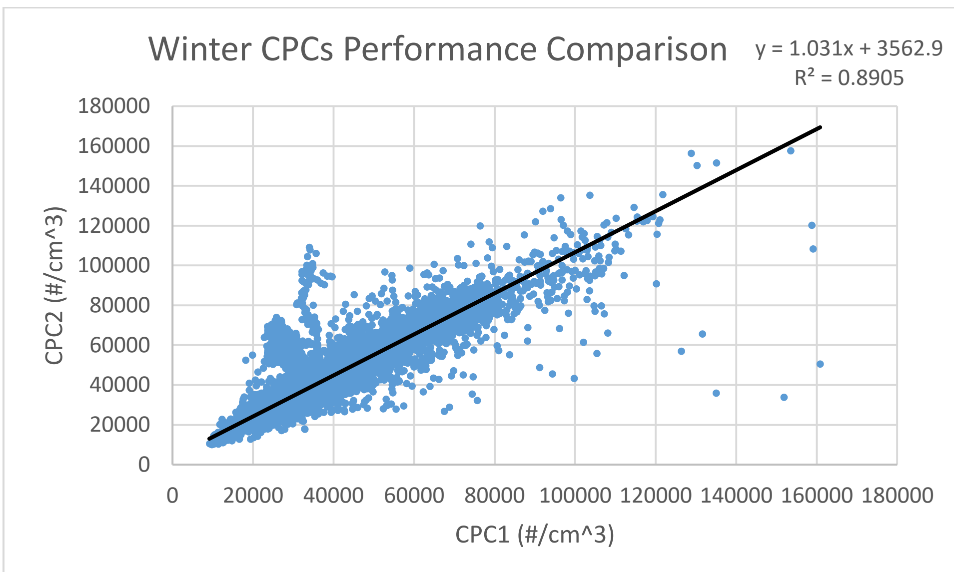

Winter Ozone's Sunday Box Plot
50
40
30
20
10
0
-10
-20
-30
O3 (ppb)

Appendix H: CPCs' Performance Comparison and Measurements at Different Altitude Regression Fits

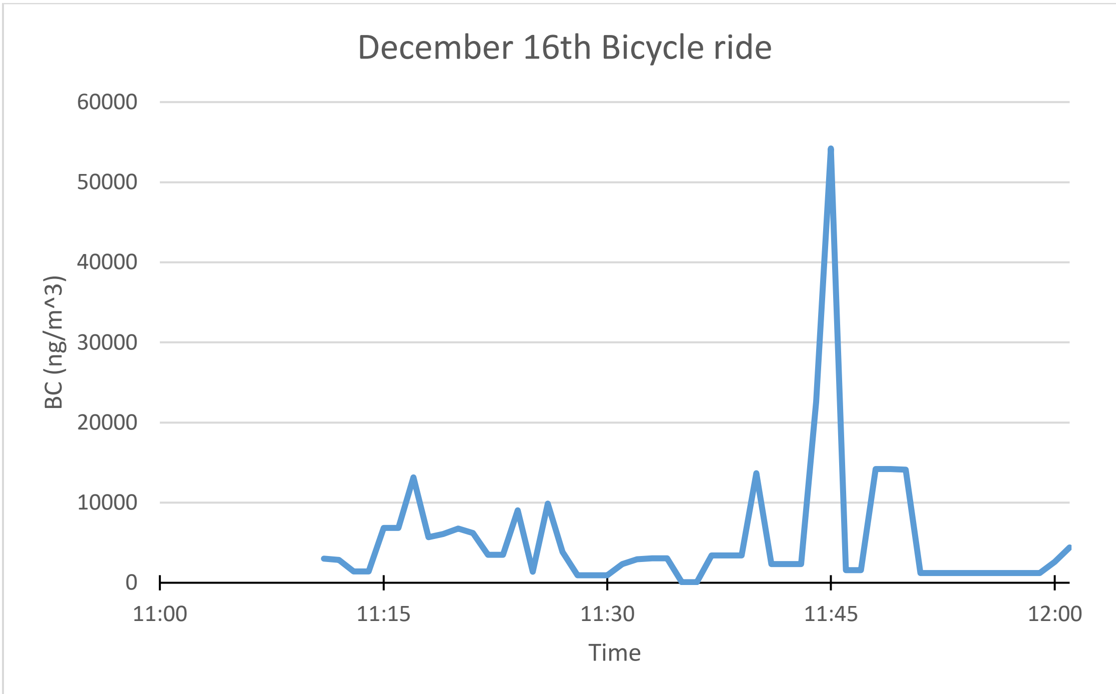


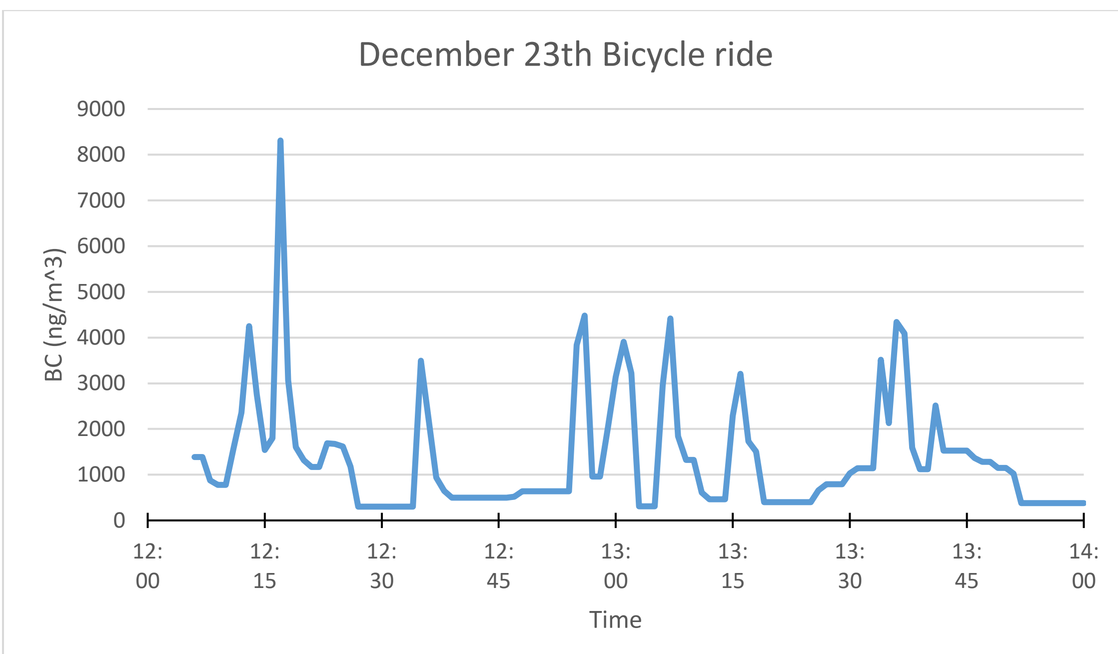


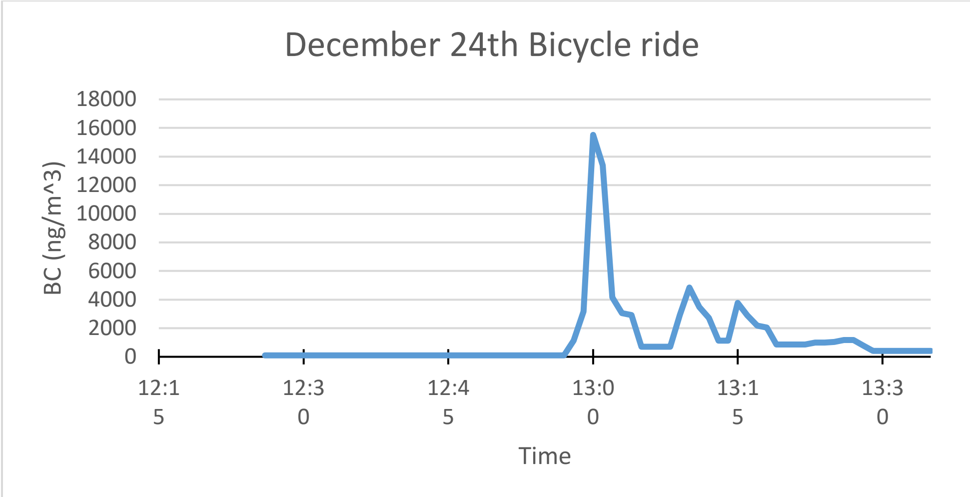

Winter CPCs Altitude Comparison facing Canyon Boulevard
y = 0.8982x + 4730.4
R² = 0.8048
Third floor (#/cm^3)
Second floor (#/cm^3)
0
20000
40000
60000
80000
100000
120000
140000

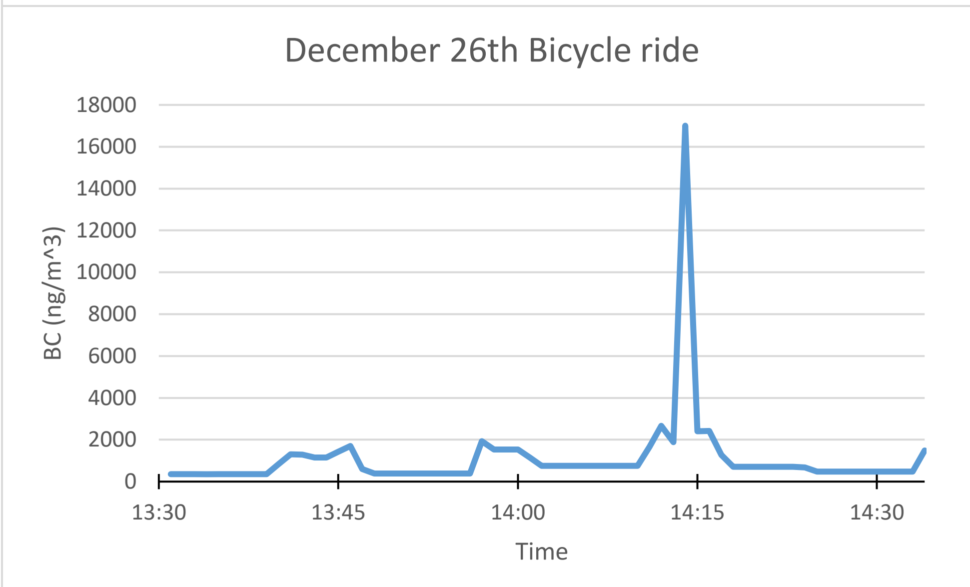

Winter CPCs Performance Comparison
y = 1.031x + 3562.9
R² = 0.8905
CPC2 (#/cm^3)
CPC1 (#/cm^3)
0
20000
40000
60000
80000
100000
120000
140000
160000
180000

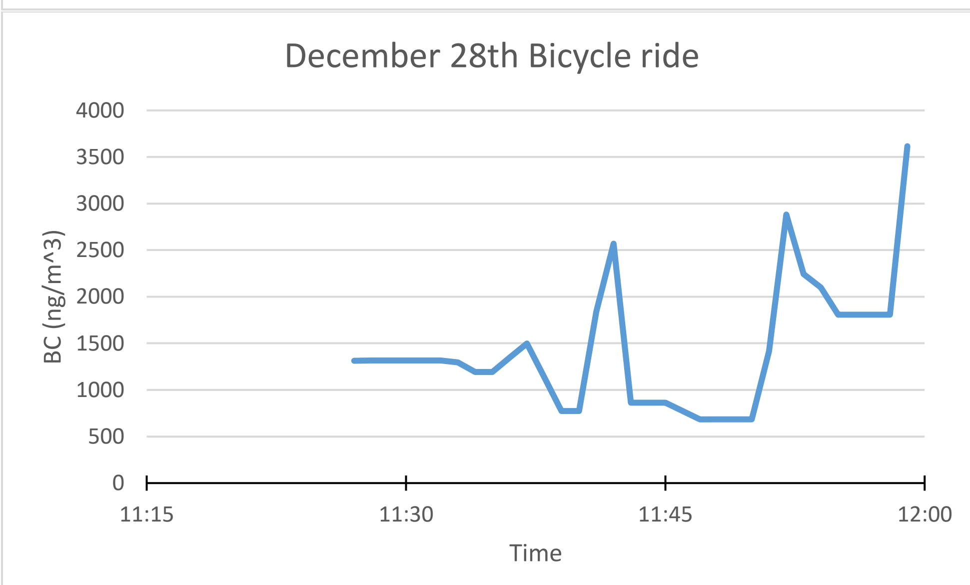
Appendix I: Bicycle Ride Black Carbon Concentration Plots



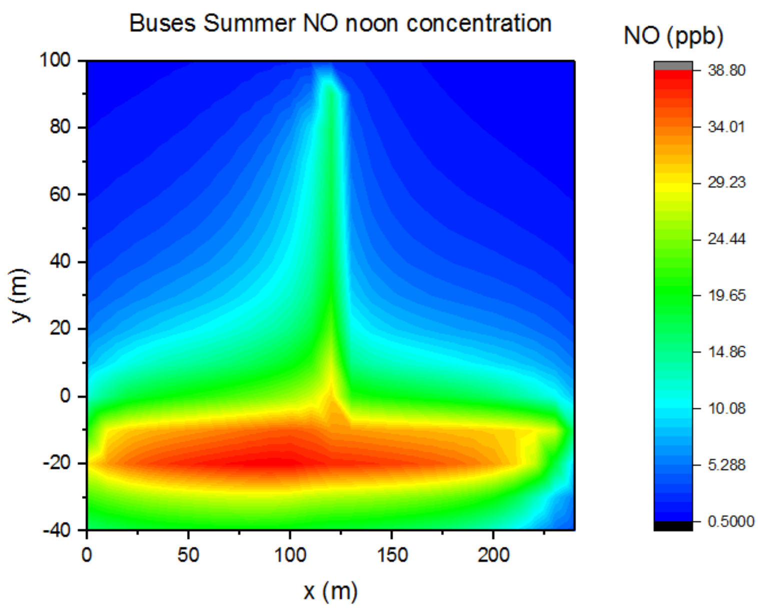


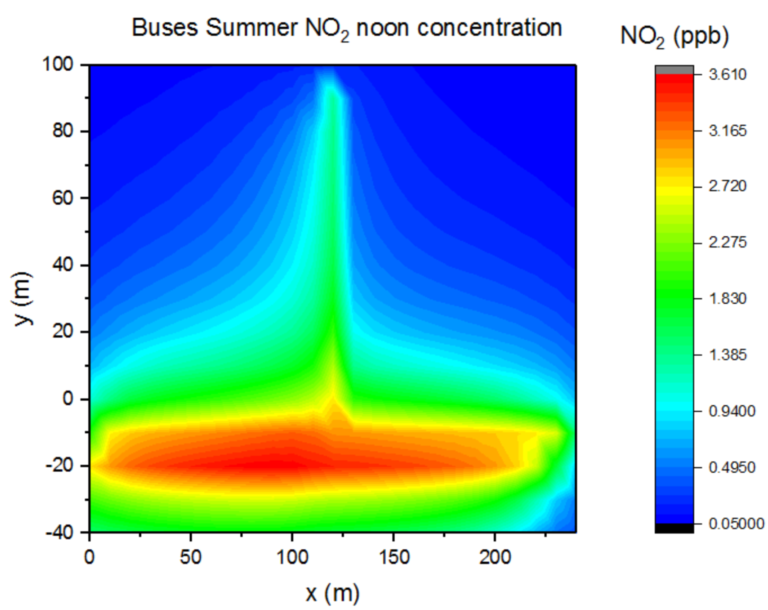

December 24th Bicycle ride
BC (ng/m^3)
18000
16000
14000
12000
10000
8000
6000
4000
2000
0
12:1
5
12:3
0
12:4
5
13:0
0
13:1
5
13:3
0
Time

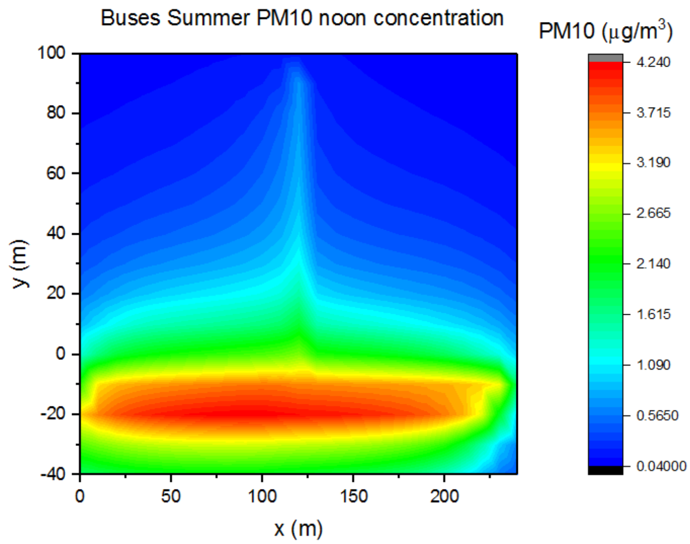

December 26th Bicycle ride
BC (ng/m^3)
18000
16000
14000
12000
10000
8000
6000
4000
2000
0
13:30
13:45
14:00
14:15
14:30
Time

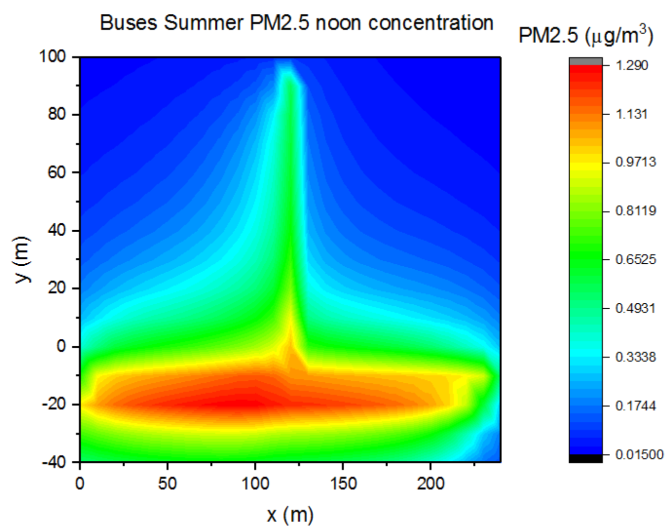

December 28th Bicycle ride
BC (ng/m^3)
4000
3500
3000
2500
2000
1500
1000
500
0
11:15
11:30
11:45
12:00
Time

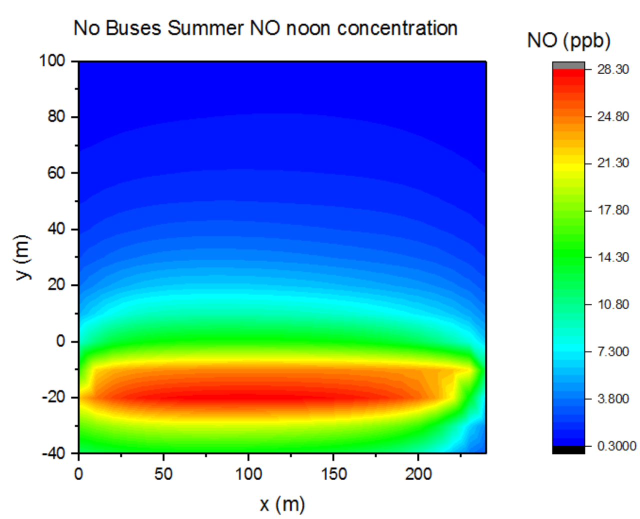
Appendix J: R-Line Contour Concentration Plots

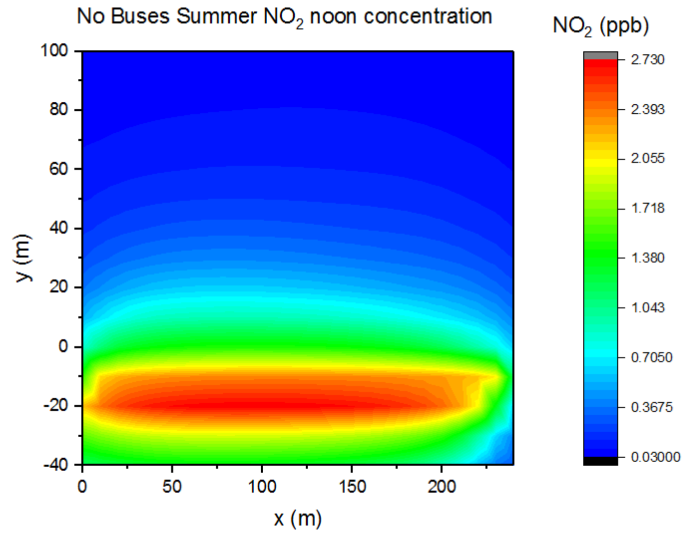




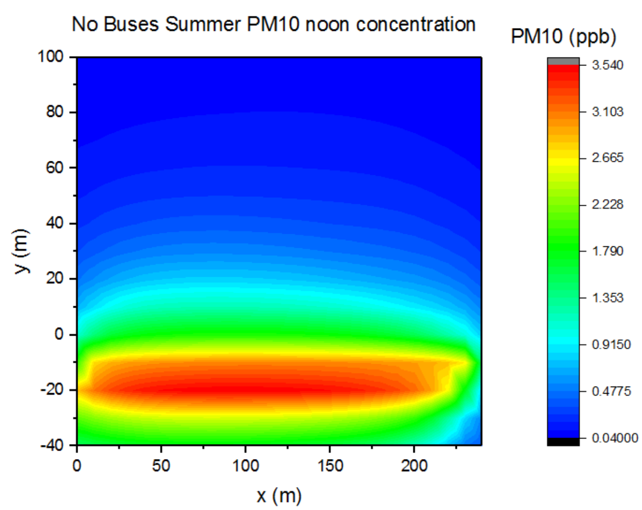

Buses Summer PM10 noon concentration
PM10 (μg/m3)
4.240
3.715
3.190
2.665
2.140
1.615
1.090
0.5650
0.04000
y (m)
x (m)


Buses Summer PM2.5 noon concentration
PM2.5 (μg/m3)
1.290
1.131
0.9713
0.8119
0.6525
0.4931
0.3338
0.1744
0.01500
y (m)
x (m)

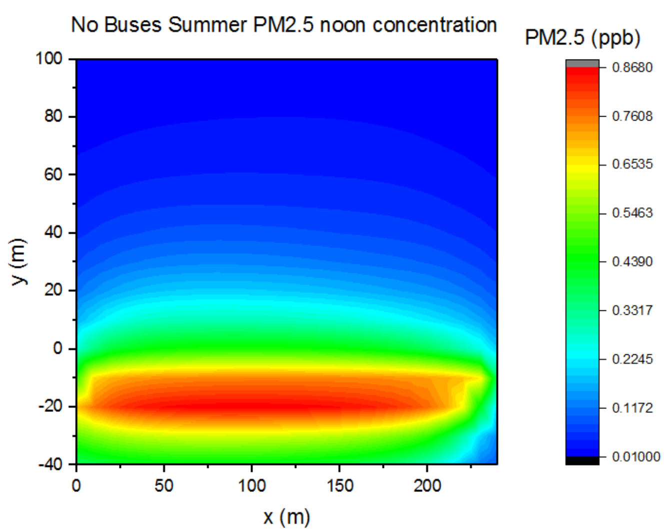

No Buses Summer NO noon concentration
NO (ppb)
28.30
24.80
21.30
17.80
14.30
10.80
7.300
3.800
0.3000
y (m)
x (m)



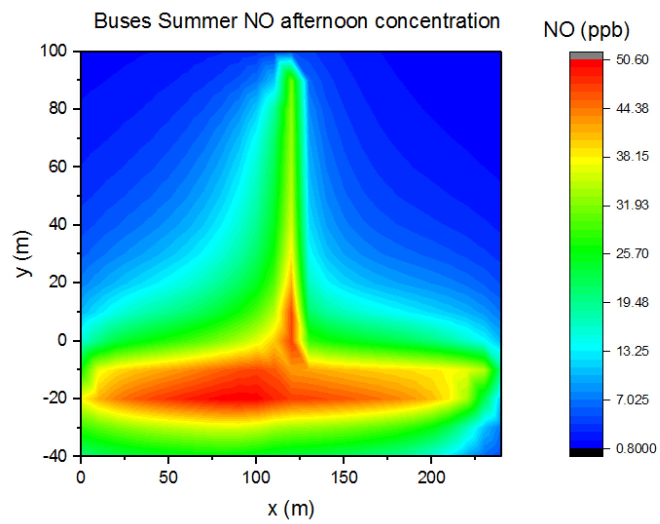
No Buses Summer NO_2 noon concentration
NO_2 (ppb)
2.730
2.393
2.055
1.718
1.380
1.043
0.7050
0.3675
0.03000
y (m)
x (m)

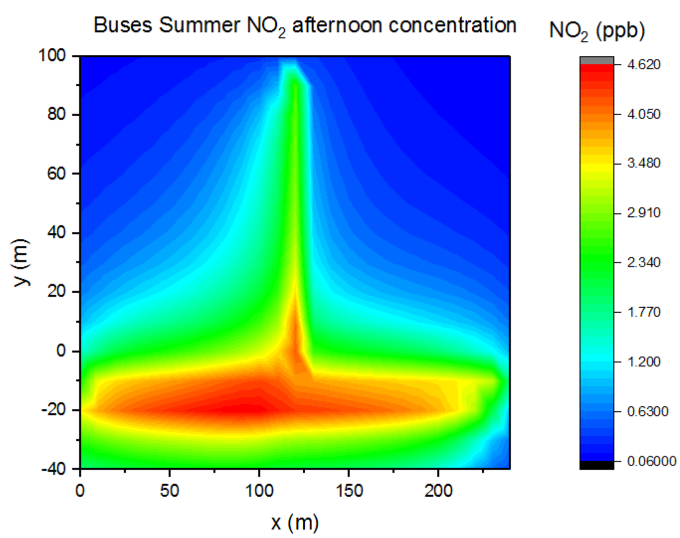


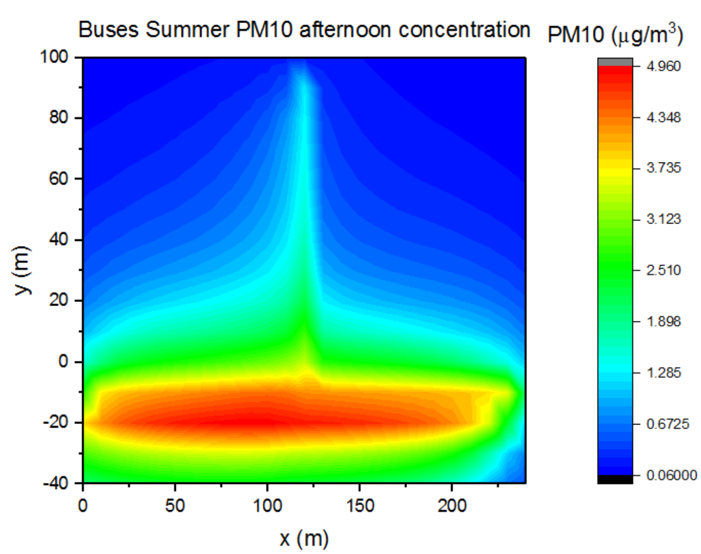
No Buses Summer PM10 noon concentration
PM10 (ppb)
3.540
3.103
2.665
2.228
1.790
1.353
0.9150
0.4775
0.04000
y (m)
x (m)

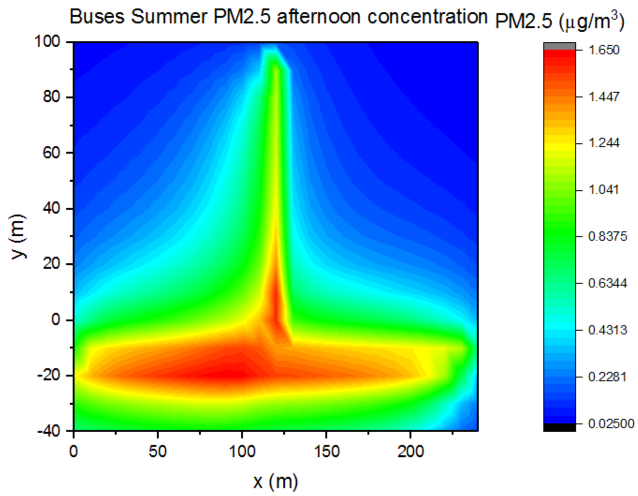


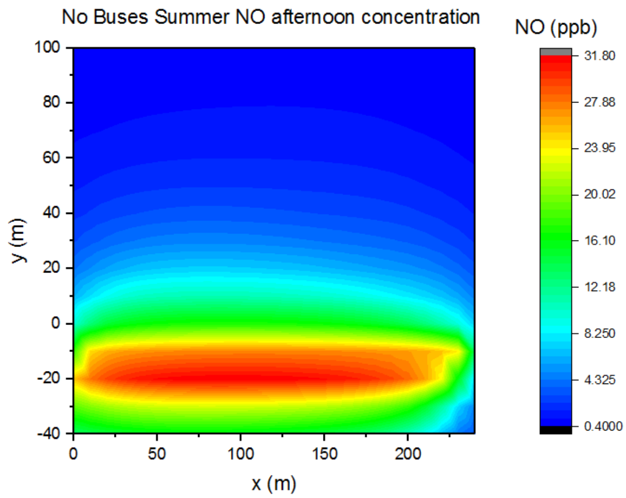
No Buses Summer PM2.5 noon concentration
PM2.5 (ppb)
0.8680
0.7608
0.6535
0.5463
0.4390
0.3317
0.2245
0.1172
0.01000
y (m)
x (m)

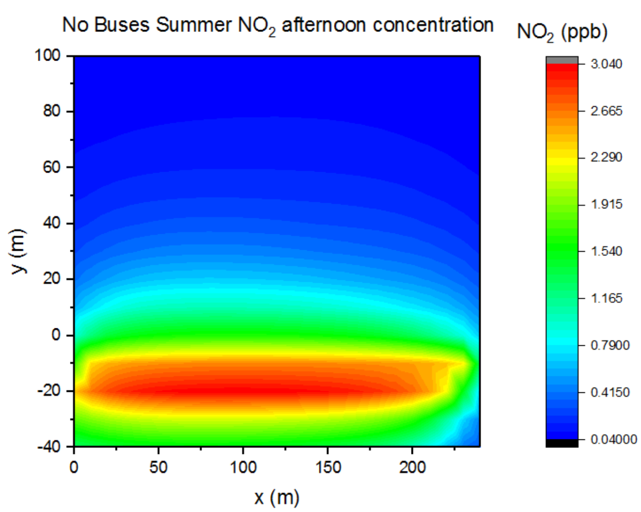

Buses Summer NO afternoon concentration
NO (ppb)
50.60
44.38
38.15
31.93
25.70
19.48
13.25
7.025
0.8000
y (m)
x (m)

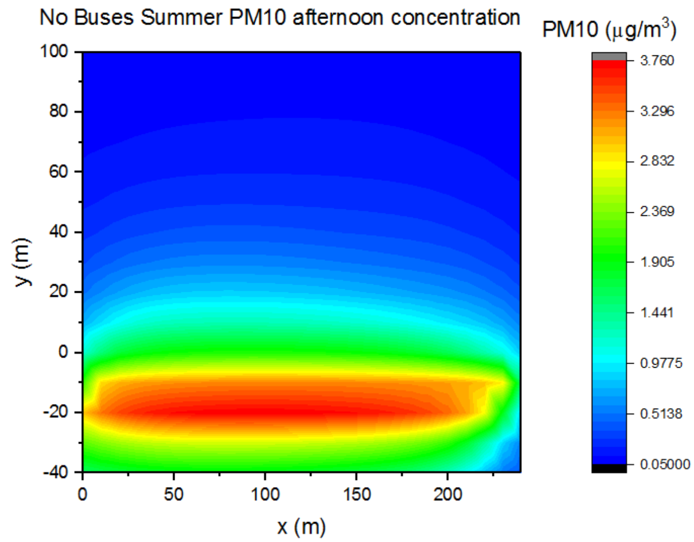

Buses Summer NO_2 afternoon concentration
NO_2 (ppb)
4.620
4.050
3.480
2.910
2.340
1.770
1.200
0.6300
0.06000
y (m)
x (m)

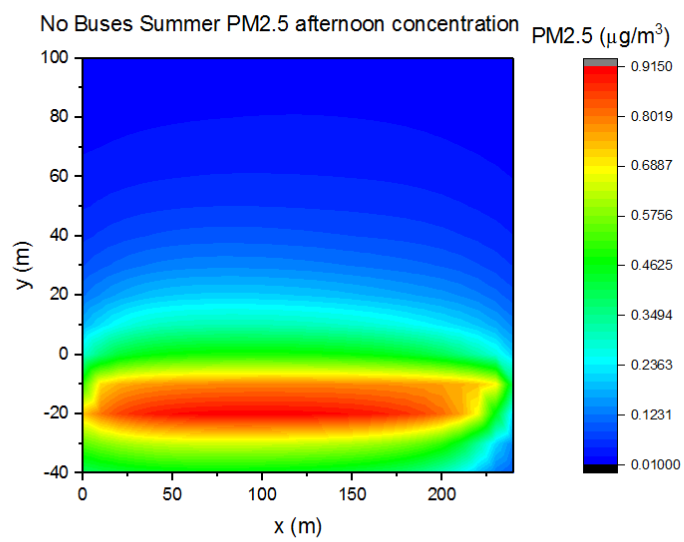

Buses Summer PM10 afternoon concentration
PM10 ($\mu g/m^3$)
4.960
4.348
3.735
3.123
2.510
1.898
1.285
0.6725
0.06000
y (m)
x (m)

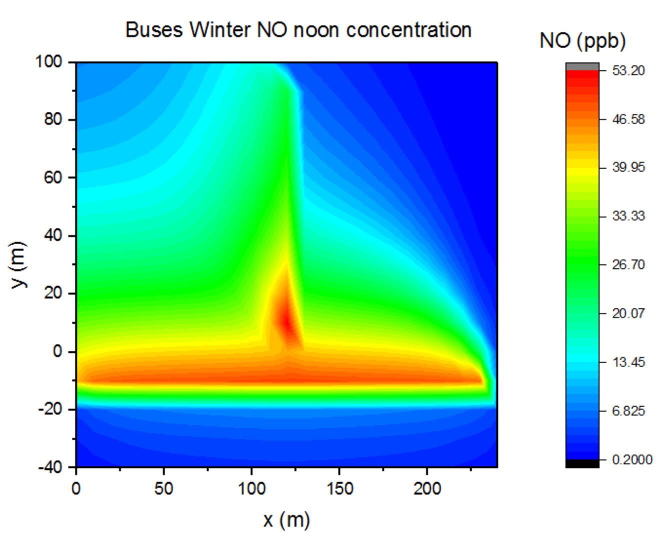

Buses Summer PM2.5 afternoon concentration
PM2.5 (μg/m3)
1.650
1.447
1.244
1.041
0.8375
0.6344
0.4313
0.2281
0.02500
y (m)
x (m)

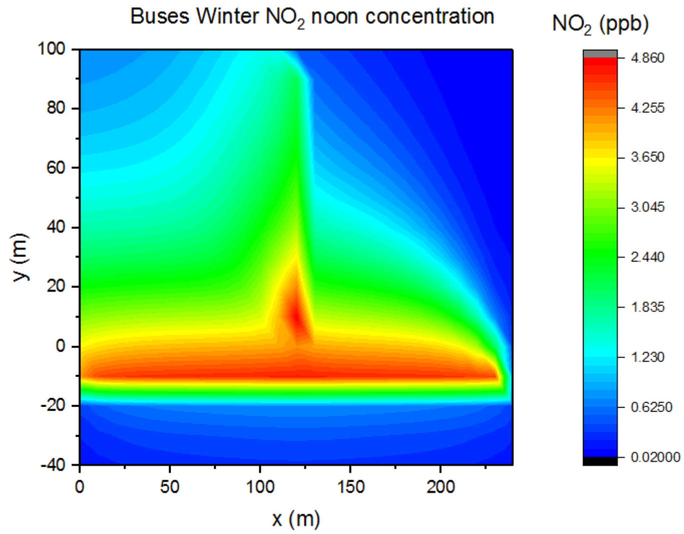

No Buses Summer NO afternoon concentration
NO (ppb)
31.80
27.88
23.95
20.02
16.10
12.18
8.250
4.325
0.4000
y (m)
x (m)

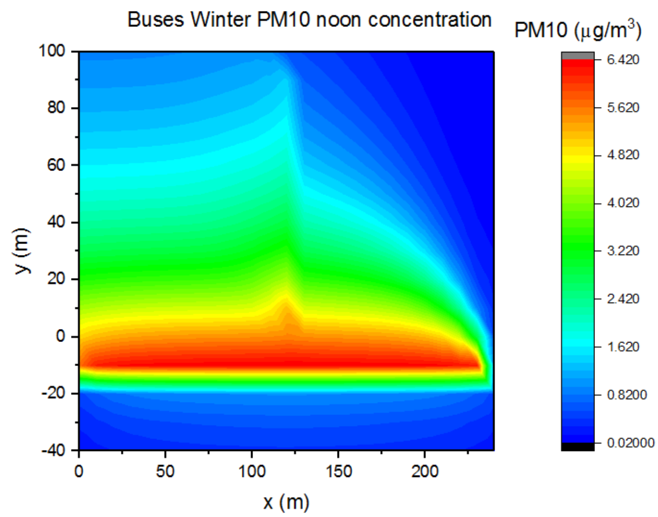

No Buses Summer NO2 afternoon concentration
NO2 (ppb)
3.040
2.665
2.290
1.915
1.540
1.165
0.7900
0.4150
0.04000
y (m)
x (m)

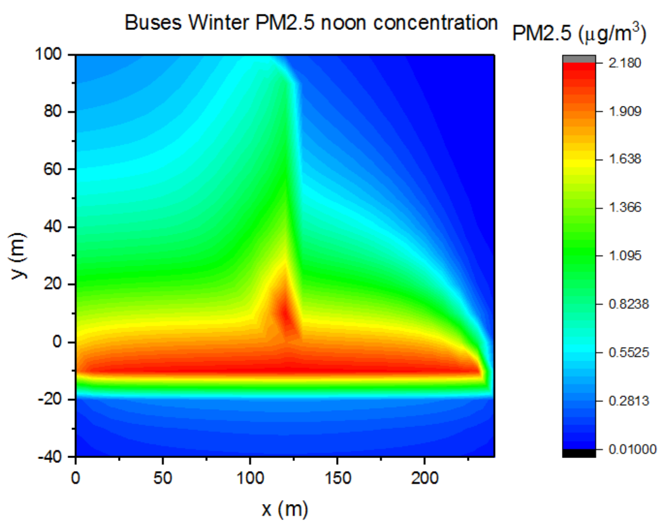

No Buses Summer PM10 afternoon concentration
PM10 (µg/m³)
3.760
3.296
2.832
2.369
1.905
1.441
0.9775
0.5138
0.05000
y (m)
x (m)

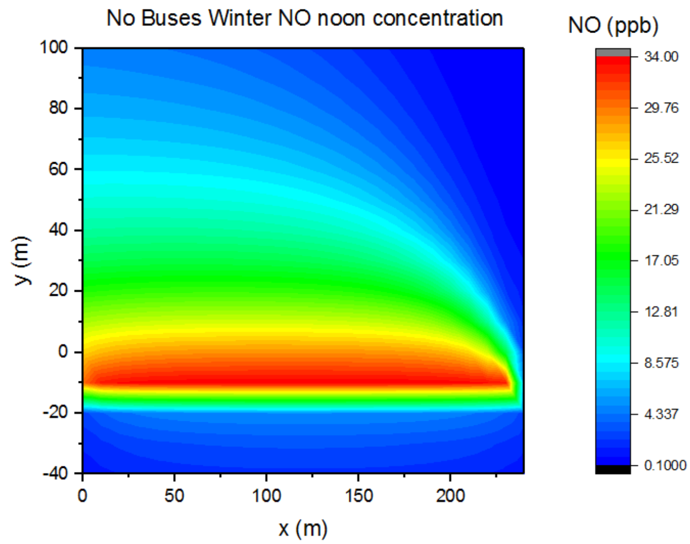

No Buses Summer PM2.5 afternoon concentration
PM2.5 (µg/m³)
0.9150
0.8019
0.6887
0.5756
0.4625
0.3494
0.2363
0.1231
0.01000
y (m)
x (m)

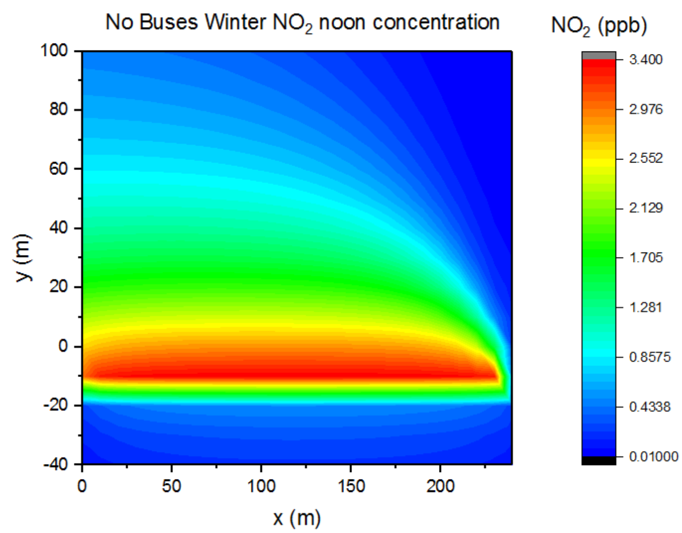

Buses Winter NO noon concentration
NO (ppb)
53.20
46.58
39.95
33.33
26.70
20.07
13.45
6.825
0.2000
y (m)
x (m)

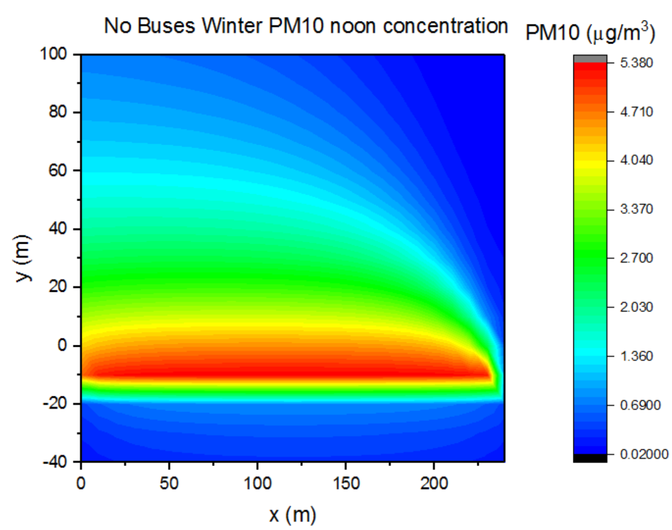

Buses Winter NO2 noon concentration
NO2 (ppb)
y (m)
x (m)
4.860
4.255
3.650
3.045
2.440
1.835
1.230
0.6250
0.02000

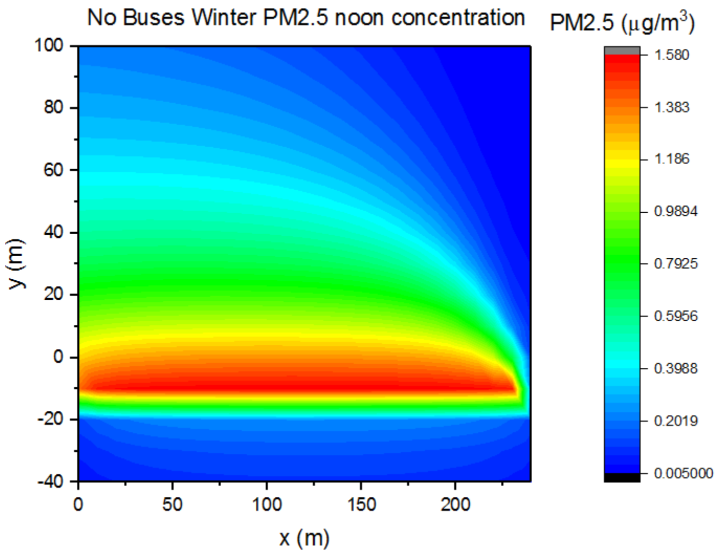

Buses Winter PM10 noon concentration
PM10 (μg/m3)
y (m)
x (m)
6.420
5.620
4.820
4.020
3.220
2.420
1.620
0.8200
0.02000

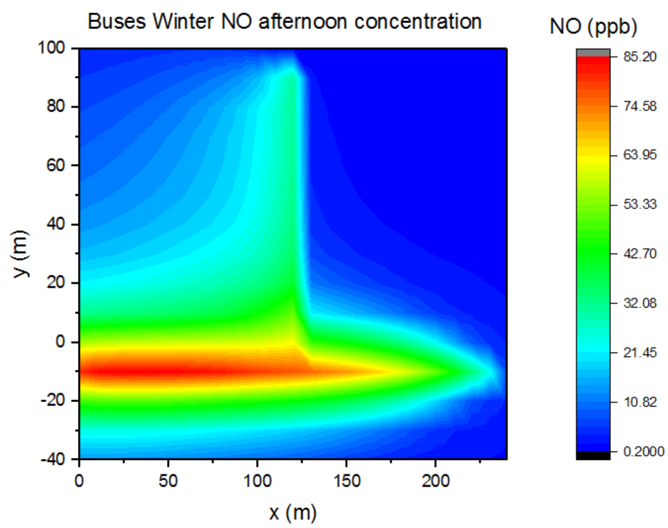

Buses Winter PM2.5 noon concentration
PM2.5 (μg/m3)
y (m)
x (m)
2.180
1.909
1.638
1.366
1.095
0.8238
0.5525
0.2813
0.01000

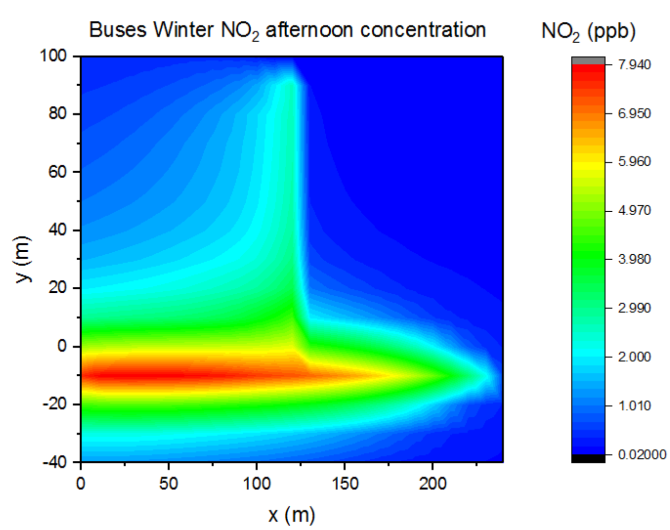

No Buses Winter NO noon concentration
NO (ppb)
34.00
29.76
25.52
21.29
17.05
12.81
8.575
4.337
0.1000
y (m)
x (m)

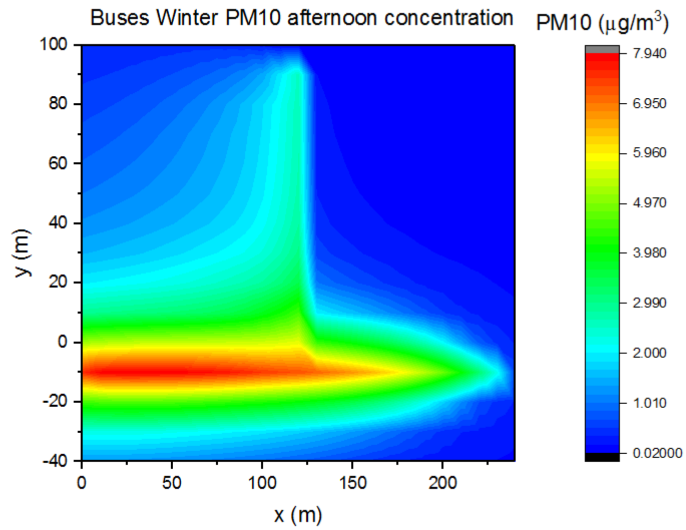

No Buses Winter NO_2 noon concentration
NO_2 (ppb)
3.400
2.976
2.552
2.129
1.705
1.281
0.8575
0.4338
0.01000
y (m)
x (m)


No Buses Winter PM10 noon concentration
PM10 ($\mu g/m^3$)
5.380
4.710
4.040
3.370
2.700
2.030
1.360
0.6900
0.02000
y (m)
x (m)

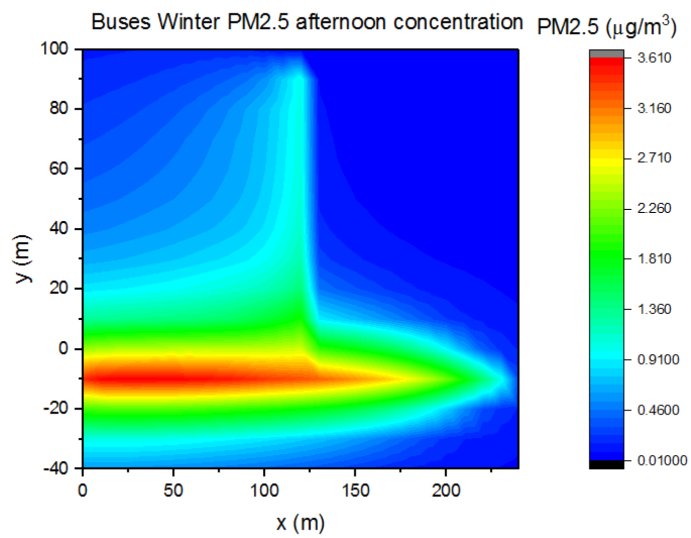

No Buses Winter PM2.5 noon concentration
PM2.5 (μg/m3)
1.580
1.383
1.186
0.9894
0.7925
0.5956
0.3988
0.2019
0.005000
y (m)
x (m)
100
80
60
40
20
0
-20
-40
0
50
100
150
200


Buses Winter NO afternoon concentration
NO (ppb)
85.20
74.58
63.95
53.33
42.70
32.08
21.45
10.82
0.2000
y (m)
x (m)
100
80
60
40
20
0
-20
-40
0
50
100
150
200

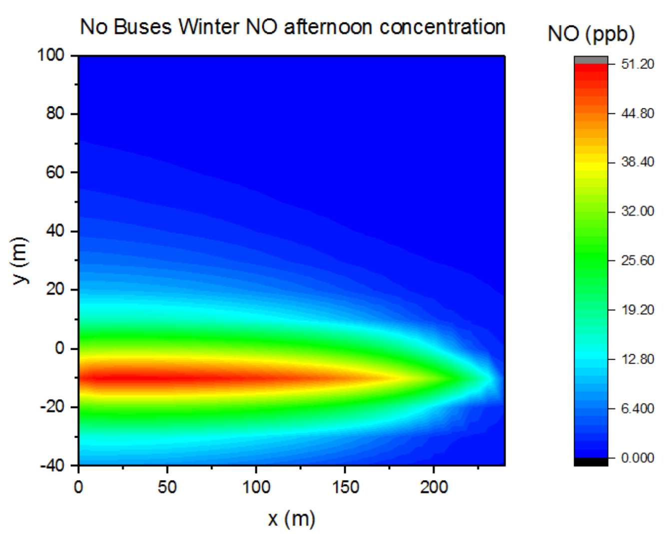

Buses Winter NO2 afternoon concentration
NO2 (ppb)
7.940
6.950
5.960
4.970
3.980
2.990
2.000
1.010
0.02000
y (m)
x (m)
100
80
60
40
20
0
-20
-40
0
50
100
150
200



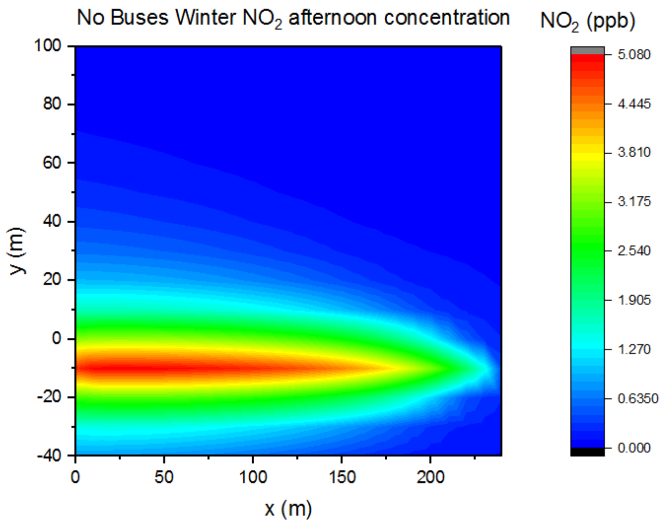
Buses Winter PM10 afternoon concentration
PM10 (μg/m3)
7.940
6.950
5.960
4.970
3.980
2.990
2.000
1.010
0.02000
y (m)
x (m)

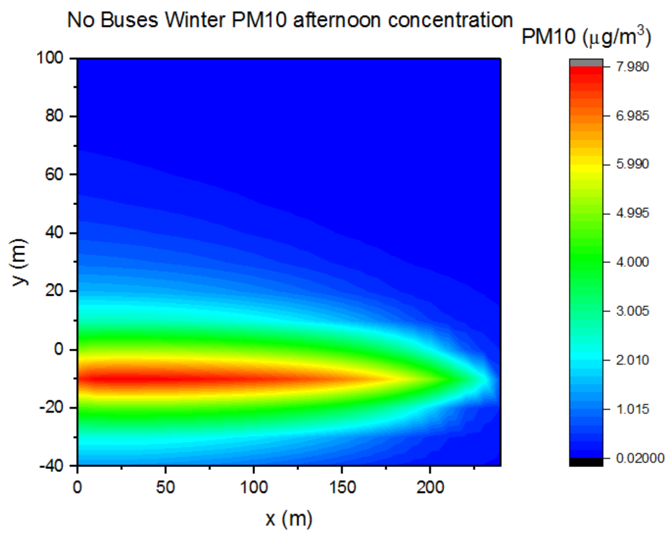


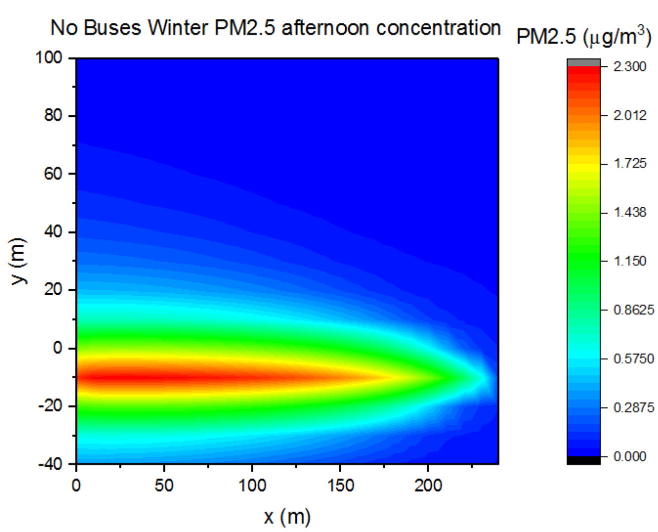
Buses Winter PM2.5 afternoon concentration
PM2.5 (μg/m3)
3.610
3.160
2.710
2.260
1.810
1.360
0.9100
0.4600
0.01000
y (m)
x (m)



No Buses Winter NO afternoon concentration
NO (ppb)
51.20
44.80
38.40
32.00
25.60
19.20
12.80
6.400
0.000
y (m)
x (m)


No Buses Winter NO_2 afternoon concentration
NO_2 (ppb)
5.080
4.445
3.810
3.175
2.540
1.905
1.270
0.6350
0.000
y (m)
100
80
60
40
20
0
-20
-40
x (m)
0
50
100
150
200


No Buses Winter PM10 afternoon concentration
PM10 ($\mu g/m^3$)
7.980
6.985
5.990
4.995
4.000
3.005
2.010
1.015
0.02000
y (m)
100
80
60
40
20
0
-20
-40
x (m)
0
50
100
150
200


No Buses Winter PM2.5 afternoon concentration
PM2.5 ($\mu g/m^3$)
2.300
2.012
1.725
1.438
1.150
0.8625
0.5750
0.2875
0.000
y (m)
100
80
60
40
20
0
-20
-40
x (m)
0
50
100
150
200