# A Study of the Impact of Diesel Buses on Downtown Boulder

Shelly L. Miller, Professor, Mechanical Engineering Department and Environmental Engineering Program, University of Colorado Boulder

Josue Hernandez Pedroza, MS candidate, Fulbright Scholar, Mechanical Engineering Department, University of Colorado Boulder

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# Executive Summary

- Diesel exhaust is a known carcinogen. It is comprised of gases and particulate matter. Two very toxic compounds in diesel exhaust are particulate black carbon and oxides of nitrogen (NOx). Black carbon is a possible carcinogen and NOx is a respiratory irritant associated with cardio-pulmonary disease.
- RTD conducts more than 1,000 diesel bus trips per day in Boulder, CO (counting trips to and from both bus stations in Boulder, the total is approximately 1400).
- Boulder residents commissioned this study of the air quality impact of these bus trips.
- Stationary tests of air quality on downtown Boulder condominium balconies showed elevated levels of NOx that correlate with bus traffic, but did not reveal a serious current threat to health.
- Air quality tests on a bicycle following buses (replicating bicycle commuters and pedestrians, including children) varied widely among buses. Older *Jump* buses created extremely high, bursts of black carbon (possible carcinogen, component of diesel exhaust) and ultrafine particles when traveling directly behind the bus.
- The introduction of electric buses in Boulder would substantially improve air quality and enhance the health and well-being of Boulder residents.

A measurement campaign was conducted during the summer in downtown Boulder, from July 25$^{th}$ to July 31$^{st}$, 2016. A suitable location next to the Boulder Downtown Bus Station was selected to take measurements, which would capture fresh emissions from transiting buses. Two condo units were employed during the measurements and the bus count was taken to correlate the measured data and bus density. The objective of the study was to characterize the level of emissions from RTD diesel buses and determine the possible risk for the well-being and health of the population.

Several instruments were employed to measure particulate matter, including instruments that measured ultrafine, fine and coarse size particles. Ultrafine and especially fine particulate matter have been connected with respiratory diseases, and they affect lungs, blood vessels, and heart when penetrate deep into the respiratory system. Diesel engines emit particulate matter primarily in the range of ultrafine and fine.

Black carbon measurements were also part of the study and it is a major component of diesel exhaust. Diesel exhaust is a group 1 carcinogen (carcinogenic to humans), from the International Agency for Research on Cancer (IARC). Nitrogen oxides (NOx) were another pollutant measured

during the study, since the emissions of NOx are considerably higher from diesel engines compared to gasoline. NOx increases respiratory diseases, hospital admissions and the risk of suffering asthma.

Traffic-related air pollutant concentrations typically vary between weekends and weekdays, primarily because of the traffic density and vehicle type. This study showed a lower number of buses traveling through downtown Boulder on the weekend (exactly as expected from the RTD schedule); the number of heavy duty trucks was also lower during the weekend. Some differences were found for the car traffic. The early afternoon on Saturday has a higher number of cars compared to weekdays and the density decreases through the afternoon; however, on weekdays the car density is low in the early afternoon and it increases in the late afternoon.

The results from the stationary measurements of particulate matter did not present a direct connection with vehicle density. Atmospheric particulate matter measured during the campaign was a result of regional urban pollution and not local traffic sources. Black carbon and ozone was highly constant and did not vary with vehicle density. Nitrogen oxides were correlated with the bus count, in the morning they went up and in the late afternoon they were even higher. Nitrogen oxides were the only pollutant that had a direct link with diesel bus density.

An additional bicycle ride was carried out on August 4$^{th}$, 2016. The aim of this test was to chase cars and buses for the purpose of capturing direct emissions behind vehicles. The pollutants measured were particulate matter (ultrafine and fine), black carbon, and ozone. The route was designed to collect measurements in areas without any vehicles, and also in areas with cars and buses. The bicycle ride measurements were highly correlated to the emissions of vehicles, since the bicycle rider was right behind cars and buses. The results showed low concentrations in places without vehicles; elevated concentrations were shown immediately after riding behind buses. When following some buses, the measurements were only slightly elevated. However, certain RTD routes showed an exorbitant rise when riding behind them. This behavior demonstrates that specific buses of the RTD fleet emit different concentration of pollutants depending on their exhaust control system and age of the bus (measurements exhibited higher readings when following the older buses). The average highest concentration of pollutants was found in all the zones surrounding the bus station. Black carbon, which is a main constituent of diesel particulate matter, was highly linked with the concentration level of particulate matter during the bicycle ride. An important finding of the bicycle ride is the fact that the highest reading obtained during the entire campaign was taken when riding right behind an RTD bus.

Pedestrians and bicycle commuters are exposed daily to these air pollutants that represent a threat to health. Minimizing the number of diesel buses would improve the air quality in downtown Boulder, but it would also reduce carbon emission and improve the health of the Boulder population.

The infographic below on health risks of diesel exhaust is courtesy of the Southern CA Environmental Health Centers based at USC.


http://envhealthcenters.usc.edu/infographics/infographic-living-near-diesel-exhaust

# Introduction

Freshly emitted air pollutants downwind from major roadways include elevated levels of particulate matter, black carbon, and oxides of nitrogen (NOx). People living within 200 m of highways are exposed to these pollutants more so than persons living farther away. Health studies show elevated risk from exposure to traffic-related air pollutants for cardio and pulmonary mortality and disease (Hart et al.), high blood pressure (, lung cancer, childhood asthma (Morgenstern et al.  and behavioral problems in school children (Forns et al. 2015). 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 (microns).

The inhalation of PM is a big concern for human health. Ultrafine and fine particles, in particular, can travel deep into the respiratory system, causing in some cases the death of the affected individual (Fruin et al. 2008). Fine PM (PM2.5, particles with diameters less than 2.5 microns) has also been related to illnesses and mortality, since it affects the blood vessels, lungs, and heart when it penetrates deep in the respiratory system. 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% ("Environments Tracking Air Quality - CDC Tracking Network" 2016). 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; it 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 human being deaths (Wang et al. 2012). The exposure of any type of PM increases the risk of illnesses in newborn babies, breath problems, decrease of lungs' growth, and early deaths ("Environments Air and Health - CDC Tracking Network" 2016a).

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 the nitrogen oxides (NOx) emitted in the environment, and diesel trucks are the biggest contributors, since the number of trucks is high in Beijing. In a study conducted in Beijing, NOx emissions in urban areas produced by trucks accounted for up to 60% of the total NOx emissions (Huo et al. 2012).

Nitrogen oxides are associated with respiratory diseases and hospital admissions, where long exposures 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). Nitrogen oxides emitted in the atmosphere take part in chemistry responsible for secondary formation of both ozone and PM2.5.

Ozone degrades the function of the lungs and increases chronic respiratory illnesses, including bronchitis, pneumonia, and lung and throat irritation ("Environments Air and Health - CDC Tracking Network" 2016b). Some studies have analyzed the co-exposure effects of ozone and diesel exhaust particulates (DEP) (Jang et al. 2005). In this study they concluded that DEP and ozone increases 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 their lung injury. Their experiments suggest that ozone can augment the potency of PM bioactivity. The ozonized PM generates more injuries and lung inflammation issues compared to non-ozonized PM.

Black carbon (BC, also called elemental carbon or EC) is a main PM constituent emitted by diesel vehicles and it represents the biggest percentage of the mass. After carbon dioxide it is considered as the second most important anthropogenic pollutant emitted (Zheng et al. 2015). The relative risk of daily mortality was correlated with increasing PM2.5 concentrations and elemental carbon (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 elemental carbon was 1.024, in each case with 95% confidence interval above 1. These results show that a major contributor to mortality is the elemental carbon within the fine PM.

Black carbon has been designated as a Group 2B carcinogen by the Interagency for Research on Cancer (IARC) (possibly carcinogenic to humans) 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 Monographs-Classifications" 2016).

The US Environmental Protection Agency regulates PM, as well as NOx 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 to which it is reasonable to be exposed without degrading health. The standards are: 53 ppb (parts per billion) annual mean for nitrogen dioxide, 70 ppb 8-h mean for ozone, 12 $\mu g/m^3$ annual mean for PM2.5, 35 $\mu g/m^3$ and 24-h mean for PM2.5. Note the Denver Metro area is in compliance with all NAAQS except for ozone.

After looking at the risks caused by traffic-related air pollution, where combustion and specifically diesel combustion engines are responsible for many of the most dangerous contaminants for human being welfare and health, a high density of diesel vehicle operation represents a serious hazard for people living or spending several hours within the surrounding areas. In Boulder, 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. The high concentration of diesel buses traveling in this area may be a huge concern for air quality and health. This pilot study was developed to provide data on the air quality in the downtown region of Boulder, Colorado. In this study measurements were conducted of traffic-related air pollutants over the course of a week. Data was also gathered on bus trips and bus routes during the measurement campaign.

# Methodology

A measurement campaign was carried out during the summer week of July 25$^{th}$ to 31$^{st}$, which was executed in a stationary location, and an additional bicycle ride on August 4$^{th}$, 2016. The aim was to measure to concentration of traffic-related air pollutants and describe the air quality in downtown Boulder. Additionally, the readings have been compared with the RTD bus density and routes next to the measurement location as a way to explore a relationship with the contaminant concentrations. The bicycle ride route was designed to determine the effects of following buses by bicycle commuters; thus during the test buses were chased at some moments, only cars at other periods, and also to follow a route without any vehicles.

## *Instruments*

The devices employed during the measurement campaign were selected to measure the major emissions from traffic. Figures 1 and 2 show the instruments and the setup utilized during the stationary

measurements in a condo. The used devices are a condensation particle counter (CPC), aerodynamic particle sizer (APS), ultrahigh sensitive aerosol spectrometer (UHSAS), all from the University of Colorado Boulder Air Quality laboratory. an Aethalometer to measure black carbon and a personal ozone monitor (POM) were borrowed from 2B Technologies, and a Thermo 42i was rented to measure NOx. All of these instruments are described below.

*Figure 1. Instruments utilized in the stationary measurement (left view).*

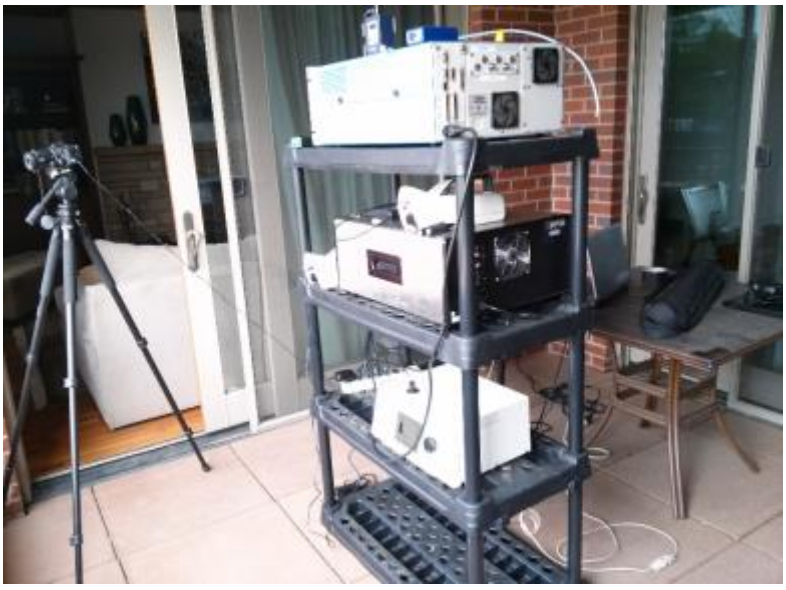

*Figure 2. Instruments utilized in the stationary measurement (right view).*

## Condensation Particle Counter (CPC)

The TSI CPC 3007 is a portable particle counter, which measures the particle number concentration from 10 nm (ultrafine particles) to more than 1 µm (fine particles). The versatility of this instrument allowed it to be employed for measurements both at the stationary location and during the bicycle ride. The device has only two drawbacks. The first one is that it does not measure the particle size distribution; consequently, it is not possible to the determine what are the diameters of the particles measured. The

second one is that the instrument can only work continuously for only 6 hours; it uses a wick that must be wetted with high quality isopropyl alcohol. When the wick dries up the measurement are inaccurate. Accordingly, the wick must be refilled in order to continue the measurements. Do to this, the CPC must be shut down, refilled and warmed up for 10 minutes to stabilize before the readings are accurate once again. Since the measurements were carried out in condos and to avoid inconveniences to the residents and neighbors, it was not possible to do more than 6 hours of measurements with the CPC. The CPC was sent back for calibration to TSI prior to deployment.

### Aerodynamic Particle Sizer (APS)

The TSI Aerodynamic Particle Sizer Spectrometer 3321 measures the number, surface area, and mass concentration of particulate matter from 0.5 µm (fine particles) to 20 µm. For this study, the mass concentration was important to measure since most health studies show that mortality is associated with mass concentrations of PM. The APS has the advantage that it can be used for long periods of time since it logs the data directly to a computer and the setup of the instrument allows the operator to create a schedule of measurements. In this way, the user does not have to be present to start the device. Unfortunately, this device was not calibrated prior to deployment. A calibration is planned in the near future and the data will be adjusted if needed.

### Ultra-High Sensitivity Aerosol Spectrometer (UHSAS)

The UHSAS from Droplet Measurement Technologies measures from 55 nm to 1 µm particle number concentrations and particle size distributions. The UHSAS has an internal PC with the software Microsoft Windows. The device can be employed for extended periods of time and the data is directly exported in a spreadsheet format for further analysis. This instrument was calibrated in the laboratory prior to use.

### Aethalometer

The Aethlabs MicroAeth AE51 kindly provided by 2BTechnologies Inc. (www.twobtech.com) was employed to measure black carbon (BC) mass concentrations. The small size of the instrument makes it extremely easy to use when making nonstationary measurements such as during bike riding. The MicroAeth is able to work continuously for around 6 hours, since it uses a filter to capture BC; after this time the readings are harmed. The filter must be changed to continue taking the measurements. The device requires 15 minutes to stabilize; hence, the first readings tend to be inaccurate. The MicroAeth data can be combined with ozone monitor data to produce a map of the route used during measurements.

### Ozone monitor

The Personal Ozone Monitor (POM) generously provided by 2BTechnologies Inc. was used to measure the mass concentration of ozone. The small size of this device makes it a good choice for nonstationary measurements. The battery does not allow it to take measurements for long periods of time, since it lasts for around 6 hours. One of the advantages of the instrument is the internal GPS which allows all the data to be correlated with the location where it was taken and ultimately create a map of black carbon and ozone readings, since the MicroAeth and the POM can work together.

### Nitrogen Oxides Monitor

The Thermofisher 42i-LS Low Source NO- $NO_2$-NOx Analyzer was used the measure nitrogen oxides. The large size of the device makes it useful only for stationary measurements. The data is logged in the

device, and easily transferred to a computer. Zero air gas was used to verify the calibration of the device. The device was calibrated prior to this study by the company from which it was rented.

## *Measurements Plan*

The measurements were divided into two categories: stationary and bicycle ride. The purpose of these tests was to analyze the concentration that people are exposed to when living close to a place with a high density of diesel buses, and study the concentration that bicycle commuters are exposed to when riding behind or close to buses. Comparisons between measurements collected on weekdays, on the weekend and during the bicycle ride were made to analyze their relation with bus and vehicle traffic. The collected data was averaged over 5 minute intervals for the stationary measurements, and for bicycle ride measurements the data was averaged for 1 minute. The one-second CPC data are presented to illustrate the instantaneous peak particle concentrations experienced while riding behind buses. For some of the instruments outliers were eliminated from the analysis. The outliers represented data points of abnormal value that were far away from the rest of the data. For the purpose the analysis, only extreme outliers were deleted.

## *Stationary Measurements*

A neighbor living in a condo next to the Boulder Downtown Bus Station (Preston Padden) kindly arranged for access to two homes.

A video camera was employed to manually count the number of buses that passed by the home on three of the measurement days, and these data were compared to the schedule provided by the Regional Transportation District - Denver (RTD). Some other vehicles such as heavy duty trucks and hybrid buses were also counted. Figure 3 shows the routes close to the condo. On July 27 and 30 the buses routes shown in Figure 3 as streets 4 and 5 were counted. On July 28 only the routes denoted in street 3 were counted. Table 1 indicates the bus routes for each street.


*Figure 3. Buses routes on streets close to the stationary measurement location.*

Table 1. Buses Routes Driven on the Streets Near the Stationary Measurement Location

| 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 | | | | | |

Measurements in condo one on the second floor of the building were carried out from Monday to Wednesday, July 25-27, 2016, between 12 to 6 pm, and again on Thursday and Saturday afternoon, July 28 and 30, 2016. This unit is located on the north side of Canyon Boulevard, where the arrow indicates the measurement location (Figure 3); this area of town has high bus and car traffic. Every day, the instruments were verified to check their appropriate operation.

The measurements in condo two on the third floor of the building were carried out from Thursday to Sunday. This condo is located on street number 3 in Figure 3, about 150 feet north from the corner. The instruments were left working from Thursday at noon to Sunday at 11 am, July 28-31, 2016. However, the CPC, MicroAeth, and POM collected data only on Thursday from 12 to 6pm. Since these instruments cannot work indefinitely and to avoid disturbing the condo owner, they were not put in operation in this unit after Thursday.

## *Bicycle Ride*

For the bicycle ride test the CPC, MicroAeth, and the POM were deployed. The route was designed so that different conditions could be evaluated. These conditions are chasing buses, chasing only cars, and riding through areas with no vehicles. The advantage of using the POM is that the black carbon and ozone readings can be coordinated with GPS and mapped to location. The readings of the CPC were correlated with the black carbon and ozone data by connecting with the time the measurements were made. The bicycle ride was carried out from 10:30 am to 2:20 pm.

The bicycle route started at the Sustainability, Energy, and Environment Complex (SEEC) at 4001 Discovery Drive, Boulder, CO 80303. Then it followed the Boulder Creek Path west to connect with Arapahoe Avenue. Several loops are carried out on Walnut Street and Canyon Boulevard. The route finished back at the starting point at SEEC. Figure 4 shows the map of the bicycle ride (with pollutant concentrations traced on the map, red for ozone, yellow for black carbon; these will be discussed later).

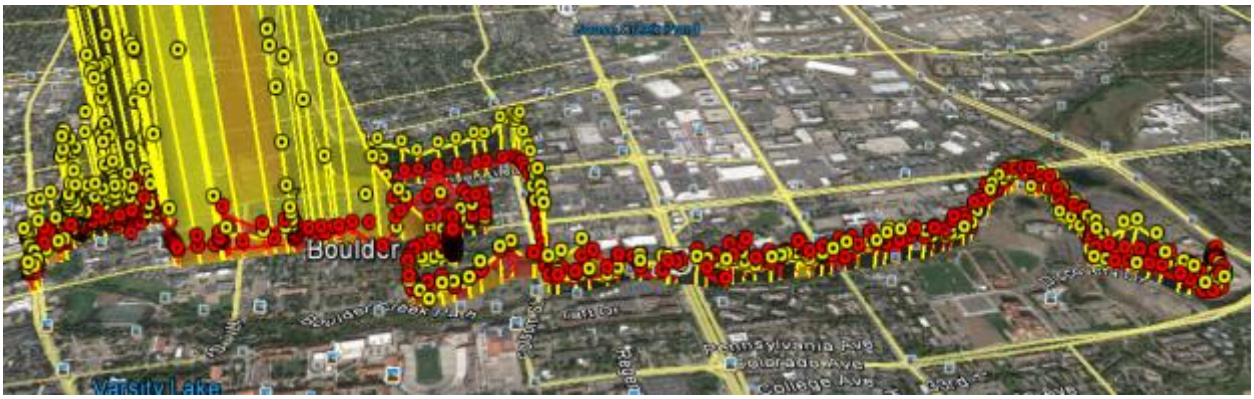


*Figure 4. Bicycle route shown on a map of Boulder, CO. The red colored trace is the ozone profile measured during the ride, while the yellow trace is the black carbon profile, which peaks when rider is directly behind a bus.*

Tables 2, 3, and 4 show the instruments, period of time and the date that each of the instruments were employed in condo 1, condo 2, and bicycle ride, respectively.

Table 2. Sampling in Canyon Condo 1

| Date | Instrument | Time |
|---|---|---|
| Monday 7/25/16 | CPC, APS, UHSAS, MicroAeth AE51, POM | 12 pm – 6 pm |
| Tuesday 7/26/16 | CPC, APS, UHSAS, MicroAeth AE51, POM | 12 pm – 6 pm |
| Wednesday 7/27/16 | CPC | 11:10 am – 6 pm |
| Wednesday 7/27/16 | APS, UHSAS, MicroAeth AE51, POM, Thermo 42i, Video | 12 pm – 6 pm |
| Thursday 7/28/16 | CPC | 12:40 pm – 6 pm |
| Saturday 7/30/16 | CPC | 12:45 pm – 6 pm |
| Saturday 7/30/16 | Video | 12:25 pm – 6 pm |

Table 3. Sampling in Canyon Condo #2

| Date | Instrument | Time |
|---|---|---|
| Thursday 7/28/16 | CPC, MicroAeth, POM | 12 pm – 6 pm |
| Thursday 7/28/16 | APS, UHSAS | 12 pm – 12 am |
| Thursday 7/28/16 | Video | 12:15 pm – 6 pm |
| Thursday 7/28/16 | Thermo 42i | 12:20 pm – 12 am |
| Friday 7/29/16 | APS, UHSAS, Thermo 42i | 12 am – 12 am |
| Saturday 7/30/16 | APS, UHSAS, Thermo 42i | 12 am – 12 am |
| Sunday 7/31/16 | APS, UHSAS, Thermo 42i | 12 am – 11 am |

Table 4. Bicycle ride

| Date | Instrument | Time |
|---|---|---|
| Thursday 8/4/16 | CPC, MicroAeth, POM | 10:30 am – 2:20 pm |

# Results

The results of the measurement campaign are presented below. They are divided in stationary measurements and bicycle ride; a description of the results is presented for all the instruments. A comparison between condos, weekdays and weekend, stationary and bicycle measurements, our results and CDPHE data is presented. Outliers are treated and statistics are presented.

## *Stationary Measurements*

The stationary measurements were collected in two condos at Canyon Boulevard and 14$^{th}$ Street in Boulder, Colorado.

### Monday-Wednesday Analysis

The first three days of the campaign consisted of measurements in condo one. These measurements were carried out Monday through Wednesday, July 25$^{th}$ to July 27$^{th}$, 2016. The main findings for each measurement device are described below.

#### APS PM2.5

The measurements for PM2.5 were very consistent. This pollutant is considered a regional pollutant, and is more spatially homogeneous than other pollutants. The results for each of the three days were around 2 µg/m$^3$, which is considerably lower than the National Ambient Air Quality Standards for PM2.5: 12 µg/m$^3$ annual average and 25 µg/m$^3$ 24-hour average (US EPA 2016b); even the maximum obtained reading was lower than these values. Figure 5 shows the readings taken on Wednesday, which was typical for these measurements. NOTE: this instrument was not calibrated prior to this measurement campaign but is being calibrate at the present. Results will be updated if needed.

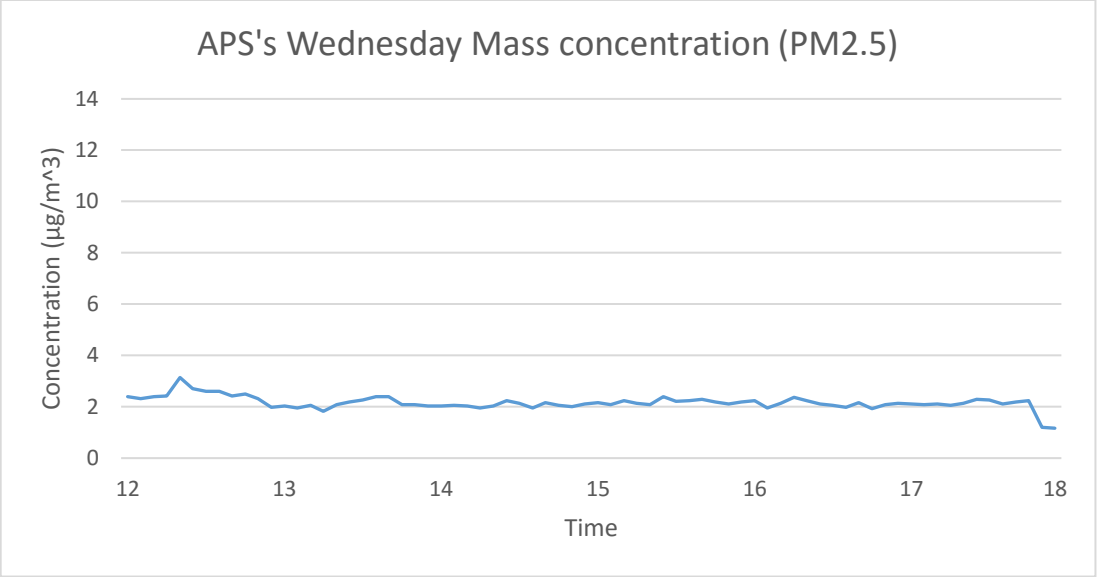


*Figure 5. Wednesday PM2.5 result.*

APS PM10-2.5

The analysis of coarse particulate matter provided higher mass concentrations than the measurements of PM2.5. This outcome is expected, since larger diameter particles have more mass. PM10-2.5 is a pollutant that is influenced by local sources, so that it can be more variable with time compared to PM2.5, as is seen in Figure 6 (Tuesday measurements). The mean value during these days was between 5.7 and 7.4 µg/m$^3$, and the maximum was around 20 µg/m$^3$.

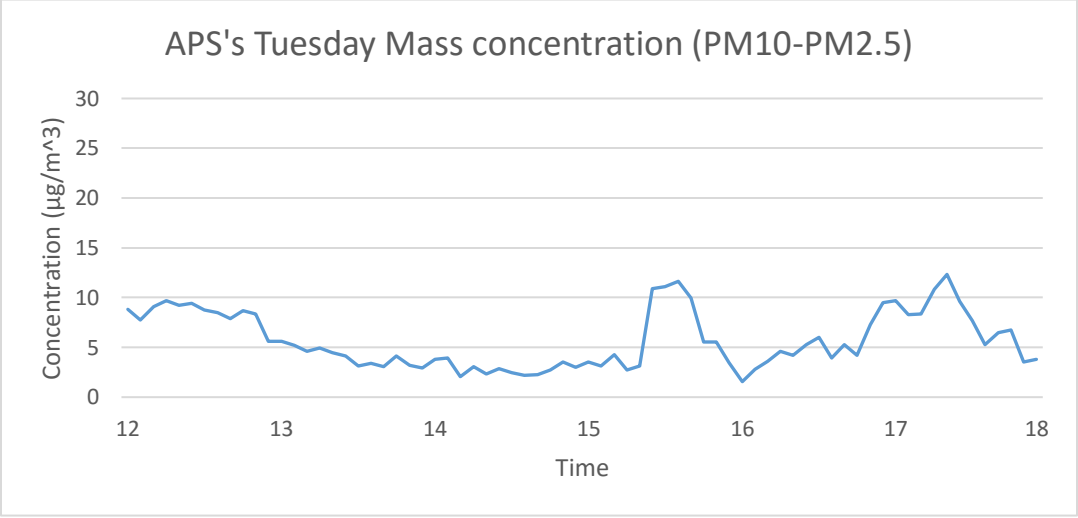


*Figure 6. Tuesday PM10-2.5 result.*

UHSAS

The readings on Monday were almost two times higher than on Tuesday and Wednesday, where the last two were similar. Interestingly, Monday's minimum value was higher than the mean on the other days. The reason of this behavior is not clear, but it may be that since this instrument measures number

concentrations for particles between 55 and 1000 nm, it could be influenced by local sources and weather. Figure 7 shows the output of the UHSAS measurements taken on Wednesday.

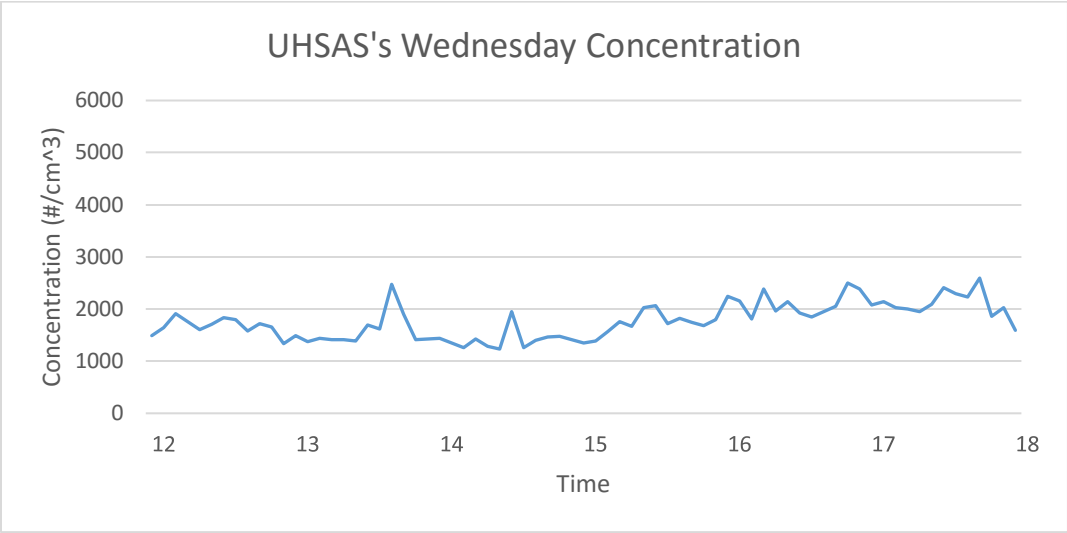


*Figure 7. Wednesday UHSAS result.*

CPC

The CPC measurements provide a notable difference between Tuesday and the results of Monday and Wednesday. Tuesday outcome was around three times smaller. The Tuesday maximum value was never higher than 50,000 #/cm$^3$, while on Monday and Wednesday was 135,730 and 94,550 #/cm$^3$, respectively. This instrument measures ultrafine number concentrations, and sources are combustion and gas-to-particle conversion processes in the atmosphere. The mean value of Wednesday was higher than on Monday. Monday's readings were higher from 12-1 pm compared with the rest of the time; after 1 pm the readings went slowly down. Therefore, an extended period of time was used on Wednesday to study this behavior, starting at 11 am instead of 12 pm. The results showed low readings from 11 am to 12 pm, and after 12 pm the readings went up exactly in the same way as on Monday. It is not clear why Tuesday's measurements did not behave similarly to Monday and Wednesday. Compared to a study done in urban areas of Milan, Italy, the mean exposure of pedestrians was lower in our study. In our study the mean ranged from 10,710 to 34,170 whereas in Milan the mean was 100,200 #/cm$^3$ (Cattaneo et al. 2009), more than two times of measurements taken in Boulder. Figure 8 shows the CPC result on Wednesday.

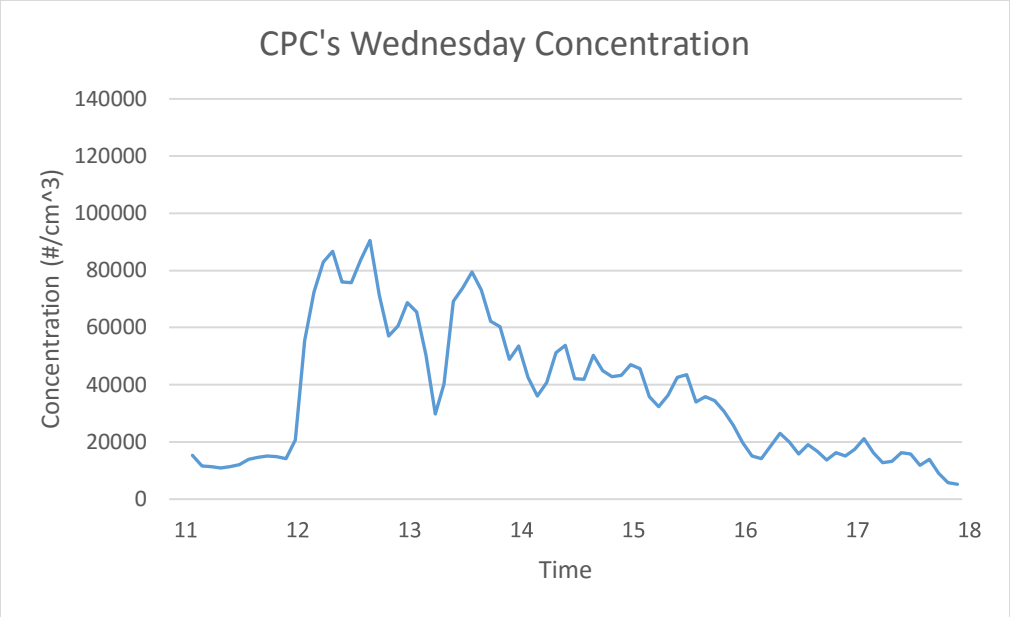


*Figure 8. Wednesday CPC result.*

Aethalometer

The mean results obtained for black carbon were relatively similar across days, having a range of 1.6-1.9 µg/m³. According to the Occupational Safety and Health Administration (OSHA) the limit of black carbon should be below 3.5 mg/m³ for an 8-hour total weight average (TWA) ("Chemical Sampling Information | Carbon Black" 2016). However, this value only applies to healthy working adults, and not the general population that includes children and the elderly. Black carbon was higher on Tuesday: four times higher compared to Monday and two times compared to Wednesday. There was no clear connection between measurements of the CPC and the Aethalometer. Figure 9 shows the result of black carbon on Tuesday.

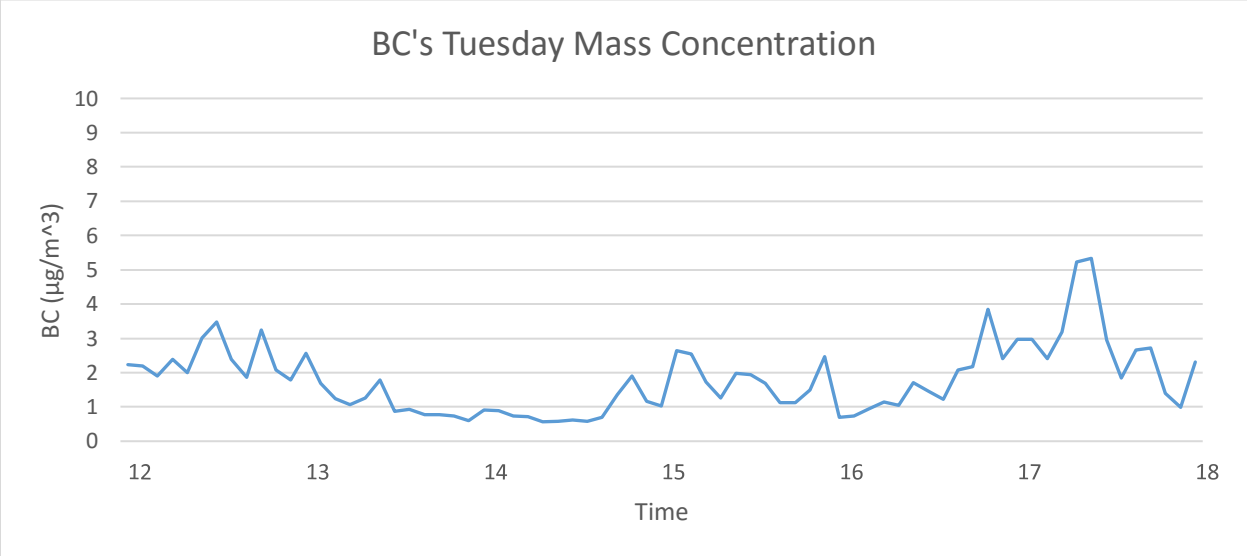


*Figure 9. Tuesday black carbon result.*

### Ozone Monitor

The ozone readings were lower on Tuesday compared to readings on Monday and Wednesday. For every day of this study, the mean values were lower (32-62 ppb) than the NAAQS of 70 ppb 8-hour average (US EPA 2016b). Figure 10 shows the result on Monday.

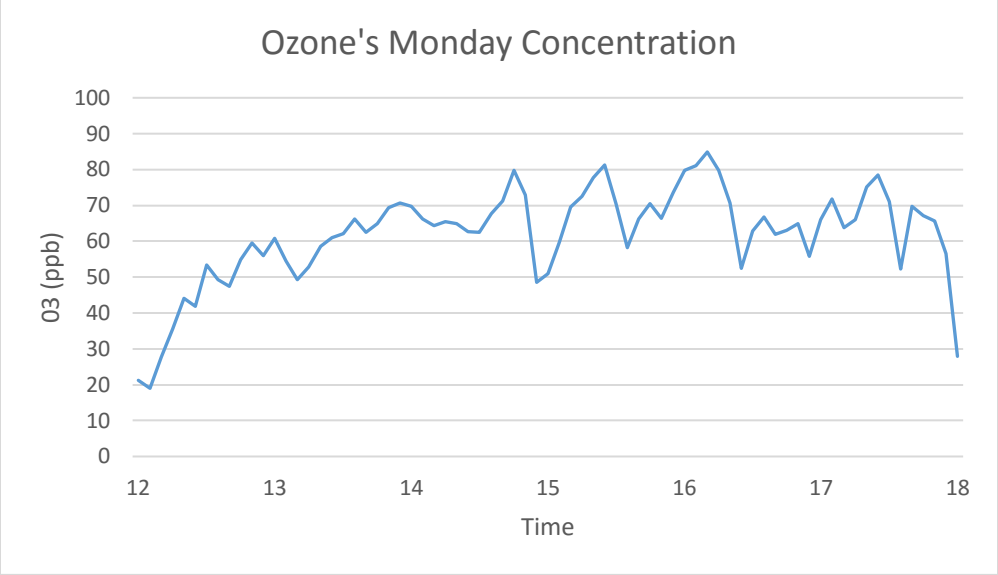


*Figure 10. Monday ozone result.*

### Nitrogen Oxides Monitor

The measurements using the Thermo 42i were not carried out on Monday and Tuesday since the instrument was not yet available. Figure 11 shows the results on Wednesday's measurement. The levels of NO are lower than the levels of $NO_2$, which is expected. Usually, the increase in NO2 was accompanied with an increase in NO. The $NO_2$ levels measured in this study were below the NAAQS of 53 ppb annual average and 100 ppb 1-hour average.

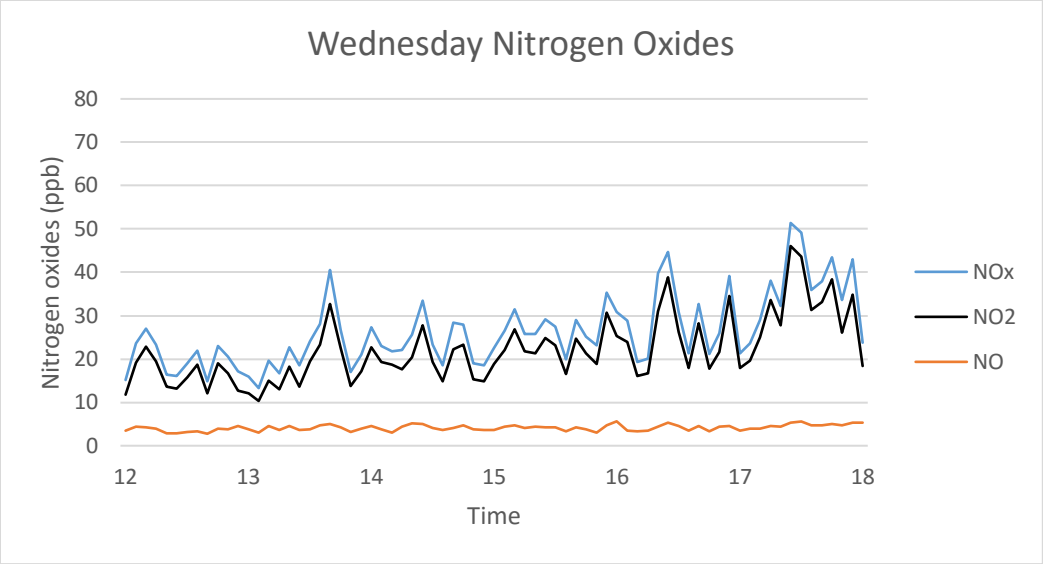


*Figure 11. Wednesday nitrogen oxides result.*

### Vehicle Counts

A video camera was employed on Wednesday to count the number of buses, hybrid buses, and heavy duty vehicles on streets 4 and 5 (see map in methodology section, Figure 3). Figure 12 shows the number of vehicles counted using the video camera per hour. The results from the CPC do not show a connection between the number of buses and particle number concentration. The number concentration peaked between 12 and 1 pm, while the number of buses peaked between 3 and 6 pm. The APS showed relatively constant PM2.5 concentrations during the period of measurements and did not change with the bus density. For black carbon, the results had frequent variations. However, hour averages tend to be quite similar, so no connection is clearly seen. The UHSAS had an increase in its readings from 3 to 6 pm, which shows a connection between the readings and the bus count. The ozone outcome shows no direct connection with the bus count, because it was virtually constant during the measurement period. The NOx readings increased from 3 to 6 pm, similar to the UHSAS. The largest number of heavy duty vehicles was counted between 1 and 2 pm but the smallest number of buses. Hybrid buses were barely seen, with a maximum of one per hour and in some cases no hybrid buses per hour.

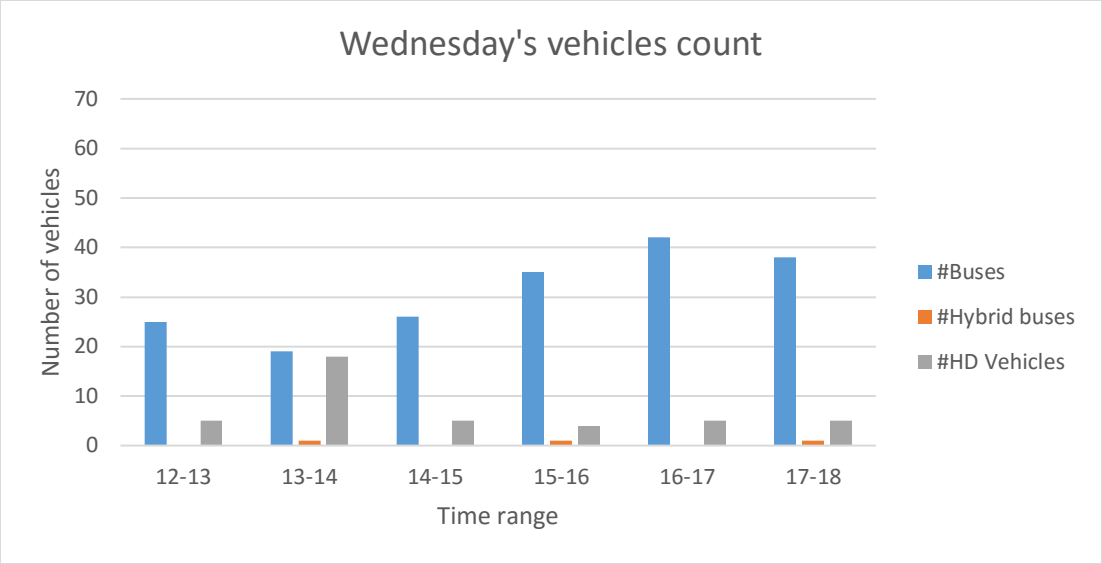


*Figure 12. Vehicles count on Wednesday.*

## Thursday-Sunday Analysis

The remaining four days of stationary measurements consisted of measurements in condo two with additional CPC and video recording in unit one. These measurements were carried out from July 28th to July 31st, 2016. The main findings are described below for each measurement device.

### APS PM2.5

The readings during the measurements were again very consistent, with a mean value from 1.9 to 3.1 µg/m³ (these results represent the Friday and Sunday measurements). The maximum value was never higher than the NAAQS. Figure 13 shows the outcome on Friday and Sunday.

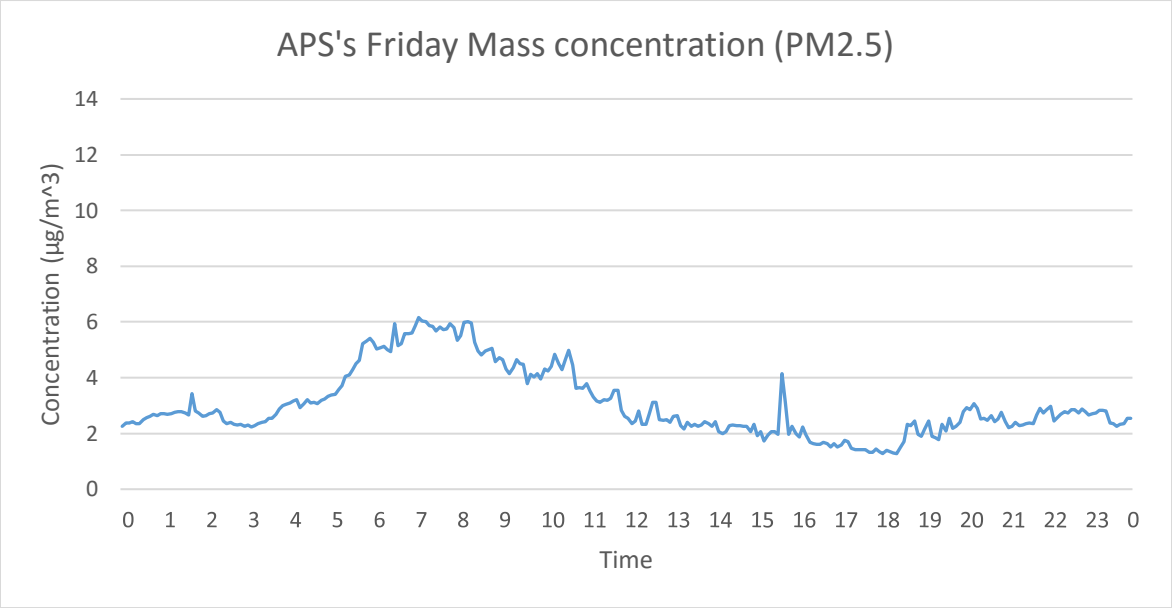


*Figure 13. Friday PM2.5 result.*

APS PM10-2.5

The mean value was between 2.7 and 5.1 µg/m$^3$, and the maximum was around 18 µg/m$^3$. Except for Sunday when extremely high readings were collected between 9 and 10 am with a maximum of 116 µg/m$^3$. It is not clear the reason of this high value. Friday and Saturday evenings an increase in concentrations was recorded. Figure 14 shows the result on Friday.

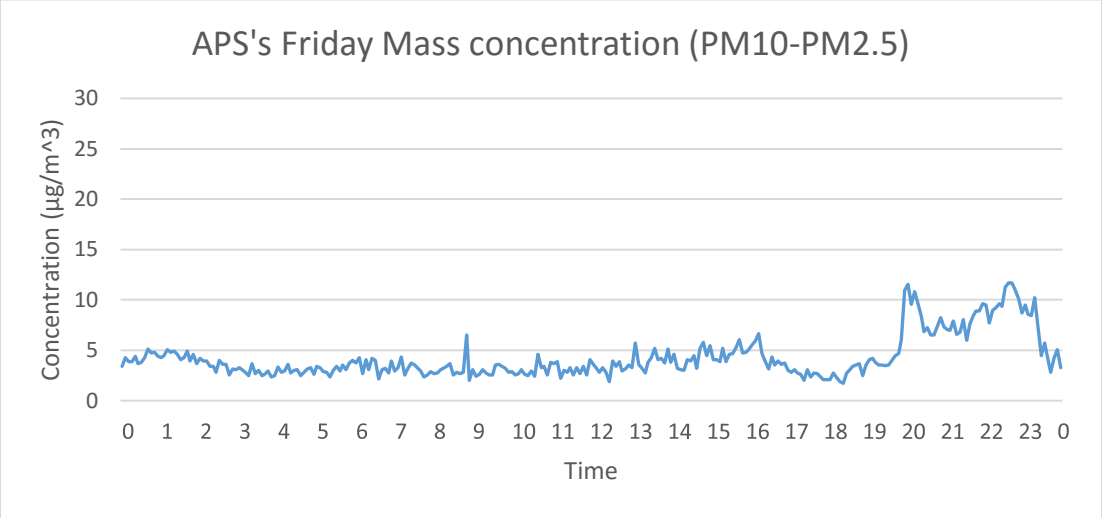


*Figure 14. Friday PM10-2.5 result.*

UHSAS

The mean values from Thursday to Sunday were similar, ranging from 1460 to 1710 #/cm$^3$. Evening readings were higher on Friday and Saturday compared to Thursday. In condo two the maximum values were more than twice the values measured in condo one, but this may be because evening measurements were not taken in condo one. Figure 15 shows the result of the measurements on Saturday.

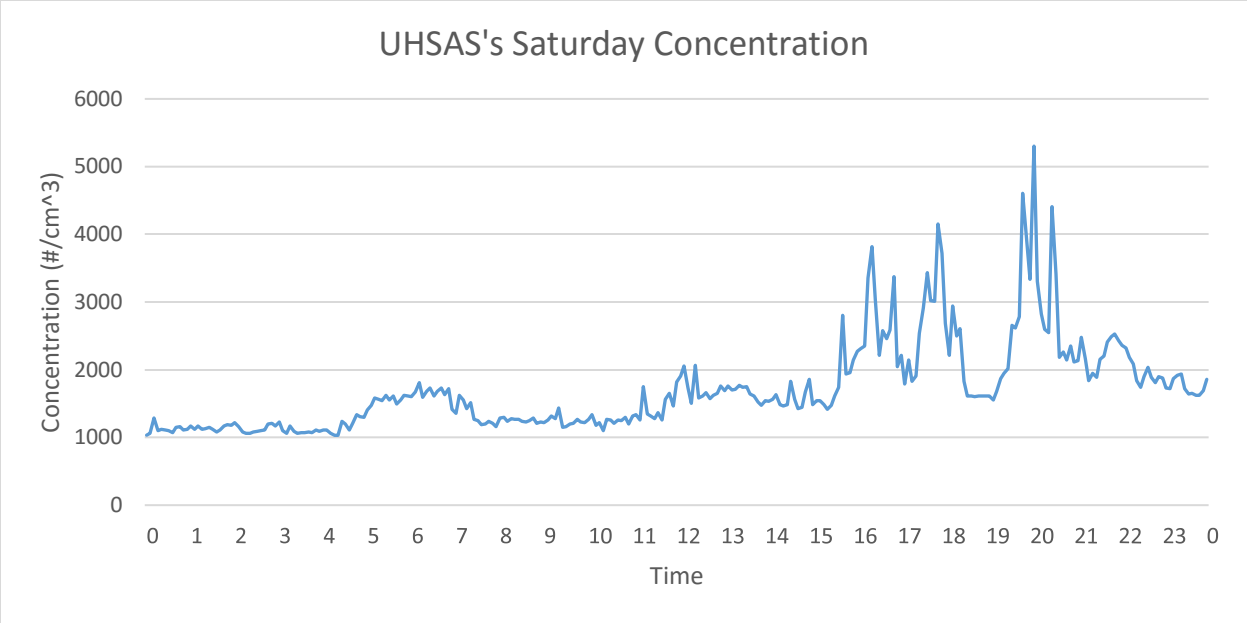


*Figure 15. Saturday UHSAS result*

CPC

Measurements taken on Thursday in both condos were around three times lower compared with Saturday measurements, where the mean value on Thursday was below 10,000 #/cm$^3$ and the mean value on Saturday was over 30,000 #/cm$^3$. Thursday was constant and low; however, Saturday readings went up to 60,000 #/cm$^3$ from 1 to 3:30 pm. After this time, they went down again to around 10,000 #/cm$^3$. Figures 16 and 17 show the result of the CPC on Thursday and Saturday, respectively.

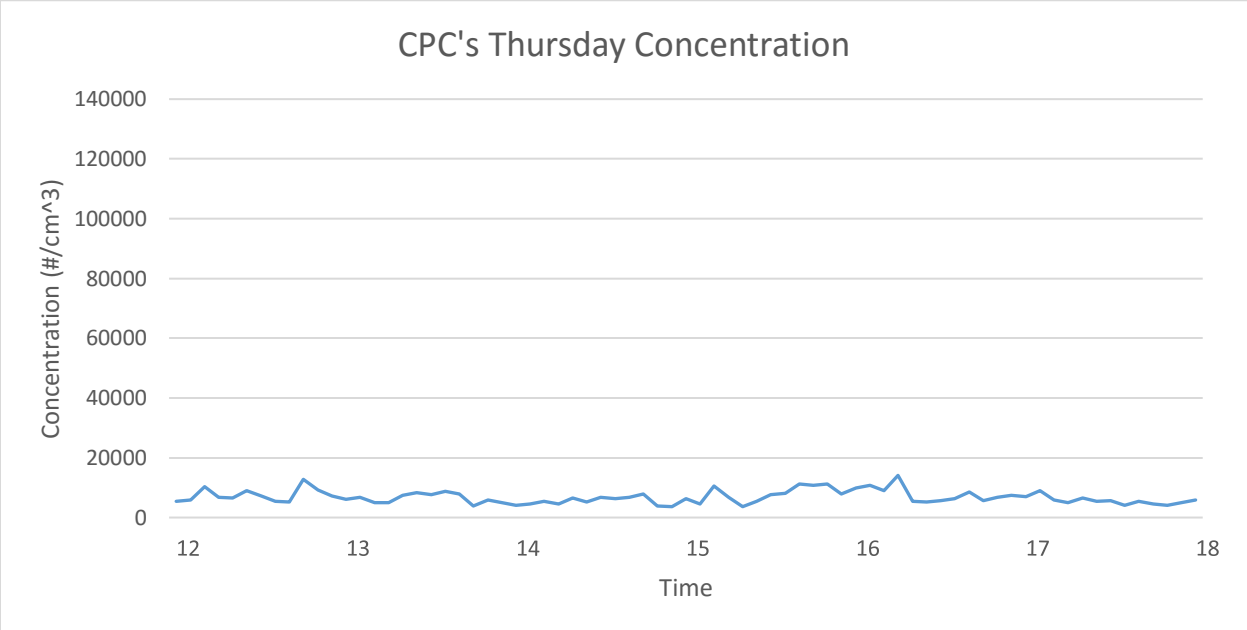


*Figure 16. Thursday CPC result.*

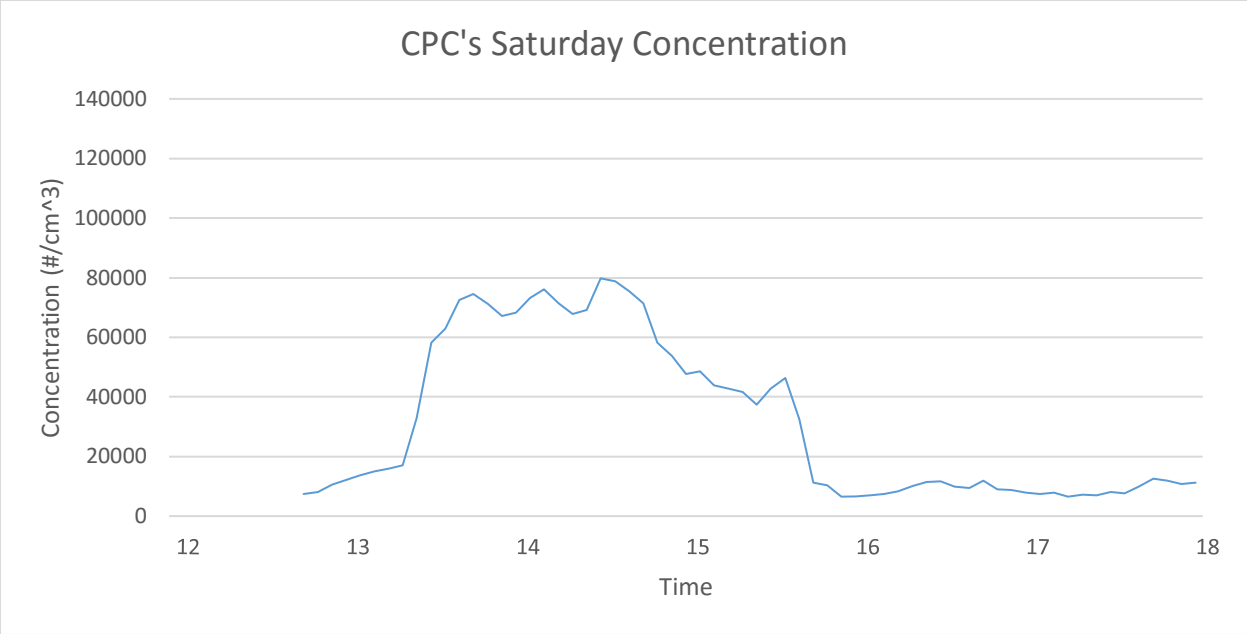


*Figure 17. Saturday CPC result.*

Aethalometer

Measurements of black carbon were only taken on Thursday at unit two. The mean value obtained was 1 µg/m$^3$. The readings were constant, similar to behavior of the CPC, APS and UHSAS on Thursday. Figure 18 shows the result of black carbon on Thursday.

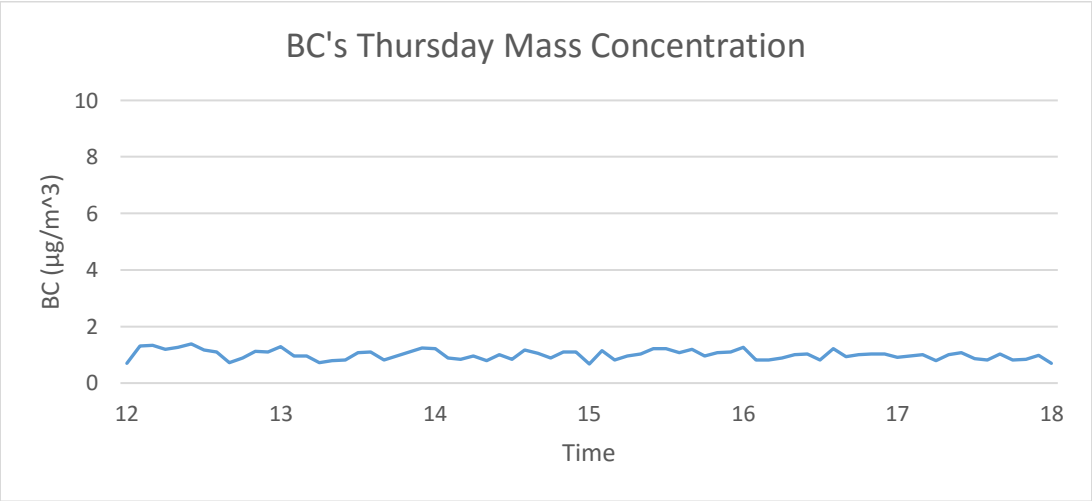


*Figure 18. Thursday black carbon result.*

### Ozone monitor

Measurements of ozone were only taken on Thursday at condo two. They were below the NAAQS with a mean value of 57.9 ppb and the variations over time were negligible. Figure 19 shows the result of ozone on Thursday.

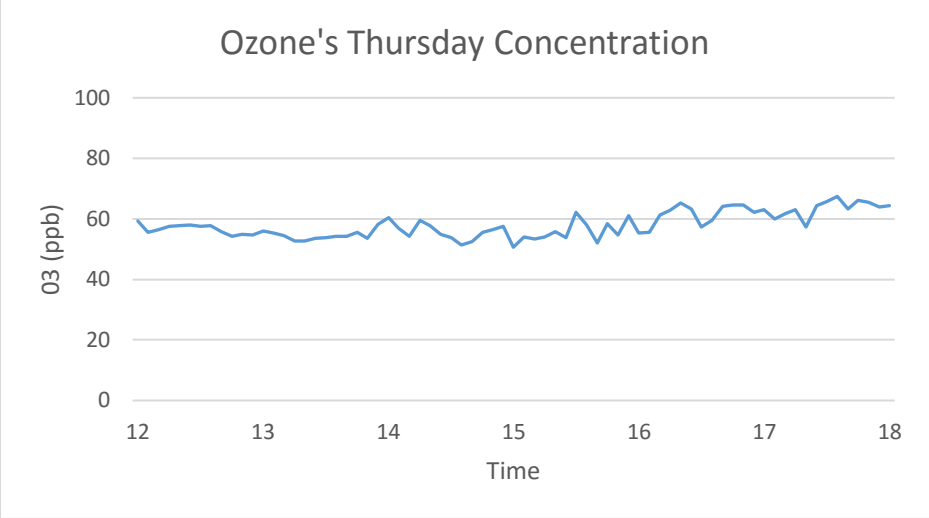


*Figure 19. Thursday ozone result.*

### Nitrogen Oxides Monitor

The Thermo 42i measurements were carried out from Thursday to Sunday. The results were lower than the NAAQS of 100 ppb 1-hour average for $NO_2$ (US EPA 2016b). The highest readings on Thursday were obtained from 2 to 6 pm. Similar behavior was seen on Friday; additionally, there were very high peaks between 4 and 5 pm. This situation was not observed on Thursday. Saturday's levels were quite different; the highest measurements for this day were obtained in the evening, between 7 pm and 10 pm, probably indicating a change in meteorology such as an inversion. High levels of NOx were found on Sunday morning. Typically, NOx is highest during the morning commute hours, however in this study we did not observe this behavior. Usually, NO increased with $NO_2$. Figure 20 shows the result of nitrogen oxides on Friday.

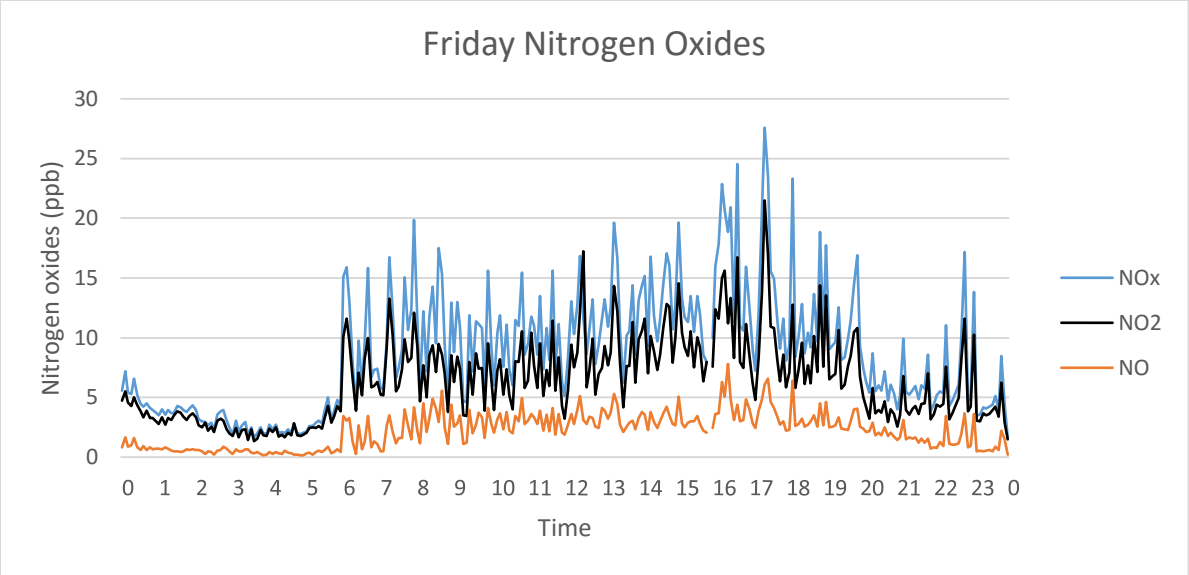


*Figure 20. Friday nitrogen oxides result.*

## Vehicles Count

A vehicle count was conducted on Thursday and Saturday. Thursday's count was for street 3 and Saturday's count was on street 4 and 5 (the counting method was the same as on Wednesday). Please see the methodology section and Figure 3 for information about the routes. Figure 21 shows the number of vehicles per hour on Thursday. Since the count started at 12:15 pm, not all the vehicles that passed by the video were counted for the 12 to 1pm period. However, the count shows more buses from 12-1 pm than 1-2pm. The CPCs in both condos had almost the same outcome in terms of tendency. The only difference was a small increase of the concentration in unit one between 3:30 and 4 pm, but no direct connection between the bus density and CPC measurements was found. However, the difference in number of buses was relatively small between hour. The APS PM2.5 outcome showed a decreasing mass concentration. However, the bus count augmented in the last hours. The APS PM10-2.5 had a higher concentration at 5 pm and the maximum bus density was observed between 4 and 5 pm. The UHSAS readings went down from 12 to 1:30 pm and stayed quite constant after this time. They did not increase with the bus number. The ozone readings were constant during the period of measurements and no association was found with bus count. The NOx readings increased from 2 to 5 pm. However, there was a reduction in concentration around 5:30 pm, but the concentration went up again before 5:45 pm. It appears that the bus count had some relationship with the measurements of NOx. No connection was found with the number of cars in street 3 and the number of heavy duty vehicles per hour was one or zero.

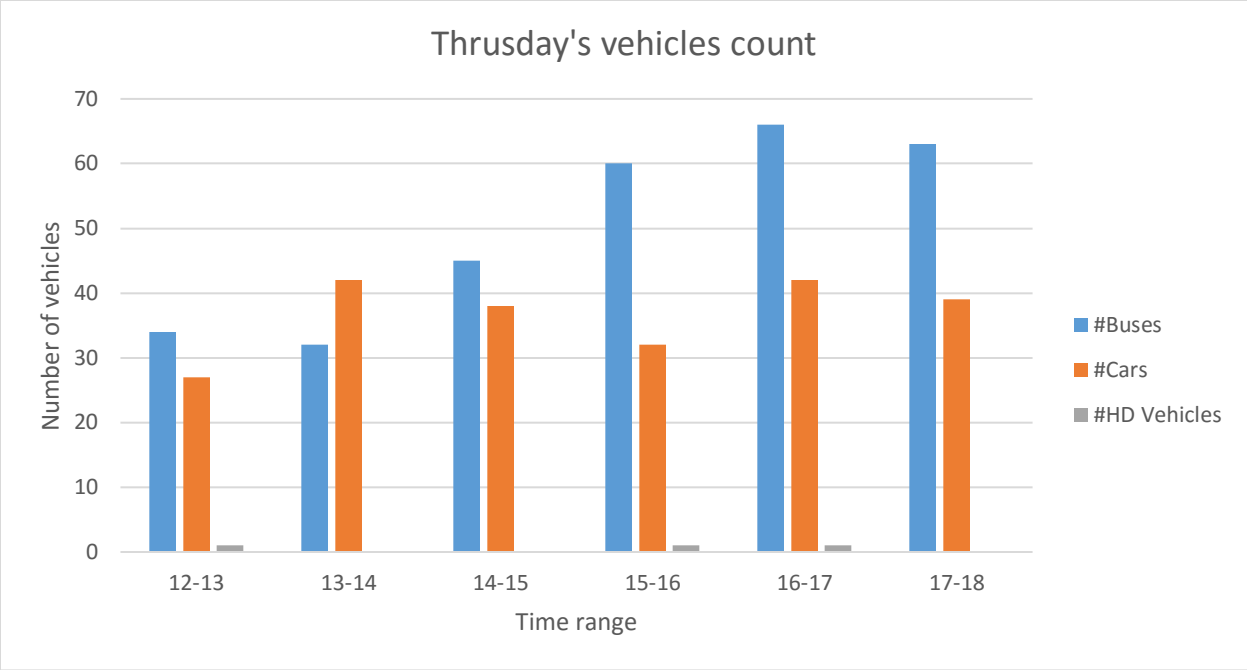


*Figure 21. Vehicles count on Thursday.*

Figure 22 shows the vehicles per hour on Saturday. Since counting started at 12:25 pm, around half may have not been counted between 12 and 1 pm. A high amount of cars was seen from 12:25 to 2:50 pm (cars where not counted since the number was so high). The car density was higher than every other day of the week that counting was done but the bus number was lower every hour as expected. The CPC readings from unit one had an increase in the concentration from 1:15 to 3:45 pm, which is slightly similar to the result obtained on Wednesday. Since, the bus count was almost identical throughout the day there is no relation to this increase in concentration. It looks more similar to the car density, but the low concentration at the beginning of the test makes this statement arguable. The APS PM2.5 readings were constant during the counting period, but it is not clear if this is connected with the bus count. The APS PM10-2.5 showed a behavior related to car number, where in the last 15 minutes before 3 pm it went down. An increase in the UHSAS concentration was found from 3 to 6 pm. There is no apparent relation of this either with the bus count. The ozone readings were higher between 1 and 3 pm, which is the period when a high number of cars was seen. The NOx measurements went up at 12 pm and started to go down at 3 pm, similar to the cars density observed in the recordings. Heavy duty vehicles were barely seen compared with the recording made on Wednesday.

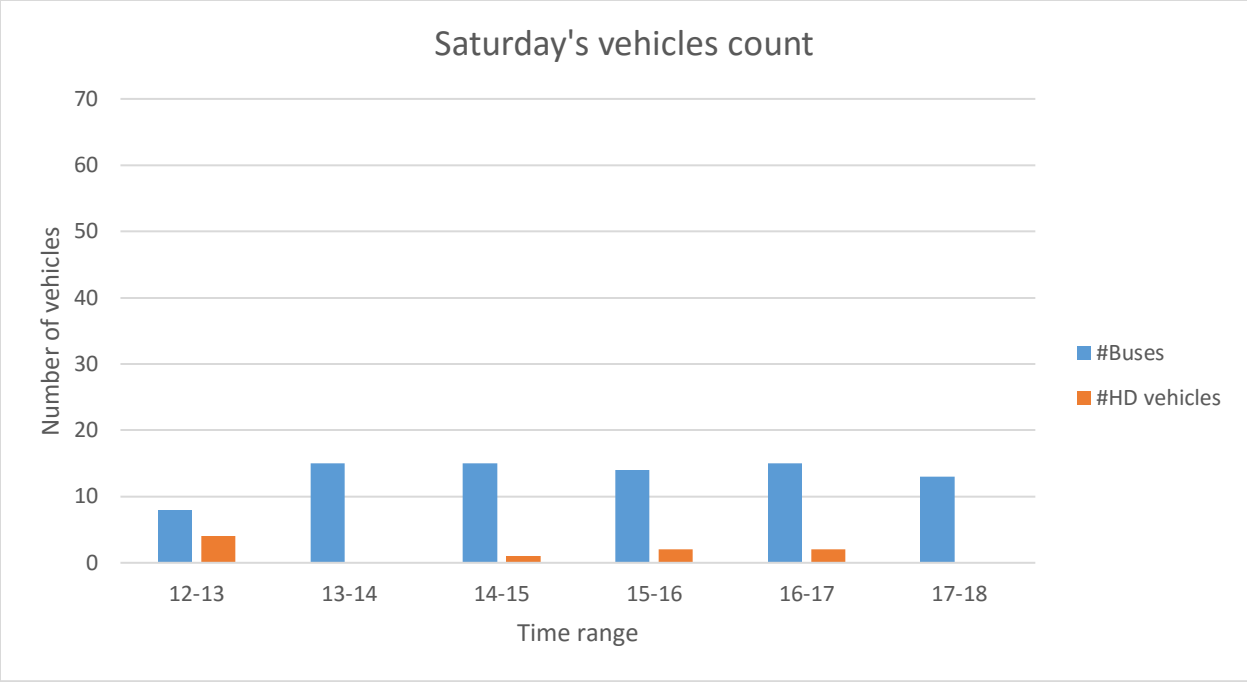


*Figure 22. Vehicles count on Saturday.*

## *Bicycle Ride*

One bicycle route was carried out on August 4th, 2016 by a resident of Boulder, Preston Padden. For the purpose of this test, only the portable equipment was employed, the CPC, the aethalometer and the ozone POM. The main findings for each measurement device are described below.

### CPC

The mean particle number concentration was around 12,000 #/cm$^3$. A very high difference was seen depending on the location and riding conditions. According to the description from the bicycle rider, all along the Boulder Creek Path very low concentrations were measured. Immediately after entering at Arapahoe Avenue the readings increased, the same was seen when riding through Walnut Street and Canyon Boulevard. This result was expected since these zones have more vehicles. One observation from the rider was that when chasing older RTD buses such as the Jump, an extreme increase in particulate number was exhibited, where the maximum value was 200,190 #/cm$^3$. The rider also mentioned that when following the newer RTD buses the impact on the readings was small. Figure 23 shows the results from the CPC (one-second resolution).

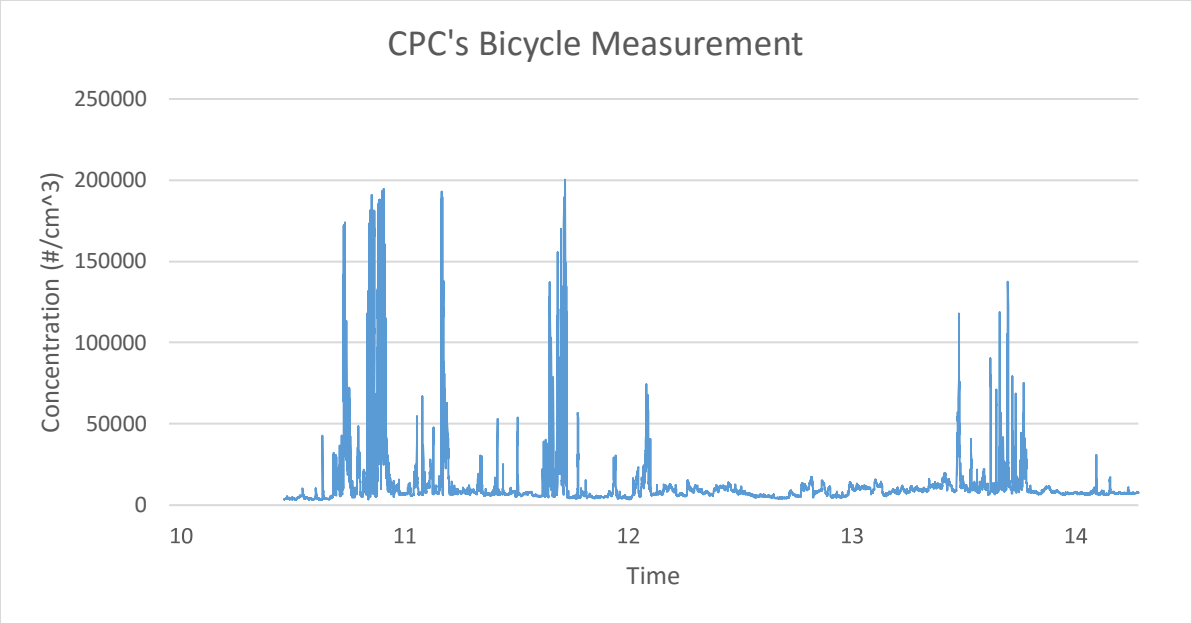


*Figure 23. Bicycle ride CPC result.*

Aethalometer

Very high readings were observed on Walnut Street and Canyon Boulevard, similar to the high particulate matter (from the CPC) observed by the bicycle rider. The data shows low levels of black carbon all the way along the Boulder Creek Path, which is expected since there are not many vehicles surrounding this area. Figure 24 shows the data averaged for 10 seconds and Figure 25 shows the data averaged for 5 minutes and excluding outliers.

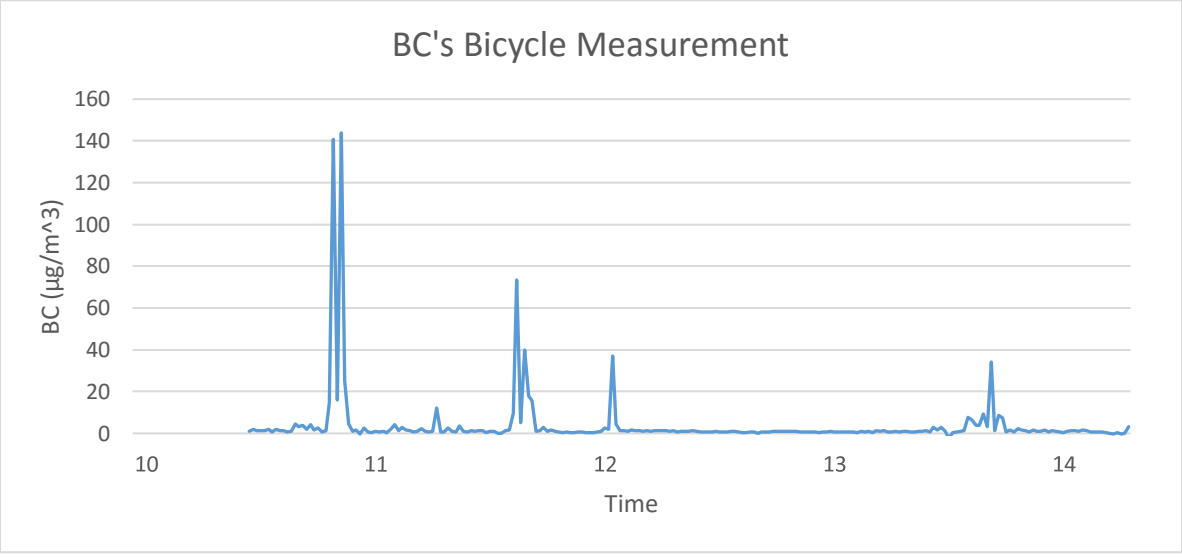


*Figure 24. Bicycle ride black carbon result (10-second averaged).*

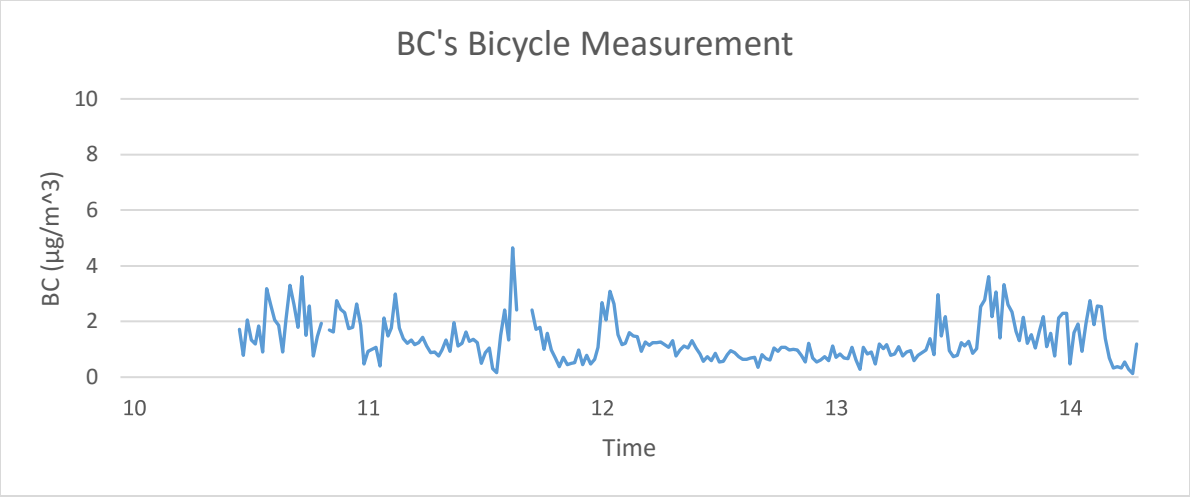


*Figure 25. Bicycle ride black carbon result (5-minute averaged).*

Ozone Monitor

The mean value was 36.9 ppb and the concentration was constant. Only at one point on Canyon did the ozone level increase. Figure 26 shows the results for ozone.

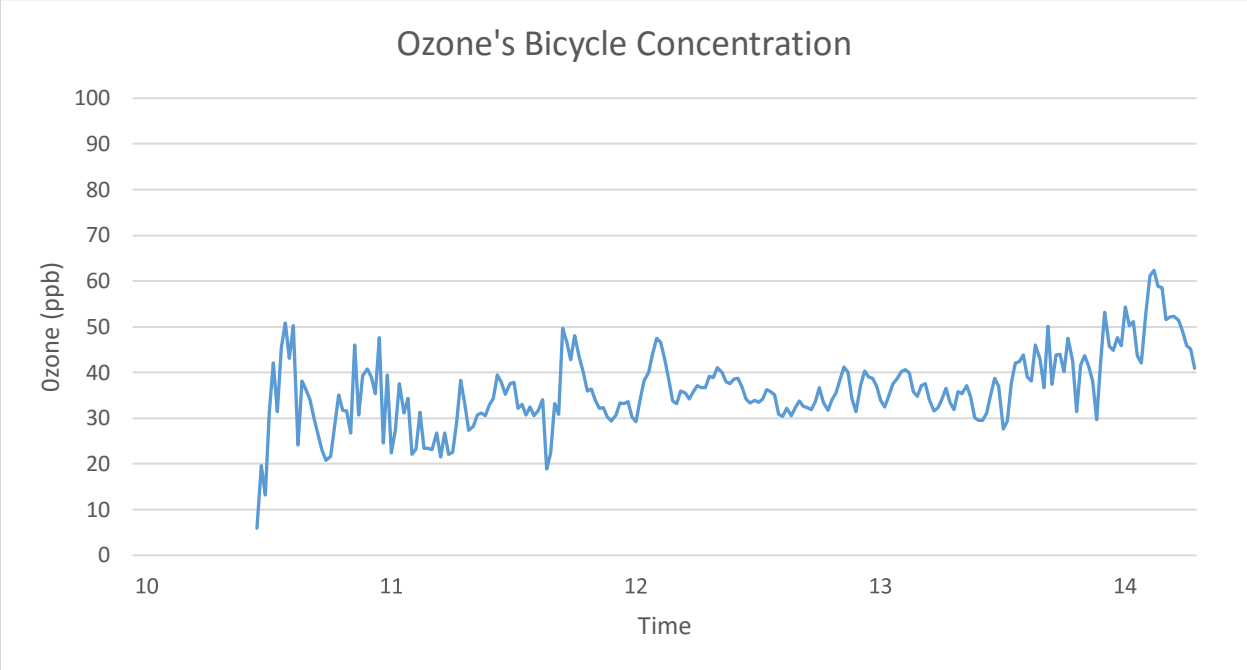


*Figure 26. Bicycle ride ozone result.*

## *Comparison Between Condos*

Two CPCs were used on Thursday, one in the unit one and the other in the unit two. Results shows that the ultrafine number concentration measured at condo one were higher than the number concentrations at condo two. The difference between mean values of the units was around 3,000 #/cm$^3$.

This could be considered a significant difference because the levels were low that day, 9,690 and 6810 #/cm$^3$ for condo one and two, respectively. Some factors that could have explain this difference is the elevation and street location of the two condos.

PM2.5 measured with the APS was lower at unit one; however, coarse PM was higher at unit one. The UHSAS mean values were relatively close at both condos except on Monday when the concentrations doubled at unit one. Black carbon tended to be higher at condo one compared to condo two. The ozone outcome was comparable between the two condos; except on Tuesday when it was low by about half at condo one. NOx on Wednesday at condo one exhibited a mean value around twice the measurements at unit two collected Thursday through Saturday. Note that the results from unit one were only from 12 pm to 6 pm, which was generally the part of the day with the highest concentrations with the exception of Saturday measurements at unit two, when evening readings where the highest. Generally, from 12 am to 12 pm NOx was lower than the rest of the day, which had an effect of reducing the mean value in unit two. The number of buses passing through street 3 (in front of unit two) was higher than street 4 and 5 (in front of unit one). However, the number of heavy duty vehicles and cars was higher in front of condo one.

## *Comparison Between Weekdays and Weekends*

Typically traffic-related air pollutant concentrations differ between weekend and weekdays due to differences in traffic density and type of vehicle. Commonly diesel related pollutants decrease on weekends because there are less heavy duty trucks on the road. In this study not much difference was seen between weekend and weekday for the pollutants that were measured. The vehicles count exhibited some differences; on Saturday there were less buses and a small number of heavy duty vehicles. The number of cars from noon to around 3 pm on Saturday was higher than afternoon weekdays. However, the density of cars in the late afternoon was higher on weekdays.

## *Comparison Between Stationary Measurements and Bicycle Ride*

The ultrafine particles measured with the CPC during the bicycle ride were higher than the stationary measurements on Tuesday and Thursday. However, they were considerably lower than the measurements on Monday, Wednesday, and Saturday. The maximum value on the bicycle ride was much higher when a bus was being chased than during the stationary measurements. The black carbon as measured by the aethalometer was similar during the bicycle ride and the stationary measurements. A huge difference, however, was found in the maximum value: during the bicycle ride the peak was a factor of 10 higher. The average ozone during the bicycle ride was lower than the stationary measurements, except for Tuesday. The ozone maximum value during the bicycle ride was a factor of 10 higher than the stationary measurements.

## *Comparison between measurements and CDPHE data*

The APS PM2.5 concentrations are compared with the CDPHE air quality report for PM2.5 at Boulder. Their data is collect hourly at Athens, 2120 Marine Street. Surprisingly, their data was higher than the data obtained in our measurements. The APS was almost constant; however, the CDPHE data showed more fluctuations. The NOx measurement results were slightly higher than the CDPHE CAMP data in Denver. The CDPHE showed the highest values during the day in the early morning; nevertheless, our measured data showed maximum values in the late afternoon or the late evening. Increase in our measurements was observed in the early morning, but the magnitude of it was not as high as the

magnitude in the second half of the day. The ozone readings compared with the CDPHE CAMP data were virtually the same, in terms of magnitude and the behavior of the data.

## *Observations and RTD schedule*

Three routes are compared between the observations from the video recordings and the RTD summer schedule. The routes selected are 204, 208 and Dash. The analysis was done for Wednesday. The recorded video showed exactly the same amount of the buses leaving from the Boulder Downtown Station. 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 with the video camera. There was agreement also for route 208 between the recording and the schedule, 12 buses leaving. The route Dash had the same number of buses leaving the station compared with the video, 20 buses. However, on two occasions there were an extra bus leaving and two other times buses did not leave.

Other discrepancies were observed in other routes compared to the RTD GIS data. Routes 205 and 225 did not pass through street 5. Apparently, these two routes turn right on Walnut Street instead of Canyon Boulevard to go to the bus station. The routes GS and some Flatiron flyers enter in the street 3. However, they are not supposed to pass through this street. The reason of this is not clear. For details about the streets, please see stationary measurements in the methodology plan section.

## *Outliers*

Outliers were eliminated from the analyses for the aethalometer, ozone POM, and Thermo 42i data. The outliers were classified as mild and extreme outliers. As mentioned in the methodology section only extreme outliers were not taken into account for the analysis. The statistical data is based on the outliers' elimination. The lower outer fence (LOF) and in the upper outer fence (UOF) are the limits for the case of extreme outliers, which are the ones used in the study; therefore, the lower inner fence (LIF) and the upper inner fence (UIF) are not considered. They are represented as follows:

LOF: Q1-3*IQ

UOF: Q3+3*IQ ("7.1.6. What Are Outliers in the Data?" 2016)

where Q1 is the lower quartile, IQ is the interquartile, and Q3 is the upper quartile.

Tables 5, 6, 7, 8, and 9 show the outlier information for black carbon, ozone, NO, $NO_2$, and NOx, respectively. Additionally, Figures 27, 28, and 29 show the box plot for Thursday's black carbon, ozone, and NOx.

Table 5. Black Carbon (µg/m$^3$) outlier information

| Day | Monday | Tuesday | Wednesday | Thursday | Thursday |
|---|---|---|---|---|---|
| Monitor Period | 12-18 (7/25/16) | 12-18 (7/26/16) | 12-18 (7/27/16) | 12-18 (7/28/16) | 10:30-14:20 (8/4/16) |
| Location | Canyon Apt. 1 | Canyon Apt. 1 | Canyon Apt. 1 | Canyon Apt. 2 | Bicycle Ride |
| Median | 1.5 | 1.5 | 1.2 | 1.0 | 1.0 |
| Q1 | 1.2 | 0.9 | 0.9 | 0.8 | 0.5 |
| Q3 | 1.9 | 2.4 | 1.7 | 1.2 | 1.7 |
| IQ | 0.7 | 1.5 | 0.7 | 0.4 | 1.2 |
| LIF | 0.2 | -1.3 | -0.1 | 0.1 | -1.3 |
| UIF | 2.9 | 4.6 | 2.7 | 1.8 | 3.5 |
| LOF | -0.8 | -3.5 | -1.2 | -0.5 | -3.0 |
| UOF | 3.9 | 6.8 | 3.8 | 2.5 | 5.2 |

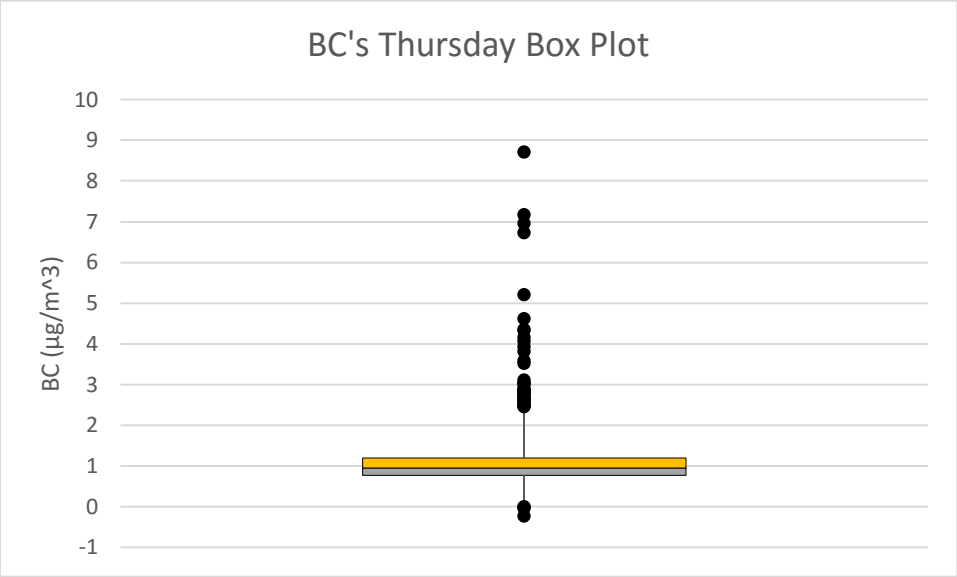


*Figure 27. Thursday black carbon box plot.*

Table 6. Ozone (ppb) outlier information

| Day | Monday | Tuesday | Wednesday | Thursday | Thursday |
|---|---|---|---|---|---|
| Monitor Period | 12-18 (7/25/16) | 12-18 (7/26/16) | 12-18 (7/27/16) | 12-18 (7/28/16) | 10:30-14:20 (8/4/16) |
| Location | Canyon Apt. 1 | Canyon Apt. 1 | Canyon Apt. 1 | Canyon Apt. 2 | Bicycle Ride |
| Median | 63.4 | 33 | 56.5 | 57.3 | 35.5 |
| Q1 | 56.4 | 20.8 | 49.7 | 54.6 | 31.2 |
| Q3 | 71.3 | 44 | 63.4 | 61.3 | 41.0 |
| IQ | 14.9 | 23.2 | 13.7 | 6.7 | 9.8 |
| LIF | 34.05 | -14 | 29.2 | 44.6 | 16.5 |
| UIF | 93.65 | 78.8 | 84.0 | 71.4 | 55.7 |
| LOF | 11.7 | -48.8 | 8.6 | 34.5 | 1.8 |
| UOF | 116 | 113.6 | 104.5 | 81.4 | 70.4 |

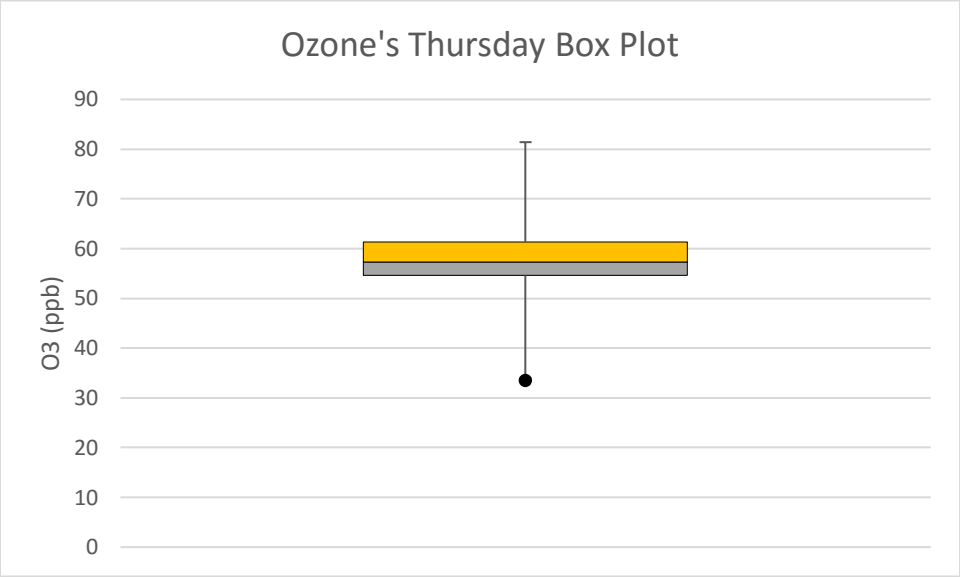


*Figure 28. Thursday ozone box plot.*

Table 7. NO (ppb) outlier information

| Day | Wednesday | Thursday | Friday | Saturday | Sunday |
|---|---|---|---|---|---|
| Monitor Period | 12-18 (7/27/16) | 12:20-00 (7/28/16) | 00-00 (7/29/16) | 00-00 (7/30/16) | 00-11 (8/4/16) |
| Location | Canyon Apt. 1 | Canyon Apt. 2 | Canyon Apt. 2 | Canyon Apt. 2 | Canyon Apt. 2 |
| Median | 4.0 | 2.3 | 2.0 | 2.4 | 1.0 |
| Q1 | 3.4 | 1.6 | 0.7 | 1.0 | 0.4 |
| Q3 | 4.8 | 3.2 | 3.0 | 3.3 | 2.5 |
| IQ | 1.3 | 1.6 | 2.3 | 2.4 | 2.2 |
| LIF | 1.4 | -0.8 | -2.7 | -2.6 | -2.9 |
| UIF | 6.8 | 5.6 | 6.5 | 6.9 | 5.8 |
| LOF | -0.6 | -3.2 | -6.2 | -6.2 | -6.2 |
| UOF | 8.8 | 8.1 | 9.9 | 10.5 | 9.1 |

Table 8. $NO_2$ (ppb) outlier information

| Day | Wednesday | Thursday | Friday | Saturday | Sunday |
|---|---|---|---|---|---|
| Monitor Period | 12-18 (7/27/16) | 12:20-00 (7/28/16) | 00-00 (7/29/16) | 00-00 (7/30/16) | 00-11 (8/4/16) |
| Location | Canyon Apt. 1 | Canyon Apt. 2 | Canyon Apt. 2 | Canyon Apt. 2 | Canyon Apt. 2 |
| Median | 19.6 | 8.2 | 5.2 | 5.4 | 3.3 |
| Q1 | 15.4 | 5.9 | 3.4 | 3.2 | 1.7 |
| Q3 | 27.1 | 11.3 | 8.5 | 9.6 | 5.8 |
| IQ | 11.6 | 5.4 | 5.1 | 6.4 | 4.2 |
| LIF | -2.0 | -2.2 | -4.2 | -6.4 | -4.6 |
| UIF | 44.6 | 19.4 | 16.1 | 19.2 | 12.1 |
| LOF | -19.5 | -10.3 | -11.8 | -16.0 | -10.8 |
| UOF | 62.0 | 27.5 | 23.8 | 28.8 | 18.3 |

Table 9. NOx (ppb) outlier information

| Day | Wednesday | Thursday | Friday | Saturday | Sunday |
|---|---|---|---|---|---|
| Monitor Period | 12-18 (7/27/16) | 12:20-00 (7/28/16) | 00-00 (7/29/16) | 00-00 (7/30/16) | 00-11 (8/4/16) |
| Location | Canyon Apt. 1 | Canyon Apt. 2 | Canyon Apt. 2 | Canyon Apt. 2 | Canyon Apt. 2 |
| Median | 23.8 | 10.5 | 7.1 | 7.5 | 4.3 |
| Q1 | 18.8 | 7.7 | 4.3 | 4.5 | 2.0 |
| Q3 | 31.7 | 14.3 | 11.6 | 13.3 | 8.2 |
| IQ | 12.9 | 6.6 | 7.3 | 8.8 | 6.2 |
| LIF | -0.6 | -2.1 | -6.7 | -8.7 | -7.4 |
| UIF | 51.2 | 24.1 | 22.6 | 26.5 | 17.5 |
| LOF | -20.0 | -11.9 | -17.7 | -21.8 | -16.7 |
| UOF | 70.6 | 33.9 | 33.6 | 39.6 | 26.8 |

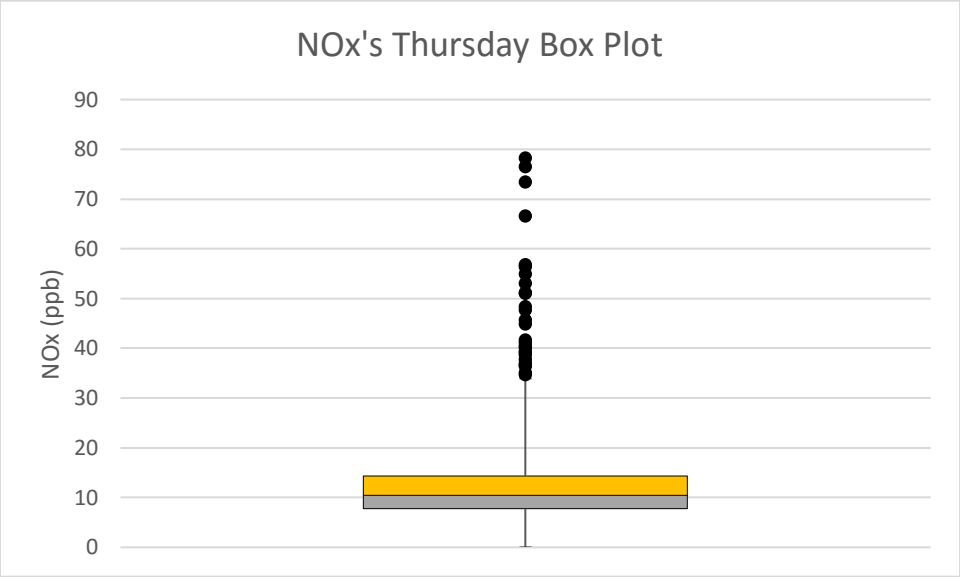


*Figure 29. Thursday NOx box plot.*

## *Statistics*

Statistics were calculated for all the days and instruments deployed during the measurement campaign. Tables 10–18 show the statistical information for the CPC, APS PM2.5, APS PM10-2.5, UHSAS, black carbon, ozone, NO, $NO_2$, and NOx, respectively.

Table 10. CPC (#/cm$^3$) Statistics

| Day | Monday | Tuesday | Wednesday | Thursday | Thursday | Saturday | Thursday |
|---|---|---|---|---|---|---|---|
| Monitor Period | 12-18 (7/25/16) | 12-18 (7/26/16) | 11:10-18 (7/27/16) | 12:40-18 (7/28/16) | 12-18 (7/28/16) | 12:45-18 (7/30/16) | 10:30-14:20 (8/4/16) |
| Location | Canyon Apt. 1 | Canyon Apt. 1 | Canyon Apt. 1 | Canyon Apt. 1 | Canyon Apt. 2 | Canyon Apt. 1 | Bicycle Ride |
| Mean | 32,190 | 11,440 | 37,200 | 9,690 | 6,810 | 32,010 | 12,510 |
| Standard Error | 219 | 37 | 150 | 40 | 30 | 196 | 158 |
| Median | 17,340 | 10,710 | 34,170 | 8,440 | 5,760 | 14,230 | 7,930 |
| Standard Deviation | 32,130 | 5,340 | 23,560 | 5,500 | 4,330 | 26,870 | 18,520 |
| Range | 126,880 | 43,790 | 91,240 | 76,530 | 90,850 | 79,600 | 196,960 |
| Minimum | 8,840 | 2,990 | 3,320 | 3,760 | 2,070 | 5,030 | 3,230 |
| Maximum | 135,730 | 46,770 | 94,550 | 80,290 | 92,920 | 84,640 | 200,190 |
| Count | 21,470 | 21,400 | 24,580 | 19,360 | 21,510 | 18,830 | 13,750 |

Table 11. APS PM2.5 (µg/m$^3$) Statistics

| Day | Monday | Tuesday | Wednesday | Thursday | Friday | Saturday | Sunday |
|---|---|---|---|---|---|---|---|
| Monitor Period | 12-18 (7/25/16) | 12-18 (7/26/16) | 12-18 (7/27/16) | 12-00 (7/28/16) | 00-00 (7/29/16) | 00-00 (7/30/16) | 00-11 (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 | 1.9 | 2.0 | 2.2 | 2.9 | 3.1 | 2.7 | 2.3 |
| Standard Error | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Median | 1.8 | 1.8 | 2.1 | 2.8 | 2.7 | 2.8 | 2.2 |
| Standard Deviation | 0.2 | 0.6 | 0.3 | 0.7 | 1.3 | 0.5 | 0.8 |
| Range | 1.6 | 3.4 | 4.3 | 4.9 | 8.9 | 9.8 | 10.9 |
| Minimum | 1.4 | 0.9 | 0.8 | 1.8 | 1.0 | 1.6 | 1.1 |
| Maximum | 3.0 | 4.3 | 5.1 | 6.8 | 10.0 | 11.4 | 11.9 |
| Count | 720 | 720 | 720 | 1442 | 2880 | 2825 | 1319 |

Table 12. APS PM10-2.5 (µg/m$^3$) Statistics

| Day | Monday | Tuesday | Wednesday | Thursday | Friday | Saturday | Sunday |
|---|---|---|---|---|---|---|---|
| Monitor Period | 12-18 (7/25/16) | 12-18 (7/26/16) | 12-18 (7/27/16) | 12-00 (7/28/16) | 00-00 (7/29/16) | 00-00 (7/30/16) | 00-11 (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 | 6.2 | 5.7 | 7.4 | 5.1 | 4.3 | 4.0 | 2.7 |
| Standard Error | 0.1 | 0.1 | 0.1 | 0.1 | 0.0 | 0.0 | 0.1 |
| Median | 5.7 | 4.9 | 7.2 | 4.7 | 3.6 | 3.8 | 2.2 |
| Standard Deviation | 2.5 | 3.4 | 2.1 | 2.1 | 2.5 | 1.9 | 4.2 |
| Range | 22.6 | 19.6 | 13.8 | 15.4 | 17.4 | 16.0 | 115.2 |
| Minimum | 1.3 | 0.6 | 1.5 | 1.2 | 0.5 | 0.5 | 0.4 |
| Maximum | 23.9 | 20.2 | 15.2 | 16.6 | 17.9 | 16.5 | 115.7 |
| Count | 720 | 720 | 720 | 1442 | 2880 | 2825 | 1319 |

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

| Day | Monday | Tuesday | Wednesday | Thursday | Friday | Saturday | Sunday |
|---|---|---|---|---|---|---|---|
| Monitor Period | 12-18 (7/25/16) | 12-18 (7/26/16) | 12-18 (7/27/16) | 12-00 (7/28/16) | 00-00 (7/29/16) | 00-00 (7/30/16) | 00-11 (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 | 3260 | 1660 | 1770 | 1510 | 1710 | 1710 | 1460 |
| Standard Error | 8 | 13 | 8 | 9 | 10 | 8 | 9 |
| Median | 3230 | 1590 | 1720 | 1300 | 1440 | 1550 | 1460 |
| Standard Deviation | 387 | 603 | 395 | 601 | 965 | 745 | 543 |
| Range | 2510 | 3750 | 2530 | 6020 | 6860 | 11660 | 11530 |
| Minimum | 2200 | 653 | 1000 | 798 | 802 | 905 | 832 |
| Maximum | 4710 | 4400 | 3530 | 6820 | 7670 | 12560 | 12360 |
| Count | 2160 | 2160 | 2160 | 4320 | 8640 | 8640 | 4000 |

Table 14. Black Carbon ($\mu g/m^3$) Statistics

| Day | Monday | Tuesday | Wednesday | Thursday | Thursday |
|---|---|---|---|---|---|
| Monitor Period | 12-18 (7/25/16) | 12-18 (7/26/16) | 12-18 (7/27/16) | 12-18 (7/28/16) | 10:30-14:20 (8/4/16) |
| Location | Canyon Apt. 1 | Canyon Apt. 1 | Canyon Apt. 1 | Canyon Apt. 2 | Bicycle Ride |
| Mean | 1.6 | 1.8 | 1.3 | 1.0 | 1.3 |
| Standard Error | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Median | 1.5 | 1.5 | 1.2 | 0.9 | 1.0 |
| Standard Deviation | 0.6 | 1.2 | 0.6 | 0.4 | 1.0 |
| Range | 3.6 | 6.5 | 3.6 | 2.4 | 5.2 |
| Minimum | 0.3 | 0.3 | 0.1 | 0.0 | 0.0 |
| Maximum | 3.9 | 6.8 | 3.8 | 2.4 | 5.2 |
| Count | 2124 out of 2161 | 2132 out of 2161 | 2040 out of 2161 | 2117 out of 2161 | 1152 out of 1381 |

Table 15. Ozone (ppb) Statistics

| Day | Monday | Tuesday | Wednesday | Thursday | Thursday |
|---|---|---|---|---|---|
| Monitor Period | 12-18 (7/25/16) | 12-18 (7/26/16) | 12-18 (7/27/16) | 12-18 (7/28/16) | 10:30-14:20 (8/4/16) |
| Location | Canyon Apt. 1 | Canyon Apt. 1 | Canyon Apt. 1 | Canyon Apt. 2 | Bicycle Ride |
| Mean | 62.3 | 32.3 | 56.0 | 57.9 | 36.2 |
| Standard Error | 0.3 | 0.3 | 0.2 | 0.1 | 0.3 |
| Median | 63.4 | 33.6 | 56.5 | 57.3 | 35.4 |
| Standard Deviation | 13.5 | 13.1 | 10.0 | 5.1 | 10.5 |
| Range | 77.5 | 55.4 | 63.1 | 36.0 | 67.5 |
| Minimum | 11.9 | 0.4 | 18.1 | 36.8 | 2.0 |
| Maximum | 89.4 | 55.8 | 81.2 | 72.8 | 69.5 |
| Count | 2155 out of 2157 | 2132 out of 2161 | 2156 out of 2156 | 2160 out of 2161 | 1321 out of 1382 |

Table 16. NO (ppb) Statistics

| Day | Wednesday | Thursday | Friday | Saturday | Sunday |
|---|---|---|---|---|---|
| Monitor Period | 12-18 (7/27/16) | 12:20-00 (7/28/16) | 00-00 (7/29/16) | 00-00 (7/30/16) | 00-11 (8/4/16) |
| Location | Canyon Apt. 1 | Canyon Apt. 2 | Canyon Apt. 2 | Canyon Apt. 2 | Canyon Apt. 2 |
| Mean | 4.1 | 2.5 | 2.2 | 2.5 | 1.9 |
| Standard Error | 0.1 | 0.1 | 0.0 | 0.0 | 0.1 |
| Median | 3.9 | 2.2 | 2.0 | 2.4 | 1.0 |
| Standard Deviation | 1.0 | 1.4 | 1.7 | 1.7 | 2.0 |
| Range | 5.5 | 7.7 | 9.5 | 10.4 | 8.9 |
| Minimum | 2.2 | 0.3 | 0.0 | 0.0 | 0.0 |
| Maximum | 7.7 | 8.0 | 9.5 | 10.4 | 9.0 |
| Count | 342 out of 359 | 670 out of 700 | 1378 out of 1440 | 1368 out of 1440 | 525 out of 661 |

Table 17. $NO_2$ (ppb) Statistics

| Day | Wednesday | Thursday | Friday | Saturday | Sunday |
|---|---|---|---|---|---|
| Monitor Period | 12-18 (7/27/16) | 12:20-00 (7/28/16) | 00-00 (7/29/16) | 00-00 (7/30/16) | 00-11 (8/4/16) |
| Location | Canyon Apt. 1 | Canyon Apt. 2 | Canyon Apt. 2 | Canyon Apt. 2 | Canyon Apt. 2 |
| Mean | 22.1 | 9.1 | 6.2 | 7.2 | 4.3 |
| Standard Error | 0.5 | 0.2 | 0.1 | 0.2 | 0.2 |
| Median | 19.6 | 7.9 | 5.0 | 5.3 | 3.2 |
| Standard Deviation | 9.1 | 4.5 | 4.0 | 5.8 | 3.8 |
| Range | 47.7 | 24.7 | 21.5 | 28.8 | 18.1 |
| Minimum | 8.7 | 2.8 | 0.7 | 0.6 | 0.0 |
| Maximum | 56.4 | 27.5 | 22.3 | 29.4 | 18.1 |
| Count | 359 out of 359 | 697 out of 700 | 1428 out of 1440 | 1430 out of 1440 | 571 out of 661 |

Table 18. NOx (ppb) Statistics

| Day | Wednesday | Thursday | Friday | Saturday | Sunday |
|---|---|---|---|---|---|
| Monitor Period | 12-18 (7/27/16) | 12:20-00 (7/28/16) | 00-00 (7/29/16) | 00-00 (7/30/16) | 00-11 (8/4/16) |
| Location | Canyon Apt. 1 | Canyon Apt. 2 | Canyon Apt. 2 | Canyon Apt. 2 | Canyon Apt. 2 |
| Mean | 26.5 | 11.5 | 8.4 | 9.7 | 5.9 |
| Standard Error | 0.5 | 0.2 | 0.2 | 0.2 | 0.2 |
| Median | 23.8 | 10.1 | 6.8 | 7.4 | 3.8 |
| Standard Deviation | 10.4 | 5.5 | 5.9 | 7.4 | 5.7 |
| Range | 58.4 | 30.3 | 32.1 | 37.9 | 26.2 |
| Minimum | 11.8 | 3.5 | 1.1 | 0.5 | 0.0 |
| Maximum | 70.2 | 33.9 | 33.2 | 38.5 | 26.2 |
| Count | 359 out of 359 | 685 out of 700 | 1426 out of 1440 | 1429 out of 1440 | 579 out of 661 |

## *Atmospheric Conditions*

The measurement campaign was carried out during summer, when it is quite warm in Boulder, Colorado. Table 19 summarizes the ambient weather during the stationary measurement campaign. The conditions were very similar on each day of the study.

High atmospheric temperatures reduce the nucleation of ultrafine particles in fresh vehicle emissions, whereas low temperatures promote nucleation of ultrafine particles (Lee et al. 2015). Thus ultrafine particles from fresh vehicle emissions were most likely lower during the study compared to if the study had taken place in wintertime.

Atmospheric temperature inversions in Colorado are less frequent during the summer, and more frequent during the winter, similar to other locations in the US, such as Albuquerque, Tucson, Flagstaff, Santa Teresa and Salt Lake City (Bailey et al. 2011). Inversions trap pollution closer to the ground and levels are often higher during an inversion. A study in Ontario, Canada showed that night inversions were associated with an increase of PM2.5 and $NO_2$ of around 50%; however, daytime inversions produce a smaller increase in $NO_2$, only 11%.

Table 19. Ambient Weather Conditions during Stationary Measurements

| | Monday 7/25/16 | Tuesday 7/26/16 | Wednesday 7/27/16 | Thursday 7/28/16 | Friday 7/29/16 | Saturday 7/30/16 | Sunday 7/31/16 |
|---|---|---|---|---|---|---|---|
| Mean temperature (F) | 72 | 76 | 73 | 72 | 75 | 75 | 77 |
| Max temp (F) | 88 | 91 | 90 | 82 | 86 | 90 | 91 |
| Min temp (F) | 55 | 61 | 55 | 61 | 64 | 59 | 63 |
| Dew point (F) | 54 | 44 | 47 | 56 | 55 | 55 | 48 |
| Average humidity (%) | 61 | 38 | 41 | 64 | 58 | 60 | 39 |
| Max humidity (%) | 90 | 60 | 57 | 90 | 87 | 97 | 60 |
| Min humidity (%) | 31 | 16 | 24 | 37 | 29 | 23 | 18 |
| Wind speed (mph) | 3 | 4 | 3 | 4 | 5 | 3 | 4 |
| Wind direction | NNE | SW | ENE | NNE | NNE | N | SSW |
| Max wind speed (mph) | 8 | 20 | 10 | 15 | 16 | 8 | 28 |
| Precipitation (in) | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Pressure (in) | 30.2 | 30.1 | 30.2 | 30.2 | 30.1 | 30.0 | 30.0 |

Considering that in winter there is a higher level of particulate matter formation in the atmosphere because of the lower temperatures, and there are more inversion episodes, especially in December and January (Bailey et al. 2011), this situation could produce an increase of the concentration of $NO_2$and PM2.5 in wintertime.

## *Conclusions*

The measurement campaign was successfully carried out in Boulder, Colorado. The connection between the measurements and the bus density was analyzed. The results of the CPC (ultrafine particulate number concentrations) did not show a direct connection with the bus density for stationary measurements and it appeared to be more dependent on the time of day, where it was frequently higher in the early afternoon. The APS data for fine and coarse PM (mass concentrations) also did not correlate with bus density; and a similar behavior was seen for the UHSAS (fine particulate number concentration). Thus, preliminary conclusions are that the atmospheric particulate matter measured during the study was due more to regional urban pollution and not local traffic sources.

The aethalometer and the ozone POM did not show a connection with the bus count. The nitrogen oxides were correlated with the bus count, where in the morning they went up and in the late afternoon

they were even higher. However, the reason for the high levels of NOx in the evening are not clear but could be due to a rare summer temperature inversion.

During the bicycle ride when chasing buses, the CPC and aethalometer readings were correlated with location and traffic density. When directly behind and close to a bus, extremely high levels of ultrafine PM and black carbon occurred. After the bus accelerated away from the rider, the readings decreased due to the increased distance between the rider and the bus. Elevated PM and black carbon was not observed behind all buses. It only occurred on certain routes behind older buses.

The results of the APS, CPC, aethalometer, and Thermo 42i tended to be higher at the condo on the second floor compared to the third floor. The ozone POM and UHSAS output was similar at both elevations. Apparently, at lower elevation there is a higher concentration of pollutants. Perhaps this is because it is closer to the level of the roadway. On the other hand, the location of both condo was not exactly the same. The unit on the second floor is located in front of Canyon Boulevard and the unit on the third floor is on 14th Street. Therefore, the unit in the second floor was more affected by traffic.

It is recommended to develop a measurement campaign during the winter season, to compare to summer measurements. Summer concentrations should be lower compared to winter. For a winter campaign it is recommended to use the portable monitors only and also possibly rent the NOx monitor again. Furthermore, more bicycle rides are recommended to obtain a better understanding of the pollutants' behavior and the exposure of pedestrians and bicycle riders in Boulder.

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