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hereby submit this original work as part of the requirements for the degree of:

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An Exploratory Study of Urban Transportation and Air Quality Issues Using

CO as an Indicator

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This work and its defense approved by:

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Mingming Lu, PhD

An Exploratory Study of Urban Transportation and Air Quality Issues Using CO as an Indicator

A Thesis Proposal Sent to the

Division of Research and Advanced Studies of the University of Cincinnati

In partial fulfillment of the requirement for the degree of

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By

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Abstract

Carbon monoxide levels were monitored at intersections, bus stops, in enclosed parking garages, and in vehicles. Variation in CO levels was then compared with traffic variables. The effect of traffic volume, traffic delay, site location, time of day and meteorological variables were investigated during ambient testing. Incoming and outgoing vehicle volume as well as the effect of the time of day were studied during garage testing. Finally CO variation with vehicle speed, acceleration, road grade and vehicle specific power (VSP), a variable that measures a vehicles engine load per unit mass were investigated during in vehicle tests. The type of vehicle, the surrounding environment and time of day were also considered.

Two studies were performed at two different locations. One study was done in Singapore during the fall of 2009 and one in Cincinnati where tests were done from the winter to the summer of 2010. Similar tests were performed at both locations. Ambient monitoring in Singapore was performed around the NUS (National University of Singapore) campus at bus stops within the campus and around the perimeter of the campus. Ambient testing in Cincinnati was done during winter and spring time at a large intersection. An enclosed parking garage was studied at both locations as well as in vehicle tests. Singapore buses were studied while personal vehicles and city buses were studied in Cincinnati.

Consistent correlations between CO and traffic counts were not seen for the most part at ambient testing sites. A 5 minute interval was used and test periods were typically 1 to 2 hours long. Bus delay at busy bus stops showed consistent positive correlations with CO at the Singapore site. Vehicle delay counted by hand at intersections showed a positive correlation in some cases but was not consistently over each test period. The most consistent pattern around CO concentrations was a peak just after an acceleration period of a traffic cycle (after a green light for an approach with a large queue). Morning tests showed the highest CO levels during the ambient tests. Ambient CO levels ranged from 0 to 1.5 ppm in most cases at both locations. A 3 day test near a major highway showed

that CO concentrations during peak periods were elevated when compared to non peak periods.

Better correlations between traffic and CO were observed in the parking garages. High levels of traffic both at the 5 minute interval and across testing periods consistently showed the highest CO levels. CO measurements at the Singapore car park were done just outside the enclosed garage and although low levels of CO were observed the correlation with traffic was the highest of any of the test sites. Good correlations were also seen at the parking garage in Cincinnati although variations in idling time, a wider range of vehicle ages and a more complex entrance may have lead to less consistent correlations than those observed in Singapore. The highest levels were observed in the evening hours as cold start emissions and long idle times led to higher levels of CO.

Elevated levels of CO were observed in all the vehicles tested relative to the ambient environment. CO increased by 0.2 to 0.6 ppm in most cases. A direct correlation with speed, acceleration, road grade and VSP was not observed over a 5 second interval that was tested. Large buses such as a double decker and double long buses in Singapore showed higher levels of CO than normal 12 meter long buses that were taken. The highest levels of CO were seen during cold starts in the morning in personal cars. CO was shown to exponentially decrease with distance driven in the morning which is the same pattern seen by other studies when looking at direct vehicle emissions.

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1. Objective

More and more new community development and revitalization efforts have included driving less initiatives, such as the implementation of more bicycle lanes, more walking zones, and more public transportation. While effective in reducing short driving trips, these practices can potentially result in more people's exposure to traffic generated pollutants. This warrants detailed transportation-air quality analysis in order to better protect public health and the sustainable development of livable communities.

The first step is to map the seemingly very broad (general) research topic into feasible research activities. So we selected some representative air pollutants (CO in this case), and identified representative transportation modes for the urban centers. The next step is to design the data collection processes to be representative and meaningful from both transportation and air quality aspects. The third step is to analyze the data with proper methods as the data quantity can be large with various affecting parameters. Mobility and environmental quality are two essential parameters to the well being of any urban environment. In order to sustain the healthy operation of the urban centers, the balance of accessibility with environmental protection should be integrated into the daily functions of people and organizations. It is necessary to understand the air quality impacts of different transit modes in the urban centers. The ultimate goal is to be able to study the transportation and air quality issues at other urban centers with similar approaches.

This research will try to identify the factors that consistently have the highest impact on CO concentrations. The research will look to further substantiate the correlation between traffic volume, traffic delay, and type with CO concentration as well as relate meteorological factors such as wind speed and direction, temperature, and seasonal effects. For in-vehicle tests we will look to better understand what has the greatest impact on the in-vehicle CO concentration. We will study the surrounding environment as well as vehicle GPS data that can relate speed, acceleration, road grade, and VSP to CO.

2. Introduction and Literature Review

2.1 About Carbon Monoxide

Carbon monoxide (CO) is one of the six criteria air pollutants regulated by the NAAQS[1] in the US. The primary source is the exhaust of automobiles, especially in urban areas. 85-95% of CO concentration in urban areas is the result of motor vehicle exhaust [1]. Chronic exposure to CO can lead to reduced alertness, headaches and nausea. Exposure to extreme levels will lead to a coma and eventually death. Exposure can significantly impact the health of urban commuters. Emission controls have improved over the past 30 years resulting in a 79% decrease in CO ambient concentration [2]. Although CO controls are improving the volume of traffic on the roads has doubled during the same 30 year period. As populations and vehicle use increase the relationship between CO levels and traffic needs to be understood. Table 1 shows a list of ambient standards for CO.

Table 1[2]: CO Ambient Air Quality Standards

Limit / Level	Type	Organization	Industry / Area	Sources
9 PPM	TWA (8 Hours)	EPA	General	[3]
9 PPM	TWA (8 Hours)	World Heallth Organization	General (Outdoor)	[4]
9 PPM	Ceiling	ASHRAE	General (Living Areas)	ASHRAE [5]
25 PPM	TWA (8 Hours)	ACGIH	General	[6]
35 PPM	TWA (1 Hour)	NIOSH	General	[7]
35 PPM	TWA (1 Hour)	EPA	General	[1]
50 PPM	OSHA PEL as TWA (8 Hours)	OSHA	General	[7]
50 PPM	OSHA PEL as TWA (8 Hours)	OSHA	Construction	[7]
50 PPM	OSHA PEL as TWA (8 Hours)	OSHA	Maritime	[7]
125 PPM	Excursion Limit (EL)	ACGIH	General	Based on definition of EL in 2004 ACGIH Handbook, and the fact that there is no defined STEL for CO in this handbook. [6]
200 PPM	Ceiling	NIOSH	General	[7]

[1] NAAQS (National Ambient Air Quality Standards)

[2] Credits: Nemalapuri, V.J.

- **TWA** – Time Weighted Average: Average level of CO experienced over a specific time period. Typically this is 8 hours.
- **PEL** – Permissible Exposure Limit: OSHA term used for its exposure limits. The PELs here are time weighted averages.
- **Ceiling** – A level where the CO should never rise above at any point in time.
- **STEL** – Short Term Exposure Limit: a time weighted average over a shorter period of time. Here it is 15 minutes.
- **Excursion Limit** – An ACGIH term that refers to a ceiling limit over a short period of time. It is used when no STELs are available to use.

2.2 Using CO as an Indicator of Near Road Air Quality

This research studies three high exposure areas and attempts to understand what factors have the greatest impact on the CO concentration. CO was monitored along roadways (intersections and bus stops), inside enclosed parking garages and inside vehicles themselves. Traffic was monitored along roadways using either a video camera or traffic counts were recorded by hand. Traffic volume and type were analyzed for its relationship with CO concentration. Similarly in the parking garage, traffic in and out of the garage was counted while the CO was measured at the entrance and inside the garage. The in vehicle testing was done by monitoring CO levels inside the vehicle while recording the vehicle movement with a GPS device. An initial study was done at the National University of Singapore used similar tests in another urban area. This study is discussed in section 4.

The research investigates several variables that effect CO concentrations in high risk areas:

Intersections/Bus stops/Parking Garage

- Traffic volume
- Traffic composition

- Idle time (delay)
- Meteorology
- Time of day (AM/PM Peak, off Peak)
- Seasonal

In vehicle (transit bus/shuttle bus/personal vehicle)

- Vehicle Specific Power (VSP) – a measure of engine load per unit mass
- Acceleration
- Speed
- Road grade
- Type of vehicle
- Outside Environment

2.3 Roadside Monitoring

With the changing regulations affecting and/or establishing the near-road monitoring protocols, and the enhanced capabilities of monitoring equipment, the roadway monitoring projects around the country will provide scientists and researchers with data to produce detailed health impact assessment reports and develop human exposure models [8]. CO concentration is usually higher near intersections where traffic volume is highest and vehicles are more often in an accelerating state leading to higher emissions. Previous studies have shown that factors influencing CO concentration include fleet speed, acceleration and deceleration speed, queuing time in idle mode with a red signal time, queue length, traffic-flow rate and ambient conditions. The vehicular composition also affects emissions [9]. CO concentrations have been shown to be higher during the morning rush hour. Baldauf *et al* showed that CO concentrations along an urban highway in Raleigh, North Carolina were greatest during the early morning rush hour (6-8am). The peak CO concentration reached a peak of 1.4 ppm in the morning rush hour while staying mostly below 0.5 ppm during off-peak and evening hours [10]. These readings were taken at a site 20m from the roadway while another site

300m away showed a similar pattern with lower concentrations. The high concentrations observed in the morning hours are usually the result of cold start conditions and cooler temperatures.

Meteorological conditions are an important factor when considering the dispersion of a pollutant such as CO. Pollutants are carried downwind from their source. Tomlin et al 2009 [11] showed that the maximum CO concentrations near an intersection in a London street canyon occurred in downwind samples taken as opposed to directly at the intersection. The study further estimated that a change in wind direction can alter CO concentrations at the intersection by as much as 80%. CO concentrations are typically greatest during the winter time when vehicle emissions are greatest and atmospheric inversion at night is more frequent.

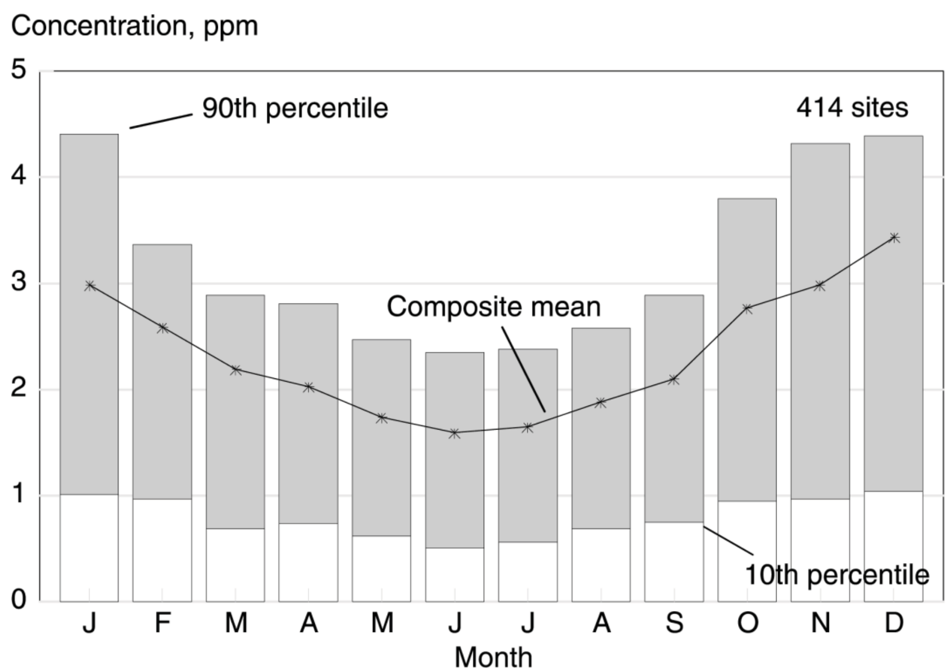

Figure 1: National Average CO Concentration by Month for 1998 - US EPA [12].

Areas with slower traffic will see higher levels of CO than regions with similar volume and faster moving traffic. De Vlieger et al 2000 [13] showed that traveling on city or rural roads resulted in similar CO emissions per kilometer traveled while highway driving resulted in about half of the emissions per kilometer traveled. The same study found that aggressive driving, particularly on urban and rural roads, could increase CO emissions by as much as 40%.

Hagler et al showed that local meteorological conditions and nearby roadside features can significantly influence the absolute concentration and spatial patterns of pollutants [14]. The study found that the absolute and spatial variability in CO concentration with respect to a major highway varied widely based on what location the measurements were made. The week long test in urban and suburban North Carolina showed similar CO concentrations along busy arterial roadways and major highways. The majority of the data fell between 0.3 to 0.6 ppm under both conditions. Background concentrations were shown to be around 0.2ppm. Rubio et al showed also showed that within 40m of the roadway CO concentration was variable while a noticeable vertical gradient in concentration was not seen until a height of at least 40m was reached [15].

Traffic delay is a frequently used method to determine effectiveness of intersections. It is also an important parameter when looking at roadside emissions as emission factors increase when a vehicle experiences delay mainly due to acceleration. There are three types of delay [16]:

> Control delay – This is the total delay due to a traffic light at an intersection. It combines delay due to deceleration, acceleration, and idling. Control delay is rarely measured due to the tediousness required in calculating it.
>
> Approach delay – This is the difference between the actual time it takes for any vehicle to travel from a fixed point in traffic upstream to the stop bar at the intersection, and the same distance covered at normal speed. Approach delay is often estimated from stopped delay.
>
> Stopped delay – This is this most commonly used and measures the total stopped time at an intersection. Average stopped delay is the total stopped delay experienced by all vehicles during a designated period divided by the total

vehicle volume. This research focuses on stopped delay since it is easier to calculate and can be used as an estimator of control delay.

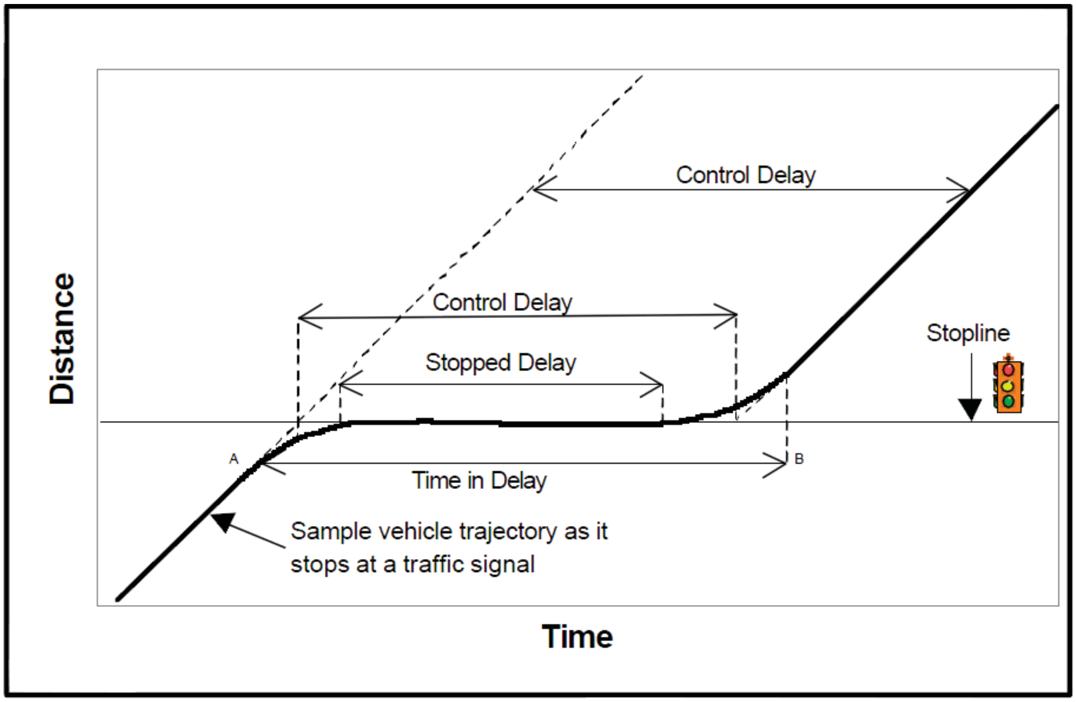

Figure 2: Concept of Delay Events on a Time Distance Graph [18]

Galatioto and Zito [17] showed that queue length accounted for 67% of the variation of CO concentration at an intersection. Rouphail et al [18] showed that NOx, CO, and hydrocarbon emissions are at least twice as high when a vehicle is in control delay mode as opposed to cruising mode. The study found that the highest emission rates were observed during vehicle acceleration while the lowest occurred in idle mode as shown in Figure 3.

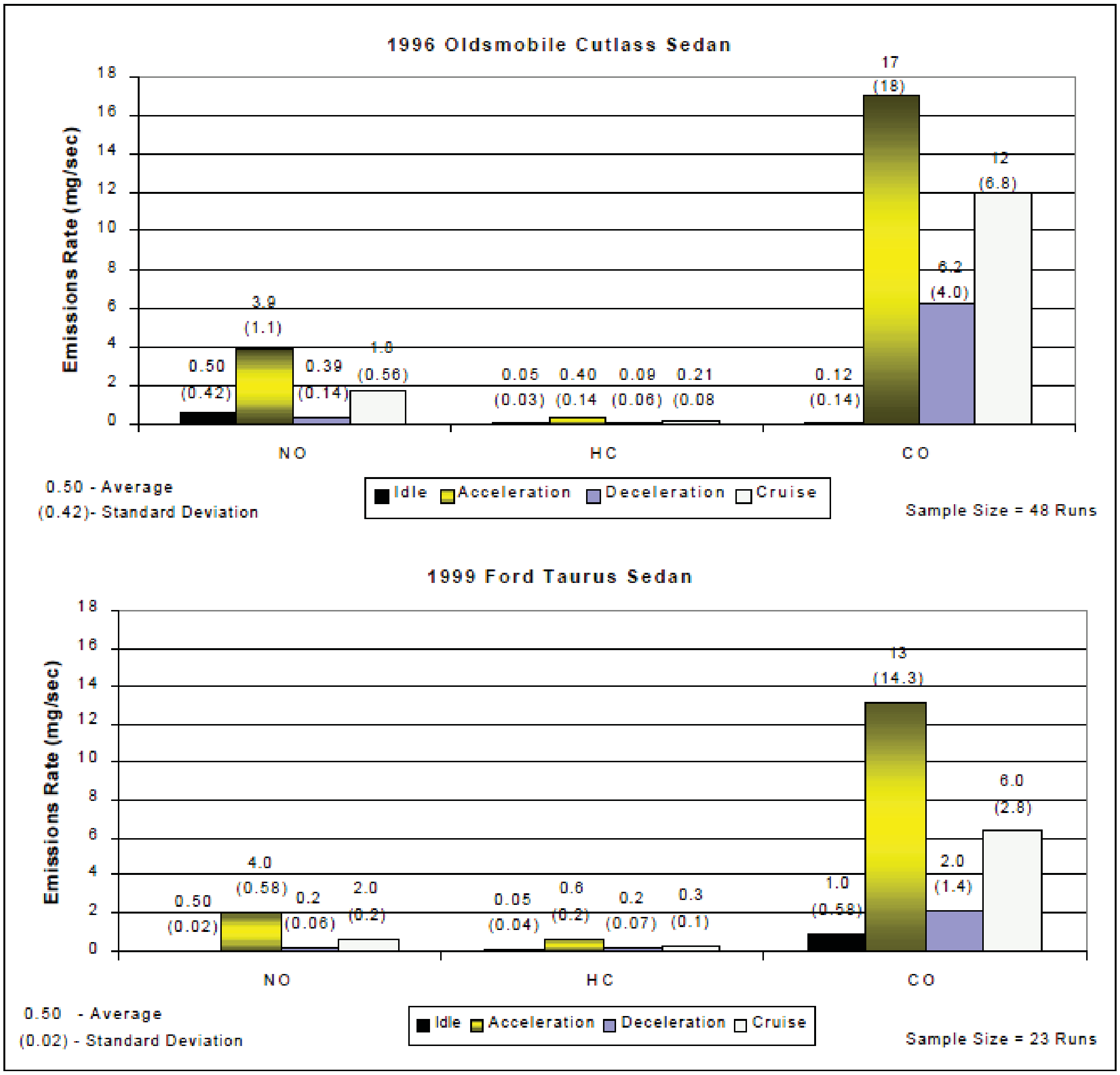

Figure 3: Vehicle Emissions by Driving Mode [18]

Schmidt and Schafer 1998 [19] found that the best measure of vehicle emissions at an intersection can be found by understanding the dynamic flow of the traffic. Good analysis of fleet speed and acceleration i.e. stop and go vs. cruise situations can find better results than traffic counts alone. The study also measured the emission factors for cold starts. It found that the first couple kilometers of driving from a cold start can yield significantly higher emission factors especially after a cold start.

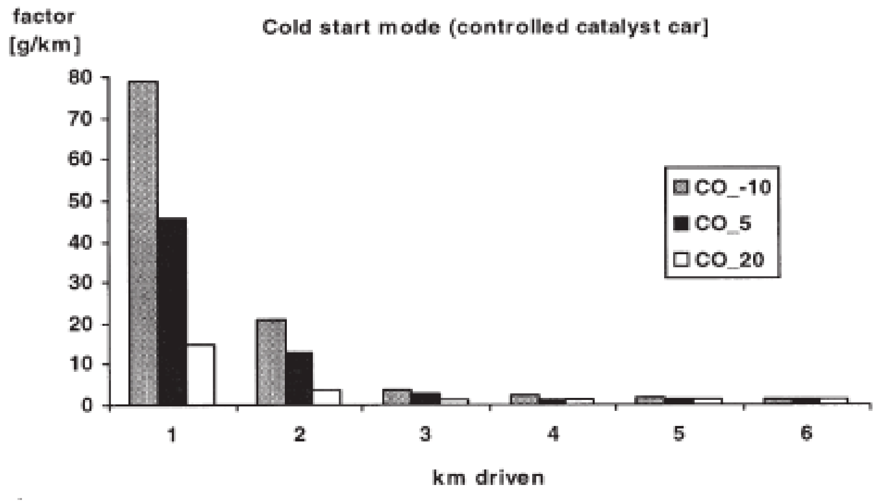

Figure 4: CO Emission Factors from a Cold Start per Kilometer Driven at -10, 5 and 20° C [19]

Cold temperatures have a positive effect of CO concentrations. Figure 4 also separates the emission factors into -10, 5 and 20°C bins. A significant trend is observed with the highest CO concentrations occurring in the coldest temperatures. Another study by Cook et al showed that emission models can underestimate pollutants in cold temperature conditions. The study looked at a variety of pollutants and their predicted and actual concentrations according to Mobile 6.2 [20].

2.4 Parking Garages

The main focus of our study in parking garages is on the traffic in and out of the garage and what factors attribute to high CO concentrations. Incoming traffic volume, outgoing traffic volume, traffic period, temperature, and seasonal changes will be evaluated for effect on CO concentrations. Evaluating and understanding source attribution is critical in order to develop effective control strategies like tunnels [21][22] or toll facilities [23].

Enclosed parking garages have the highest CO concentrations of the three areas studied. It is necessary for underground or enclosed garages to have proper ventilation to allow pollutants to disperse into the outside atmosphere. CO concentrations have been shown to be significantly decrease with proper ventilation [24][25]. A. Duci et al [25] showed that low ventilation (1m/s) decreased CO concentration by 30% and high ventilation

(2m/s) decreased CO concentration by 50%. Cars often start from a cold start in the garage increasing the emissions particularly when vehicles are leaving the garage. This research took place at the CCM (College-Conservatory of Music) garage at UC. It is a 3 level underground garage entirely enclosed except for the main entrance/exit, 1 side entrance and 1 side exit. A toll booth is located at the main entrance. Testing results show that toll booth operators can be exposed to CO levels of 20 ppm and higher for extended periods of time.

Unlike roadside monitoring which takes place in an open environment and is exposed to the atmosphere the parking garage is a more controlled environment where traffic and CO concentration has had higher correlations near the main entrance. This has been observed both at the University Hall Carpark at the National University of Singapore and at the CCM garage at the UC campus discussed further in sections 4.3 and 5.3.

Fewer studies have been done relating air quality in garages to the vehicle traffic in comparison to ambient studies. Kim et al [26] looked at an 8 story urban parking garage. The study monitored several pollutants (including CO), meteorological factors and traffic. The study found an average increase in CO of 0.31% per vehicle and used a 30 minute sampling interval. The CO concentration was observed to increase with temperature ($r = 0.48$) due to an increase in air conditioning. The study found that light duty trucks made a slightly higher contribution to CO concentrations than cars.

One important factor when looking at CO concentration is the time of day. In the morning traffic is coming into the garage. The vehicles arriving have been running for several miles in most instances and give off lower CO emissions as a result. In the evening the vehicles are leaving the garage. Many of the vehicles have been sitting in the garage since the morning and thus begin at a cold start leading to higher CO values in the evening hours. Figure 5 shows a study by Kim et al [26] that evaluated CO vs time in an urban parking garage. Higher CO values were observed during the morning and evening peak travel times. The morning had slightly higher CO concentrations than the evening peak period although this is also when the most traffic was seen.

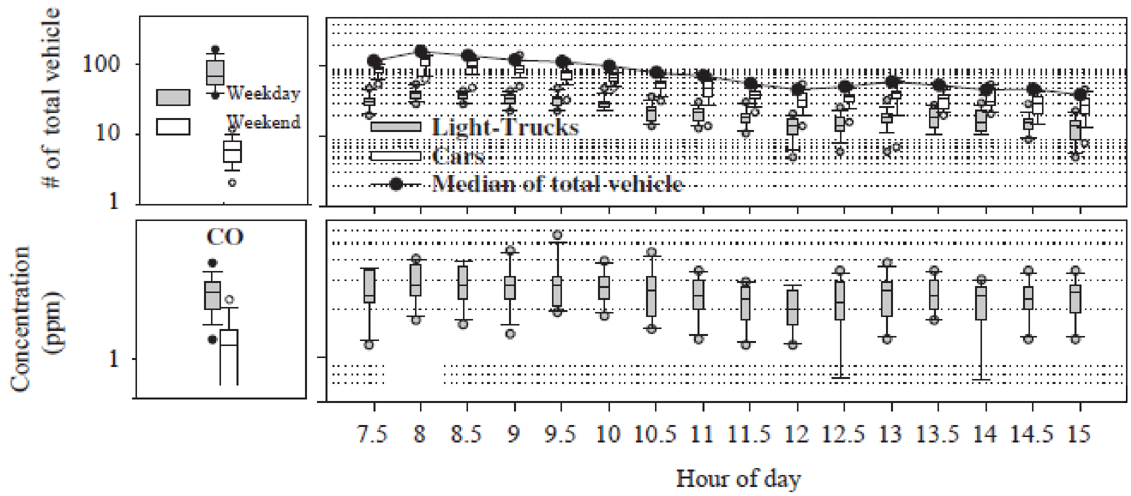

Figure 5: CO Fluctuation with Time Inside an 8 Story Parking Garage [26]

The importance of a cold start is magnified in an enclosed parking garage since the vehicle start takes place within the garage and the resulting high emissions take place within the garage environment.

2.5 In Vehicle

Carbon monoxide (CO) is one of the six criteria air pollutants monitored by the clean air act and enforced by the US EPA. The primary source is the exhaust of automobiles, especially in urban areas. Chronic exposure to CO can lead to reduced alertness, headaches and nausea. Exposure to extreme levels will lead to a coma and eventually death. Exposure can significantly impact the health of urban commuters. Previous studies have shown that the CO levels outside a vehicle are similar to those inside the vehicle but that there is a smoothing effect (the CO level inside varies less) [27]. Other variables that have shown to have an impact of CO concentrations inside vehicles include: vehicle type, wind speed, and time of day. Passenger cars have been shown to have the highest CO concentrations due to their low air intakes taking in more exhaust from surrounding vehicles and higher engine out CO emissions when compared to diesel vehicles [28][29]. Wind speed has been shown to effect the amount of CO concentrations measured in vehicles with the lower concentrations observed at higher wind speeds [30][31][32][33]. In vehicle CO concentrations are higher on average during peak traffic time periods during the morning and evening commuting hours [29][34]. Little has been done, however, to study the correlation between the operation mode of the individual vehicle and the CO concentration inside the vehicle microenvironment.

In this research continuous sampling was done with a T15n electrochemical CO measurer. Two methods have been used to measure in vehicle CO concentrations. As the name implies continuous sampling involves continuous monitoring of the CO concentration inside the vehicle typically using either an electrochemical sensor or NDIR. Grab sampling involves drawing a sample inside a syringe, container, or flexible bag and analyzing the contents. This method allows the average CO concentration to be integrated over the entire test period but doesn't allow for temporal variations in concentration to be observed. With proper calibration it has been shown that results from both methods are comparable [35].

Road type is another parameter that has shown to affect CO concentration within a vehicle. Several studies have shown that in vehicle CO concentrations are higher when traveling on large urban roadways as opposed to smaller rural roads [34][36][37]. This research will look to expand on this research by comparing CO concentrations along different routes and locations within those routes.

Speed, acceleration, and road grade all influence the emissions of a vehicle. A recent factor introduced to emission analysis is VSP (Vehicle Specific Power). This parameter was introduced by Jimenez 1999 [38]. It incorporates acceleration, speed, and road grade to come up with an engine load per unit mass. This research looks at acceleration, speed, road grade, and VSP to see how well these parameters effect CO concentrations inside vehicles as they are calculated on a 5 second interval using a GPS device.

2.6 VSP Definition and Use

VSP (Vehicle Specific Power) is a measure of engine load per unit mass of a vehicle. It takes into consideration the power generated by the engine, the rolling resistance, and aerodynamic drag. The general equation is as follows [38]:

Vehicle Specific Power (VSP) =

$$\text{Vehicle Specific Power} = \frac{\frac{d}{dt}(KE + PE) + F_{rolling} \cdot v + F_{Aerodynamic} \cdot v}{m}$$

$$= \frac{\frac{d}{dt}(\frac{1}{2} m \cdot (1+\varepsilon_i) \cdot v^2 + mgh) + C_R mg \cdot v + \frac{1}{2}\rho_a C_D A (v + v_w)^2 \cdot v}{m}$$

$$= v \cdot (a \cdot (1+\varepsilon_i) + g \cdot grade + g \cdot C_R) + \frac{1}{2}\rho_a \frac{C_D \cdot A}{m}(v + v_w)^2 \cdot v$$

Variables:

m: Mass of the vehicle (kg)

v: Speed of the vehicle (m/s)

a: Acceleration of the vehicle (m/s^2)

ε_i: "Mass factor", this is the translational mass of the rotating parts of the vehicles such as the wheels, axles, etc.

grade: The increase in height of the road/road length (%)

g: Gravitational acceleration (9.81 m/s^2)

C_R: Dimensionless coefficient of rolling resistance

C_D: Drag coefficient

A: Frontal area of the vehicle (m^2)

P_a: Density of air (Kg/m^3)

V_w: Headwind into the vehicle. (Assumed to be zero)

For this research, the equation can be simplified to that of a typical transit bus by using some typical coefficient values represented for a transit bus [39][40]. The coefficient values are listed below:

Table 1. VSP Coefficients

	Explanation	Value and Unit
ρ_a	Density of air	1.2 Kg/m^3
C_R	Rolling resistance coefficient	0.00938
A	Frontal area of the vehicle	7 m^2
C_D	Drag coefficient	0.6
M	Mass of vehicle	12,020 Kg

So, the equation for calculating VSP of a transit bus is as follows [41]:

$$v \times (a + g \times \sin(\varphi) + 0.092) + 0.00021 \times v^3$$

Where φ is the road grade (%); 0.092 is the value of the rolling resistance term coefficient ($g*C_R$); 0.00021 is the drag resistance term coefficient (1/2 $\rho_a C_D A/m$); We can assume 0 headwind on the bus as we observed calm conditions in Singapore during the testing. Another assumption that is made in this equation is substituting sin (grade) for sin (atan(grade). For a road with less than 11% grade the difference between these functions is less than 1%.

A study by (Zhai et al 2008) [41] tested for correlations of the same variables with direct tail pipe emissions as opposed to in-vehicle values we did here. The study took place in London and found a correlation coefficient of 0.02 with road grade, 0.37 with vehicle speed, 0.55 with acceleration and 0.53 with VSP.

3. Instruments Used

3.1 Instrument Descriptions

Non Dispersive Infrared Analyzer (NDIR) – NDIR measurement the method used by EPA Reference method 10, measuring CO from stationary sources [42] and generally accepted as the most reliable measurement. CO has a characteristic infrared adsorption near 4.6µm. Based on the amount of infrared light absorbed by the sample gas and comparing it to a reference gas with no CO the CO concentration in the sample is obtained. The NDIR was mainly used to calibrate the T15 and WSN sensors.

Langan T15n CO measurer – Measures ambient CO concentration using an electrochemical sensor. Electrochemical sensors use acid as an electrolyte and platinum as a catalyst to break down CO according to the following equations:

Working Electrode: $CO + H_20 \rightarrow CO_2 + 2H^+ + 2e^-$

Counter Electrode: $\frac{1}{2} O_2 + 2H^+ + 2e^- \rightarrow H_2O$

The excess electrons create a current proportional to the CO concentration. Most of the CO data from this project was obtained with the T15 due to its portability, ease of use, and higher reliability over the WSN sensor. The T15n measurements are recorded at requested intervals. The memory of the instrument is then read out by the software. The T15 is calibrated in a controlled chamber regularly with an NDIR (EPA approved method). The instrument has an operating range of -5°C to 40°C and ± 10% of standard atmospheric pressure [43]. Three T15s were used during the course of this research identified by the T15-1,2, and 3. Instruments 1 and 2 are used for a majority of the testing. Instrument 3 was used during some of the final tests after instrument 2 was lost.

Figure 6: T15n CO Measurer

WSN (Wireless Sensor Network) Sensor – Measures CO concentration using an electrochemical sensor on the same principle as the T15n. The measurements are not recorded on the instrument but rather transmitted wirelessly to a base station that records the data. The WSN is also calibrated in a controlled chamber with the NDIR. In most cases several of these sensors are used simultaneously in an ad hoc network. Signals from one sensor can be relayed through other sensors which allows for an extended range.

Figure 7: WSN CO Sensor

Calibration Chamber – The T15n and WSN CO sensors were calibrated in a controlled chamber using an NDIR as a reference. Detailed calibration procedures are outlined in section 3.2.

Figure 8: Calibration Chamber

Qstarz BT-Q1200 Ultra GPS - Instrument for acquiring GPS data in vehicles. Vehicle location, altitude and speed are recorded at a requested interval. Most tests were done at a 5 second interval. From the data, acceleration, distance traveled, and VSP are calculated.

Figure 9: Q1200 Ultra GPS

Anemometers: Extech 45158 and Skymaster SM-28 – Handheld instruments used to measure local temperature, humidity, and wind speed during field tests.

Figure 10: Handheld Anemometers

University of Cincinnati Met Tower – Located on top of Rhodes Hall at the University of Cincinnati west camps. Wind speed, wind direction, temperature, and relative humidity are recorded continuously at 2 minute intervals.

Figure 11: Rhodes Hall Met Tower. University of Cincinnati.

National University of Singapore Met Tower – Similar to the met tower located at the University of Cincinnati it is located on top of building E2 in the Kent Ridge campus and is at a height of 90m above sea level. The tower contains instruments that measure temperature, humidity, wind speed and wind direction. Met data is recorded at 5 minute intervals.

Figure 12: NUS Met Tower [44]

Local Weather Data – Local weather station data was used when met data was not available from the met towers. The data consists of hourly data from the Cincinnati/Northern Kentucky airport or bihourly data from the Changi airport in Singapore. The Cincinnati airport is 10 miles southwest of the UC campus and the Changi airport is 15 miles East of the NUS campus where testing was done.

Video Camera – Sites were often videotaped so that the traffic count and vehicle types could be preserved.

Traffic Counter – Used to count traffic. The device enables the user to quickly count each moment for each approach as well as record 2 different types of vehicles simultaneously.

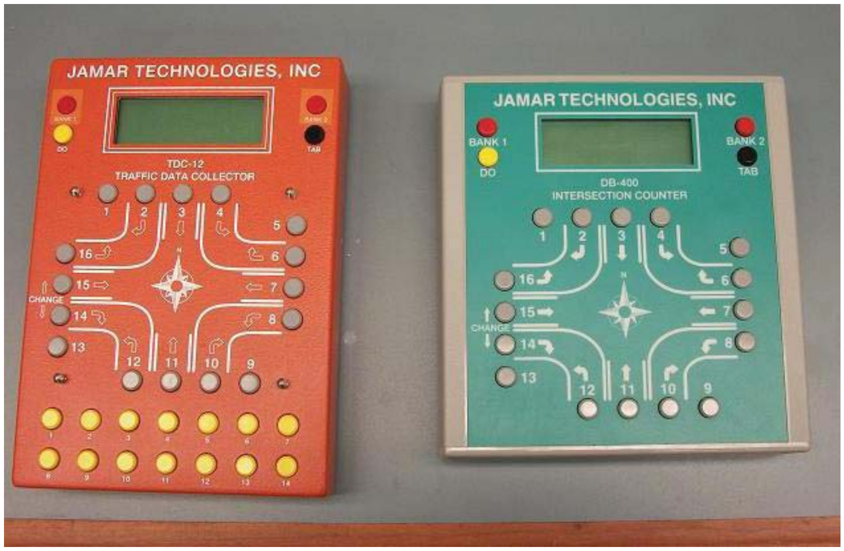

Figure 13: Traffic Counters – Jamar Technologies Model TDC 12 and DB 400

3.2 Instrument Calibration

Both the T15 and WSN instruments were calibrated regularly with an NDIR to ensure accurate readings. The chamber allows the user to vary CO concentration as well as control temperature and humidity. The chamber uses zero air and gas flow rate controls to allow the user to easily adjust the CO concentration within the chamber. 10 ppm or 40ppm CO was pumped into the chamber along with zero air. The calibrations began using a small amount of CO (0-0.2ppm) and gradually the CO was increased in relation to the zero air until a complete calibration curve was produced. Approximately 20 minutes of settling time was used to allow the chamber time to reach a steady state.

Calibrations were typically done either before or after a set of field tests were to be done. During the spring testing at the UC campus instrument calibration was done based off of side by side tests with the NDIR in the CCM garage. The calibration curve was produced by solving for the smallest amount of error between the two instruments. Calibration curves are shown in appendix A. Details have been provided by Toruska [45].

4. Singapore Study

4.1 About Singapore and Site Selection

Singapore is a heavily urbanized city in Southeast Asia. It is located near the equator (1° latitude) and has a tropical climate. Singapore has a large network for public transit consisting of both rail and bus transit. The Singapore government encourages use of public transit to reduce congestion and air pollution through regulation of vehicle licenses and subsidizing public transit.

Figure 14: Singapore Site Location [46]

Tests were done around the National University of Singapore (NUS) campus from August to October 2009. The campus location is shown in Figure 14. Areas of focus included busy bus stops, an enclosed parking garage and in vehicle monitoring done inside the Singapore city buses as well as the NUS campus buses. The traffic composition is mainly passenger cars. Bus traffic, motorcycles, and trucks also make up a significant portion of the vehicle mix. Traffic around the NUS campus is composed of about 83% passenger cars, 7% motorcycles, 3% buses and 7% heavy duty trucks. Bus traffic is higher within the campus. Many residents rely solely on public transport (train and bus) to get around the city. The National University of Singapore is the largest university in Singapore and one of the biggest in southwest Asia. It is home to 36,966 students including 26,418 undergraduate and 10,548 graduate students. In addition to the student population 8,947 faculty, researchers, and staff are employed by the university. The Kent Ridge campus is the main campus and was the location of this study while its 2 satellite campuses, Bukit Timah and Outram are also located in Singapore [47].

Testing was mainly done around the NUS campus on the southwestern part of the island west of downtown. One large intersection was selected for ambient testing as well as three busy bus stops within the campus. Test sites were selected based on the typical traffic activities, and level of exposure to the pedestrians. Testing was done inside the main parking garage underneath the University Hall administration building. The garage was chosen because of its large size and because it is an enclosed environment. Finally in vehicle testing was done on bus routes either going to and from campus or internal bus routes. The locations and methodology are described further later in this chapter.

4.2 Bus Stops

4.2.1 Locations

Four bus stop locations were used for testing around the NUS campus. The locations are shown in figure 14 along with the location of the University Hall Car Park where garage testing was done. Descriptions of the individual sites are given later in the section. Detailed photographs depicting sensor locations are shown in appendix B. Driving is done on the left side of the road in Singapore. Following the overall map of the test sites are a map of each individual site and a description.

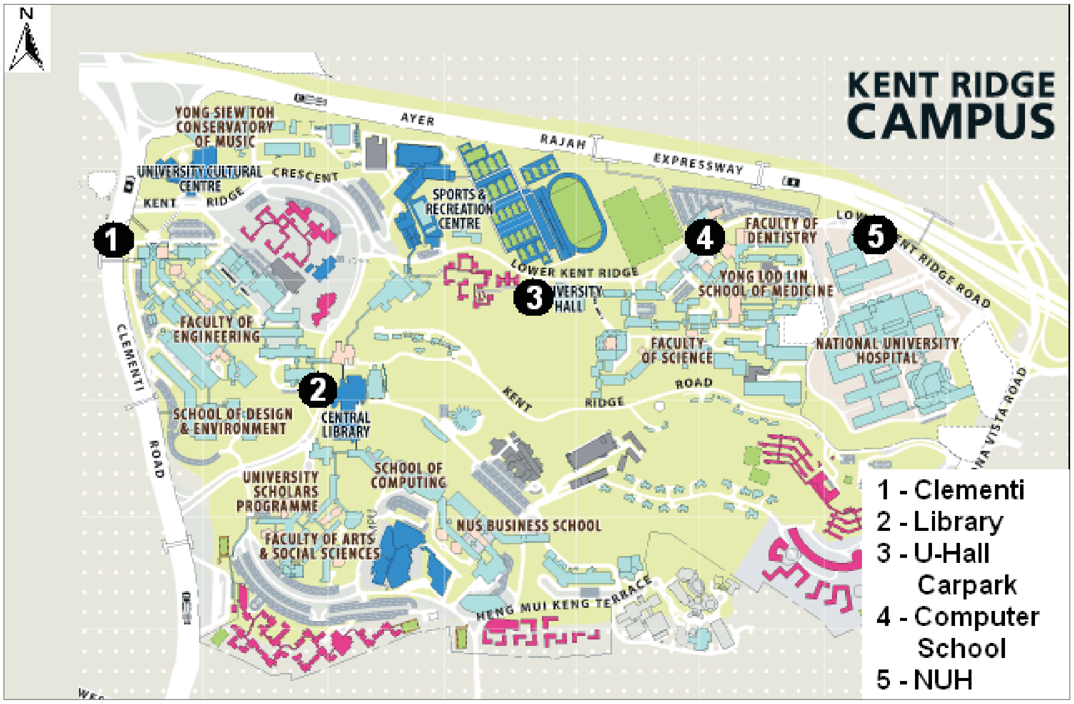

Figure 15: Bus Stop and Parking Garage Testing Locations [48]

Clementi Intersection

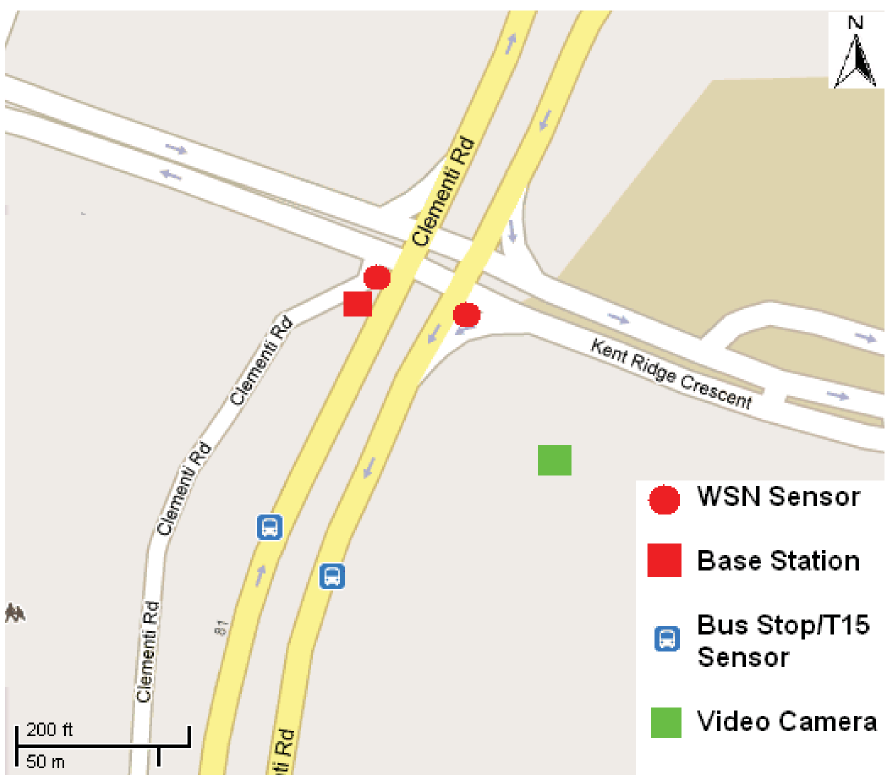

Figure 16: Clementi Intersection and Bus Stop – 2010 Google Map Data

Clementi Road is a busy 6 lane road forming the west border of the Kent Ridge Campus. Clementi Rd starts at an industrial area on the southwest part of the island before traveling past the NUS campus and heading toward downtown. The two locations tested included the intersection of Clementi Road and Kent Ridge Road and a bus stop about 300' south of the intersection. Clementi Rd is the busy 8 lane arterial road running north-south. Kent Ridge Road runs east-west going from the Kent Ridge residences into the NUS campus. Much of the traffic going into and out of the campus comes into the east approach of Kent Ridge Road from the north approach of Clementi. All three westbound lanes are used as right turn lanes with the left lane also acting as a left turn and through lane. The west approach of Kent Ridge Road goes into a residential facility used by many students. This approach has the least amount of traffic although buses frequently carry students from the residences to the campus.

The bus stop shown in red is used by both normal buses and by double length buses. The two stops are connected by an overpass which leads to one of the campus buildings. Video for this site was shot on a hill in the southeast part of the intersection. In most cases the T15 instruments were placed at the bus stop and traffic was counted by hand or traffic video was recorded. The sensors were placed 0.8m off the ground on the edge of the bus lane on small concrete pillars. WSN sensors were placed at the intersection at 1.8m on a traffic pole in some of the tests. The base station was put on a ledge in the southwest corner of the intersection. See appendix B for details.

The Central Library

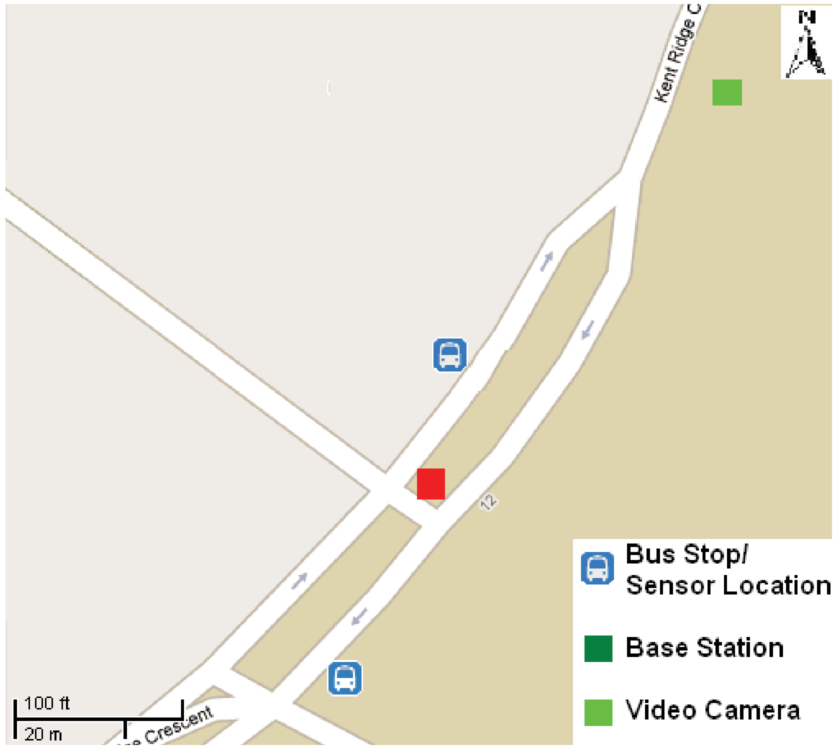

Figure 17: Library Bus Stop – 2010 Google Map Data

The library bus stop is the busiest bus stop within the NUS. The library's heavy use and its central location make it a frequently used bus stop for students. There can be 50 or more people waiting for buses at the site. Buses often idle for long periods (1-2 minutes) waiting for people to get off and on. Buses will often queue behind each other at the bus stop 3-4 deep. Other vehicle traffic is light although there are a higher number of personal cars stopping to pick up and drop off students. The library is located to the right of the road and bus stops shown in Figure 17.

T15 and WSN sensors were placed together at each bus stop at 0.8m on small concrete pillars located on the edge of the roadway. The base station was placed on an island in between the northbound and southbound lanes. Video was taken from an overpass just north of the bus stops.

Computer School and National University Hospital (NUH)

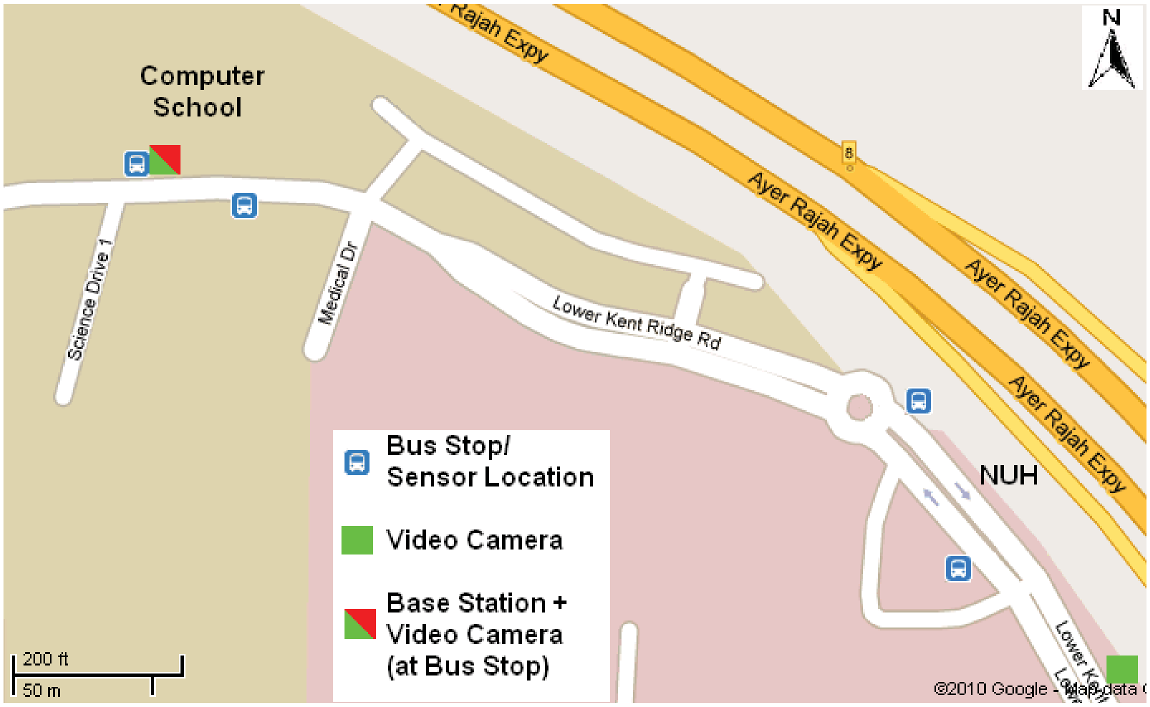

Figure 18: Computer School and NUH Bus Stops – 2010 Google Map Data

The computer school and NUH sites are located close in proximity on the northeastern part of campus. The computer school is a busy bus stop and a transition point for people to get off the NUS bus system and get on the city bus system. The traffic is higher than the library and can back up to the bus stop at peak times, but lighter than the NUH or Clementi sites. Bus idle times can be high as large groups get on and off the buses here and buses will queue behind each other. A roundabout is located in between the Computer School and NUH sites. Many buses coming from the computer school turn around here and head back to the computer school in the opposite direction while many passenger cars heading from the NUH site turn around at the roundabout and head back to the NUH site in the opposite direction.

The NUH site is the busiest site inside campus that we tested with regards to vehicle traffic. It is a 4 lane road with many parking lots adjacent to it and is a main access to the University. The vehicle traffic is high. The bus traffic is light and buses that do stop do not idle for long periods.

T15 and WSN sensors at the computer school were placed at the bus stops on concrete pillars on the edge of the road at 0.8m in height. The basestation and video camera were also located at the bus stop for outgoing traffic. At the NUH site only T15 sensors were used. They were placed at each bus stop at 1.8m in height. Traffic video was shot from the outgoing traffic side of the road looking back at the two bus stops.

4.2.2 Methods

CO measurements and traffic counts were performed at each location simultaneously. Traffic was counted in 5 minute intervals typically running for one to one and a half hours. Traffic was either counted on site by hand or recorded by video and counted at a later date. T15 CO measurements were set to record at 10 second intervals on most occasions. Occasionally a 5 second or 30 second interval was used. Frequency of WSN readings varied because a point was recorded every time the signal was received by the base station. This varied depending on the distance of the WSN sensor to the base station, the positioning of the sensors and software settings used. The frequency typically ranged from 5 to 20 seconds but ranged from less than 1 second to a couple minutes.

Regardless of the interval chosen the CO data was averaged over 5 minutes to match the traffic data. Two types of analysis were done to examine the relationship between traffic and CO. The main type of analysis done used correlation coefficients or R values to determine how well the CO and traffic compared with each other. This allows us to objectively compare the correlation between traffic and CO and quickly compare a lot of data. The second way the data was analyzed was plotting the traffic and CO on the same plot vs time. This allows us to notice patterns and pick up on relationships that may not be seen by a simple correlation coefficient such as a delay in a CO peak after a traffic peak. The assumption behind the tests is that large amounts traffic, as the major source of CO emissions will increase the CO concentration. Higher CO will be seen at peak traffic times and lower CO levels will be seen during periods of light traffic. In addition to looking at the CO and traffic data that was taken simultaneously correlation coefficients were also calculated for CO data that occurred 1 minute later than the traffic data. For instance if the traffic data took place from 0-5 minutes we compare it to CO data taken from 1-6 minutes. This is done to account for the time between when the traffic passes the sensor and the time when the CO reaches the sensor and then is recorded by the sensor.

Traffic was separated into passenger vehicles, motorcycles, and heavy duty vehicles (trucks and buses). Light duty trucks were either included in passenger vehicles during counting or counted separately and combined later for analysis. Although diesel and gasoline vehicles are counted together in the passenger car category the vehicle fractions did not change much at each site. Most of the taxis in Singapore are also diesel and were included in passenger cars. Traffic for each type of vehicle and for total vehicles was acquired and compared with the simultaneous CO data and CO data offset by 1 minute.

Along with traffic counts bus delay was also looked at to see if long idling times by buses had an influence on CO levels. During most of the testing at the three sites within the campus bus delay was counted in addition to vehicle traffic. Bus delay is defined as the number of vehicle seconds buses idle at the bus stop. If two buses are queued at a bus stop and one is idle for 30 seconds and the other for 50 seconds we say the bus delay is the sum of all buses idling at the stop so it is 80 vehicle seconds.

4.2.3 Results and Discussion

Tables Table 2 through

Table 9 give the correlation coefficients for each location, test period and vehicle type. The instrument used, duration, and average CO for each test is also given. Data taken during the same time period but with different instruments is listed under the same date. All traffic data is for sensor side traffic only. More tables are given in appendix B that includes meteorological data, vehicle volume, exact time of the tests, and correlation coefficients for total traffic volume. Sensor locations are the same as given in 5.2.1

unless specified otherwise. The HD column stands for heavy duty vehicles and includes large trucks and buses.

Time periods are defined as follows with each test put into the period where the majority of the time occurs:

- 7-9:30 AM – AM PK
- 9:30-11AM – MM (mid morning)
- 11AM-1PM – Noon
- 1-4PM – MA (mid afternoon)
- 4-7PM – PM PK

Table 2: Clementi - NUS Side, NUS Side Traffic Only

					Simultaneous R Values				1 Minute Offset R Values			
Date	Time Period	Instrument	Duration	Ave CO (ppm)	Cars	Motorcycles	HD	Total Traffic	Cars	Motorcycles	HD	Total Traffic
24-Sep	AM	T15-1	1:25	0.46	-0.5	-0.05	0.38	-0.36	-0.53	0.00	0.33	-0.39
6-Oct	AM	T15-2	1:30	1.51	-0.41	-0.03	0.33	-0.32	-0.37	0.02	0.28	-0.28
6-Oct	Noon	T15-2	0:50	0.87	-0.06	0.58	0.61	0.18	-0.12	0.67	0.41	0.07
30-Sep	MA	T15-1	1:00	0.46	-0.39	-0.52	0.67	-0.33	-0.39	-0.50	0.66	-0.33
6-Oct	MA	T15-2	1:55	0.63	0.61	0.45	0.38	0.61	0.57	0.43	0.36	0.57
24-Sep	PM	T15-1	1:30	1.24	-0.28	-0.20	-0.33	-0.35	-0.30	-0.09	-0.28	-0.33
28-Sep	PM	T15-1	0:25	0.39	-0.26	-0.60	0.87	-0.27	-0.30	-0.64	0.92	-0.3
1-Oct	PM	T15-2	1:15	0.74	0.52	0.28	-0.24	0.47	0.52	0.31	-0.23	0.48
6-Oct	PM	T15-2	1:55	1.12	-0.03	-0.10	-0.02	-0.05	-0.08	-0.13	-0.02	-0.09

Table 3: Clementi - Opposite NUS, Opposite NUS Side Traffic Only

					Simultaneous R Values				1 Minute Offset R Values			
Date	Time Period	Instrument	Duration (H:MM)	Ave CO (ppm)	Cars	Motorcycles	HD	Total Traffic	Cars	Motorcycles	HD	Total Traffic
24-Sep	AM	T15-2	1:20	0.37	-0.32	0.41	0.02	-0.15	-0.18	0.47	-0.07	-0.03
6-Oct	AM	T15-1	1:30	2.07	-0.17	-0.24	-0.03	-0.19	-0.14	-0.21	-0.01	-0.14
		WSN 21	1:30	1.01	-0.5	-0.54	-0.35	-0.56	-0.49	-0.56	-0.36	-0.55
6-Oct	Noon	T15-1	0:50	0.57	0.79	-0.32	-0.87	0.62	0.74	-0.38	-0.84	0.55
		WSN 21	0:50	1.17	-0.1	-0.34	0.23	-0.09	0.35	-0.26	-0.13	0.35
29-Sep	MA	T15-1	1:00	0.88	0.04	0.29	-0.44	0.02	0.04	0.28	-0.44	0.01
		WSN 21	1:00	1.00	-0.48	-0.48	0.14	-0.37	-0.36	-0.36	0.04	-0.3
6-Oct	MA	T15-1	1:00	0.7	0.55	0.46	-0.31	0.38	0.67	0.56	-0.2	0.54
		WSN 21	1:00	0.76	0.37	0.58	-0.26	0.29	0.36	0.66	-0.41	0.23
24-Sep	PM	T15-2	1:15	0.65	0.05	0.26	0.28	0.18	0.17	0.45	0.17	0.3
28-Sep	PM	T15-2	0:25	0.87	-0.46	-0.12	-0.81	-0.63	-0.46	-0.08	-0.86	-0.63

*29-Sep	PM	T15-1	1:00	0.51	0.59	0.38	0.11	0.68	0.53	0.38	0.11	0.62
		T15-2	1:00	0.51	-0.44	0.06	0.22	-0.36	-0.37	0.07	0.18	-0.29
		WSN 21	1:00	0.82	0.48	0.27	-0.14	0.53	0.39	0.39	-0.06	0.52
1-Oct	PM	T15-1	2:20	1.12	0.07	-0.07	-0.26	-0.06	0.00	-0.02	-0.33	-0.13
		T15-2	1:05	0.33	-0.23	-0.24	0.43	-0.04	-0.23	-0.06	0.4	-0.03
		WSN 21	1:00	1.23	-0.45	-0.69	0.03	-0.55	-0.55	-0.7	0.12	-0.63
6-Oct	PM	T15-1	1:10	1.07	0.01	0.08	0.02	0.02	0.08	-0.02	0.06	0.09
		WSN 21	1:10	0.89	-0.05	-0.33	0.23	-0.07	0.07	0.13	-0.19	0.07

*All 3 instruments placed together at southwest corner of the Clementi intersection

Table 4: Library - Library Side, Library Side Traffic Only

					Simultaneous R Values					1 Minute Offset R Values				
Date	Time Period	Instrument	Duration (H:MM)	Ave CO (ppm)	Cars	Motor-cycles	HD	Bus Delay	Total Traffic	Cars	Motor-cycles	HD	Bus Delay	Total Traffic
16-Sep	AM	T15-2	1:35	1.14	0.45	0.21	0.45	0.23	0.45	0.56	0.05	0.56	0.26	0.56
8-Oct	AM	T15-2	1:30	0.55	0.00	0.18	-0.20	0.1	0.02	0.13	0.31	-0.11	0.11	0.19
15-Oct	AM	T15-2	0:50	0.65	0.31	-0.08	0.58	0.25	0.52	0.38	-0.15	0.72	0.13	0.55
8-Oct	Noon	T15-2	2:05	0.46	-0.09	0.17	-0.02	-0.02	-0.1	-0.04	0.22	-0.16	0.04	-0.08
2-Oct	MA	T15-1	1:15	1.05	0.27	-0.52	-0.32	0.21	0.45	0.29	-0.47	-0.95	0.26	0.53
8-Oct	MA	T15-2	1:25	0.4	-0.04	-0.45	0.27	-0.35	-0.05	-0.08	0.17	0.32	-0.18	0.02
15-Sep	PM	T15-2	1:20	1.19	0.56	-0.27	-0.97	NA	0.42	0.58	-0.29	-0.24	NA	0.5
8-Oct	PM	T15-2	1:30	0.59	0.06	0.38	0.28	0.16	0.15	0.12	0.48	0.25	0.15	0.21

Table 5: Library - Opposite Library, Opposite Library Side Traffic Only

					Simultaneous R Values					1 Minute Offset R Values				
Date	Time Period	Instrument	Duration (H:MM)	Ave CO (ppm)	Cars	Motor-cycles	HD	Bus Delay	Total Traffic	Cars	Motor-cycles	HD	Bus Delay	Total Traffic
16-Sep	AM	T15-1	1:40	0.69	0.18	-0.07	-0.16	-0.08	0.08	0.10	-0.12	-0.2	-0.09	-0.01
8-Oct	AM	T15-1	1:30	0.67	0.04	0.05	0.19	0.02	0.05	0.05	0.09	0.12	-0.07	0.01
15-Oct	AM	T15-1	0:50	0.27	-0.20	-0.14	0.41	0.36	-0.01	-0.28	-0.10	0.56	0.49	-0.03
8-Oct	Noon	T15-1	2:35	0.76	-0.02	0.16	0.18	0.04	0.02	-0.04	0.17	0.23	0.11	0.04
2-Oct	MA	T15-2	1:20	0.65	-0.01	0.22	0.21	0.46	0.29	-0.04	0.22	0.16	0.44	0.26
15-Sep	PM	T15-1	1:20	0.5	0.44	0.17	0.46	0.58	0.66	0.41	0.22	0.40	0.53	0.62
8-Oct	PM	T15-1	1:30	0.72	-0.05	-0.23	0.03	0.06	-0.05	0.11	-0.08	0.25	0.22	0.18

Table 6: Computer School – Inbound, Inbound Traffic Only

					Simultaneous R Values					1 Minute Offset R Values				
Date	Time Period	Instrument	Duration (H:MM)	Ave CO (ppm)	Cars	Motor-cycles	HD	Bus Delay	Total Traffic	Cars	Motor-cycles	HD	Bus Delay	Total Traffic
18-Sep	AM	T15-2	0:30	1.04	-0.89	-0.51	0.65	0.23	-0.78	-0.97	-0.72	0.46	0.50	-0.8
9-Oct	AM	T15-1	1:05	0.7	0.16	0.18	0.28	0.12	0.19	0.26	0.34	0.54	0.35	0.35
19-Oct	AM	T15-2	1:20	1.52	0.38	0.11	0.25	0.41	0.49	0.33	0.01	0.19	0.41	0.43
9-Oct	MM	T15-1	1:15	1.35	-0.04	-0.20	-0.57	-0.23	-0.18	0.03	0.04	-0.54	-0.26	-0.07
7-Oct	noon	T15-2	1:25	0.74	0.19	0.06	-0.11	-0.07	0.17	0.23	0.03	-0.24	-0.12	0.20
7-Oct	noon	WSN 21	1:25	1.61	0.12	-0.15	0.35	-0.21	0.06	0.16	0.09	0.46	0.11	0.19
7-Oct	MA	WSN 21	1:05	1.38	-0.16	-0.11	-0.32	0.17	-0.14	-0.03	0.23	0.35	0.45	-0.14
7-Oct	PM	WSN 21	0:45	1.12	-0.08	-0.42	-0.25	0.29	-0.11	-0.04	-0.41	-0.11	0.29	-0.06
19-Oct	PM	T15-1	1:15	0.56	-0.14	-0.08	-0.02	-0.22	-0.20	-0.20	-0.06	-0.13	-0.18	-0.23

Table 7: Computer School – Outbound, Outbound Traffic Only

					Simultaneous R Values					1 Minute Offset R Values				
Date	Time Period	Instrument	Duration (H:MM)	Ave CO (ppm)	Cars	Motor-cycles	HD	Bus Delay	Total Traffic	Cars	Motor-cycles	HD	Bus Delay	Total Traffic
2-Oct	AM	WSN 21	1:45	1.27	0.25	0.54	0.59	-0.04	0.19	0.11	-0.84	0.63	-0.15	0.08
9-Oct	AM	T15-2	1:05	0.5	-0.19	-0.17	-0.11	-0.53	-0.35	-0.32	-0.11	-0.08	-0.42	-0.43
9-Oct	AM	T15-2	1:00	0.35	-0.43	-0.46	-0.46	-0.17	-0.39	-0.28	-0.37	-0.37	-0.29	-0.26
19-Oct	AM	T15-1	1:20	1.38	0.79	0.47	0.09	0.16	0.79	0.75	0.45	0.14	0.21	0.76
9-Oct	MM	WSN 21	1:00	0.79	-0.27	-0.05	-0.05	-0.12	-0.26	-0.65	0.23	0.23	-0.43	-0.66
7-Oct	Noon	WSN 21	1:05	0.89	-0.38	0.31	0.32	-0.06	-0.36	-0.14	0.19	-0.06	-0.13	-0.17
7-Oct	MA	T15-1	1:25	0.94	0.21	0.2	-0.02	-0.03	0.23	0.21	0.09	-0.13	-0.13	0.19
10-Sep	PM	T15-2	1:20	0.57	-0.05	-0.35	-0.27	-0.23	-0.24	-0.03	-0.38	-0.23	-0.24	-0.23
7-Oct	PM	WSN 21	1:20	1.09	-0.09	-0.17	0.36	0.13	-0.06	-0.07	-0.15	0.44	0.23	-0.01
19-Oct	PM	T15-2	1:15	0.33	-0.21	-0.44	-0.45	-0.30	-0.37	-0.29	-0.14	-0.17	-0.25	-0.37

Table 8: NUH – Inbound, Inbound Traffic Only

					Simultaneous R Values					1 Minute Offset R Values				
Date	Time Period	Instrument	Duration (H:MM)	Ave CO (ppm)	Cars	Motor-cycles	HD	Bus Delay	Total Traffic	Cars	Motor-cycles	HD	Bus Delay	Total Traffic
18-Sep	AM	T15-2	0:55	0.98	-0.48	-0.44	-0.31	-0.13	-0.56	-0.56	-0.43	-0.33	-0.08	-0.62
7-Oct	AM	T15-2	1:35	0.51	-0.24	-0.04	-0.05	-0.08	-0.21	-0.34	-0.13	-0.16	-0.19	-0.33
9-Oct	AM	T15-1	0:25	0.96	-0.78	-0.08	-0.65	-0.87	-0.78	0.24	-0.57	0.10	0.57	0.12
9-Oct	Noon	T15-1	1:20	0.79	-0.06	0.33	-0.36	-0.41	-0.04	-0.31	0.57	-0.31	-0.15	-0.2
17-Sep	MA	T15-2	1:20	0.71	-0.11	-0.21	0.09	0.42	-0.01	0.07	-0.18	0.00	0.22	0.16
2-Oct	MA	T15-1	1:30	0.78	0.00	-0.08	-0.07	0.01	0.00	-0.02	-0.24	-0.07	-0.01	-0.05
7-Oct	MA	T15-1	0:50	0.67	-0.25	0.25	0.05	-0.22	-0.2	-0.27	0.39	-0.03	-0.34	-0.21
7-Oct	PM	T15-1	1:05	0.73	0.03	0.40	0.42	0.53	0.21	0.33	0.11	0.33	0.12	0.37

Table 9: NUH Outbound, Outbound Traffic Only

					Simultaneous R Values					1 Minute Offset R Values				
Date	Time Period	Instrument	Duration (H:MM)	Ave CO (ppm)	Cars	Motor-cycles	HD	Bus Delay	Total Traffic	Cars	Motor-cycles	HD	Bus Delay	Total Traffic
18-Sep	AM	T15-1	1:45	1.28	0.29	0.09	-0.02	-0.05	0.27	0.25	0.11	-0.05	-0.05	0.23
7-Oct	AM	T15-1	1:30	0.68	0.17	0.27	0.36	0.10	0.27	0.14	0.29	0.29	0.06	0.23
9-Oct	MM	T15-2	1:00	0.35	0.13	0.13	0.38	0.10	0.4	0.18	0.17	0.10	0.23	0.38
9-Oct	Noon	T15-2	1:20	0.4	-0.19	0.16	-0.06	0.30	-0.06	-0.16	0.18	-0.08	0.61	-0.08
17-Sep	MA	T15-1	1:20	0.64	-0.15	-0.65	0.37	0.13	-0.21	-0.14	-0.55	0.10	0.10	-0.23
2-Oct	MA	T15-2	0:45	0.8	0.02	0.13	-0.25	-0.27	0.07	-0.22	0.01	-0.09	-0.01	-0.14
7-Oct	MA	T15-2	0:45	0.55	-0.27	-0.3	0.12	0.40	-0.04	0.11	-0.12	-0.22	0.57	0.35
11-Sep	PM	T15-1	1:20	0.84	0.09	0.15	0.14	0.31	0.14	0.22	0.32	0.25	0.29	0.25
7-Oct	PM	T15-2	1:00	0.61	0.22	0.57	-0.07	0.69	0.55	0.17	0.47	0.01	0.76	0.49

A consistent correlation with traffic was not observed with any type of traffic or the total traffic volume. Offsetting the CO data did not noticeably improve the correlations. It has also been shown in other studies that pure traffic counts do no correlate well with CO. Possible reasons for this include the complex source and dispersion patterns in an open environment caused by both meteorological factors and vehicle turbulence. A single poor emitting vehicle can emit more CO than many other vehicles that emit less. Fast moving vehicles in cruise mode emit much less in the area than a vehicle that stops and then accelerates away. One reason establishing a correlation with traffic counts might be particularly difficult at these sites is because of the large amount of bus traffic at every site tested. Although diesel buses emit less CO than gasoline vehicles the large amount of idling in close proximity to the sensors may have more of an effect than the number of cars passing by. The site that showed the most consistent positive correlations with traffic is the NUH outbound site which sees heavy vehicle traffic and light bus traffic.

The other correlation shown in the tables is bus delay comparing the amount of idling time by the buses at the bus stop with CO. Although the correlations are small a positive correlation was shown for 6 of the 7 Library tests and 5 of the 7 tests on the opposite library side with 3 of the opposite library tests having a R value of above 0.4. The library has the highest bus traffic with the longest idling times and the least amount of other vehicle traffic making it the best place to compare bus delay with CO. The location with the second most bus idling is the computer school. The inbound side showed a good relationship with 5 of the 9 tests showing a positive correlation of 0.29 or higher. The outbound side at the computer school showed mostly negative correlations. This data may not be as reliable as the library data since the video shot at the computer school did not catch many of the idling buses on the outbound side and times had to be estimated. In addition much of the data at the computer school was acquired with WSN sensors whose reliability in the field is still being proven. The NUH has the least amount of bus traffic and buses that do stop do so for short periods of time. Even so surprisingly high correlations were seen on the outbound side of the site. No negative correlations below -0.05 were observed and 3 tests showed correlations of 0.57 or higher. Not many strong positive or negative correlations were shown for the inbound NUH site.

Correlations shown in Table 2 through Table 9 deal with CO varying over 5 minute intervals. Figure 19 through Figure 21 display the average CO data for the entire test period. Figure 19 looks at the average CO level for each site during AM peak hours, at PM peak hours and in between during mid day. Figure 20 compares CO for each site during light traffic periods, normal traffic periods and heavy traffic periods. Figure 21 does the same thing for bus delay. The CO from 1/3 of tests with the highest traffic was averaged and 1/3 of tests with the middle and lowest amount of traffic were averaged to create the plots.

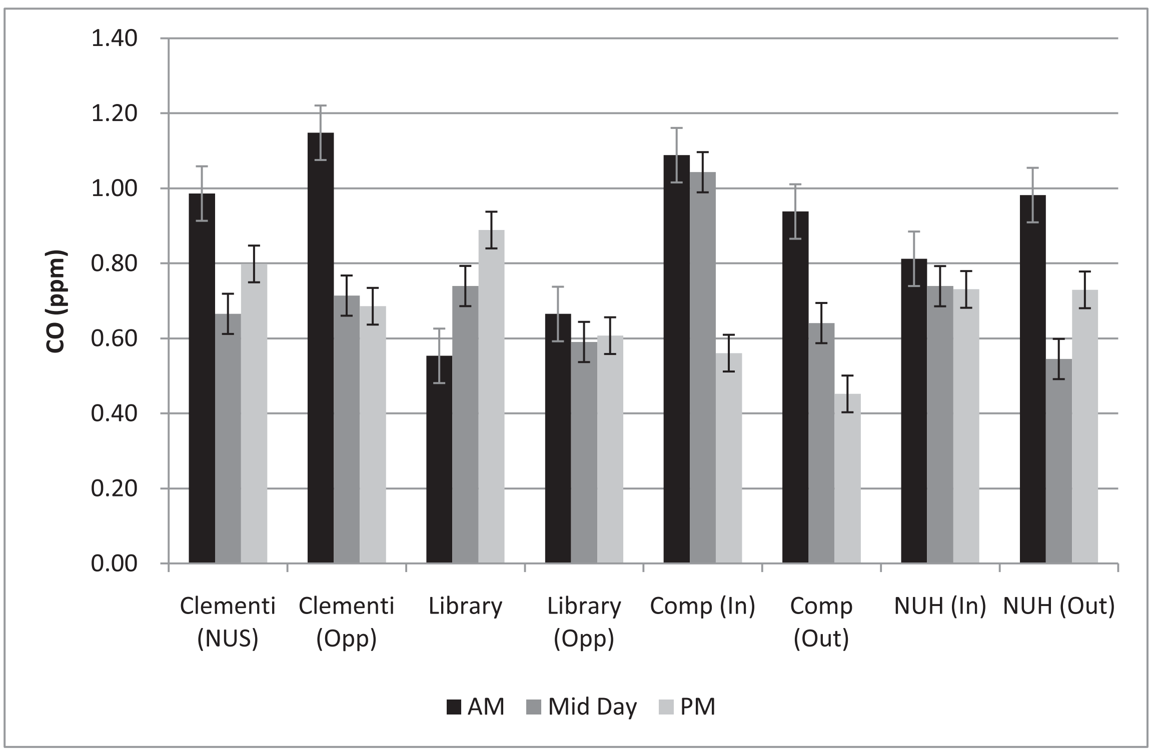

Figure 19: Average CO Levels by Location and Time of Day

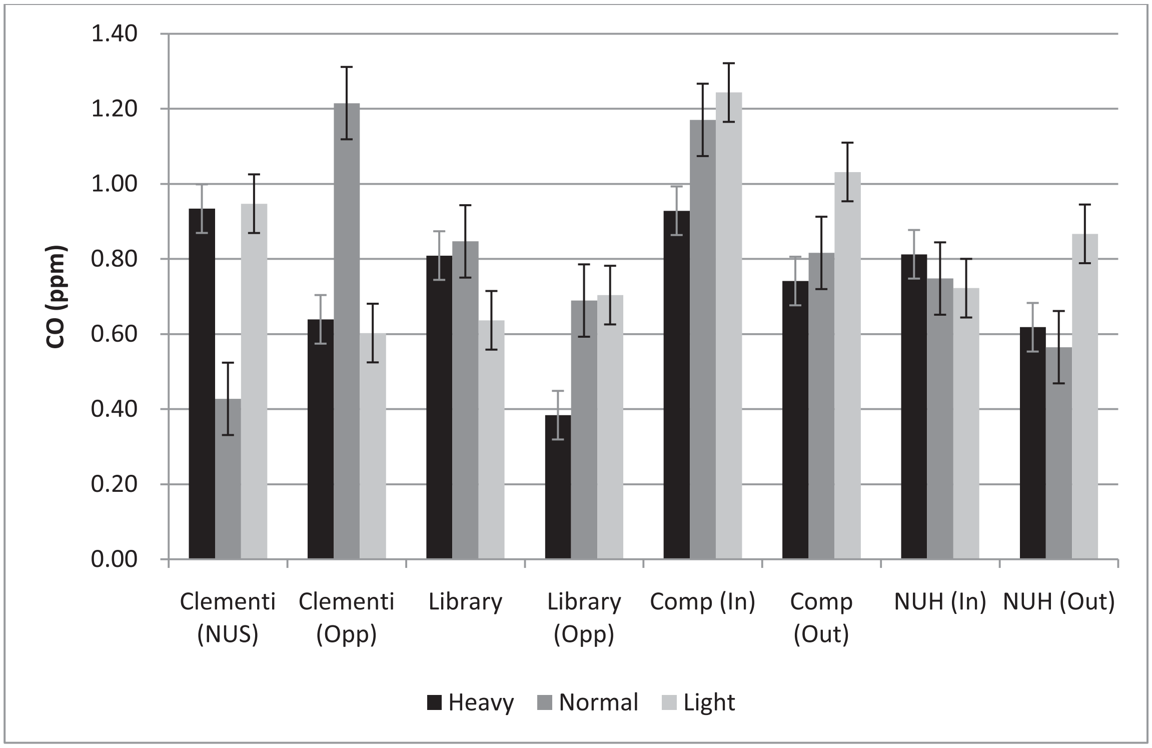

Figure 20: Average CO Levels by Traffic Volume

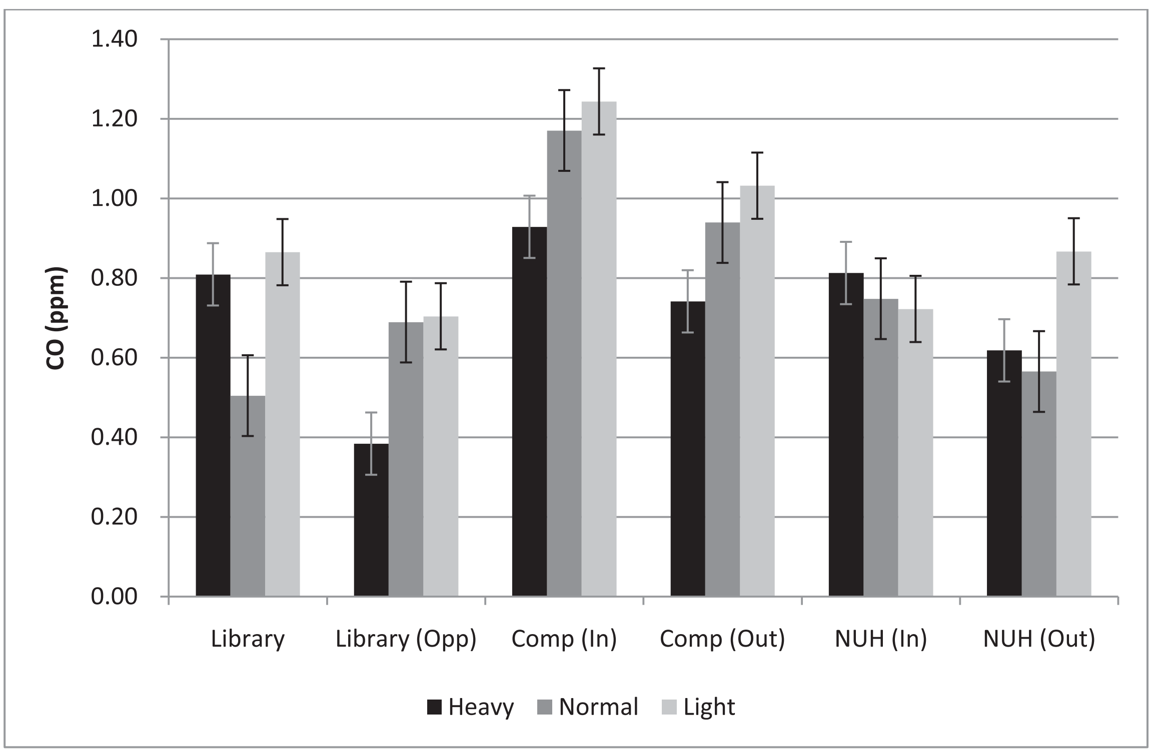

Figure 21: Average CO Levels by Bus Delay

CO was shown to be higher in the morning at all but one of the 8 locations. The library was the only site that had low CO in the morning. More vehicles are running at a cold start in the morning which may lead to higher CO emissions. The site that had low CO (Library) has the least amount of traffic. When comparing the CO levels at the different locations the computer school has the highest CO and the library the lowest CO levels. The library is located in the middle of campus away from most traffic and parking lots which leads to lower CO levels. The proximity of the computer school and NUH sites to the AYE highway as well as high traffic on site may lead to higher CO levels even though Clementi has the highest traffic volume of the 4 sites tested. All 8 locations had similar CO levels averaging from 0.4 to 1.2ppm well below ambient standards. Figure 19 shows there is no consistent pattern of periods with heavy traffic having more CO than periods of lesser traffic. Periods with high amounts of bus idling did not consistently show the highest levels of CO.

Finally the correlation between the traffic signal cycle and CO concentration was studied. The signal cycle at the intersection is not fixed. In order to accurately tell when the each cycle began traffic video was used. 7 cycles of the intersection are shown in Figure 22. The Clementi traffic cycle varies between 120 and 150 seconds with a green light length of 80-100 seconds. show the temporal variation with CO and vertical lines indicate the point in which the Clementi northbound and southbound turns green. Figure 23 and Figure 24 show the temporal variation of CO with the beginning of the green traffic cycle (northbound/southbound) indicated by vertical lines.

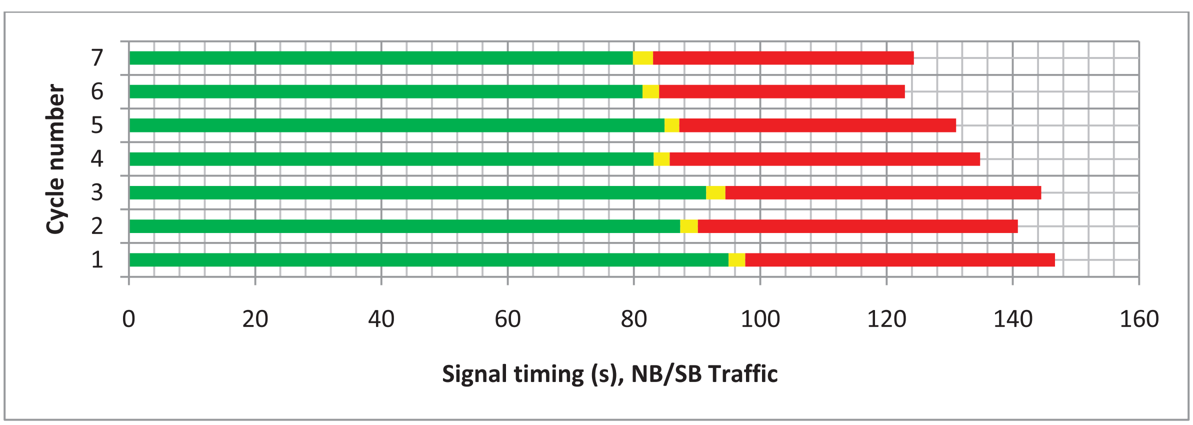

Figure 22: Clementi Signal Cycle

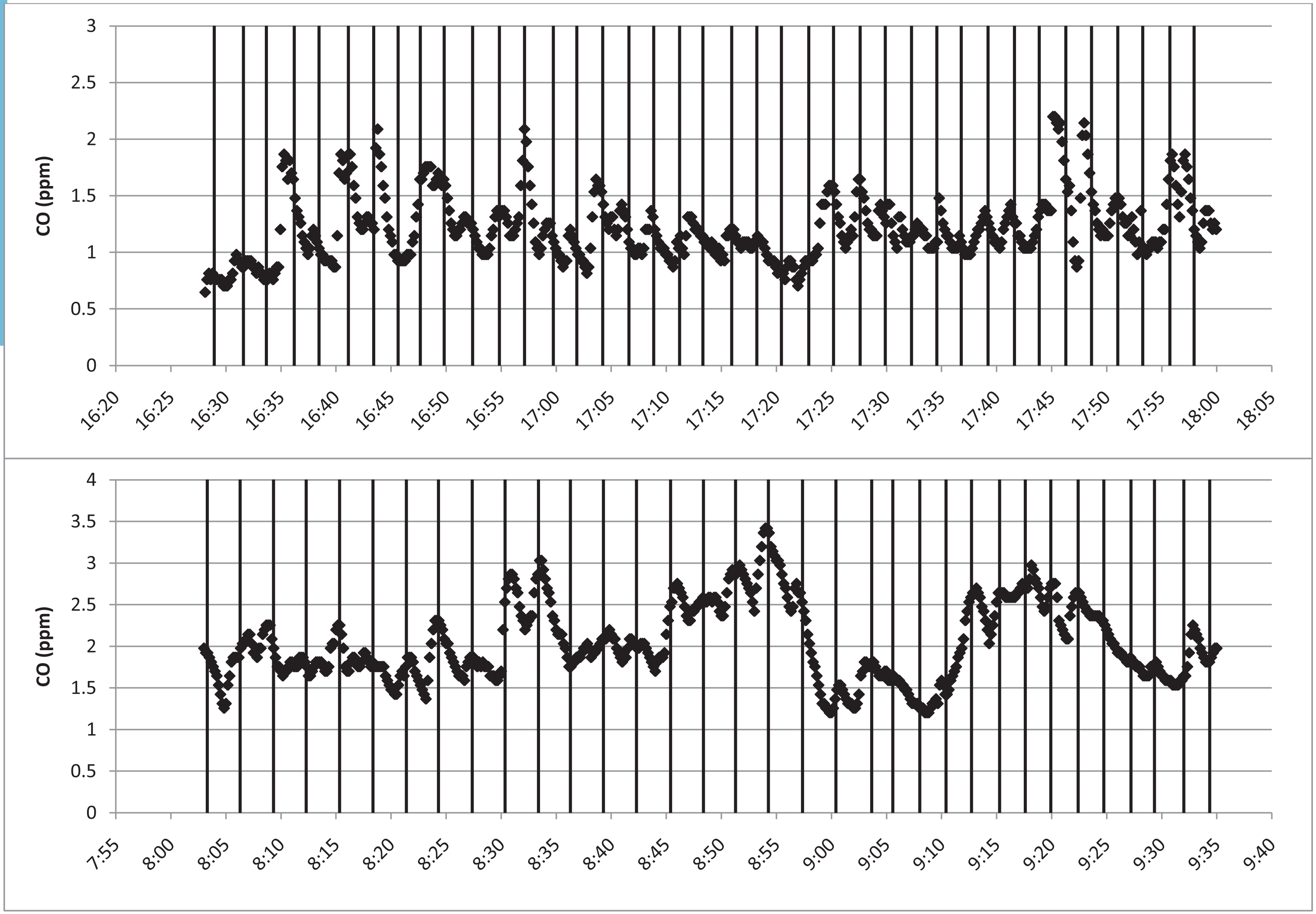

Figure 23: Clementi Temporal Variation of CO with the Traffic Cycle, Northbound Traffic 10-1-09 (top), 10-6-09 (bottom)

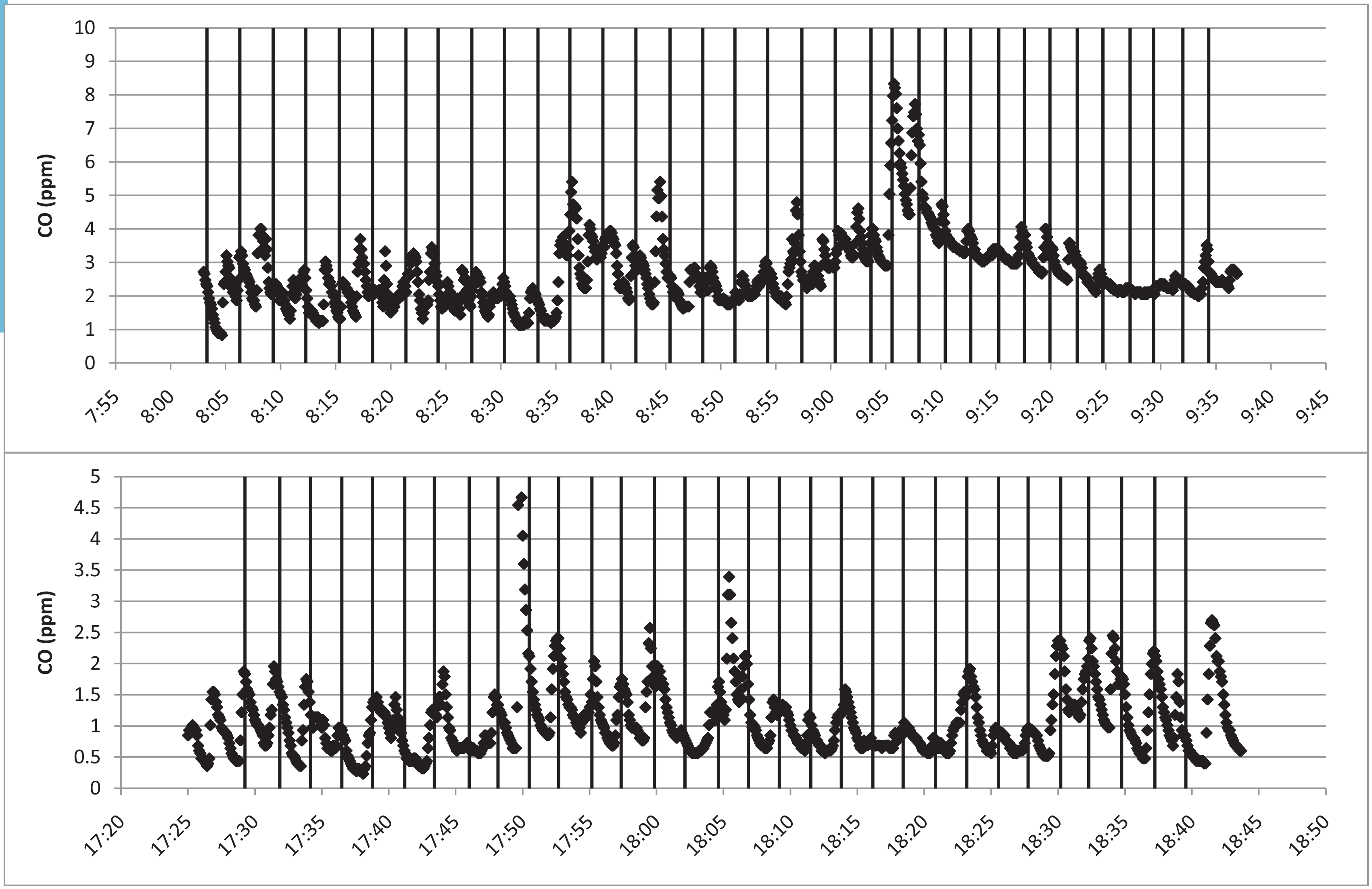

Figure 24: Clementi Temporal Variation of CO with the Traffic Cycle, Southbound Side 10-6-09

CO peaks mainly occur on the vertical lines where the green light cycle begins and the cars that are held in queue on the northbound and southbound lanes reach a state of acceleration. The sensor in this case are located about 300' south of the intersection. Sensor on the northbound side are located next to traffic in the queue while southbound sensors are on the opposite side of the road and are also more exposed to southbound traffic as it passes through the intersection. Sensors on both sides showed a similar pattern. CO peaks do appear steeper on the southbound (NUS) side sensors. A similar pattern was shown by Zito [49].

In addition to the testing done on CO some periodic measurements of PM were done with an optical particle counter. Measurements were done at bus stops during periods of no traffic, with idling buses, and just after buses have left. The measurements are given in Appendix B. The results from this preliminary measurement do not indicate a consistent relationship between bus activity and PM. More tests in a more controlled setting may produce better results.

4.3 University Hall Parking Car Park

4.3.1 About the Car Park

One car park was studied in the middle of campus beneath the administrative University Hall building. The car park had a capacity of 175 cars with additional space for motorcycles. The car park consists of two levels. The cars enter the lower level. A ramp to level 2 is in the back of the car park. Level 2 is a smaller area with mostly visitor parking. The car park is enclosed aside from the main entrance/exit shown in Figure 25 and a side exit on level 2. The gate is located just outside the enclosed area. The T15 sensor was used for every test at the site and was placed on one of the pedestals at the entrance shown in Figure 25. The vast majority of traffic entering and leaving the garage are gasoline powered personal vehicles.

Figure 25: Carpark Main Entrance/Exit

4.3.2 Methods

Testing at the site included monitoring the CO at the main entrance/exit and counting the traffic in 5 minute intervals, separately counting cars, motorcycles, and light duty trucks. The CO was also checked inside the garage during most tests. Each testing period took place during the AM peak (7:30-9am), Midday (11:30am-1pm) or during the PM peak (4-6pm) times. A Langan T15 CO measurer was placed next to the gate at 1m height to measure CO.

Tests were done for 2 AM, 2 Noon, and 3 PM periods. However, CO data was not recorded during a noon test on October 12th leaving data for only 1 noon period. Once the traffic and CO data were acquired analysis was done to see the correlation between incoming, outgoing, and total traffic with CO concentration. The first test performed on August 31st counted traffic in half hour periods so no correlation analysis was performed for that day.

4.3.3 Results and Discussion

Some of the best correlations between traffic and CO concentrations were observed at this car park. Table 10 gives a summary of each test done and some overall statistics. The average traffic per 5 minute interval stayed consistent throughout most of the tests. All but one of the tests fell between 5.2 and 5.9 cars per 5 minute interval with August 31st seeing 7.5 cars per 5 minute interval and also seeing the highest CO of all the tests. The CO levels were not much different than those seen during the ambient testing. Since the sensor was located just outside the car park the pollutants from the vehicles were allowed to disperse. CO readings from inside the garage reached a maximum of between 3 ppm and 15 ppm on the ground floor.

Table 10: University Hall Car Park Summary

Date	Start	End	Duration (H:MM)	Time Period	Average CO (ppm)	Max CO (ppm)	Standard Deviation	Vehicles Per 5 Minute Interval
8-Sep	7:00	9:30	2:30	AM	0.63	1.08	0.13	5.9
14-Oct	7:40	9:30	1:50	AM	0.93	1.57	0.22	5.6
14-Sep	12:20	14:20	2:00	MA	0.55	1.39	0.28	5.5
31-Aug	17:50	18:50	1:00	PM	1.03	1.44	0.59	7.5
1-Sep	17:05	18:30	1:25	PM	0.40	1.26	0.37	5.2
15-Oct	17:25	18:50	1:25	PM	0.81	2.10	0.50	5.5

Table 11 shows the correlation coefficients associated with each test. The correlation with traffic was good at this location. Every test showed a positive correlation of at least 0.37 with total traffic. Traffic in the morning periods is dominated by incoming traffic and traffic in evening periods is dominated by outgoing traffic. The correlation of incoming traffic and CO during the morning periods was 0.31 and 0.35. The correlation of outgoing traffic and CO during evening periods was very high at 0.81 and 0.79. The only small negative correlation observed was for incoming vehicles during evening hours when incoming traffic is light.

One reason for the high correlation at this site is the consistency of traffic flow through the gate. Cars stopped for a relatively uniform amount of time at the gate as the sensor read the parking pass. The vehicles that traveled in and out of the car park were personal cars less than 10 years old in most cases. Some diesel powered light duty trucks and motorcycles did visit the garage but they made up a small portion of the vehicle population. The proximity of the sensor to the vehicle traffic is also higher than in the ambient testing allowing for less dispersion before the pollutant reaches the sensor.

Table 11: University Hall Car Park Correlations

		R Values		
Date	Time Period	Incoming Vehicles	Outgoing Vehicles	Total Vehicles
8-Sep	AM	0.31	0.53	0.41
14-Oct	AM	0.35	0.21	0.37
14-Sep	MA	0.71	0.09	0.56
31-Aug	PM	NA	NA	NA
1-Sep	PM	(0.14)	0.81	0.78
15-Oct	PM	(0.12)	0.79	0.75

One additional level of analysis was done for the car park since the CO concentration did not vary significantly between AM and PM tests. Each 5 minute interval was placed into a bin corresponding to the total number of cars that went into or out of the garage during the period. The CO values in each bin were then averaged and plotted in Figure 26. This plot compares data across all the test periods and shows a high correlation with traffic. From the plot each car increased the CO concentration by 60ppb on average and the background CO concentration was shown to be 0.31ppm.

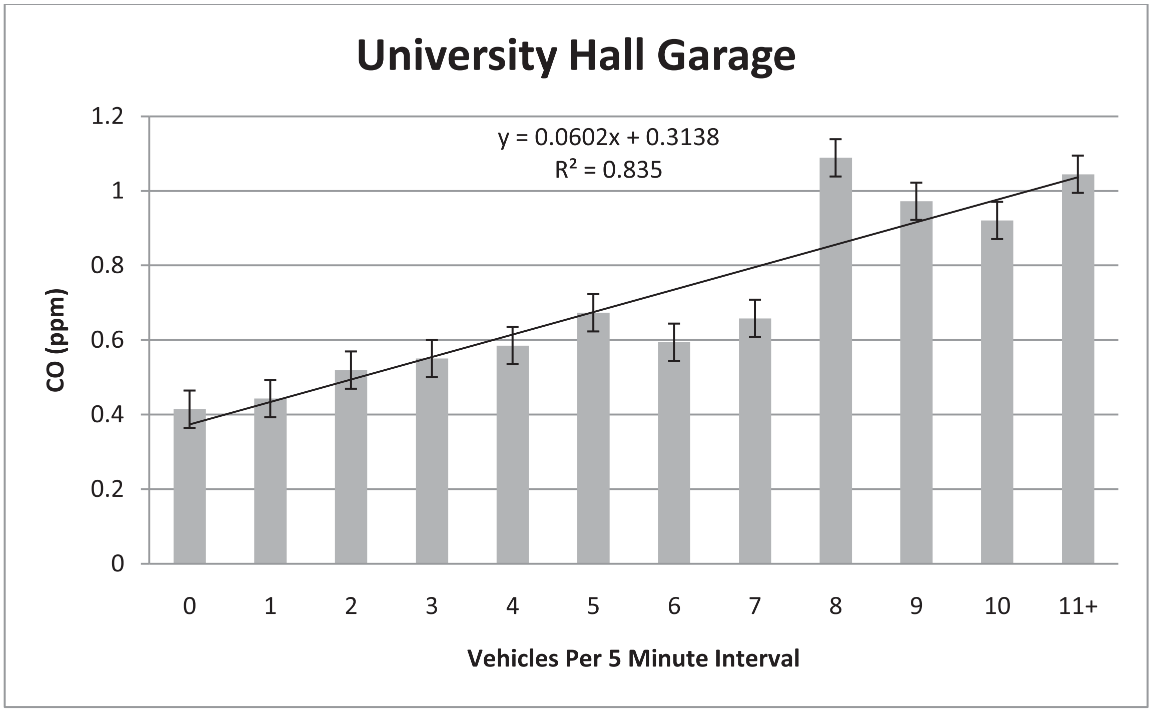

Figure 26: University Hall Car Park Combined Data

4.4 CO Exposure on Bus Routes

4.4.1 About the Singapore Bus System and Route Selection

Passengers are often exposed to elevated levels of CO concentrations as they commute to and from work or school. Bus is the main mode of transportation around the NUS. There are many bus routes connecting the campus to other areas in Singapore and also several intra campus routes for traveling between different areas of campus. Testing was done inside the bus using the T15 CO measurer, a GPS device, and a met instrument. The GPS and CO measurer recorded data every 5 seconds while the temperature and humidity were recorded periodically, typically at bus stops. The CO data was then compared with the GPS data.

There are two competing bus companies in Singapore, SBS Transit Limited and SMRT Buses. Both fleets consists mainly of 12 meter long single deck buses. SBS Transit operates a double decker bus used in this study for some of the 97 routes. SMRT operates a double long bus which was taken in this study for some of the 963 routes.

Route 963 is the only SMRT route taken. Routes 33, 95 and 97 are operated by SBS Transit while the National University of Singapore operates its own internal buses listed here as A1/A2 and BTC routes. All routes taken are typical routes taken by students and faculty for commuting to and from the NUS campus.

Figure 27: Singapore Bus Types, Regular City Bus (Top Left), SBS Double Decker (Top Right), SMRT Long bus (Bottom Left), NUS Bus (Bottom Right)

The segment of Bus 33 we measured starts from the Clementi bus stop right outside of NUS engineering building. The route ends at Alexandra Rd. and is 6.4 km long. It travels through a busy 6 lane road on the west side of the NUS campus, a 2 lane suburban road and on the AYE (Ayer Rajah Expressway) which is the major highway in Singapore. Depending on traffic, and number of stops the route the typical duration ranges from 12-20 minutes. Bus 33 has the most varied terrain of the routes taken with significant amount of distance traveled on highway, arterial roadways, and 2 lane uncongested roadways.

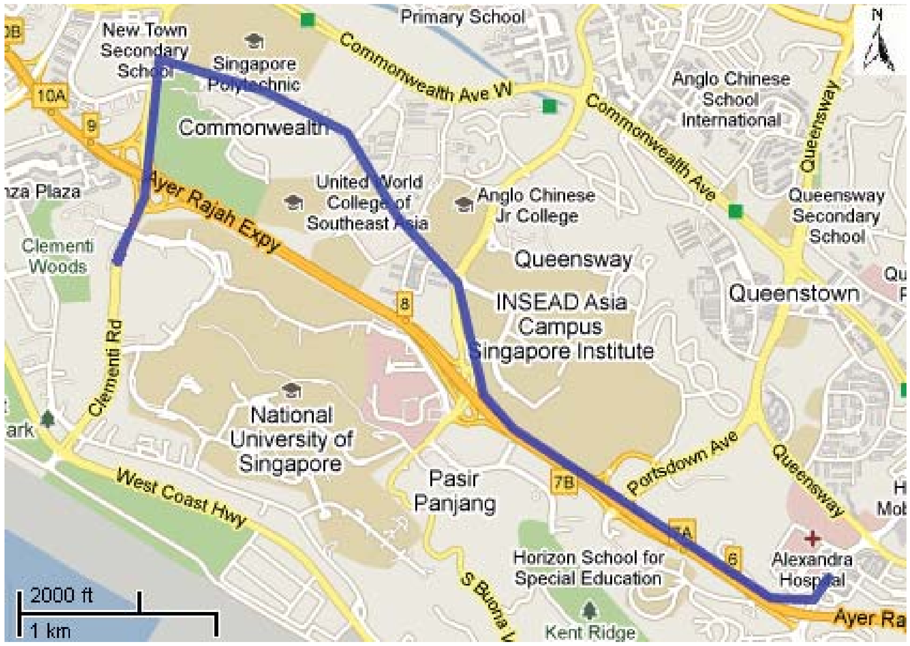

Figure 28: Route 33 – 2010 Google Map Data

The 95 route goes through the NUS campus and makes 7 stops on campus starting from the Kent Ridge Terminal to the Buona Vista MRT station (the subway system in Singapore) which leads to downtown. It is 4.2 km in length. It makes its way along the 2 lane roads around campus with light to medium vehicle traffic and heavy pedestrian traffic. Once it exits the campus area it heads north along a busy 6 lane road towards the MRT station. Depending on traffic this route's duration ranges from 16 to 32 minutes. For each route studied nine trips were taken where the full data was acquired.

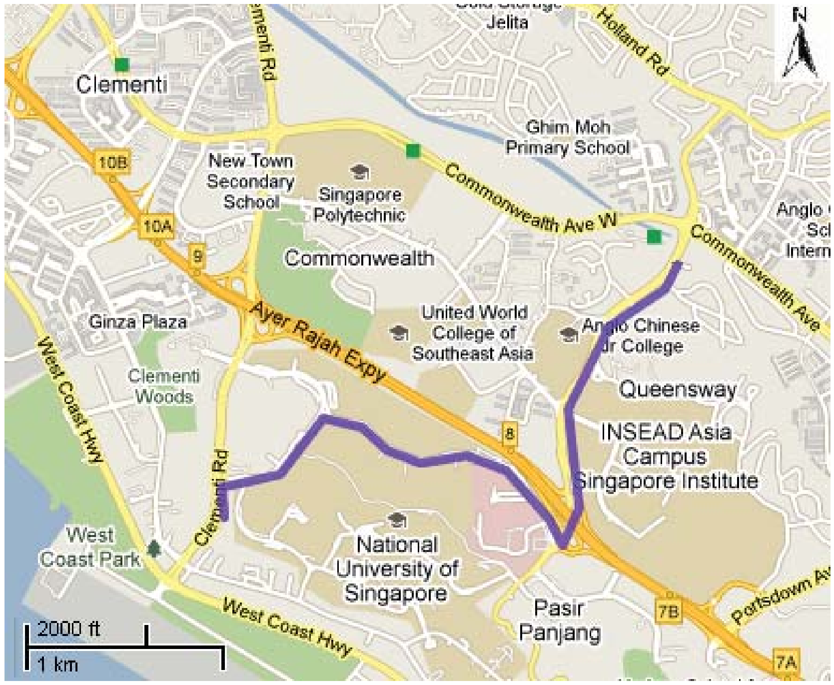

Figure 29: Route 95 – 2010 Google Map Data

The measured portion of Routes 97 and 963 travels along the same route and have the same stops. The route begins on Alexandra road but quickly turns onto the AYE highway where it remains for the rest of the trip. This is a shorter commute route (2.5 km) from NUS housing off campus to the medical campus and is used by NUS visitors and employees. The route does divert slightly from the highway to drop off and pick up residents. These routes connect the NUS campus to a residential area (Gillman Heights) which is a contracted apartment to the NUS and used by many students and faculty. The routes are short ranging from 5-10 minutes. Route 963 is the only SMRT bus route taken in this study. The 963 route has both long and normal sized buses. Both types were taken for comparison. Route 97 has normal sized and double decker buses. Both types were taken for comparison.

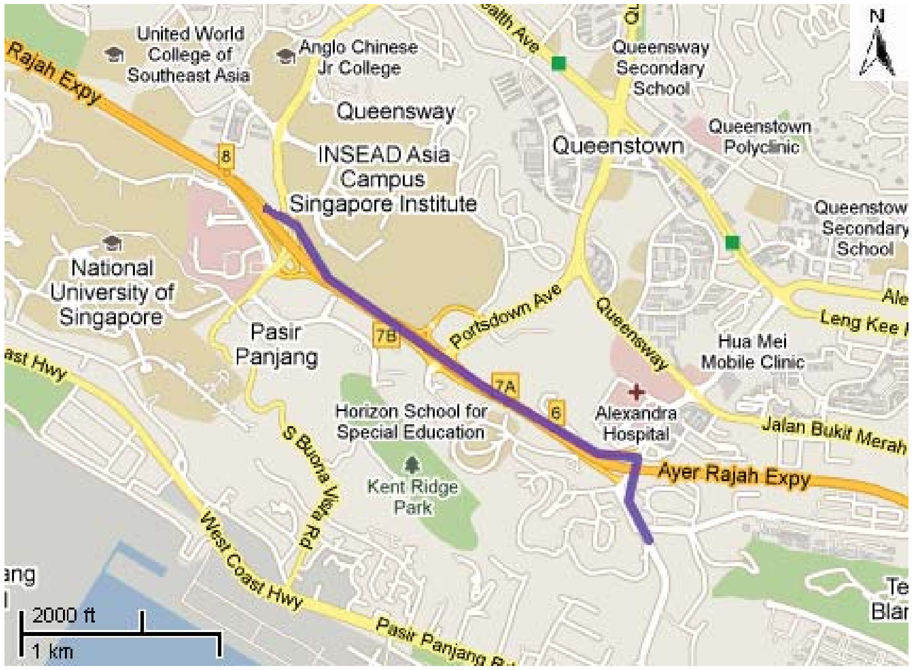

Figure 30: Routes 97 and 963 – 2010 Google Map Data

Routes A1 and A2 are NUS bus routes that occur entirely within the limits of the NUS campus. A1 travels counterclockwise around the campus while A2 travels clockwise around the campus. Each route begins and ends at the Prince George Park bus stop. There is a small lot next to the bus stop where buses will idle before and after traveling a circuit around the campus. The amount of passengers on the bus can vary depending on when class begins. In the morning the bus is crowded from the Prince George Park residences until it reaches the library bus stop where most people get off. In the evening the route to the library is less crowded while the trip from the library back the residences is more crowded. Each loop is about 5 km long and takes between 25-45 minutes depending on traffic and number of riders entering and leaving the bus.

Figure 31: Routes A1 and A2 – 2010 Google Map Data

The BTC route travels between the NUS campus and a satellite campus. The buses used are the same type or a slightly smaller version as those used on the A1 and A2 routes. The route begins just west of the NUS campus on Kent Ridge Rd and proceeds throughout campus stopping several times before leaving on the east side of campus and heading northeast toward the Bukit Timah satellite campus. On return the route is the same except the bus travels directly to Kent Ridge Rd along the Aye highway instead of traveling through campus. This route was the longest route studied at 11.8km in length. Traveling to the Bukit Timah satellite campus from the main campus takes between 35-60 minutes. Congestion in evening times was responsible for the longer durations. Traveling to the NUS campus is typically about 25-35 minutes.

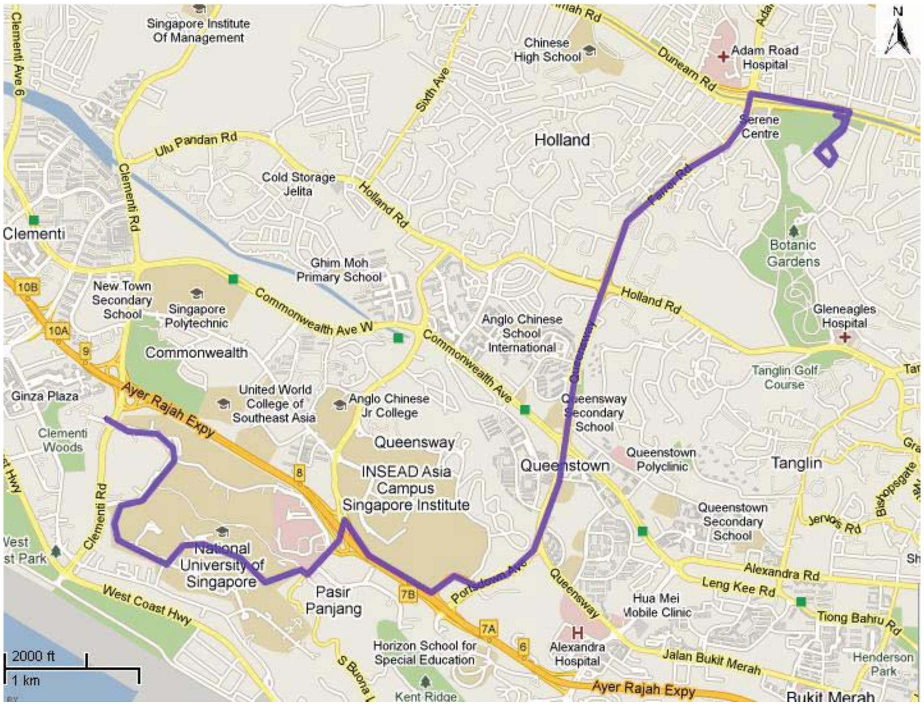

Figure 32: BTC Route – 2010 Google Map Data

4.4.2 Methods

During each route a T15 CO sensor and a GPS instrument were used to acquire data. The T15 instrument was set continuously record CO data before during and after each trip. CO data was set to record at 5, 10, or 30 second intervals. GPS data acquired location data at either 3 or 5 second intervals. This data was used to acquire altitude, speed, acceleration, road grade, and distance traveled. VSP was then calculated using the equation for a transit bus give in section 2.6. Met data was recorded on most routes using a handheld anemometer. Temperature and humidity readings were taken periodically throughout the route either at a set interval or at bus stops in most cases.

The data acquired on the route was the separated into route taken and time taken. Routes were separated into AM Peak routes which occur during the morning rush hour (7:30-9:30AM), PM Peak routes which occur during evening rush hour (5-7:30PM), and Off Peak routes. Peak hour times are the same as those used by the Singapore taxi system

[50]. AM and PM routes were taken in reverse direction for the city routes as the researcher on board traveled to the NUS campus in the morning and away from campus in evening times. Data was analyzed to see the CO variation with vehicle speed, acceleration, road grade and VSP. CO variation based on the route taken, time of day, type of bus, and route section will also be covered.

4.4.3 Results and Discussion

Table 12: Bus Route Summary shows a summary of results for Bus routes taken in Singapore. Each Route is separated into an AM, PM or off peak time. The number of routes, average speed, average CO, maximum CO, and the average increase in CO concentration over the ambient levels are given. Ambient CO levels are the concentrations read at the bus stop before getting in the bus.

Detailed tables for each route are given in appendix D including correlation coefficients with speed, acceleration, road grade an VSP for routes with full GPS data. Some of this data is shown in Table 13 and Table 14 for routes 33 and 95. These routes were chosen because of their length, and the number of trips taken with full GPS data. Correlation between CO and the traffic variables shown were done both simultaneously and at a 30 second lag between the time the GPS data was taken and when the CO measurement took place. This is to allow time for the emissions from the engine to reach the instrument inside the cabin.

Table 12: Bus Route Summary

Route	Length (km)	AM/PM	# Taken	Average Duration (mm:ss)		Average Speed (km/h)	Average CO (ppm)	Maximum CO (ppm)	Average CO Increase Over Ambient	Total Routes
33	6.4	AM	7	18:41		20.6	1.36	1.99	0.28	26
		PM	12	18:06		21.2	1.12	1.35	0.30	
		Off	7	14:10		27.1	0.95	1.68	0.08	
95	4.2	AM	3	19:28		12.9	0.88	1.10	0.22	14
		PM	6	22:07		11.4	1.21	2.17	0.63	
		Off	5	15:16		16.5	1.22	1.91	0.51	
97	2.5	AM	15	09:15		16.2	1.30	2.02	0.54	23
		PM	5	06:06		24.6	1.66	1.87	0.52	
		Off	3	09:29		15.8	1.13	1.93	0.46	
963	2.5	AM	5	07:28		20.1	1.31	2.11	0.56	17
		PM	4	05:55		25.4	1.28	2.51	0.23	
		Off	8	10:20		14.5	1.82	2.05	0.66	
A1	4.3	AM	5	24:00		10.8	0.81	0.90	0.46	12
		PM	4	20:12		12.8	0.76	0.84	0.24	
		Off	3	20:45		12.4	0.37	0.63	0.44	
A2	4.8	AM	1	23:40		12.2	0.46	NA	(0.27)	6
		PM	3	32:55		8.8	0.65	0.65	0.21	
		Off	2	23:38		12.2	0.33	0.33	0.36	
BTC*	10.0 / 9.5	AM	4	0:35:40	0:18:40	16.8	1.10	1.70	0.46	11
		PM	3	0:43:23	NA	13.8	1.29	3.51	0.47	
		Off	4	0:34:53	0:17:50	17.2	0.46	1.59	0.29	

* It is 10km from the NUS main campus to the BTC campus and 9.5 km on the return trip. The 2nd duration for the BTC routes is for the return trip (2 each for AM and Off peak)

Table 13: Correlation Coefficients Between CO and Traffic Variables, Route 33

		Speed		Acceleration		VSP		Grade	
Date	Type		lag		lag		lag		lag
14-Sep	AM Peak	0.12	0.24	(0.09)	(0.03)	(0.04)	(0.04)	(0.03)	(0.05)
16-Sep	AM Peak	0.04	0.03	(0.01)	0.00	0.07	0.08	(0.11)	(0.11)
5-Oct	AM Peak	(0.08)	(0.13)	0.03	0.01	0.00	0.01	(0.11)	(0.05)
29-Sep	PM Peak	0.16	0.28	(0.02)	0.01	(0.09)	(0.13)	(0.07)	(0.09)
30-Sep	PM Peak	0.09	0.19	(0.05)	(0.01)	0.01	(0.01)	0.00	0.02
14-Oct	PM Peak	0.30	0.40	(0.05)	(0.05)	(0.08)	(0.04)	(0.07)	0.01
6-Oct	Off Peak	(0.04)	0.14	0.09	0.04	(0.10)	(0.18)	(0.64)	(0.54)
14-Oct	Off Peak	(0.14)	(0.06)	(0.05)	(0.12)	(0.09)	(0.10)	(0.09)	(0.03)
14-Oct	Off Peak	0.03	0.27	(0.18)	(0.09)	(0.05)	(0.03)	0.01	(0.05)
Averages		0.05	0.15	(0.03)	(0.04)	(0.05)	(0.12)	(0.10)	(0.10)

Table 14: Correlation Coefficients Between CO and Traffic Variables, Route 95

		Speed		Acceleration		VSP		Grade	
Date	Type		lag		lag		lag		lag
23-Sep	AM Peak	0.13	0.11	(0.04)	(0.03)	0.09	0.10	0.16	0.02
29-Sep	AM Peak	(0.17)	(0.24)	0.02	(0.01)	(0.09)	(0.08)	(0.12)	(0.08)
1-Oct	AM Peak	0.11	0.12	0.01	0.01	(0.03)	0.00	(0.02)	0.02
2-Oct	AM Peak	0.07	0.07	(0.01)	(0.05)	0.18	0.07	0.34	0.31
23-Sep	PM Peak	0.13	0.32	(0.09)	0.07	0.16	0.22	0.11	0.08
2-Oct	PM Peak	0.02	0.00	(0.01)	0.00	(0.07)	(0.06)	(0.11)	(0.10)

8-Oct	PM Peak	0.16	0.18	(0.09)	0.04	0.00	(0.06)	(0.06)	(0.13)
12-Oct	PM Peak	(0.14)	(0.16)	0.01	(0.01)	(0.04)	0.06	0.06	0.17
14-Oct	PM Peak	0.04	(0.02)	0.06	(0.07)	0.02	(0.13)	0.08	0.09
Averages		0.04	0.04	(0.02)	0.00	0.02	0.01	0.05	0.04

A noticeable correlation was not seen with the traffic variables studied in this case. Plots of CO vs time in appendix D indicate that that change in CO concentration is much slower and smoother than changes in acceleration, speed, road grade or VSP. Comparing the CO data with a lag did not improve the results in this case. Similar results were obtained with the other routes in which GPS data was taken.

By comparing the CO concentrations before and after getting on the bus it was shown that CO levels significantly increased on all routes typically from 0.2 to 0.6 ppm as shown in Table 12. Only one decrease in CO was observed on an AM route for bus A2 which only reflected one route. The maximum CO exposure for any route was 3.5 ppm indicating no threat to human health. Looking at the average CO concentrations for AM peak, PM peak and off peak periods no time period showed consistently higher CO levels than the other two. The average CO concentration for the city routes for the AM peak period was 1.27 ppm, for PM routes it was 1.26 ppm and it was 1.33 for off peak routes. During the ambient testing AM CO levels were shown to be the highest. CO concentrations may be more influenced by engine out CO emissions than the ambient concentrations evidenced by the increase in CO levels when entering the vehicle.

The correlations between CO emissions and VSP were also analyzed based on VSP bins [51]. For this analysis we simply classified the data into 3 different VSP bins which are shown in Figure 33 along with the % of each route that occurred in each bin. In addition to the Singapore bus routes two routes taken in Cincinnati are also shown for comparison.

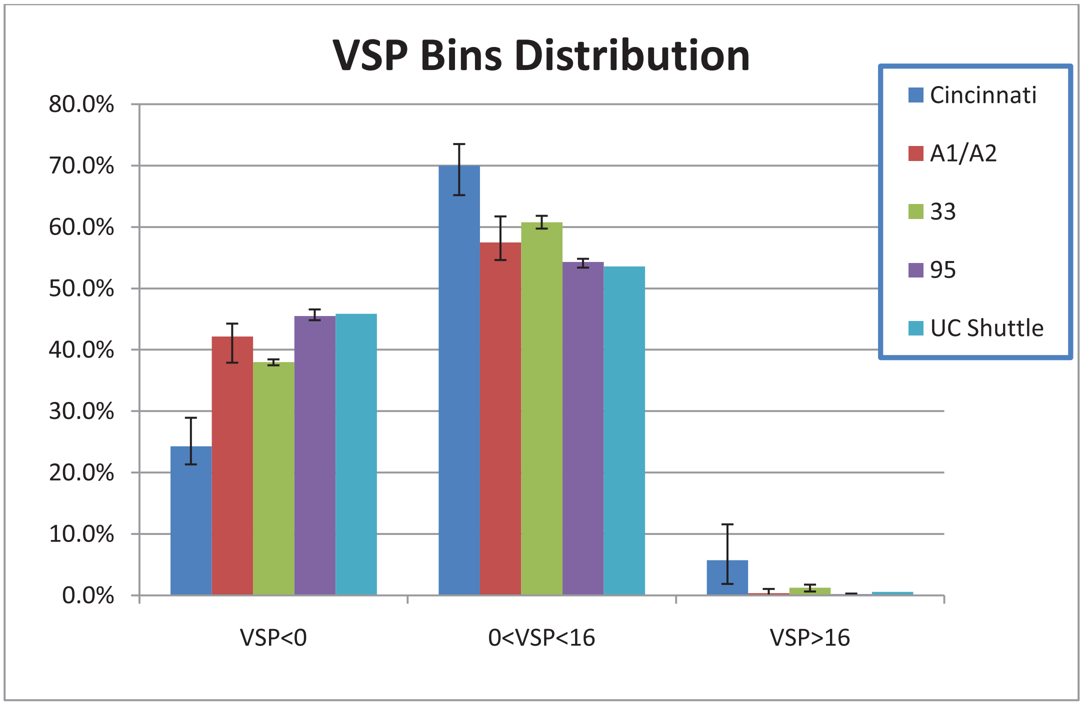

Figure 33: VSP Bin Distribution for Bus Routes

Each VSP bin has a comparable contribution to the total emissions. VSP Bin 1 indicates a decelerating or down slope driving, which corresponds to the lowest emission rates. VSP Bin 2 and 3 characterize emissions when VSP is positive. High VSP can be obtained from a combination of high speed, high acceleration and high positive road grade. VSP Bin 2 has data with VSP greater than 0 and less than 16. Emission rate increases with VSP increases but it has a limited range which is relatively low. VSP Bin 3 includes the data with VSP greater than 16 which indicates very high emission rate of pollutants. For both of the bus routes, the vast majority of VSPs values obtained are in the first two bins, an indication that the emissions rates of CO are relatively low.

Figure 34 looks at the average CO concentration for each route. The four city bus routes showed higher CO concentrations than the three campus routes. The results suggest that the type of bus taken may have a significant effect on CO levels. Routes 97 and 963 showed the highest levels of CO. Many of the routes taken on these two buses were taken on large double long (route 963) and double decker (route 97) buses. Trips taken on double decker and double long buses showed higher level of CO than trips taken on the same route on a normal bus. An average CO concentration of 1.18 ppm was seen on route 97 for the single decker bus while an average CO concentration of 1.37 was seen for the double decker bus. An average CO concentration of 1.31 was seen for the the normal 963 bus while an average concentration of 1.66 ppm was seen for the double long bus. Route 33 and 95 had the same type of bus and averaged about the same CO levels. Route 95 is a much slower route with more stops and a more crowded bus. Route 33 is less crowded and has periods with few stops. Even with this difference is vehicle behavior similar CO levels were shown further indicating that traffic variables such as speed, acceleration, road grade, and VSP may not significantly influence the CO levels inside the cabin of the vehicle.

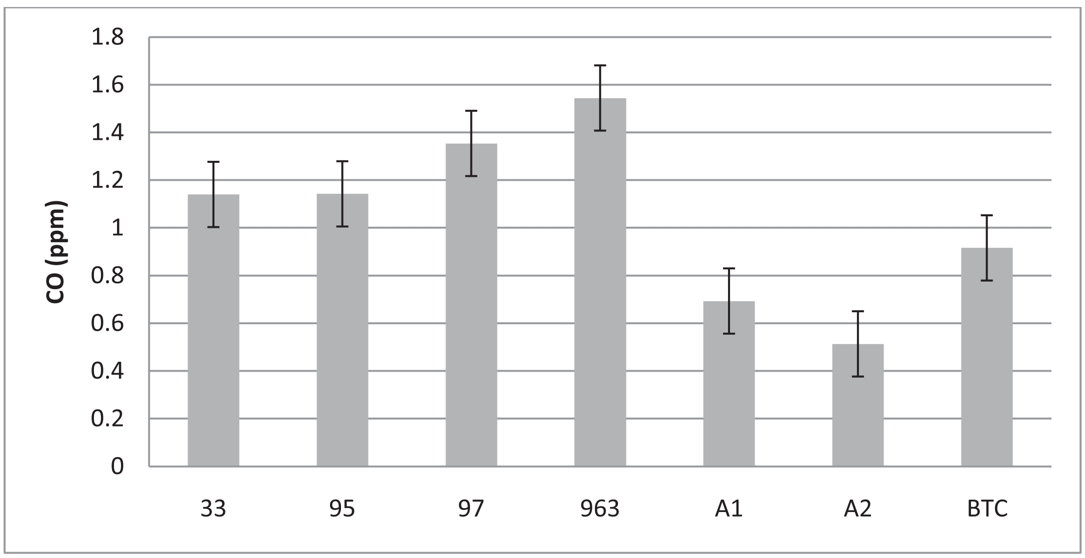

Figure 34: Average CO Concentration by Route

Route 33 was analyzed to determine if CO concentration varied based on the location of the vehicle. Route 33 was chosen because of the varied terrain in which the route is located. Heading toward the NUS campus the route begins on the AYE highway before exiting onto a busy 6 lane arterial road briefly before turning onto a 2 residential road. Finally the route turns onto Clementi, a 6 lane arterial road and heads toward the campus. The route was split into 3 sections. The AYE highway and Bueno Vista Road (highway), Depot Road (residential), and Clementi Road (arterial). Table 15: Route 33 by Location shows the average CO concentration for each location based on the time of day the route was taken. In the case of both AM and PM situations the CO decreased during the travel period. AM routes begin in the Clementi section and end up in the AYE section and vice versa. Off peak routes which can be taken either to the campus or away from campus showed relatively flat levels of CO concentrations across each location with slightly higher CO levels observed in the middle of the route in the residential areas.

Table 15: Route 33 by Location

	Clementi (Busy Arterial)	Depot Rd (Residential)	AYE (Highway)
AM	1.09	1.21	1.42
PM	1.25	1.16	1.06
Off	0.91	1.05	0.92

In Table 16 we compare the results from our study with those from different parts of the world. Included in the table are bus results from Hong Kong [27], Mexico City [30], Taipei [53] and a study in London [52].

Table 16: Comparison of in Vehicle CO with Other Studies

Location	Year	Average CO conc. (ppm)
Singapore	2009	1.3
Hong Kong	2000	2.0
London	2008	0.7
Mexico City	2003	12
Taipei	1991	11.6

There are several possible reasons for the low CO concentration in Singapore. The government limits the number of vehicles on the road through economic measures, such as imposing 30% peak hour taxi-fee, and requiring high fees to operate a personal vehicle. Old vehicles (buses and cars) are also taken off the street. Once a vehicle is 10 years old the owner is required to pay a fee to keep it in operation, and most banks will not offer loans to older vehicles [54]. Meanwhile the import cars should be less than 3 years old [55]. In fact, Singapore has been rated as the best place to live in Asia in a 2005 survey, one of the reasons being the good air quality [56].

Finally the relationship between temperature and CO was examined. Data from handheld met instruments was compared with CO. In most cases in inverse relationship was observed. This could also be the result of CO increasing upon entering the vehicle (due to elevated in vehicle CO) and temperature decreasing due to air conditioning. Further testing will need to be done to further substantiate this relationship.

Table 17: In Bus CO Correlation with Temperature

Route	Date	Correl vs Simultaneous CO	Correl vs 1min Avg.
33	10-5 AM	0.11	
33	10-14 Non-PK	-0.62	-0.35
33	10-6 PM	-0.33	-0.29
33	9-30 PM	-0.22	-0.27
95	10-1 AM	0.84	
95	10-2 AM	-0.08	0.01
95	10-2 PM	-0.74	
95	10-14 PM	0.82	
A2	10-13	-0.72	-0.71
A2	10-15	-0.39	-0.38
A2	10-19 #1	-0.63	-0.64
A2	10-19 #2	0.20	0.20
A1	10-13	0.84	0.99
A1	10-6 #2	-0.70	-0.69
A1	10-6 #3	-0.84	-0.85

5. Cincinnati Study

5.1 About the University of Cincinnati and Site Selection

Tests done in Cincinnati were primarily focused around the University of Cincinnati main campus. The campus is home to 39,667 undergraduate and graduate students and 9,846 faculty and staff [57]. The main campus is divided into two sections, the east and west campuses. The east campus contains the medical school while the west campus contains most of the other academic buildings and facilities. Cincinnati is located in the Midwest United States. The greater Cincinnati area is home to more than 2 million people although the city is much more sprawled out than Singapore. The climate is temperate with four distinct seasons with hot summers and cold winters.

CO trends in the area have gone down gradually over the past 40 years along with national CO trends. Over the past 10-15 years CO levels have leveled out with the 2[nd] highest 8 hour average remaining between 3 and 4 ppm well below the national standard. Figure 35 shows the CO trend in downtown Cincinnati between 1990 and 2008 as measured by reported by the US EPA [58].

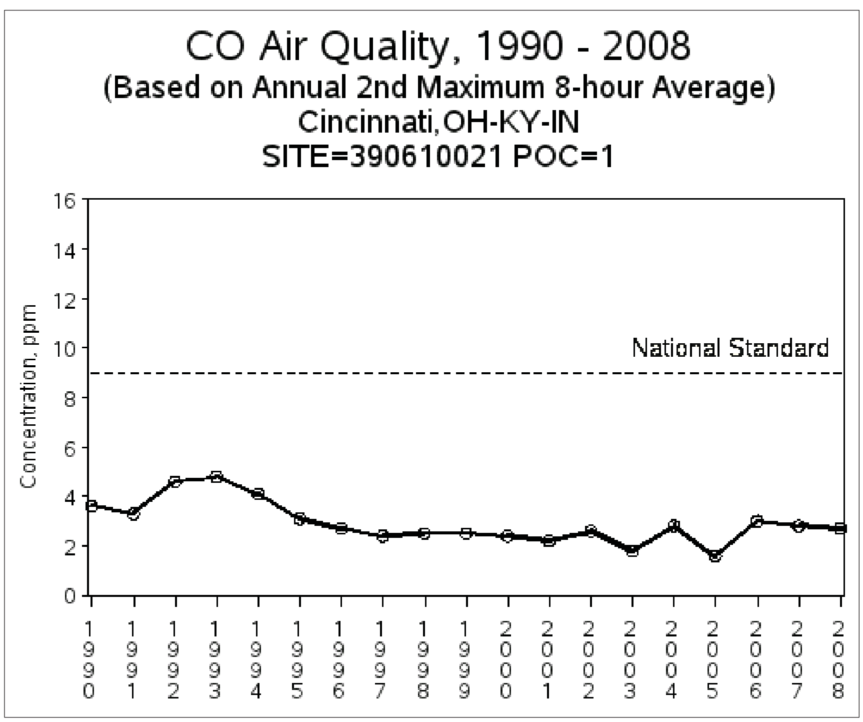

Figure 35: Hamilton County CO Trend 1990-2008

Ambient tests were done at the MLK/Clifton during winter and spring periods. The intersection is one of 4 major intersections around the UC campus and the second biggest by traffic volume. Much of the commuter traffic to and from campus travels through this intersection as it is located between the university and I-75 a major expressway. This traffic travels eastbound through the intersection in the morning and westbound through the intersection in the evening. This location was selected because of the high traffic volume, consistent signal timing, and normal shape of the intersection. The CCM (College-Conservatory of Music) garage at UC was selected to perform CO monitoring tests due to its large size, enclosed space, and exposure to operators who work at the entrance and exit gate to the garage.

Monitoring was also done in commuter routes to and from the UC campus. This included personal cars, city buses, and an internal shuttle bus. These routes extended beyond the campus limits and further route details are given in section 5.4 and in appendix G.

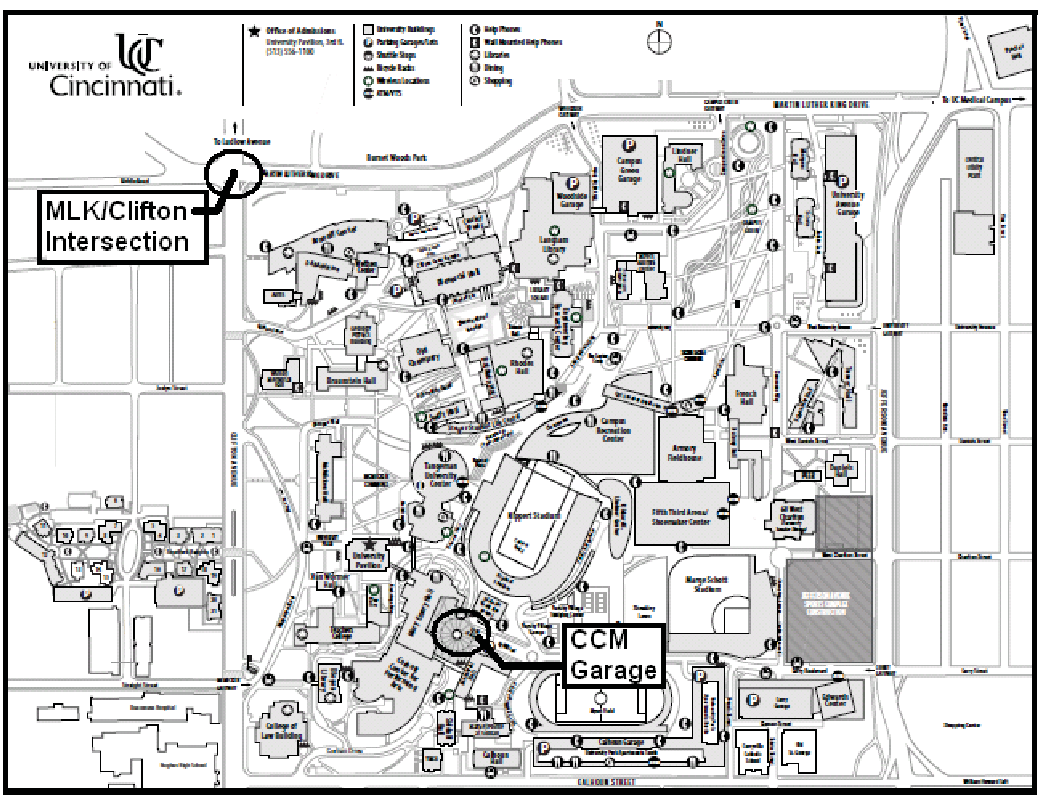

Figure 36: UC West Campus

5.2 MLK/Clifton Intersection

5.2.1 About the Location and Instrument Layout

The intersection of Martin Luther King Dr. and Clifton Ave at the northwestern corner of the UC west campus is one of the busiest intersections around the UC campus. The intersection occurs between two six lane roads and is used by many university commuters on their way to and from the university. It is in close proximity to I-75 and is used by many commuters to go between the campus and the highway each day. In addition a Cincinnati metro bus stop is located just south of the intersection (180 ft). The bus stop is only used a few times per hour and idle time is typically minimal with only 1 or 2 passengers getting on or off the bus when it stops.

Tests were done during winter and spring periods (2010) at the intersection where CO levels were monitored and traffic was videotaped. During winter tests six sensors were set up around the intersection and the bus stop. One sensor was located at each corner of the intersection on an island between the intersection and the right turn lane. Two sensors were set up at the bus stop, one on each side of the road. All sensors were put at 1.8m (breathing height). The WSN base station was located inside a building southwest of the intersection. Two video cameras were set up although primary videotaping for traffic counting was done on the east approach of MLK facing the intersection. A map showing the locations of the sensors and the video cameras is shown in Figure 37. No NOx or PM measurements were taken during the winter period. Individual sensor locations for each test are shown in appendix E.

Spring 2010 tests only utilized the two T15 instruments. One was placed at the northeast corner during each test and the other was placed at the southwest corner for 7 of the 10 tests and the southeast corner for the other 3 tests. Video was shot from one direction only coming from the east approach on MLK. Instruments to record NOx and PM were set up at the southeast corner of the intersection.

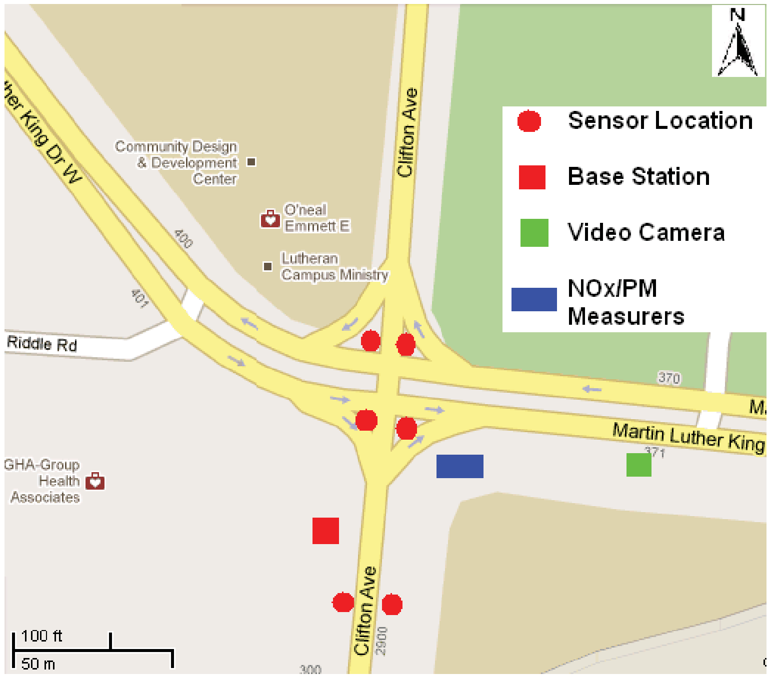

Figure 37: MLK Clifton Intersection Layout

In addition to the winter and spring tests that are the main focus of this research a preliminary study was done in the fall of 2008 that measured the CO levels at the intersection for 1 week before classes began at the UC campus and 1 week after classes started. A single T15 instrument (T15-1) was placed in an open enclosure 15ft above the intersection and recorded data continuously. The daily trends are given in Figure 38 and Figure 39. The highest CO levels were observed between 3PM and 6PM in both cases. Higher levels of CO were observed after classes started as expected with the increase in traffic. The moving average topped out at about 0.4 ppm for the first week and increased to 0.5ppm during peak periods after classes began. A noticeable peak is also observed during the AM peak hours between 7AM and 9AM. This peak is still significantly smaller than the CO levels observed during the middle of the day. One exception to this trend was observed on Friday, September 19th where the highest levels were observed in the evening hours. A possible explanation for this is people arriving for the home football game the following day.

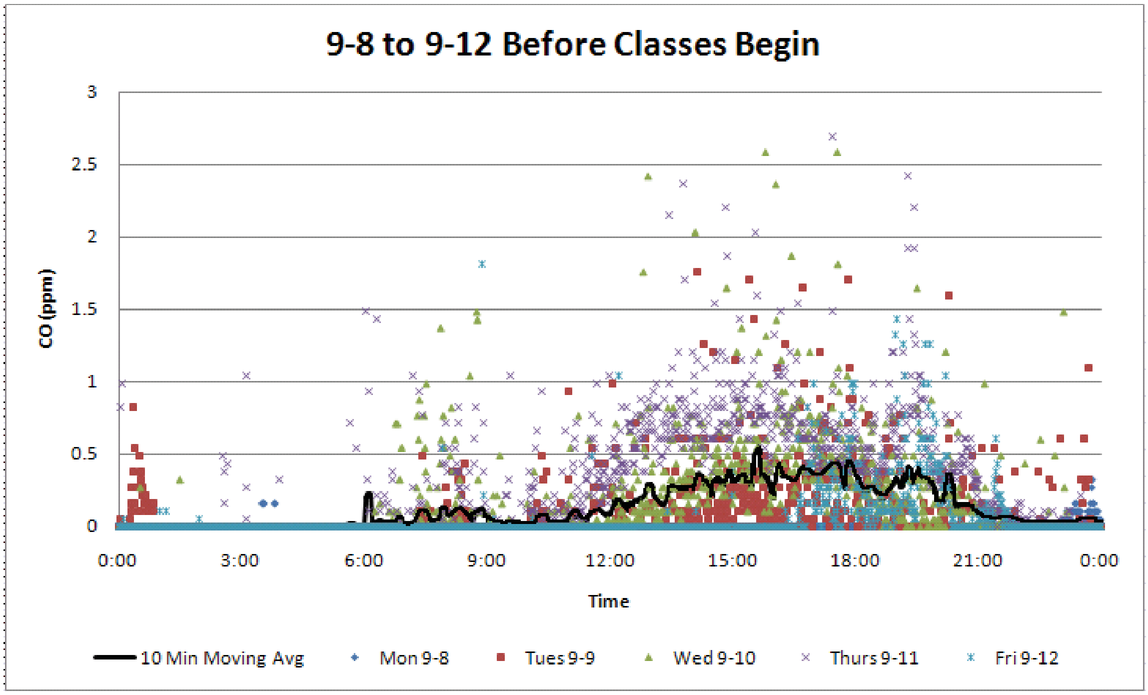

Figure 38: Fall 2008 CO Daily Trend Before Classes Begin

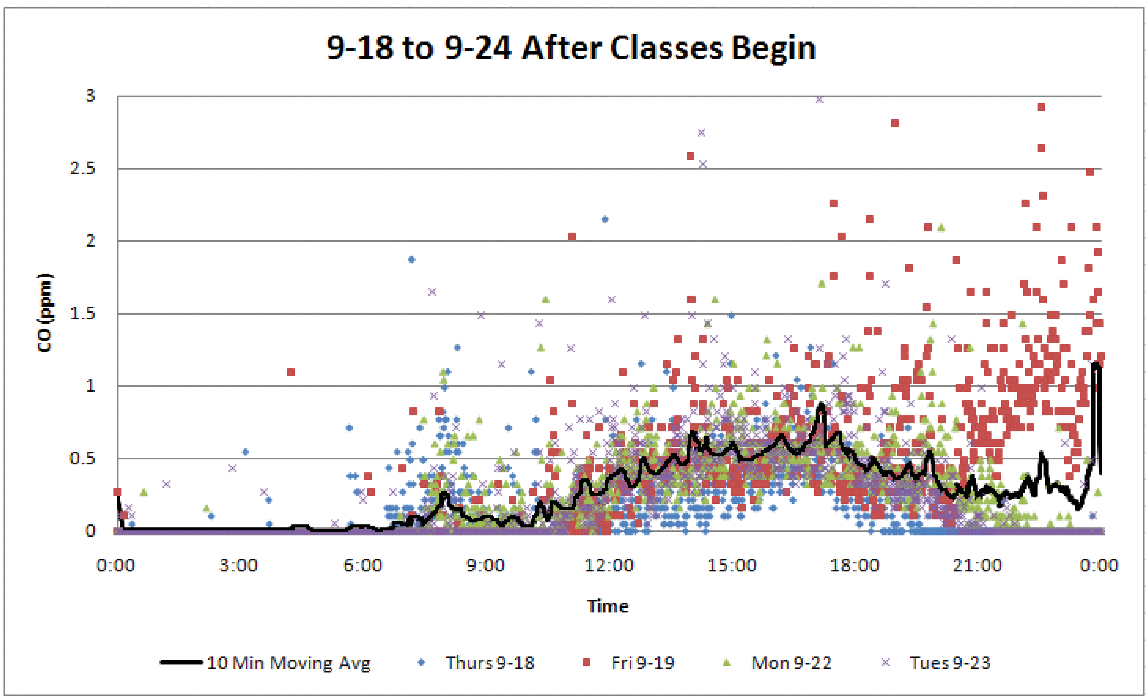

Figure 39: Fall 2008 CO Daily Trend After Classes Start

5.2.2 Methods

T15 and WSN sensors were placed at each of the six sensor locations prior to each test. Most tests utilized a standard layout while 3 of the tests used a different sensor layout. The sensor layouts for the winter test are given in appendix E. Once the sensors were put in place and the video camera set up the test began and ran for about an hour and a half. The base station was placed just inside a building southwest of the intersection depicted in Figure 37. 2 AM, 2 Noon, and 3 PM tests were done during the winter 2010 sampling period. Traffic counts were recorded from the video and compared with CO. 5 minute averages were used in both cases.

The same test was set up in the spring time. This time only the T15 sensors were used and no sensors were placed at the bus stop due to infrequent bus activity. Sensor T15-2 was kept at the same location for every test this time and only 2 variations in sensor layout were used. NOx and PM measurements were also performed at the southeast corner of the intersection. The results of those measurements are not discussed here. In order to better calculate the dynamic flow of traffic, traffic delay was counted for each approach in 15 second intervals. The number of stopped vehicles was counted every 15 seconds and multiplied by 15 seconds to get the delay in vehicle seconds. 4 AM, 2 Noon, and 4 PM tests were done during the spring sampling. 5 minute CO averages were compared with both traffic count and traffic delay in the analysis.

5.2.3 Results and Discussion – Winter 2010

Table 18 gives a summary of the winter tests indicating the times, average traffic flow, and meteorological conditions. Table 19 through

Table 22 present summary data for the individual sensors that were set up and also the correlation coefficients with traffic. A camera malfunction on the 17^{th} of February caused the loss of video and traffic data for both the AM and PM test that day. CO data was still acquired as normal. Data that is blank indicates that either no data was obtained or the sensor was malfunctioning that day. WSN Sensor 5 and 6 were also used during the tests, however the data obtained was inconsistent and unreasonable indicating a problem with the sensor. The sensor layout is given in appendix E.

Consistent correlations with traffic were not frequently observed. The best correlation seen is with northbound traffic and the 2 WSN sensors. Offsetting the data by 1 minute improved the data further. A positive correlation was observed for all four tests WSN 20 was active and a correlation of 0.34 or higher was seen for 3 of the 4 tests. WSN 21 showed a positive correlation with northbound traffic of at least 0.15 for 4 out of the 5 test periods with traffic data.

Table 18: Winter 2010 MLK-Clifton Summary

Date	Time Period	cars/hour	Start	End	Wind Speed (mph)	Wind Direction	Temp (C)	RH
8-Feb	PM	3817	16:42	17:45	0.88	ENE	-2.7	2.4
11-Feb	Noon	2731	11:08	12:40	0.85	WSW	-3.5	71.6
11-Feb	PM	3685	16:13	17:40	0.87	W	-1.8	60.8
17-Feb	AM		6:54	8:53	3.23	W	-4.4	81.5
17-Feb	PM		16:16	17:45	2.26	N	7.4	29.9
18-Feb	AM	3642	7:18	9:06	0.41	N	6.7	87.5
18-Feb	Noon	3187	11:56	13:16	0.53	N	10.4	83.2

Table 19: Winter 2010 Test MLK-Clifton Sensor 20

						Direct					1 Minute Offset				
Date	Time Period	Location	Avg. CO	Max	Time Max	NB	SB	EB	WB	Total	NB	SB	EB	WB	Total
8-Feb	PM	SE	0.25	0.92	17:39:42	0.14	0.61	(0.33)	(0.51)	(0.25)	0.35	0.65	(0.23)	(0.62)	(0.08)
11-Feb	Noon	NE	0.20	0.92	12:09:22	0.20	(0.21)	0.04	0.35	0.16	0.34	0.00	(0.05)	0.42	0.29
11-Feb	PM	SE	0.34	0.92	17:39:40	0.24	(0.22)	0.18	0.33	0.25	0.12	(0.34)	0.19	0.36	0.16
17-Feb	AM	SE	0.15	0.76	8:29:24										
17-Feb	PM	NE	0.32	1.24	17:03:02										
18-Feb	AM	SE	0.00	1.24	7:31:22										
18-Feb	Noon	SE	5.76	12	12:01:39	0.37	0.00	(0.45)	0.33	0.01	0.41	(0.06)	(0.52)	0.40	(0.04)

Table 20: Winter 2010 Test MLK-Clifton Sensor 21

						Direct					1 Minute Offset				
Date	Time Period	Location	Avg. CO	Max	Max Time	NB	SB	EB	WB	Total	NB	SB	EB	WB	Total
8-Feb	PM	NE	1.27	2.53	17:25:26	0.29	0.32	(0.23)	(0.44)	(0.09)	0.22	0.38	(0.12)	(0.41)	(0.07)
11-Feb	Noon	SE	0.94	1.88	11:50	0.22	(0.14)	0.30	0.52	0.35	0.28	(0.03)	0.22	0.49	0.40
11-Feb	PM	NE	0.8	2.2	17:21:23	0.44	0.02	(0.07)	0.20	0.28	0.46	0.06	(0.11)	0.15	0.28
17-Feb	AM	NE	0.72	2.53	8:38:12										
17-Feb	PM	SE	0.53	1.72	17:26:19										
18-Feb	AM	NE	0.79	1.88	8:27:07	(0.41)	(0.03)	0.02	(0.28)	(0.40)	(0.43)	(0.04)	0.05	(0.23)	(0.36)
18-Feb	Noon	NE	0.5	0.92	12:31:37	0.01	(0.07)	(0.07)	0.28	0.04	0.15	0.18	(0.08)	0.07	0.17

Table 21: Winter 2010 Test MLK-Clifton T15-1

						Direct					1 Minute offset				
Date	Time Period	Location	Avg. CO	Max CO	Max Time	NB	SB	EB	WB	Total	NB	SB	EB	WB	Total
8-Feb	PM	W Bus	0.79	2.70	16:08:29	(0.27)	(0.02)	(0.21)	0.21	(0.24)	(0.27)	(0.02)	(0.21)	0.21	(0.24)
11-Feb	Noon	W Bus	0.77	3.60	11:03:23	0.06	(0.11)	0.21	0.13	0.13	(0.02)	0.10	(0.09)	0.21	0.11
11-Feb	PM	W Bus	0.74	2.28	16:11:13	0.02	(0.45)	0.02	0.00	(0.15)	0.32	(0.23)	0.42	0.27	0.33
17-Feb	AM	W Bus	1.01	5.48	7:15:55										
17-Feb	PM	SW	0.73	1.58	16:06:35										
18-Feb	AM	W Bus	0.89	2.49	7:14:30										
18-Feb	Noon	W Bus	0.69	1.58	11:39:20	0.05	0.27	0.14	(0.08)	0.19	0.29	0.23	0.15	(0.24)	0.16

Table 22: Winter 2010 Test MLK-Clifton T15-2

						Direct					1 Minute Offset				
Date	Time Period	Location	Avg. CO	Max CO	Max Time	NB	SB	EB	WB	Total	NB	SB	EB	WB	Total
8-Feb	PM	NW	0.92	3.22	17:21:46	(0.00)	0.55	(0.29)	(0.54)	(0.38)	0.01	0.58	(0.34)	(0.57)	(0.42)
11-Feb	Noon	SW	0.39	1.85	11:01:22	(0.33)	0.05	(0.38)	(0.51)	(0.46)	(0.52)	(0.21)	0.18	(0.44)	(0.51)
11-Feb	PM	NW	0.81	4.59	17:04:52	(0.15)	0.10	(0.31)	(0.28)	(0.24)	(0.09)	0.10	(0.31)	(0.22)	(0.18)
17-Feb	AM	NW	0.39	1.94	7:37:31										
17-Feb	PM	W Bus	0.57	2.35	16:11:01										
18-Feb	AM	NW	0.69	1.58	7:50:51	0.36	(0.03)	0.14	0.31	0.50	0.27	0.02	0.22	0.23	0.43
18-Feb	Noon	NW	0.40	2.53	11:41:41	(0.32)	0.13	(0.04)	0.02	(0.03)	(0.32)	0.13	(0.04)	0.02	(0.03)

5.2.4 Results and Discussion – Spring 2010

The most complete set of ambient monitoring data was obtained for the spring sampling at MLK-Clifton intersection. 10 tests were performed with consistent instrument locations. Both T15s were placed at the intersection, traffic delay counts were done by hand, and two complete hours of data were taken for each test.

Table 23 and Table 24 give a summary of the traffic, met data and CO data taken by each instrument. Table 25 and Table 28 give correlation coefficients for traffic counts and traffic delays for each approach. For these tables the average CO of the two sensors is used. The correlations are given both for simultaneous data and for CO data that is offset by 1 minute. Appendix E shows the correlation coefficients for data offset by up to 5 minutes.

Table 26 and Table 28 display only the correlations of traffic with a sensor downwind of that approach. Only data from one sensor is utilized in these tables.

Although consistent correlations were not seen there were good results for some of the tests. In some cases the CO lagged behind the traffic by more than 1 minute. The amount of lag varies from test to test and some tests do not give a good relationship. Strong relationships between CO and traffic conditions downwind of the sensors were not significant.

Table 23: Traffic and Met Data Summary, MLK Clifton Spring 2010

				Cars/Hour					Delay Vehicle Seconds/Minute								
Date	Time Period	Start	End	NB	SB	WB	EB	Total	NB	SB	WB	EB	Total	Wind Speed (mph)	Wind Dir	Temp (C)	RH
19-May	AM	7:10	9:10	683	724	645	1339	3391	248	301	218	378	1145	2.3	W	14.7	88.0
24-May	AM	7:15	9:15	679	708	596	1349	3193	308	311	213	318	1150	2.5	SE	23.3	70.1
25-May	AM	7:10	9:10	641	785	563	1422	3412	281	341	193	510	1325	6.8	ESE	20.9	70.5
27-May	AM	7:10	9:10	635	734	675	1277	3322	254	205	177	235	871	2.2	SW	24.3	66.4
19-May	Noon	11:10	13:10	561	949	966	796	3271	234	196	280	279	989	3.2	SW	16.6	78.8
24-May	Noon	11:00	13:00	546	817	808	850	3020	170	189	241	273	873	6.8	E	28.0	49.3
18-May	PM	16:00	18:00	731	934	1475	757	3898	443	407	407	272	1529	2.3	W	16.6	76.7
20-May	PM	16:10	18:10	677	869	1521	789	3856	428	361	433	251	1473	8.5	ESE	23.1	56.7
26-May	PM	16:00	18:00	646	1073	1405	987	4111	486	575	407	289	1757	1.6	SSW	20.8	77.1
27-May	PM	16:00	18:00	859	1012	1568	1036	4475	604	783	403	709	2499	8	WNW	27.0	55.2

Table 24: Sensor Summary, MLK Clifton Spring 2010

		New T15				Old T15			
Date	Time Period	Location	Avg. CO	Max CO	Time Max	Location	Avg. CO	Max CO	Time Max
19-May	AM	NE	0.72	4.79	8:55	SW	0.17	0.92	7:51
24-May	AM	NE	0.66	4.27	9:02	SE	1.57	3.25	8:25
25-May	AM	NE	0.39	1.67	7:27	SW	0.29	0.87	8:01
27-May	AM	NE	0.45	1.56	7:26	SW	1.16	2.74	7:53
19-May	Noon	NE	0.37	2.32	12:34	SW	0.22	1.93	13:08
24-May	Noon	NE	1.15	12.08	12:14	SE	1.03	2.45	12:25
18-May	PM	NE	0.67	1.63	16:48	SW	0.21	2.30	16:57
20-May	PM	NE	0.83	2.54	16:57	SE	0.46	1.86	17:40
26-May	PM	NE	0.26	1.96	17:21	SW	1.04	3.24	17:42
27-May	PM	NE	0.35	1.84	16:31	SW	0.81	2.79	16:54

Table 25: Correlation Coefficients with Traffic Counts, MLK Clifton Spring 2010

		Simultaneous					1 Minute Offset				
Date	**Time Period**	**NB**	**SB**	**EB**	**WB**	**Total**	**NB**	**SB**	**EB**	**WB**	**Total**
19-May	AM	0.63	0.15	0.19	0.43	0.53	0.38	0.33	(0.02)	0.28	0.36
24-May	AM	(0.14)	(0.00)	(0.36)	(0.40)	(0.41)	(0.13)	0.04	(0.27)	(0.34)	(0.31)
25-May	AM	(0.06)	0.05	0.09	0.24	0.10	(0.07)	0.14	0.17	0.31	0.18
27-May	AM	(0.04)	0.45	0.13	(0.23)	0.07	(0.01)	0.45	(0.00)	(0.12)	0.08
19-May	Noon	(0.36)	(0.17)	0.16	0.03	(0.10)	(0.38)	(0.08)	0.10	0.06	(0.08)
24-May	Noon	(0.13)	(0.08)	(0.19)	(0.10)	(0.20)	(0.11)	(0.16)	(0.10)	(0.10)	(0.19)
18-May	PM	(0.15)	(0.11)	0.13	(0.38)	(0.40)	(0.34)	(0.26)	0.27	(0.27)	(0.42)
20-May	PM	0.21	0.19	(0.19)	0.03	0.08	0.24	(0.01)	0.02	(0.18)	(0.05)
26-May	PM	0.28	0.28	0.17	(0.01)	0.37	0.26	0.34	0.29	(0.19)	0.37
27-May	PM	0.07	0.33	(0.13)	(0.25)	(0.06)	0.05	0.37	(0.07)	(0.22)	0.02

Table 26: Downwind Correlation Coefficients with Traffic Counts, MLK Clifton Spring 2010

		Simultaneous					1 Minute Offset				
Date	Time Period	**NB**	**SB**	**EB**	**WB**	**Total**	**NB**	**SB**	**EB**	**WB**	**Total**
19-May	AM		(0.08)			0.16		0.20			(0.03)
24-May	AM				(0.39)					(0.32)	
25-May	AM	0.25			0.16		0.21			0.20	
27-May	AM	(0.30)		0.08		(0.50)	(0.24)		0.10		(0.47)
19-May	Noon	(0.25)		0.12			(0.29)		0.02		
*24-May	Noon				(0.27)					(0.40)	
*24-May	Noon				(0.03)					0.01	
18-May	PM		(0.10)			(0.32)		(0.21)			(0.34)
20-May	PM				0.01					(0.09)	
26-May	PM	0.28		0.24		0.35	0.32		0.33		0.40
27-May	PM		0.11					0.23			

*Both sensors are downwind, T15-1 is listed above T15-2

Table 27: Correlation Coefficients with Traffic Delay, MLK-Clifton Spring 2010

		Simultaneous					1 Minute Offset				
Date	**Time Period**	**NB**	**SB**	**EB**	**WB**	**Total**	**NB**	**SB**	**EB**	**WB**	**Total**
19-May	AM	0.31	0.36	0.24	0.22	0.40	0.55	0.45	0.36	0.15	0.53
24-May	AM	(0.04)	0.05	0.19	0.48	0.19	(0.00)	0.06	0.22	0.45	0.21
25-May	AM	0.02	(0.14)	0.06	0.40	0.05	0.08	(0.20)	0.04	0.44	0.04
27-May	AM	0.34	0.41	0.50	(0.01)	0.48	0.27	0.43	0.46	(0.02)	0.44
19-May	Noon	(0.27)	(0.38)	0.05	0.20	(0.06)	(0.20)	(0.41)	0.07	0.21	(0.03)
24-May	Noon	0.01	0.10	0.09	(0.16)	0.02	0.01	0.01	0.03	(0.13)	(0.03)
18-May	PM	0.25	(0.14)	0.05	0.07	0.08	0.30	(0.18)	0.06	0.07	0.08
20-May	PM	(0.31)	0.00	0.42	0.11	0.00	(0.25)	0.11	0.39	0.09	0.06
26-May	PM	0.07	(0.13)	(0.03)	0.09	(0.04)	(0.01)	(0.01)	(0.12)	0.19	0.03
27-May	PM	0.20	(0.28)	0.07	(0.12)	(0.10)	0.26	(0.31)	0.15	(0.07)	(0.02)

Table 28: Downwind Correlation Coefficients with Traffic Delay, MLK-Clifton Spring 2010

		Simultaneous					1 Minute offset				
Date	Time Period	**NB**	**SB**	**EB**	**WB**	**Total**	**NB**	**SB**	**EB**	**WB**	**Total**
19-May	AM		0.36			0.27		0.56			0.50
24-May	AM				0.36					0.33	
25-May	AM	0.22			0.06		0.37			(0.00)	
27-May	AM	0.02		0.15		(0.01)	(0.03)		0.06		(0.06)
19-May	Noon	(0.11)		0.22			(0.12)		0.23		
24-May	Noon				(0.04)					(0.09)	
24-May	Noon				(0.14)					(0.10)	
18-May	PM		(0.08)			0.11		(0.13)			0.15
20-May	PM				0.01					0.07	
26-May	PM	0.09		(0.23)		(0.13)	0.06		(0.27)		(0.08)
27-May	PM		(0.49)					(0.49)			

Highlighted numbers represent periods of strong wind in that direction.

Traffic Delay was also simulated using VISSUM [59], a traffic simulation software to see if traffic delay counted by hand and computed by the software were compareable. Figure 40Error! Reference source not found. shows the variation of delay vs time for both the hand counted and simulated delay. The figures on the right side depict 5 simulations of the software while the left side uses an average. Although the average delay was similar when comparing the actual counted delay and the simulated delay the software was not accurate on every 5 minute calculation and results can change based on the simulation.

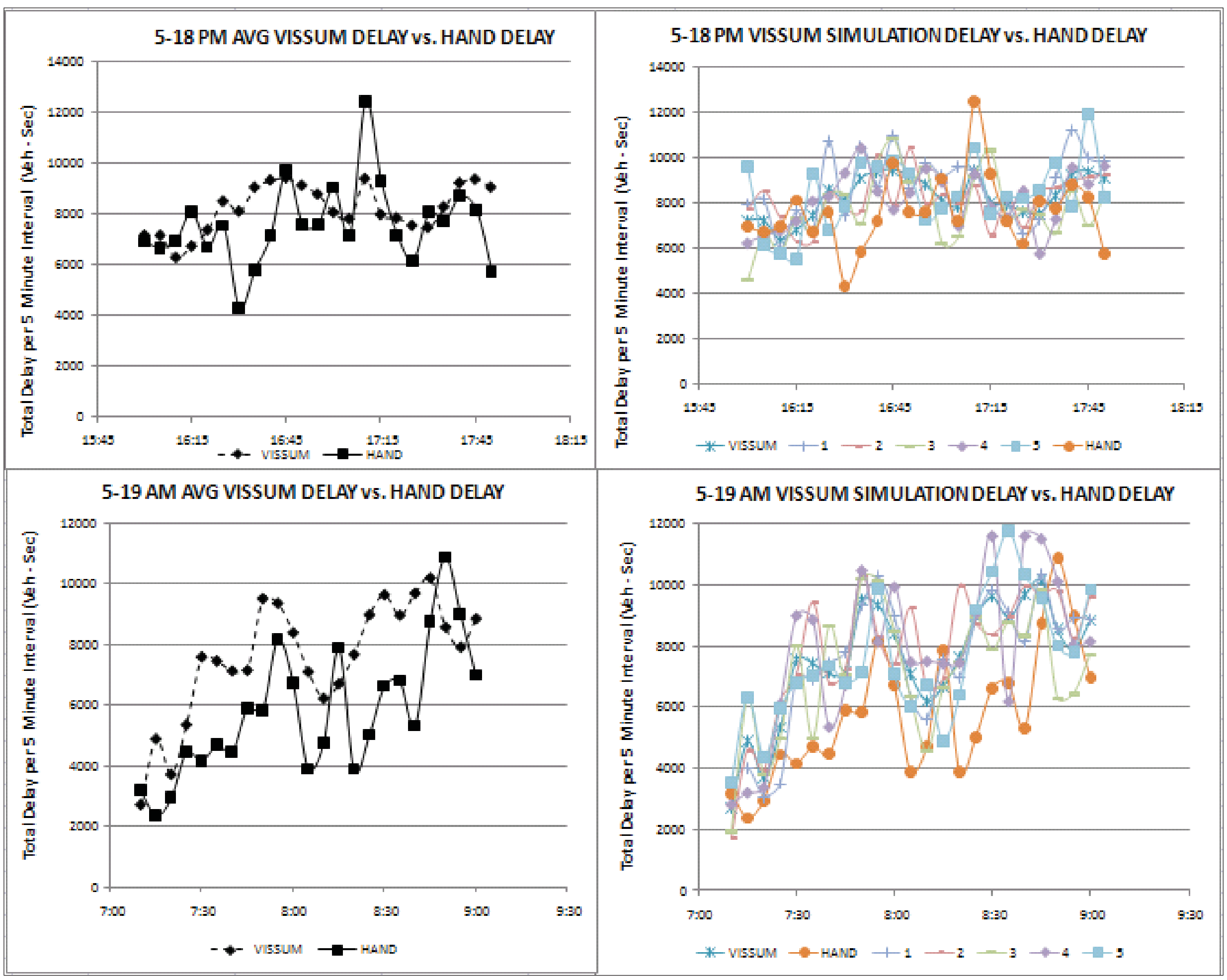

Figure 40: Vissum Simulation vs Hand Count Delay

The effect of the traffic cycle on CO levels was also examined similar to the analysis done for the Clementi intersection. The traffic cycle for the MLK/Clifton intersection is on a fixed 90 second loop during AM and PM rush hour periods. The signal cycle is detailed in Figure 41. Red sections indicate that all approaches are under a red light and occur in between green light cycles of MLK and Clifton. The other sections of the cycle occur as follows:

For AM Cycle:

1) SB green with left turn arrow
2) NB/SB green
3) EB/WB green

For PM Cycle:

1) NB/SB left turn arrow
2) NB/SB green
3) EB/WB left turn arrow
4) WB green with left turn arrow
5) EB/WB green

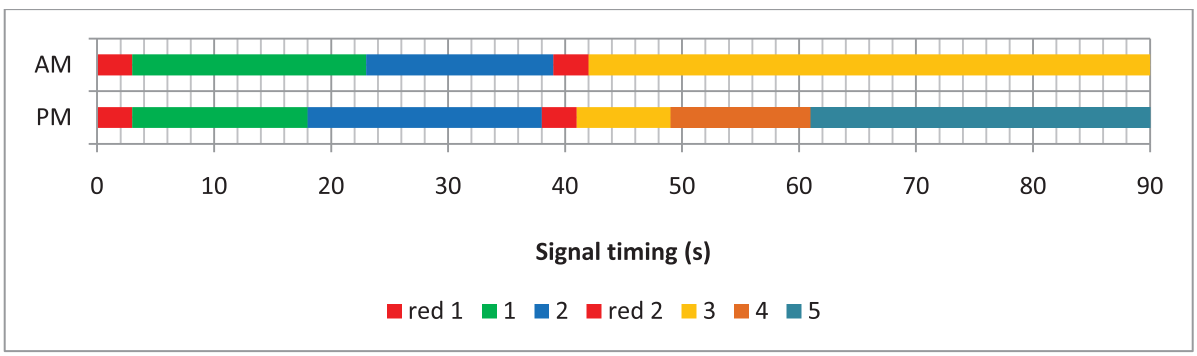

Figure 41: MLK/Clifton Signal Cycle

Figure 42 and Figure 43 show the temporal variation of CO concentration during 2 AM and 2 PM test periods. Each vertical line indicates the beginning of a 90 second traffic cycle which is the same one outlined in Figure 41.

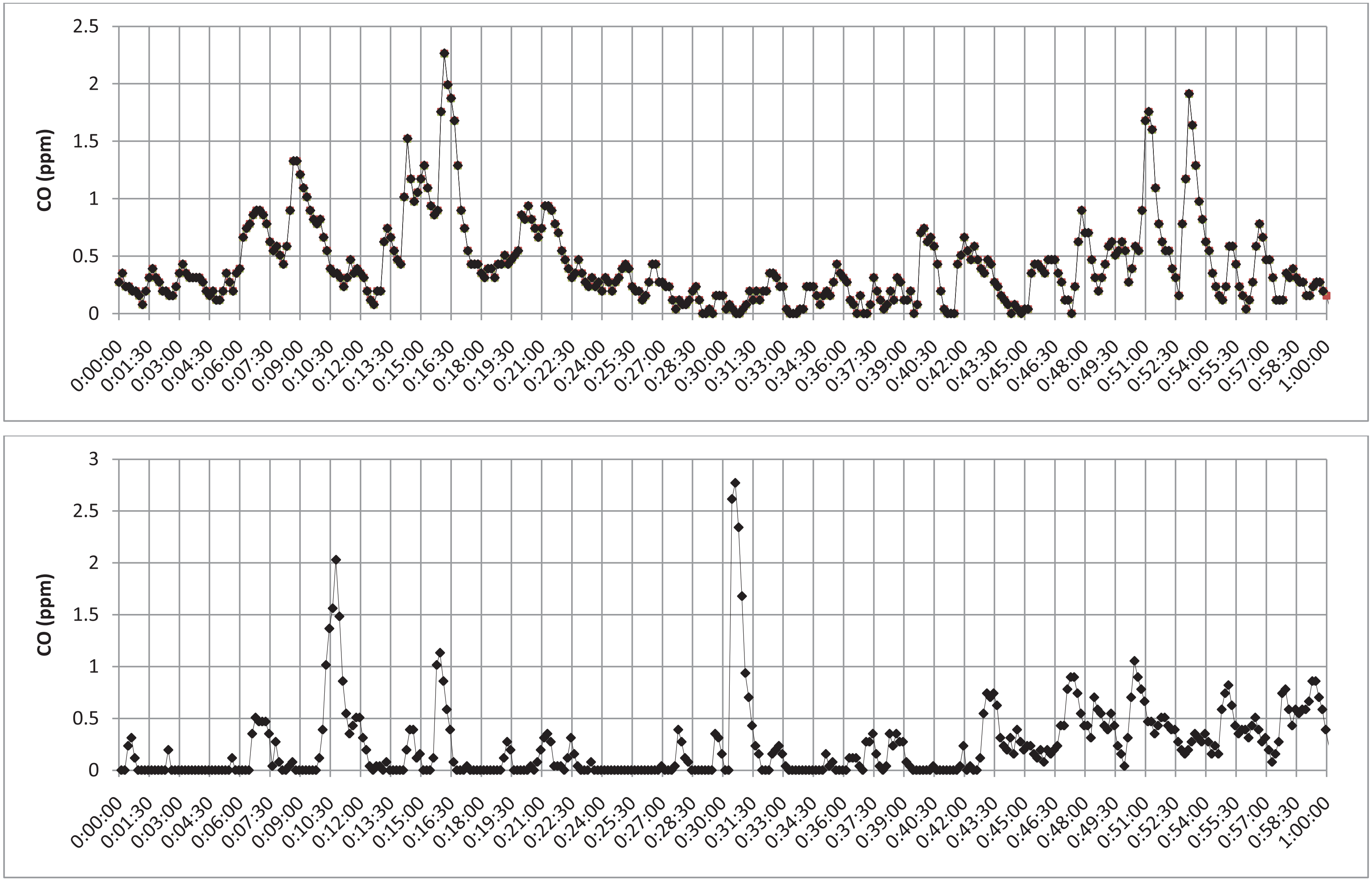

Figure 42: Temporal Variation of CO with Signal Cycle, PM Tests, 5-25-10 (Top), 5-27-10 (Bottom)

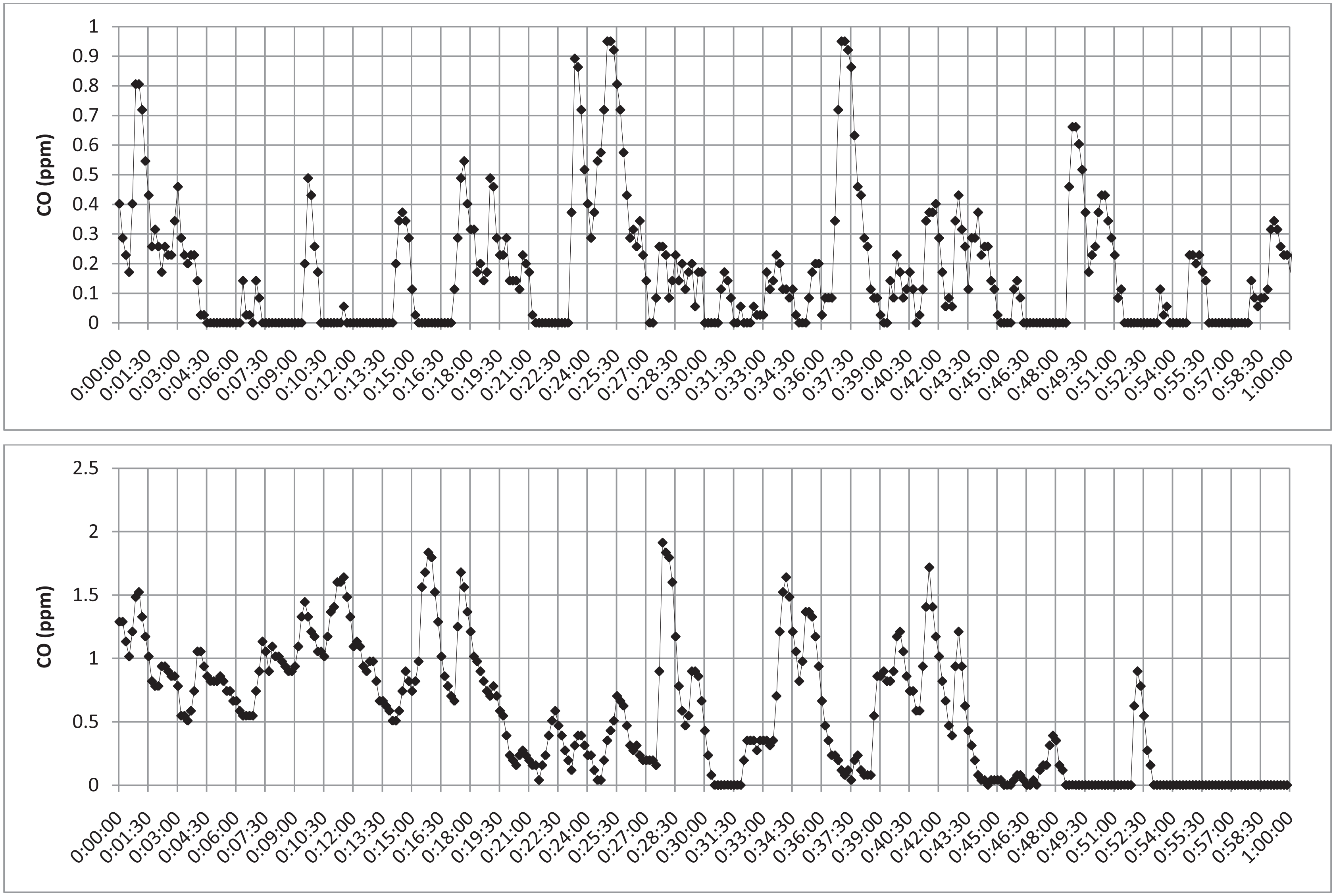

Figure 43: Temporal Variation of CO with Signal Cycle, AM Tests, 5-19-10 (Top), 5-27-10 (Bottom)

During the AM peak traffic period the peaks in CO concentration were typically seen between the 60-80 second mark of the cycle. This is just after the green light signal is given for the eastbound and westbound traffic lanes which can be epected since the eastbound approach coming from I-75 contains the highest levels of traffic. During PM peak traffic periods. CO peaks are seen at a similar time frame for the PM peak period. The latter part of the cycle also contains the eastbound/westbound green period. The highest levels of traffic are heading westbound toward I-75. Some peaks do not occur during these times occur possibly due to acceleration patterns of other approaches. Dispersion patterns and emission rates varying widely across the vehicle fleet can have a significant impact on when peak CO levels are observed.

5.3 CCM Parking Garage

5.3.1 Location Selection

The CCM garage located in the center of UC west campus is a large 3 level underground parking garage. Some of the highest CO concentrations around campus were observed in the garage. It is a large, frequently used, enclosed parking garage. Testing in the garage occurred at the main entrance and exit point located at the end of a tunnel entrance. Spot checks were also done in the middle and lower portions of the garage. Incoming and Outgoing Traffic was counted during peak periods and compared with CO measurements taken. The main entrance/exit is on the top floor of the 3 story underground garage and consists of 3 lanes. One lane is for traffic entering the garage, one for exiting traffic and one that changes allowing incoming traffic in the beginning of the day and exiting traffic at the end of the day. There is also a side exit on the opposite side of the main entrance/exit on the top floor and a side entrance one level down. Each floor is in the shape of a rectangle with the ramp to the floor above and below located in the middle of the garage. More photos of the garage are available in appendix F.

Figure 44: Tunnel to the main Entrance/Exit of the CCM Garage

5.3.2 Methods

Similar to the University Car Park in Singapore traffic counts were done and CO was measured simultaneously at the main entrance exit. Traffic at the garage is nearly all personal vehicles so traffic was not segregated by type. Unlike the Car Park in Singapore the main entrance/exit occurs inside a tunnel and because some cars use a parking pass and some cars exit using cash the idling time of vehicles at the exit varies. Figure 45 shows the entrance of the garage as well as the sensor locations used. In most cases T15 sensors were placed at both the entrance and exit of the garage, although sensor positions varied and are noted in the result section. An NDIR was used during some of the spring tests and was placed near the exit lane as shown in the figure.

Tests were done during the morning 7:30-9:30AM, afternoon 11:00AM – 1:00 PM and evening 4:00PM-6:30PM for the each test period with the exception of the summer tests which omit the noon period. The winter test period consisted of 2 days of testing in which AM, noon, and PM tests were done. One of those days, February 9th the University closed midway through the day due to snow resulting in an unusual traffic pattern. A normal traffic pattern was observed for the remaining tests.

Figure 45: CCM Main Entrance/Exit

5.3.3 Results and Discussion

A summary of the results for each season can be found in Table 29 through Table 32: Fall 2010 CCM Test Summary. Average and maximum CO levels for each instrument, instrument locations, and average traffic flow volumes are presented. Blank spaces indicate that an instrument either wasn't used or wasn't working properly and no data was obtained for that statistic.

Table 33 through Table 36 show the correlation coefficients for each test. Coefficients are not shown for entering or exit traffic if the sensor was located on the opposite side. The exception is during the winter testing when only one sensor was used. The correlation coefficient for outgoing vehicles is not displayed during morning tests due to the infrequent exiting of vehicles from the garage. All the data uses 5 minute averages, this includes the maximum CO data which is the largest 5 minute average observed.

Table 29: Winter 2010 CCM Test Summary

Date		Start	End	T15-2	Average CO (ppm)	Max CO	Vehicles per 5 Minute Interval: in	out	Total
4-Feb	AM	7:30	8:50	entrance	0.58	0.86	10.2	0.3	10.5
9-Feb	AM	7:30	9:30	entrance	0.71	2.00	5.8	0.3	6.0
4-Feb	Noon	11:30	13:00	entrance	0.26	0.78	4.2	4.2	8.4
9-Feb	Noon	11:15	13:00	entrance	7.79	14.73	0.5	6.3	6.9
4-Feb	PM	16:10	18:30	entrance	1.26	3.27	3.0	6.6	9.6
9-Feb	PM	15:55	17:35	entrance	1.84	5.36	0.2	0.8	1.0

Table 30: Spring 2010 CCM Test Summary

							T15-1		T15-2		NDIR		Vehicles per 5 Min Interval		
Date	Time Period	Start	End	T15-1	T15-2	NDIR	Average CO (ppm)	Max CO	Average CO (ppm)	Max CO	Average CO (ppm)	Max CO	In	Out	Total
6-May	AM	7:30	9:00	entrance	entrance		0.23	1.44	0.35	3.36			9.8	0.2	10.0
11-May	AM	7:30	9:30		entrance				0.84	12.45			9.0	0.5	9.4
14-May	AM	7:30	9:30	bottom	entrance	exit	0.70	0.81	0.85	3.32	1.47	34.0	5.6	0.4	6.0
6-May	Noon	11:25	13:30	exit	entrance		1.18	6.02	0.48	3.01			4.0	3.8	7.8
11-May	Noon	11:30	13:30		exit	exit			2.22	5.58	1.42	3.6	4.7	3.1	7.8
13-May	Noon	11:35	13:30	bottom	exit	exit	1.90	7.92	6.22	21.66	2.70	29.0	3.6	4.8	8.4
6-May	PM	16:05	18:45	exit	entrance		3.97	15.88	2.82	25.60			4.3	5.4	9.7
10-May	PM	16:20	18:45	exit	entrance		1.29	4.71	0.96	5.42			3.6	5.3	8.8
12-May	PM	16:10	18:30	exit	bottom	exit	4.14	14.52	13.41	15.77	9.00	40.8	3.4	6.8	10.2

Table 31: Summer 2010 CCM Test Summary

						T15-1		T15-3		Vehicles per 5 Min period		
Date	Time Period	Start	End	T15-1	T15-3	Average CO (ppm)	Max CO	Average CO (ppm)	Max CO	in	out	total
30-Aug	AM	7:30	9:30	entrance	exit	0.91	2.80	1.27	6.66	4.0	0.3	4.3
31-Aug	AM	7:30	9:30	entrance	exit	0.82	1.97	1.17	6.54	4.3	0.3	4.7
1-Sep	AM	7:30	9:30	entrance	exit	1.14	5.61	1.36	10.26	4.5	0.3	4.8
30-Aug	PM	15:15	17:30	entrance	exit	2.17	7.87	5.16	22.10	1.9	2.6	4.6
31-Aug	PM	16:00	18:00	entrance	exit	3.66	8.13	7.90	105.72	0.5	4.0	4.5
1-Sep	PM	16:00	18:00	entrance	exit	3.57	8.97	5.77	18.62	2.0	3.2	5.2

Table 32: Fall 2010 CCM Test Summary

						T15-1		T15-3		Vehicles per 5 Min Interval		
Date	Time Period	Start	End	T15-1	T15-3	Average CO (ppm)	Max CO	Average CO (ppm)	Max CO	In	Out	Total
1-Nov	AM	7:30	9:00	entrance	exit	0.02	0.15	0.24	1.57	7.2	0.3	7.5
2-Nov	AM	7:30	9:30	entrance	exit	0.48	3.10	0.46	1.91	8.8	0.4	9.3
3-Nov	AM	7:30	9:30	entrance	exit	0.57	2.45	0.93	2.48	8.5	0.5	9.0
2-Nov	Noon	11:00	13:00	entrance	exit	0.20	1.68	0.68	4.28	4.0	5.4	9.4
3-Nov	Noon	11:00	13:00	entrance	exit	1.96	4.11	2.79	4.56	4.0	3.3	7.2
1-Nov	PM	16:00	18:00	entrance	exit	0.04	0.51	0.98	3.02	3.0	8.0	11.0
2-Nov	PM	16:00	18:00	entrance	exit	0.51	3.96	2.03	8.17	4.0	8.5	12.5
3-Nov	PM	16:00	18:00	entrance	exit	8.63	14.70	11.46	16.46	2.4	7.0	9.4

Table 33: CCM Winter 2010 Correlation Coefficients

Date	Time Period	T15-2	Incoming Vehicles	Outgoing Vehicles	Total Vehicles
4-Feb	AM	Entrance	0.36		0.37
9-Feb	AM	Entrance	0.02		0.01
4-Feb	Noon	Entrance	0.23	(0.13)	0.07
9-Feb	Noon	Entrance	(0.54)	(0.18)	(0.40)
4-Feb	PM	Entrance	(0.37)	0.61	0.33
9-Feb	PM	Entrance			

Table 34: CCM Spring 2010 Correlation Coefficients

		T15-1			T15-2			NDIR		
Date	Time Period	Incoming Vehicles	Outgoing Vehicles	Total Vehicles	Incoming Vehicles	Outgoing Vehicles	Total Vehicles	Incoming Vehicles	Outgoing Vehicles	Total Vehicles
6-May	AM	0.08		0.06	0.09		0.07			
11-May	AM				0.19		0.18			
14-May	AM				(0.04)		(0.01)			(0.01)
6-May	Noon		0.64	0.55	0.04		0.50			
11-May	Noon					0.43	0.13		0.58	0.28
13-May	Noon				(0.00)	0.31	0.27		0.15	0.12
6-May	PM		0.12	0.26	0.42		0.33			
10-May	PM		(0.12)	(0.02)	0.21		(0.11)			
12-May	PM	0.13	0.25	0.29					0.65	0.62

Table 35: CCM Summer 2010 Correlation Coefficients

		T15-1			T15-3		
Date	Time Period	Incoming Vehicles	Outgoing Vehicles	Total Vehicles	Incoming Vehicles	Outgoing Vehicles	Total Vehicles
30-Aug	AM	(0.21)		(0.18)			(0.10)
31-Aug	AM	(0.08)		(0.01)			(0.26)
1-Sep	AM	(0.23)		(0.21)			(0.28)
30-Aug	PM	0.13		0.31		0.47	0.36
31-Aug	PM	0.01		0.08		0.04	(0.01)
1-Sep	PM	0.17		0.08		0.22	0.26

Table 36: CCM Fall 2010 Correlation Coefficients

		T15-1			T15-3		
Date	Time Period	Incoming Vehicles	Outgoing Vehicles	Total Vehicles	Incoming Vehicles	Outgoing Vehicles	Total Vehicles
1-Nov	AM	0.45		0.49			0.18
2-Nov	AM	0.43		0.50			0.39
3-Nov	AM	0.62		0.57			0.32
2-Nov	Noon	(0.02)		0.11		0.67	0.37
3-Nov	Noon	0.33		0.11		0.62	0.56
1-Nov	PM	0.33		0.45		0.74	0.56
2-Nov	PM	(0.07)		0.07		0.55	0.32
3-Nov	PM	0.03		0.28		0.78	0.51

The highest CO levels were observed during PM testing periods which averaged 4.20 ppm. Noon tests averaged 1.80ppm and the average CO concentration for AM tests was 0.71ppm. This is most likely due to vehicles starting from a cold start during PM tests. The values are much higher than those seen at the University Hall Car Park most likely due to the enclosed environment. With emission factors highest during winter periods CO is expected to be highest at that time. During the one normal day of testing on February 4th CO levels were lower than tests taken during other seasons. During the other test on February 9th high levels (7.79 ppm average) were seen during the noon test period when most of the traffic was leaving. CO levels observed during the remaining seasons were comparable. During the PM periods where the highest concentrations were observed an average CO concentration of 4.4 3ppm was seen for spring, 4.71 ppm was observed during summer and 3.94 ppm was observed during the fall test. Although traffic was lighter in the summer the highest levels of CO were observed during that period.

Traffic levels did not change drastically as most days on campus consist of the same traffic pattern with the same vehicles coming in and leaving. Individual cars with high CO emissions can skew the results by causing a spike in the CO reading while cars with low CO emissions can have a much smaller effect on the sensor especially if the car passes quickly through the gate. Although the CCM is less influenced by ambient conditions and wind pattern the traffic is less uniform than what was observed at the University Hall Car Park.

Positive correlations were seen with traffic and CO although not as high as observed in the University Hall Car Park. The lack of consistency in vehicle idling time and a handful of poorly emitting vehicles may skew the correlations. The highest correlations were seen during evening tests. 8 of the 10 PM cases had a correlation coefficient of at least 0.22 with the T15 instrument located at the exit. The NDIR showed a correlation coefficient of 0.65 for the one PM test it was used for.

During 3 of the tests a T15 instrument was placed at the bottom of the garage, one during an AM test period, one during a noon test period and one during an evening test period. Average concentrations of 0.7, 1.9, and 13.4 ppm were seen respectively. These tests were done on different days and the highest CO reading occurred during a day where high CO levels were observed at the main entrance/exit as well.

5.4 In Vehicle Testing

5.4.1 Background, Route and Vehicle Selection

In Singapore the focus was on buses that had been running for several hours in most cases. Here we looked at passenger cars and measured CO from the engine start to the end of a route. We also looked at a city bus and a shuttle bus for comparison with the Singapore buses. Two personal vehicles were used in this study, a 1997 Saturn SL2 and a 2008 Toyota Camry Hybrid. Both cars were used to commute from the suburbs of Cincinnati to the urban University of Cincinnati campus. Both routes utilized residential roadways, interstate highways, and urban throughways as part of the commutes.

Similar to the Singapore study, CO inside buses were also measured in Cincinnati. The Metro is a 12 m long transit bus and is used by many Cincinnati residents in their daily commute. The UC shuttle bus is part of the Bearcat Transportation System (BTS), a free service to students and faculty. Routes take place around the UC campus and the surrounding urban area.

Figure 46: Test vehicles in Cincinnati: Saturn (top left), Camry Hybrid (top right), UC shuttle (bottom left), Metro Bus (bottom right)

The personal commute for both vehicles travelled toward the UC campus in the morning and away from UC campus toward residential areas during the evening hours. Routes were taken during both winter and summer months for the 97 Saturn and the car was started from a cold start in during every route. Travel was done during peak traffic periods during both AM and PM routes. The total route length taken is 16.8km and separated into 3 sections. The first section takes place in a suburban setting starting in a residential neighborhood and moving toward a 4 lane arterial roadway (Reading Rd) before entering the highway portion of the trip on Interstate 75 which leads toward downtown. The first section is 4.9km long. The highway section is 7.9km long. After exiting the highway, the route continues in an urban setting on 4 and 6 lane arterial roadways before arriving at campus. The final section is 4.3km long. The route is the reverse in the evening and usually takes between 20 and 40 minutes depending on traffic conditions.

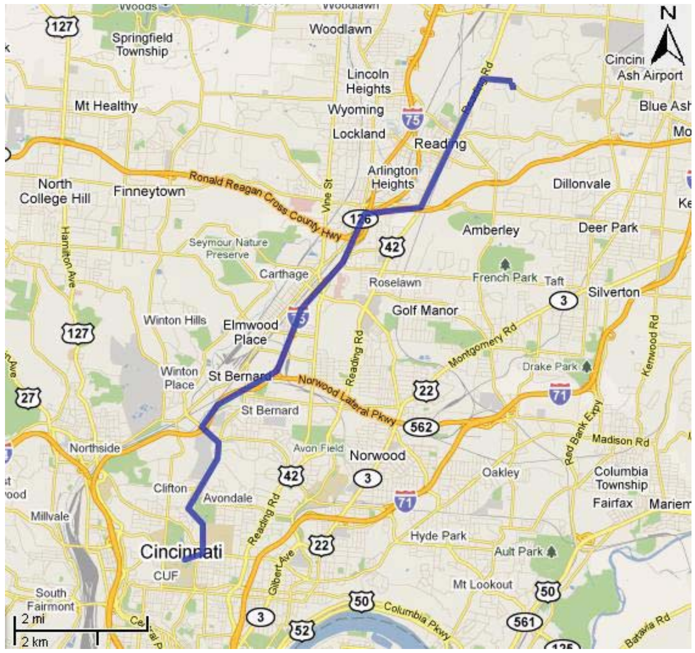

Figure 47: The Route by the Saturn on I75 – 2010 Google Map Data

Similarly, the route taken by the 2008 Toyota Camry Hybrid went through residential, highway and urban areas during the daily commute, and each route taken was initiated from a cold start. The route is taken in the same fashion starting with residential roadways leading to Interstate 71 (between exits 3 and 19) taken south toward UC campus. The route utilizes residential, highway, and urban roadways and is similar to those used by many UC commuters who live in the suburbs. Upon exiting the route utilized 4 and 6 lane arterial roadways before arriving at campus. The highway portion of this trip is the dominant portion with less travel taken before and after getting on the highway. The route is also a longer route taking between 35 and 50 minutes depending on traffic conditions. The residential section is 5.6km long while the highway and urban sections are 26.8km and 5.2km long respectively.

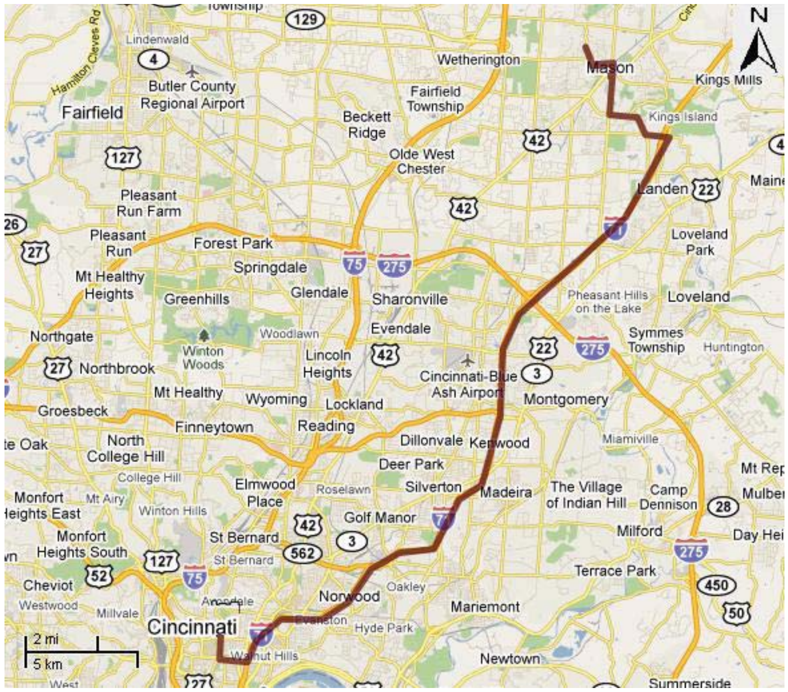

Figure 48: The Route by the Camry Hybrid on I-71 – 2010 Google Map Data

The Metro route (#78) taken also begins around the suburbs of Cincinnati and makes its way to the UC campus. It is on Vine Street (4 lane arterial roadways) for the large majority of the trip. The route begins in a commercial area in suburban Cincinnati and makes its way south toward campus passing through a variety of residential and commercial neighborhoods as it picks up residents. There are few passengers on the bus at the north end of the route and as it nears UC campus and downtown more passengers get on until most seats are occupied. Similar to the personal commute pattern, the Metro was taken towards campus during AM hours and away from campus during the PM hours. AM routes were taken just after the peak traffic period (9-10AM).

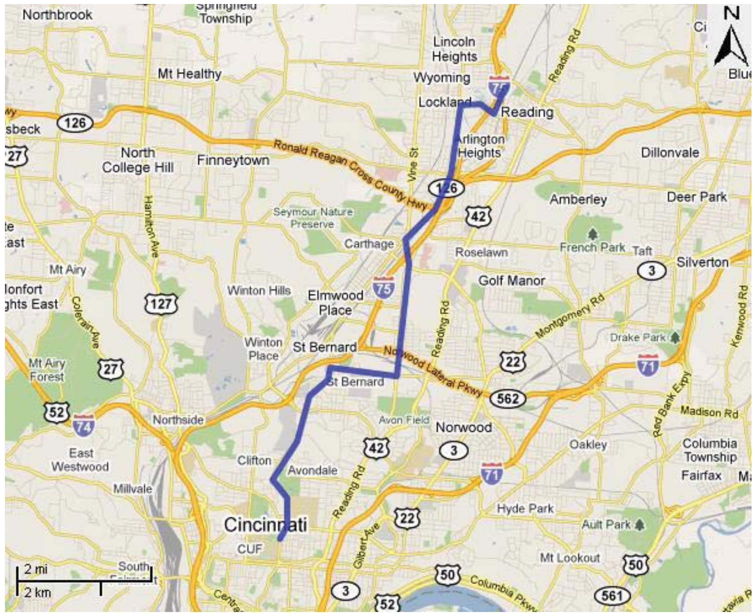

Figure 49: Metro Bus Route – 2010 Google Map Data

The final type of vehicle taken was the BTS shuttle bus. This is a small bus that sits 10-12 people and is a free service to students and faculty of the University of Cincinnati. Three different routes were taken on the shuttle bus, in the UC campus and surrounding area. The BTS north route visits both the west and east campus before traveling to residential areas north and northwest of UC main campus. The BTS east route also visits the west and east campuses before traveling to residential areas east of the west campus and south of the east campus. The last route taken is the CCM-Eden route which is used mainly to transport students within the west and east campus areas. It also travels to residential areas east of campus but all scheduled stops take place on campus property. Maps of the routes are shown in Appendix G.

5.4.2 Methods

During each route a T15 CO sensor and a GPS instrument were used to acquire data in the same manner used on the Singapore routes. The T15 instrument was set to continuously record CO data before during and after each trip. CO data and GPS data was set to record at 5 second intervals. Location, speed, acceleration, altitude, and road grade, and VSP data either obtained from the GPS or calculated from the GPS data. Met data was recorded on most routes using a handheld anemometer. On some routes temperature and humidity readings were taken.

Routes taken in the personal vehicles and on the metro bus were done at AM and PM peak times only with the exception of the Camry Hybrid AM routes which were just after the AM peak hour. Routes taken on the shuttle bus had varying times. Many were taken close together.

5.4.3 Results and Discussion

Table 37 shows a summary of results for vehicles taken in Cincinnati. Routes are separated into AM and PM periods. The number of routes, average speed, average CO, maximum CO, and the average increase in CO concentration over the ambient levels are given. Ambient CO levels are the concentrations read at the bus stop before getting in the bus and consist of a 1-2 minute average before entering the vehicle. These are not given for personal vehicles since the engine is not started when the researcher enters. Average CO levels are given for the Urban, highway, and residential sections for the personal vehicles. The other routes are not separated into regions since there is no distinct split in the routes. Detailed tables for each route are given in Appendix G.

In addition to the driving tests a control test was done inside a passenger car to see if the CO would increase without the engine on. The CO measurer was first exposed to the ambient environment where an average reading of 0.23 ppm was observed over a 10 minute interval. The T15 CO measurer was then placed inside the car without the engine turned on. Over a 10 minute interval the average CO reading was 0.27 ppm. Finally with a human sitting in the passenger seat a reading of 0.28 ppm was observed over the final 10 minute interval. Although a slight increase in CO was observed this control test shows that in vehicle CO concentrations reflect those of the surrounding environment when the engine is off.

Table 37: Vehicle Summary, Cincinnati

Vehicle	Season	Route Length (km)	Travel Period	# Taken	Average Duration (mm:ss)	Average Speed (km/h)	Average CO	Max CO	Average CO Increase Over Ambient	Urban (Ave CO)	Highway (Ave CO)	Residential (Ave CO)
Saturn	Winter	16.8	AM	6	0:24:41	40.8	1.03	12.74	NA	0.75	0.59	1.60
			PM	4	0:30:33	33.0	0.76	2.98	NA	0.92	0.82	0.44
Saturn	Summer	16.8	AM	6	0:24:41	40.8	0.78	2.33	NA	0.40	0.77	1.11
			PM	6	0:27:37	36.5	1.24	2.51	NA	1.291	1.41	1.00
Hybrid	Winter	35.2	AM	5	0:41:27	50.9	0.79	4.44	NA	0.76	0.68	1.31
			PM	4	0:43:14	48.8	0.29	7.00	NA	2.36	1.09	0.75
Metro	Summer	15.3	AM	5	0:34:33	26.6	0.52	4.52	0.40	NA	NA	NA
			PM	5	0:42:24	21.7	0.93	2.39	0.85	NA	NA	NA
BTS - North	Winter	6	varies	7	0:21:27	16.9	1.75	4.85	0.65	NA	NA	NA
BTS - East	Winter	5.4	varies	2	0:24:21	13.09	0.95	1.17	NA	NA	NA	NA
CTS CCM	Winter	5.3	varies	2	0:22:12	14.79	0.97	1.72	NA	NA	NA	NA

Table 37 shows a summary of the vehicle data taken in Cincinnati. Correlation with speed, acceleration, road grade and VSP was done but good correlations were not found. The highest levels of CO were observed in the BTS North route with the BTS East and CCM-Eden routes reporting levels similar to the metro bus in Cincinnati and levels observed in Singapore. Data from the North route was taken over 3 days at different times of the day and values of 1.4 ppm and up were observed over all 7 tests. Since this was not observed on the other shuttle routes this may be due to 1 or 2 vehicles used on these routes with poor emissions.

The metro bus showed the lowest levels of CO of the vehicles used and was more in line with routes taken from Singapore. Higher CO levels were observed during the evening periods on the Saturn summer tests, the Hybrid tests and the metro tests. The difference between the AM and PM CO levels was also about the same in all three vehicles (~0.4 ppm). An opposite trend was observed in the winter tests for the Saturn. This is mostly due to a spike in CO levels after the car is started from a cold start.

When analyzing the data by location not one area shows consistently higher CO. Instead a trend of declining CO as the trip progresses is observed in each case. This is most likely due to high emissions at a cold start and then increasingly better emissions of the vehicle as the trip progresses. Maximum CO levels observed indicate no threat to human health as the maximum observed for any route was only 12.74 ppm. Figure 50 shows a bar chart with average CO levels for each route and separated into AM and PM periods. Since few Bearcat Shuttle routes were taken they were combined into one average that includes mostly mid day routes with a few in the late morning and early evening.

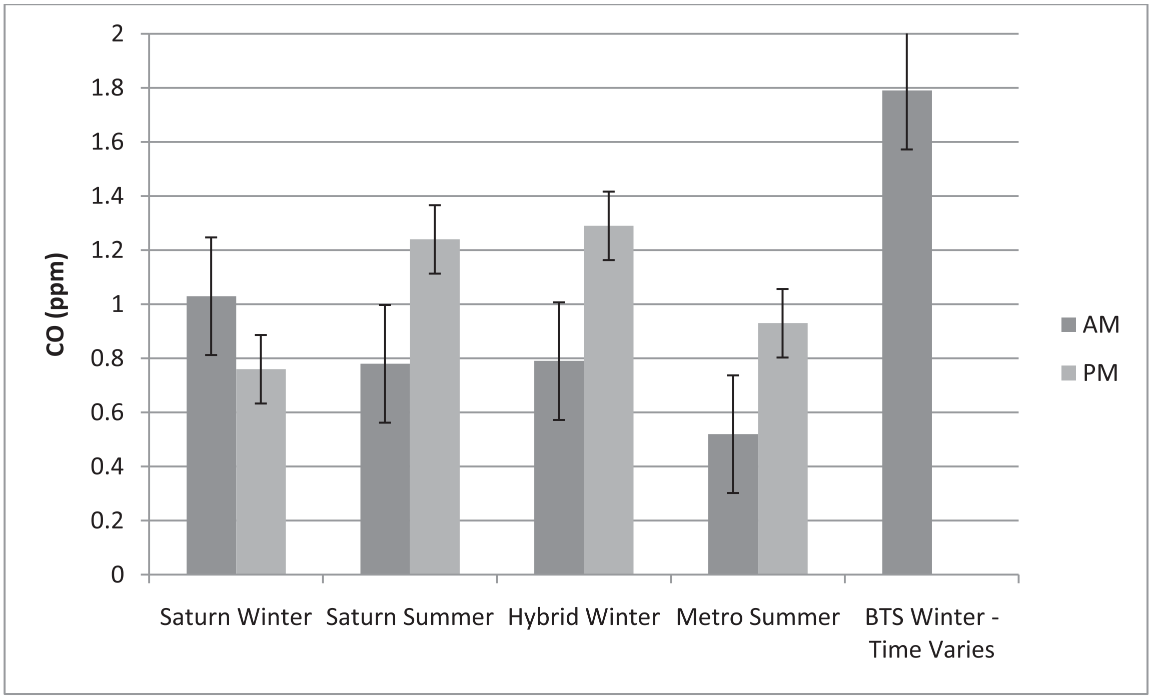

Figure 50: CO Levels of Routes Taken (Cincinnati)

Figure 4 in the literature review for in vehicle CO illustrates a trend in which CO emissions decrease as driving distance and time increase after a cold start. It was found that emissions are greatest during the coldest time periods and decrease as temperatures increase. This plot was replicated for the Saturn and Hybrid cars during AM and PM periods and shown in Figure 51. It was found that for both the Saturn and Hybrid cars a similar trend was seen during the winter tests in the morning hours. The Saturn was specifically able to produce a very similar graph during the winter test period. It was during this period that the highest levels of CO were observed. On average the in cabin CO levels were 4.2 ppm for the first kilometer driven. The Hybrid showed a slower decrease in CO possibly due to the engine characteristics of a hybrid vehicle. PM routes did not display as strong a pattern as AM tests. During the winter periods there is a decrease in CO with time for the first 3 km in the Saturn and for the second through sixth km driven in the Hybrid. During summer tests in the Saturn much lower CO levels were observed during the morning and a relatively flat pattern was observed in the evening indicating that vehicle emissions are either flat or increasing slightly with time.

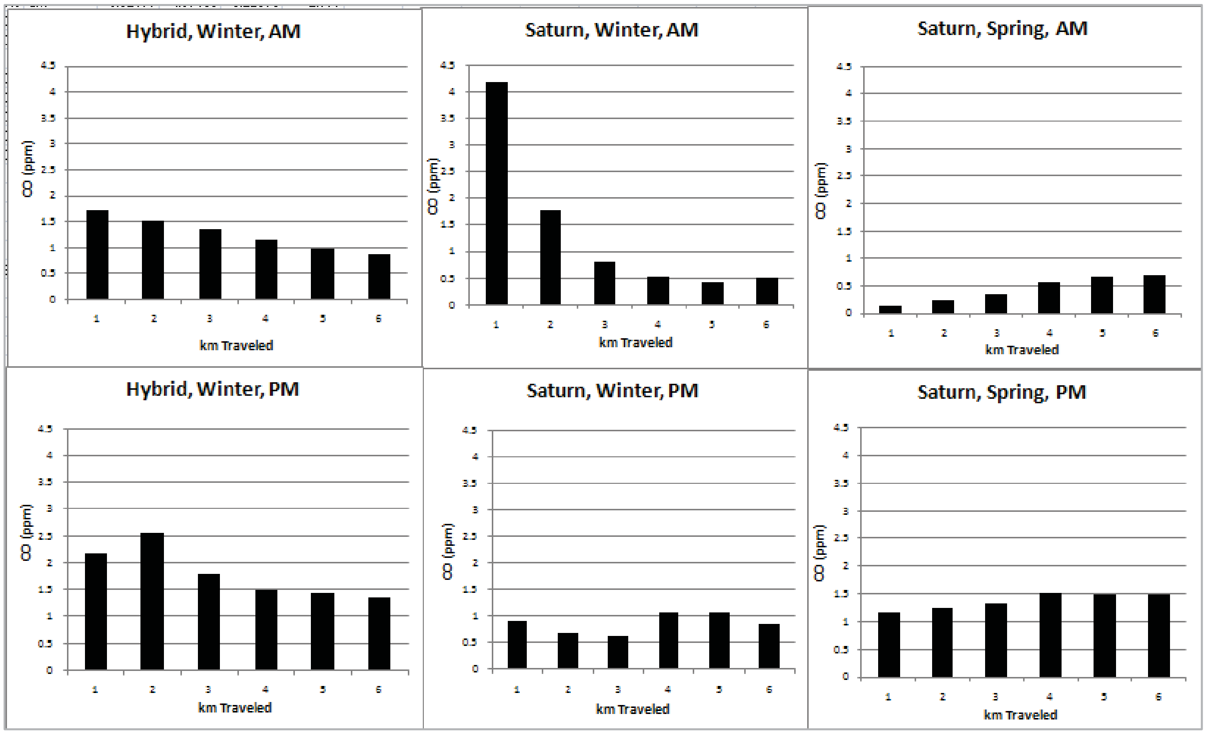

Figure 51: CO Trends in Vehicles after a Cold Start

5.5 Hayes Porter Study

5.5.1 Background and Location

A preliminary study was done at Hayes Porter Elementary to understand the impact of transportation characteristics upon air pollutant concentrations at an inner city school site. Both local roadways and the impact of I-75, a major interstate highway, were studied. The school is home to over 500 elementary students and is located in Cincinnati's west end. School begins at 7:45AM and lets out at 2:15PM. Carbon monoxide has been selected as a representative traffic generated pollutant and the traffic column is used to represent transportation. This information could offer helpful information to the health related evaluation of the students in the school. CO sensors were set up at several locations around the site. Three areas were studied to understand their impact on CO at the site.

- School Bus Drop off (AM) and Pick Up (PM) Times
- Local Traffic
- I-75 Traffic

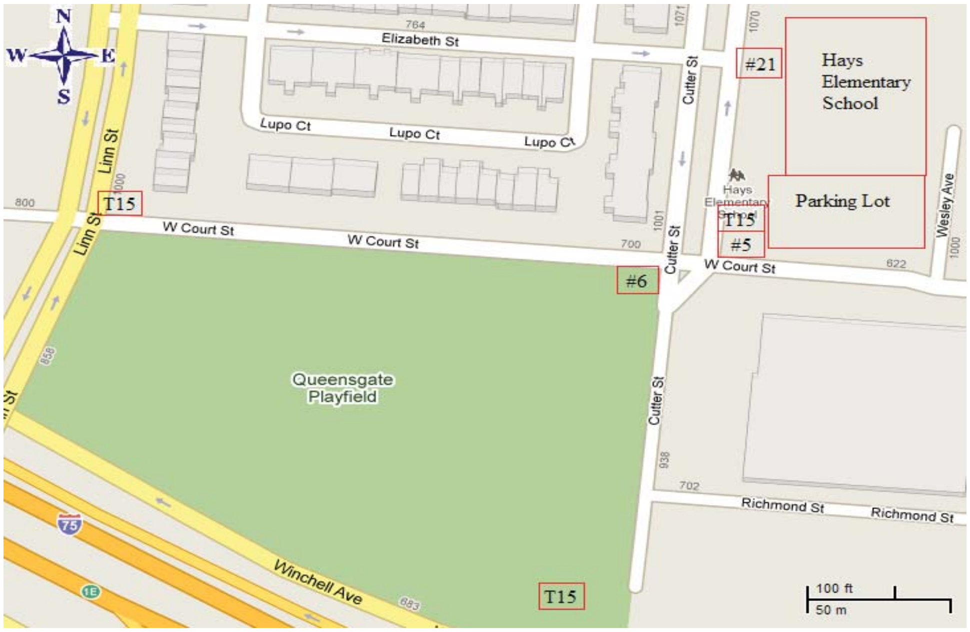

Figure 52: Hayes Porter Elementary Site – 2010 Google Map Data

There is a short period of time in the morning and in the afternoon when school buses arrive at the school. In the morning the buses arrive at slightly different times between 7:20 and 8:00AM and in the afternoon the buses arrive at the similar times and wait idling for school to let out between 2 and 2:30 PM. The buses usually wait on the north side of Queensgate Playfield before pulling up to the front of the school to pick up the kids.

Traffic directly around the site is very light on Court and Cutter streets while heavier traffic is seen at the Lynn and Court Intersection. The location and proximity of the school to I-75 is what stands out about the school relative to other schools. The school is located near downtown Cincinnati and is downwind from I-75, a large 8 lane expressway. The highway is about 850 ft from the school.

5.5.2 Methods

CO measurements were taken in front of the school during school bus drop off and pick up times, at Court and Cutter intersection periodically and near I-75. Both WSN and T15 sensors were used, however readings from the WSN indicate the data may be unreliable so results from only the T15 are used here. Tests were done during the afternoon of March 4th, the morning of March 5th and all day from March 16th to March 18th 2010.

During times of school bus activity an instrument was placed on a sign near the front of the school at 1.8m in height where the buses picked up and dropped off students. Bus activity was recorded in field notes noting when buses arrived and left and how long idle times were. Notes are shown in appendix H.

Traffic Counts were done at the Lynn and Court Intersection at peak traffic times. From these traffic counts traffic at Court and Cutter was obtained. As a result traffic that did not come from the west approach or travel to the west approach of the Court and Cutter intersection was not accounted for. This represents less than a quarter of the total traffic as the west approach is the busiest of the four.

CO measurements were taken during most test periods near I-75. Due to the amount of traffic and difficulty in filming the location a standard traffic pattern for I-75 was used to simulate the traffic pattern.

5.5.3 Results and Discussion

Figure 53 shows the CO trends vs time during periods of bus activity. Corresponding notes are given in appendix H. Most of the peaks in CO concentration did not directly correspond to bus activity with the exception of the afternoon test on March 17th where a small spike was seen at 2:12 PM when the buses arrived. Only one major spike during the six test periods occurred where the CO concentration rose to over 10 ppm at 7:58 AM on March 16th. This didn't respond to any bus activity at the time and may have been due to a car passing by with poor emissions.

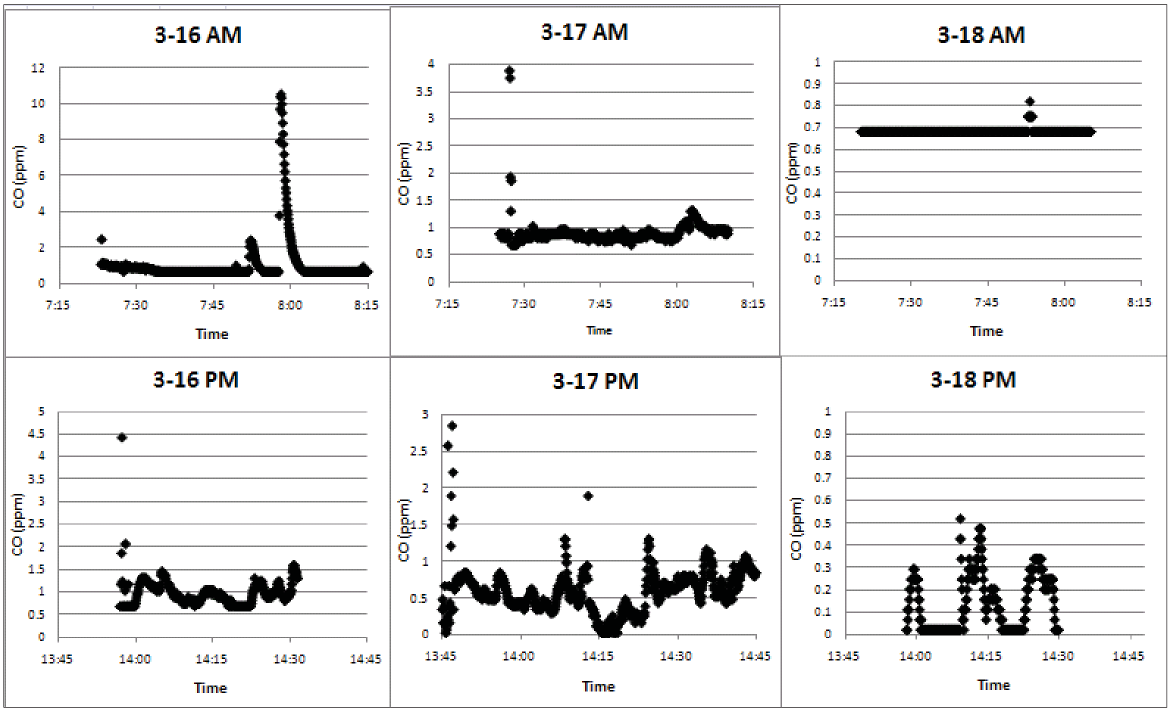

Figure 53: CO Trends During School Bus Drop Off and Pick Up Times

Table 38 shows the CO concentrations observed at the Court and Cutter (CC) intersection at peak times during the day.

Table 39 shows the same information for the Lynn and Cutter intersection (LC). All measurements are well below the current NAAQ standard for carbon monoxide of 9 ppm on average in an 8 hour period.

Table 38: CO Concentrations at Court and Cutter Intersection

Date	Time	Instrument	Avg. CO (ppm)	Max CO	Max time
4-Mar	14:40-15:35	T15-1	0.73	1.90	14:38
5-Mar	7:50-9:00	T15-2	2.25	3.26	7:52
16-Mar	7:20-16:40	T15-2	0.19	1.31	7:55
17-Mar	7:10-7:25	T15-1	1.08	1.44	7:10
	15:30-18:30	T15-1	1.46	3.40	17:57
18-Mar	7:10-7:25	T15-2	0.43	0.55	7:13
	11:00-14:00	T15-1	0.83	1.86	13:43
	14:30-18:30	T15-1	1.13	5.34	17:51

Table 39: CO Concentrations at Lynn and Cutter Intersection

Date	Time	Instrument	Avg. CO (ppm)	Max CO	Max time
16-Mar	14:35-19:05	T15-1	0.81	2.09	18:28
17-Mar	14:00-15:30	T15-1	1.38	2.23	13:58
4-Mar	14:50-15:35	T15-2	0.03	0.17	15:08
5-Mar	8:00-8:50	T15-1	0.72	1.17	8:45

Table 40 shows the correlation of CO with traffic counts that were obtained. CC stands for the Court and Cutter intersection while LC stands for the Lynn and Court intersection. Empty spaces mean there was no sensor located at that location. For the Lynn and Court intersection correlations were obtained for both the total traffic counts of the entire intersection and traffic counts for only vehicles on the side of the intersection the sensor was located on. Overall no consistent correlation was observed between the local traffic and CO levels possibly due to the relatively low amount of traffic at the site.

Table 40: CO Correlation with Traffic

Date	Period	Sensor Location	Begin	End	LC Correl	CC Correl	Correl w Sensor side traffic only
16-Mar	AM Pk	CC	7:25	9:00		(0.00)	
17-Mar	AM Pk	CC	7:15	7:25		0.75	
18-Mar	AM Pk	CC	7:15	7:25		0.22	
16-Mar	noon	CC	10:55	13:00		(0.28)	
16-Mar	MA	CC	13:35	15:30		(0.12)	
16-Mar	MA	LC	14:35	16:30	0.08		0.02
17-Mar	MA	LC	13:55	15:10	0.33		0.08
18-Mar	MA	CC	13:49	15:20		(0.17)	
16-Mar	PM Pk	CC	15:35	16:40		(0.33)	
16-Mar	PM Pk	LC	16:35	18:50	(0.04)		0.17
17-Mar	PM Pk	CC	16:55	18:05		0.17	
18-Mar	PM Pk	CC	16:25	18:25		0.19	

Monitoring CO from I-75 was done approximately 20 feet from an entrance ramp at a height of about 15 feet. The CO was monitored for extended periods on each day.

Figure 54 through Figure 56 show the CO variation with time and also the normal traffic pattern on I-75. Hourly averages are used in the plot. CO levels were shown to increase during peak hours and a correlation coefficient for traffic and CO of 0.18 found for March 17th. A correlation coefficient of 0.19 was found for data on the 18th. A negative correlation was found on the 16th however the use of two different instruments and baseline drift in the calibration curve makes the data less reliable. Calm wind conditions were observed all 3 days with the Cincinnati/Northern Kentucky airport reporting either no wind or a slight wind coming from the north. Met data is shown in appendix H.

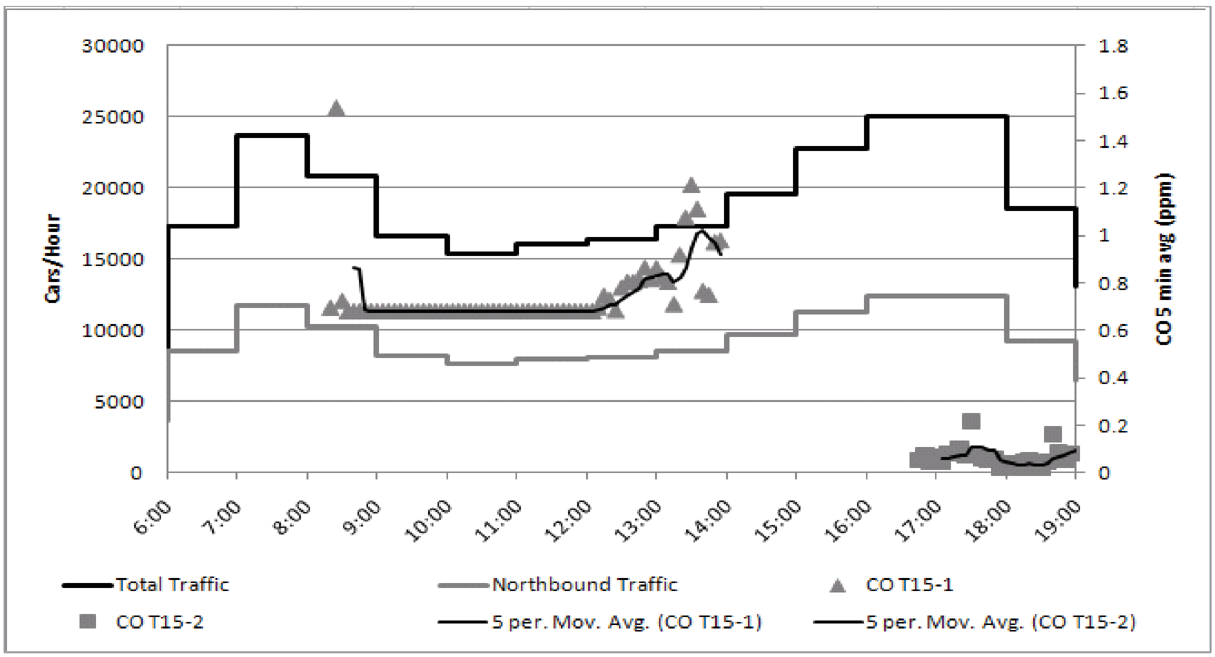

Figure 54: I-75 Traffic and CO Trends, 3-16-10

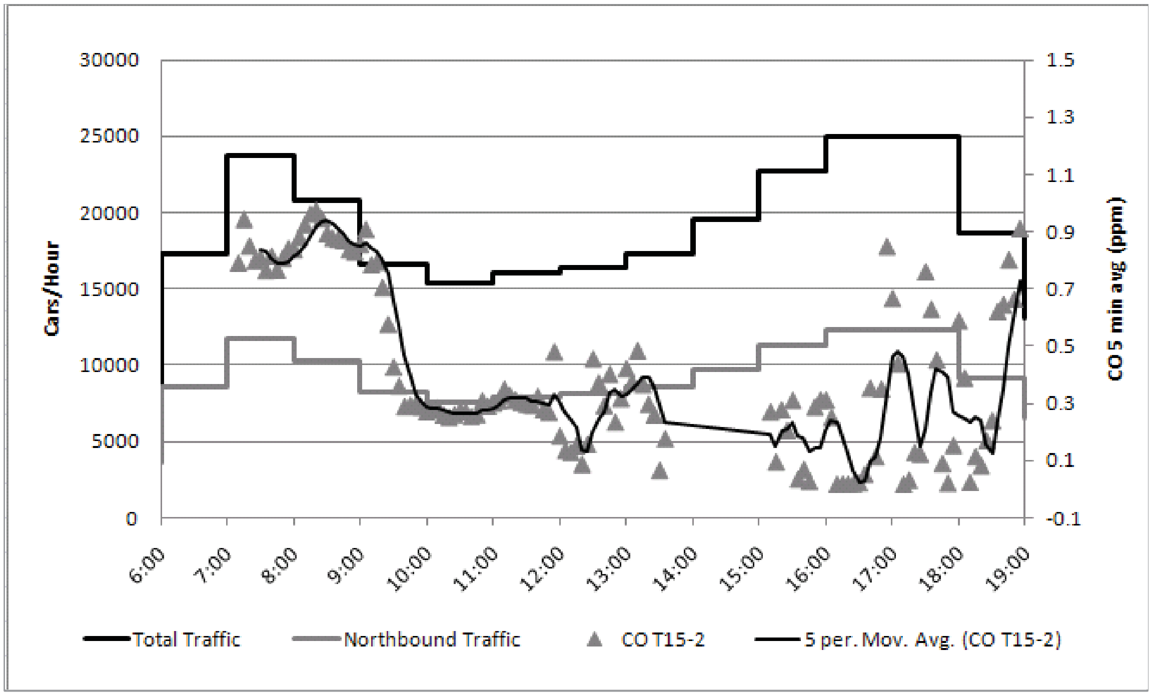

Figure 55: I-75 Traffic and CO Trends, 3-17-10

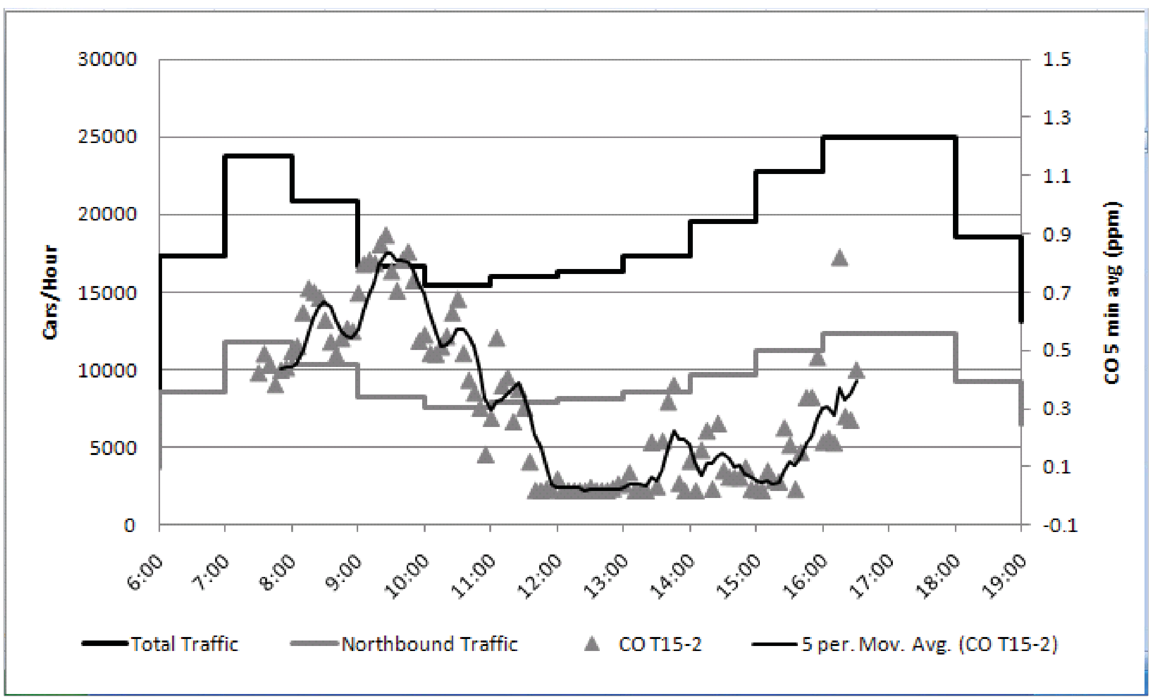

Figure 56: I-75 Traffic and CO Trends, 3-18-10

6. Conclusions

The correlations of CO and traffic indicators (such as traffic volume, bus delay, speed, acceleration, stopped delay, vehicle types etc.) were investigated in this study at two very different urban university campuses, the National University of Singapore and the University of Cincinnati. Representative locations investigated included busy intersections, bus stops, enclosed garages and inside buses and commuter vehicles. Measurements were taken at representative time periods, including morning and afternoon peak hours and non peak hours. Direct correlations with vehicle volume at a 5 minute interval were not seen on a consistent basis during ambient testing. Dynamic factors such as vehicle delay showed a better correlation especially at the busy bus stops around the NUS campus in Singapore. A cycle of peaks in CO concentration was observed with the traffic signal timing particularly at the Singapore location where the sensors were exposed mainly to one approach. A brief test along a highway showed elevated CO levels during peak traffic times. Investigating a longer time period and performing more traffic delay calculations may yield a more significant relationship between traffic and CO concentrations.

Between the two garages tested the garage with a more consistent pattern of traffic entering and exiting the garage showed a higher correlation. Both garages showed consistent positive correlations with traffic. At the CCM garage the highest levels of CO were observed especially in the PM hours when cars are exiting after coming off of a cold start. Future tests investigating daily trends in CO levels and examining different garages with varying entrance and exit systems may prove useful in enforcing these findings. Vehicle emissions were shown to have an impact on the CO levels within the cabin. Elevated CO levels were observed when compared with ambient concentrations and larger buses were shown to have the highest CO concentrations compared with other bus routes. Personal cars that started from a cold start in winter times showed the highest in cabin CO levels of any vehicle tested. This is expected with gasoline powered personal vehicles have the highest CO emissions during winter time after a cold start.

7. Future Work

Future work can take several different directions. Although CO is the focus of this study future studies will investigate several different pollutants, NOx and PM in particular which are at elevated concentrations near roadways. Data acquired during this study can also be further examined for a more in depth analysis such as implementation in a dispersion model or for use in a neural network analysis which has been shown to be effective in predicting roadside concentrations of CO [17].

We can also build upon some of the significant findings that were observed in this study. Here we observed that bus delay had an impact on CO levels when the sensor was in close proximity to the bus and surrounding traffic was light. Future work may examine whether this same phenomenon is observed when the sensor is placed further away or study a location where cars are picking up and dropping off passengers since cars have higher CO emissions. The state of acceleration was shown to be a very important parameter when examining CO levels in the ambient environment. Future work may examine this further by examining the queue of cars just before the traffic signal is green to see if the spike in CO is caused by a longer queue or a certain mix of vehicles. Traffic counts or delay calculations should be performed with the signal cycle length in mind so that each period has the same parts of the signal cycle. IE if the cycle is 90 seconds traffic counts should be in multiples of 90 seconds.

Future garage tests can take a few different approaches. It was shown that a consistent pattern of passing through the traffic gate yielded predictable levels of CO while a more complex pattern that was seen in the CCM garage yielded less predictable. A more detailed test can be done where the time idle for each car is recorded as well when it arrives and when it leaves also the length of the queue if any. The type and age of car are also important to emissions and could be recorded. The temporal variation of CO during this test will show more specifically which of these parameters is the most important. Finally at the other end of the spectrum simply examining the daily trend of CO within the garage for several days at different parts of the year as well as general traffic info will allow us to see what conditions yield the highest levels of CO within the garage. Other pollutants can also be studied in the same manner.

In vehicle tests have shown that both the vehicle's own emissions and the concentration of the surrounding environment influence the level of the pollutant within the vehicle. Future work may look to substantiate this further by isolating a single vehicle and monitoring ambient concentration, in vehicle concentrations and direct emissions from the vehicle.

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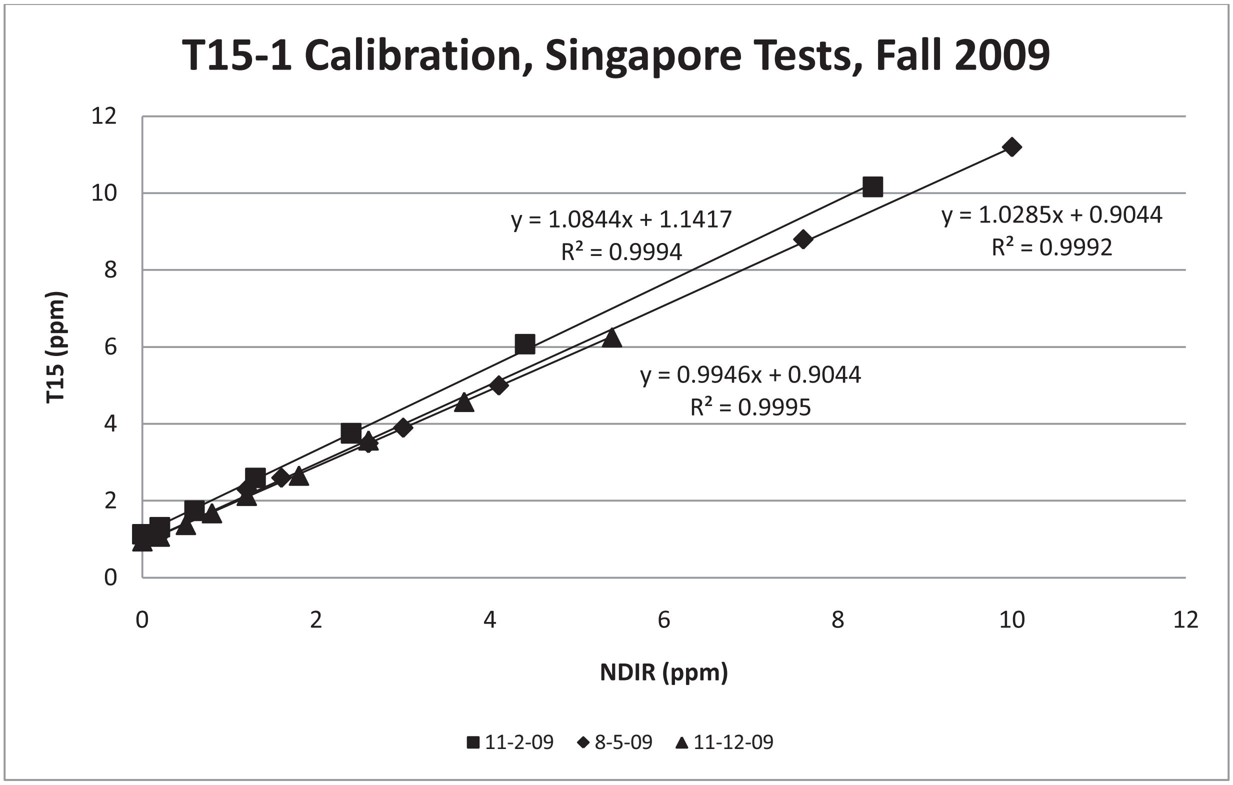
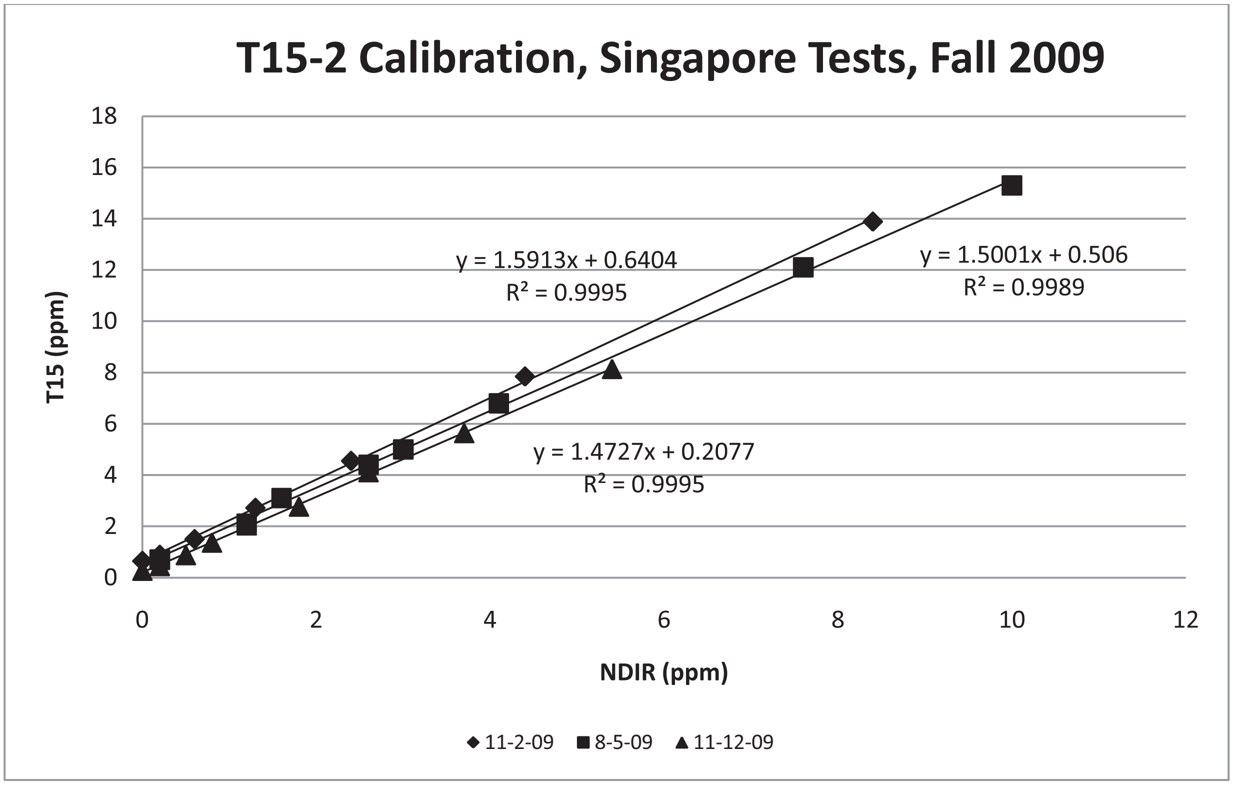
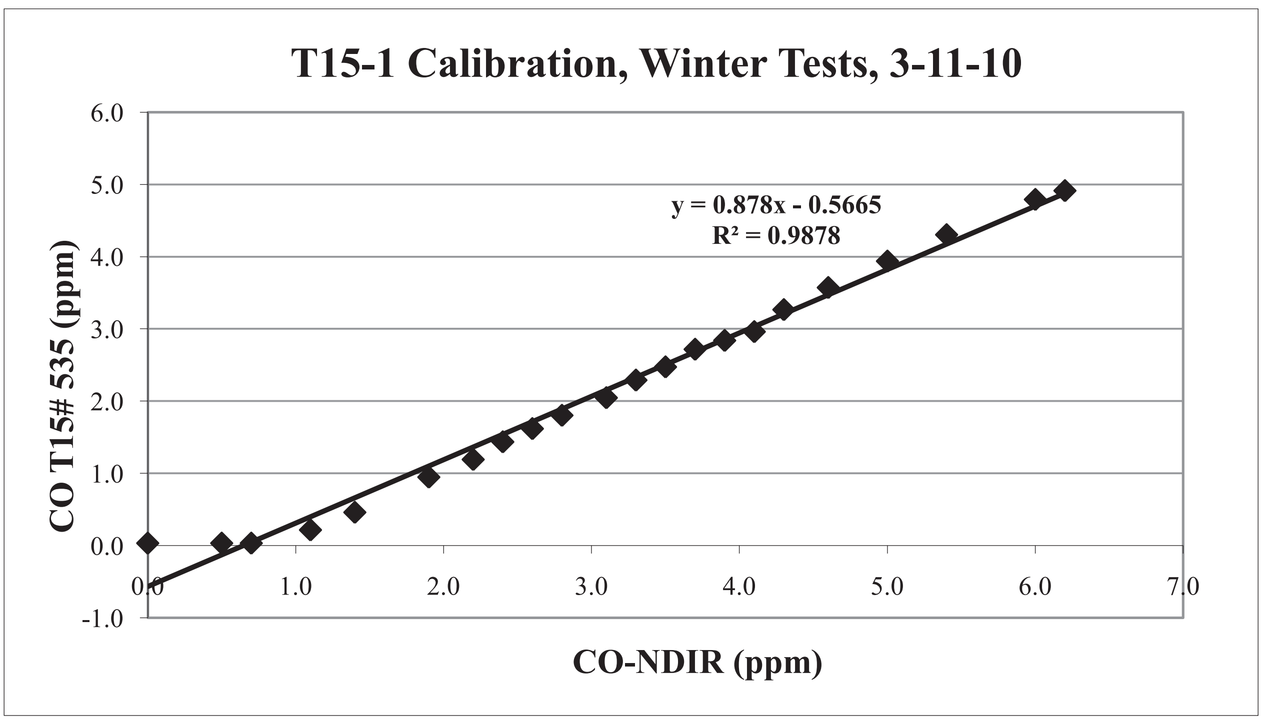
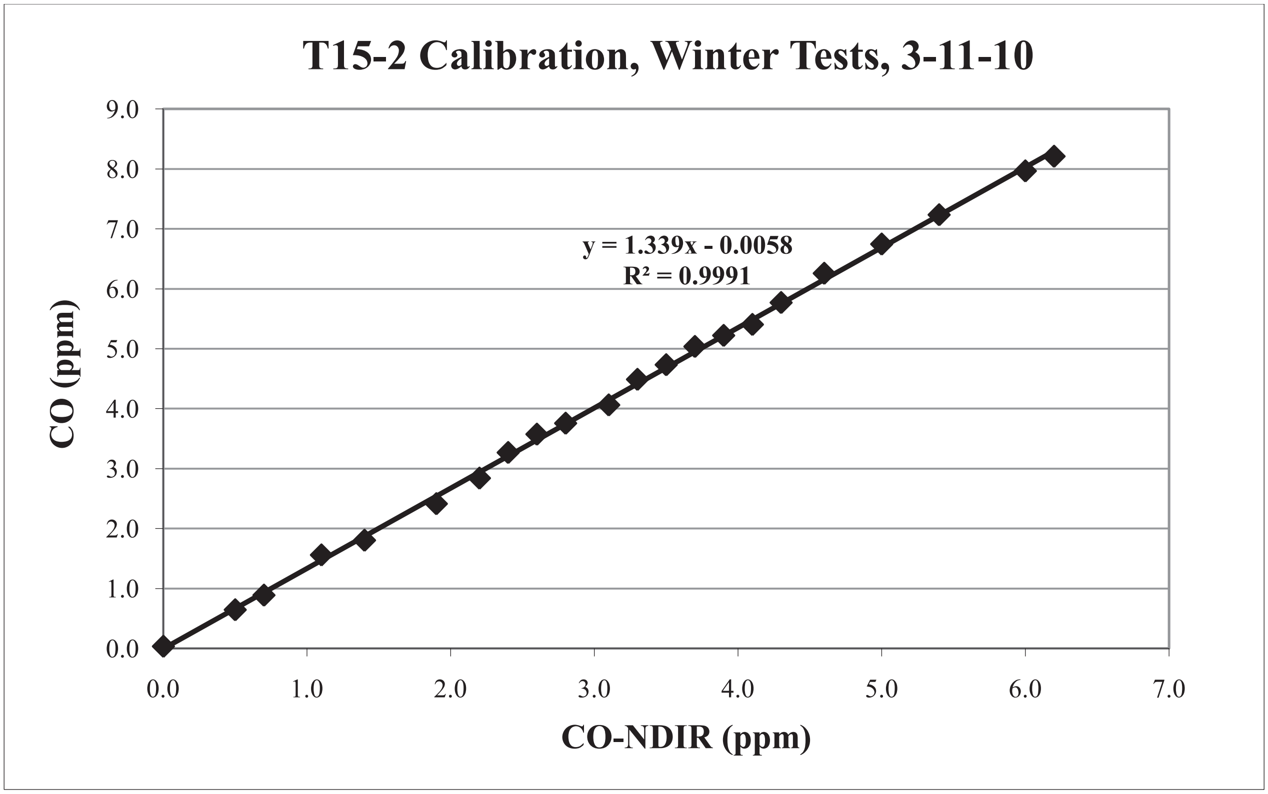
Appendix A: Calibration Curves





Calibration from 8-5-09 and 11-12-09 were averaged since incorrect conditions were used on 11-2.

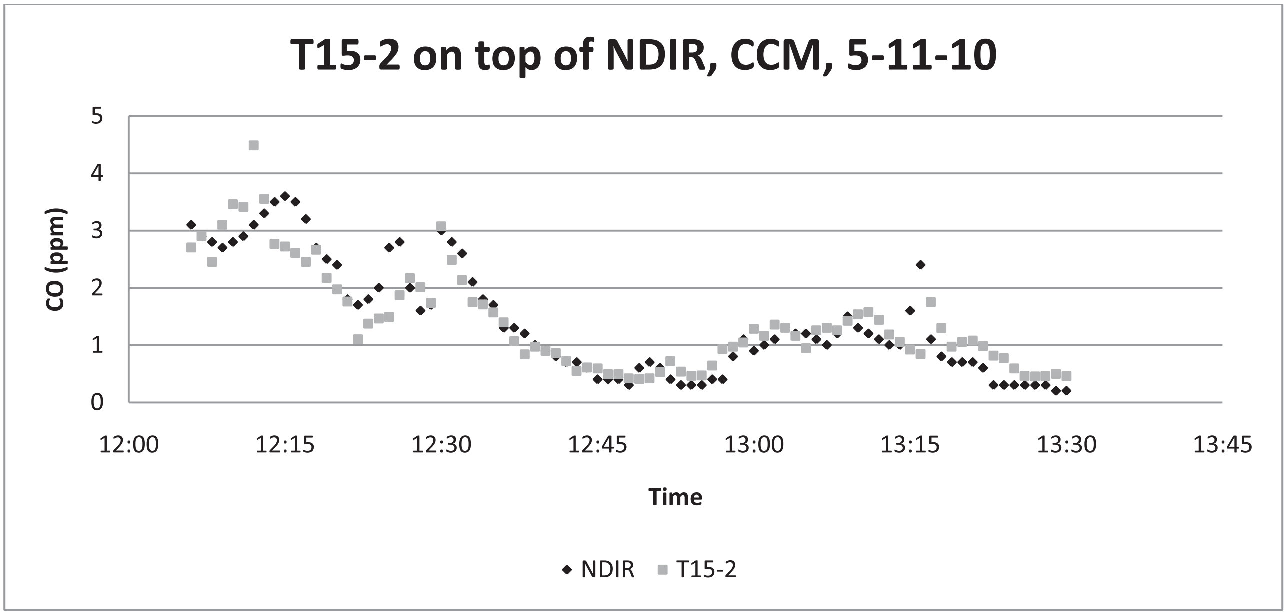


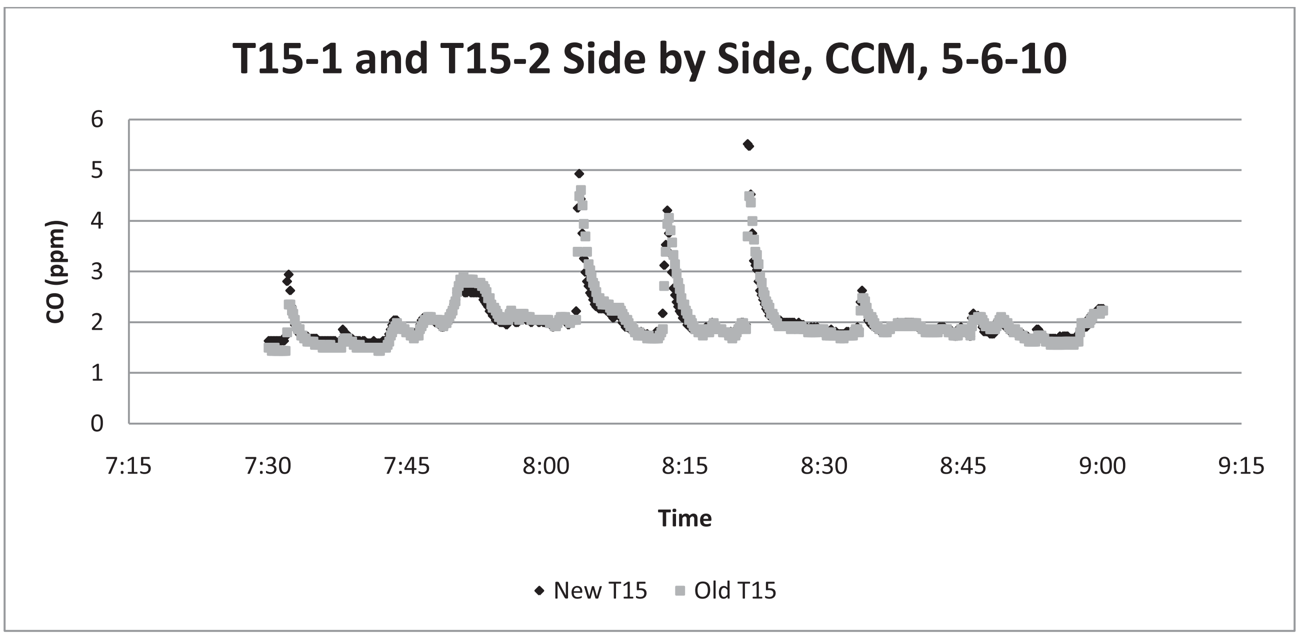


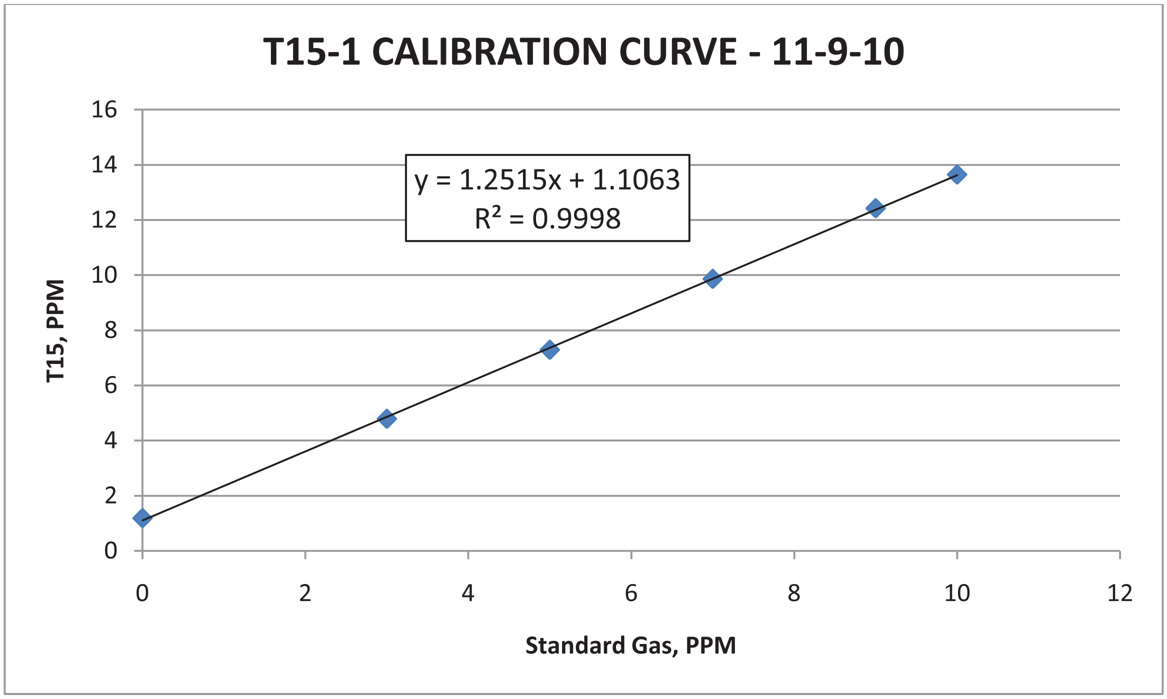
Due to unavailability of instruments a test in the CCM garage was used to calibrate the T15 sensors for the Spring Tests. Below are plots comparing the NDIR and T15-2 and T15-1 and T15-2 when they were side by side. The plot of the dependent instrument in each case was created by solving for the least amount of cumulative error between the two. The baseline of the calibration from these plots was adjusted to reflect normal observed baselines from other tests.

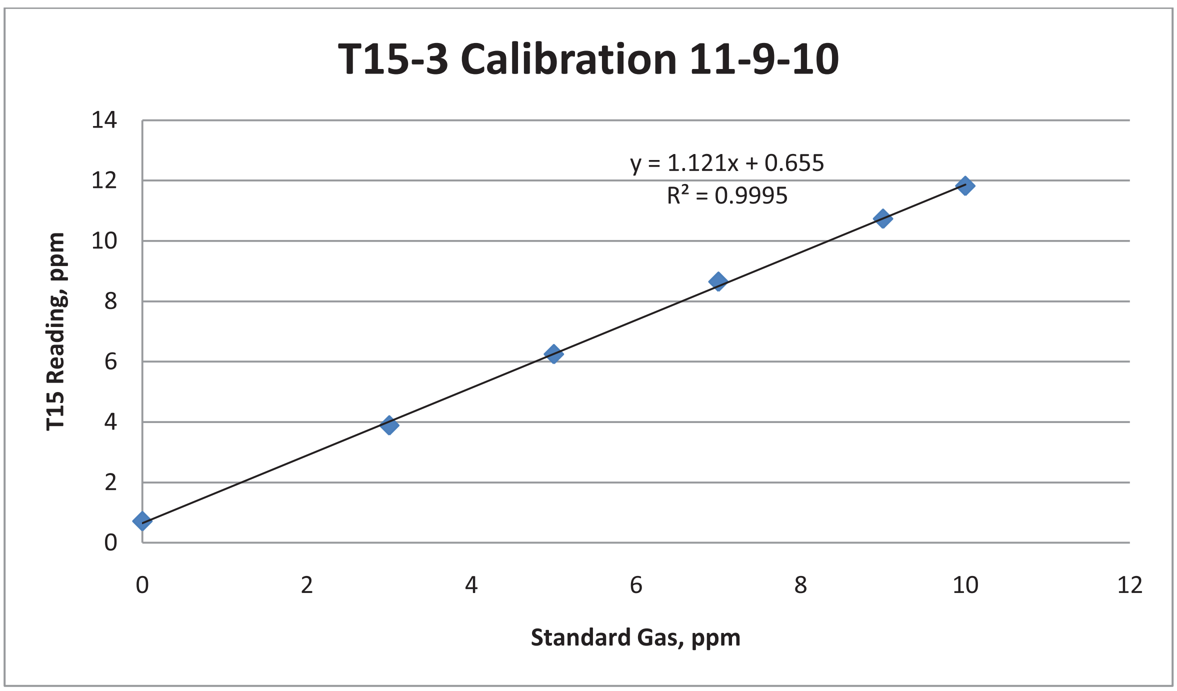
T15 – 1 equation: CO = (Measured CO - 1.5) / 2.116

T15 – 2 equation: CO = (Measured CO - 1.8) / 1.564


T15-2 on top of NDIR, CCM, 5-11-10
CO (ppm)
0
1
2
3
4
5
12:00
12:15
12:30
12:45
13:00
13:15
13:30
13:45
Time
NDIR
T15-2


T15-1 and T15-2 Side by Side, CCM, 5-6-10
CO (ppm)
0
1
2
3
4
5
6
7:15
7:30
7:45
8:00
8:15
8:30
8:45
9:00
9:15
Time
New T15
Old T15





Appendix B: NUS Bus Stops

Clementi Intersection

NUS Bus Stop, NUS Side

NUS Bus Stop, Opposite NUS

Computer School Inbound

Computer School Outbound

Library

NUH Inbound

NUH Outbound

NUS Bus Stop Timing, Traffic, and Met Data Summary

Clementi – NUS Side

Date	Time Period	Start	End	Duration	Avg Veh	Wind Speed (mph)	Wind Dir	Temp (C)	RH
24-Sep	AM	7:54	9:19	1:25	136.3	6.4	N	22.8	87.6
6-Oct	AM	8:05	9:35	1:30	179.4	2.0	SW	25.8	74.8
6-Oct	Noon	11:10	12:00	0:50	83.2	2.4	SSW	27.3	77.3
30-Sep	MA	15:15	16:14	0:59	114.9	No Met Data			
24-Sep	PM	17:48	19:18	1:30	95.3	6.0	SW	28.4	66.8
28-Sep	PM	18:30	18:54	0:24	102.8	3.6	SSE	29.4	65.3
29-Sep	PM	17:27	18:31	1:04	105.9	4.5	SSW	29.4	58.0
1-Oct	PM	16:29	17:44	1:15	96.4	4.7	SSW	27.7	73.0
6-Oct	PM	15:34	19:27	3:53	116.2	4.6	WSW	28.5	66.0

Clementi – Opp NUS

Date	Time Period	Start	End	Duration	Avg Veh	Wind Speed (mph)	Wind Dir	Temp (C)	RH
24-Sep	AM	7:55	9:14	1:19	107.4	6.4	W	22.8	87.6
6-Oct	AM	8:05	9:35	1:30	115.3	2.0	SW	25.8	74.8
6-Oct	AM	8:05	9:35	1:30	115.3	2.0	SW	25.8	74.8
6-Oct	Noon	11:10	12:00	0:50	108.0	2.4	SSW	27.3	77.3
6-Oct	Noon	11:10	12:00	0:50	108.0	2.4	SSW	27.3	77.3
29-Sep	MA	15:15	16:14	0:59	119.9	6.9	W	29.4	58.0
29-Sep	MA	15:15	16:14	0:59	119.9	6.9	W	29.4	58.0
24-Sep	PM	18:00	19:14	1:14	182.3	6.0	SW	28.4	66.8
28-Sep	PM	18:30	18:54	0:24	78.5	3.6	SSE	29.4	65.3
29-Sep	PM	17:27	18:26	0:59	222.1	4.5	SSW	29.4	58.9
29-Sep	PM	17:27	18:26	0:59	222.1	4.5	SSW	29.4	58.9
29-Sep	PM	17:27	18:26	0:59	222.1	4.5	SSW	29.4	58.9
1-Oct	PM	16:30	18:51	2:21	197.2	4.7	SSW	27.7	73.0
1-Oct	PM	17:45	18:51	1:06	197.2	4.7	SSW	27.7	73.0

1-Oct	PM	16:41	17:45	1:03	197.2	4.7	SSW	27.7	73.0
6-Oct	PM	15:35	16:35	1:00	116.2	4.6	WSW	28.5	66.0
6-Oct	PM	17:30	18:40	1:10	197.8	3.5	SW	28.1	70.3
6-Oct	PM	15:35	16:35	1:00	116.2	4.6	WSW	28.5	66.0
6-Oct	PM	17:30	18:40	1:10	197.8	3.5	SW	28.1	70.3

Library – Library Side

Date	Time Period	Start	End	Duration	Avg Veh	Avg Delay	Wind Speed (mph)	Wind Dir	Temp (C)	RH
16-Sep	AM	12:45	14:19	1:34	21.7	88	5.3	SW	29.4	68.8
8-Oct	AM	7:51	9:20	1:29	22.1	106.4	2.7	SE	28.4	75.1
15-Oct	AM	13:29	14:18	0:49	24.1	151	4.1	S	27.1	76.8
8-Oct	Noon	12:40	15:14	2:34	13.1	105.2	1.7	SSE	26.2	73.8
8-Oct	MA	15:40	17:04	1:24	17.8	88.1	2.1	SE	25.9	76.2
15-Sep	PM	17:30	18:49	1:19	26.8	NA	4.5	SSE	29.0	71.7
2-Oct	PM	15:45	17:00	1:15	14.9	89.2	4.5	SSW	29.8	67.4
8-Oct	PM	17:15	18:46	1:31	26.0	127.8	0.3	SSW	26.9	69.9

Library – Opp Library

Date	Time Period	Start	End	Duration	Avg Veh	Avg Delay	Wind Speed (mph)	Wind Dir	Temp (C)	RH
16-Sep	AM	12:45	14:24	1:39	18.4	108.5	5.3	SW	29.4	68.8
2-Oct	AM	15:44	17:03	1:19	17.4	176	4.5	SSW	29.8	67.4
8-Oct	AM	7:51	9:20	1:29	20.9	80.7	2.7	SE	28.4	75.1
15-Oct	AM	13:29	14:18	0:49	23.3	161.5	4.1	S		
8-Oct	noon	12:40	15:14	2:34	18.6	113.8	1.7	SSE	26.2	73.8
15-Sep	PM	17:34	18:53	1:19	22.7	NA	4.5	SSE	29.0	71.7
8-Oct	PM	17:15	18:46	1:31	20.0	163.6	0.3	SSW	26.9	69.9

Computer School - Inbound

Date	Time Period	Start	End	Duration	Avg Veh	Avg Delay	Wind Speed (mph)	Wind Dir	Temp (C)	RH
18-Sep	AM	8:40	9:09	0:29	32.8	73	0.3	ESE	22.8	87.6
9-Oct	AM	8:47	9:51	1:04	35.7	84.6	2.5	S	28.8	70.0
19-Oct	AM	8:00	9:19	1:19	39.7	96.2	0.3	SSW	28.5	70.0
9-Oct	MM	10:23	11:37	1:14	32.8	67.7	4.1	S	29.7	63.0
7-Oct	noon	11:59	13:23	1:24	28.6	90.2	4.4	SW	29.3	62.4
7-Oct	noon	11:59	13:24	1:25	28.6	90.2	4.4	SW	29.3	62.4
7-Oct	MA	15:35	16:42	1:07	24.4	106.5	1.6	S	29.9	60.1
7-Oct	PM	17:38	18:22	0:44	30.6	76.1	2.4	SSW	29.8	55.5
19-Oct	PM	17:45	18:59	1:14	40.4	79.3	4.5	S	29.8	64.2

Computer School - Outbound

Date	Time Period	Start	End	Duration	Avg Veh	Avg Delay	Wind Speed (mph)	Wind Dir	Temp (C)	RH
2-Oct	AM	13:02	14:47	1:45	22.0	71.1	4.8	S	30.1	64.0
9-Oct	AM	8:47	9:51	1:04	40.4	27.7	2.5	S	28.8	70.0
19-Oct	AM	8:00	9:19	1:19	38.5	53.1	0.3	SSW	28.5	70.0
7-Oct	MM	9:30	10:34	1:04	30.9	52.6	4.8	SW	28.0	70.9
9-Oct	MM	10:30	11:30	1:00	77.6	30	4.1	S	29.7	63.0
9-Oct	MM	10:30	11:30	1:00	77.6	30	4.1	S	29.7	63.0
7-Oct	noon	12:00	13:24	1:24	27.7	41.7	4.4	SW	29.3	62.4
10-Sep	PM	17:30	18:49	1:19	36.5	NA	4.5	S	29.0	69.0
7-Oct	PM	17:38	18:57	1:19	30.9	93.3	2.4	SSW	29.8	55.5
19-Oct	PM	17:45	18:59	1:14	33.8	78.3	4.5	S	29.8	64.2

NUH - Inbound

Date	Time Period	Start	End	Duration	Avg Veh	Avg Delay	Wind Speed (mph)	Wind Dir	Temp (C)	RH
18-Sep	AM	7:35	8:29	0:54	90.0	60	0.3	ESE	27.1	76.5
7-Oct	AM	8:14	9:48	1:34	76.7	37.8	3.7	SSW	27.8	73.5
9-Oct	AM	8:08	8:32	0:24	87.3	68.2	1.0	SSE	28.1	76.7
17-Sep	MA	12:45	14:04	1:19	68.9	21	2.4	SE	27.4	72.7
2-Oct	MA	13:19	14:52	1:33	72.3	30.4	4.8	S	30.1	64.0
7-Oct	MA	15:41	16:30	0:49	71.6	19.7	1.6	S	29.9	60.1
9-Oct	MA	11:53	13:16	1:23	75.3	34.9	5.1	SSW	30.0	64.1
7-Oct	PM	17:54	18:58	1:04	65.8	25.8	2.4	SSW	29.8	55.5

NUH - Outbound

Date	Time Period	Start	End	Duration	Avg Veh	Avg Delay	Wind Speed (mph)	Wind Dir	Temp (C)	RH
18-Sep	AM	7:15	8:59	1:44	74.6	18.6	0.3	ESE	27.1	76.5
7-Oct	AM	8:14	9:43	1:29	66.8	29.2	3.7	SSW	27.8	73.5
9-Oct	MM	10:30	11:30	1:00	80.3	22.8	4.1	S	29.7	63.0
9-Oct	Noon	11:53	13:13	1:20	81.1	20	5.1	SSW	30.0	64.1
17-Sep	MA	12:50	14:09	1:19	70.5	19.1	2.4	SE	27.4	72.7
2-Oct	MA	13:27	14:11	0:44	80.0	17.6	4.8	S	30.1	64.0
7-Oct	MA	15:41	16:25	0:44	81.0	15	1.6	S	29.9	60.1
11-Sep	PM	17:36	18:56	1:19	104.3	NA	3.2	SSE	26.4	78.1
7-Oct	PM	17:55	18:54	0:59	83.8	16.3	2.4	SSW	29.8	55.5

NUS Bus Stops, Correlation With Total Traffic

Clementi NUS			Simultaneous R Values					1 Minute Delay R Values				
Date	Period	Instrument	cars	bikes	LD	HD	Total Traffic	cars	bikes	LD	HD	Total Traffic
Sep-10	AM	T15-1	0.52	(0.18)	0.65	0.48	1.00	0.85	0.93	0.22	(0.23)	0.22
Sep-10	PM	T15-1	(0.47)	(0.22)	0.12	(0.32)	(0.50)	(0.40)	(0.15)	0.14	(0.23)	(0.42)
Sep-10	PM	T15-1	(0.16)	(0.09)	NA	0.92	(0.06)	(0.22)	0.05	NA	0.94	(0.11)
Sep-10	PM	NO CO data										
Sep-10	Off	T15-1										
Oct-10	PM	T15-2	0.88	0.58	NA	(0.51)	0.84	0.86	0.70	NA	(0.51)	0.84
Oct-10	AM	T15-2	(0.21)	0.05	NA	0.27	(0.14)	(0.19)	0.11	NA	0.26	(0.12)
Oct-10	Noon	T15-2	(0.08)	0.18	NA	0.51	0.09	(0.23)	0.25	NA	0.39	(0.11)
Oct-10	PM	T15-2	0.74	0.71	0.19	(0.41)	0.71	0.73	0.68	0.15	(0.45)	0.69

Clementi – Opp NUS			Simultaneous R Values					1 Minute Delay R Values				
Date	Period	Instrument	cars	bikes	LD	HD	Total Traffic	cars	bikes	LD	HD	Total Traffic
24-Sep	AM	T15-2	(0.58)	0.42	0.10	0.14	(0.40)	(0.50)	0.39	0.06	0.09	(0.36)
24-Sep	PM	T15-2	(0.07)	0.18	0.59	0.33	0.05	0.04	0.23	0.61	0.33	0.15
28-Sep	PM	T15-2	(0.26)	0.29	NA	(0.82)	(0.34)	(0.27)	0.32	NA	(0.85)	(0.35)
29-Sep	MA	T15-1	0.15	(0.24)	NA	(0.25)	0.05	0.12	(0.01)	NA	(0.37)	0.03
29-Sep	MA	WSN 21	(0.46)	(0.63)	NA	0.05	(0.52)	(0.56)	(0.64)	NA	0.07	(0.61)
29-Sep	PM	T15-1										
29-Sep	PM	T15-2										
29-Sep	PM	WSN 21										
1-Oct	PM	T15-1	0.15	(0.24)	0.28	(0.25)	0.05	0.12	(0.01)	0.17	(0.37)	0.03
1-Oct	PM	T15-2										
1-Oct	PM	WSN 21	(0.46)	(0.63)	NA	0.05	(0.52)	(0.56)	(0.64)	NA	0.07	(0.61)
6-Oct	AM	T15-1	0.16	0.05	NA	0.00	0.14	0.14	0.07	NA	0.06	0.13
6-Oct	Noon	T15-1	0.80	(0.27)	NA	(0.65)	0.66	0.79	(0.26)	NA	(0.64)	0.65

6-Oct	PM	T15-1	0.36	0.45	NA	(0.15)	0.35	0.45	0.56	NA	(0.14)	0.44
6-Oct	PM	T15-1										
6-Oct	AM	WSN 21	(0.66)	(0.65)	NA	(0.52)	(0.70)	(0.68)	(0.68)	NA	(0.49)	(0.71)
6-Oct	Noon	WSN 21	0.54	(0.57)	NA	0.10	0.50	0.56	(0.37)	NA	0.18	0.58
6-Oct	PM	WSN 21	0.17	0.55	NA	0.00	0.15	0.11	0.61	NA	(0.51)	0.08
6-Oct	PM	WSN 21										

Library			Simultaneous R Values						1 Minute Delay R Values					
Date	Period	Instrument	cars	bikes	LD	HD	Bus Delay	Total Traffic	cars	bikes	LD	HD	Bus Delay	Total Traffic
15-Sep	PM	T15-2	0.08	0.04	(0.42)	(0.48)	NA	(0.06)	0.07	(0.02)	(0.35)	(0.51)	NA	(0.08)
16-Sep	AM	T15-2	0.37	0.42	0.04	(0.12)	0.26	0.38	0.47	0.39	0.03	(0.04)	0.30	0.49
2-Oct	AM	T15-1	0.18	0.30	0.03	(0.11)	0.16	0.19	0.31	0.23	(0.08)	(0.29)	0.18	0.21
8-Oct	AM	T15-2	(0.13)	0.21	(0.38)	(0.06)	0.10	(0.15)	0.02	0.29	(0.35)	(0.08)	0.13	0.00
8-Oct	Noon	T15-2	(0.09)	0.32	0.19	(0.08)	(0.06)	(0.07)	(0.06)	0.40	0.13	(0.09)	(0.00)	(0.03)
8-Oct	MA	T15-2												
8-Oct	PM	T15-2	0.29	0.53	0.01	0.19	0.27	0.38	0.28	0.65	(0.05)	0.10	0.23	0.34
15-Oct	AM	T15-2	(0.43)	0.07	0.58	0.61	0.33	0.18	(0.47)	(0.05)	0.72	0.64	0.23	0.16

Opp Library			Simultaneous R Values						1 Minute Delay R Values					
Date	Period	Instrument	cars	bikes	LD	HD	Bus Delay	Total Traffic	cars	bikes	LD	HD	Bus Delay	Total Traffic
15-Sep	PM	T15-1	0.62	0.51	(0.13)	0.57	0.16	0.79	0.58	0.55	(0.10)	0.50	0.10	0.72
16-Sep	AM	T15-1	(0.15)	(0.50)	(0.17)	(0.07)	0.02	(0.24)	(0.25)	(0.58)	(0.18)	(0.10)	(0.01)	(0.35)
2-Oct	AM	T15-2	0.02	0.06	0.12	0.26	0.00	0.15	(0.02)	0.03	0.09	0.26	0.08	0.10
8-Oct	AM	T15-1	(0.16)	(0.23)	0.12	0.05	(0.46)	(0.16)	(0.13)	(0.21)	0.11	(0.01)	(0.46)	(0.15)
8-Oct	noon	T15-1	(0.05)	0.29	0.14	(0.11)	0.17	(0.05)	(0.05)	0.28	0.13	(0.07)	0.28	(0.04)
8-Oct	PM	T15-1	(0.26)	0.01	0.26	0.29	0.22	(0.13)	(0.24)	0.14	0.46	0.46	0.30	(0.05)
15-Oct	AM	T15-1	(0.09)	(0.06)	0.41	0.52	0.71	0.35	(0.11)	(0.11)	0.56	0.62	0.62	0.40

Comp School Inbound			Simultaneous						1 Minute Delay					
Date	Period	Instrument	cars	bikes	LD	HD	Bus Delay	Total Traffic	cars	bikes	LD	HD	Bus Delay	Total Traffic
18-Sep	AM	T15-2												
7-Oct	noon	T15-2	0.16	(0.06)	(0.01)	(0.26)	(0.13)	0.11	0.26	(0.11)	(0.02)	(0.22)	(0.05)	0.21
7-Oct	noon	WSN 21	0.03	(0.18)	0.03	(0.38)	(0.41)	(0.06)	0.08	0.01	0.13	(0.14)	(0.09)	0.06
7-Oct	AM	WSN 21												
7-Oct	PM	WSN 21	(0.40)	(0.57)	0.13	0.04	0.33	(0.56)	(0.41)	(0.56)	0.20	0.05	0.35	(0.56)
9-Oct	AM	T15-1	0.13	0.04	0.13	0.04	(0.22)	0.12	0.22	0.08	0.09	0.19	(0.10)	0.24
9-Oct	MM	T15-1	(0.23)	(0.42)	(0.50)	(0.13)	0.12	(0.31)	(0.32)	(0.25)	(0.67)	(0.30)	0.18	(0.39)
19-Oct	AM	T15-2	0.73	0.49	0.26	0.37	(0.28)	0.75	0.72	0.47	0.23	0.34	(0.33)	0.74
19-Oct	PM	T15-1	(0.06)	(0.08)	(0.16)	(0.14)	(0.29)	(0.11)	(0.16)	(0.06)	(0.23)	(0.08)	(0.12)	(0.17)

Comp School Outbound			Simultaneous R Values						1 Minute Delay R Values					
Date	Period	Instrument	cars	bikes	LD	HD	Bus Delay	Total Traffic	cars	bikes	LD	HD	Bus Delay	Total Traffic
10-Sep	PM	T15-2												
2-Oct	AM	WSN 21												
7-Oct	off	WSN 21												
7-Oct	noon	T15-1	0.14	0.12	0.11	(0.05)	(0.24)	0.15	0.20	0.11	(0.03)	(0.15)	(0.24)	0.19
7-Oct	PM	WSN 21												
9-Oct	AM	T15-2	0.60	0.10	0.12	0.26	0.34	0.71	0.32	0.07	0.61	0.68	0.42	0.41
9-Oct	off	T15-2	(0.43)	(0.34)	(0.31)	0.11	(0.15)	(0.41)	(0.27)	(0.25)	(0.07)	0.23	0.09	(0.27)
9-Oct	off	WSN 21	(0.54)	(0.27)	(0.72)	(0.87)	(0.06)	(0.62)	(0.60)	(0.38)	(0.76)	(0.85)	(0.15)	(0.66)
19-Oct	AM	T15-1	0.80	(0.37)	0.30	0.49	(0.30)	0.79	0.76	(0.42)	0.25	0.57	(0.33)	0.76
19-Oct	PM	T15-2	(0.29)	(0.03)	(0.21)	(0.64)	(0.12)	(0.31)	(0.30)	(0.16)	(0.30)	(0.54)	(0.08)	(0.34)

NUH - Inbound			Simultaneous R Values						1 Minute Delay R Values					
Date	Instrument	Period	cars	bikes	LD	HD	Bus Delay	Total Traffic	cars	bikes	LD	HD	Bus Delay	Total Traffic
17-Sep	T15-2	MA	(0.23)	(0.32)	0.52	0.51	(0.19)	(0.18)	0.01	(0.26)	0.55	0.49	(0.44)	0.06
18-Sep	T15-2	AM	(0.21)	(0.45)	(0.33)	(0.30)	0.29	(0.34)	(0.30)	(0.45)	(0.34)	(0.28)	0.35	(0.40)
2-Oct	T15-1	MA	(0.06)	0.13	0.01	0.04	0.54	(0.12)	(0.03)	(0.08)	0.08	0.14	0.40	(0.15)
7-Oct	T15-2	AM	(0.36)	(0.01)	(0.21)	0.01	0.22	(0.29)	(0.37)	(0.06)	(0.16)	(0.05)	0.14	(0.32)
7-Oct	T15-1	MA	(0.24)	0.12	(0.39)	(0.36)	(0.26)	(0.26)	(0.16)	0.31	(0.55)	(0.45)	(0.30)	(0.17)
7-Oct	T15-1	PM	0.03	0.20	0.63	0.55	0.36	0.22	0.14	(0.12)	0.47	0.58	0.31	0.23
9-Oct	T15-1	AM												
9-Oct	T15-1	Noon	(0.05)	0.13	(0.13)	(0.19)	(0.52)	(0.01)	(0.24)	0.51	0.10	0.12	(0.26)	(0.06)

NUH - Outbound			Simultaneous R Values						1 Minute Delay R Values					
Date	Period	Instrument	cars	bikes	LD	HD	Bus Delay	Total Traffic	cars	bikes	LD	HD	Bus Delay	Total Traffic
11-Sep	PM	T15-1												
17-Sep	MA	T15-1	(0.17)	(0.62)	(0.01)	0.21	0.24	(0.25)	(0.15)	(0.44)	0.02	0.13	(0.02)	(0.23)
18-Sep	AM	T15-1	0.06	0.14	0.08	0.27	(0.26)	0.13	0.05	0.22	0.11	0.28	(0.31)	0.12
2-Oct	MA	T15-2	(0.34)	0.05	(0.49)	(0.87)	0.27	(0.38)	(0.55)	(0.05)	(0.58)	(0.62)	0.47	(0.57)
7-Oct	AM	T15-1	0.21	0.43	(0.14)	0.28	0.55	0.34	0.20	0.44	(0.13)	0.23	0.45	0.32
7-Oct	MA	T15-2	(0.27)	0.22	(0.08)	(0.15)	(0.24)	(0.11)	0.06	0.52	(0.01)	0.02	(0.42)	0.24
7-Oct	PM	T15-2	0.11	0.74	0.60	0.54	0.07	0.38	0.13	0.64	0.65	0.63	0.22	0.38
9-Oct	MM	T15-2												
9-Oct	Noon	T15-2	(0.29)	0.48	0.14	0.18	(0.18)	(0.09)	(0.27)	0.35	0.31	0.31	(0.30)	(0.19)

OPC Data Analysis – NUS Campus Fall 2009

All data is taken October 9th 2009.

GMD is the geometric mean diameter. GMD = Sqrt (Dp_i * Dpi_{-1}).

Time 11:45:45

bus stop, bus present

size	cumulative	differential	Dp	GMD	logGMD	log#/logGMD
0.5µm	2335	1874	0.5	0.591608	-0.22797	-14.3564
0.7µm	461	246	0.7	0.83666	-0.07745	-30.8703
1.0µm	215	120	1	1.414214	0.150515	13.81378
2.0µm	95	79	2	2.44949	0.389076	4.877271
3.0µm	16	14	3	3.872983	0.588046	1.949046
5.0µm	2	2	5	7.071068	0.849485	0.354368

Time 12:26:53

normal roadside traffic

size	cumulative	differential	Dp	GMD	logGMD	log#/logGMD
0.5µm	1936	1500	0.5	0.591608	-0.22797	-13.9323
0.7µm	436	236	0.7	0.83666	-0.07745	-30.6376
1.0µm	200	119	1	1.414214	0.150515	13.78964
2.0µm	81	72	2	2.44949	0.389076	4.773706
3.0µm	9	9	3	3.872983	0.588046	1.622735
5.0µm	0	0	5	7.071068	0.849485	#NUM!

Time 12:38:17

no traffic

size	cumulative	differential	Dp	GMD	logGMD	log#/logGMD
0.5µm	4428	2988	0.5	0.591608	-0.22797	-15.2452
0.7µm	1440	732	0.7	0.83666	-0.07745	-36.9848
1.0µm	708	391	1	1.414214	0.150515	17.22205
2.0µm	317	239	2	2.44949	0.389076	6.112945
3.0µm	78	54	3	3.872983	0.588046	2.946019
5.0µm	24	24	5	7.071068	0.849485	1.624762

Time 12:53:30

no traffic

size	cumulative	differential	Dp	GMD	logGMD	log#/logGMD
0.5µm	1671	1192	0.5	0.591608	-0.22797	-13.4945
0.7µm	479	223	0.7	0.83666	-0.07745	-30.3199
1.0µm	256	141	1	1.414214	0.150515	14.2791
2.0µm	115	100	2	2.44949	0.389076	5.140389

3.0µm	15	15	3	3.872983	0.588046	2
5.0µm	0	0	5	7.071068	0.849485	NA

Time 12:55:05

normal traffic

size	cumulative	differential	Dp	GMD	logGMD	log#/logGMD
0.5µm	1978	1404	0.5	0.591608	-0.22797	-13.8063
0.7µm	574	295	0.7	0.83666	-0.07745	-31.8888
1.0µm	279	159	1	1.414214	0.150515	14.62577
2.0µm	120	101	2	2.44949	0.389076	5.151496
3.0µm	19	18	3	3.872983	0.588046	2.134652
5.0µm	1	1	5	7.071068	0.849485	0

Time 13:05:31

near idling buses at bus stop

size	cumulative	differential	Dp	GMD	logGMD	log#/logGMD
0.5µm	5625	3504	0.5	0.591608	-0.22797	-15.5487
0.7µm	2121	1244	0.7	0.83666	-0.07745	-39.9584
1.0µm	877	609	1	1.414214	0.150515	18.5006
2.0µm	268	249	2	2.44949	0.389076	6.158698
3.0µm	19	17	3	3.872983	0.588046	2.092438
5.0µm	2	2	5	7.071068	0.849485	0.354368

Time 13:06:10

bus just left

size	cumulative	differential	Dp	GMD	logGMD	log#/logGMD
0.5µm	6481	4084	0.5	0.591608	-0.22797	-15.8405
0.7µm	2397	1243	0.7	0.83666	-0.07745	-39.9539
1.0µm	1154	781	1	1.414214	0.150515	19.21836
2.0µm	373	360	2	2.44949	0.389076	6.570194
3.0µm	13	12	3	3.872983	0.588046	1.8352
5.0µm	1	1	5	7.071068	0.849485	0

Time 13:09:00

no traffic

size	cumulative	differential	Dp	GMD	logGMD	log#/logGMD
0.5µm	2482	1570	0.5	0.591608	-0.22797	-14.0192
0.7µm	912	498	0.7	0.83666	-0.07745	-34.825
1.0µm	414	267	1	1.414214	0.150515	16.12139
2.0µm	147	132	2	2.44949	0.389076	5.450287
3.0µm	15	13	3	3.872983	0.588046	1.894314

5.0µm	2	2	5	7.071068	0.849485	0.354368

Time 13:11:22

no traffic, many people

size	cumulative	differential	Dp	GMD	logGMD	log#/logGMD
0.5µm	1664	1103	0.5	0.591608	-0.22797	-13.3466
0.7µm	561	263	0.7	0.83666	-0.07745	-31.245
1.0µm	298	163	1	1.414214	0.150515	14.69746
2.0µm	135	100	2	2.44949	0.389076	5.140389
3.0µm	35	29	3	3.872983	0.588046	2.486878
5.0µm	6	6	5	7.071068	0.849485	0.916027

Time 13:11:54

bus at stop

size	cumulative	differential	Dp	GMD	logGMD	log#/logGMD
0.5µm	1612	1119	0.5	0.591608	-0.22797	-13.3741
0.7µm	493	250	0.7	0.83666	-0.07745	-30.9607
1.0µm	243	142	1	1.414214	0.150515	14.29949
2.0µm	101	87	2	2.44949	0.389076	4.984942
3.0µm	14	12	3	3.872983	0.588046	1.8352
5.0µm	2	2	5	7.071068	0.849485	0.354368

Time 13:12:11

after bus left

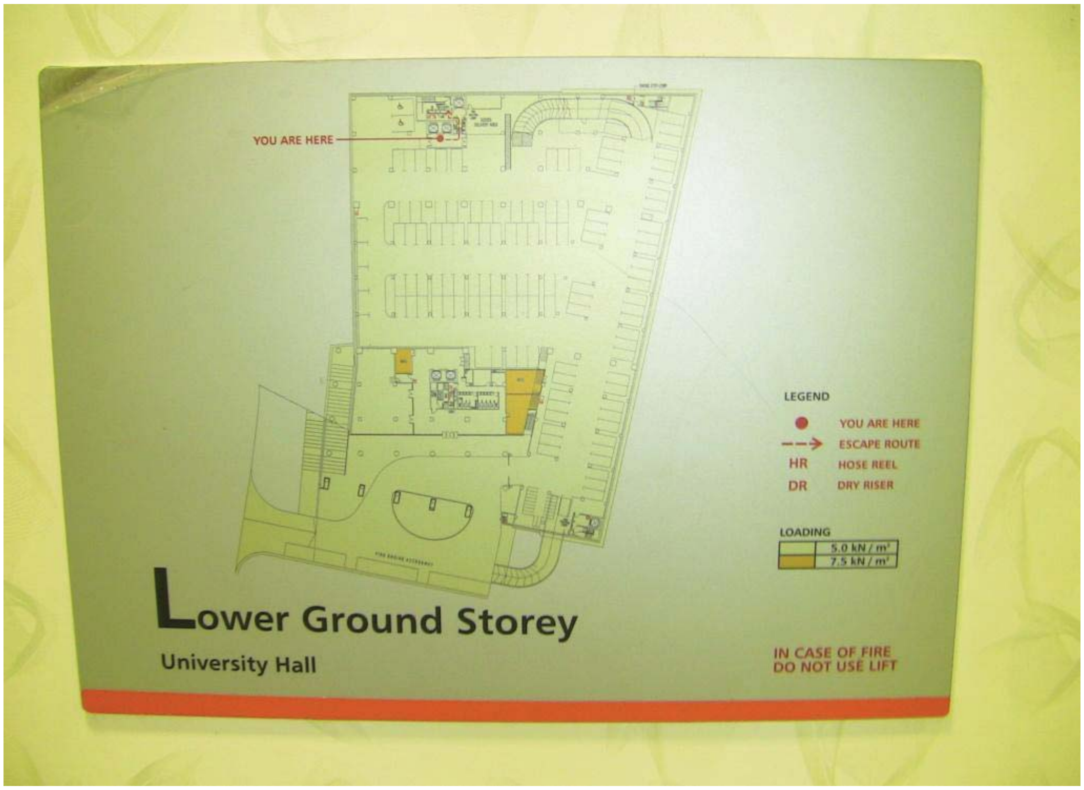
size	cumulative	differential	Dp	GMD	logGMD	log#/logGMD
0.5µm	1501	984	0.5	0.591608	-0.22797	-13.1291
0.7µm	517	232	0.7	0.83666	-0.07745	-30.5417
1.0µm	285	155	1	1.414214	0.150515	14.55225
2.0µm	130	116	2	2.44949	0.389076	5.306058
3.0µm	14	10	3	3.872983	0.588046	1.700548
5.0µm	4	4	5	7.071068	0.849485	0.708735

Time 13:14:08

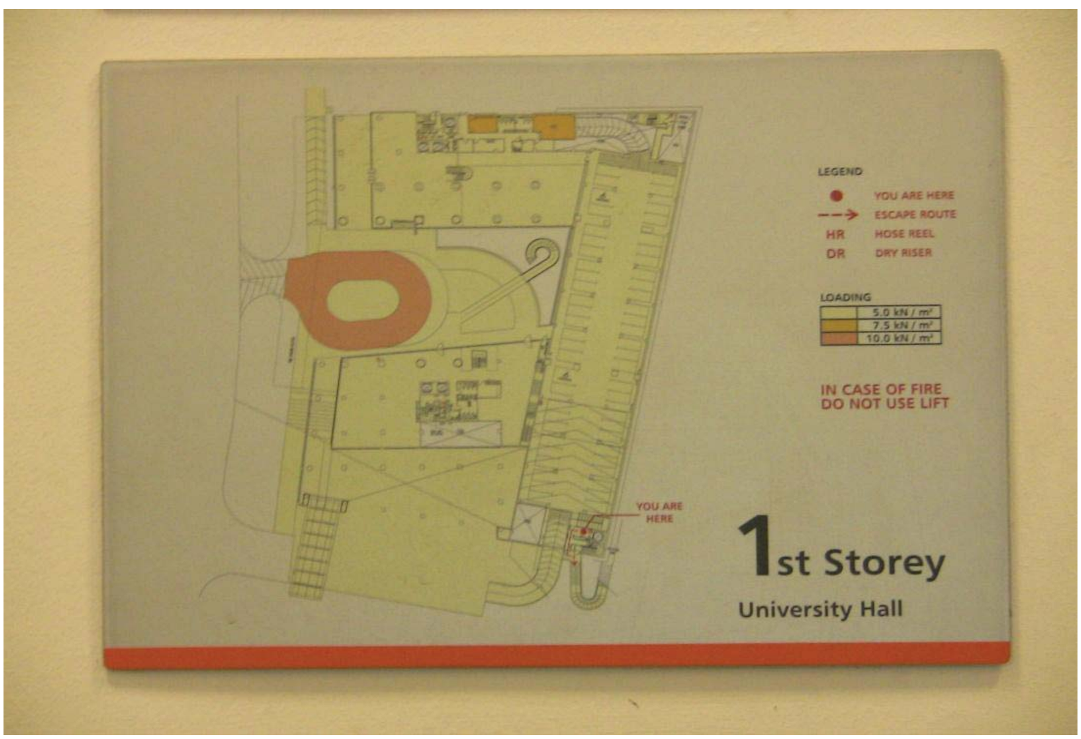
after large crane passes

size	cumulative	differential	Dp	GMD	logGMD	log#/logGMD
0.5µm	1646	1165	0.5	0.591608	-0.22797	-13.4508
0.7µm	481	267	0.7	0.83666	-0.07745	-31.3296
1.0µm	214	132	1	1.414214	0.150515	14.08879
2.0µm	82	68	2	2.44949	0.389076	4.709904
3.0µm	14	9	3	3.872983	0.588046	1.622735
5.0µm	5	5	5	7.071068	0.849485	0.822816

Appendix C: University Hall Car Park



Layout of 1st Level, Main Level



Layout of 2nd Level, Visitor Parking

University Hall Car Park, Ground Floor

University Hall Car Park Level 2

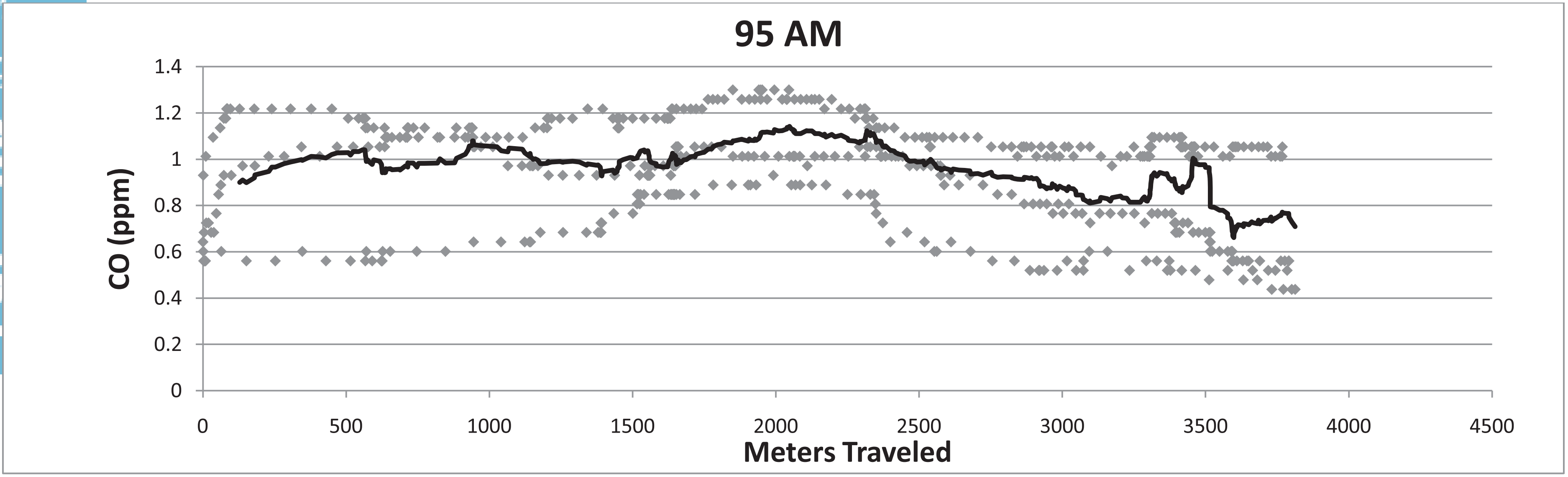
Appendix D: NUS Buses

97

Date	Period	Type	Bus Type	Start	Stop	Duration	St Dev (ppm)	Max (ppm)	Min (ppm)	PreAmb (ppm)	PostAmb (ppm)
7-Sep	Am	AM pk	DD	9:20:00 AM	9:24:23 AM	0:04:23	0.31	1.87	0.24	0.07	1.04
18-Sep	Am	AM Pk	DD	7:00:53 AM	7:08:20 AM	0:07:27	0.18	1.70	0.82	1.27	0.64
18-Sep	Pm	AM Pk	DD	7:23:33 AM	7:32:03 AM	0:08:30	0.18	1.70	0.82	1.27	0.64
28-Sep	Am	AM Pk	DD	8:22:00 AM	8:33:00 AM	0:11:00	0.02	0.27	0.19	0.22	0.22
29-Sep	Am	AM Pk	DD	8:29:32 AM	8:34:02 AM	0:04:30	0.07	0.98	0.62	0.98	0.40
30-Sep	Am	AM Pk	DD	8:49:39 AM	8:56:29 AM	0:06:50	0.29	1.75	0.40	0.27	0.85
5-Oct	Am	AM Pk	DD	8:52:36 AM	9:05:07 AM	0:12:31	0.18	1.87	0.52	0.31	0.88
28-Sep	Am	AM Pk	DD	8:54:32 AM	8:59:22 AM	0:04:50	0.02	1.51	1.42	1.47	0.85
2-Oct	Am	AM Pk	DD	9:15:37 AM	9:24:22 AM	0:08:45	0.07	1.37	1.15	1.24	0.80
21-Sep	Pm	off	DD	1:09:37 PM	1:14:55 PM	0:05:18	0.28	1.92	0.60	1.39	0.41
9-Sep	Pm	off	DD	9:16:00 PM	9:22:00 PM	0:06:00	0.15	1.63	1.05	1.06	0.31
15-Oct	Pm	off	DD	7:38:16 PM	7:45:16 PM	0:07:00	0.05	1.96	1.75	1.46	1.05
22-Sep	Pm	PM Pk	DD	5:00:13 PM	5:08:08 PM	0:07:55	0.42	1.31	(0.02)	0.83	0.22
17-Sep	Pm	PM Pk	DD	6:33:03 PM	6:47:33 PM	0:14:30	0.28	1.96	0.44	0.91	1.22
25-Sep	Pm	PM Pk	DD	6:43:00 PM	6:53:00 PM	0:10:00	0.10	2.08	1.67	0.86	0.51
8-Sep	Am	AM Pk	reg	7:49:39 AM	8:07:15 AM	0:17:36	0.03	0.65	0.48	0.51	0.60
22-Sep	Am	AM Pk	reg	8:06:53 AM	8:15:53 AM	0:09:00	0.14	1.76	0.95	0.97	0.71
14-Oct	Am	AM Pk	reg	8:25:10 AM	8:36:30 AM	0:11:20	0.15	2.65	1.55	1.30	1.26
9-Sep	Am	AM Pk	reg	8:51:00 AM	9:06:00 AM	0:15:00	0.31	1.92	0.70	0.77	0.46
14-Sep	Am	AM Pk	reg	9:23:51 AM	9:36:21 AM	0:12:30	0.27	1.18	0.36	0.75	0.36
16-Sep	Am	AM Pk	reg	9:10:39 AM	9:15:09 AM	0:04:30	0.16	1.63	1.14	0.65	1.09
1-Sep	Pm	PM Pk	reg	7:04:00 PM	7:14:00 PM	0:10:00	0.12	1.55	1.18	0.84	
8-Sep	Pm	PM Pk	reg	5:29:00 PM	5:34:00 PM	0:05:00	0.14	0.48	0.04	0.00	0.20

Date	Period	Bus Type	Start	Stop	Duration	Avg CO (ppm)	St Dev (ppm)	Max (ppm)	Min (ppm)	PreAmb (ppm)	PostAmb (ppm)
3-Sep	AM	Reg	7:36:00	7:42:00	0:06:00	0.23	0.02	0.27	0.19	0.23	0.19
15-Oct	AM	Reg	8:34:56	8:44:36	0:09:40	2.11	0.32	2.49	0.89	0.87	0.99
17-Sep	AM	Reg	9:03:03	9:12:03	0:09:00	2.02	2.02	2.02	2.02	1.30	1.55
1-Oct	AM	Reg	9:16:07	9:23:47	0:07:40	0.83	0.11	0.93	0.46	0.60	0.36
18-Sep	AM	Long	9:26:26	9:31:26	0:05:00	1.37	0.22	1.75	0.89	0.78	0.44
13-Oct	Off	Long	9:32:53	9:37:43	0:04:50	1.08	0.29	1.26	0.15	0.17	1.06
25-Sep	Off	Reg	9:47:30	9:54:30	0:07:00	1.22	0.13	1.37	0.81	0.65	0.91
15-Sep	Off	Reg	10:08:19	10:13:19	0:05:00	0.90	0.04	0.97	0.85	0.62	0.57
18-Sep	Off	Reg	13:29:47	13:36:35	0:06:48	1.41	0.15	1.53	0.81	1.06	0.67
28-Sep	Off	Reg	16:26:34	16:31:45	0:05:11	0.25	0.01	0.29	0.25	0.27	0.24
29-Sep	Off	Reg	19:36:10	19:43:30	0:07:20	1.43	0.15	1.63	0.78	1.48	0.62
7-Oct	Off	Reg	19:36:40	19:41:40	0:05:00	1.87	0.08	2.04	1.75	1.99	1.06
1-Oct	Off	Reg	19:55:08	20:01:18	0:06:10	2.05	0.19	2.29	1.14	2.09	0.85
9-Oct	PM	Long	17:06:10	17:13:25	0:07:15	1.71	0.18	1.92	0.97	0.61	0.19
8-Sep	PM	Long	17:52:30	18:01:20	0:08:50	2.51	1.06	3.96	0.57	2.28	0.54
11-Sep	PM	Long	18:30:00	18:46:00	0:16:00	1.63	0.23	2.00	1.09	0.68	0.57
17-Sep	PM	Reg	18:50:59	19:00:14	0:09:15	1.44	0.25	1.82	0.78	1.08	0.54

Date	Time Period	Start	Stop	Duration	Average CO (ppm)	St Dev (ppm)	Max (ppm)	Min (ppm)	PreAmb (ppm)	PostAmb (ppm)
29-Sep	AM	9:10:17	9:29:07	0:18:50	0.68	0.14	0.93	0.44	0.39	0.26
1-Oct	AM	9:11:28	9:29:53	0:18:25	0.87	0.23	1.22	0.23	0.95	0.27
2-Oct	AM	8:53:45	9:14:55	0:21:10	1.10	0.11	1.30	0.64	0.64	0.75
2-Sep	Off	15:14	15:27:00	0:13:00	0.91	0.23	1.26	0.68	0.75	0.59
9-Sep	Off	20:53:10	21:05:40	0:12:30	0.88	0.08	1.01	0.77	0.50	0.40
23-Sep	Off	9:59:29	10:17:19	0:17:50	0.80	0.13	1.07	0.46	1.04	0.14
28-Sep	Off	15:29:40	15:49:50	0:20:10	2.17	0.36	2.74	1.05	0.69	1.15
1-Oct	Off	20:18:45	20:31:35	0:12:50	1.34	0.20	1.61	0.34	0.56	1.10
8-Oct	PM	19:25:43	19:43:33	0:17:50	0.81	0.10	0.97	0.48	0.47	0.89
9-Sep	PM	18:01:30	18:27:20	0:25:50	1.21	0.27	1.67	0.46	0.51	1.34
23-Sep	PM	19:04:34	19:19:39	0:15:05	0.42	0.12	0.70	0.16	0.16	0.56
2-Oct	PM	17:58:22	18:30:37	0:32:15	1.91	0.29	2.39	1.13	1.13	2.24
12-Oct	PM	17:54:50	18:20:35	0:25:45	1.82	1.03	7.17	0.48	0.42	1.71
14-Oct	PM	17:59:38	18:15:33	0:15:55	1.07	0.08	1.18	0.89	0.78	0.64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CO (ppm)
Meters Traveled
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1.2
1
0.8
0.6
0.4
0.2
0
0
500
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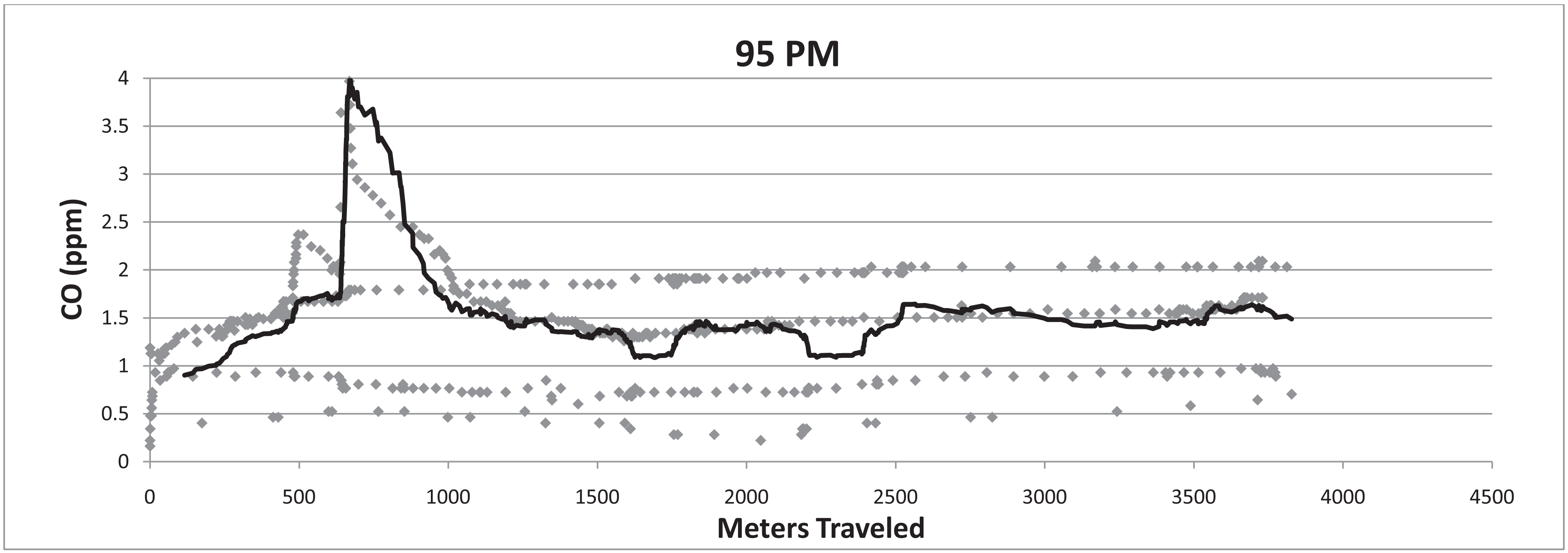
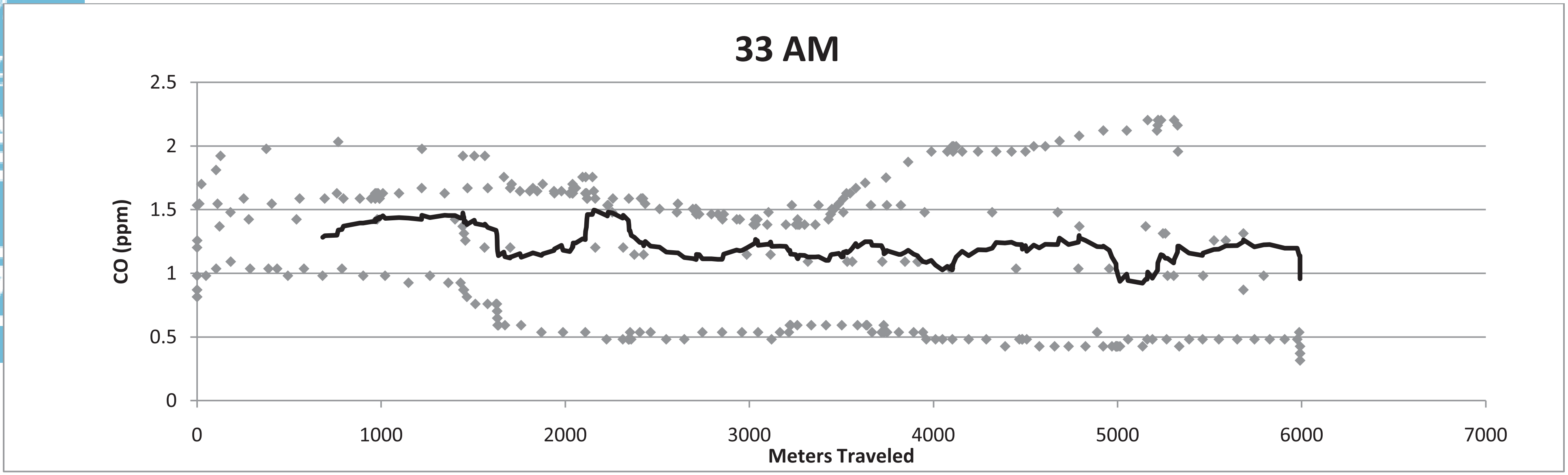
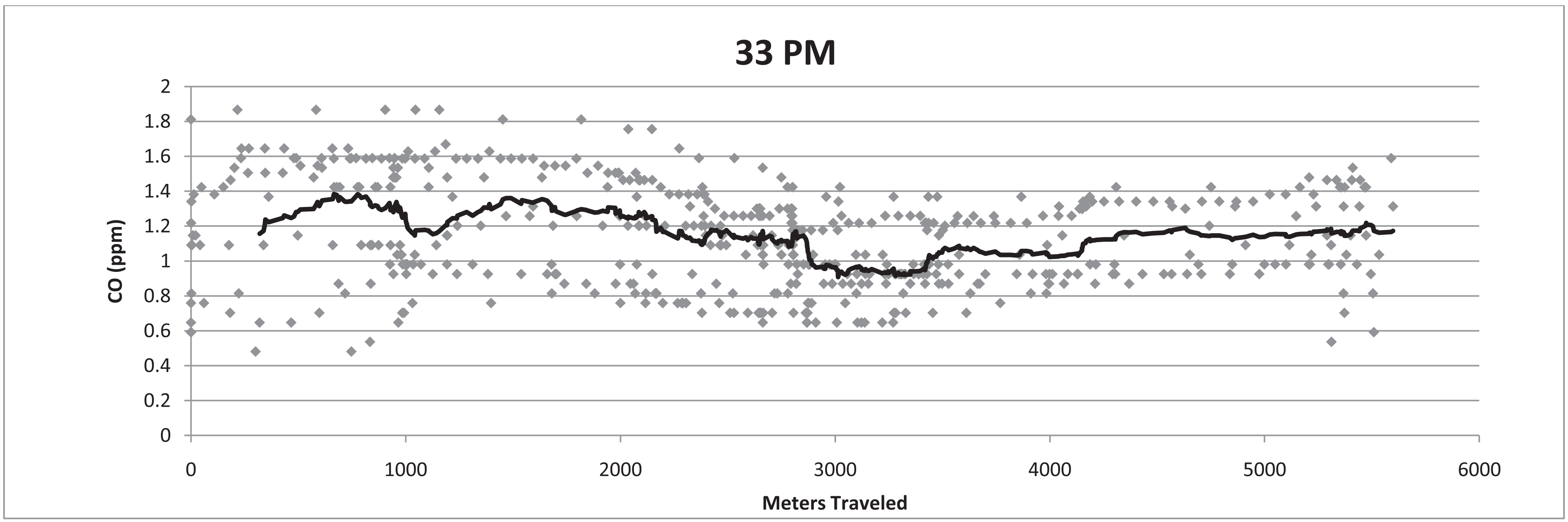
1500
2000
2500
3000
3500
4000
4500


95 PM
CO (ppm)
Meters Traveled
4
3.5
3
2.5
2
1.5
1
0.5
0
0
500
1000
1500
2000
2500
3000
3500
4000
4500

33

Date	Period	Start	Stop	Duration	Ave CO (ppm)	St Dev (ppm)	Max (ppm)	Min (ppm)	PreAmb (ppm)	PostAmb (ppm)	Clem CO (ppm)	Depot CO (ppm)	AYE CO (ppm)
11-Sep	AM	9:06:36	9:23:27	0:16:51	1.18	0.15	1.48	0.98	1.17	0.57	0.99	1.08	1.28
14-Sep	AM	8:45:00	9:07:00	0:22:00	1.63	2.03	0.26	0.50					
16-Sep	AM	8:27:35	8:50:14	0:22:39	1.59	0.23	2.03	0.87	1.13	0.37	1.26	1.49	1.72
17-Sep	AM	8:35:00	8:54:00	0:19:00	1.99	2.37	1.09	0.31					
30-Sep	AM	9:14:37	9:33:02	0:18:25	0.61	0.21	1.48	0.31	0.59	0.16	0.45	0.50	0.76
15-Oct	AM	7:51:00	8:05:50	0:14:50	1.80	0.11	1.98	1.53	1.89	1.07	1.67	1.76	1.92
15-Oct	AM	8:49:26	9:06:26	0:17:00	0.69	0.27	1.30	0.36	0.58	0.38			
10-Sep	Off	9:32:01	9:47:34	0:15:33	1.03	0.23	1.48	0.59	1.10	0.51	1.20	0.97	0.76
21-Sep	Off	10:57:23	11:10:20	0:12:57	0.88	0.21	1.20	0.54	1.06	0.36	0.71	0.77	1.03
5-Oct	Off	9:38:40	9:56:50	0:18:10	0.90	0.28	1.20	0.26	0.74	0.33	0.36	1.02	1.01
6-Oct	Off	20:06:59	20:18:49	0:11:50	0.72	0.17	1.53	0.59	1.11	0.57	1.01	0.68	0.67
14-Oct	Off	14:24:14	14:36:49	0:12:35	0.77	0.04	0.85	0.60	0.52	0.77	0.76	0.76	0.78
14-Oct	Off	16:34:37	16:48:42	0:14:05	1.00	0.15	1.26	0.59	0.44	0.73	0.79	1.12	0.93
14-Oct	Off	19:45:01	19:59:01	0:14:00	1.35	0.17	1.67	(0.06)	1.10	0.79	1.50	1.37	1.28
4-Sep	PM	18:45:11	19:07:02	0:21:51	1.24	0.28	1.65	0.87	0.54	0.51	1.52	1.31	0.92
4-Sep	PM	18:47:00	19:06:00	0:19:00	1.18	0.10	1.34	0.97	0.91	1.14			
7-Sep	PM	19:06:00	19:22:01	0:16:01	0.71	0.25	1.09	0.44	0.95	0.44	1.05	0.97	0.52
8-Sep	PM	18:26:00	18:48:00	0:22:00	1.16	0.19	1.63	0.72					
11-Sep	PM	18:44:55	19:03:55	0:19:00	0.88	0.19	1.31	0.48	0.22	0.93	0.61	0.81	1.01
14-Sep	PM	17:47:55	18:05:37	0:17:42	0.90	0.13	1.15	0.59	0.42	0.70	0.77	0.89	0.95
14-Sep	PM	18:45:21	19:00:21	0:15:00	0.92	0.09	1.05	0.81	0.64	0.77			
15-Sep	PM	19:14:55	19:29:01	0:14:06	1.58	0.20	1.87	1.31	1.26	1.08	1.85	1.66	1.42
16-Sep	PM	18:34:32	19:02:17	0:27:45	1.28	0.23	1.65	0.70	0.61	0.85	1.51	1.23	1.11
29-Sep	PM	19:19:55	19:35:15	0:15:20	0.86	0.15	1.15	0.65	1.05	0.87	1.05	0.81	0.79
30-Sep	PM	19:08:26	19:26:21	0:17:55	1.68	0.24	2.20	1.38	1.60	1.38	1.59	1.59	1.77
14-Oct	PM	16:41:00	16:52:30	0:11:30	1.12	0.09	1.26	0.93	0.92	0.91			


33 AM
CO (ppm)
2.5
2
1.5
1
0.5
0
0
1000
2000
3000
4000
5000
6000
7000
Meters Traveled


33 PM
CO (ppm)
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
1000
2000
3000
4000
5000
6000
Meters Traveled

A1

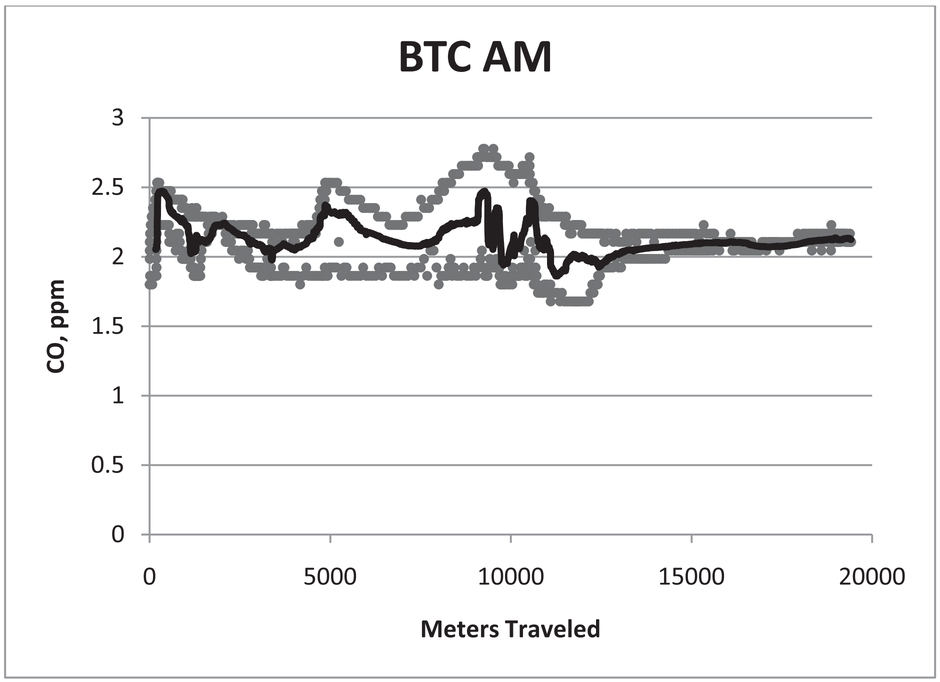
Date	Route	Period	Start	Stop	Duration	Avg CO (ppm)	St Dev (ppm)	Max (ppm)	Min (ppm)	PreAmb (ppm)	PostAmb (ppm)
3-Sep	A1	AM	8:13:32 AM	8:38:32 AM	0:25:00	0.85	0.20	1.17	0.40	0.44	0.22
3-Sep	A1	AM	8:41:02 AM	9:07:02 AM	0:26:00	0.90	0.17	1.17	0.22	0.22	0.29
3-Sep	A1	AM	9:13:02 AM	9:34:02 AM	0:21:00	0.73	0.07	0.87	0.52	0.27	0.41
3-Sep	A1	AM	9:39:02 AM	9:58:02 AM	0:19:00	0.90	0.16	1.17	0.52	0.41	0.35
13-Oct	A1	AM	9:49:40 AM	10:12:55 AM	0:23:15	0.67	0.13	1.55	0.48	0.41	0.47
9-Sep	A1	PM	4:00:15 PM	4:08:12 PM	0:07:57	0.79	0.06	0.87	0.63	0.68	0.68
9-Sep	A1	PM	4:11:54 PM	4:32:06 PM	0:20:12	0.84	0.09	1.05	0.57	0.58	0.52
9-Sep	A1	PM	4:35:27 PM	4:46:03 PM	0:10:36	0.77	0.10	1.05	0.46	0.42	0.60
15-Oct	A1	PM	7:05:59 PM	7:22:24 PM	0:16:25	0.63	0.07	1.09	0.40	0.40	0.51
6-Oct	A1	OFF	1:11:37 PM	1:21:37 PM	0:10:00	0.63	0.07	0.76	0.45	0.36	0.33
6-Oct	A1	OFF	1:11:37 PM	1:21:37 PM	0:10:00	0.59	0.21	1.96	(0.06)	0.35	0.38
6-Oct	A1	OFF	1:25:00 PM	1:42:40 PM	0:17:40	0.53	0.15	0.85	0.15	0.09	0.31
6-Oct	A1	OFF	1:45:05 PM	2:08:55 PM	0:23:50	0.61	0.13	1.14	0.19	0.18	0.30

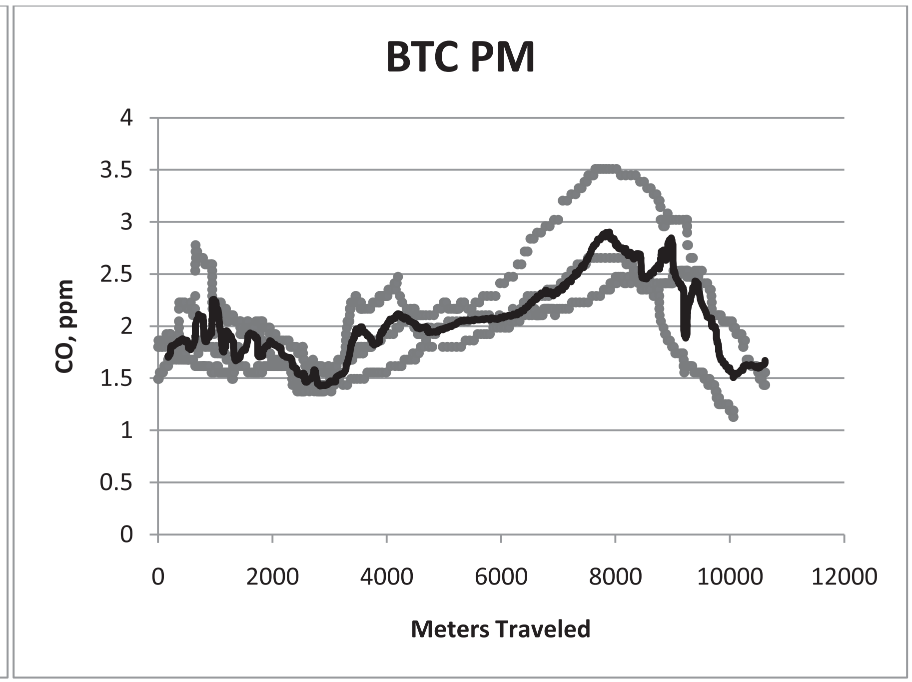
A2

15-Oct	A2	AM	8:56:25 AM	9:20:05 AM	0:23:40	0.46	0.05	0.60	0.36	0.73	0.27
13-Oct	A2	PM	6:43:17 PM	7:06:02 PM	0:22:45	0.67	0.13	1.55	0.48	0.41	0.47
19-Oct	A2	PM	5:53:26 PM	5:59:06 PM	0:05:40	0.71	0.12	0.81	0.43	0.30	0.58
19-Oct	A2	PM	6:01:14 PM	6:34:09 PM	0:32:55	0.67	0.06	0.81	0.37	0.42	0.54
19-Oct	A2	PM	6:41:54 PM	7:08:09 PM	0:26:15	0.61	0.19	1.15	0.20	0.50	0.54
6-Oct	A2	OFF	1:22:27 PM	1:47:12 PM	0:24:45	0.45	0.16	0.70	0.09	0.32	1.50
6-Oct	A2	OFF	2:12:52 PM	2:35:22 PM	0:22:30	0.53	0.15	0.85	0.15	0.09	0.31
6-Oct	A2	OFF	2:43:22 PM	2:51:42 PM	0:08:20	0.61	0.13	1.14	0.19	0.18	0.30

BTC

Date	Rider	Type	Start	Stop	Duration	Avg CO (ppm)	St Dev (ppm)	Max (ppm)	Min (ppm)	PreAmb (ppm)	PostAmb (ppm)
13-Oct	**B**	**AM**	8:59:14	9:51:09	0:51:55	0.94	0.13	1.26	0.48	0.50	1.12
15-Oct	**B**	**AM**	8:12:57	9:09:42	0:56:45	1.27	0.17	1.70	1.04	0.85	0.23
13-Oct	**B**	**PM**	18:01:29	18:59:44	0:58:15	0.83	0.40	1.70	0.00	0.38	0.04
16-Oct	**B**	**PM**	18:00:20	18:38:20	0:38:00	2.09	0.58	3.51	1.43	1.24	0.88
22-Sep	**L**	**PM**	18:29:53	18:47:43	0:17:50	0.28	0.12	0.56	0.15	0.15	0.46
15-Oct	**B**	**OFF**	19:01:22	19:35:17	0:33:55	0.93	0.30	1.48	0.43	0.83	0.44
22-Sep	**L**	**OFF**	13:33:13	14:13:53	0:40:40	0.50	0.31	1.59	0.11	0.12	0.19
29-Sep	**L**	**OFF**	13:17:59	13:47:04	0:29:05	0.49	0.09	0.68	0.36	0.28	0.24
29-Sep	**L**	**OFF**	13:59:19	14:17:09	0:17:50	0.56	0.13	0.85	0.15	0.63	0.23



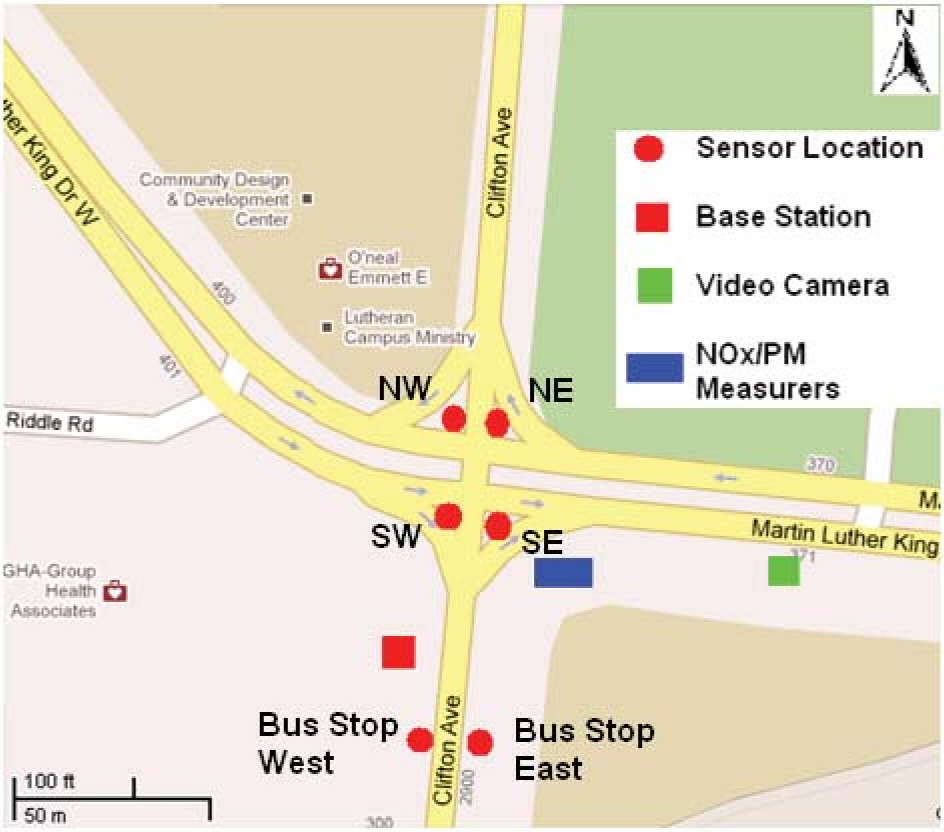


Appendix E: MLK/Clifton Intersection

Intersection

South Side of Intersection near Bus Stop

MLK/Clifton Sensor Locations



Sensor Locations were the same as "Default" except for the three special conditions given below

	NE	NW	SE	SW	Bus Stop East	Bus Stop West
Default	WSN 21	T15-2	WSN 20	WSN 5	T15-1	WSN 6
Feb 11 Noon	WSN 20	WSN 6	WSN 21	T15-2	WSN 5	T15-1
Feb 17 AM	WSN 21	T15-2	WSN 20	WSN 6	T15-1	WSN 5
Feb 17 PM	WSN 20	WSN 6	WSN 21	T15-1	WSN 5	T15-2

R Values of Traffic Delay vs CO at Varied Offset Times (Offset in parentheses)

May 18 PM	NB	SB	WB	EB	Combined
T15-1	(0.13)	(0.18)	(0.02)	(0.02)	(0.16)
T15-2	0.19	(0.09)	0.08	0.02	0.08
T15-2 (1)	(0.27)	(0.12)	(0.14)	0.06	(0.24)
T15-2 (1)	0.29	(0.13)	0.11	0.02	0.12
T15-1 (2)	(0.36)	(0.11)	0.05	(0.11)	(0.19)
T15-2 (2)	0.42	(0.18)	0.05	(0.01)	0.09

T15-1 (3)	(0.22)	(0.03)	0.01	(0.23)	(0.16)
T15-2 (3)	0.57	(0.09)	(0.05)	0.02	0.14
T15-1 (5)	0.07	(0.00)	0.17	(0.31)	0.05
T15-5 (5)	0.60	0.10	(0.17)	(0.02)	0.17

May 19 AM	NB	SB	WB	EB	Combined
T15-1	0.12	(0.16)	0.18	0.02	0.10
T15-2	(0.15)	(0.33)	0.13	0.17	(0.02)
T15-2 (1)	0.19	(0.16)	0.23	0.04	0.17
T15-2 (1)	(0.13)	(0.37)	0.09	0.20	(0.02)
T15-1 (2)	0.26	(0.12)	0.32	0.10	0.27
T15-2 (2)	(0.10)	(0.39)	0.03	0.20	(0.04)
T15-1 (3)	0.20	(0.13)	0.46	0.08	0.29
T15-2 (3)	(0.12)	(0.40)	(0.14)	0.25	(0.11)
T15-1 (5)	0.13	(0.27)	0.33	0.08	0.17
T15-5 (5)	(0.15)	(0.31)	(0.44)	0.08	(0.29)

May 19 Noon	NB	SB	WB	EB	Combined
T15-1	0.12	(0.16)	0.18	0.02	0.10
T15-2	(0.15)	(0.33)	0.13	0.17	(0.02)
T15-2 (1)	0.19	(0.16)	0.23	0.04	0.17
T15-2 (1)	(0.13)	(0.37)	0.09	0.20	(0.02)
T15-1 (2)	0.26	(0.12)	0.32	0.10	0.27
T15-2 (2)	(0.10)	(0.39)	0.03	0.20	(0.04)
T15-1 (3)	0.20	(0.13)	0.46	0.08	0.29
T15-2 (3)	(0.12)	(0.40)	(0.14)	0.25	(0.11)
T15-1 (5)	0.13	(0.27)	0.33	0.08	0.17
T15-5 (5)	(0.15)	(0.31)	(0.44)	0.08	(0.29)

May 20 PM	NB	SB	WB	EB	Combined
T15-1	(0.14)	0.25	0.23	0.41	0.25
T15-2	(0.20)	(0.07)	0.13	0.39	0.04
T15-2 (1)	(0.05)	0.40	0.12	0.35	0.27
T15-2 (1)	(0.16)	(0.00)	0.19	0.41	0.12
T15-1 (2)	0.00	0.40	0.03	0.20	0.21
T15-2 (2)	(0.04)	0.04	0.20	0.32	0.18
T15-1 (3)	(0.07)	0.37	(0.01)	0.09	0.12
T15-2 (3)	0.01	0.08	0.19	0.21	0.19
T15-1 (5)	(0.03)	0.18	0.08	(0.26)	0.03
T15-5 (5)	0.07	(0.02)	0.21	0.08	0.17

May 24 AM	NB	SB	WB	EB	Combined
T15-1	0.16	0.26	0.59	0.34	0.40
T15-2	(0.23)	(0.13)	0.24	(0.01)	(0.05)
T15-2 (1)	0.19	0.26	0.58	0.41	0.42
T15-2 (1)	(0.19)	(0.11)	0.21	(0.01)	(0.05)
T15-1 (2)	0.22	0.20	0.54	0.40	0.39
T15-2 (2)	(0.16)	(0.09)	0.21	0.02	(0.02)
T15-1 (3)	0.31	0.17	0.48	0.40	0.40
T15-2 (3)	(0.14)	(0.04)	0.15	(0.02)	(0.02)
T15-1 (5)	0.35	0.15	0.40	0.36	0.37
T15-5 (5)	(0.14)	0.00	0.15	(0.04)	(0.01)

May 24 Noon	NB	SB	WB	EB	Combined
T15-1	0.05	(0.25)	(0.04)	(0.16)	(0.17)
T15-2	(0.05)	0.15	(0.14)	0.04	0.01
T15-2 (1)	0.03	(0.28)	(0.09)	(0.15)	(0.20)
T15-2 (1)	(0.03)	0.08	(0.10)	0.01	(0.01)
T15-1 (2)	(0.06)	(0.29)	(0.19)	(0.08)	(0.23)
T15-2 (2)	(0.02)	0.03	(0.07)	(0.02)	(0.03)
T15-1 (3)	(0.15)	(0.21)	(0.29)	0.03	(0.22)
T15-2 (3)	0.00	0.03	0.01	(0.08)	(0.02)
T15-1 (5)	(0.15)	(0.13)	(0.25)	0.01	(0.18)
T15-5 (5)	0.10	0.14	0.30	(0.19)	0.10

May 25 AM	NB	SB	WB	EB	Combined
T15-1	0.25	(0.02)	0.61	0.27	0.30
T15-2	(0.09)	(0.22)	0.05	(0.10)	(0.15)
T15-2 (1)	0.40	0.02	0.61	0.20	0.32
T15-2 (1)	(0.15)	(0.32)	(0.01)	(0.11)	(0.23)
T15-1 (2)	0.46	0.04	0.56	0.21	0.33
T15-2 (2)	(0.19)	**(0.37)**	(0.11)	(0.13)	(0.28)
T15-1 (3)	0.47	0.05	0.48	0.21	0.32
T15-2 (3)	(0.25)	(0.31)	(0.18)	(0.12)	(0.28)
T15-1 (5)	0.33	0.11	0.28	0.21	0.28
T15-5 (5)	(0.14)	(0.30)	(0.23)	(0.17)	(0.29)

May 26 PM	NB	SB	WB	EB	Combined
T15-1	0.01	0.15	(0.19)	0.26	0.12
T15-2	0.09	(0.27)	0.27	(0.23)	(0.13)
T15-2 (1)	(0.10)	0.20	0.00	0.16	0.16
T15-2 (1)	0.06	(0.15)	0.24	(0.27)	(0.07)

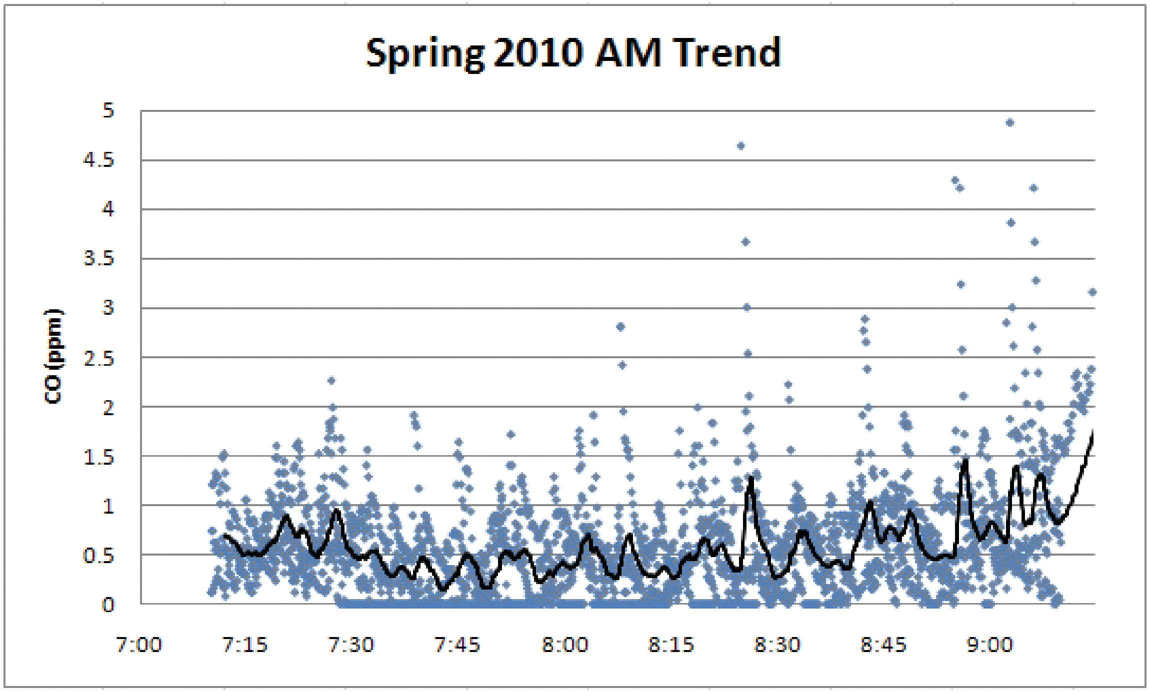
T15-1 (2)	(0.06)	0.19	0.11	0.08	0.19
T15-2 (2)	(0.03)	(0.07)	0.21	(0.30)	(0.07)
T15-1 (3)	(0.12)	0.20	(0.05)	0.02	0.09
T15-2 (3)	(0.15)	(0.02)	0.24	(0.34)	(0.09)
T15-1 (5)	(0.17)	0.16	(0.08)	0.03	0.02
T15-5 (5)	(0.36)	0.10	0.15	(0.36)	(0.15)

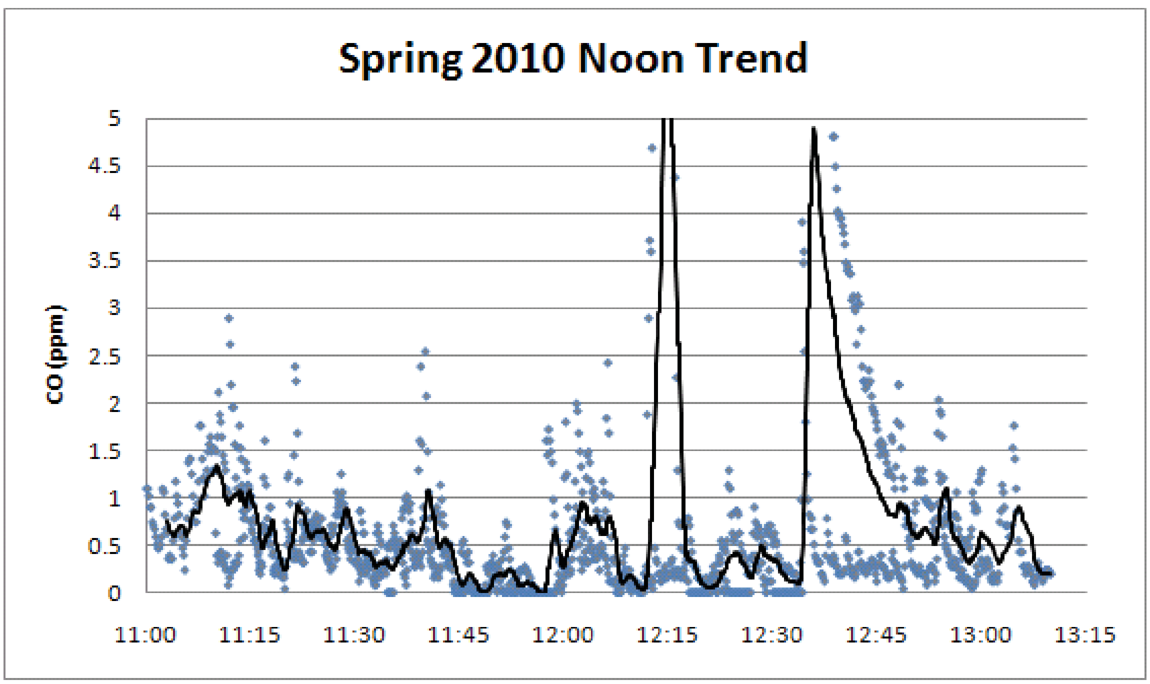
May 27 AM	NB	SB	WB	EB	Combined
T15-1	0.29	0.34	0.29	0.39	0.54
T15-2	(0.01)	0.04	(0.28)	0.26	0.05
T15-2 (1)	0.27	0.37	0.25	0.35	0.52
T15-2 (1)	(0.06)	0.01	(0.26)	0.22	(0.00)
T15-1 (2)	0.29	0.38	0.21	0.32	0.50
T15-2 (2)	(0.10)	(0.08)	(0.21)	0.16	(0.07)
T15-1 (3)	0.30	0.33	0.18	0.35	0.49
T15-2 (3)	(0.18)	(0.08)	(0.15)	0.09	(0.12)
T15-1 (5)	0.27	0.27	0.36	0.16	0.41
T15-5 (5)	(0.26)	(0.05)	(0.10)	0.01	(0.16)

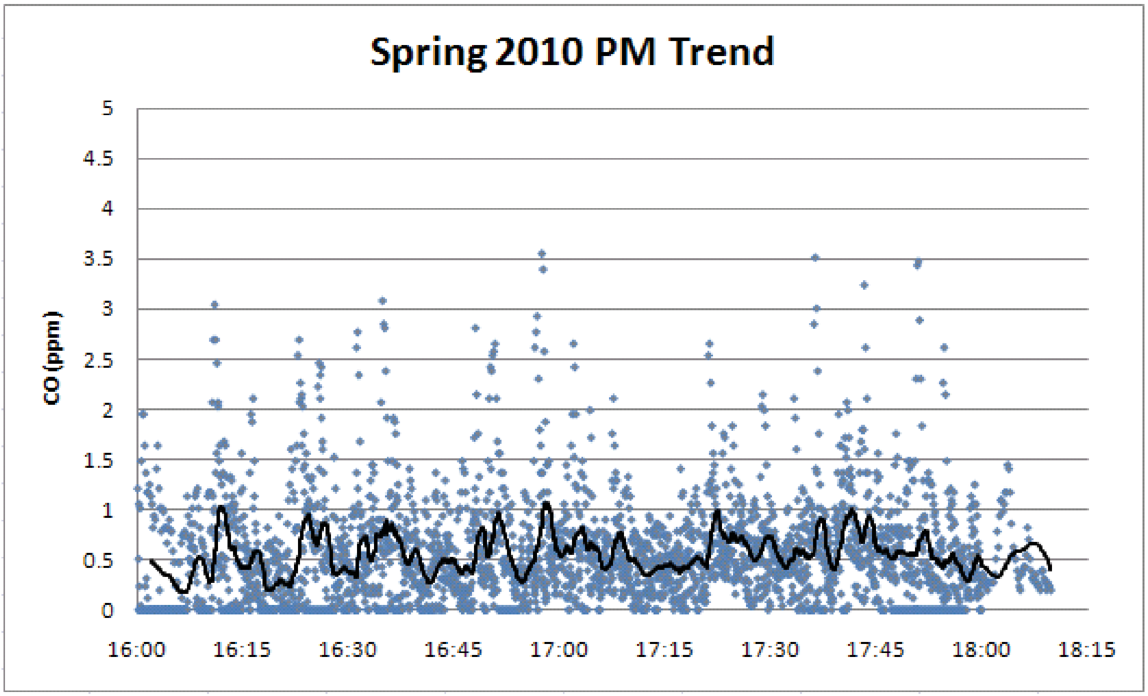
May 27 PM	NB	SB	WB	EB	Combined
T15-1	(0.14)	0.29	0.36	0.45	0.50
T15-2	0.34	(0.44)	(0.36)	(0.23)	(0.39)
T15-2 (1)	(0.20)	0.21	0.40	0.44	0.44
T15-2 (1)	0.44	(0.43)	(0.36)	(0.17)	(0.31)
T15-1 (2)	(0.24)	0.18	0.36	0.52	0.44
T15-2 (2)	0.60	(0.33)	(0.39)	(0.14)	(0.18)
T15-1 (3)	(0.26)	0.11	0.27	0.56	0.38
T15-2 (3)	0.59	(0.32)	(0.33)	(0.14)	(0.16)
T15-1 (5)	(0.17)	0.18	0.26	0.46	0.39
T15-5 (5)	0.59	(0.39)	(0.32)	(0.15)	(0.21)

Daily Trends in CO Concentration.

4AM, 2Noon, and 4PM tests were compiled to create the figures. All data is from T15-2 since the location was constant.







Spring 2010 PM Trend
CO (ppm)
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
16:00
16:15
16:30
16:45
17:00
17:15
17:30
17:45
18:00
18:15

Appendix F: CCM

Main Entrance/Exit

General Layout with ramp in the middle and parking on both sides and at the other end.

Side exit on level 1.

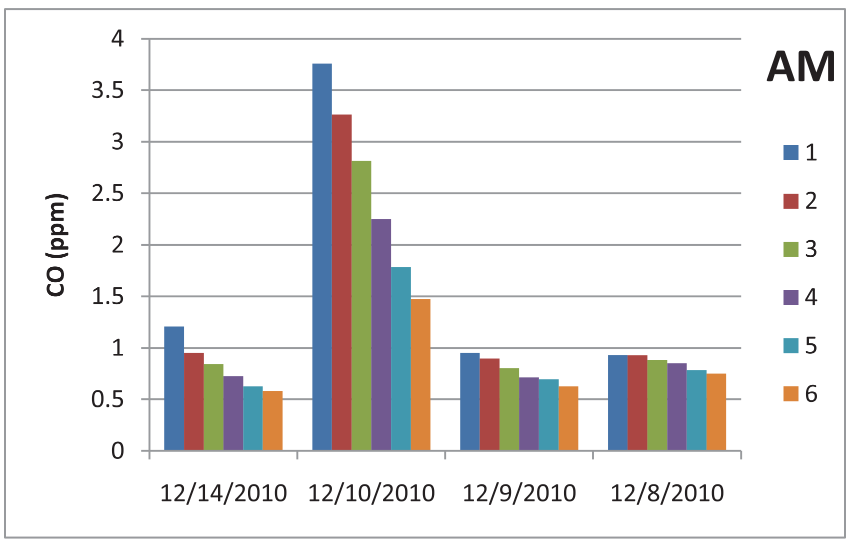
Side entrance one level below main entrance/exit.

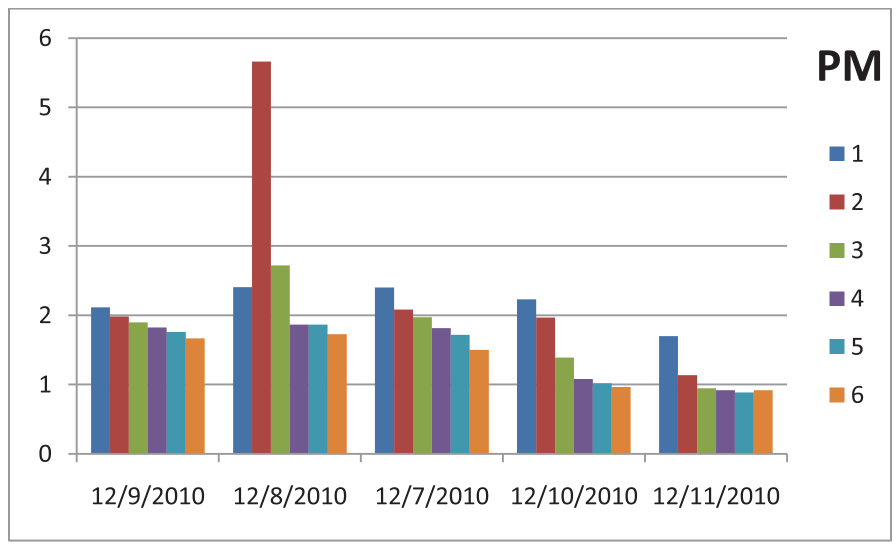
Appendix G: Cincinnati Vehicles

Hybrid

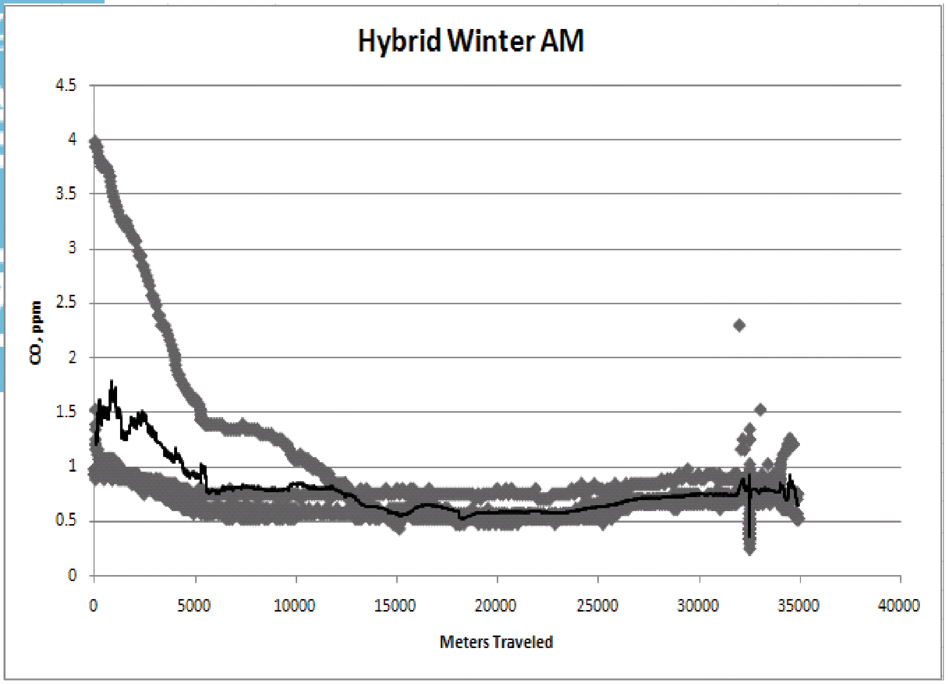
				Correlation Coefficients										
	Start	Stop	Duration	CO vs. Grade	CO V.S. speed	CO V.S. acceleration	CO V.S. VSP	Avg CO (ppm)	St Dev (ppm)	Max CO (ppm)	Max Time	Min CO (ppm)	PreAmb (ppm)	PostAmb (ppm)
12-8 AM	9:35:00	10:12:20	0:37:20	0.09	-0.51	-0.03	-0.28	0.86	0.15	2.30	10:04:02	0.66	1.08	1.16
12-9 AM	9:26:20	10:15:41	0:49:21	-0.19	-0.02	0.02	-0.01	0.31	0.30	1.34	9:56:19	0.03	0.08	0.43
12-10 AM	9:08:32	9:55:57	0:47:25	0.02	-0.08	0.02	-0.01	1.22	1.05	4.44	9:08:32	0.43	4.76	0.72
12-11 AM	8:39:27	9:17:03	0:37:36	-0.06	-0.20	0.13	-0.06	0.86	0.12	1.30	9:13:00	0.61	0.31	0.98
12-14 AM	8:52:28	9:28:03	0:35:35	0.05	-0.70	-0.02	-0.40	0.71	0.24	1.16	8:52:28	0.20	1.64	0.72
12-7 PM	20:24:19	20:56:00	0:31:41	-0.03	-0.29	0.08	-0.12	1.16	0.58	2.80	20:24:19	0.61	2.58	0.66
12-8 PM	18:37:57	19:25:16	0:47:19	-0.27	-0.49	0.03	-0.28	1.52	1.50	8.00	18:43:49	0.47	0.34	0.51
12-9 PM	17:22:55	18:14:30	0:51:35	0.10	-0.16	0.04	-0.07	1.16	0.43	2.25	17:22:55	0.57	1.69	1.67
12-10 PM	17:35:49	18:18:12	0:42:23	0.16	-0.07	0.06	0.04	1.33	0.48	2.34	17:37:00	0.31	0.14	0.72

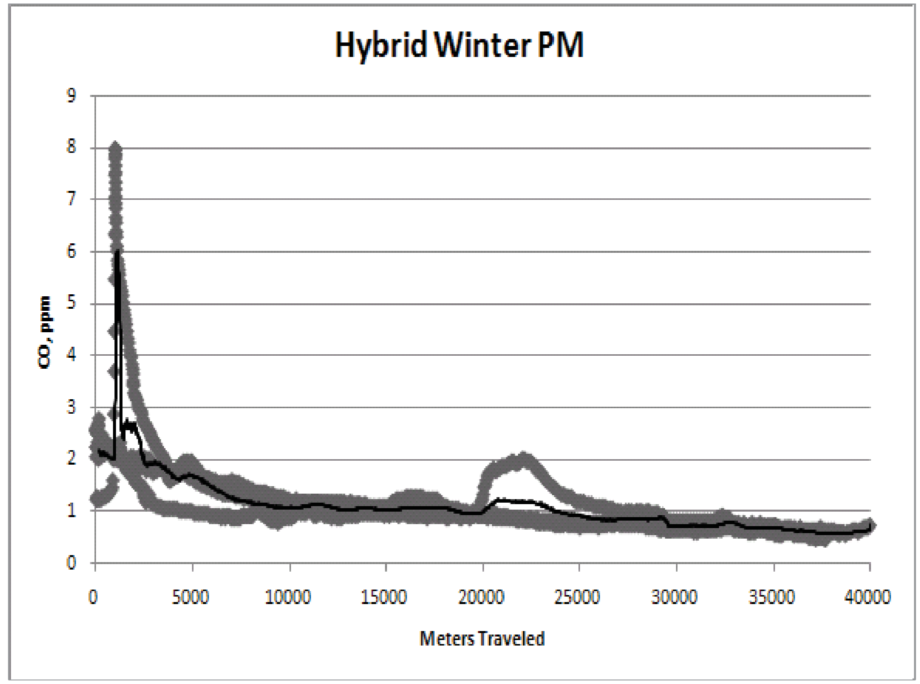
Plots of CO Concentration by Kilometer Traveled





Plots of CO vs Time in the Vehicle

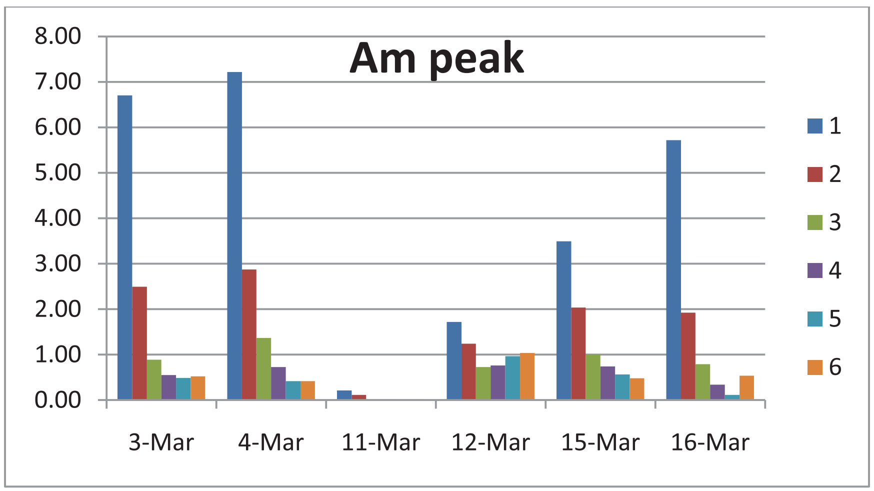


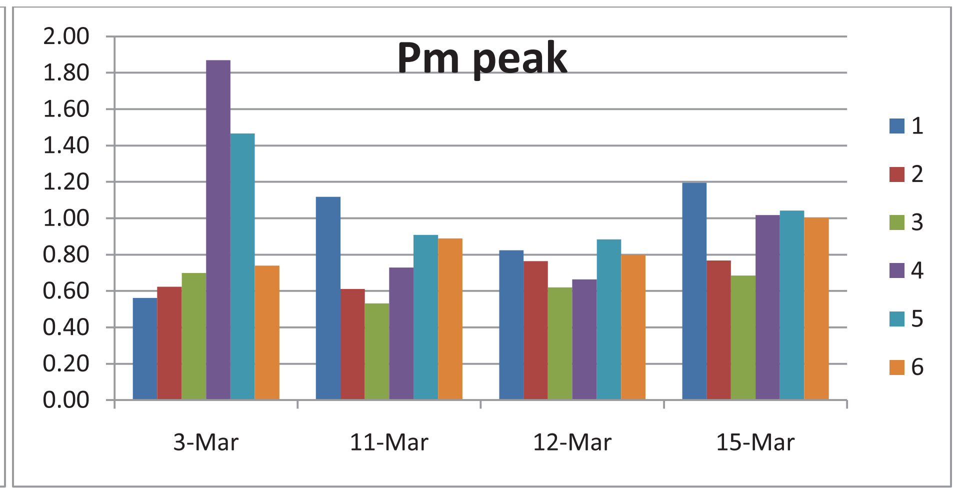


Saturn - Winter

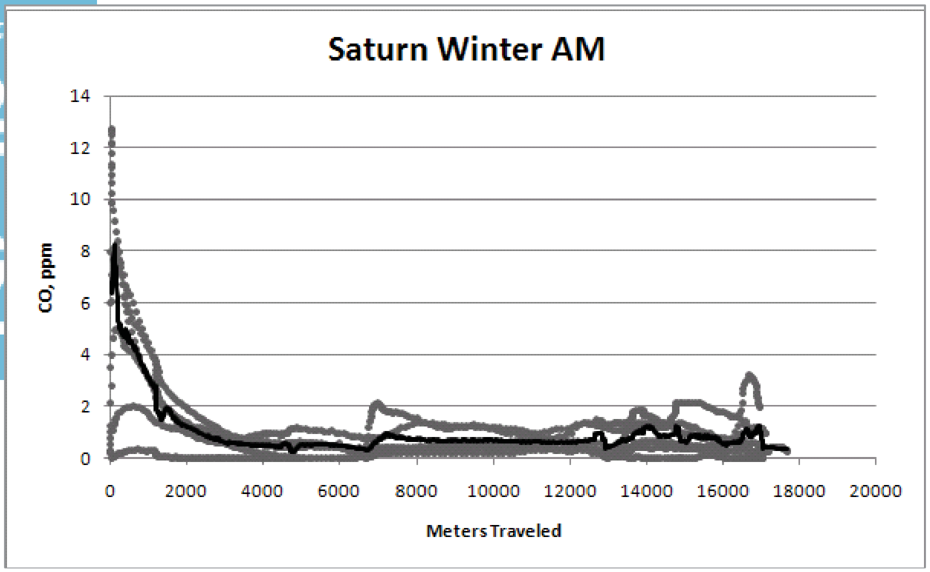
Date	Start	Stop	Duration	Correlation Coefficients CO vs grade	CO vs speed	CO vs accel	CO vs VSP	Avg CO (ppm)	St Dev (ppm)	Max (ppm)	Min (ppm)	PreAmb (ppm)	PostAmb (ppm)
3-Mar AM	8:21:44	8:50:34	0:28:50	0.10	(0.03)	0.02	0.02	1.04	1.44	8.13	0.16	0.11	0.25
4-Mar AM	8:40:05	9:07:05	0:27:00	0.09	(0.23)	0.06	(0.01)	1.61	2.64	12.74	0.20	0.02	0.20
11-Mar AM	8:41:02	9:06:47	0:25:45	0.07	(0.15)	(0.02)	(0.01)	0.67	0.66	2.16	0.02	0.03	0.82
12-Mar AM	8:38:24	9:01:39	0:23:15	0.09	(0.23)	0.01	(0.08)	1.24	0.53	3.21	0.61	0.08	1.75
15-Mar AM	10:10:58	10:33:33	0:22:35	(0.01)	(0.14)	0.06	(0.04)	0.86	1.00	4.99	0.20	0.14	0.30
16-Mar AM	6:01:24	6:22:04	0:20:40	0.01	(0.08)	0.10	0.01	0.73	1.59	7.95	0.02	0.02	0.02
3-Mar PM	17:13:56	17:46:51	0:32:55	(0.02)	(0.30)	0.02	(0.08)	0.87	0.59	2.98	0.16	1.01	0.13
11-Mar PM	18:01:25	18:29:06	0:27:41	0.04	(0.01)	(0.01)	0.06	0.89	0.25	1.48	0.43	0.89	0.25
12-Mar PM	17:12:27	17:54:22	0:41:55	(0.00)	(0.37)	0.04	(0.15)	0.55	0.28	1.02	0.02	0.55	0.02
15-Mar PM	18:24:13	18:43:53	0:19:40	0.15	0.23	0.13	0.19	0.72	0.31	1.57	0.25	1.73	0.21

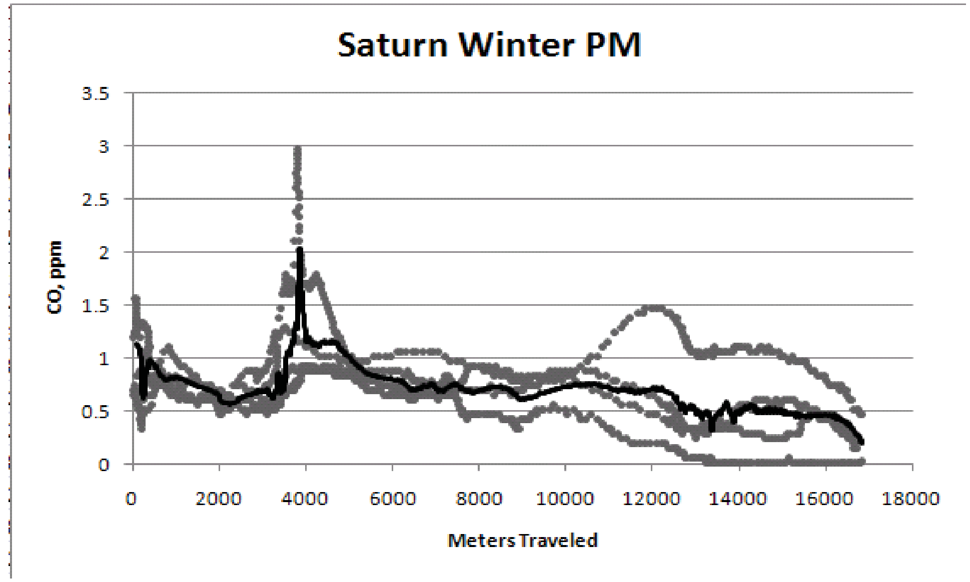
Plots of CO Concentration by Kilometer Traveled





CO vs Time, Saturn – Winter

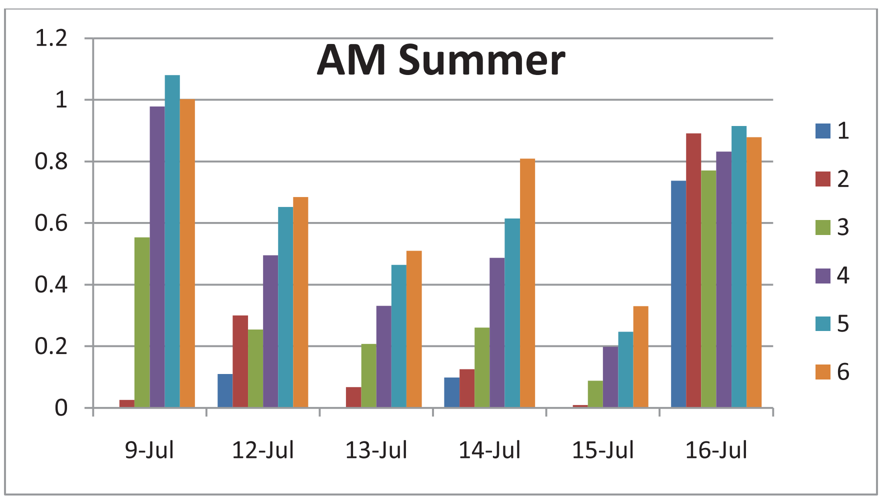


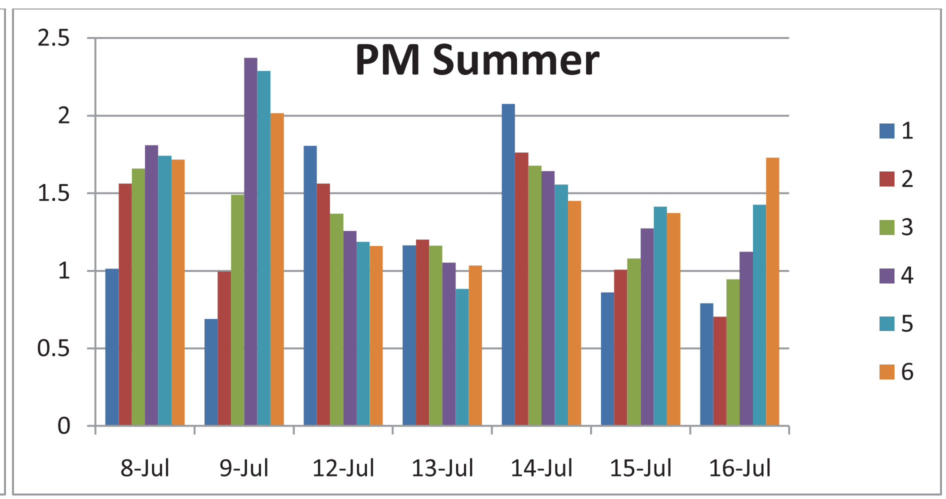


Saturn - Summer

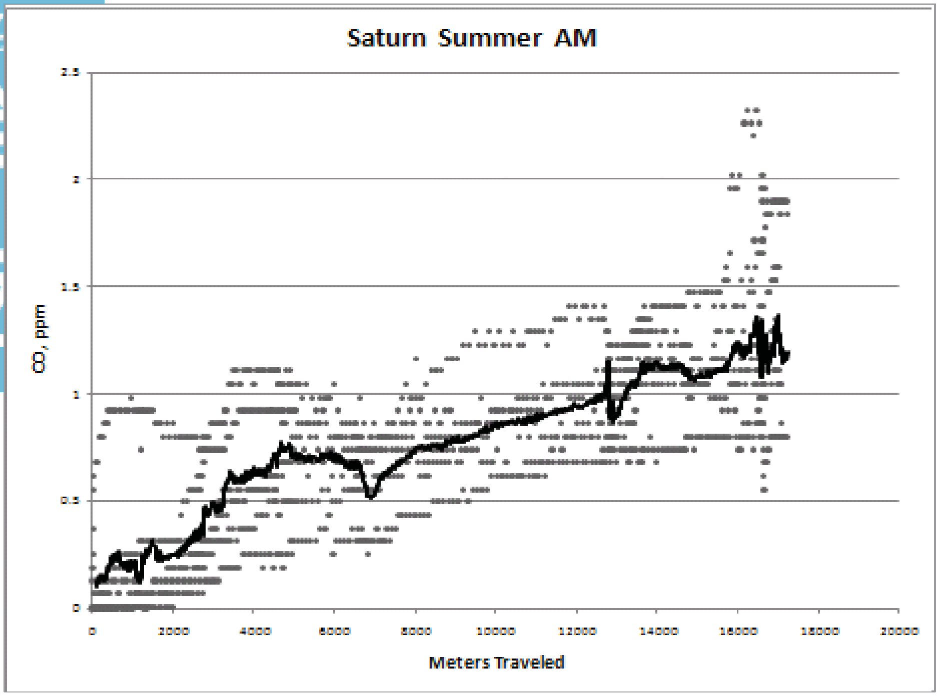
Date	Start	Stop	Duration	CO vs grade	CO vs speed	CO vs accel	CO vs VSP	Avg CO (ppm)	St Dev (ppm)	Max (ppm)	Min (ppm)	PreAmb (ppm)	PostAmb (ppm)
9-Jul AM	8:37:01	8:58:56	0:21:55	0.04	0.11	(0.01)	0.10	0.72	0.34	1.17	0.00	0.00	0.11
12-Jul AM	8:33:06	8:58:56	0:25:50	(0.01)	(0.12)	(0.06)	(0.03)	0.89	0.54	2.33	0.00	0.03	0.90
13-Jul AM	8:32:38	8:56:58	0:24:20	0.07	(0.04)	(0.03)	0.01	0.78	0.51	1.72	0.00	0.05	1.21
14-Jul AM	8:32:23	8:58:48	0:26:25	(0.02)	0.11	(0.03)	0.05	0.86	0.43	1.53	0.00	0.13	0.49
15-Jul AM	8:32:29	8:58:14	0:25:45	0.17	(0.11)	(0.04)	(0.00)	0.56	0.41	1.29	0.00	0.04	0.64
16-Jul AM	8:34:31	8:58:21	0:23:50	(0.02)	(0.09)	(0.01)	0.04	0.85	0.16	1.29	0.13	0.10	0.04
8-Jul PM	17:34:06	18:02:23	0:28:17	0.02	0.10	0.07	0.09	1.28	0.54	2.45	0.00	0.00	1.45
9-Jul PM	16:54:05	17:18:15	0:24:10	(0.03)	0.32	0.03	0.18	1.36	0.55	2.51	0.43	0.31	1.78
12-Jul PM	16:38:54	17:02:34	0:23:40	0.17	(0.03)	0.04	0.01	1.16	0.38	1.96	0.50	0.87	0.00
13-Jul PM	17:28:05	18:07:10	0:39:05	0.03	0.22	(0.05)	0.00	1.03	0.15	1.41	0.74	0.51	0.00
14-Jul PM	17:35:59	18:02:09	0:26:10	0.18	(0.15)	0.04	(0.03)	1.47	0.37	2.33	0.68	2.09	0.08
15-Jul PM	16:33:29	17:01:14	0:27:45	0.04	(0.08)	(0.00)	0.00	1.18	1.18	1.18	1.18	1.18	1.18
16-Jul PM	17:31:07	17:55:22	0:24:15	0.04	0.52	0.02	0.24	1.17	0.40	1.78	0.00	0.33	0.00

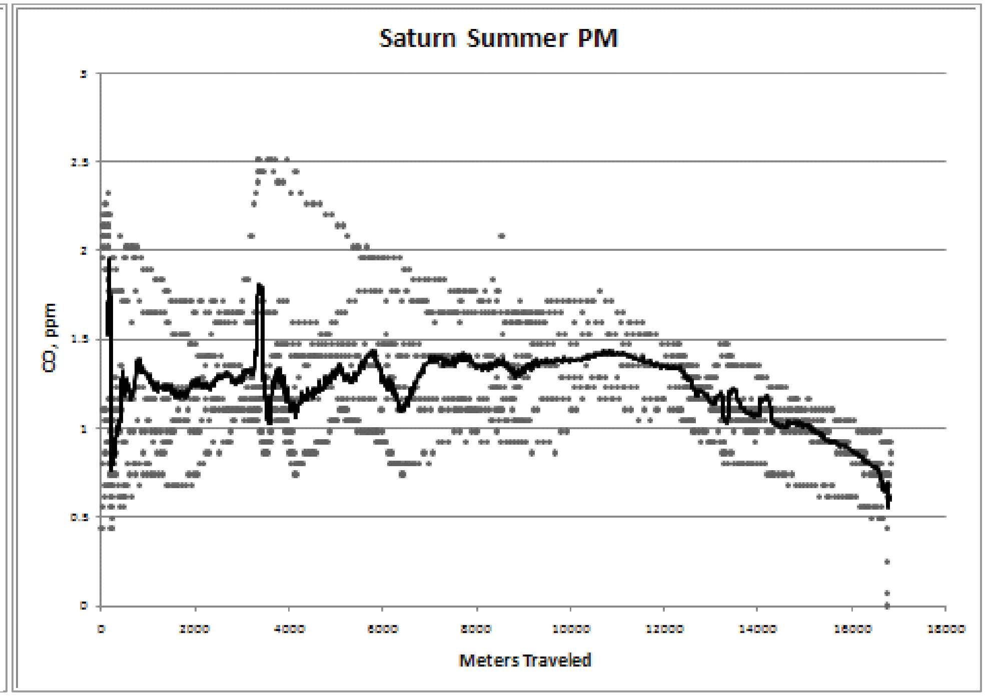
Plots of CO Concentration by Kilometer Traveled





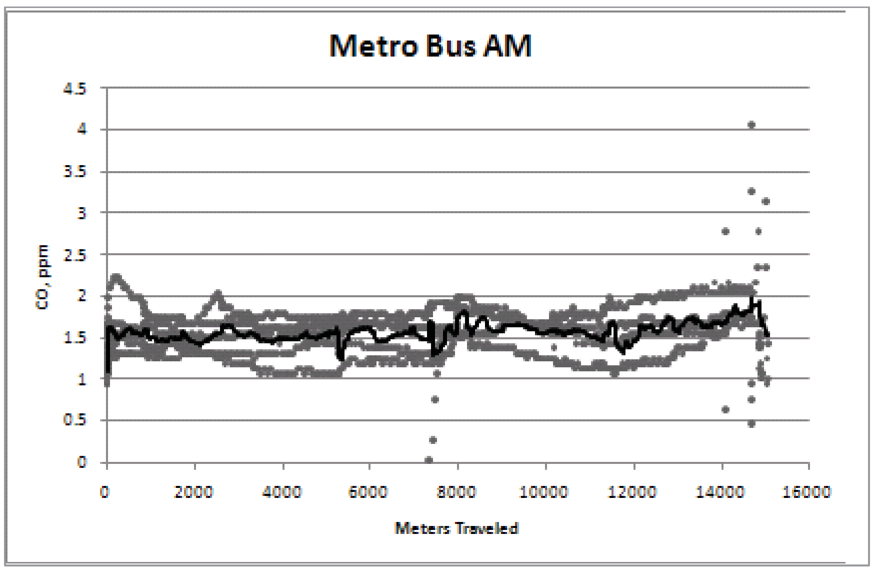
CO vs Time, Saturn - Summer

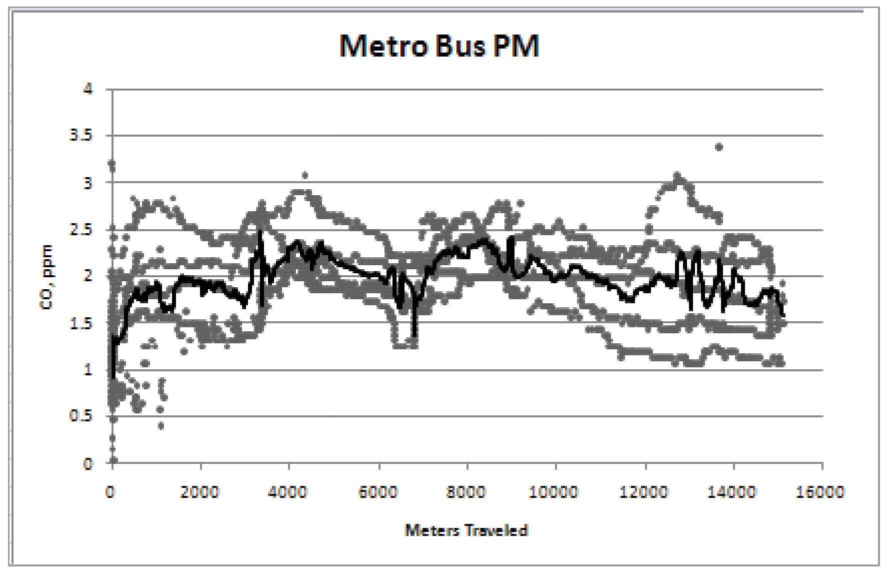




Metro - Summer

Date	Start	Stop	Duration	CO vs grade	CO vs speed	CO vs accel	CO vs VSP	Avg CO (ppm)	St Dev (ppm)	Max (ppm)	Min (ppm)	PreAmb (ppm)	PostAmb (ppm)
19-Jul AM	8:37:03	9:19:19	0:42:16	0.06	0.12	0.01	(0.03)	0.67	0.38	1.35	0.01	0.13	0.21
20-Jul AM	8:42:26	8:59:01	0:16:35	(0.09)	0.13	(0.01)	(0.09)	0.33	0.41	4.52	0.00	0.17	0.33
21-Jul AM	8:42:06	9:17:46	0:35:40	(0.00)	(0.13)	0.01	(0.06)	0.67	0.22	1.78	0.00	0.48	0.11
22-Jul AM	8:36:08	9:17:58	0:41:50	0.06	0.26	0.00	(0.06)	0.58	0.21	1.05	0.00	0.00	0.00
23-Jul AM	8:38:25	9:14:50	0:36:25	0.00	0.04	0.00	0.00	0.34	0.26	1.23	0.00	0.00	0.00
19-Jul PM	17:11:05	17:50:30	0:39:25	0.09	0.19	(0.04)	0.06	0.88	0.60	2.39	0.00	0.00	0.87
20-Jul PM	17:13:08	17:55:53	0:42:45	(0.03)	(0.06)	0.02	(0.03)	0.61	0.33	2.08	0.00	0.14	0.41
21-Jul PM	17:11:06	17:57:51	0:46:45	0.02	(0.02)	0.01	0.00	0.93	0.36	1.66	0.07	0.05	0.37
22-Jul PM	17:08:58	17:53:13	0:44:15	(0.10)	0.21	(0.00)	0.05	1.25	0.81	2.08	0.00	0.21	0.24
23-Jul PM	17:12:05	17:50:55	0:38:50	(0.14)	0.27	0.02	(0.08)	0.98	0.37	2.20	0.00	0.00	0.25



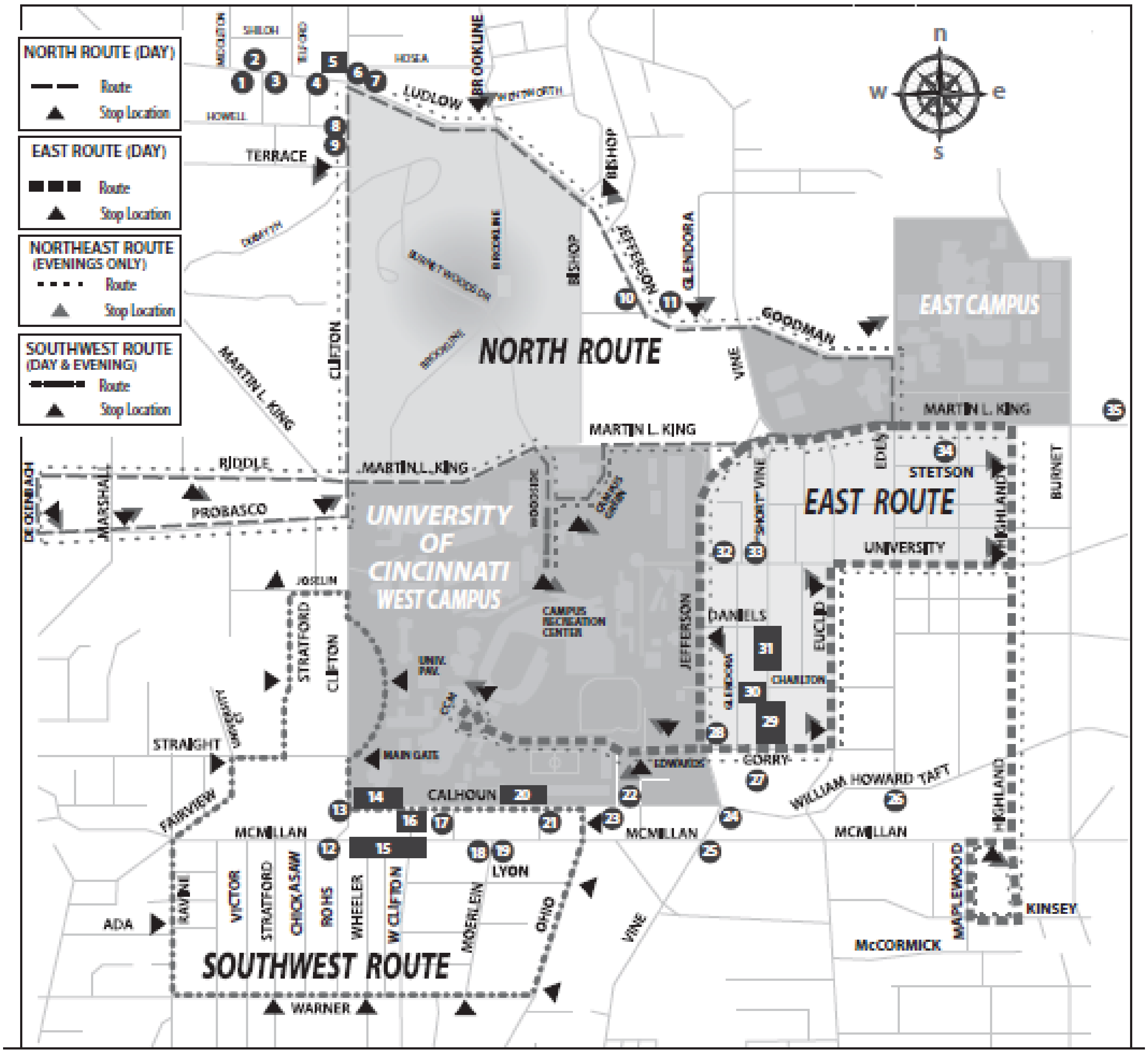


UC Bearcat Transit System, Shuttle Bus - Winter

Time on	Time off	Duration	Avg.CO (ppm)	Max CO (ppm)	Stdev (ppm)	Min (ppm)	Pre-Amb.	CO Increase (ppm)	Post-Amb. (ppm)	Avg speed (km/h)	Grade	Speed	Accel.	VSP
9:46:20	10:09:11	0:22:51	0.82	1.17	0.08	0.68	0.80	0.02	1.27	13.65	(0.04)	(0.03)	(0.03)	(0.03)
10:19:08	10:42:47	0:23:39	0.84	1.72	0.18	0.68	1.32	-0.48	0.95	13.95	0.01	0.08	0.01	0.02
10:59:59	11:25:50	0:25:51	1.08	1.10	0.03	0.96	1.03	0.05	1.10	12.53	0.02	0.01	(0.07)	(0.05)
11:41:11	12:01:55	0:20:44	1.10	1.17	0.02	1.03	1.10	-0.01	1.10	15.63	(0.07)	0.03	0.03	(0.04)
10:52:12	11:13:25	0:21:13	1.82	2.42	0.34	0.68	0.73	1.09	NA	16.97	0.18	(0.02)	(0.08)	(0.00)
11:13:25	11:34:17	0:20:52	1.99	2.77	0.15	1.72	NA	NA	1.89	17.25	(0.07)	(0.07)	(0.06)	(0.05)
9:35:28	9:55:18	0:19:50	1.72	2.35	0.29	0.01	1.59	0.13	1.74	18.15	(0.06)	0.01	(0.03)	(0.01)
12:36:30	13:02:10	0:25:40	1.48	2.91	0.34	0.75	0.77	0.71	1.56	14.96	0.08	(0.03)	(0.02)	0.02
15:01:25	15:21:45	0:20:20	1.48	2.28	0.21	0.82	0.75	0.73	1.59	17.41	0.01	(0.20)	0.01	0.04
15:43:25	16:04:41	0:21:16	1.58	2.21	0.24	0.96	0.95	0.64	2.01	17.21	(0.09)	(0.08)	(0.02)	(0.05)
9:10:02	9:30:57	0:20:55	2.19	4.85	0.38	1.03	1.84	0.35	2.23	16.64	0.04	0.06	0.00	0.03

Bearcat Transportation System

MONDAY-FRIDAY DAY & EVENING ROUTE SCHEDULE

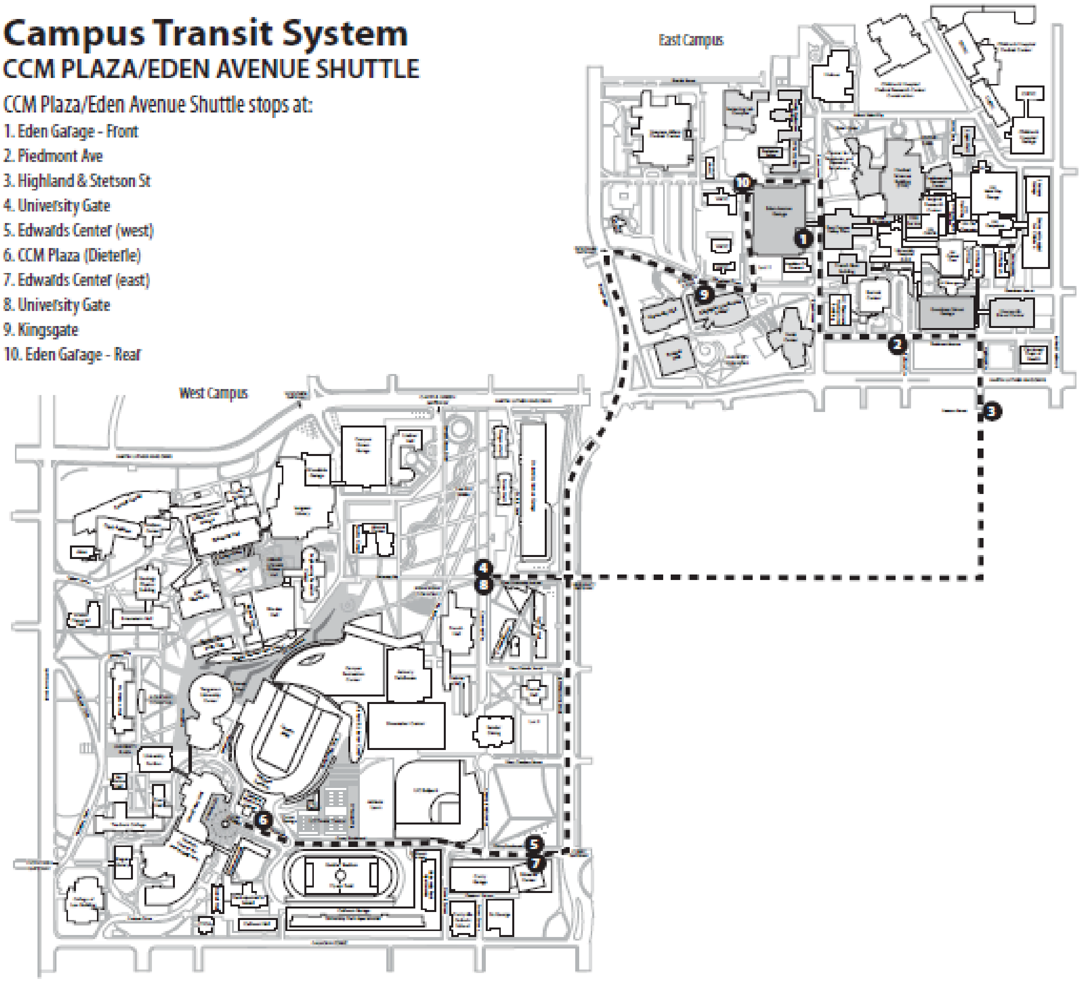


Campus Transit System

CCM PLAZA/EDEN AVENUE SHUTTLE

CCM Plaza/Eden Avenue Shuttle stops at:

1. Eden Garage - Front
2. Piedmont Ave
3. Highland & Stetson St
4. University Gate
5. Edwards Center (west)
6. CCM Plaza (Dieterle)
7. Edwards Center (east)
8. University Gate
9. Kingsgate
10. Eden Garage - Rear



Appendix H: Hayes Porter

Bus Activity 3-16 through 3-18
3-16 AM
7:23-7:25 – 1st bus, all sensors in place.
7:31-7:34, 2 more buses arrive and leave, one moves up 100' and idles till 7:44.
7:35-8:19 bus idle on court south of the school about 50' from Cutter and Court intersection.
7:37 Short school bus at side entrance.
7:40-7:48 Bus idle on court.
7:42 School Bus at side entrance.

3-17 AM
7:28-7:30 Two empty school buses arrive in front of school.
7:30 School bus at side entrance.
7:34 Scchool bus at side entrance.
7:40-8:17 School bus idling on court.
8:05 School bus passing in front of school.
8:51 School bus stopped in front of the school and turned off engine.

3-18 AM
7:24 Cars begin arriving.
7:27-7:32 Bus in front of school.
7:31-7:33 Bus in front of school.
7:30-7:35 Bus at side entrance.
7:37-7:39 Bus at side entrance.
7:41-8:19 Bus idle on court.

3-16 PM
1:54 School bus at side entrance.
1:50 Two buses stopped on the side of court near playground, 1 more arrived at 1:54.
1:54-1:57 T15 CO measurer taken to bus stop.
School buses arrive in front of school. Time not recorded, leave at 2:26.
2:00-2:35 Parents arrive and pick up kids.

3-17 PM
2:05-2:10 Short school bus at side entrance.
2:12 Three buses pull in front of school and turn off engines.
2:25 All buses are gone, 3 cars remain in front of school.

3-18 PM
1:58 T15 CO measurer taken to Queensgate playfield where 3 buses are idling.
2:10 Three buses that had been idling by Queensgate playfield west of court and cutter intersection move in front of the school.
2:14 T15 CO measurer taken to front of school at school bus pick up zone.
2:19-2:21 School bus at side entrance.
2:30 T15 returned to court and cutter intersection.

Hourly Met Data – From Cincinnati Northern Kentucky Airport. 10 Miles Southwest of Site. *** indicates a calm wind condition.

Date/Time	Wind Direction (Deg from North)	Wind Speed (mph)	Temp (C)
3/4/2010 12:53	350	9	7
3/4/2010 13:53	10	10	7
3/4/2010 14:53	340	9	5
3/4/2010 15:53	360	11	4
3/4/2010 16:53	350	5	2

Date/Time	Wind Direction (Deg from North)	Wind Speed (mph)	Temp (C)
3/5/2010 6:53	40	3	1
3/5/2010 7:53	990	6	4
3/5/2010 8:53	50	3	6
3/5/2010 9:53	30	8	7
3/5/2010 10:53	320	7	8

Date/Time	Wind Direction (Deg from North)	Wind Speed (mph)	Temp (C)
3/16/2010 6:53	40	5	10
3/16/2010 7:53	30	5	12
3/16/2010 8:53	60	6	12
3/16/2010 9:53	990	3	14
3/16/2010 10:53	30	8	15
3/16/2010 11:53	10	8	14
3/16/2010 12:53	50	6	14
3/16/2010 13:53	30	3	14
3/16/2010 14:53	***	0	14
3/16/2010 15:53	***	0	12
3/16/2010 16:53	***	0	12
3/16/2010 17:53	***	0	11
3/16/2010 18:53	***	0	10
3/16/2010 19:53	60	3	9

Date/Time	Wind Direction (Deg from North)	Wind Speed (mph)	Temp (C)
3/17/2010 6:53	60	5	7
3/17/2010 7:53	***	0	6

3/17/2010 8:53	40	3	6
3/17/2010 9:53	70	3	4
3/17/2010 10:53	360	6	5
3/17/2010 11:53	350	7	6
3/17/2010 12:53	10	6	6
3/17/2010 13:53	50	6	7
3/17/2010 14:53	10	7	8
3/17/2010 15:53	340	3	11
3/17/2010 16:53	***	0	14
3/17/2010 17:53	***	0	16
3/17/2010 18:53	***	0	17
3/17/2010 19:53	***	0	18

Date/Time	Wind Direction (Deg from North)	Wind Speed (mph)	Temp (C)
3/18/2010 6:53	***	0	11
3/18/2010 7:53	350	8	15
3/18/2010 8:53	10	5	17
3/18/2010 9:53	250	7	17
3/18/2010 10:53	270	11	18
3/18/2010 11:53	270	8	18
3/18/2010 12:53	330	7	19
3/18/2010 13:53	270	7	18
3/18/2010 14:53	260	7	17
3/18/2010 15:53	270	6	16
3/18/2010 16:53	***	0	13
3/18/2010 17:53	***	0	9
3/18/2010 18:53	***	0	8
3/18/2010 19:53	***	0	8

Total Traffic Counts at Lynn/Court and Court/Cutter Intersections

16-Mar

Begin	End	LC traffic	CC traffic
7:24	7:29	53	6
7:29	7:34	47	6
7:34	7:39	55	8
7:39	7:44	60	7
7:44	7:49	52	7
7:49	7:54	62	9
7:54	7:59	53	2
7:59	8:04	80	10
8:04	8:09	69	13
8:09	8:14	52	5
8:14	8:19	65	8
8:19	8:24	87	9
8:24	8:29	65	4
8:29	8:34	63	8
8:34	8:39	85	13
8:39	8:44	52	5
8:44	8:49	67	6
8:49	8:54	69	8
8:54	8:59	66	5
8:59	9:04	60	10

Begin	End	LC traffic	CC traffic
10:54	10:59	43	5
10:59	11:04	57	3
11:04	11:09	54	5
11:09	11:14	58	5
11:14	11:19	45	5
11:19	11:24	59	6
11:24	11:29	57	8
11:29	11:34	74	5
11:34	11:39	61	6
11:39	11:44	65	9
11:44	11:49	66	5
11:49	11:54	56	6
11:54	11:59	77	10
11:59	12:04	68	5
12:04	12:09	69	4
12:09	12:14	64	4
12:14	12:19	72	8
12:19	12:24	63	9
12:24	12:29	83	10
12:29	12:34	80	7
12:34	12:39	79	7
12:39	12:44	79	11
12:44	12:59	83	8
12:59	13:04	79	14
13:04	13:09	56	5
13:09	13:14	71	5
13:14	13:19	63	2
13:19	13:24	53	9
13:24	13:29	58	5
13:29	13:34	66	8

Begin	End	LC traffic	CC traffic
13:34	13:39	72	10
13:39	13:44	63	9
13:44	13:49	92	13
13:49	13:54	57	6
13:54	13:59	76	9
13:59	14:04	94	11
14:04	14:09	93	11
14:09	14:14	80	13
14:14	14:19	82	4
14:19	14:24	76	4
14:24	14:29	68	4
14:29	14:34	58	5
14:34	14:39	53	4
14:39	14:44	62	11
14:44	14:49	86	15
14:49	14:54	68	7
14:54	14:59	82	12
14:59	15:04	77	6
15:04	15:09	62	7
15:09	15:14	53	6
15:14	15:19	85	8
15:19	15:24	87	7
15:24	15:29	101	14
15:29	15:34	86	13

Begin	End	LC traffic	CC traffic
15:34	15:39	90	7
15:39	15:44	71	10
15:44	15:49	78	10
15:49	15:54	63	5
15:54	15:59	80	11
15:59	16:04	93	13
16:04	16:09	102	20
16:09	16:14	91	15
16:14	16:19	106	12
16:19	16:24	79	7
16:24	16:29	71	6
16:29	16:34	95	14
16:34	16:39	94	13
16:39	16:43	85	5
16:43	16:48	80	14

17-Mar

Begin	End	LC traffic	CC traffic
7:14	7:19	51	6
7:19	7:24	41	5
7:24	7:29	52	5

Begin	End	LC traffic	CC traffic
16:55	17:00	91	13
17:00	17:05	91	7
17:05	17:10	97	17
17:10	17:15	104	13
17:15	17:20	107	14
17:20	17:25	94	11
17:25	17:30	75	4
17:30	17:35	108	12
17:35	17:40	73	9
17:40	17:45	66	6
17:45	17:50	77	5
17:50	17:55	87	11
17:55	18:00	69	9
18:00	18:05	77	9
18:05	18:10	68	8

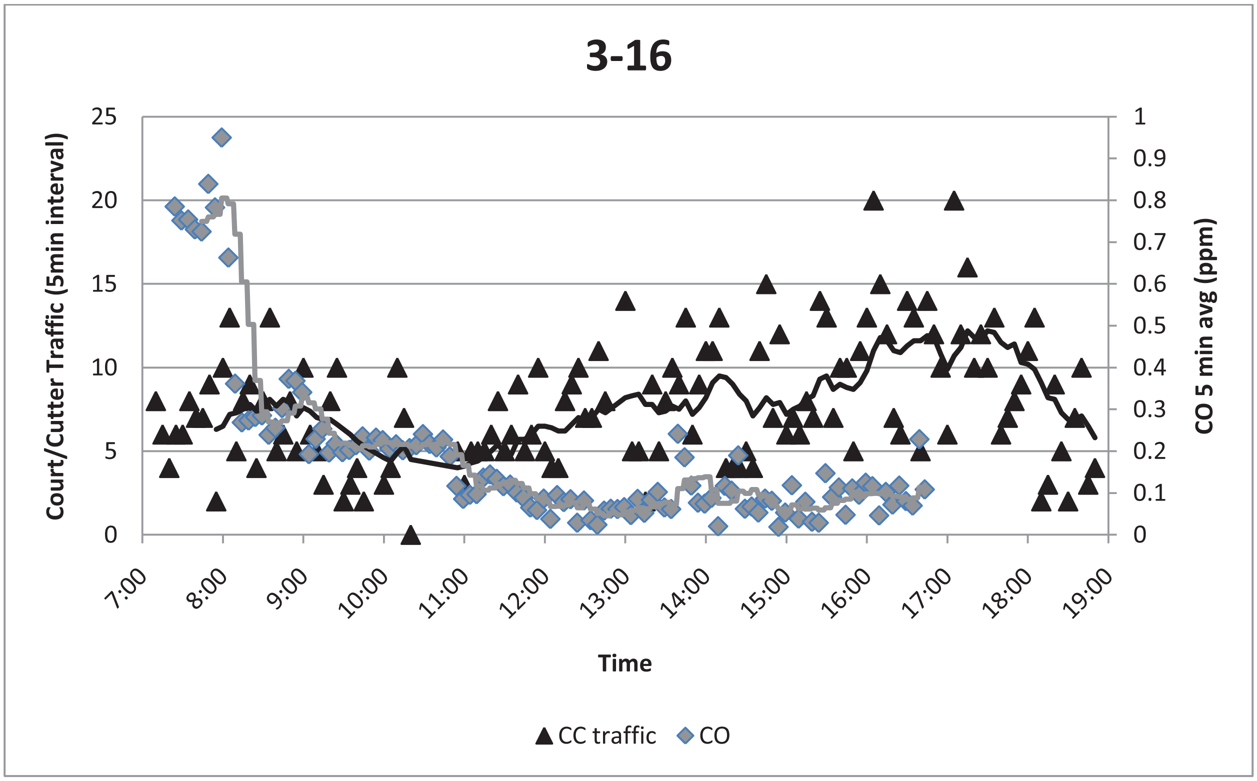
18-Mar

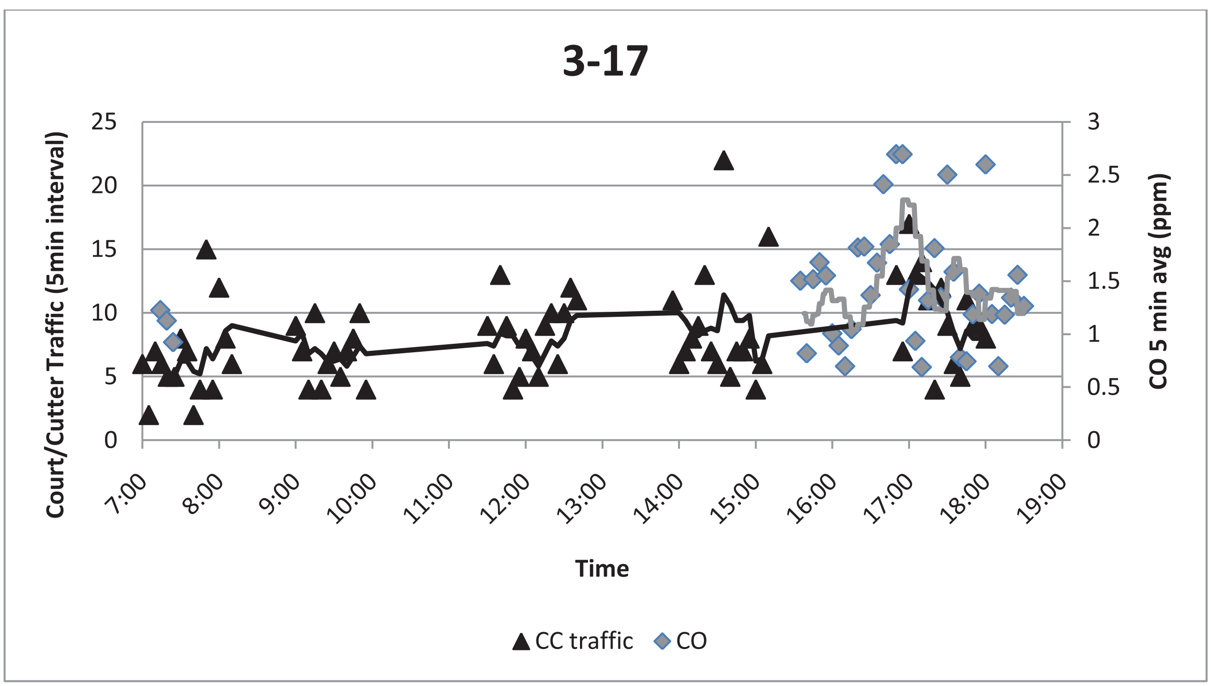
Begin	End	LC traffic	CC traffic
7:14	7:19	44	6
7:19	7:24	46	4
7:24	7:29	44	5

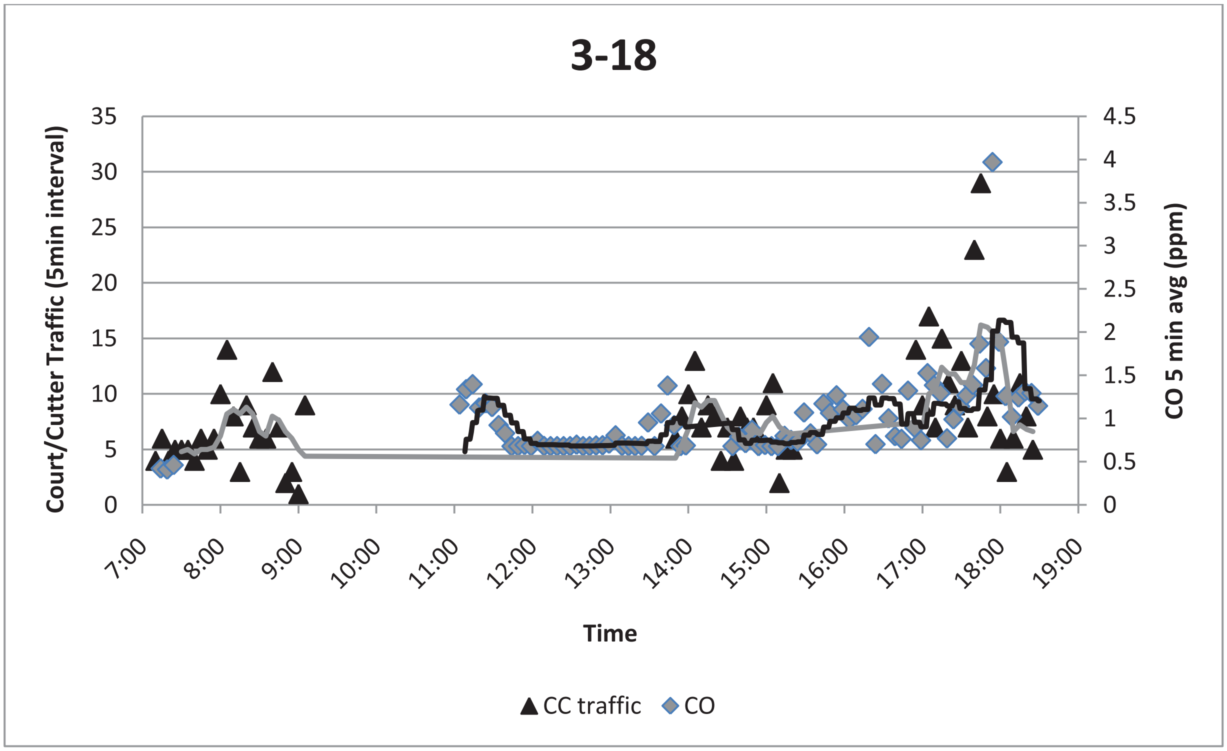
Begin	End	LC traffic	CC traffic
13:49	13:54	64	6
13:54	13:58	65	8
13:58	14:34	80	10
14:34	14:39	74	13
14:39	14:44	78	7
14:44	14:49	78	9
14:49	14:54	78	8
14:54	14:59	61	4
14:59	15:04	83	7
15:04	15:09	74	4
15:09	15:14	83	8
15:14	15:19	80	7
15:19	15:24	61	7

Plots of CO vs Time not included in document body

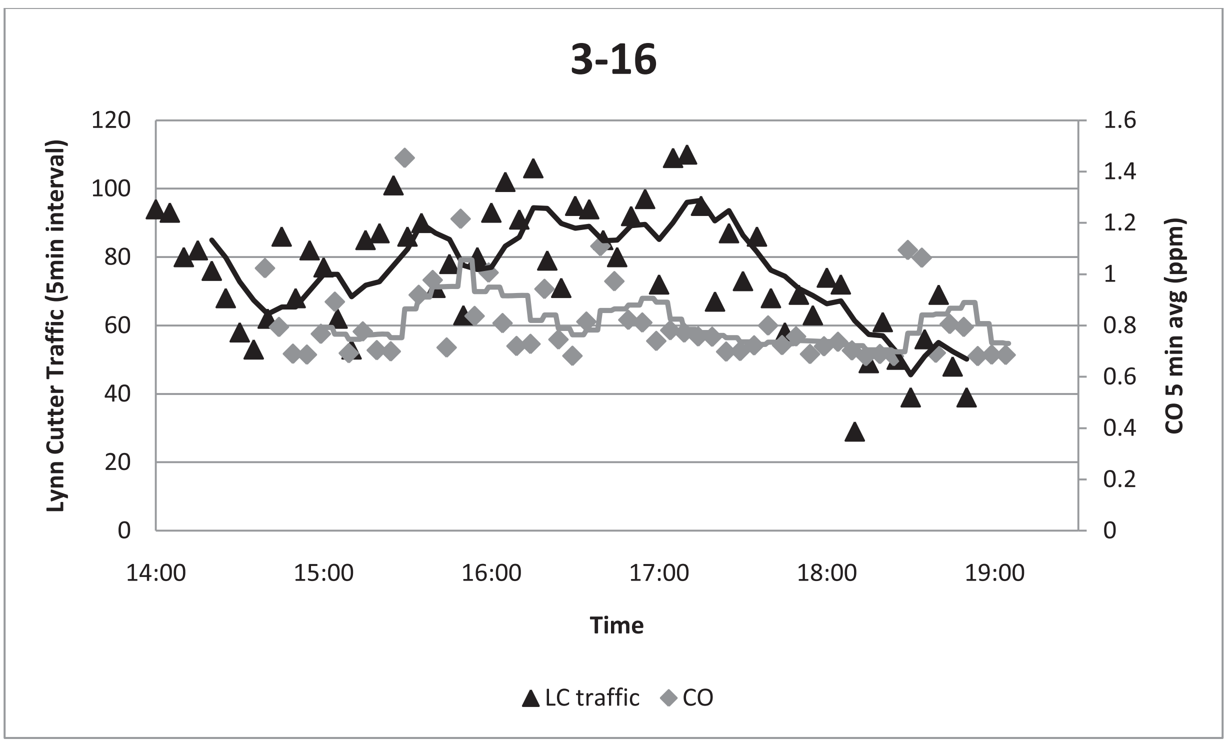
Court and Cutter Traffic vs CO

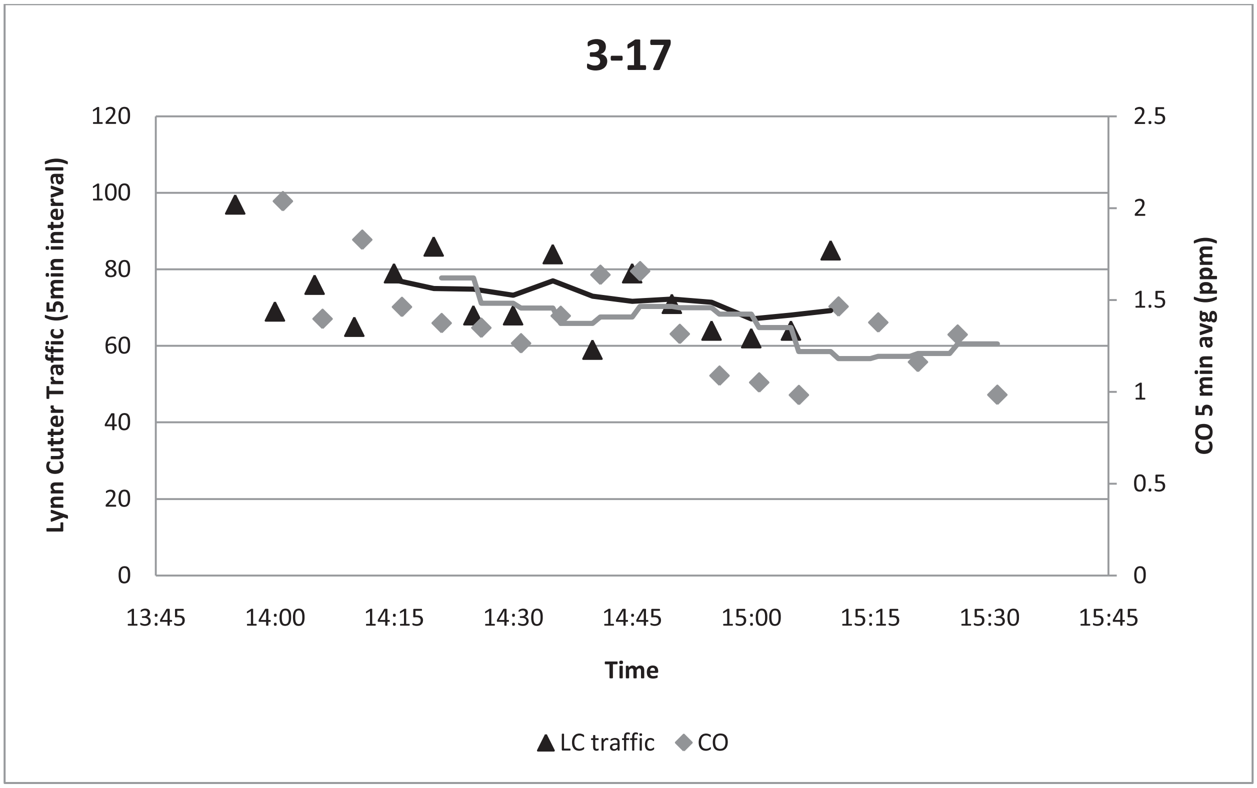






Lynn and Court Traffic




3-17
Lynn Cutter Traffic (5min interval)
CO 5 min avg (ppm)
Time
120
100
80
60
40
20
0
2.5
2
1.5
1
0.5
0
13:45
14:00
14:15
14:30
14:45
15:00
15:15
15:30
15:45
LC traffic
CO