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Indoor PM2.5 concentrations at two sites in London, Ontario - Effects of activity, outdoor concentrations and other factors

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Indoor $PM_{2.5}$ concentrations at two sites in London, Ontario – Effects of activity, outdoor concentrations and other factors

by

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ABSTRACT

Studies have shown an association between ambient fine particulate matter ($PM_{2.5}$) and health impacts, particularly for children and the elderly. As part of a larger study, $PM_{2.5}$ concentrations were measured using the DustTrak (Model 8520, TSI, St. Paul, MN, USA) at two elementary schools (Site A and B) within the city of London, Ontario (Canada).

Site A was located in a suburban environment while site B was in an urban setting. Monitoring took place for three weeks during winter (Feb. 16 – Mar. 8) and three weeks during spring (May 05 – 25) of 2010. The winter campaign monitored indoor $PM_{2.5}$ and outdoor NO_2 only, while the spring campaign added additional monitors (outdoor $PM_{2.5}$ and indoor CO_2) after the first week.

Site B's indoor $PM_{2.5}$ concentrations were greater compared to Site A. Outdoor $PM_{2.5}$ concentrations were similar at both sites. Good correlations were observed between indoor and outdoor $PM_{2.5}$ concentrations at both locations.

DEDICATION

To my family, who have always encouraged and supported my efforts from the start and up until the very end. Without their continued support I would have likely not accomplished any of this.

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Last but not least, I would like to thank my committee members, Dr. Paul Henshaw, Dr. Gary Rankin and Dr. Isaac Luginaah for their comments and suggestions which helped improve this thesis.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

NOMENCLATURE

LIST OF ABBREVIATIONS

AADTC	Annual Average Daily Traffic Count
AD	Anderson Darling statistic
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CWS	Canada-Wide Standard
EC	Elemental carbon
FEV	Forced expectorant volume
GIS	Geographical information system
GPS	Global positioning system
HCHO	Formaldehyde
HNO_3	Nitric acid
HVAC	Heating Ventilating and Air Conditioning
LOD	Limit of Detection
MDL	Minimum detection limit
MoE	Ministry of the Environment
NAAQS	National Ambient Air Quality Standards
NH_3	Ammonia
NH_4NO_3	Ammonium nitrate
NO_2	Nitrogen Dioxide
OC	Organic carbon
PEM	Personal equipment monitor
PM	Particulate Matter
$PM_{2.5}$	Particulate matter with aerodynamic diameter equal or less than 2.5 microns
PM_{10}	Particulate matter with aerodynamic diameter equal or less than 10 microns
ppm	parts per million (concentration)
PSCF	potential source contribution function
SO_2	Sulfur Dioxide
SVOC	Semi Volatile Organic Compounds
TEOM	
TSP	Total Suspended Particles
TVOC	Total Volatile Organic Compounds
UFP	Ultrafine particles
USEPA	United States Environmental Protection Agency
WHO	World Health Organization

CHAPTER 1 - INTRODUCTION

1.1. Background

Air pollution in Canada is a critical environmental and public health concern because of the many health effects associated with our exposure to it. Past studies show correlations between exposure to air pollution and premature mortality and morbidity (Horstman et al., 1982; Linn et al., 1986; Lin et al., 2002; Pope et al., 2006; OMA, 2008). Not all age groups react the same to air pollution exposure. Some age groups, in particular, infants, children and the elderly are more susceptible. According to the American Academy of Pediatrics (Kim, 2004), children are more susceptible to air pollution because of their increased level of exposure, higher lung ventilation rates and higher levels of physical activity. Children are also more vulnerable to the characteristics of local built environments due to their mobility constraints and parental controls i.e., their inability to control the time spent in a particular environment.

There is an ongoing need to study the levels of air pollution which are considered dangerous to our health as recent reports have identified adverse health effects at levels near or below the current standards for ozone, particulate matter and nitrogen dioxide (Kim, 2004). Even though the Canadian Environmental Protection Act came into force on March 31, 2000 (Environment Canada, 2011), the air in many parts of Canada is not all considered clean. In Ontario, the air quality is better in some areas compared to others (Environment Canada, 2004). The air quality in some micro-environments is different compared to others. For example, studies have shown that indoor air quality is often worse than the outdoors and that rooms with increased ventilation offer lower

concentrations compared to rooms where less ventilation is available. In order to better predict the air pollution levels in different micro-environments more research is needed to determine the concentration levels across multiple micro-environments or the exposure levels at each of the micro-environments where the concentrations are already known. Children spend much time in different micro environments each day, such as at home, outdoor when walking to school, in classrooms, in a gymnasium, school surroundings, inside a bus or private vehicles, shopping centers with parents, and others. It is imperative that more information is gathered on the typical concentrations observed in such environments so that norms and standards of acceptable levels can be established.

While many past studies focused on gathering air pollution exposure data in children's indoor environment, such as the school classroom (see Chapter 2 for in depth description), only a handful of studies examined the relationship between indoor activity in a school gym and particulate matter (PM) concentrations. In elementary schools, physical education is a mandatory activity and it usually takes place inside the school gym for most months of the school year. Very little data is available regarding the air quality inside school gyms. Since indoor PM concentration is a function of ambient concentration plus indoor concentration, and children spend time inside the gyms on a daily basis, knowing the concentration inside the gyms is important in order to accurately assess their level of exposure.

1.2. Objective

This thesis presents some of the results from a larger study entitled "Emerging Methodologies for Examining "Environmental Influences on Children's Exposure to Air Pollution." The study was conducted by a team of researchers from the University of Western Ontario in collaboration with the University of Windsor. The short term goal of the study was "to develop and test a new and improved methodology for measuring children's exposure to air pollutants in urban environments" (Gilliland et al., 2009). The long-term, on-going goal of the project is "to better identify how characteristics of physical environments impact children's activities and exposure to air pollutants" so that recommendations and interventions (behavioral or environmental) can be brought forward in order to improve children's health and quality of life. The study gathered air pollution data using personal equipment monitors (PEM) mounted to participants, indoor (inside the elementary school gymnasiums) and outdoor active $PM_{2.5}$ monitors, passive NO_2 monitors surrounding the schools and areas where the majority of the school attending children live and CO_2 monitors inside the gyms. The study also gathered comprehensive data on the participants by using daily activity questionnaires, accelerometers mounted on each participant, global position system (GPS) instruments, and before and after the study one-on-one interviews. Physical measurements and health conditions were gathered for each participant prior to the start of the study.

This research presents the results of two, three-week sessions, of continuous monitoring of $PM_{2.5}$ inside the gyms of two elementary schools in the city of London, ON, during the winter and spring of 2010. The specific objectives of this research were:

- To collect $PM_{2.5}$, NO_2 and CO_2 data by installing active and passive monitoring equipment in and around the elementary schools in question
- To determine if indoor $PM_{2.5}$ concentrations in the gyms were higher than outdoors
- To determine the effect of the following factors on $PM_{2.5}$ in the gyms:
    - Activity vs. no-activity
    - Ventilation on/off
    - Weekday/weekend
    - Seasonal differences
    - Location of gym inside the building
    - Outdoor $PM_{2.5}$ concentration
    - Outdoor NO_2 concentration
    - Indoor CO_2 concentration
- To determine which of the above mentioned factors has the largest influence on the indoor concentration of $PM_{2.5}$ inside the gyms

CHAPTER 2 - LITERATURE REVIEW

2.1. Sources of Particulate Matter

2.1.1. General characteristics of Particulate Matter

Particulates, also referred to as particulate matter, are a small discrete mass of solid and/or liquid matter that remain individually dispersed in gas or liquid emissions and are suspended in the air (Jacobson, 1999). Aerosols and raindrops are all considered particles. Airborne particles represent a complex mixture of organic and inorganic substances. They directly and indirectly affect air quality, meteorology, climate and human health.

The size of these particles tends to divide them into mainly two groups: coarse particles and fine particles. Coarse particles are larger than 2.5 micro meters (μm) in aerodynamic diameter while fine particles are smaller than 2.5 μm in aerodynamic diameter ($PM_{2.5}$). The aerodynamic diameter is referred to as the size of a unit density sphere with the same aerodynamic characteristics. The particles are sampled and described on the basis of their aerodynamic diameter which is simply called the particle size. Particles are classified by their diameter because their size governs:

- The transport and removal of the particles from the air
- The deposition within the respiratory system
- The association with the chemical composition and sources

Figure 2-1 displays the diameter of multiple items in an effort to visually show the sizes of particles in reference to each other. In the medical and health sector, PM is also

referred to based on its diameter as: inhalable, thoracic ($\leq PM_{10}$), and respirable ($\leq PM_{2.5}$) (WHO, 2000).

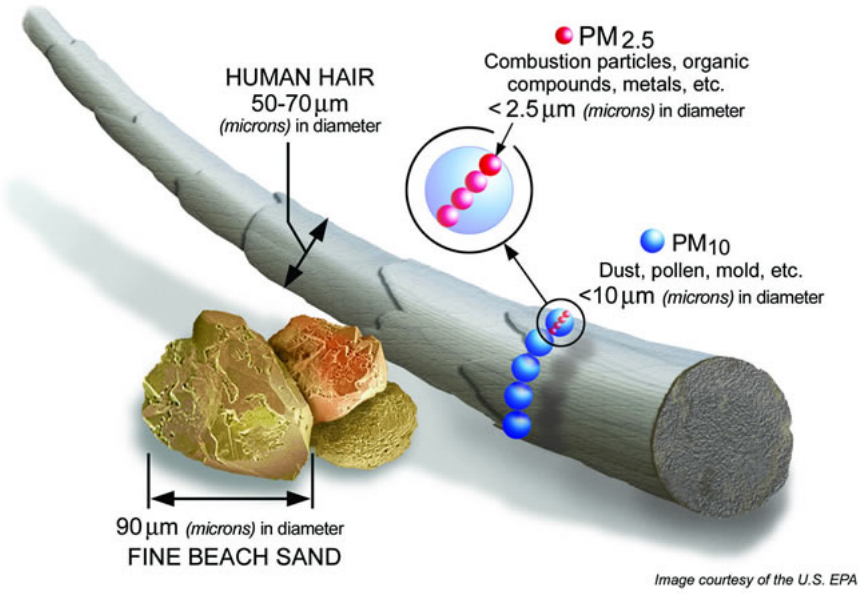

Figure 2-1: Comparison of multiple objects of different size distributions (USEPA, 2011)

Figure 2-2 displays an idealized distribution of ambient particular matter (USEPA, 2004). The size of suspended particles in the ambient air varies over 4 orders of magnitude, from nanometers (nm) to micrometers (µm). The largest of particles are called the coarse fractions and are produced by the mechanical break-up of larger solid particles. The energy amount required to break up these particles into smaller sizes increases as the size of the particle decreases, as a result, the lower limit of the production of the coarse particles is around 1 µm (USEPA, 2004).

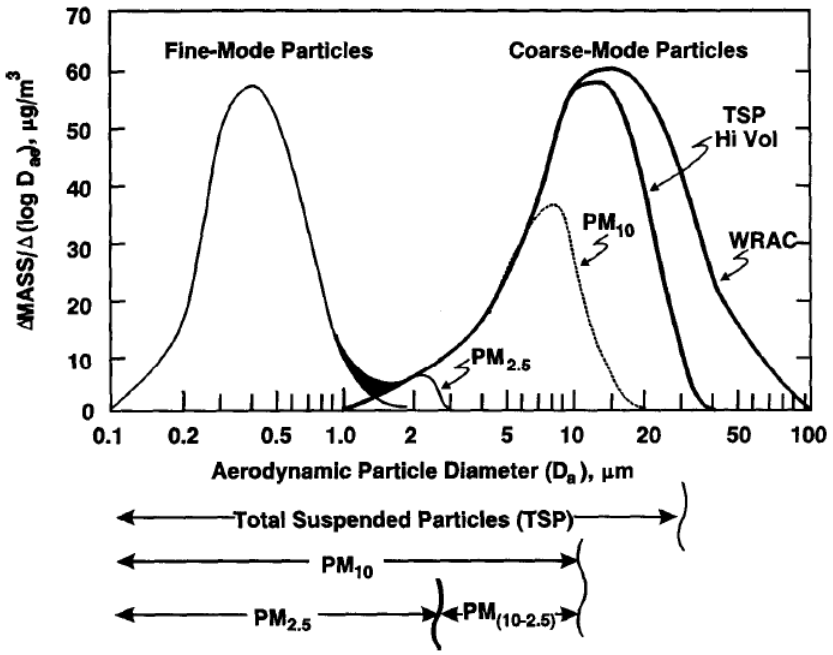

Figure 2-2: Size distribution of ambient particulate matter (USEPA, 2004)

There are two sources of coarse PM, natural and man-made. Natural sources of particles include volcanic eruptions, fire, wind induced dust, ash and pollen. Man-made sources consist of material handling (dust), smoke, fumes, dust from unpaved roads, power plants, industrial and mining operations. Road dust is produced by traffic and air turbulence can re-entrain it into the atmosphere. The evaporation of sea spray can produce large particles along coast lines. Other coarse type particles include pollen grains, mould spores, plant and insect parts (WHO, 2000). When measuring the chemical composition or particles in the air, the particle mass can be classified according to various sources that emit particles of known composition.

2.1.2. Fine Particulate Matter

Particles smaller than or equal to 2.5 μm in aerodynamic diameter are considered fine particulate matter. Within this category, particles smaller than 0.1 μm in aerodynamic diameter are further classified as ultrafine particles (UFP), also referred to as the fine fraction. They are formed by the condensation of low vapor-pressure substances, by high temperature vaporization or by chemical reactions in the atmosphere (Jacobson, 1999). These particles grow in size by a process called coagulation or by condensation. Because coagulation is mostly efficient for large numbers of particles and condensation is mostly efficient for large surface areas, the efficiency of these processes decreases as the size of the particles increases. The upper limit to these processes is around 1 μm. Particles between 0.1 μm and 1 μm tend to accumulate, thus this range is referred to as the accumulation range (World Health Organization, 2000).

The smaller $PM_{2.5}$ particles contain metal and recondensed organic vapors, combustion particles and secondary reaction aerosols. Particles under 1 μm can be produced by the condensation of metals or organic compounds which are vaporized from high temperature combustion processes. They can also be produced by the condensation of gases such as sulphur dioxide (SO_2) in the atmosphere which oxidizes to form sulphuric acid (H_2SO_4), or nitrogen dioxide (NO_2) which oxides to nitric acid (HNO_3). Nitric acid reacts with ammonia (NH_3) to form ammonium nitrate (NH_4NO_3). These particles, which are produced by secondary reactions are called secondary reaction particles. Secondary particles are the dominant component of fine particles. From the relationship of particle volume with mass, the ultra-fine particles often contribute a few percentage of

the total mass, however at the same time contributing over 90 percent of the total particle number (Jacobson, 1999).

Trans-boundary air pollution of man-made pollutants and natural occurrences (such as forest fires or volcanoes) caused by wind moving fine particles from the source location can also be considered sources. Zhou et al. (1995) and Sapkota et al. (2005) describe large trans-boundary pollution events that carried particles from the source more than a few thousand kilometers to where they were being recorded.

2.2. Particulate Matter and human health

2.2.1. Health effects associated with exposure to $PM_{2.5}$

To date, different effects of PM on health have been reviewed by many countries and organizations (World Health Organization, 2000). This section provides a brief overview of some of the research conducted regarding the association between air quality and multiple health conditions. It is outside the scope of this research to provide a detailed summary into any of the categories mentioned. Results from multiple studies suggest that associations between PM_{10}, total suspended particles (TSP) and mortalities observed may very well be due to the effects of fine rather than coarse particles. Due to the focus of this research on $PM_{2.5}$, studies involving coarse particles ($\geq PM_{2.5}$) and their effects on health (e.g., Samet et al., 2000; Goldberg et al., 2001) have been omitted. Many studies have shown that generally $PM_{2.5}$ is a better predictor of health effects than PM_{10} (particles up to 10 µm in aerodynamic diameter) and that possibly, the origins and chemical composition are sometimes more important than the $PM_{2.5}$ mass.

Controlled studies

Data from controlled human exposure to PM is limited to sulfuric acid and acid sulfates in normal and asthmatic subjects. In subjects exposed to PM for several hours, while performing intermittent exercise, studies show a general agreement that inhalation of sulfuric acid mists (1μm or less in diameter) in concentrations of up to 100 $\mu g/m^3$ does not cause any changes in lung function (Kerr et al., 1981; Horstman et al., 1982). Other studies reported very little response to exposure of concentrations up to 1500 $\mu g/m^3$ of sulfuric acid mists of the specified size (Utell et al., 1984; Avol et al., 1988). Petrovich et al. (2000) reported that exposure of young healthy volunteers to levels of concentrated ambient $PM_{2.5}$ in Toronto may not cause significant acute health effects. Their study reported only a small mean decrease of 6.4% in thoracic gas volume after exposure to high levels of $PM_{2.5}$ concentrated from ambient air.

Asthmatics subjects have been reported to be more sensitive to exposure of sulfuric acid, although the findings from different studies vary considerably. Some studies report no changes of mean lung function after exposures to concentrations of up to 3000 $\mu g/m^3$, much like normal subjects (Linn et al., 1986; Aris et al., 1991). Other studies have reported bronchoconstriction at concentrations below 1500 $\mu g/m^3$ but above 380 $\mu g/m^3$ (Utell et al., 1983; Avol et al., 1988). Out of these studies, forced expectorant volume (FEV) in asthmatic subjects fell by 4.5% after exposure to 1000 $\mu g/m^3$ of sulfuric acid and there was a 20% reduction in specific airway conductance whereas the normal subjects showed no changes. It is difficult to interpret the results from these types of

studies due to different study designs and different modes of delivery and particle size of the sulfuric acid used.

Epidemiological studies

Traditionally, epidemiological studies have played an important role in deriving guideline values for acceptable levels of airborne PM. Concerns about the health effects of airborne particles are based largely on the results of epidemiological studies suggesting effects on mortality and morbidity at low levels of exposure. This section provides a brief review of some epidemiological studies relating $PM_{2.5}$ exposure to various health endpoints.

One of the most recently published studies is the work of Pope and Dockery (2006). They reviewed six substantial lines of research published until 1997 that have helped our understanding of PM effects on health. The six lines were:

- Short-term exposure and mortality
- Long-term exposure and mortality
- Time scales of exposure
- Shape of concentration-response function
- Cardiovascular disease, and
- Biological plausibility

Based on a number of studies, the review concluded that the people who are most susceptible or at risk is dependent on the specific health endpoint evaluated and the level and length of exposure. People with chronic cardiopulmonary disease, influenza, and

asthma, especially the young and the elderly are most likely to be susceptible from short-term exposures to moderately elevated PM concentrations. Different research teams, using various analytical methods observed "consistent associations between cardiopulmonary mortality and daily changes in PM." Exposure to PM over long periods of time has more persistent cumulative effects compared to short-term transient exposure.

Time-series studies

Time-series studies attempt to relate the development of air pollution with time to some health variables such as daily mortality and hospital admissions for various symptoms. They are largely snapshots that try to find a relationship between the air pollution at a given time to various health endpoints. Data for these studies are routinely collected through various programs and air pollution levels are used as exposure variables. The sources for the health data vary, but are usually retrieved from hospital admissions and routine statistical data among other more complex methods (WHO, 2000).

There are some methodological issues with the time-series analysis, such as the need to adjust for weather and seasonal cycles. For example, winter months have higher mortality rates much like heat waves do in summer months. Weather affects both air pollution concentrations and health, making it difficult to adjust the associations of health effects to either variable. The advantage of time-series studies is that they focus on relatively short periods of days or weeks. Potential confounders such as age and smoking habits do not change over the range of such studies thus they can be ignored. According to Dockery et al. (2006), the variation of short-term average air pollution over the short

amount of time studied is often much greater than the variation in the long-term average pollution concentration which forms the basis of long-term effects of air pollution health.

Hospital admissions

A study by Thurston et al. (1994) examined air pollution and daily hospital admissions for respiratory causes in Toronto, ON. Ozone, $PM_{2.5}$, PM_{10} and TSP data were obtained for the months of July and August from 1986 to 1988. Daily counts of respiratory admissions from 22 acute care hospitals during the same time period were also obtained. The study found that associations decreased in strength from hydrogen ion to sulfates to $PM_{2.5}$ to PM_{10} to TSP, thus indicating that particle size and composition are important in defining the adverse human health effects associated with PM. It was found that summer-time haze was associated with roughly half of all respiratory admissions.

No studies have been able to make judgment on concentrations below which there are no health effects. However, effects on mortality, respiratory and cardiovascular admissions and other health end-points have been observed at levels well below 100 $\mu g/m^3$. Prevalence of bronchitis symptoms in children and reduced lung function in children and adults have been observed at annual average concentration levels below 20 $\mu g/m^3$ for $PM_{2.5}$ and were considered to be related to PM.

2.3. Particulate matter standards around the world

Similar to Canada, other countries have also acknowledged the health effects associated with increased levels of PM, and as such, standards have been implemented. The

Canada-Wide Standard (CWS) for $PM_{2.5}$ is 30 $\mu g/m^3$. The standard is over a 24-hr averaging time and it is based on the 98^{th} percentile ambient measurement annually, averaged over 3 consecutive years (Canadian Council of Ministers of the Environment, 2000). The U.S. has two different $PM_{2.5}$ standards (USEPA). The annual (arithmetic mean) based on the 3-year average of the weighted annual mean $PM_{2.5}$ concentrations from single or multiple-oriented monitors must not exceed 15 $\mu g/m^3$. The 24-hr average conditions are identical to those of the CWS except they must not exceed 35 $\mu g/m^3$ (USEPA, 2004). Unlike Canada, the U.S. also has a PM_{10} 24-hr standard of 150 $\mu g/m^3$; this is not to be exceeded more than once per year on average over 3 years. The European Union (EU) shares the standards with the World Health Organization (WHO). The EU $PM_{2.5}$ limit has an averaging time of 1 year and it is based on a 3-year running annual mean. The Australian limits are just guidelines for the time being. China has three different 24-hr PM_{10} standards based on grades (CAI Factsheet No. 2, 2010). Grades are essentially a different way to designate areas (i.e., Grade I is reserved for natural conservation areas while Grade III is for special industrial areas). $PM_{2.5}$ standards do not exist at the moment in China, this is also the case with other Asian countries such as Malaysia, Indonesia and the Republic of Korea. The allowable $PM_{2.5}$ and PM_{10} criteria from a few countries around the world are displayed in Table 2-1.

Table 2-1: Particulate matter criteria from a few countries

Pollutant	Canada[a]	United States[b]	EU[c]	Australia[d]	China[e]
$PM_{2.5}$	30	15/35	25	25	-
PM_{10}	-	150	40/50	50	50/150/250

[a]Canadian Council of Ministers of the Environment

[b]15 $\mu g/m^3$ annual, 35 $\mu g/m^3$ over 24-hr

[c]40 $\mu g/m^3$ annual, 50 $\mu g/m^3$ over 24-hr

[d]National Environment Protection (Ambient Air Quality) Measure – goal only

[e]China Grade I, Grade II and Grade III, respectively

2.4. Methods of measuring particulate matter

There are multiple methods of measuring particulate matter of different size fractions. This section explains the methodology behind two of the more recognized and commonly used instruments along with one reference method. Most instruments either use gravimetric analysis or light scattering as a means of obtaining PM concentrations.

Gravimetric analysis is a method commonly used to determine the mass of a solid. When it comes to determining PM concentration, it essentially involves the weighing of a filter before and after the filter is used. The difference in the weight of the filter is the total accumulated PM. Using the total flow of the air over the collection media (filter) the concentration can be calculated simply by dividing the weight by the volume of air circulated. This method can be very accurate depending on the accuracy of the scale used to weigh the collection media and depending on how well the quality control protocol was followed, and if proper treatment of the media was followed. This method can also be used to calibrate other instruments (as is further explained). The disadvantage of this method is that it can only provide the total mass or mass of a single pollutant by using a

treated filter or devices such as a denuder. In order to obtain the composition of that pollutant (e.g., % Pb, Elemental Carbon, Organic Carbon in $PM_{2.5}$), the method has to be paired with other more sophisticated chemical analyses (Parikh, 2000), such as X-ray fluorescence.

2.4.1. Federal Reference Method

The Federal Reference Method (FRM) is the USEPA designated method for measuring $PM_{2.5}$ concentrations. It is defined in the Federal Register Appendix L – Part 50 (USEPA, 1997). The method states that only measurements made using USEPA designated instruments and methods may be referred to and reported as $PM_{2.5}$. Measurements using other instruments and methods may not be accepted into the Federal database as $PM_{2.5}$. The method describes $PM_{2.5}$ samplers and breaks them down into reference samplers and three classes of equivalent sampling/measuring devices. The main facets of the method are presented in Appendix A.

2.4.2. Tapered Element Oscillating Microbalance Procedure

The tapered element oscillating microbalance (TEOM) is an instrument that was manufactured by Rupprecht and Patashnick (R&P) prior to it being acquired by the Thermo Scientific group (Environmental Data Pages, 2011). The most popular model used is the R&P 1400a TEOM. The instrument is still used to date by many U.S. departments as well as different ministries of the Canadian government. The instrument is cited with the FRM $PM_{2.5}$ sampler (Parikh, 2000). This instrument is a “true” gravimetric instrument that measures mass in near real time mass concentrations.

2.4.3. DustTrak 8520

The DustTrak, model 8520 is a PM measuring instrument manufactured by TSI Incorporated (TSI, St. Paul, MN, USA). It uses a simpler physics principle in its design compared to the TEOM and it is mostly used in the health and safety industry as well as occasional research studies because it provides reliable concentrations with portability, easy operation and maintenance.

Theory of operation

The DustTrak uses light scattering technology to determine mass concentration in real-time. The aerosol sample is drawn into the sensing chamber in a continuous stream at 1.7 lpm. One section of the aerosol stream is illuminated by using a small beam of laser light. The particles scatter light in all directions. A lens placed at 90° to the aerosol stream and laser directs some of the scattered light and focuses it on the photodetector. This light is in turn converted into a voltage. The voltage is proportional to the light scattering which is in-turn proportional to the concentration of the aerosol sample. The end voltage is multiplied by an internal calibration constant to yield mass concentration. The internal calibration constant is determined from the ratio of the voltage response to the known mass concentration of the test aerosol. The unit is calibrated against a gravimetric reference using A1 test dust (ISO 12103-1, Arizona Test Dust). The laser diode in this model has a wavelength of 780 nm which limits the smallest detectable particle to approximately 0.1 μm. The DustTrak owner manual specifies a lower limit of

resolution equal to 0.001 mg/m^3 (1 μg/m^3). If the averaged concentrations are below, the instrument will display a 0.000 mg/m^3.

The instrument has been used in numerous studies around the world (Yanosky et al., 2002; Evans et al., 2008; Diapouli et al., 2008; Wallace et al., 2010) some of which are further discussed in this thesis. A study published by Wallace et al. (2010) found that the limit of detection (LOD) derived using measured means and standard deviations (SD) for the DustTrak is actually 5 μg/m^3, unlike the manufacturer's much lower claim. According to the study, values lower than the minimum detection limit (MDL) are not distinguishable from zero. The instrument is not approved under the FRM. Figure 2-3 displays the general schematics of the DustTrak 8520. Although this type instrument is not as accurate as gravimetric monitors, it still provides useful information for risk management and the effect of different micro-environments on personal exposure (Wallace et al., 2010).

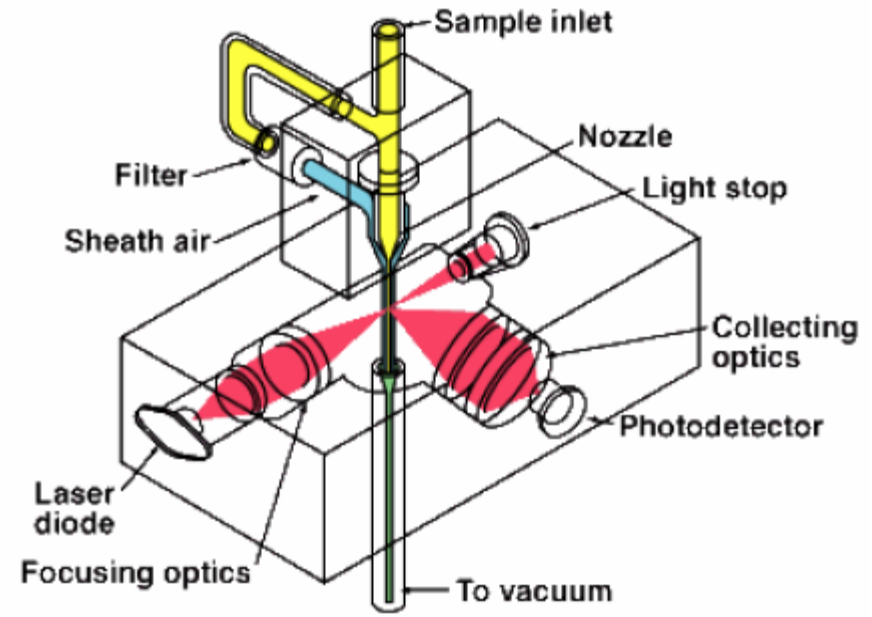

Figure 2-3: Schematics of DustTrak 8520 (Courtesy of TSI Inc.)

2.5. Studies on the exposure to indoor air pollution

Building occupants today are exposed to chemical sources that are different from the sources that occupants were exposed to 50 years ago. By knowing the differences between these chemicals we can determine the effects that pollutants have on multiple aspects of human health. A study by Weschler (2009) attempted to identify the changes of these indoor chemicals since the 1950's. The study concluded that over the last 50+ years, indoor exposure to known carcinogens (e.g., benzene, formaldehyde, asbestos, environmental tobacco smoke and radon) and "reasonably anticipated" carcinogens (chloroform, trichloroethylene, carbon tetrachloride and naphthalene) has decreased. However, exposure to endocrine disruptors (e.g., certain phthalate ester plasticizers, certain brominated flame-retardants, bisphenol-A and nonylphenol) has increased. Indoor exposures to other toxicants such as carbon monoxide (CO), SO_2, NO_2, lead (Pb)

and mercury (Hg) have also declined. The study further concludes that there is very little year to year data on the concentration of indoor air pollution particularly on semivolatile organic compounds (SVOC) and their effect on human health. The author suggests the establishment of monitoring networks that provide information about the state of pollutants in representative buildings working in conjunction with outdoor pollutant monitors and body fluid monitors. This would "enhance our knowledge of the chemicals that we inhale, ingest and absorb on a daily basis."

Lin et al. (2007) presented the emissions of 2,2,4-trimethyl-1,3-pentanediol monoisobutyrate (TMPD-MIB) from two types of latex paints (regular and glossy finishes) applied to aluminum, gypsum board and concrete. TMPD-MIB, also referred to as Texanol® ester alcohol, is a type of VOC. The study concluded that air emissions that were released the longest time were from gypsum board, with concrete and aluminum emitting less in that order.

2.6. $PM_{2.5}$ in elementary schools

2.6.1. Studies of $PM_{2.5}$ in elementary school classrooms

There have been many studies whose goals have been the reporting of indoor PM concentrations in elementary school classrooms. Attributable to the focus of the research, this section describes some of the results from $PM_{2.5}$ only studies, and excludes results from other PM studies. Some studies measured both $PM_{2.5}$ and PM_{10} concentrations. Those studies are referenced.

Scheff et al. (2000) measured and evaluated the indoor air quality at a middle school in Springfield, Illinois. Integrated samples with an eight hour sampling time for respirable ($PM_{2.5}$) and total particulate matter, short-term measurements for bioaerosols and continuous CO_2 logging were collected on three consecutive days during one week in February of 1997. Four indoor locations: the cafeteria, a science classroom, an art classroom and the lobby outside of the main office, were sampled. The school was located in an area with no known air quality problems. The science room showed the highest average $PM_{2.5}$ concentration of 30 $\mu g/m^3$ over the three days while the art classroom showed the lowest concentration of 14 $\mu g/m^3$. The study concluded that there was a linear relationship between occupancy and corresponding CO_2 and particulate concentrations and those concentrations are influenced by the indoor spaces in which they are measured.

Three elementary schools around Columbus, Ohio (one rural, one suburban and one urban site) were monitored for indoor and outdoor $PM_{2.5}$ air quality from February 1, 1999 through August 31, 2000 (Kuruvilla et al., 2007). Indoor $PM_{2.5}$ monitors were set to run from 8:00 am – 3:00 pm Monday-Friday for the entire school year while the outdoor measurements used the TEOM instrument described earlier. The mean indoor $PM_{2.5}$ concentrations at the suburban and rural sites were higher than those observed outdoors at these sites, while the outdoor concentration was higher than the indoor $PM_{2.5}$ level at the urban location. However, this pattern was not consistent during the entire study period. The authors did not mention the location of the indoor monitors within the schools. The study's main focus was the chemical composition of the particulate matter

and on potential source contribution function (PSCF) analysis. It was concluded that $PM_{2.5}$ levels did not exceed the National Ambient Air Quality Standards (NAAQS) during the entire study and the PSCF analysis provided a reasonable estimate of the influence of upwind regions on $PM_{2.5}$ contribution. Although the study did identify SO_4^{2-} as the single largest component of $PM_{2.5}$ mass contributed, it did not explain the potential health implications on children of all the pollutants measured.

In an air quality study aimed at assessing base-line concentrations of indoor air quality in Antwerp, Belgium, 18 residences and 27 primary schools were evaluated for different air pollutants including $PM_{2.5}$ and PM_{10} (Stranger et al., 2007). The 27 schools were composed of 15 inter-city schools and 12 schools from surrounding suburban areas 20 km south of Antwerp. Particulate matter was collected during two sampling campaigns (autumn-winter and spring-summer) from December 2002 to June 2003. A gravimetric method was used for a 12-hr period from Monday to Friday only. The average 12-hr indoor $PM_{2.5}$ concentration for the 27 schools was 61 $\mu g/m^3$, with a range of 11-166 $\mu g/m^3$. This concentration exceeded observations from other studies and is twice that of the CWS. However, it should be noted that they were only 12-hr measurements and thus cannot be directly compared to some standards.

PM_{10} and $PM_{2.5}$ size fractions were measured gravimetrically inside two classrooms as well as outdoors at one primary school in northern Munich, Germany for 6 weeks during the months of October and November of 2006 (Fromme et al., 2008) for 5 hours a day. The median $PM_{2.5}$ concentrations were 37.4 $\mu g/m^3$ indoors and 17.0 $\mu g/m^3$ outdoors. It

was estimated that 43% of $PM_{2.5}$ was of ambient origin. The study concluded that PM measured in classrooms has major sources other than outdoor particles and that PM generated indoors may be less toxic compared to PM in ambient air.

2.6.2. Studies of $PM_{2.5}$ in school gymnasiums

Research of indoor $PM_{2.5}$ air quality in school gymnasiums has been minimal. Past studies dealing with air quality in schools are almost entirely concerned with classrooms as already mentioned. Search results do not reveal a lot of studies aimed at directly evaluating the air quality in the gyms but rather at evaluating the air quality within the schools and surrounding areas. As a result, most studies report the $PM_{2.5}$ concentration in the classrooms. However, a few limited studies did focus on the "exposure of children to airborne particulate matter of different size fractions during indoor physical education at school." A detailed summary of studies that report $PM_{2.5}$ monitoring in school gyms is presented in this section because of their relevance to the current study.

The Prague, Czech Republic School Study

The study of Branis et al. (2009) was designed to document the exposure of children between the ages of 11-15 years to $PM_{2.5}$ during scheduled indoor physical exercise. The gym was in a naturally ventilated school with an "expected high infiltration" rate of outdoor air. The school was situated in the city centre of Prague, Czech Republic. The location was chosen because of its high traffic congestion frequency. The main source of air pollution in the city is from automobile exhaust. The results were discussed in terms

of indoor-outdoor relationships, possible indoor $PM_{2.5}$ sources and potential health effects associated with the recorded levels of aerosol in the indoor environment.

The city of Prague is the capital of the Czech Republic. It has a population of 1,250,000 and it lies at an altitude between 200 and 350 m above sea level which is comparable to the city of London, ON. The school was in a central location, with an approximate distance of 100 m to the nearest main road. According to 2006 statistics, the traffic density on this road was about 13,200 cars between 6 am and 10 pm on a working day. The gymnasium dimensions are 16.6 m x 7.2 m x 4.9 m. It is a naturally ventilated space with six large double-glazed windows. Gymnasium activity starts around 8 am. The school and its surrounding area are strictly non-smoking. Particulate matter concentrations were measured by a cascade impactor with 5 stages A to F (A: 2.5-10 μm; B: 1.0-2.5 μm; C: 0.5-1.0 μm; D: 0.25-0.5 μm; and a final stage F: <0.25 μm). One 25 mm PTFE filter was used for stages A-D and a 37 mm PTFE filter was used for the final stage. The inlet of the impactor was placed at a height of 2 m above the gym floor. Filters were changed daily before the beginning of activities. The air flow of the impactor pump was checked before and after each campaign.

Monitoring took place between November 2005 and August 2006 and it was divided into 8 campaigns, each between 7-10 days. $PM_{2.5}$ ambient concentrations were obtained from a fixed site monitor of the national air quality monitoring system located about 3.3 km away from the school.

Activity in the gym was recorded along with the number of persons present and the duration of the activity, using a written form attached to the front of the gym door. The total $PM_{2.5}$ concentration was determined by summing stages B – F, excluding stage A which measured only the coarse fraction. Indoor and outdoor concentrations were paired and compared using the Mann-Whitney U test.

The average and median indoor $PM_{2.5}$ concentrations for all 8 campaigns were 24 and 25 $\mu g/m^3$ respectively. These were similar to the outdoor monitor, which recorded 25.5 and 23.75 $\mu g/m^3$, respectively. The difference between the two data sets was not significant (p=0.81). Even though the fixed site monitor was located 3.3 km from the school, the correlation coefficient between the two data sets was 0.88, suggesting a homogeneous dispersion of pollutants within the city as well as a high infiltration rate indoors. The correlation coefficient of the smaller $PM_{2.5}$ size fractions with the fixed site monitor was greater than the coarse aerosol correlation (0.88 vs. 0.46). This indicated that a signification portion of the indoor $PM_{2.5}$ aerosol had its origin outdoors.

The regression equation between the two variables (indoor vs. outdoor) showed that more than 60% of the indoor $PM_{2.5}$ can be explained by the fixed site monitor (Indoor = 0.63*Outdoor + 8.08; R^2=0.83). The study could not conclude which concentrations were more accurate due to the different measuring techniques of the instruments used and the location and distance between the instruments. The real concentration was somewhere in between the reported outdoor and indoor concentrations. The comparison

provided support for the significant influence of ambient particles on the indoor microenvironment.

The Athens Elementary School Study

Diapouli et al. (2008) characterized the PM_{10}, $PM_{2.5}$ and UFP concentration levels at elementary schools across Athens to examine the relationship between the indoor and outdoor concentrations. Seven primary schools were chosen. The schools were distributed through the surrounding areas of the city. The indoor air intake samples were taken at table height. Three of the seven schools were monitored in multiple locations such as: a computer lab in the library, a teacher's office and the gymnasium. The outdoor measurements were carried out in the yard of the schools, in an area not accessible by the children for the security of the instrument. Each school was studied for 2-5 consecutive weekdays during school hours, 8:00 am – 4:00 pm. PM_{10} and $PM_{2.5}$ indoor and outdoor concentrations were measured using Harvard personal equipment monitors (PEM) at a flow rate of 4 lpm. Some schools used the DustTrak model 8520 to monitor PM_{10} and $PM_{2.5}$. UFP concentrations were measured using a TSI CPC3007 (Shoreview, MN, USA). The TSI instruments were programmed to record the concentration every 1 min. The indoor to outdoor ratio (I/O) for the site where the pollutants were measured inside the school gym was 1.8 with indoor $PM_{2.5}$ concentrations reaching as high as 80 $\mu g/m^3$.

Libby Montana School Study

Ward et al. (2007) present the results of an indoor size fractionated PM school sampling program in Libby, Montana. Libby is a small mountain valley community. It is one of

the only places in the western United States that exceeds the annual $PM_{2.5}$ NAAQS. Two schools, approximately 2.4 km apart were sampled during the months of January through March of 2005 for indoor $PM_{2.5}$ concentration. The sampling events (lasting 24 hr) were simultaneously collected once per week for a total of 9 sessions. Only one of the schools sampled was an elementary school. This school had the sampling instrument installed in the gymnasium while the other school (a middle school) had the sampling instrument inside a faculty supply room because the gymnasium was detached from the main building. A Sioutas impactor PM sampler with Leland Legacy (SKC, Inc., Eighty Four, PA) pump was fitted with Teflon filters to measure the gravimetric mass of five size fractions (>2.5, 1.0-2.5, 0.5-1.0, 0.25-0.5, and <0.25 μm) of the indoor PM. Ambient PM_{10} concentrations were measured simultaneously. The location of the outdoor instruments was approximately 1.6 km from the elementary school.

The average indoor $PM_{2.5}$ mass concentration at the elementary school was 41 $\mu g/m^3$ over the monitoring campaigns. This is approximately four times greater than the level reported at the middle school. The authors attribute the difference in concentrations to the age of the buildings (the elementary school was built in 1953 while the middle school was built in 1970), and the difference in the sample locations (gymnasium vs. faculty staff room) within the schools. Ambient PM_{10} concentration was not strongly correlated with the elementary school or with the middle school (correlation coefficient [*P*-value] = 0.17 [0.69] and 0.10 [0.82], respectively), which can be explained by the fact that they were not measuring the same pollutant source.

2.6.3. Study on the effects of building age on indoor PM concentration

In a study from South Korea (Yang et al., 2009), the concentrations of different indoor air pollutants within 55 public schools were characterized to compare their indoor levels with each other and to the number of years the school had been constructed. The study was conducted in order to suggest ways of reducing the exposure of school children to undesirable air pollutants. Indoor and outdoor air samples were obtained from three different locations within the schools, a classroom, a laboratory and a computer lab. The schools were selected based on the age of the building including 1, 3, 5 and 10 years old. The data was gathered for 1 day at each location during summer, autumn and winter from July to December 2004. The study measured concentrations for the following: CO, CO_2, PM_{10}, TVOC's and Formaldehyde (HCHO). The mean and standard deviation of PM_{10} for the entire study period were 77.87 and 68.90 $\mu g/m^3$, respectively. The PM_{10} indoor/outdoor (I/O) ratio for the study period was 1.43, suggesting the major PM_{10} contributor was indoor. The study concluded that for PM_{10}, building age did not show a difference in mean concentrations. The mean concentrations were between 83.39 and 84.63 $\mu g/m^3$ for the 4 building age groups. The limitations of the study included the lack of direct $PM_{2.5}$ measurements, a short monitoring period per school and no consequent day to day measuring for each location. It was also limited to buildings not being older than 10 years.

2.7. Summary

This chapter described some of the health effects associated with air pollution, general methods of $PM_{2.5}$ monitoring and results from similar previous studies. From the

research that already exists, it is apparent that increased levels of $PM_{2.5}$ concentrations can contribute to increased health problems in the adult population with severe consequences towards children and the elderly. The next sections of this thesis present the results related to the objectives outlined in Chapter 1. The school gym micro-environments are just as important as shopping centres or daily walks to school since an average child spends just as much time in them on a daily basis as they do in other more commonly thought about environments.

CHAPTER 3 - MATERIALS AND METHODS

3.1. Study design

3.1.1. Site selection

General description

The study presented in this research took place in London, ON. The city is located in South-Western Ontario. It has a metropolitan area population of approximately 492,000 making it the eleventh most populated city in Canada (Statistics Canada, 2007). It is situated among the forks of the Thames River halfway between Windsor and Toronto at an elevation of 270 m above sea level (Ministry of the Environment, 2011). Figure 3-1 displays the location of the city within the south-west part of the province of ON.

Figure 3-1: Position of London within South-Western Ontario (BEC Canada)

In order to identify and map potential "hot-zones" for ambient air pollution, land use regression modeling techniques within a Geographic Information System (GIS) were used (Luginaah et al., 2008). Two (2) elementary schools of varying outdoor concentration exposure were selected. The schools and their surrounding

neighbourhoods were monitored to assess exposure to pollutants at two different time periods (February/March and May 2010) to explore the impact of seasonality on potential levels of exposure among students. The names of these elementary schools cannot be disclosed and thus they are referred to as Sites A and B, hereafter shown in Fig. 3-2. Site A was located in a sub-urban environment to the south of the city, approximately 1.6 km north of Highway 401. Site B was located in an urban location close to city centre and surrounded by some of London's busiest roads.

The city of London's monitoring site is located to the east of Site B. Outdoor ambient concentrations, including $PM_{2.5}$ and NO_2 are continuously monitored by the MoE (Ministry of the Environment, 2007). Figure 3-2 displays the location of both sites along with the MoE site relative the others.

Figure 3-2: Sites A, B and MoE within the city of London

Gymnasium Characteristics

The oversized elementary school gym at Site A was built in 1972 with heavy renovations to the entire school in 1995 along with the addition of another building. The gym is placed in the center of the school with no direct contact to the outdoor environment with the exception of the ceiling/roof. It is of rectangular shape with a total surface area of 423 m^2. There are four different access doors to the gym. However, they all connect the gym to the school hallways.

Site B's gymnasium is attached to an elementary school built in 1949. There have been no major renovations recorded in the school's history. The gym is located to the south west of the school's geographical location and three of its walls are surrounded by the outdoor environment. It is of a smaller size compared to Site A, and has a total surface area of 278 m^2 with two doors leading outdoors and one double size door leading to the interior of the school. The main features of the schools and gyms are presented in Table 3-1.

Table 3-1: School and gym characteristics

School	Area	Ventilation	# Doors/Entrances	Area (m^2)	Building Age
Site A	Suburban, light traffic street nearby	Mechanical	Four, all leading to the interior of the school	423	Built in 1972, renovated in 1995
Site B	Urban, heavy traffic street in front	Mechanical	Two leading outdoors and one large leading inside the school	278	Built in 1949

Annual Average Daily Traffic Volume

The City of London traffic volume data (City of London, 2011) provided the Annual Average Daily Traffic Count (AADTC) for the entire city including both sites. The arterial street directly behind Site A, which runs parallel to Site A's school yard has an AADTC of 15,500 vehicles. Data for the street directly in front of Site A's entrance was not available likely because of its more residential location. The AADTC for Site B was between 30,000 – 35,000 vehicles, double that of Site A's. There are no major side streets to the sides of Site B.

3.1.2. Campaign schedule

The $PM_{2.5}$ monitoring campaign took place during two different seasons, winter and spring of 2010 for a total of approximately six weeks. The winter campaign started on February 17th and ended on March 8th. The spring campaign continued from May 5th to the 24th. Each season was monitored for approximately three weeks.

During the winter campaign, only indoor $PM_{2.5}$ concentrations and ambient NO_2 concentrations were measured. The first week of the spring campaign used the same number of measuring equipment stations at approximately the same locations as the winter. At the beginning of the second week of the spring campaign, two extra $PM_{2.5}$ measuring instruments and three CO_2 instruments were added. Thus, during the last two weeks of the spring campaign both indoor and ambient $PM_{2.5}$ concentrations were recorded along with CO_2 indoor and outdoor. Table 3-2 shows the monitoring schedule for both winter and spring campaigns.

Table 3-2: Pollutant monitoring schedule; "I" and "O" represent indoor and outdoor monitoring, respectively

Week #	Date (in 2010)	$PM_{2.5}$	NO_2 (outdoor)	CO_2 (indoor)
1	Feb. 17 - 22	✓ (I)	✓	✗
2	Feb. 22 - Mar. 01	✓ (I)	✓	✗
3	Mar. 01 - 08	✓ (I)	✓	✗
4	May 05 – 10	✓ (I)	✓	✗
5	May 10 – 17	✓ (I & O)	✓	✓ (I & O)
6	May 17 – 24	✓ (I &O)	✓	✓ (I & O)

Since the instruments were not started simultaneously at both locations due to the logistics of the operation, the first and last days of the monitored weeks' $PM_{2.5}$ data were eliminated from the analysis of both sites. The data eliminated did not capture a full day's worth of school activities and it consisted mainly of afterschool measurements.

3.2. Pollutant measurement

3.2.1. $PM_{2.5}$ methodology

Measuring Method

$PM_{2.5}$ concentrations were measured and recorded using the DustTrak Aerosol Monitor model 8520. The instrument uses light photometry to detect particles. This procedure was explained in greater detail in Chapter 2 of this thesis. Concentrations were averaged over 1-min intervals and data was stored internally for up to two weeks at a time at which point all data was downloaded into the field laptop. One unit was placed at each site in the gymnasium during the winter campaign. In the spring campaign additional units were set up to measure the outdoor concentrations during the last two weeks of the spring monitoring campaign (Table 3-2).

Location of instrument within the gyms

The location of each instrument within the gyms was different relative to each gym's physical characteristics. Each unit was placed in a small, sealable bin with a short Tygon® tube sticking out. The lengths of the tubes were similar and were shorter than the manufacturer's maximum recommended length of 1.2 m (TSI Incorporated, 2010), to

ensure optimal measuring accuracy. The bin was covered to protect the instruments from various forms of daily activities.

Site A had the DustTrak placed in the middle of the gym, between the removable dividing doors, on top of exercise mats. The height of the intake tube was approximately 1.8 m above floor level. Figure 3-3 displays the bin with the intake tube. For the spring campaign, the height of the intake was lowered to about 1.2 m to be similar with Site B's set up and because the students started using the exercise mats.

Figure 3-3: Site A winter DustTrak set up

Site B's DustTrak was placed in a small room adjacent to the gymnasium. The room serves as a mini-cafeteria for various school activities and when not in use, it is mainly used as a storage media for various goods. The room has a large sealable opening into the gym. The intake tube was drawn into the gym and taped to the side of the wall. The approximate height of the intake was 1.2 m above floor level. The intake was close to the

double sided doors which are the main entrance into the gym from the interior of the school.

Data Retrieval

Weekly recordings from the DustTrak were downloaded into a field laptop using TSI's data analysis software. The software, TrakPro (TSI, 2011), is delivered in cd-rom format with each instrument and it is also available for download from TSI's website. The software converts the recordings into formats that can be imported into Microsoft® Office Excel® (Microsoft Corporation, 2006) and other statistical analysis software.

Quality Assurance Quality Control (QA/QC) Protocol

Each unit was labeled and assigned a unit ID specific to that unit's serial number prior to the start of the study. The instruments used during the winter campaign (unit IDs: DT1 and DT2), were both sent for factory maintenance and calibration approximately two weeks prior to the start of the campaign. Each instrument was received back with a calibration certificate. The extra instruments used during the spring campaign for outdoor concentration measurements (unit IDs: DT3 and DT4) were received from Health Canada and were accompanied by factory calibration certificates.

Each instrument was cleaned and calibrated, using a known protocol which followed the manufacturer's recommended procedure, on every Monday of the monitoring campaign`s weeks. The initial start of each campaign did not take place on a Monday, thus the units

were cleaned on the day prior to the start. Appendix B contains a copy of the log sheet used during the weekly process. The weekly log sheet identified the following:

- unit ID
- operator's initials
- location of sampling (e.g., Site A, Site B, indoor or outdoor)
- start date and start time

When data was downloaded into the field laptop, the weekly log sheet was used as a guide to ensure the necessary steps were followed. The parameters that were checked included:

- the concentrations and logging of data (i.e., was the instrument found to be recording, and what was the concentration?)
- power cord and tubing connections (i.e., was the instrument connected properly)
- battery life %
- the shutdown date and time (i.e., at what time was the instrument recording stopped)
- the name of the file that was downloaded
- the instrument's current clock reading vs. the actual time, along with the correction amount (if any)

Each instrument was cleaned and calibrated at least once per week regardless if the recording was actually downloaded or not. The log sheet was used as a guide to ensure

the following components were calibrated and/or cleaned as per manufacturer recommended maintenance procedure. The parameters checked were:

- instrument pump flow rate
- re-greasing of the impactor plate
- re-zeroing the instrument using the manufacturer provided filter
- checking that the instrument's measuring time is every 1 min
- erasing the memory
- checking the battery % , intake tube and electrical connections
- instrument re-start date and time and current concentration

Inter-Instrument Comparison

An inter-instrument comparison was performed at the beginning and end of each campaign. The instruments used were set to measure simultaneously the indoor $PM_{2.5}$ concentrations in the same room at the University of Windsor. The air concentration in the room was assumed to be well mixed. During the winter campaign, the two instruments were compared before and after the campaign. Under ideal circumstances, both instruments should have recorded identical concentrations. However, the concentrations were slightly different (within 12% mean difference as the highest recorded value) likely due to internal tolerances and calibration factors.

The inter-instrument variability correction was applied to ensure that any differences between the concentration levels were not because the instruments were reading different concentrations in the same location. Therefore the assumption was that the average of

the two (or more) instruments was likely the more accurate concentration at that specific time. Each instrument was corrected to the assumed correct concentration since they measured the concentration of the same indoor particles. Since the inter-instrument comparison tests were performed in similar concentration environments, the pre and post campaign comparison tests were joined in one file for the winter campaign. This technique eliminated the need to have two different correction factors which would have been applied to both sets of data. Figure 3-4 displays an inter-instrument comparison graph for the winter campaign. The solid blue and dashed red lines represent the concentrations from the instruments deployed while the dotted green line represents the average or likely the more accurate concentration.

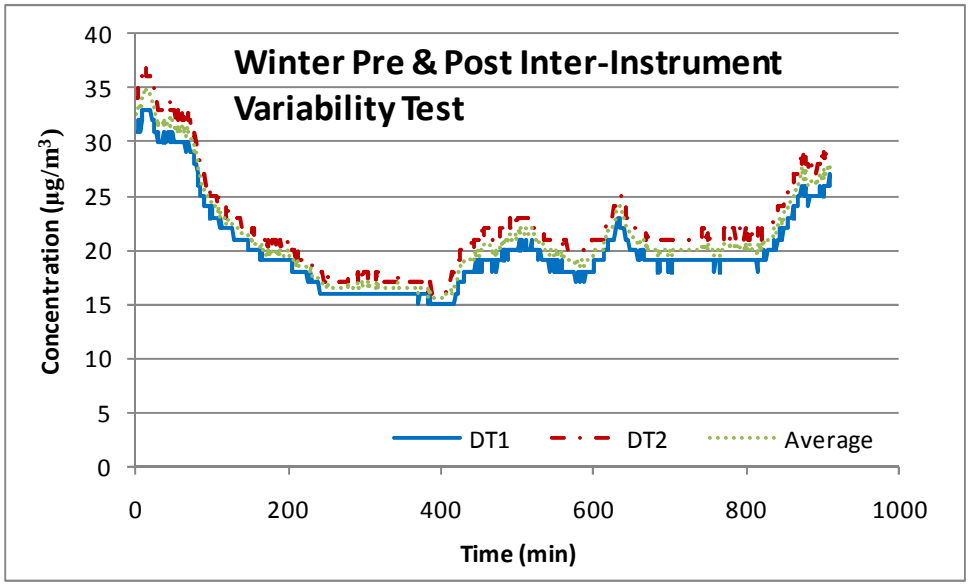

Figure 3-4: Winter campaign pre & post campaign inter-instrument comparison

In order to obtain the correction factors which were subsequently applied to each set of sampling data, regression analysis was used. Once the average of the two instruments was calculated for each time entry, each instrument`s data was plotted on a scatter graph

against the average of the two. From the scatter graph, the regression formula was used as the correction factor for each instrument. Figure 3-5 shows both DustTraks and the average value of the two along with the regression equations obtained. The intercepts were set to 0.

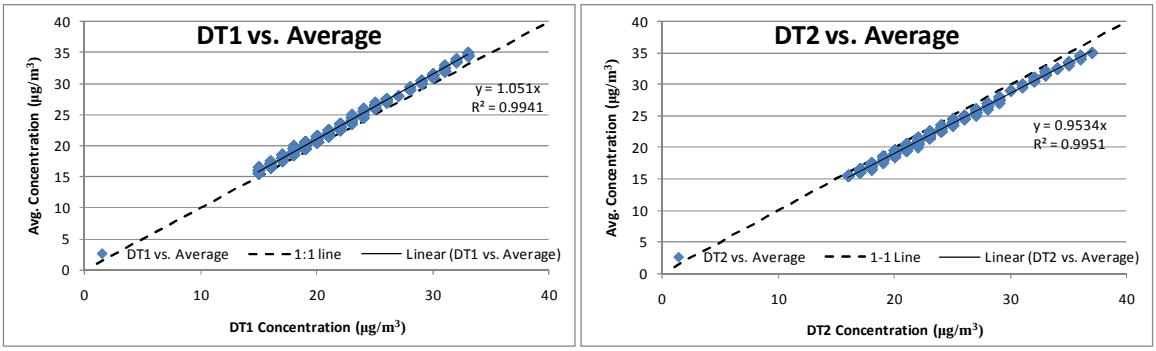

Figure 3-5: DT1 & DT2 compared to the average, regression analysis

A similar method was used for the spring campaign's inter-instrument comparison using the addition of two extra DustTraks which were used for outdoor concentration measurements. The results are presented in Chapter 4. Appendix C presents detailed information about the descriptive statistics of each inter-instrument comparison along with a more in-detail explanation of the methodology.

Overall, the winter campaign had one inter-instrument comparison before the start of the campaign and one after, with two instruments used. When only two instruments are used, if the concentrations observed in the pre and post instrument comparisons are similar (close in overall magnitude and average), the data sets can be joined into one file. Regression analysis can be used to obtain a correction factor by using the average of the two instruments' concentrations. In the spring campaign four instruments were used.

Not all instruments could be tested together pre campaign. In this case, it was decided to use the post campaign data because all four instruments were present. When four instruments are present, rather than create a fifth data set by calculating the average of all instrument concentrations, one can choose the data from the instrument that measured closest to the average. To remain on the conservative side, this study chose the data from the instrument that measured slightly higher than the average concentrations. In studies where more instruments are used, other methods are also available (Wallace et al., 2010). To remain consistent between the two campaigns, the regression based method was used.

Wallace et al. (2010), defined the LOD for continuous instruments, such as the DustTrak, to equal three times the standard deviation (SD) for the "mean of multiple collocated instruments of one type all measuring the same environment at some low concentration exceeding 3 times the SD to be considered as evidence at the 99% confidence level of a non-zero concentration." In our study's collocated tests with as many as four instruments, this criterion was not always met. In their study, Wallace et al. (2010) found the LOD to be 5 $\mu g/m^3$. Based on the manufacturer's owner's manual, the limit of resolution for the DustTrak is 1 $\mu g/m^3$. This study found the LOD to be from 7 to 19 $\mu g/m^3$. The higher LOD is an indication that the instruments should have been set to record for a longer period of time in an environment with constant concentrations. The SD would be lowered which would result in a lower LOD.

3.2.2. NO_2 methodology

Measuring method

Ogawa passive samplers (Ogawa & Co. USA, Inc., Pompano Beach, FL, USA) were used to measure the ambient NO_2 concentrations throughout three pre-selected neighbourhoods within the city of London, Ontario. The sampling phase overlapped that of the $PM_{2.5}$ measurement, the only difference is that it started on Sunday evening instead of on a Tuesday.

NO_2 site selection

The locations of the sites were selected by the University of Western Ontario based on the number of children located in each neighbourhood and the path of their potential walk to their schools. A buffer of 300 m was applied between sites. One site was collocated with the London MoE site. Originally, 33 sites were selected in total, however, they were reduced to 32 sites during the winter phase due to the vandalism of one site in week 1 after which it was decided not to replace that site. The spring phase replaced the vandalized site with a new location nearby, for a total of 33 sites. No vandalizing incidents were recorded during spring monitoring. Figure 3-6 displays the NO_2 sampler locations around each school along with the distribution of the number of students that attend each school.

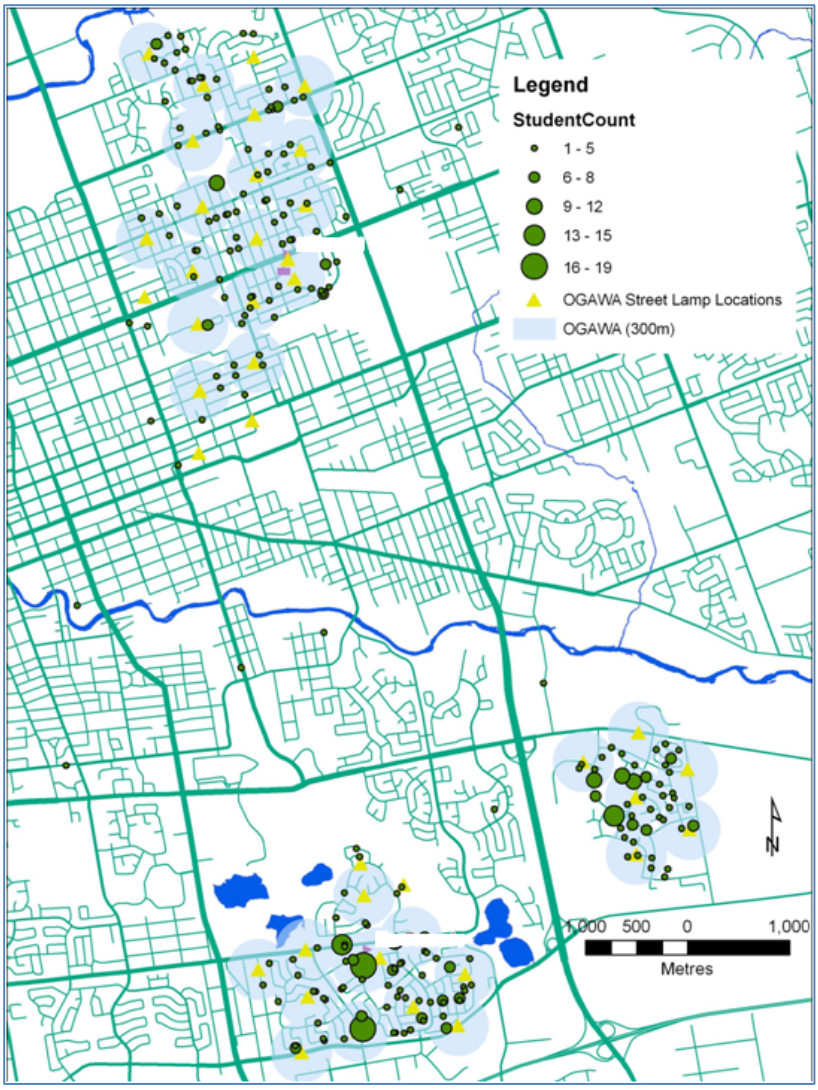

Figure 3-6: NO_2 sampler location and student distribution

Instrumentation

The Ogawa Sampler was employed for 6 week-long integrated passive monitoring of NO_2. The monitors were installed on light poles with permission from the City of London at a height of approximately 3 m to prevent contamination and vandalism from pedestrians. Stainless steel rain shelters were used to protect the samplers from inclement

weather. The setup day was every Sunday of the monitored week. The change out day was the following Sunday, a week later.

Quality Assurance/Quality Control Protocol

Nine percent of the samplers were field duplicates, which were used to assess the method consistency. Field blanks, which constituted 9% of total samples, were deployed to quantify the sample mass attributable to handling and transportation. All NO_2 concentration results were corrected using the field blanks. Each week, a batch blank was prepared; its concentration was compared to the median value of the field blanks. The batch blanks registered low concentrations suggesting the sampling medium is free of contamination. The median field blank concentration did not exceed 4 times the concentration of the batch blank for NO_2, indicating the concentration attributable to the handling and travel of sampling medium was relatively small.

The logsheets used in the field were entered into electronic format by one of the team members. An example logsheet is provided in Appendix D. The data entries were further checked by another student for completeness and correctness. The entries were further quality controlled using the laboratory logbook of all assembled samples and the field notes. Each field was assigned a fail or pass. A few entry fields were not quality controlled because they were not used, for example the UTM coordinates. For the spring campaign, week 5 had an incomplete entry in the "stop time" category which resulted in the flagging of that filter in an attempt to keep it for the analysis. The stop time was estimated using the stop time entry of the previous site and the start time of the next site,

this resulted in a maximum error of ~7 min. which is less than 0.07% of the total exposure time of that filter for that particular week.

Laboratory analysis of samples

The NO_2 samples were analyzed by Environment Canada (Egbert, Ontario) using ion chromatography. For both sessions, the laboratory conducted tests using 5 different standards, i.e., samples with known concentrations. Each standard was tested twice. As expected, the % difference between each pair of runs at the lower standard concentrations was greater compared to the higher standard concentrations. This could be because the lower standards approach the lower detection limit of the instrument.

Duplicate analysis was conducted to 16 different field samples and the % difference between each pair was calculated. The difference was less than 10%. The results of the standards and duplicate analysis showed consistency in the analytical methods used.

Meteorological information

Hourly temperature and relative humidity data from the London Airport (Environment Canada, 2010) were averaged during each of the 6 weeks for the study area to calculate the concentration coefficients. The average temperature and relative humidity during the three week winter and spring campaigns were -2.6°C and 79 %, 12°C and 71% respectively.

Data screening and exclusion

Samples from individual sites were flagged using the logsheets, lab log book and lab report. If physical damage, tampering, or contamination was noted samples could be deemed invalid. When field blanks exceeded four times the filter batch blanks all samples of that type for that particular week were flagged. Individual samples were deemed invalid if concentrations were zero or negative after blank correction or if exposure dates and times were not filled in.

All data from all filters were retained. Table 3-3 shows the sample retrieval and retention rates for all six weeks. One site was eliminated during week 1 due to vandalism. It was decided not to be replaced due to the possibility of repeat vandalism and close proximity to another site. A second site was eliminated during the second week of sampling. This site was replaced during the third week with a nearby location. The total number of samplers sent to the lab consists of the total # of samplers retrieved plus the weekly batch blanks, shown in Table 3-3.

Table 3-3: Sampler retrieval and retention rates

Season	Week # (date)	Samples planned	Samples deployed	Retrieved	Lost	Sent to lab	Included for analysis	% Retained
Winter	1 (14 – 21 Feb.)	39	39	38	1	39	38	97
	2 (21 – 28 Feb.)	39	38	36	2	37	36	95
	3 (28 Feb. – 7 Mar.)	38	38	38	0	39	38	100
	3 - wk total	117	115	112	3	115	112	97
Spring	4 (3 – 9 May)	39	39	39	0	40	38	97
	5 (9 – 16 May)	39	39	39	0	40	39	100
	6 (16 – 24 May)	39	39	39	0	40	39	100
	3 – wk total	117	117	117	0	120	116	99

Calculation of NO_2 concentration

The formulas used to calculate the final concentrations of the samples were provided by the Ogawa & Company (Ogawa & Co., 2006). The correction of the field samples was performed by using the field blank samples. A total of 9% field blanks were used during each week of each campaign. The median value of the field blank concentrations was used to correct the field samples for each week.

Analysis of duplicate samples

Each week duplicates were set up to assess the method consistency. The final concentrations present only 1 value instead of 2 for each site. The duplicate concentrations were assessed using a non-bias % difference formula (equation 1) since it was not known which of the duplicate concentrations was more accurate. Further, if the % difference was less than 10%, the average of the two was taken as the final result.

$$\%\, difference = abs\left(2 * \frac{duplicate1 - duplicate2}{duplicate1 + duplicate2}\right) * \ 100\% \quad (1)$$

Comparison with the MoE collocated site

The hourly NO_2 concentrations were retrieved from the MoE website (Ministry of the Environment, 2010). Two averages were calculated. The first was the average based on the longest possible weekly exposure time of any site, which was compared to the range of concentrations of all 33 sites. The second average was based on the exposure time of the collocated sampler which was used to compare the MoE concentration to the collocated concentration. The results are presented in Chapter 4.

3.2.3. CO_2 methodology

Measuring Method

CO_2 concentrations were recorded using the YES-206LH instrument produced by YES Environment Technologies Inc. (CETCI, Delta, BC, Canada). The YES-206LH is a battery powered, portable indoor air quality (IAQ) monitor and logger. The instrument includes a two-line LCD alpha numeric display, rechargeable battery pack, built-in programmable data logger, three sensors (Carbon Dioxide, temp and RH), carrying case and basic accessories. Concentrations were recorded during the last two weeks of the spring campaign only, due to their late arrival. The instruments were not set up to record temp and RH due to issues that were observed with the internal sensors during the pre-campaign testing of the instruments. The reason behind the usage of the CO_2 monitor is to confirm that activity was taking place in the gymnasiums during school hours. This can be used as a backup, in case the school activity schedules were not accurate. Heudorf et al. (2009) reported increased levels of CO_2 in elementary school classrooms during regular school hours. These increased concentrations were found to be diminished by intense ventilation.

Instrument selection and location

Five instruments were received from Health Canada. For calibration, the instruments were set to record the concentrations in a lab at the University of Windsor for a period of approximately 15 hrs. The data were analyzed and one instrument was dropped from the selection process because of its relatively low concentration readings compared to the other instruments. Originally, four instruments were supposed to have been used in the

field campaign, each site containing two instruments, one for indoor measurements placed in vicinity of the $PM_{2.5}$ monitor and one for outdoor measurements. Due to logistic issues, the sites could not accommodate any instrument for outdoor measurements, thus only three instruments were used in the spring campaign. Site A's CO_2 monitor was placed next to the $PM_{2.5}$ monitor while Site B's monitor was placed a short distance (less than 5 m) away from the PM monitor, due to the lack of a power source and the lack of adequate protection. The third monitor was placed close to the University of Western Ontario campus. It was set to measure ambient CO_2 concentrations. The start time of the third instrument was not the same as the other two sites because it took longer than expected to find an adequate and safe location for the instrument. The instruments were labeled C01, C03 and C05.

Data Retrieval and Analysis

The CO_2 monitor was set to record the average concentrations at 1-min intervals. At this interval, the instrument can store up to 20 days worth of data. Since the instruments were only used during the last two weeks of the campaign, data retrieval during the campaign was not necessary. The recordings were downloaded at the end of the campaign. The instrument required the use of the ACR Trend Reader software (ACR Systems Inc., 2011) to upload the data to a computer. The software can further convert it to a Microsoft Excel format.

QA/QC Protocol

The instruments did not require weekly maintenance. The deployment and retrieval of the units was logged into the field lab book for the two weeks they were deployed.

Inter-instrument comparison

An inter-instrument comparison was performed before and after the deployment of the units during the spring campaign. The results are presented in Ch. 4. The method used to obtain the correction factors for each instrument was identical to the method used for the $PM_{2.5}$ spring campaign, which was previously explained in greater detail. A total of five instruments were compared. For more details of the comparison, see Appendix C.

3.3. School schedules

Regular gym schedules

The regular school hours were different at the two sites. Table 3-4 displays the school schedules for both sites. The times mentioned in this thesis all refer to the local time at the current location, Eastern Standard Time.

Table 3-4: Sites A & B school hours

Activity	Site A	Site B
School Start	8:50	9:00
Recess 1	10:15 – 10:30	10:25 – 10:40
Lunch	11:50 – 12:50	12:00 – 13:00
Recess 2	14:10 – 14:25	14:20 – 14:35
School End	15:30	15:35

After school gym schedules

Each site had different after school activities scheduled during the campaigns. A copy of the after school activities cannot be shown because of confidentiality concerns.

3.4. Activity schedules

The activity schedules provided further information about when classes were actually scheduled in the gyms. These were unique to each school.

3.4.1. Site A

Regular Activities

A schedule showing regular school-hours activities was provided. It was assumed that activities took place if the gym had a classroom scheduled during that time. Both winter and spring regular school hour's campaign schedules are identical since they happened during the same school semester, and thus there was no change between the campaign months. This was confirmed with the school's administration office.

Afterschool Activities

Site A does not have a spring afterschool activity schedule. This schedule was not available for the month of May, when the spring campaign took place. Thus, it was assumed that there were no afterschool activities in the gym during the spring campaign. The school provided an afterschool activities schedule during the winter campaign.

3.4.2. Site B

Regular Activities

The regular school schedule was used as the activities schedule. Since no detailed schedule was provided, it was assumed that activity took place during regular school hours. This condition was assumed for both winter and spring campaigns. The spring schedule also provided lunch time activities. When they were scheduled, it was assumed they happened during the entire lunch hour of that day.

Afterschool Activities

Winter and spring after school gym activity schedules were provided. They were identical for both campaigns.

3.5. HVAC schedules

The sites were heated and cooled by central Heating Ventilating and Air-Conditioning (HVAC) units placed on the roofs of the gyms. The units were produced by the same manufacturer, Trane (Davidson, North Carolina, USA). However, the unit models are different.

Both locations had an HVAC start time of 7:00 Monday-Friday. The HVAC start and stop times for each location are presented in Table 3-5. The weekend (Wend) was defined as starting at 20:16 Friday evening and ending at 6:59 on Monday morning for both sites. The time between was defined as weekday (Wday).

Table 3-5: HVAC schedules showing operating hours

	Site A	Site B
Monday	7:00 - 20:00	7:00 - 19:15
Tuesday	7:00 - 20:00	7:00 - 19:30
Wednesday	7:00 - 20:00	7:00 - 17:00
Thursday	7:00 - 20:00	7:00 - 20:15
Friday	7:00 - 20:00	7:00 - 20:15
Saturday	Off	8:00 - 15:00
Sunday	Off	Off

Both HVAC units are equipped with motion sensors. According to the sites' maintenance engineer, the HVAC units are set to maintain a heating and cooling setpoint. The daytime heating setpoint was 21°C and the cooling setpoint was 25°C. This means that regardless if the gym is occupied or not, the units will be on until the setpoint has been met. At night time the setpoint changed to 18°C for heating and 30°C for cooling. Outdoor air was filtered. Appendix E contains information provided by the maintenance engineer along with Site A's HVAC performance specifications.

3.6. Data Processing

All statistical and graphical analysis has been performed using Microsoft® Office Excel® and Minitab® Release 14.1. (Minitab Inc., State College, Pennsylvania, USA). All maps used in this research were compiled with the use of ArcGIS (Geographical Information System) software (ESRI, 2011). The maps were created by the team at the University of Western Ontario.

All sets of data were plotted before applying the inter instrument correction factors. Unusual spikes in the concentrations were checked versus the field log book, the log

sheets and school schedules. One regular school day's $PM_{2.5}$ data was eliminated from Site A because of an out of the ordinary activity, a firefighter demonstration day, which resulted in concentrations that were significantly greater, i.e., magnitude of 1000 times, compared to regularly observed concentrations.

In total, Site A observed a $PM_{2.5}$ concentration of "0 $\mu g/m^3$", 8,316 out of a total of 28,479 1-min measurements during the spring campaign. During the winter campaign 11,694 "0 $\mu g/m^3$" out of a total of 28,092 observations were recorded at Site A. Site B did not observe any concentrations of "0 $\mu g/m^3$" during either campaign. These 0 $\mu g/m^3$ concentrations were not treated any differently but rather kept as is. The reason they were not changed to ½ of the Minimum Detection Limit (MDL) is because the detection limit was not always achieved during spring and the winter campaigns. If the zero concentrations had been altered, the distribution of the concentrations would have changed. It was decided to not alter the actual data more than necessary with the exception of the inter-instrument corrections.

3.6.1. $PM_{2.5}$ data tagging

The DustTrak recordings provided data which was imported into Excel. The categories reported were: Date (mm/dd/yyyy), Time (hh:mm:ss) and Aerosol (i.e., $PM_{2.5}$) Concentration (mg/m^3). The concentrations were further converted into $\mu g/m^3$ because these units were easier to work with. The concentrations were then multiplied by a correction factor which was derived from the inter-instrument comparisons.

$PM_{2.5}$ data for each three weeks of each campaign was combined into one file. Tags were attached based on the week #, unit ID, time of day and schedules provided. Table 3-7 displays all the tags related to the DustTrak data.

Table 3-6: $PM_{2.5}$ data tags

Week #	Location (A or B)	Unit ID	Indoor/ Outdoor	HVAC (on/off)	Activity/No-Activity	Wday/Wend	Date (mm/dd/yyyy)	Time (hh:mm:ss)	Aerosol (mg/m3)	Aerosol (µg/m3)	Aerosol w. C.F. (µg/m3)

Once the 1-min average concentrations were plotted against time and checked for unusual spikes, the concentrations were further averaged into 1-hr averages. The concentration was averaged starting from the exact time on the hour until and including the 59th minute. For example: the concentrations were averaged from 9:00 until 9:59, as 9:00. For concentrations where the full hour of data was not available because of initial setup or weekly maintenance, that hour was eliminated if the 75% rule was not met (i.e., more than 15 min out of a possible 60 min were not available).

3.7. Data analysis

3.7.1. Distribution, descriptive statistics, t-test, Spearman correlations and regression analysis

Once the study ended and all the laboratory results were received (for the NO_2 samples), the data underwent various quality control procedures to assure correctness. The results explaining the objectives of the study were calculated using various statistical tools such as time-series plots, t-tests, Spearman correlations and regression and distribution analysis.

The observed 1-min $PM_{2.5}$ concentrations were tested to see if they conformed to a particular distribution. The Anderson-Darling (AD) test was used to determine the suitability of a particular distribution. The AD statistic and the *p*-values were calculated in Minitab for different types of distributions. The smaller the AD value and the greater the *p*-value, the better the data fits the distribution. The critical values for the AD test are dependent on the specific distribution that is being tested. The *p*-value was used to accept or reject the null hypothesis of the data belonging to a particular distribution. Appendix F provides the AD statistic and *p*-value for the $PM_{2.5}$ concentrations during both campaigns. As can be observed, the data do not follow a normal distribution, which is expected.

The student's t-test and paired t-test was used to determine if sets of measurements from two different instruments were statistically different at the 95% Confidence Interval (CI) (α=0.05). The t-test assesses whether the means of two groups are statistically different from each other. The null hypothesis states that there are no differences between the two sets of concentrations.

Correlation coefficient (designated by the letter R) is a single number that describes the degree of association between two variables (Trochim, 2006). R ranges from +1 to -1. A positive value suggests a positive association. As one variable increases, so does the other. A value of 0 suggests no association. A negative value indicates a negative association, as one increases the other decreases in the same proportion. The square of the correlation coefficient estimates how much the total variation is explained by the

relationship and it is designated by R^2. Pearson correlations were used when the data distribution was normal or almost normal. Spearman correlations were used when data distribution was not normal. The Spearman correlation is a non-parametric measure of statistical dependence and it was used in many analyses that involved the comparison of indoor and outdoor measurements which are positively skewed most times. The Spearman rank correlations coefficient is denoted by the letters "r_s." The correlation coefficient was calculated in Minitab. To calculate the Spearman correlation significance (P-value), a normal distribution with the test statistic Z was used.

$$Z = r_s * sqr(n-1)$$

A normal distribution with a mean of 0, standard deviation of 1.0 and Z input constant returned the x value. The P-value equals 2*(1-x).

Regression analysis is a statistical tool used in identifying the relationship between independent and dependent variables and could be further used in developing a forecasting model between the sets of variables. In the analysis, the measure of total variation (SST) is the sum of the squares of explained variation (SSR) and sum of squares of unexplained variation (SSE). The R^2 value, which stands for Coefficient of Determination, is the proportion of total variation (SST) that is explained by the regression (SSR). Since there were two predictor variables in Chapter 4 of the study, a multiple regression analysis method was conducted. It is a known fact that the "R-Sq" value increases with the addition of more independent variables. However, some of the variables do not contribute significantly to the model. The "adjusted R-Sq" is used in multiple regressions because it takes into account the size of the sample and the number

of explanatory variables. However, in this study only two variables were used and the R-Sq and adjusted R-Sq values were very similar. Linear regression correction coefficients were calculated for $PM_{2.5}$ and CO_2 concentrations.

3.7.2. Indoor-outdoor relationships

The indoor-outdoor relationships for $PM_{2.5}$ and CO_2 were examined using time series indoor-outdoor plots and Spearman correlations for the hourly averages during the last two weeks of the spring campaign. The correlations and indoor/outdoor (I/O) ratios are discussed in Chapter 4. The median and mean indoor hourly concentrations during the campaign were divided by the hourly outdoor median and mean concentrations of the same hour to obtain the I/O ratios.

3.7.3. HVAC analysis for the Firefighter day episodes

During the Firefighter demonstration day on Feb. 19, 2010, five different very high $PM_{2.5}$ concentration episodes were identified. Two of the episodes appeared to consist of multiple demonstrations thus they were eliminated. For the remaining three episodes the concentration profiles were split into two phases: production and elimination. A linear regression model was used to calculate both production and elimination rates. The rates were estimated by measuring the increase and decline of $PM_{2.5}$ concentrations following the individual peaks for each episode. Both the concentration rise and concentration decline were approximately linear. A first-order elimination profile was considered, however the model agreed more with a linear elimination rate rather than an exponential

profile. Figure 3-7 displays the $PM_{2.5}$ concentration profile during the last episode of the Firefighter demonstration day, as an example.

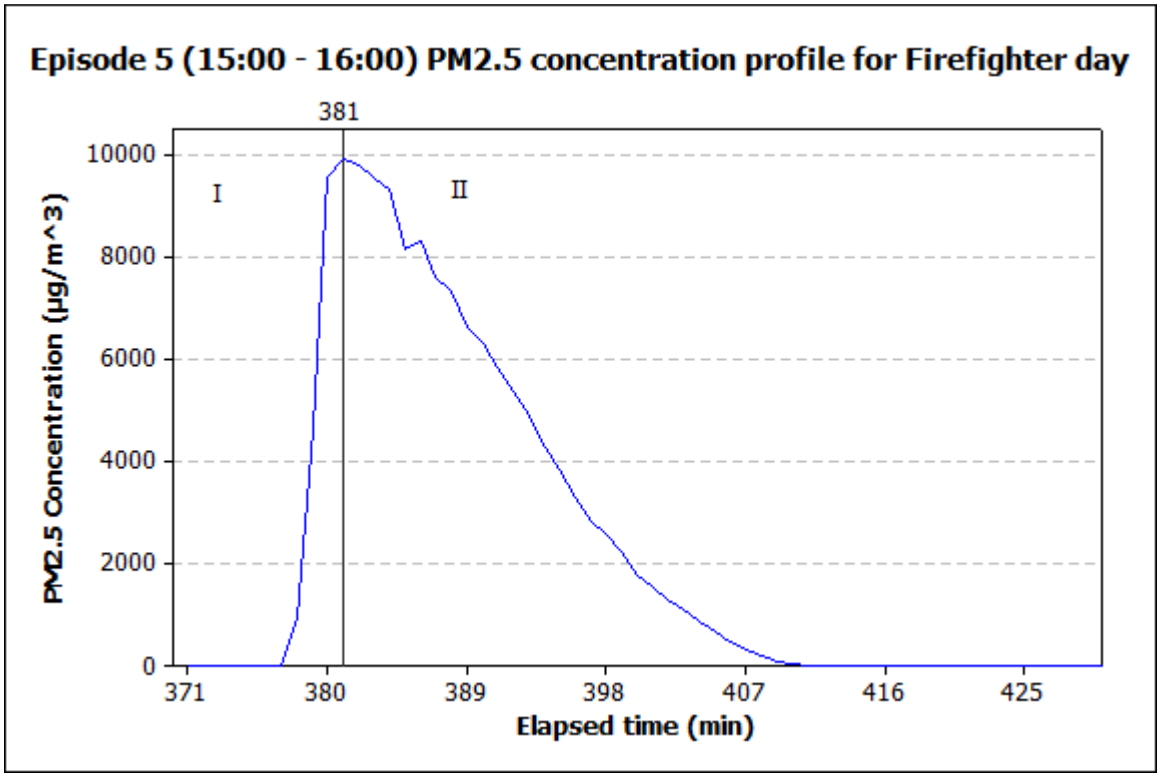

Figure 3-7: $PM_{2.5}$ concentration profile during the last episode of the Firefighter day indicating regions of production and elimination: I-production, II-elimination

CHAPTER 4 - RESULTS AND DISCUSSIONS

4.1. Inter-instrument comparisons summary

A detailed explanation of the inter-instrument comparison process for the $PM_{2.5}$ and CO_2 instruments is provided in Appendix C. This section presents the final correction results along with brief explanations.

4.1.1. $PM_{2.5}$ instrumentation

The winter pre and post campaign inter-instrument comparison data sets were joined into one file in order to eliminate having two sets of correction factors for the same campaign. This is justified because the concentrations observed during both comparisons were very similar. The winter campaign correction factors used are presented in Table 4-1.

Table 4-1: Winter campaign $PM_{2.5}$ correction factor equations

Season	Correction Factor Equation
Winter	$(DT1_{Corrected}) = 1.0541 * (DT1_{observed})$
	$(DT2_{Corrected}) = 0.9534 * (DT2_{observed})$

During the spring campaign, two more DustTraks were added for the last two weeks of testing, they were coded DT3 and DT4. Attributable to shipping logistics, the two extra instruments arrived late, thus they could not be compared before the start of the campaign along with the two original DustTraks used during the winter campaign. Post-campaign, all instruments were set to measure and record the indoor concentration in the same lab used during the winter campaign, at the University of Windsor. The spring correction factors obtained using the post campaign are presented in Table 4-2.

Table 4-2: Spring campaign $PM_{2.5}$ correction factor equations

Season	Correction Factor Equation
Spring	$(DT1_{Corrected}) = 1.0611 * (DT1_{observed})$
	$(DT2_{Corrected}) = 0.9513 * (DT2_{observed})$
	$(DT3_{corrected}) = (DT3_{observed})$
	$(DT4_{Corrected}) = 1.0122 * (DT4_{observed})$

All $PM_{2.5}$ data presented from here on forth, which originated from measurements undertaken by using a DustTrak, were corrected with the above correction factors for their respective campaign. Appendix C should be consulted for more information, the methodology and results of the comparison tests.

4.1.2. CO_2 instrumentation

Similar to the $PM_{2.5}$ inter-instrument variability methodology used for the spring campaign, instrument C03's concentrations were chosen as the reference since the median and mean concentrations were approximately in the middle compared to those of the other instruments. From the regression analysis between the three instruments, the correction factors used are presented in Table 4-3.

Table 4-3: Spring campaign CO_2 correction factor equations

Season	Correction Factor Equation
Spring	$(C01_{Corrected}) = 0.8095 * (C01_{observed}) + 28$
	$(C03_{corrected}) = (C03_{observed})$
	$(C05_{Corrected}) = 1.0385 * (C05_{observed}) + 40$

All CO_2 data presented from here on forth have been corrected using the above correction factors. Appendix C contains detailed information pertaining to the method and results.

4.2. $PM_{2.5}$ concentrations

The results are presented in backwards chronological order because more data was captured during the spring campaign. This made a stronger argument for the methodology used during the winter campaign.

4.2.1. Spring campaign results

The spring $PM_{2.5}$ indoor measurements started on Tuesday May 4 and ended on Tuesday May 25, 2010. The instruments (DT1 and DT2) were started and stopped within hours of each other attributable to the logistics of the operation which consisted of only one field technician team. The 1-min average indoor concentrations time series are shown in Fig. 4-1. It should be noted that, although the measurements were stopped in the morning of May 25th, May 24th fell on a Monday which was a national holiday and as such, the schools were not open. There was also a level of uncertainty concerning the operating hours of the HVAC units on holidays. Therefore, measurements past 7 am on May 24th were not used. Site B concentrations were consistently higher compared to Site A for the most part. The peak concentration was around 32 $\mu g/m^3$ at Site A, while Site B had a peak of over 90 $\mu g/m^3$ with concentrations over 20 $\mu g/m^3$ on a regular occurrence.

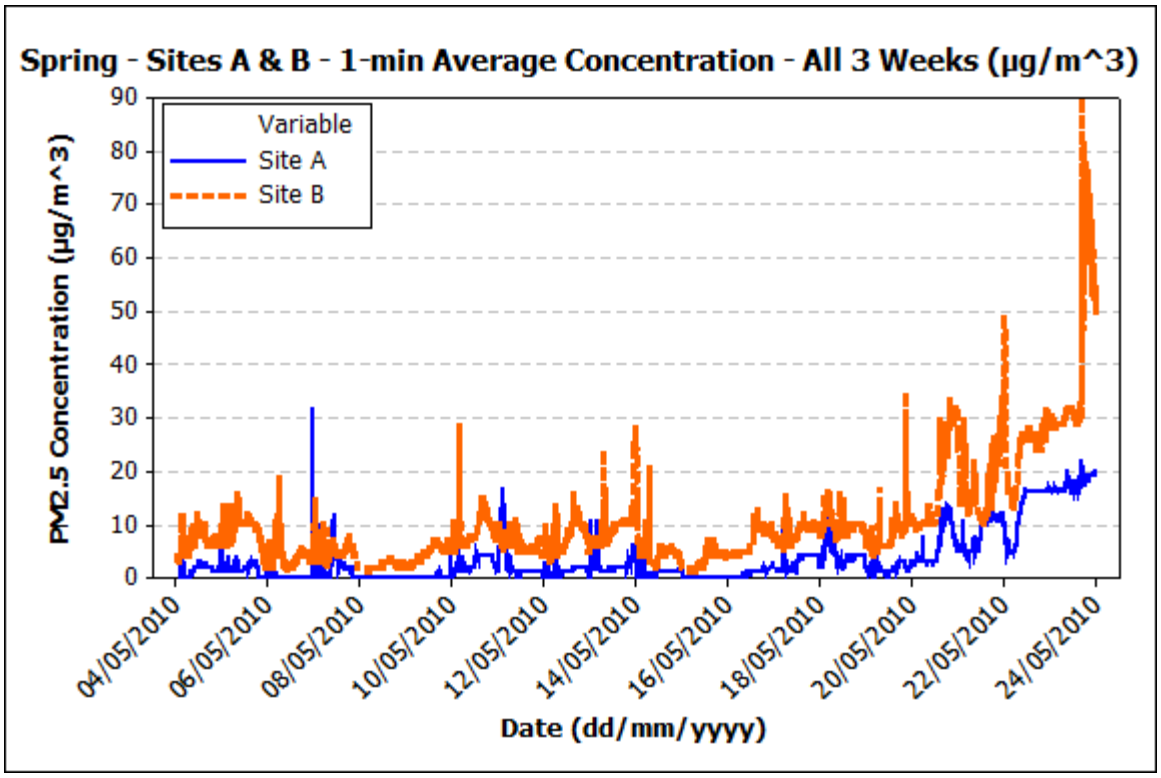

Figure 4-1: Indoor $PM_{2.5}$ concentrations during the spring 2010 campaign

Table 4-4 displays the 1-min statistics during the spring campaign. Site B`s mean concentration (10.3 µg/m^3) was 3 times greater than Site A's (3.4 µg/m^3). The median concentration for Site B was 3.5 times greater compared to Site A, while the range was 2.8 times greater.

Table 4-4: Spring - $PM_{2.5}$ 1-min concentrations (µg/m^3); May/04/2010 to May/24/2010

Campaign	Site	Location	Mean	SD	Min	Median	Max	Range
Spring	Site A	Indoor	3.4	4.8	0	2	32	32
	Site B	Indoor	10.3	10.1	1	7	90	89

Hourly outdoor mean concentrations were calculated at both sites for comparison with the MoE recordings. Figure 4-2 displays the outdoor hourly concentrations over the last

two weeks of the spring campaign. A close-up of the concentrations from May 10 to May 20, 2010 is shown in Fig. 4-3.

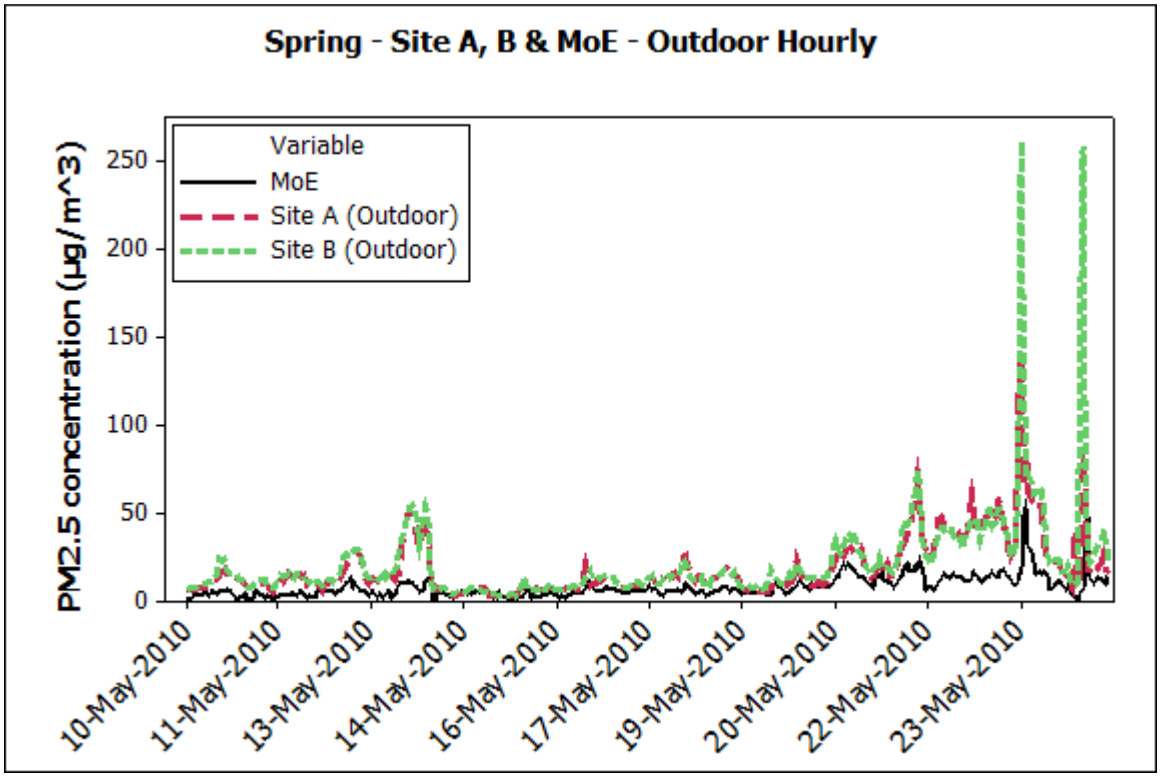

Figure 4-2: Spring - $PM_{2.5}$ - Outdoor hourly concentrations

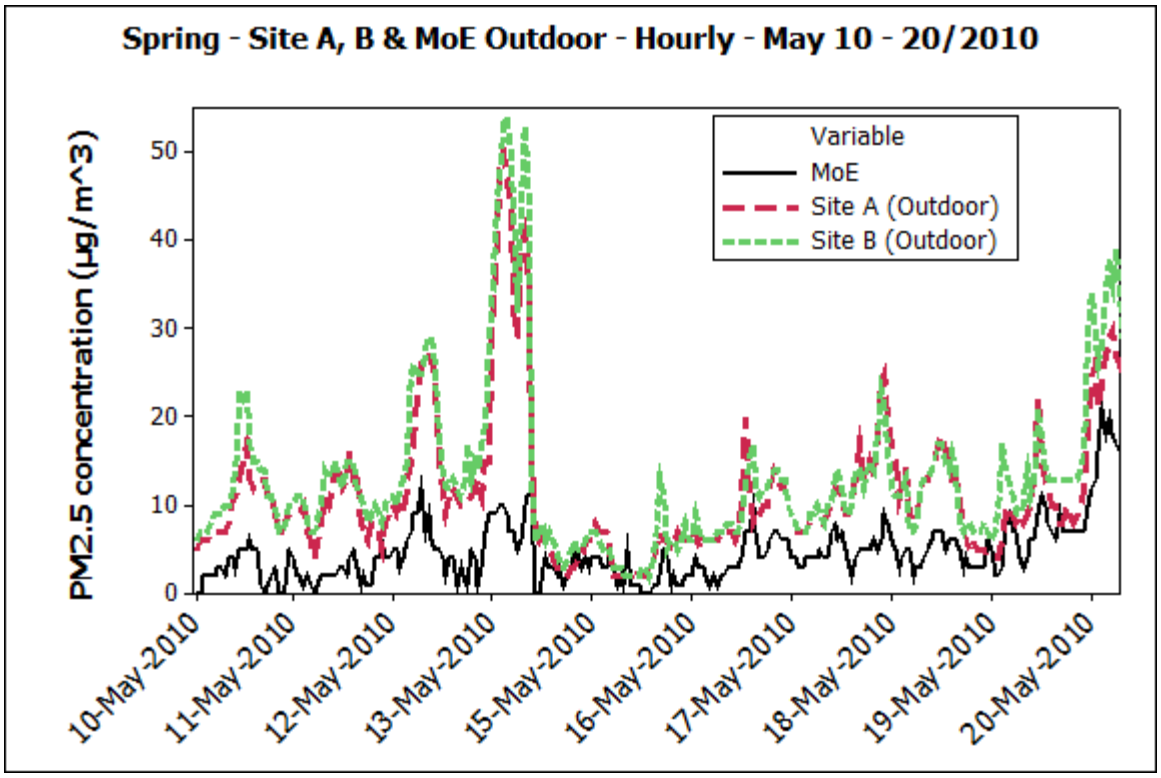

Figure 4-3: Spring - $PM_{2.5}$ - Outdoor hourly concentrations, close-up

A paired t-test was performed on the hourly outdoor concentrations at Site A and Site B. The T-stat was equal to 1.8 which is less than the T-critical value of 1.96. The results show that at the 95% confidence level the difference between the paired concentrations are statistically insignificant and thus considered similar.

Although the concentrations at the outdoor Sites A and B are close together in magnitude, they both follow the concentration trends found MoE site. The objective of the overall outdoor hourly comparison was not to compare the magnitude of the concentrations from the two sites with those of the MoE since two different measuring methods were used, but rather to check for similar trends.

The outdoor Pearson correlations between Site A, B and MoE during the last two weeks of the spring campaign are shown in Figs. 4-4, 4-5 and 4-6. Good correlations can be observed between Site A and MoE, and Site B and MoE. A strong correlation was present between Site A and Site B which was expected since the concentrations were not significantly different. These correlations indicate a strong regional influence in the city, and that the impact of local sources was rather small during the spring campaign.

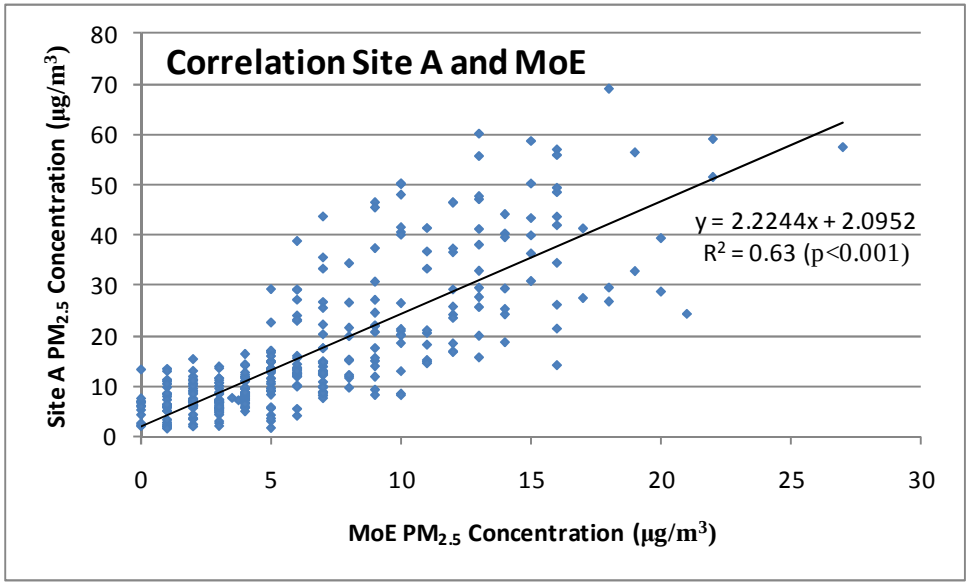

Figure 4-4: Spring – Outdoor - Hourly $PM_{2.5}$ correlation Site A and MoE

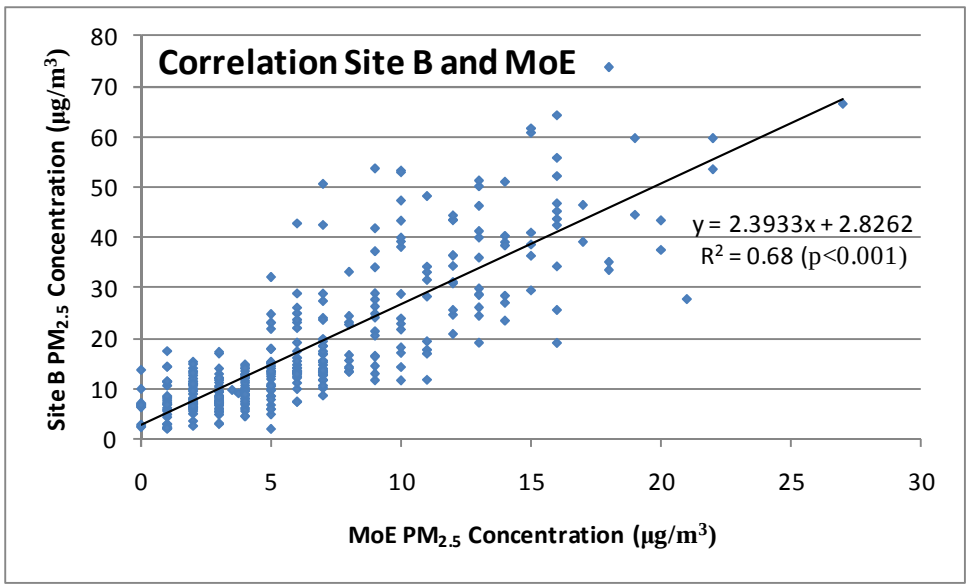

Figure 4-5: Spring – Outdoor – Hourly $PM_{2.5}$ correlation Site B and MoE

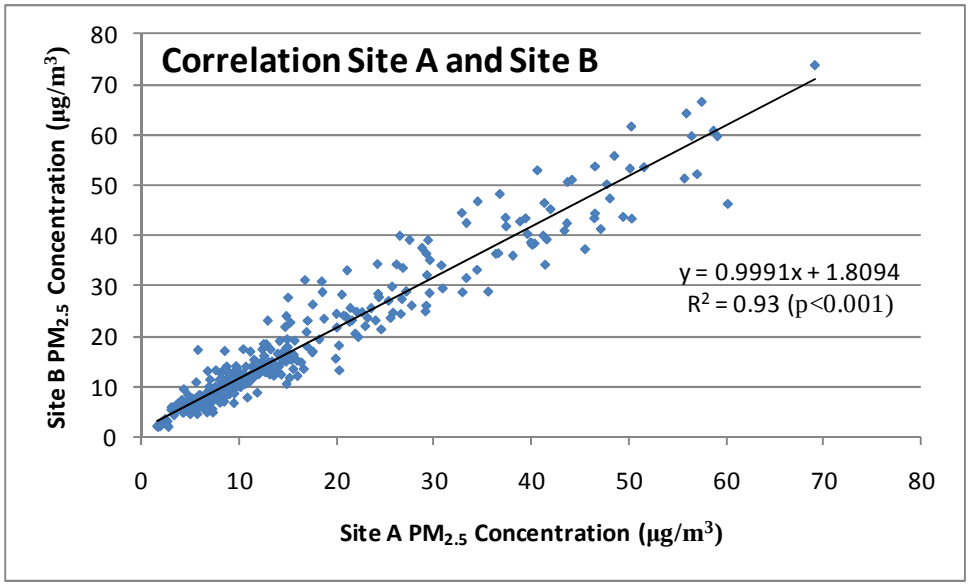

Figure 4-6: Spring – Outdoor – Hourly $PM_{2.5}$ correlation Site A and Site B

Table 4-5 displays the descriptive statistics for the last two weeks of the spring campaign. The median values for Sites A and B were 12 and 13 µg/m^3, respectively. MoE site had a median concentration of 5 µg/m^3, approximately 2.5 times smaller compared to each of

the two sites. The mean MoE hourly concentrations were approximately 3 times smaller compared to each site. Similar magnitude differences in PM mass concentrations between instruments using the FRM and the DustTrak have been observed in previous studies (Yanosky et al., 2002; Evans et al., 2008), with magnitude differences between 2.4 to 3.0. The reason for this difference in magnitude is related to the differences in the methodology used by both types of instruments. If the relative humidity (RH) is less than 75%, a factor of up to 2.3 has been previously observed in other southwestern Ontario studies (Evans et al., 2008; Stieb et al., 2008). If the RH is greater than 75%, the difference between TEOM and DustTrak becomes exponential with increasing RH %. This is partly because the TEOM has an integrated air drier and water molecules are evaporated before they enter the TEOM chamber, while the DustTrak does not have such a feature. During days with high relative humidity the most abundant substance in particles is typically liquid water (Jacobson, 1999). However, largely, the magnitude factor is attributed to the different methodology and physics principles used by the two instruments, as was described in Chapter 2.

Table 4-5: Spring - Hourly outdoor $PM_{2.5}$ concentrations ($\mu g/m^3$) during the last two weeks (May 10 - 25, 2010) of the campaign

Campaign	Site	Mean	SD	Min	Median	Max	Range
Spring	Site A	18.1	17.1	2	12	139	137
	Site B	21.1	25.4	2	13	261	259
	MoE	7.0	6.6	0	5	53	53

A direct comparison between the indoor and outdoor $PM_{2.5}$ concentrations was possible during the last two weeks of the spring campaign. The hourly $PM_{2.5}$ concentrations for Site A are shown in Fig. 4-7. The gap in the line graph on May 17, 2010 represents the time when maintenance was performed and the 75% completion rate criterion wasn't

met. As can be observed, the outdoor concentration was greater compared to the indoor concentration. Table 4-6 displays the statistics of the hourly averages. Site A`s mean outdoor concentration was 3.5 times greater compared to the indoor concentration. The median outdoor concentration was 4 times greater than indoor.

Table 4-6: Spring – Site A - Hourly $PM_{2.5}$ concentrations (µg/m^3) indoor vs. outdoor (May 10 - 25, 2010)

Location	N	N*	Mean	SD	Min	Median	Max
Site A - Indoor	357	1	5.2	5.7	0	3	20
Site A - Outdoor	356	2	18.1	17.1	2	12	139

**"N" represents the total number of samples, in hours, while "N*" represents the total number of hours that were excluded due to failure to meet the 75% completion criterion.*

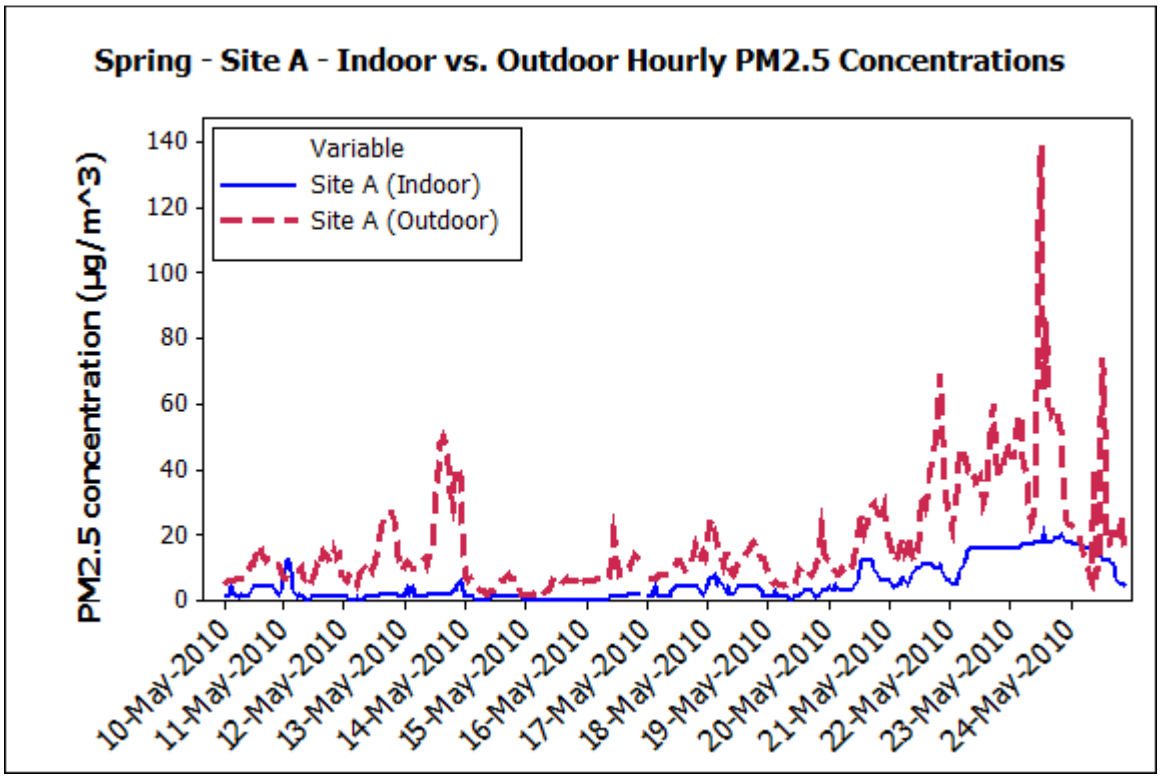

Figure 4-7: Spring - $PM_{2.5}$ – Site A - Indoor and outdoor hourly concentrations

The Indoor/Outdoor (I/O) median concentration ratio for the two weeks was 0.25, which indicates that outdoor concentrations may not have had a significant influence over the

indoor. Figure 4-8 displays the hourly averages scatter plot for the indoor and outdoor concentrations at Site A. Pearson correlation analysis shows an R^2 value of 0.51 (p<0.05) indicating a moderate correlation between the two, thus some of the indoor concentrations can be attributed to the outdoors. The I/O concentration ratio should be used with the correlation coefficient to make an interpretation on the significance of infiltrated outdoor air. From Fig. 4-7 it is evident that hourly outdoor peaks in concentrations did not have much of an impact on the indoor concentrations. It would appear that the location of the gym within the building is better protected from outdoor infiltration of particles. Another reason for the lower indoor concentrations could be attributed to the HVAC system since some increasing trends were observed on the weekends and the unit was turned off from Friday to Monday mornings. Lastly, the indoor hourly concentrations did not surpass the CWS of 30 µg/m^3 for any 24 hour period.

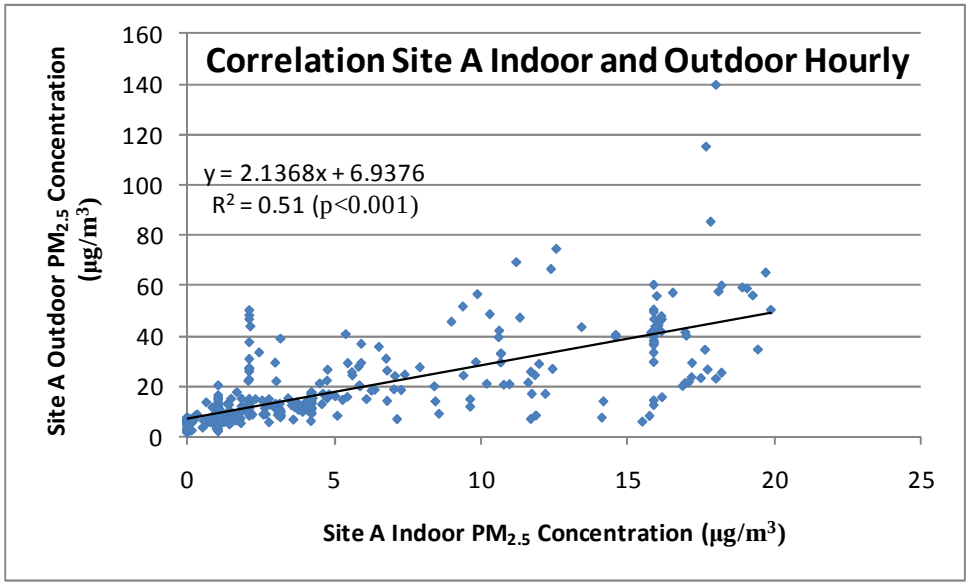

Figure 4-8: Spring - $PM_{2.5}$ – Site A - Indoor and outdoor hourly correlation plot

The indoor and outdoor hourly average $PM_{2.5}$ concentrations for Site B are shown in Fig. 4-9. As can be observed, the concentrations tracked each other. However, the outdoor concentration was greater than the indoor concentration for the majority of the days. From Table 4-7, the mean outdoor concentration was 1.5 times greater compared to the indoor concentration. The median outdoor concentration was 1.4 times greater, similar to the mean. The I/O median concentration ratio was 0.7 suggesting indoor concentrations were influenced by the outdoor concentrations, at least on a level more influential when compared to Site A. An R^2 value of 0.41 (p<0.05) was calculated (hereafter shown in Fig. 4-10), indicating a moderate correlation between outdoor and indoor concentrations. The outdoor concentration is greater than the indoor concentration, similar to Site A, the differences in magnitude between the two concentrations were smaller than the differences observed at Site A, mainly because the indoor concentrations were highest at Site B.

Table 4-7: Spring – Site B - Hourly $PM_{2.5}$ concentrations (µg/m^3) indoor vs. outdoor (May 10 - 25, 2010)

Location	N	N*	Mean	SD	Min	Median	Max
Site B - Indoor	358	0	13.9	12.7	2	9	73
Site B - Outdoor	358	0	21.1	25.4	2	13	261

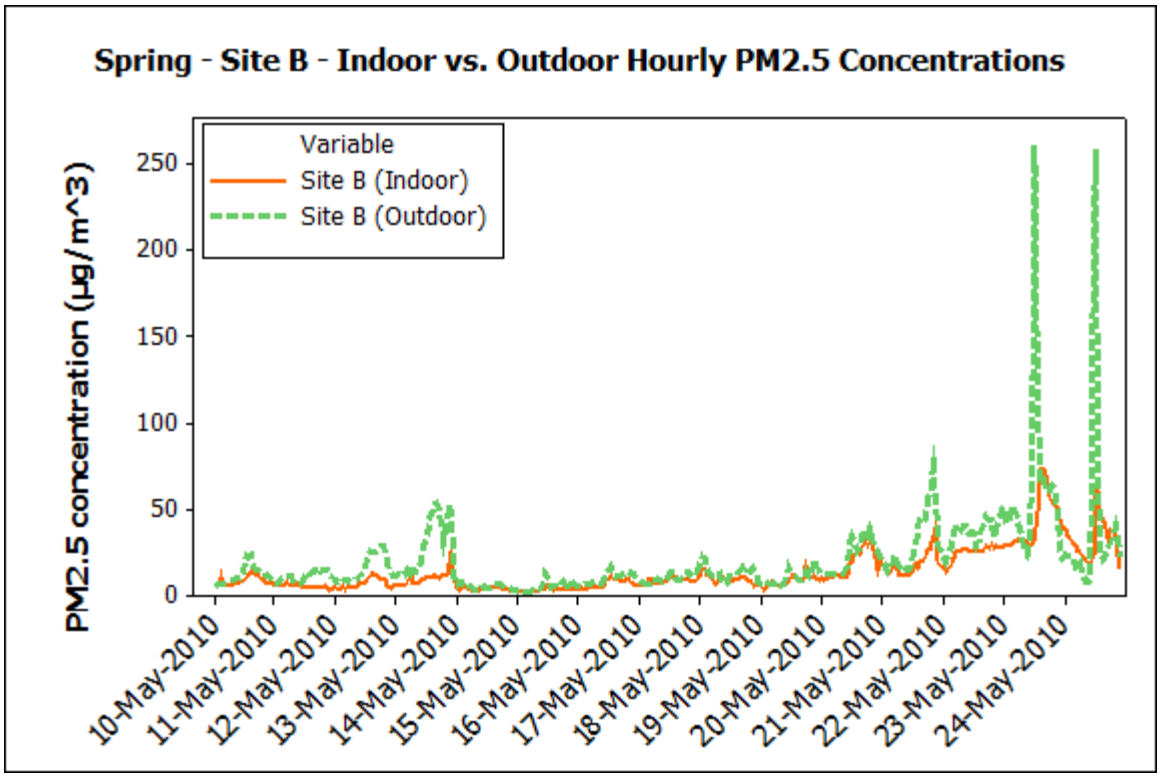

Figure 4-9: Spring - $PM_{2.5}$ – Site B - Indoor and outdoor hourly concentrations

Similar to Site A, Site B's trends of the weekend indoor concentrations follow closely those of the outdoors. This is not unexpected since the HVAC unit was mostly off during the weekends, much like Site A. The indoor concentrations at Site B are much closer in magnitude with those of the outdoors. Although the I/O ratio was not equal to one, it is much closer to one, compared with Site A's I/O ratio for the mean and median concentrations of indoor and outdoor $PM_{2.5}$, respectively. This suggests that the building envelope at Site B is more susceptible to outdoor infiltration. Since the outdoor concentrations at the sites were strongly correlated, it implies that the daily traffic did not necessarily influence the indoor average concentrations to the same degree. Site B surroundings were exposed to twice the amount of daily traffic compared to Site A. However, this fact does not appear to influence the outdoor concentrations, since the

median and mean concentrations were similar at both locations (Table 4-5). Thus some possible explanations for the higher indoor concentration could be the HVAC system and the location of the gym within the building. The HVAC system can likely be eliminated since both schools used similar units from the same manufacturer. The most plausible explanation is the location of the gym within the building and its walls surrounded by the outdoors with the two doors that lead directly outside. A conversation with the site's custodian also revealed that the gym was often directly exposed to outside air by opening the doors for the purpose of ventilation. It is unclear exactly how often this took place because the custodian does not record these events and they were largely weather dependent. Unexpected is the lower correlation between the outdoor and indoor at Site B compared to Site A. This lower value ($R^2 = 0.41$) is likely caused by the Pearson correlation used which is affected by outliers. The Spearman correlations reveal a different trend, as explained in the following paragraph. The CWS of 30 $\mu g/m^3$ was also not surpassed for any 24-hr period, similar to Site A.

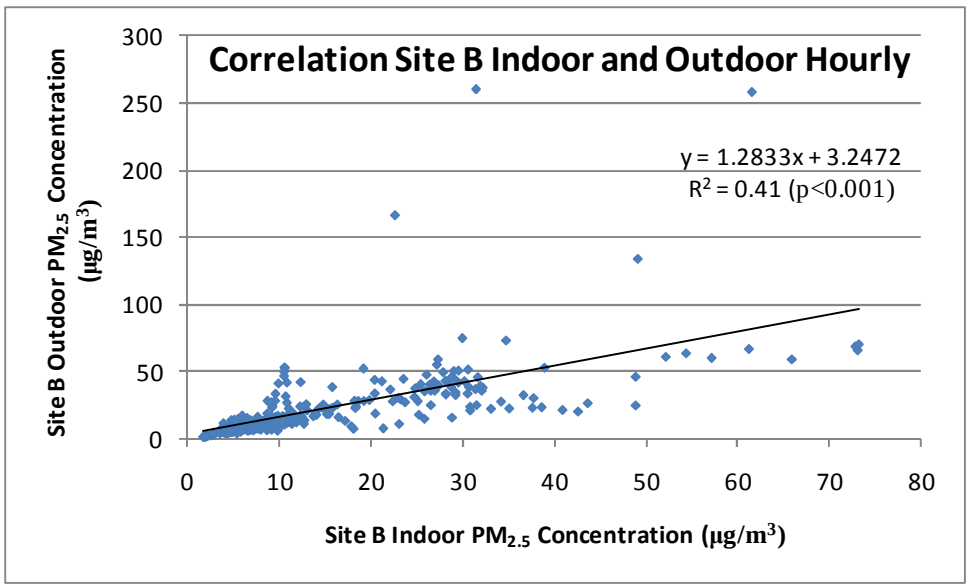

Figure 4-10: Spring - $PM_{2.5}$ – Site B - Indoor and outdoor hourly correlation plot

The Spearman correlations for the spring campaign are shown in Table 4-8. They are in general agreement with the Pearson correlations. However, their values are higher compared to the Pearson correlations. This is expected since the data did not follow a normal distribution for the most part. In such cases, the Spearman correlation usually provides a better representation. Most interesting is the strong correlation between Site B indoor and outdoor data. This was not well reflected with the Pearson correlation. The Spearman correlations are not influenced by outliers because they are based on a rank system, thus providing a better representation of the actual correlations.

Table 4-8: Spearman correlations for spring campaign, hourly concentrations (all *p*<0.001)

	Site A Outdoor	Site B Outdoor	Site A Indoor	Site B Indoor
MoE	0.80	0.82	0.73	0.82
Site A - Outdoor		0.95	0.79	
Site B - Outdoor				0.86

4.2.2. Winter campaign results

The 1-min concentration time series are presented in Fig. 4-11. Site B's concentrations are consistently higher compared to Site A as in the spring campaign. The peak concentration is around 16 µg/m^3 for Site A, while Site B has a peak of approximately 50 µg/m^3 with concentrations over 15 µg/m^3 a regular occurrence. Table 4-9 displays the descriptive statistics during the winter campaign, starting on February 16 to March 08, 2010. Site B`s average concentration (7.8 µg/m^3) was 5 times greater than at Site A (1.5 µg/m^3 for Site A). The median concentration for Site B was 6 times greater compared to Site A while the range was 3 times greater.

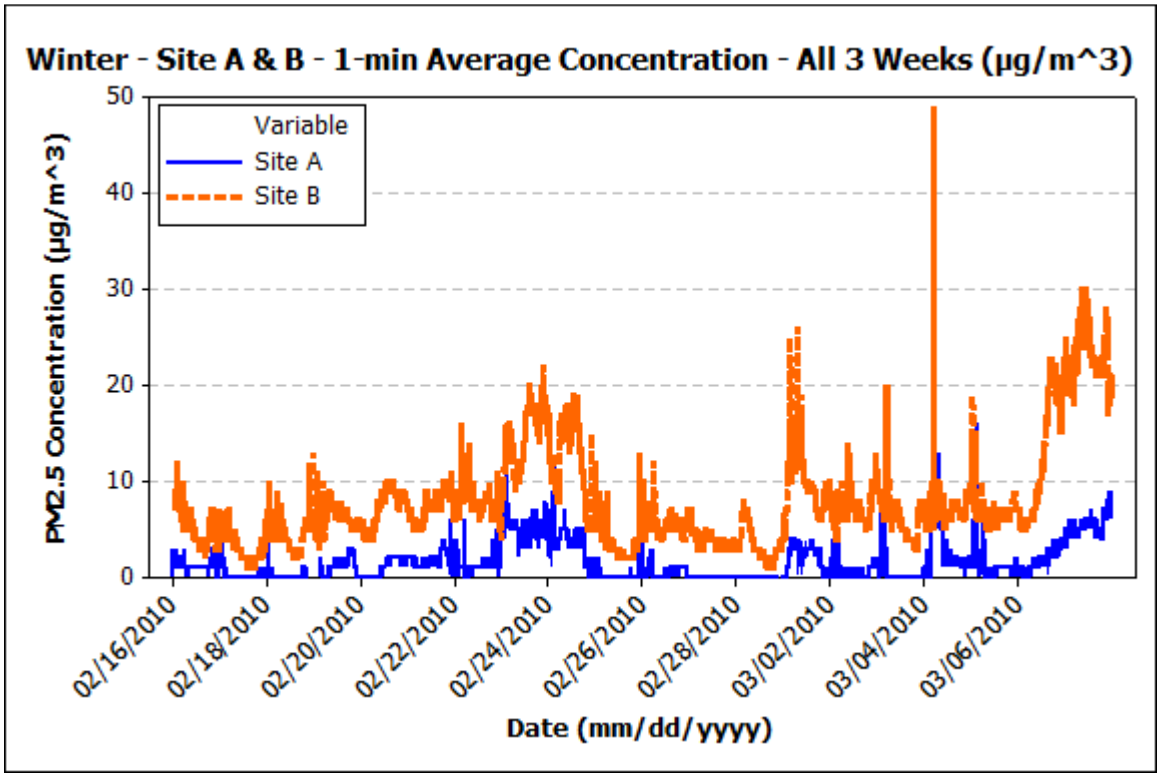

Figure 4-11: $PM_{2.5}$ concentrations during the winter 2010 campaign, Site A & B – indoor

Since the outdoor concentrations were not measured during the winter campaign, it is difficult to make a statement on the exact impact of the outdoor to indoor infiltration at either site. However, by comparing the winter results with those of the spring, the trend is similar. Site B concentrations were consistently greater compared to Site A. This could be attributed to greater outdoor infiltration. It is also evident that the CWS standard was not surpassed for either site.

Table 4-9: Winter - $PM_{2.5}$ 1-min average concentration ($\mu g/m^3$) Feb/16/2010 to Mar/08/2010

Campaign	Site	Location	Average	SD	Min	Median	Max	Range
Winter	Site A	Indoor	1.5	1.9	0	1	16	16
	Site B	Indoor	7.8	5.3	1	6	49	48

The Spearman correlations for the winter campaign are displayed in Table 4-10. A good correlation can be observed between the MoE and Site A hourly $PM_{2.5}$ concentrations. A strong correlation can be observed between MoE and Site B. This result is in-line with the spring results and it provides a strong argument for the hypothesis that a larger amount of outdoor air infiltrated Site B compared to Site A. However, caution should be used since the indoor $PM_{2.5}$ concentrations could largely be reflective of indoor activities rather than outdoor infiltration. This correlation analysis suggests outdoor air did influence the indoor concentrations, as expected. Comparing the actual magnitudes of the hourly concentrations between MoE and both sites is not recommended since the measuring methods were different and the sites did not have any outdoor monitors installed.

Table 4-10: Spearman correlations for winter campaign – hourly averages

	Site A (Indoor)	Site B (Indoor)
MoE	0.61 ($p<0.001$)	0.80 ($p<0.001$)

4.3. The influence of activity on $PM_{2.5}$

This section discusses the 1-min average $PM_{2.5}$ concentrations sorted by the Activity and No-Activity categories. Each 1-min entry was classified as either Activity or No-Activity. This was achieved by using the information provided from the schedules received from each school (Table 3-4). It was assumed that during school hours, the gyms were occupied unless the schedules clearly showed that no classes were scheduled during certain time periods. Tables 4-11 and 4-12 show the winter and spring campaign 1-min descriptive statistics classified by Activity and No-Activity for both sites. The 95th percentile values were used as max and not the largest actual concentration measured. This was done in order to avoid inconsistent spikes that might not reflect actual maximum concentrations derived by activity.

Table 4-11: Winter campaign 1-min average $PM_{2.5}$ concentration statistics for the activity and no-activity classifications

Location	Activity	N	Mean	SD	Min	Median	95th percentile
Site A	**Activity**	3950	1.8	2.3	0	1	5.5
	No Activity	24174	1.5	1.9	0	1	4.6
Site B	**Activity**	4813	7.5	3.7	2	6	13.0
	No-Activity	23707	7.9	5.6	1	6	17.1

Table 4-12: Spring campaign 1-min average $PM_{2.5}$ concentration statistics for the activity and no-activity classifications

Location	Activity	N	Mean	SD	Min	Median	95th percentile
Site A	**Activity**	3608	2.7	2.7	0	2	7.1
	No-Activity	24838	3.5	5.1	0	1	11.9
Site B	**Activity**	5713	7.5	3.7	1	7	13.6
	No-Activity	22849	10.9	11.1	1	7	29.1

During the winter campaign, Site A showed higher average and max concentrations during activity periods while the median concentrations were equal to that of no-activity periods. The median concentrations were the equal. The spring campaign results are not consistent with those of the winter, for Site A. The mean and max concentrations were higher during no-activity hours. However, the median concentrations were higher during activity hours. For Site A, it could be concluded that during the winter campaign the results were as expected, higher concentrations during activity hours. The results for the spring campaign are unexpected since the concentrations were greater during non-activity hours.

Site B showed higher concentrations during the no-activity periods during winter and spring campaigns for the mean and max. The median concentrations were equal during both campaigns for activity and no-activity. Although Site B's results are unexpected, they are consistent within both campaigns. One of the reasons that could explain this unexpected result would be if the custodian regularly ventilated the gym by opening the gym doors so that fresh unfiltered air could enter. The assumption is that he would have done so while nobody was in the gym (no-activity scheduled) since otherwise that would

have interfered with the classroom activities. This could explain why the no-activity concentrations were slightly higher compared to the activity ones.

It should be noted that if the mean concentrations are rounded to the nearest $\mu g/m^3$ for the winter campaigns, the concentrations would be identical at both sites, thus showing no significant increase in $PM_{2.5}$ concentrations during activity and no-activity periods for both sites. However, a two-sample t-test confirms that the means are statistically different at the 95% CI level for both sites ($p<0.005$).

During the spring campaign, the concentrations were greater during the no-activity periods for both sites. Based on these results it can be concluded that $PM_{2.5}$ levels decreased when activities were present inside those two school gyms. This sounds counter intuitive since activity leads to PM production. However, effective PM filtration of HVAC systems can lead to fast reduction of indoor PM levels. For future studies, more detailed information gathering is recommended. The counter intuitive observations could have resulted from the factors listed below:

- Lack of accurate records on the use of the gym. The researchers relied on the assumption that a scheduled gym class took place inside the gym, while it could have taken place outdoors.
- The assumption that there was a gym class scheduled during certain time periods. The opposite could also have been assumed, that there wasn't a gym class scheduled during all school periods.

- Lack of detailed information on the type of activity that took place (i.e., basketball vs. stretching) since some activities may have generated more PM compared to others.
- Lack of occupant count inside the gyms.
- Possible interference between activity and the HVAC system. The HVAC system theoretically brought in fresh air and removed stagnant air while activity was supposed to increase $PM_{2.5}$ concentrations. One phenomenon worked to counteract the other. It is unsure how much the HVAC has compensated for $PM_{2.5}$ production.
- Lack of information on the number of times the gym was ventilated by using outdoor air from having the gym doors open by the custodian.

4.4. Effects of heating, ventilating and air conditioning

The elementary school gyms were both heated and cooled by mechanical ventilation. The air-handling units were manufactured by Trane and are of similar specifications. The HVAC schedule for both sites was provided in Chapter 3. The analysis of the HVAC effects on indoor $PM_{2.5}$ concentration is very challenging because of the many logic operators attached to the HVAC programming and also due to the lack of detailed information on the number of persons in the gym and the gym internal temperatures. As mentioned in Chapter 3, the daytime heating setpoint was 21°C and the cooling 25°C. The nighttime setpoint was 18°C for heating and 30°C for cooling. Once the setpoint was reached, the units would normally turn off, unless the gym was occupied, at which point the units would continue to bring in fresh air. The fresh air amount depended on what the

units calculated as appropriate. Since there were no indoor air temperature sensors installed and there was no accurate description on how many people were present or the exact time when they were present, it was impossible to determine if the HVAC units were actually on or off. The analysis is based solely on the set schedule that was provided, fully acknowledging the units could have been on past the times they were scheduled. Tables 4-13 and 4-14 present the 1-min average $PM_{2.5}$ concentrations at Sites A and B for the winter and spring campaigns HVAC on/off schedules.

Table 4-13: Winter 1-min average $PM_{2.5}$ concentrations for HVAC

Location	HVAC	N	Mean	SD	Min.	Median	Max
Site A	**On**	10256	1.7	2.3	0	1	16
	Off	17868	1.4	1.7	0	1	7
Site B	**On**	11287	7.2	3.6	2	6	49
	Off	17233	8.3	6.2	1	7	30

Table 4-14: Spring 1-min average $PM_{2.5}$ concentrations for HVAC

Location	HVAC	N	Mean	SD	Min.	Median	Max
Site A	**On**	10580	2.1	2.4	0	1	32
	Off	17866	4.2	5.7	0	2	22
Site B	**On**	11329	7.5	4.6	1	7	30
	Off	17233	12	12.2	1	9	90

For the winter campaign Site A showed a higher average and max concentration when the HVAC system was on; the median concentrations were equal. Having a higher average and median concentration when the HVAC was on is expected since when the system was switched on activity was also expected. Although, this depended on the HVAC's efficiency of removing $PM_{2.5}$. During the spring campaign Site A showed higher average and median concentrations when the HVAC was off, however the max concentration was

highest during HVAC on hours. The results contradict those found for Site A during the winter campaign.

Site B showed a higher average and median concentration when the HVAC was off but the max concentration was highest with the HVAC on, for the winter campaign. Site B's spring results are consistent with those of the winter campaign, the average, median and max concentrations were highest during HVAC off hours.

When activity was present in the gym, the HVAC should have been on. However, when the HVAC was on, it didn't always mean that activity was present. The two factors, activity and HVAC, worked against each other. Activity is expected to raise the $PM_{2.5}$ concentrations but the HVAC could have potentially lowered them, since it was bringing fresh filtered air from the outside and removing and re-filtering air from the inside. Attributable to this contradictory interaction and the inability to isolate the two factors from each other, the HVAC explanations present challenges, more so for Site A where the results are different between spring and winter. Site B's results are at least consistent and could be interpreted differently. For Site B, it makes more sense to have higher concentrations when the HVAC was off. This would imply that outdoor air infiltrated in the building since it is known that outdoor concentrations were higher compared to indoor when nobody was in the gym. Thus, when higher $PM_{2.5}$ concentrated outdoor air infiltrated the building the concentrations increased.

Site B results contradict those found at Site A during the winter campaign. One possible explanation could be that of the location of the gym within the perimeter of the school. Site B showed higher Spearman correlations with the outdoor concentrations, thus when the HVAC system was off, a higher infiltration rate could be the cause of the increased concentrations during the HVAC off hours.

Site A's results could perhaps be justified by the activities associated with seasonal differences. For the spring, it is possible more activity took place outside the gym since the outdoor temperatures during spring were greater than the winter. Site A spring results are consistent with those of Site B for both campaigns.

Another possible HVAC explanation is the positive pressurization inside the gym. Building pressurization means the maintenance of a pressure differential between the inside and the outside of a building or between different areas within the building (Hitchcock et al., 2006). Positive pressurization is when the pressure inside the building is greater compared to the outdoor pressure. This prevents particles from entering the building. Site A could be designed differently and thus have a higher indoor compared to outdoor air pressure. Site B could have a lower indoor pressure (or negative pressurization) compared to the outdoors. The design and other characteristics of the building (including age) play important roles in building pressurization. If the washrooms, which tend to be designed to have a negative pressurization for the purpose of exhausting air, are placed close to other rooms, they tend to have a negative effect on the rooms` pressure. Site B`s gym was surrounded by the outdoors and had two doors

leading directly outside. Since the building age is significantly older compared to Site A, it`s unlikely the HVAC`s system would have been designed to keep a positive pressure inside the gym.

4.4.1. Detailed effect of HVAC

A secondary analysis was undertaken to examine if the effects of the HVAC could be isolated. The HVAC schedule indicated that the units were off all day on Sundays at both sites, provided the temperature setpoint was met and no activity was present (none was scheduled). The units turned on every Monday morning at 7 am. This analysis took a closer look at the time before the HVAC started and immediately after. It consisted of a closer examination between the hours of 5:30-8:30am on the Monday mornings of each campaign. Each campaign captured three Mondays, thus in total, 12 graphs were generated. The 1-min concentrations from Sites A and B of each Monday morning, during both campaigns are presented in Figs. 4-12 and 4-13.

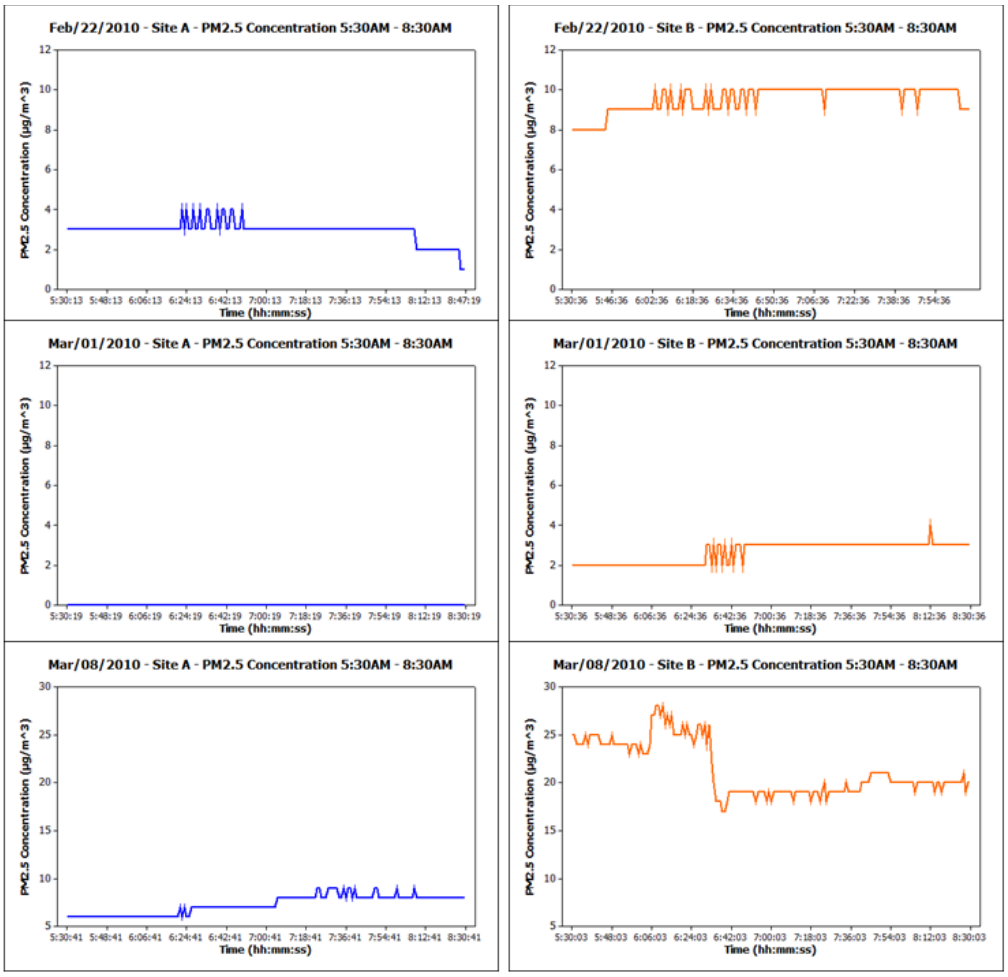

Figure 4-12: Winter campaign - $PM_{2.5}$ concentrations between 5:30 am to 8:30 am on Monday mornings

For winter, the HVAC units were set to start at 7 am after a weekend of having been turned off. No significant increase or decrease in concentrations can be observed to have occurred immediately before or after 7 am during the first two weeks. Based on Fig. 4-12, it cannot be concluded that the HVAC units had no reproducible effect on the indoor concentrations during the first two weeks. The largest change in concentration observed was 1 $\mu g/m^3$. In the last Monday of the winter campaign, Site B shows a sudden decrease in concentrations around 6:30 am. Site A shows an increase around the same time.

Based on the last Monday of the winter campaign, conflicting conclusions can be drawn about the HVAC removal of $PM_{2.5}$ concentrations at both schools.

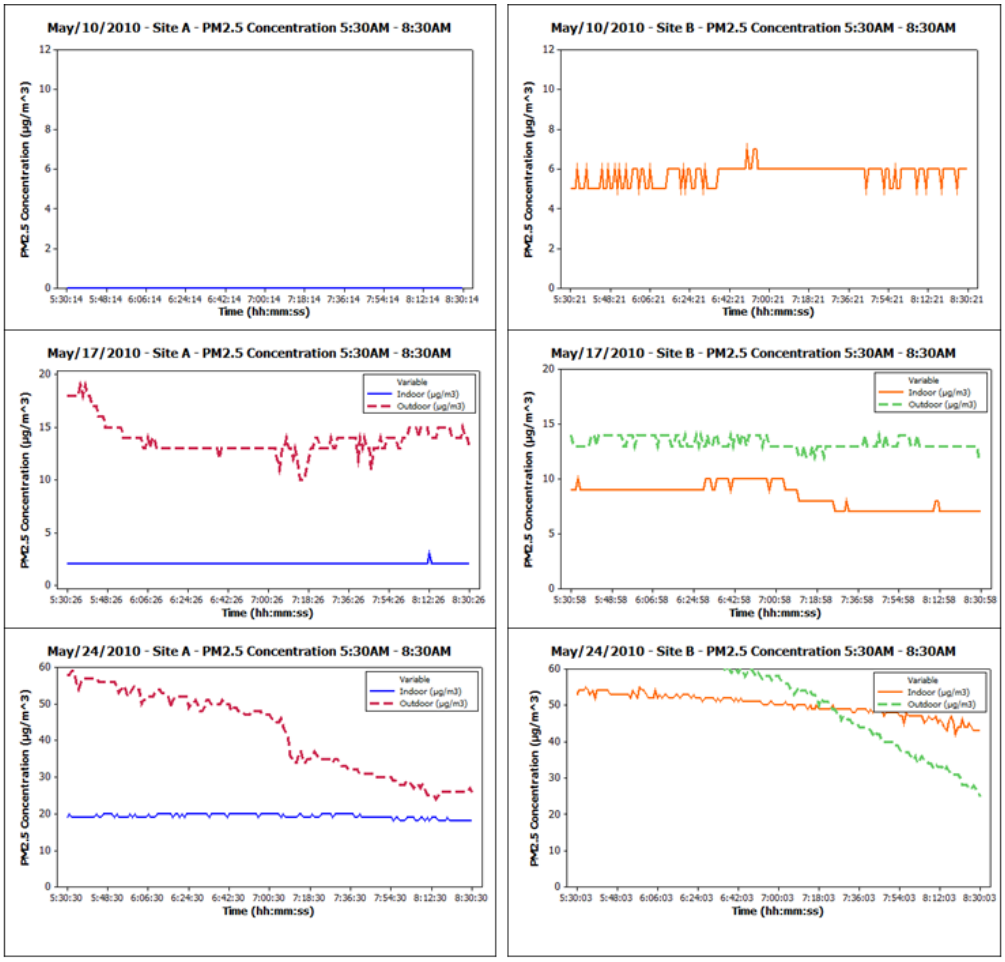

Figure 4-13: Spring campaign - $PM_{2.5}$ concentrations between 5:30 am to 8:30 am on Monday mornings

Figure 4-13 displays the $PM_{2.5}$ concentrations between 5:30-8:30 am at Sites A and B during each Monday of the spring campaign. The outdoor concentrations were also added for the last two Mondays. Site B`s May 17 and 24 graphs show slight drops in concentrations occurring after 7 am. Site A does not show any change, consistent with the winter results. While the outdoor concentrations also gradually drop on May 24, the rate at which Site B's concentration drops is much slower. Apart from the observation on

May 24, the rest of the concentrations appear to be constant. This could have been related to the setpoint settings of the HVAC units. It was assumed that they turned on at 7 am based on the schedules they were programmed. However, the setpoint logic indicates that if the setpoint was not matched, the units could have theoretically been running prior to 7 am in order to match the nighttime setpoint. If that was the case, the units could have either been running between 5:30-8:30 am or they could have been stopped. For future studies, it is recommended that data is gathered from the HVAC units themselves by the use of sensors which would indicate if the HVAC is on or off. Alternatively, temperature sensors could be placed inside the school gyms close to the HVAC air outlets. The second proposition will not be as accurate as the first, and will still depend on the researcher to analyze all other logic operators during the analysis. It would be simpler to just determine if the unit is on or off at any particular time.

4.5. Weekend and weekday $PM_{2.5}$ concentrations

The data was also classified as weekday and weekend. As mentioned, the weekday category was defined as starting on Monday at 7 am and ending on Friday at 8 pm partially based on the HVAC schedule. Tables 4-15 and 4-16 display the $PM_{2.5}$ indoor concentrations observed during these categories.

Table 4-15: Winter 1-min average $PM_{2.5}$ indoor concentration, weekday and weekend categories

Location	Category	N	N*	Mean	SD	Min.	Median	Max
Site A	**Weekday**	17552	416	1.6	2.1	0	1	16
	Weekend	10572	0	1.4	1.7	0	1	7
Site B	**Weekday**	17948	0	7.3	4.1	1	6	49
	Weekend	10572	0	8.7	6.8	1	6	30

Table 4-16: Spring 1-min average $PM_{2.5}$ indoor concentration, weekday and weekend categories

Location	Category	N	Mean	SD	Min.	Median	Max
Site A	**Weekday**	17874	2.4	2.5	0	2	32
	Weekend	10572	5.1	6.9	0	1	22
Site B	**Weekday**	17990	8.6	4.9	1	8	35
	Weekend	10572	13	15.0	1	5	90

The weekday sample size is almost double that of the weekend, since there are more week days compared to weekend days. During the winter campaign Site A`s average and max concentrations were greater in the weekday compared to the weekend. The median concentrations were the same. For the spring, Site A`s average was higher during weekends while the median and max concentrations were highest during the weekday. The results contradict each other.

Site B showed a greater average concentration during the weekends. The median concentrations were the same and the max concentration was greater during the weekdays. During the spring campaign, Site B showed similar results to those of the winter campaign, that is, a greater concentration during weekends. Overall, Site A showed inconsistent results between the two campaigns while Site B's results were more consistent. This is much like the previous sections, where Site A was also inconsistent between the two campaigns.

4.6. Effect of season on $PM_{2.5}$ concentrations

MoE – Hourly $PM_{2.5}$ concentrations winter and spring campaign

Figures 4-14 and 4-15 display the hourly $PM_{2.5}$ concentrations as observed at the MoE site during the winter and spring campaigns, respectively. Table 4-17 displays the hourly

statistics associated. Visually, one can observe that the spring concentrations are greater compared to the winter concentrations. The statistics confirm this with slightly higher mean and median concentrations during the spring.

Table 4-17: MoE hourly $PM_{2.5}$ concentrations (µg/m^3) winter and spring campaigns

Campaign	Site	Location	Mean	SD	Min	Median	Max	Range
Winter	MoE	Outdoor	3.7	3.3	0	3	17	17
Spring	MoE	Outdoor	5.8	6.1	0	4	53	53

$PM_{2.5}$ is not a pollutant whose concentration changes with each season. Thus, to make a statement about the meaning of the slightly higher spring concentrations observed, an in-depth $PM_{2.5}$ trend analysis for the London area should be undertaken. From the observed MoE concentrations, it should not be concluded that the differences of the indoor concentrations at both sites could be attributed to seasonal differences.

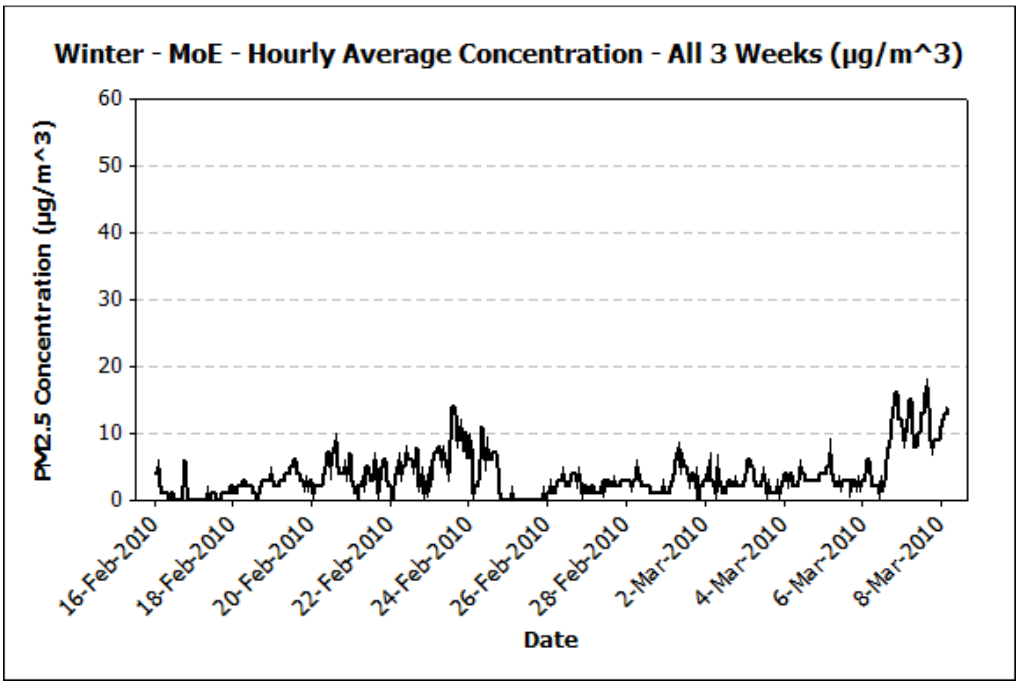

Figure 4-14: Winter campaign - $PM_{2.5}$ - MoE hourly concentrations

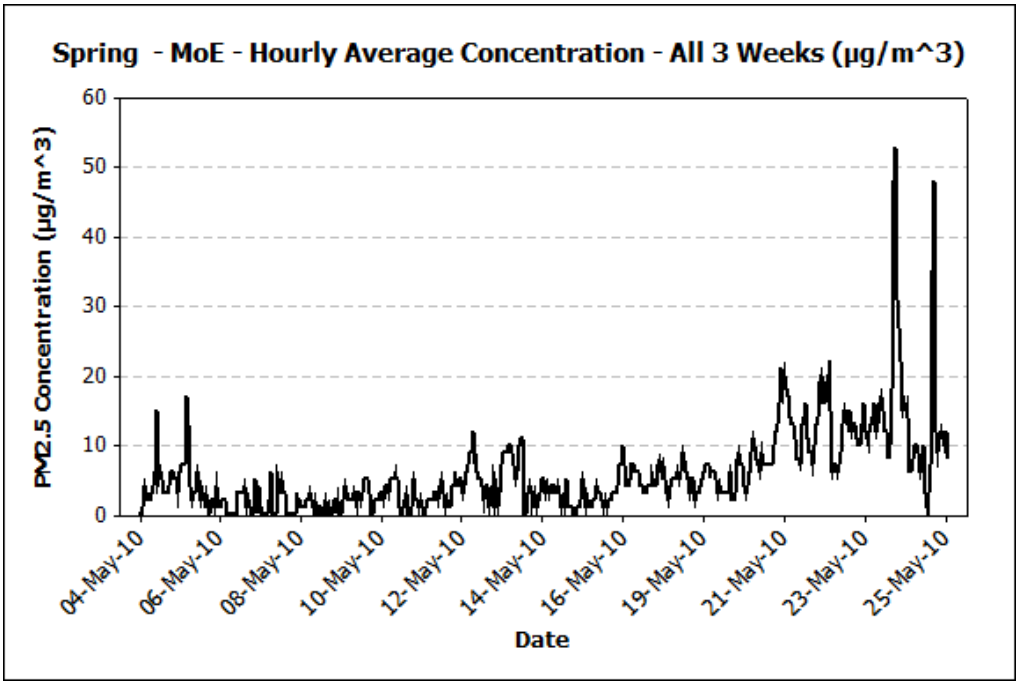

Figure 4-15: Spring campaign - $PM_{2.5}$- MoE hourly concentrations

4.7. Weekly NO_2 and $PM_{2.5}$ concentrations

The weekly NO_2 concentrations around Site A and Site B were measured using the Ogawa passive samplers as described in Chapter 3. Since the study used 33 NO_2 sites within three different areas of the city, only the NO_2 locations around a radius of 1.4 km from each site will be discussed. The results for the sites that were not within this radius are not discussed in this thesis. Within the radius selected, Site A was surrounded by 9 NO_2 sites and Site B had 12 usable NO_2 sites for the winter campaign and 10 for the spring. The average weekly concentrations were compared to the MoE site and the indoor and outdoor $PM_{2.5}$ concentrations as recorded by the DustTraks. Figures 4-16 and 4-17 show the results from the winter and spring campaigns for each site including MoE.

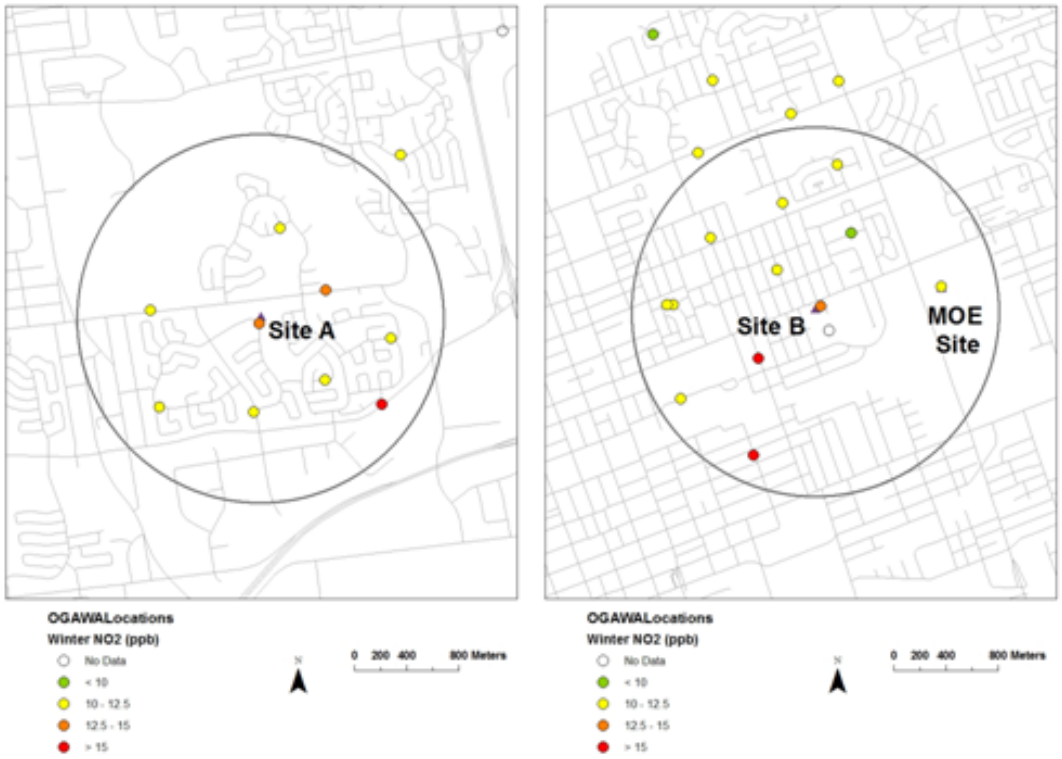

Figure 4-16: Winter Campaign - Site A & B - NO_2 average concentrations

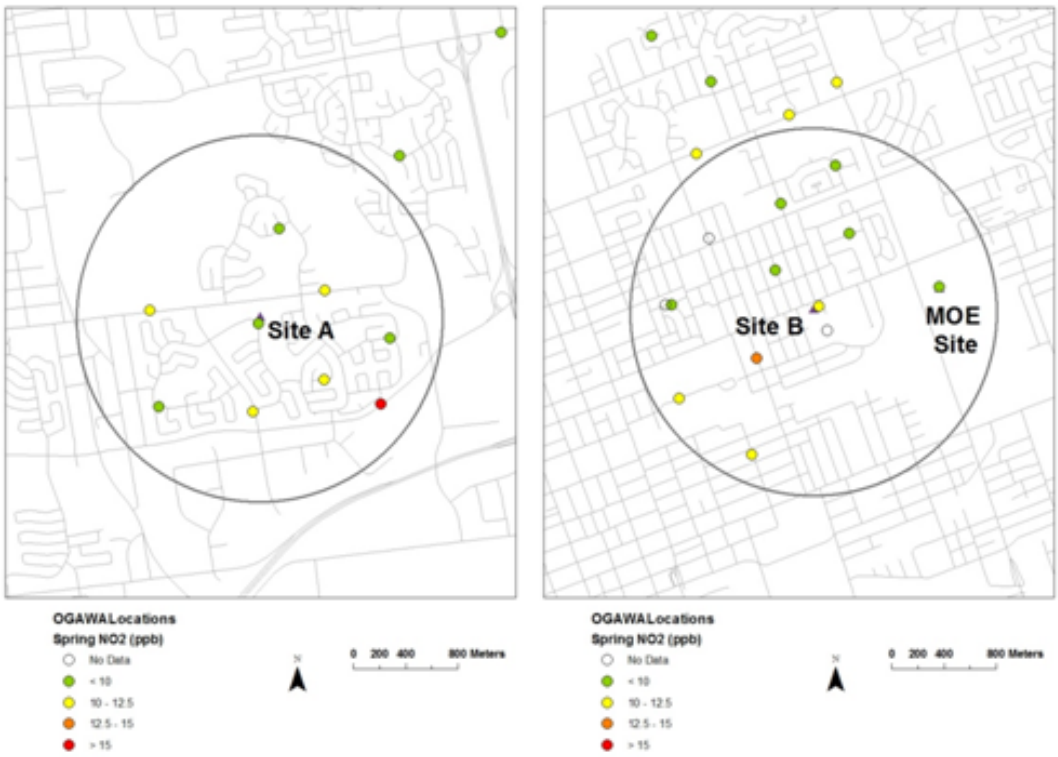

Figure 4-17: Spring Campaign - Site A & B - NO_2 average concentrations

The NO_2 concentrations for winter, spring and MoE are shown in Table 4-18. Site A showed higher NO_2 concentrations during both campaigns compared to Site B, opposite of the findings for $PM_{2.5}$ indoor and outdoor. However, statistically Site A and B's NO_2 concentrations are similar since a t-test shows the differences are insignificant. The MoE site NO_2 concentrations were lower compared to both sites. This could be attributed to the difference in the methodology used to measure NO_2. However, even though the concentrations were lower, the seasonal trend was the same. The spring concentrations were lower compared to the winter concentrations, consistent with the results at our sites. The MoE $PM_{2.5}$ trend was opposite to that of NO_2, concentrations were higher in the

spring compared to winter. From the results of our short term monitoring it can be said that NO_2 was not a good proxy of weekly $PM_{2.5}$ concentrations during the study periods.

Table 4-18: Winter and spring campaign NO_2 and $PM_{2.5}$ average concentrations in ppb and µg/m^3, respectively

	Site A NO_2	Site B NO_2	MoE NO_2	MoE $PM_{2.5}$	Site A $PM_{2.5}$ Indoor	Site A $PM_{2.5}$ Outdoor	Site B $PM_{2.5}$ Indoor	Site B $PM_{2.5}$ Outdoor
Winter	12.6	11.9	9.7	4.0	1.5	N/A	7.8	N/A
Spring	10.5	10.1	7.6	6.0	3.4	18.1	10.3	21.1

4.8. CO_2 concentrations and $PM_{2.5}$

CO_2 measurements were added for the spring campaign in an attempt to better identify if indoor activity in the gyms was present, separately from the schedules provided. In past studies CO_2 was used as an indicator of activities and number of people present in the room (Lee et al., 1999; Blondeau et al., 2005; Heudorf et al., 2009).

The 1-min CO_2 concentrations recorded during the spring campaign are displayed in Fig. 4-18. Site A showed a predominantly higher concentration compared to Site B and the outdoor site. Visually, a similar trend can be observed for Site A and Site B. Ideally, the level of CO_2 in the gyms should increase every time activity is present. This observation should have been independent of the outdoor CO_2 levels, as they were expected to vary little throughout the day. Although variation was observed at the two sites, as soon as the outdoor concentration was plotted, beginning on May 18, a different trend could be observed with the outdoor site.

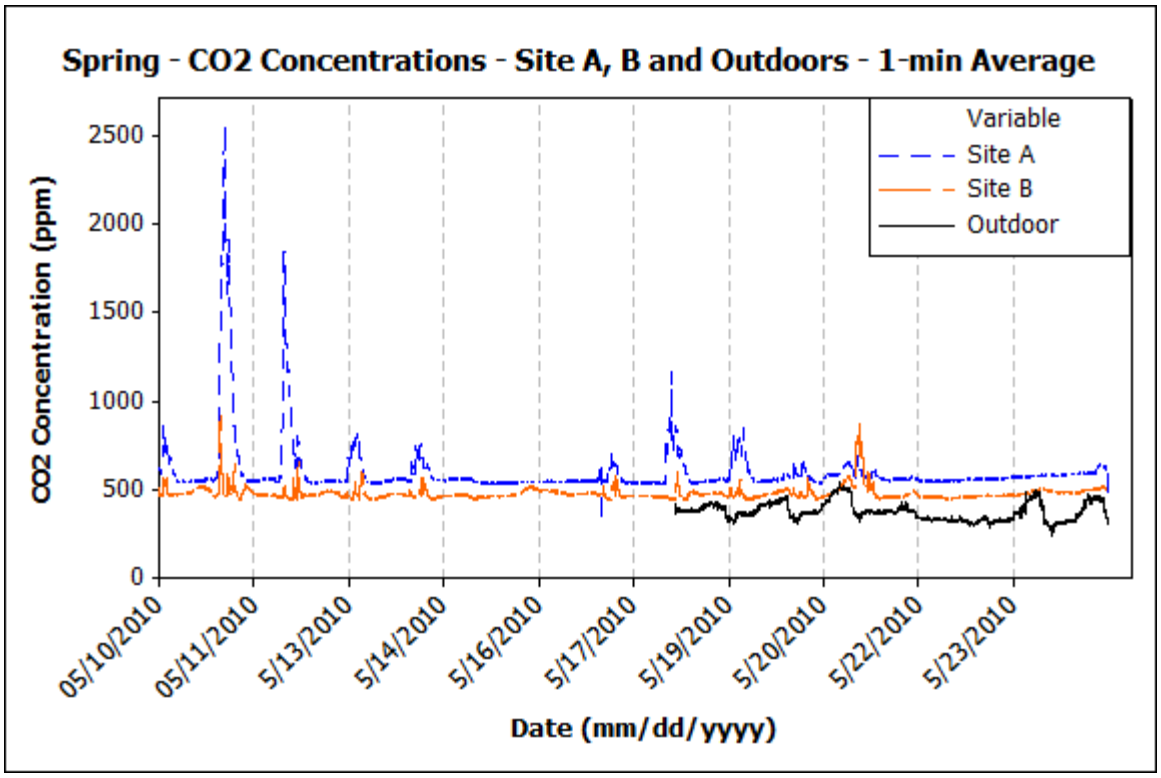

Figure 4-18: Spring - CO_2 concentrations vs. time

The descriptive statistics over the measured campaign are displayed in Table 4-19. The average over the studied period was approximately half of the critical value of 1000 ppm which is the commonly accepted upper limit for acceptable perceived indoor air quality as well as the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) critical value (ASHRAE, 2011). The CO_2 levels did exceed this critical value during three out of fifteen days at Site A. Site B`s levels did not exceed the critical value and the outdoor site was always lower than 600 ppm.

Table 4-19: Spring – CO_2 descriptive statistics (ppm)

Campaign	Site	Location	Mean	SD	Min	Median	Max	Range
Spring	Site A	Indoor	538	41	497	529	986	489
	Site B	Indoor	479	40	440	471	911	471
	Western	Outdoor	418	35	384	411	732	348

The R^2 between Site A and Site B was 0.24 (p<0.05), Site A and outdoor 0.09 (p<0.05), and Site B and outdoor 0.22 (p<0.05) (further shown in Chapter 4.10). These values might appear low after visually observing the time-series in Fig. 4-18. The low correlations are expected since the CO_2 levels are dependent on the activity and number of occupants at each site. An interesting observation is that the correlation between Site B and the outdoor site was almost 3 times greater when compared to the correlation between Site A and the outdoor site. A possible explanation could be that of a higher infiltration rate from the outdoor at Site B.

If we look at the concentrations from a weekday vs. weekend perspective, an interesting observation can be noted. The CO_2 levels "flat-line" during the weekend, which is consistent with a lack of activity based on the information in the schedules.

To show a stronger argument for CO_2 instrumentation, two days were chosen for further examination; Friday and Monday, May 21st and 24th respectively. Each graph displays the concentrations from 7 am to 8 pm. Friday May 21, was a regular school day with regularly scheduled activities and with the HVAC system scheduled to turn off at 8 pm. Monday, May 24 was a national holiday with no activities scheduled and the schools closed. Figure 4-19 shows the time series graph for Friday, May 21st. Large variation is observed at Site B and some variation is observed at Site A. The outdoor CO_2 levels drop during the early hours, much like the levels at both sites. Where the CO_2 levels remain constant at the outdoor site, the levels vary inside each gym before settling to relatively

constant readings after 6 pm. This is a clear observation of activity taking place inside the gyms.

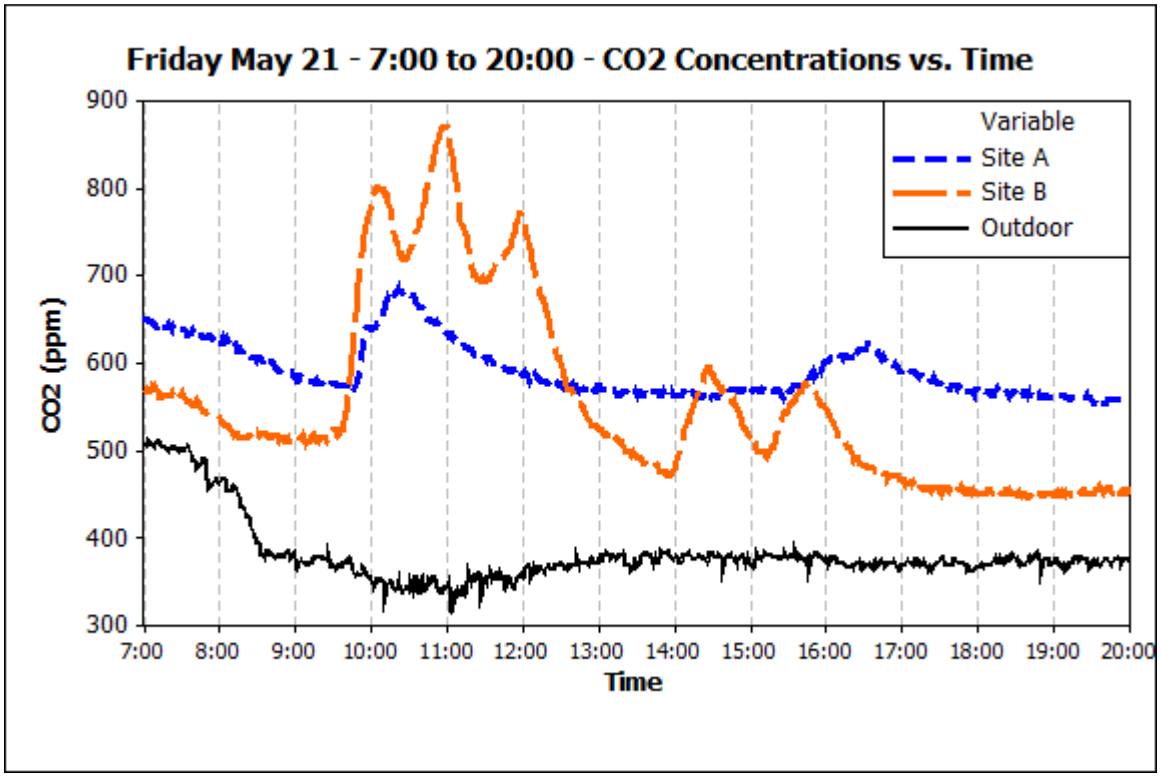

Figure 4-19: Friday May 21 - CO_2 concentration

Figure 4-20 shows the time series for Monday, May 24. Some variability is observed at the outdoor site, where the levels of CO_2 drop during the hours of the morning and then remain constant throughout the day. The levels inside the gyms remained constant. This is consistent with a lack of activity, which was expected since the schools were closed. Looking back at Fig. 4-18, it can be observed that night time CO_2 levels were slightly higher compared to daytime levels at the outdoor site. This is displayed in more detail in Fig. 4-21.

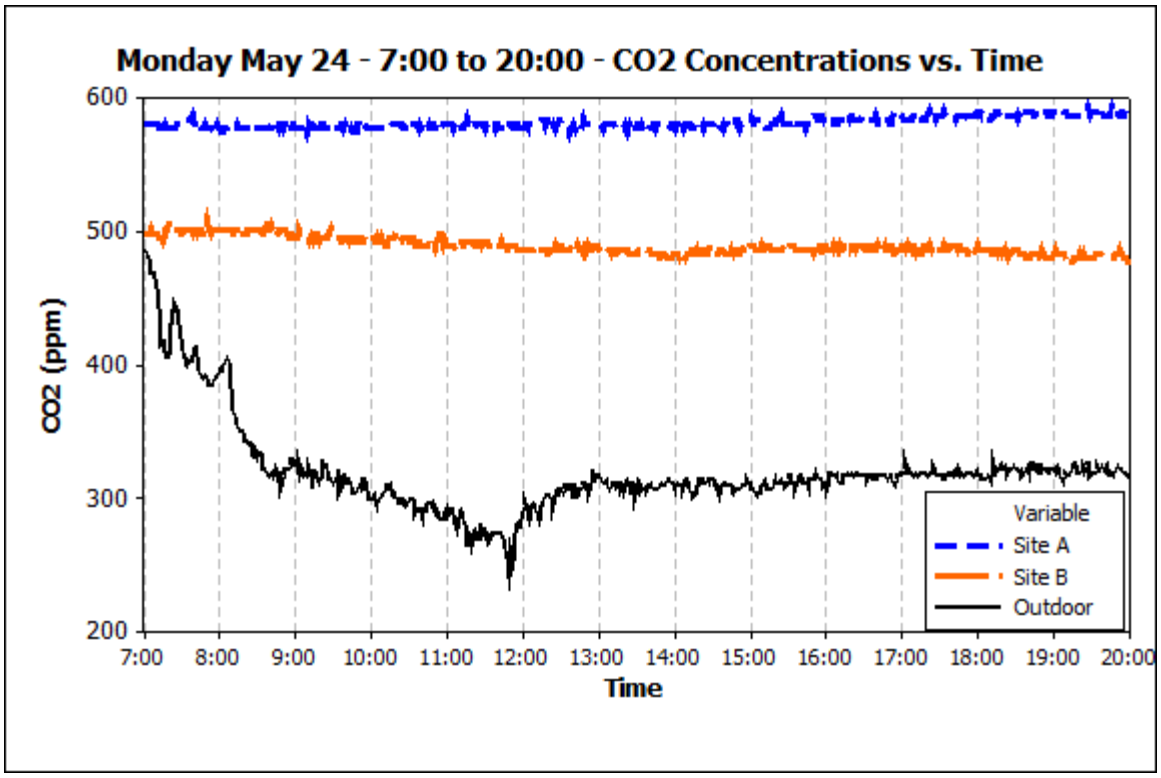

Figure 4-20: Monday May 24 - CO_2 concentration

To better illustrate the increase in CO_2 levels for the nighttime hours, Fig. 4-21 displays the CO_2 concentrations from 8 pm on Tuesday May 18 to 12 pm (noon) Wednesday May 19. It can be observed that the outdoor CO_2 levels gradually increase starting around 11 pm and decrease sharply around 8:30 am. The levels at both schools remain constant over the duration of the night and increase sharply around 9:30 am, an indication of activity inside the gyms.

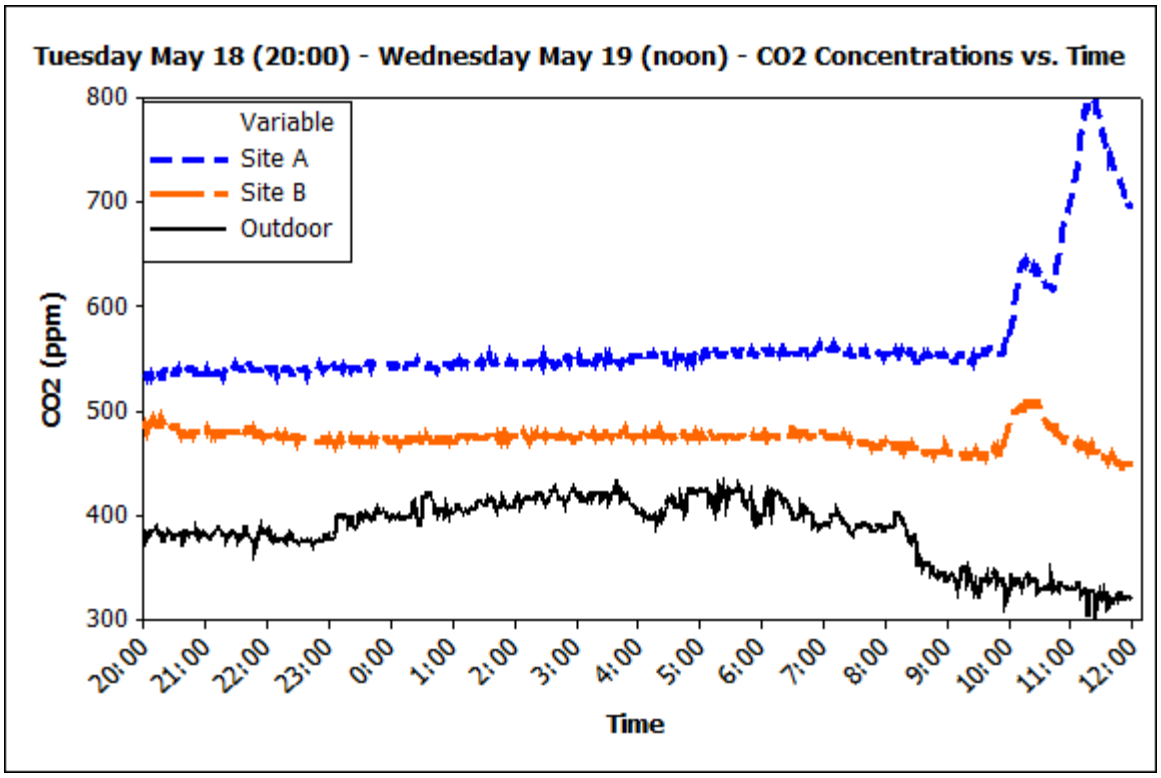

Figure 4-21: Tuesday May 18 to Wednesday May 19, CO_2 concentrations

When the 1-min concentrations of CO_2 are checked for correlations against $PM_{2.5}$ during the entire period they were both simultaneously running in the gyms, the results show weak correlations. The correlations between CO_2 and $PM_{2.5}$ at Site A and B were 0.06 and 0.05 respectively (p>0.05). Thus it cannot be concluded that an increase in CO_2 resulted in an increase in $PM_{2.5}$.

This part of the results supports that CO_2 instrumentation can be used as an identifier of activity in an indoor environment. Ideally, it would have been better if a total person count was also recorded. Although the instruments did not show the same CO_2 magnitudes, a change in the level could still be used to signal activity which was part of the objective of this study. It is unclear why the concentrations did not equal during

nighttime periods and no-activity or occupancy present. However, even though the magnitudes of the concentrations were not equal, the instruments consistently displayed the same trends when they were paired together in the inter-instrument variability tests.

4.9. A high $PM_{2.5}$ concentration episode on firefighters day

The $PM_{2.5}$ concentrations recorded during the first week at Site A revealed unusually high concentrations on Friday February 19, 2010. Upon investigation, it was discovered that Site A had a Firefighter demonstration day in the gymnasium the entire day. The city of London firefighters hosted a show and tell session which was performed during different times of the day. It consisted of multiple presentations and smoke demonstrations. Figure 4-22 shows the 1-min $PM_{2.5}$ concentrations during that day.

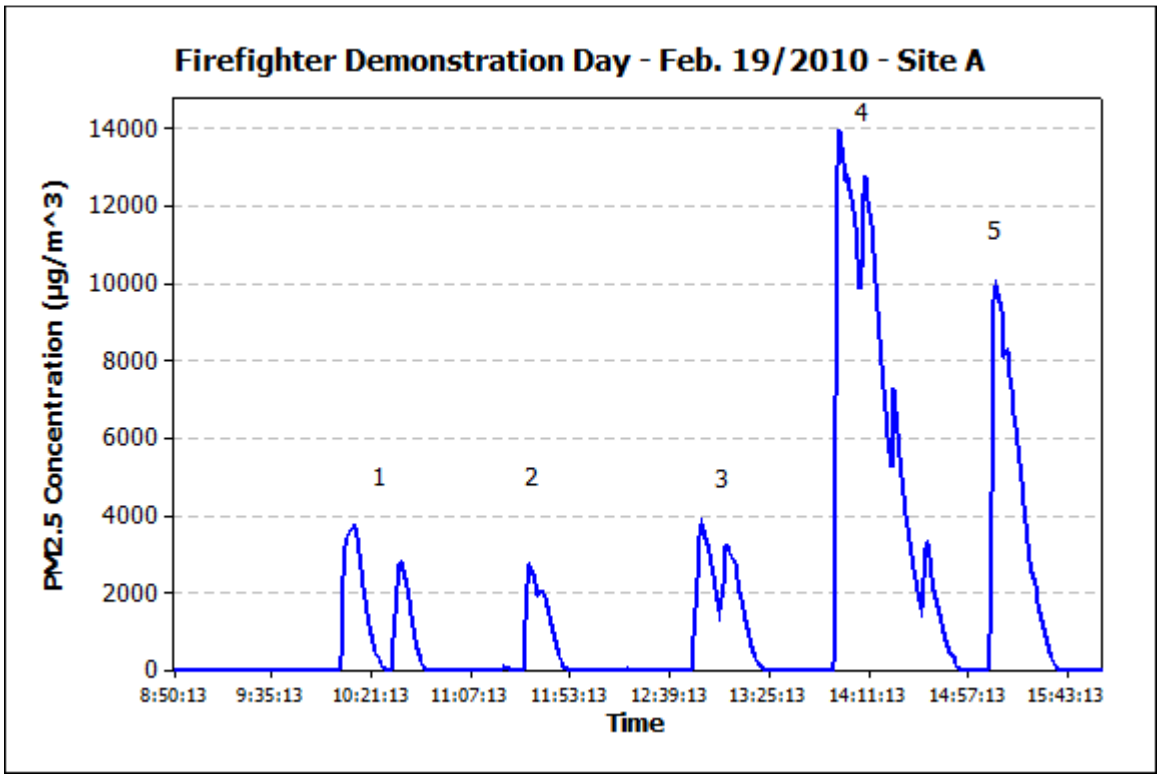

Figure 4-22: Site A indoor $PM_{2.5}$ concentrations during Firefighter demonstration day – Feb/19/2011; Five different episodes are observed

The concentrations peaked around 14,000 μg/m^3, with regular episodes all greater than 2,000 μg/m^3. Without having further details other than the fact that firefighters were present and used smoke as demonstration, five different episodes can be observed during morning, noon, afternoon intersession and the end of school day. After the peak of the last episode, around 15:10, the concentration dropped and stabilized around 1 μg/m^3, consistent with much of the concentrations observed during the winter campaign. Due to the lack of detailed information, after examining the school day's concentration profile, it was decided that episodes 1 and 3 should be dropped out of the production and elimination rate calculations because it appears that multiple smoke demonstrations were released. Episodes 2, 4 and 5 are discussed in greater detail. Figure 4-23 displays the concentrations profile during episode 2 as an example. The production and elimination concentration profiles were regressed against time. The data had a greater agreement with a linear model compared to a first-order exponential rate. Appendix G contains detailed graphs for all three episodes.

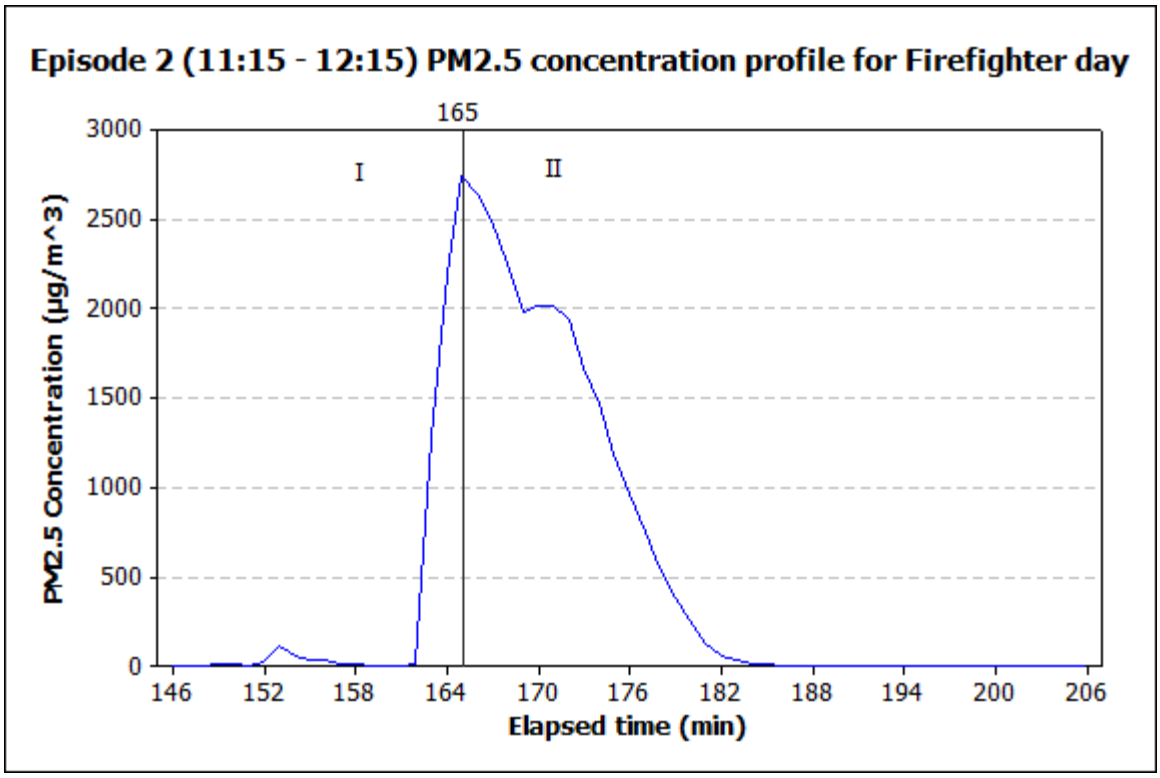

Figure 4-23: Episode 2 of the Firefighter day $PM_{2.5}$ concentration profile identifying the production and elimination areas.

"I" stands for phase I (one) which identifies the $PM_{2.5}$ production and ends when the concentration peaks at 2742 µg/m^3. "II" stands for phase II (two) which identifies the $PM_{2.5}$ elimination.

Production rate

The production rates for $PM_{2.5}$ were calculated for each episode and are displayed in Table 4-20. The highest production rate of 68 µg/m^3 s was observed during episode 4. It is challenging to comment on the production rates since no studies have been found that observed production rates during firefighter smoke demonstrations. Compared to the Evans et al. (2008) study which reports the production rates of $PM_{2.5}$ (0.13 µg/m^3 s) while cooking indoors, these rates are two orders of magnitude greater. This is not unexpected since dense smoke filled some part of the room during the event at a much faster rate than

reported in Evans et al.'s study. The productions rates in the current study were within the same order of magnitude and consistent within a factor of 7. The time it took for the concentrations to reach the 90 and 95% peak rates were similar.

Table 4-20: $PM_{2.5}$ production rates on Firefighter day

Episode #	Production Rate ($\mu g/m^3$ s)	Time to 90% Peak (sec)	Time to 95% Peak (sec)	R^2
2	10	192	205	0.88
4	68	166	177	0.92
5	47	173	184	0.94

Elimination rate

The elimination rates for $PM_{2.5}$ were calculated for each episode and are displayed in Table 4-21. The fastest elimination rate was observed during episode 5. The rates are all within the same order of magnitude and one order less than the production rates.

Table 4-21: $PM_{2.5}$ elimination rates on Firefighter day

Episode #	Elimination Rate ($\mu g/m^3$ s)	Time to 90% Elimination (sec)	Time to 95% Elimination (sec)	R^2
2	2.1	1082	1147	0.91
4	4.1	2800	2970	0.93
5	5.6	1623	1567	0.95

The firefighter demonstration day proved that the low concentrations observed at Site A were not attributed to instrument error but rather to the site's indoor conditions and that the instrument can respond to high concentrations when exposed. The instrument used at Site A was clearly capable of detecting a high range of concentrations, had they been present. The event also shows the efficiency of the HVAC for removing particles

The event was eliminated from the overall analysis because of two reasons. 1) it was not a regularly scheduled activity, thus students' exposure to this type of high level

concentration in school gyms is no more than once per year if at all, and 2) its undue influence on the overall campaign's mean and median concentrations as demonstrated in Table 4-22. When the entire data set was tested, with the event and without, the t-test showed the two sets were statistically different.

Table 4-22: Winter campaign – Site A – $PM_{2.5}$ Concentration ($\mu g/m^3$) statistics with and without the Firefighter event

	N	Mean	SD	Median
All days	28540	24.3	404	1
Firefighter Day	416	1566	2972	8
All days excluding Firefighter Day	28124	1.5	2.0	1

4.10. $PM_{2.5}$ concentration - results of regression modeling

Regression analysis was used to investigate the relationship between hourly indoor $PM_{2.5}$ concentration and indoor CO_2 and outdoor $PM_{2.5}$. Since data for both factors together was only available during the last two weeks of the spring campaign, only that data set was used.

A correlation matrix was first calculated to determine whether 1) the independent variables are correlated with the dependent variables, and 2) the independent variables are collinear or correlated with each other. When two or more independent variables in multiple regressions are correlated, it is described as multicollinearity. This can cause challenges when trying to draw inferences about the relative contribution of each predictor variable to the overall success of the model. The independent variables selected were $PM_{2.5}$ outdoor and CO_2 indoor. The correlation matrices for Sites A and B are presented in Tables 4-23 and 4-24, respectively.

Table 4-23: Correlation matrix for Site A variables (hourly)

	$PM_{2.5}$ Indoor	$PM_{2.5}$ Outdoor
$PM_{2.5}$ Outdoor	0.711 (p<0.001)	
CO_2 Indoor	0.037 (p<0.481)	-0.115 (p=0.03)

Table 4-24: Correlation matrix for Site B variables (hourly)

	$PM_{2.5}$ Indoor	$PM_{2.5}$ Outdoor
$PM_{2.5}$ Outdoor	0.643 (p<0.001)	
CO_2 Indoor	0.091 (p<0.085)	-0.022 (p<0.672)

At both sites, the $PM_{2.5}$ outdoor concentrations were correlated to $PM_{2.5}$ indoor. Multicollinearity was not observed between the predictor variables since the CO_2 indoor concentrations were not correlated to indoor $PM_{2.5}$. The final regression models were generated using indoor $PM_{2.5}$ as a predictor, as shown in Table 4-25. Appendix H provides the coefficients and ANOVA results for the regression model for indoor $PM_{2.5}$ concentrations at Sites A and B.

Table 4-25: Linear regression models for indoor $PM_{2.5}$ at Sites A & B

Location	Regression Model
Site A	$(PM_{2.5})_{Indoor} = 0.863 + 0.239*(PM_{2.5})_{Outdoor}$ $R^2 = 50.5\%$
Site B	$(PM_{2.5})_{Indoor} = 7.13 + 0.322*(PM_{2.5})_{Outdoor}$ $R^2 = 41.3\%$

As seen in Table 4-25, 40-50% of the variation in indoor $PM_{2.5}$ can be explained by outdoor concentrations. These values could be considered to represent a fair prediction of the indoor concentrations by the regression models. When comparing the R^2 values from both sites, a 10% difference is observed. Accordingly, Site A's R^2 value would suggest that its model produced a better fit. This is contrary to the Spearman correlations, which showed a greater correlation at Site B with the outdoor concentrations

(Table 4-18). The positive coefficients indicate indoor $PM_{2.5}$ concentrations increase with increasing outdoor levels. Between the two sites, Site B had a larger intercept and a larger outdoor coefficient compared to Site A. This result suggests higher indoor concentrations at Site B compared to Site A when outdoor levels are the same, which is consistent with higher concentrations observed at Site B (Tables 4-6 and 4-7), and with the I/O ratio which was greater for Site B.

4.11. Overall results summary

The results from this thesis show that overall the indoor and outdoor $PM_{2.5}$ concentrations did not exceed or equal that of the CWS at any point during the monitored campaigns. The indoor $PM_{2.5}$ concentrations were lower compared to all of the studies discussed in Chapter 2. The DustTrak, compared to gravimetric methods tends to overestimate the concentrations it reports. Therefore, when a DustTrak reports a low concentration, it is truly a low concentration. In that regard, Site A concentrations were low by any current standard, which is a positive result for air quality. Site B's concentrations were well below the CWS.

Table 4-26 summarizes the effects of different factors on the observed indoor $PM_{2.5}$ concentrations at the two sites during the winter and spring campaigns. The outdoor vehicle traffic count did not influence the indoor concentrations. The building characteristics, specifically the location of the gym within the building, may have decreased the concentrations at Site A and increased them at Site B. Activity showed decreases in concentrations at Site B but mixed results for Site A. HVAC was found to

decrease concentrations. Seasonal differences, in particular the warmer season, and outdoor $PM_{2.5}$ had an increasing effect on indoor concentrations while NO_2 and CO_2 did not have a significant effect on indoor $PM_{2.5}$ concentrations at both sites.

Table 4-26: Summary table for the effects of different factors on indoor $PM_{2.5}$ concentrations

Variable	Site A – Indoor $PM_{2.5}$	Site B – Indoor $PM_{2.5}$
Outdoor Vehicle Traffic	None	None
Building Characteristics	-	+
Activity	+ Winter; - Spring	-
HVAC	-	-
Seasonal Differences (warmer season)	+	+
NO_2	None	None
CO_2	None	None
Outdoor $PM_{2.5}$	+	+

"-" represent a decrease in indoor PM2.5 concentrations
"+" represents and increase in indoor PM2.5 concentrations

The results of lower indoor concentrations would suggest the ventilation of the gyms using unfiltered outside air should be omitted as much as possible. Another indirect observation suggests that a gym that is placed in the center of a building (e.g., Site A) creates an improved building envelope compared to one that has its walls surrounded by the outdoors (e.g., Site B). However, if more time is spent in classrooms each day, it would be beneficial to place the classrooms in the center of the schools since $PM_{2.5}$ concentrations could be lower. Both sites showed comparable outdoor $PM_{2.5}$ concentrations regardless of the fact that one site had double the AADTC. Regional sources appeared to have been most responsible for the overall outdoor $PM_{2.5}$ concentrations, suggesting that in London, the location of the school within the city was perhaps less important than the physical characteristics, such as roads and traffic, of the location.

The study accomplished its primary objectives of determining the concentrations in one type of micro environment, the elementary school gymnasium. It also showed the methodology used was successful at reporting $PM_{2.5}$, NO_2 and CO_2 concentrations. The study also reported some of the weaknesses and possibilities for improvement in the methodology for future studies.

CHAPTER 5 - CONCLUSION AND RECOMMENDATIONS

5.1. Conclusions

This thesis presents the results of indoor $PM_{2.5}$ air quality at two sites in London ON and the effects of activity, outdoor concentrations and other factors. The monitoring campaigns were undertaken during the winter and spring of 2010. Based on the analysis undertaken, the following conclusions can be drawn:

- The methodologies used for determining $PM_{2.5}$, NO_2 and CO_2 concentrations with accuracy, are able to be used in future studies to collect the respective pollutant information.
- Based on hourly and 1-min averages, $PM_{2.5}$ concentrations were higher outdoors compared to indoors during the last two weeks of the spring campaign when indoor and outdoor concentrations were measured at each site using the same methods. This was likely due to low indoor sources, HVAC filtration and good building impermeability.
- The hourly $PM_{2.5}$ concentrations inside the schools did not surpass the Canada Wide Standard of 30 $\mu g/m^3$ during any 24-hr period at both locations.
- Site B`s results show that $PM_{2.5}$ mean concentrations were higher during No-Activity times compared to Activity for both campaigns. Thus, for Site B, PM production was not linked to Activity. Site A`s results show that mean concentrations were higher during Activity times in the winter campaign and lower in the spring campaign compared to No-Activity.
- The indoor $PM_{2.5}$ concentrations at Site B were greater compared to Site A's during both campaigns and they were significantly different from each other

meaning the two sites were not equally affected by the outdoor concentrations which were similar at both sites.

- The I/O median concentration ratios for the spring campaign were 0.25 and 0.7 for Site A and B, respectively; an indication that Site B's $PM_{2.5}$ concentrations are more influenced by the outdoors.
- The outdoor $PM_{2.5}$ spring concentrations at each site showed strong correlations with each other and good correlations with the MoE site (r_s=0.80 and 0.82 for Site A and MoE and Site B and MoE, respectively). Indicating a strong regional influence for $PM_{2.5}$.
- The spring campaign's indoor concentrations were greater compared to those of the winter. This is consistent with the outdoor MoE concentrations which were greater during the spring.
- The outdoor NO_2 concentrations from the sites surrounding the schools followed the same trend as the MoE site but overall they followed an opposite trend compared to $PM_{2.5}$ concentrations for the two campaigns. Therefore, outdoor NO_2 concentrations were not a good indicator of weekly $PM_{2.5}$ concentrations.
- Indoor CO_2 monitors were useful in showing that activity was present inside the school gyms. This methodology can be used in future studies to identify gym occupancy.
- The largest observed factor for indoor $PM_{2.5}$ was outdoor concentration, based on the hourly regression analysis for the spring campaign.

5.2. Recommendations

Based on the analysis of the study, the following recommendations are made for similar future studies:

- The logging of indoor activities in the gymnasium needs to be monitored with methods other than what the school regularly tracks. This method could consist of a separate log sheet. The log sheet could be attached to the entrance of the gym, and each teacher would have to fill out the activity that is taking place, the number of persons in the room and the times when they entered and left. Such detailed information and log sheet, were not available and were not implemented in this study.
- The HVAC system needs to be monitored based on actual on/off inputs. It is challenging to find if the HVAC is actually running based solely on the logic parameters in its controller.
- Indoor Relative Humidity measurements are necessary if a comparison between indoor $PM_{2.5}$ concentrations and outdoor $PM_{2.5}$ concentrations recorded by a TEOM instrument is required. This is imperative if comparisons other than trends are required, such as magnitude for example.
- Detailed planning for the installation of each monitoring instrument needs to be addressed well before the start of sampling. Some instruments have special requirements and cannot be placed indoors or outdoors without previous consideration as to their exact installation position.

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APPENDIX A

Federal Reference Method

$PM_{2.5}$ definition

The scientific definition of $PM_{2.5}$ is based on the particle size-selection characteristics of the Well Impactor Ninety-Six (WINS) Impactor. This type of impactor must be used downstream of the USEPA developed first stage inlet. The full schematics of the proprietary inlet are available in the Federal Register Appendix L pp. 66 – 84. (USEPA, 1997).

Design criteria

It was decided that in order for independent manufacturers to be able to meet the design criteria, the specifications should be provided in the FRM. The components of a typical sampler include the first stage filter, the second stage separator (WINS), the upper filter holder, the filter cassette and the filter support screen. Figure A-1 shows a schematic diagram of a single-channel $PM_{2.5}$ FRM sampler.

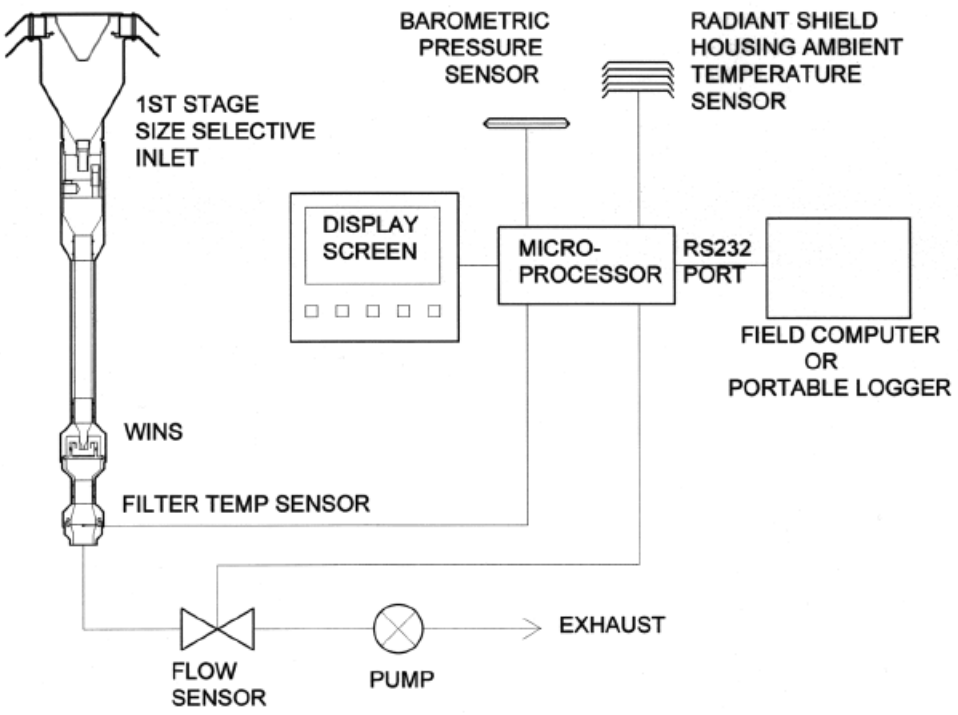

Figure A-1: Schematic diagram of a single-channel $PM_{2.5}$ FRM sampler (Source USEPA, 1997)

Performance criteria

The FRM specifies strict guidelines and controls as well as the range of precision and accuracy of these controls. The flow rate must be 16.67 lpm. The volumetrically controlled flow rate must have a precision of 5% and accuracy of 2%. The flow control must be upgraded at the minimum every 30 seconds and logged every 5 minutes. The measurements must be made on the same schedule as barometric pressure, ambient temperature and filter temperature. The filter temperature must not exceed the ambient temperature by more than 5°C for more than 30 minutes. The instrument must provide accurate performance over a temperature range from -20° to 40°C, and it must function in temperatures as low as -30°C.

Candidate instruments must be subjected to rigorous test protocols involving environmental test chambers. A 10 day minimum field trial is required and must contain three candidate collocated instruments at a field site. The concentrations must be collected above 10 $\mu g/m^3$ with a precision of less than 2 $\mu g/m^3$. Each instrument must include an RS232 port for the purpose of data extraction to a portable computer or data logger. Data must also be able to be recorded by hand, thus the instruments must have a display screen.

Single and sequential filter samplers

The method provides for sequential filters in order to permit the gathering of data on continuous run days without the need to locate two samplers at the same site and attend to them seven days per week. The sequential samplers must meet the criteria of single filter samplers and contain an additional mechanism that automatically changes the filter. Each time a filter is changed a new data gathering cycle must be initiated.

Sampling protocols

Each filter must be removed from the field within 96 hours after the 24-hour completion of a run. Thus on a sequential filter sampler, filters must be serviced every four days. The 96-hour maximum time allowed is to minimize the potential for mass change in the deposited particulate matter.

$PM_{2.5}$ Federal Equivalent Method (FEM) samplers

The regulations tabulate the aerodynamic size selection curve of the WINS impactor and require that any equivalent $PM_{2.5}$ sampling device must have a 50% penetration value of 2.5 ± 0.2 μm. The sampling bias for $PM_{2.5}$ concentrations must be less than ± 5%. The sampling bias is calculated numerically for three generalized ambient aerosol size distributions (fine, typical and coarse) which are also defined in the regulations. The measured characteristics of any alternative sampling device can be tested against these criteria to determine whether its performance meets the requirements. Further tests that require that i) the candidate sampler continues to meet the standard after loading with dust, and ii) give comparable results to a reference sampler under field conditions, are established.

APPENDIX B

2010 London Children's Activity and Exposure Study
Weekly Instrument Logsheet
DustTrak (Particle Size 2.5 μm)

Unit ID: _____ Operator's Initials: _____

Location of sampling: _____

Start Date (dd/mm/year): _____ Start Time: _____ EST □ DST □

Shutting down & Downloading Data

Logging data & conc. (mg/m3)	Connections	Battery (%)	Shutdown date & time	Data Download File Name	Instrument Clock (EST)*
Recording Yes ☐ No ☐ Conc.:			Date (dd/mm/year): Time (EST):	 Data Looks Normal ☐	Actual Time: Instrument Reading: Time offset (+/-): Time adjusted? No ☐ Yes ☐
Comments:					

Cleaning/Calibration and Redeployment Phase (note new ID if applicable)

Cleaning and Calibration Date (dd/mm/year): _____

Flow Rate (LPM)	Weekly Maintenance	Final Checks	Connection	Logging & conc. (mg/m3)
Before Adjustment	Cleaned & Regreased ☐ Zero filter reading:	Interval Time: 1 min ☐		Re-Start Time:
After Adjustment ☐ No adjustment	Calibration needed Yes ☐ No ☐ Zero filter reading:	Memory: 100% ☐ Battery (%):		Re-Start Date: Recording ☐ Conc:
Comments:				

APPENDIX C

Inter-instrument Comparisons

$PM_{2.5}$ instruments

Inter-instrument comparisons were performed pre and post study campaigns. The winter campaign used only two DustTraks®, coded DT1 and DT2, while the spring campaign used the same instruments during the first week and added two more instruments during the last two weeks of measurements.

The winter pre and post campaign inter-instrument comparison data sets were joined into one file in order to eliminate having two sets of correction factors for each campaign. For example, the winter campaign had one set of measurements before the start of the campaign and one set after the end of the campaign. This data was joined into one file because the concentrations observed were very similar, and one correction factor was calculated. Both sets of data (pre and post measurements) were acquired from measurements taken from a lab within the University of Windsor. The winter graph is displayed in Fig. 3.4.

Table C-1 shows the statistics from the joined set of measurements. “N” represents the number of 1-min measurements. SD is the standard deviation and LOD stands for limit of detection. As it can be observed, the mean % difference is slightly greater after the study period compared to before, as expected. The non-bias mean % difference was calculated using the formula provided in equation (1).

Table C-1: Winter descriptive statistics for the $PM_{2.5}$ inter-instrument variability tests pre-study and post-study, LOD in µg/m^3

Statistics	Pre-Testing		Post-Testing	
	DT1	DT2	DT1	DT2
N	405	405	504	504
Min	15	16	15	16
Median	19	20	19	21
Max	33	37	27	29
Mean	21.0	22	20.0	22
SD	5.6	6.2	5.1	5.5
LOD	17	19	7	7
Mean % Difference	7.5		11.6	

Figure C-1 shows the DT1 concentration vs. the average of the two instruments during the winter campaign. The y-intercept in the original regression formula was very small (i.e., less than 0.2 µg/m^3) and therefore the regression line was forced through (0,0). Thus, all DT1 (Site A) concentrations were multiplied by a factor of 1.051 or, in other words, increased by approximately 5%.

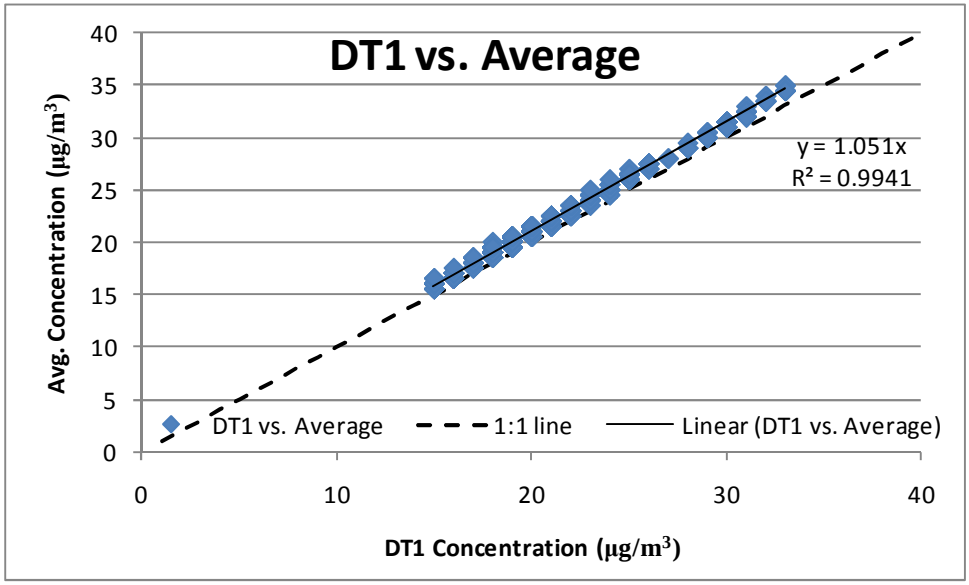

Figure C-1: Winter correction factor from inter-instrument variability test

During the spring campaign, two more DustTraks were added for the last two weeks of testing, they were coded DT3 and DT4. Due to unforeseen shipping issues, the two extra instruments arrived late, thus they could not be compared before the start of the campaign along with the two original DustTraks used during the winter campaign. Post-campaign, all instruments were set to measure and record the indoor concentration in the same lab used during the winter campaign, at the University of Windsor. The pre spring campaign inter-instrument variability between DT1 and DT2 was not used, because data for all four instruments was not available. However, the pre-study spring comparison graphs between DT1- DT2, and DT3 - DT4 are displayed in Figures C-2 and C-3 respectively.

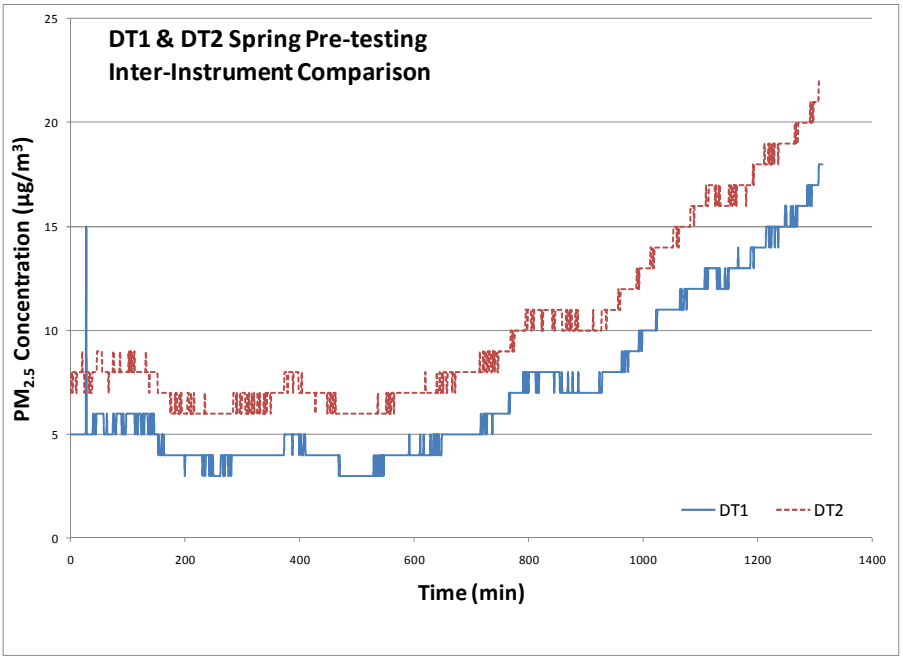

Figure C-2: Spring $PM_{2.5}$ pre-study inter-instrument comparison DT1 and DT2

From Fig. C-2 it appears the difference between DT1 and DT2 is close to 3 $\mu g/m^3$ which is less than the difference observed in the post instrument comparison. The DT1 concentrations were consistently lower compared to DT2 throughout the study. The

mean concentration difference in the inter-instrument comparisons ranged from 1 – 5 $\mu g/m^3$ between the two instruments.

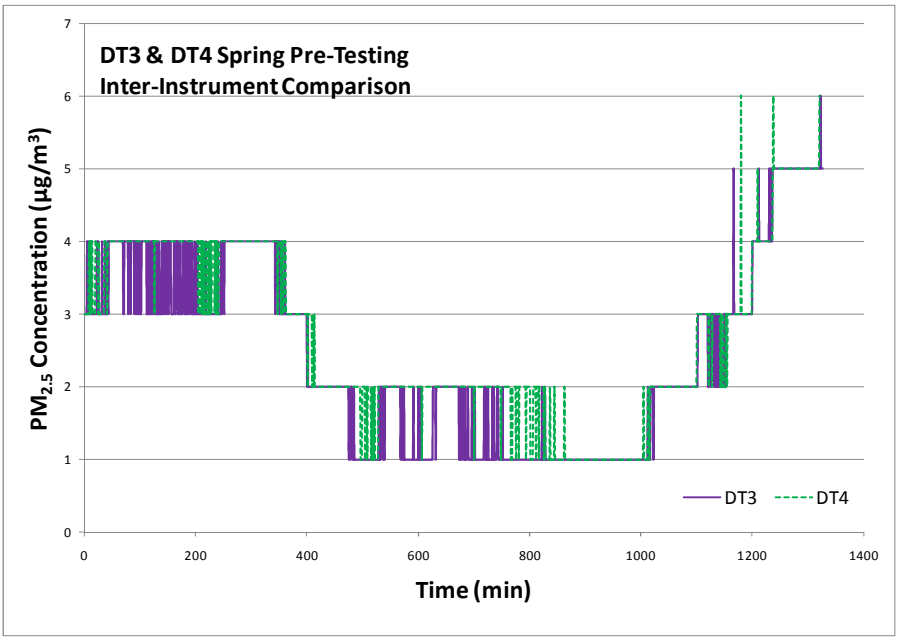

Figure C-3: Spring $PM_{2.5}$ pre inter-instrument comparison DT3 and DT4

Figure C-3 displays the pre-campaign comparison graph for instruments DT3 and DT4. Apart from a few spikes in the concentrations, the instruments appear to record the same concentration. This is consistent with the post-campaign results. The mean difference between the two instruments was 1 $\mu g/m^3$ during both pre and post campaign comparisons.

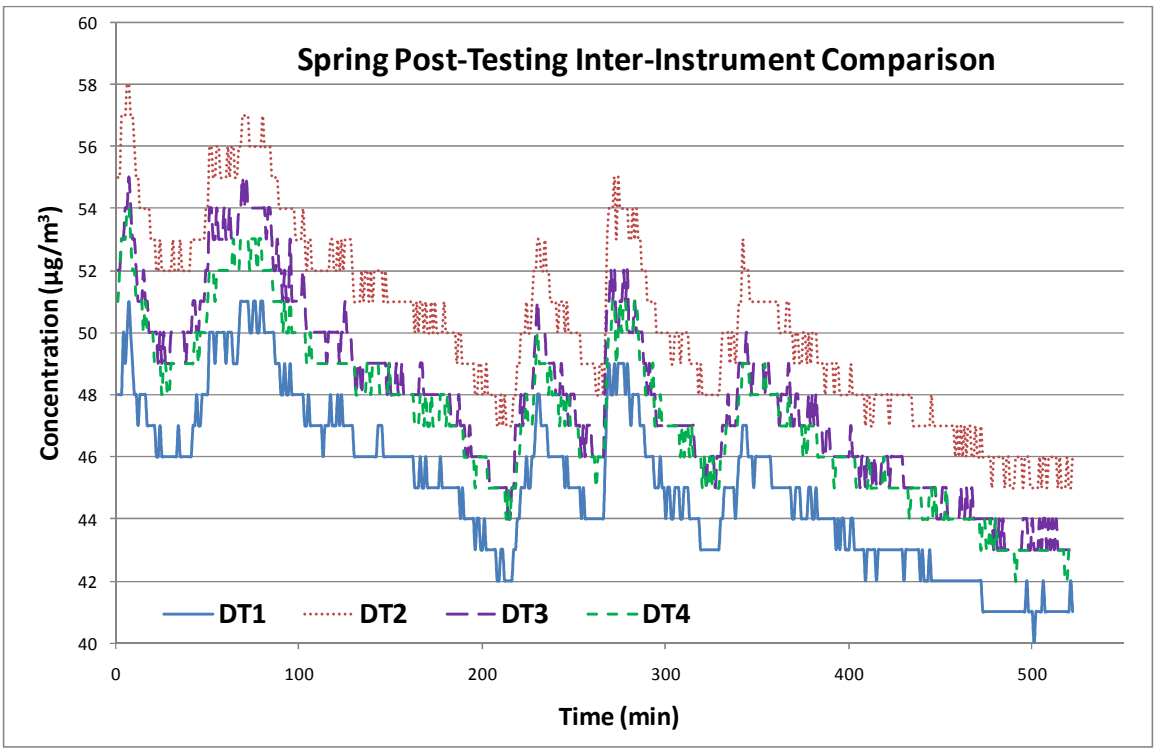

Figure C-4: Spring campaign, post study $PM_{2.5}$ inter-instrument comparison

Table C-2 displays the descriptive statistics of the four instruments for the measurements taken post spring campaign. Concentrations from instruments DT3 and DT4 were in between the concentrations recorded by DT1 and DT2 as can be observed in Fig. C-4. The mean % difference between DT1 and DT2, which were used for the indoor measurements, was close to 11%, consistent with the post-testing winter campaign. The mean % difference for units DT3 and DT4, which were used for outdoor measurements, was closer to 1%. It is unsure why there was such a difference between the two sets of instruments, likely to be attributed to internal differences and calibration factors as well as hours of operation after factory calibration. The instruments used for outdoor measurements (DT3 and DT4) were received from Health Canada, and it is unclear as to

their exact calibration date. However, they were calibrated within 2 months prior to campaign usage.

Table C-2: Spring descriptive statistics for the $PM_{2.5}$ post campaign inter-instrument variability test with N=522, units in µg/m^3

Statistics	Post-Testing			
	DT1	DT2	DT3	DT4
Min	40	45	43	42
Median	45	50	48	47
Max	51	58	55	54
Mean	45	50	48	47
SD	3.0	3.0	3.0	3.0
LOD	8.0	9.0	9.0	8.0
Mean % Difference from DT3	6.0	5.0	-	1.2

The methodology for determining the correction factor for the spring campaign was similar to that of the winter campaign. Since the median and mean concentrations for instruments DT3 and DT4 were approximately equal to the average of the four instruments, as can be observed from Table C-2, it was decided to choose the higher concentration of the two, DT3, as the reference concentration. Thus, all other instruments were corrected to the DT3 values. An identical method was used for deriving the correction factors from the regression analysis, as in the winter campaign. All $PM_{2.5}$ correction factors are presented in Tables 4-1 and 4-2.

CO_2 monitors

The inter-instrument comparison concentrations are presented in Fig. C-5 and the descriptive statistics of the tests in Table C-3. Similar to the methodology used for the $PM_{2.5}$, C03 was chosen as the reference since the median and mean concentrations for

instrument C03 are approximately in the middle (Table C-3). The CO_2 correction factors are presented in Table 4-3.

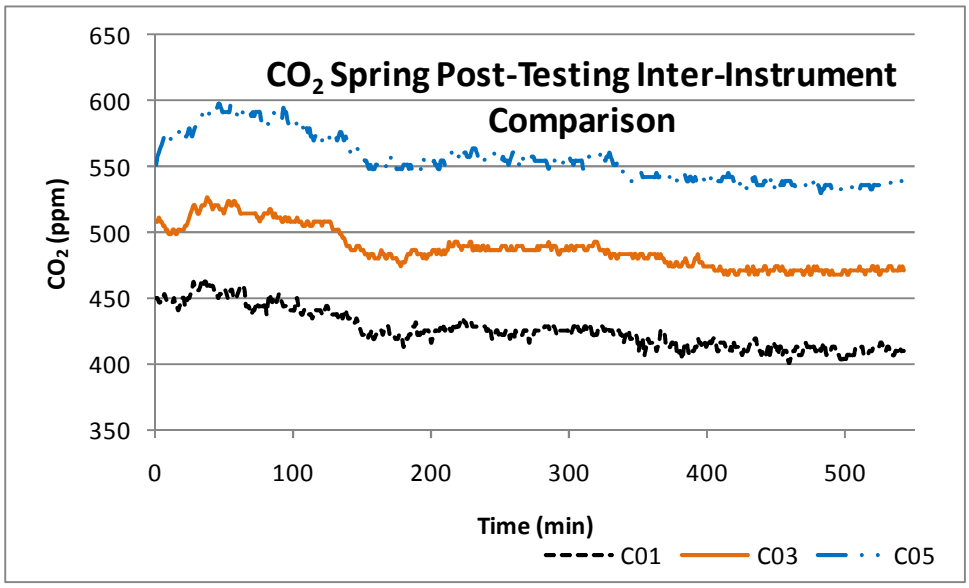

Figure C-5: Spring campaign, CO_2 post study inter-instrument comparison, concentration vs. time

Table C-3: Spring statistics for CO_2 inter-instrument variability test with N=583, units in ppm

	Post-Testing		
Statistics	**C01**	**C03**	**C05**
Min	16	15	19
Median	422	483	551
Max	466	527	598
Mean	402	463	520
SD	96	107	134
Range	450	511	579

APPENDIX D

London Children's Activity and Exposure Study Spring 2010
OGAWA LOG SHEET

Site ID:_____ **Start Date (dd/mm/yyyy):**_____

Operator's Initials Setup:_____ **Takedown:**_____

Same Location As Last Time: ☐ **Pole ID:** _____

Coordinates Setup	**GPS Unit ID No:**	**UTM Coordinates:**
	Waypoint ID:	**Estimated Accuracy:**
***Street Address**	**Same Address As Site List:** ☐	
Description*	**Same Description As Site List:** ☐	

**Either write down or use the check box, but not both*
***Describe exact location so that it could easily be found by another technician, and take a few pictures*

Ogawa Passive Sample

Pollutant	Label ID	Start Time* (hh:mm)	Stop Date (dd/mm/yyyy)	Stop Time* (hh:mm)	Comments:
NO_2					

** local time in military format, e.g. 7:00, 14:00*

Blank ID (as applicable)

Label ID	Comments

APPENDIX E

HVAC Setpoint Information and Site A HVAC Performance Specifications

On Tu! e, 30 Nov 2010 11:48:17 -0500 "Homm, Peter" wrote:

> > The units will always maintain a heating and cooling setpoint. The daytime heating setpoint is 21C, cooling is 25C. This means that the units will come on until setpoint is met, then turn off unless gym is occupied. The night setback is 18C heat, 30C cool. There is filtration on the units, outdoor air intake is through dampers from 20% minimum fresh air up to 100% when required by setpoint.

> > Peter

Ordering Number Summary

Option Description	Part Number
1st Year Labor Warr Whole Unit	2705-1000-01-00

Unit Performance

Tagging:
BSS-AHU-1

Description	Value	Unit of Measure	Source
Base Unit			
Solution number	1.00	Each	PRODSEL
Design airflow	6000	cfm	PRODSEL
Total preheat capacity	302.20	MBh	PRODSEL
Preheat EAT	45.00	F	PRODSEL
Preheat LAT	91.44	F	PRODSEL
Preheat ent fluid Temp	180.00	F	PRODSEL
Preheat lvg fluid temp	160.00	F	PRODSEL
Preheat delta T	20.00	F	PRODSEL
Preheat flow rate	30.18	gpm	PRODSEL
Preheat fluid PD	2.79	ft H2O	PRODSEL
Preheat coil face velocity	484	ft/min	PRODSEL
Preheat fluid freeze pt	32.00	F	PRODSEL
Elevation	0.00	ft	PRODSEL
ESP	1.00	in H2O	PRODSEL
TSP	1.44	in H2O	PRODSEL
Actual motor power reqd	3.383	hp	PRODSEL
Fan speed	753	rpm	PRODSEL
Preheat APD	0.13	in H2O	PRODSEL
Filter/Mixing section APD	0.31	in H2O	PRODSEL
Face & bypass section APD	0.00	in H2O	PRODSEL
Outlet velocity	2360	ft/min	PRODSEL
Full load amps	14.20	A	PRODSEL
Max fuse size	30.00	A	PRODSEL
Min circuit ampacity	17.75	A	PRODSEL
Unit length	69.250	in	PRODSEL
Unit width	68.220	in	PRODSEL
Unit height	82.000	in	PRODSEL
Installed weight	1154.4	lb	PRODSEL
Rigging weight	1135.2	lb	PRODSEL

APPENDIX F

$PM_{2.5}$ Concentration Distribution Analysis

Appendix F was used solely to show the data did not follow a normal distribution throughout the campaign. The AD co-efficient refers to the respective distribution from the distribution column. The statistical software used (Minitab) does not provide a *p*-value for certain types of distribution curves. The AD coefficients are arranged in an ascending order, from smallest to largest. As mentioned in Chapter 3, the smaller the AD value and the greater the *p*-value, the better the data fits the particular distribution. The critical values for the AD test are dependent on the specific distribution that is being tested. The *p*-value was used to accept or reject the null hypothesis of the data belonging to a particular distribution. As can be observed, most data do not follow a normal distribution, whereas lognormal distribution is a better fit in some cases.

Spring Campaign

Table F-1: MoE hourly spring distribution identification for $PM_{2.5}$ concentrations

Distribution	Anderson Darling Co-efficient	P-value
3-Parameter Lognormal	4.501	*
3-Parameter Loglogistic	4.660	*
Largest Extreme Value	7.763	<0.010
Logistic	16.083	<0.005
2-Parameter Exponential	19.235	<0.010
Normal	30.758	<0.005
3-Parameter Gamma	62.5	*
3-Parameter Weibull	64.527	<0.005
Smallest Extreme Value	89.818	<0.010

* *p*-values not available

Table F-2: Spring Site A indoor hourly distribution identification for $PM_{2.5}$ concentrations

Distribution	Anderson Darling Co-efficient	P-value
Largest Extreme Value	35.983	<0.010
Logistic	42.093	<0.005
3-Parameter Gamma	50.045	*
Normal	52.818	<0.005
Smallest Extreme Value	64.154	<0.010
3-Parameter Weibull	67.033	<0.005
3-Parameter Loglogistic	70.396	*
3-Parameter Lognormal	76.566	*
2-Parameter Exponential	147.057	<0.010

* *p*-values not available

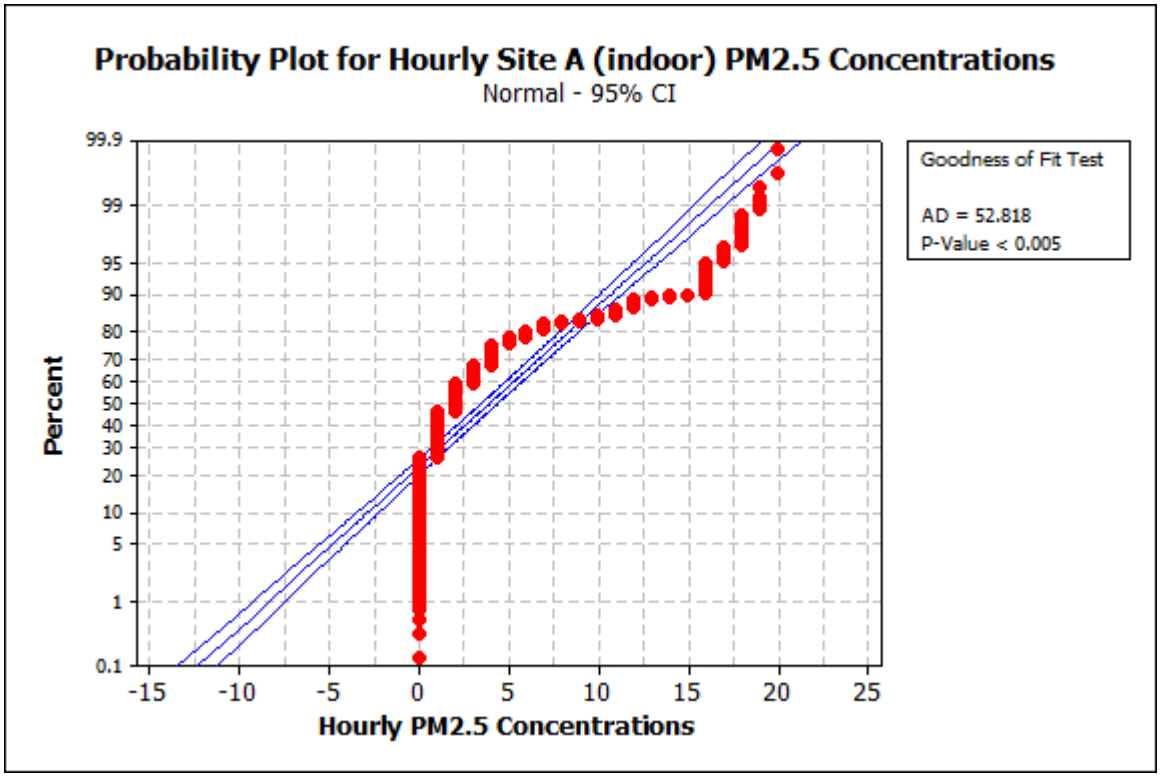

Figure F-1: Cumulative probability distribution plot and Anderson-Darling statisitic for Site A – indoor, Spring

Table F-3: Spring Site A outdoor hourly distribution identification for $PM_{2.5}$ concentrations

Distribution	Anderson Darling Co-efficient	P-value
3-Parameter Loglogistic	1.766	*
3-Parameter Lognormal	1.999	*
Normal	2.267	<0.005
Lognormal	2.267	<0.005
Loglogistic	2.338	<0.005
2-Parameter Exponential	4.691	<0.010
3-Parameter Gamma	4.954	*
3-Parameter Weibull	4.968	<0.005
Gamma	6.961	<0.005
Weibull	7.762	<0.010
Exponential	11.824	<0.003
Largest Extreme Value	12.908	<0.010
Logistic	18.927	<0.005
Smallest Extreme Value	48.643	<0.010

* *p*-values not available

Table F-4: Spring Site B indoor hourly distribution identification for $PM_{2.5}$ concentrations

Distribution	Anderson Darling Co-efficient	P-value
3-Parameter Loglogistic	4.173	*
Loglogistic	4.334	<0.005
3-Parameter Lognormal	4.359	*
Lognormal	5.266	<0.005
3-Parameter Gamma	10.702	*
3-Parameter Weibull	10.983	<0.005
2-Parameter Exponential	13.345	<0.010
Gamma	14.772	<0.005
Weibull	15.870	<0.010
Exponential	19.386	<0.003
Largest Extreme Value	23.426	<0.010
Logistic	33.324	<0.005
Normal	47.291	<0.005
Smallest Extreme Value	72.459	<0.010

* *p*-values not available

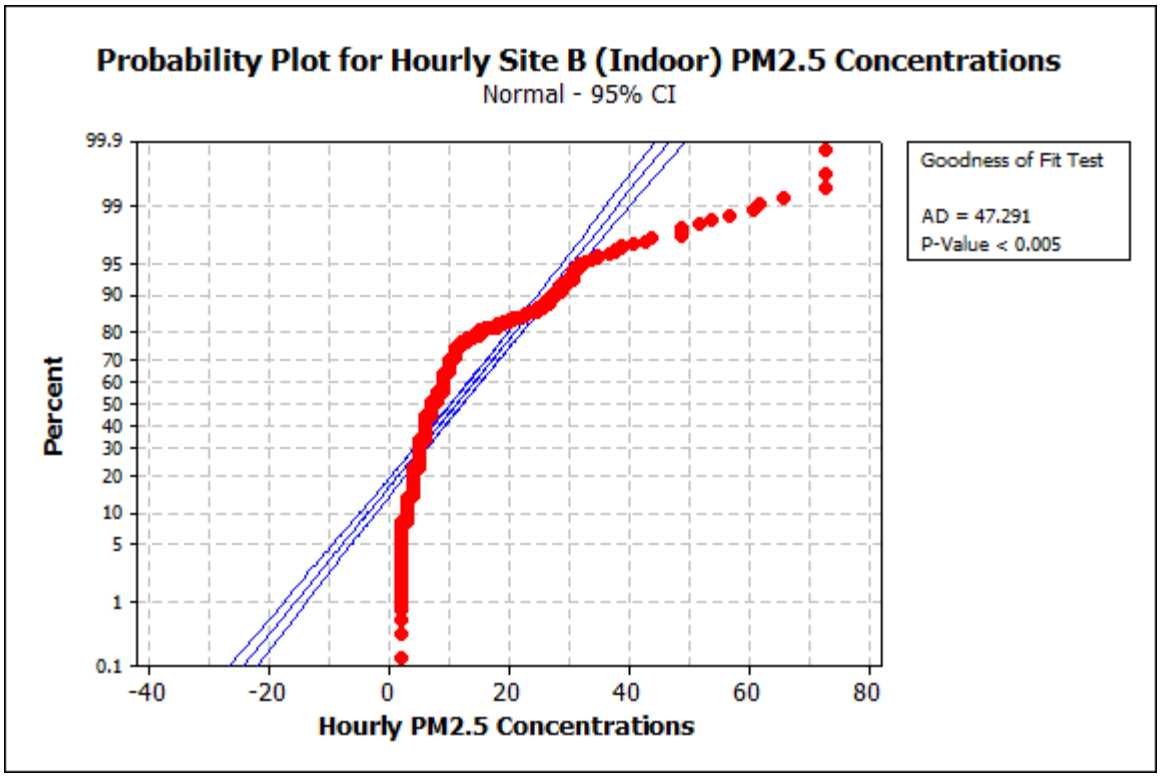

Figure F-2: Cumulative probability distribution plot and Anderson-Darling statisitic for Site B – indoor, Spring

Table F-5: Spring Site B outdoor hourly distribution identification for $PM_{2.5}$ concentrations

Distribution	Anderson Darling Co-efficient	P-value
Normal	1.704	<0.005
3-Parameter Loglogistic	1.752	*
3-Parameter Lognormal	2.041	*
Loglogistic	2.287	<0.005
Lognormal	2.288	<0.005
3-Parameter Gamma	5.651	*
3-Parameter Weibull	6.583	<0.005
2-Parameter Exponential	6.605	<0.010
Gamma	7.799	<0.005
Weibull	9.736	<0.010
Largest Extreme Value	12.245	<0.010
Exponential	13.538	<0.003
Logistic	17.946	<0.005
Smallest Extreme Value	80.171	<0.010

* *p*-values not available

Winter Campaign

Table F-6: MoE winter distribution identification for $PM_{2.5}$ concentrations

Distribution	Anderson Darling Co-efficient	P-value
3-Parameter Loglogistic	5.710	*
3-Parameter Lognormal	5.873	*
Largest Extreme Value	8.304	<0.010
Logistic	15.515	<0.005
2-Parameter Exponential	21.417	<0.010
Normal	25.748	<0.005
Smallest Extreme Value	56.401	<0.010
3-Parameter Gamma	60.669	*
3-Parameter Weibull	62.901	<0.005

* *p*-values not available

Table F-7: Winter Site A indoor hourly distribution identification for $PM_{2.5}$ concentrations

Distribution	Anderson Darling Co-efficient	P-value
Logistic	32.206	<0.005
Largest Extreme Value	33.093	<0.010
Normal	36.782	<0.005
Smallest Extreme Value	45.260	<0.010
3-Parameter Gamma	60.736	*
3-Parameter Loglogistic	63.593	*
3-Parameter Weibull	68.846	<0.005
3-Parameter Lognormal	70.889	*
2-Parameter Exponential	330.365	<0.010

* *p*-values not available

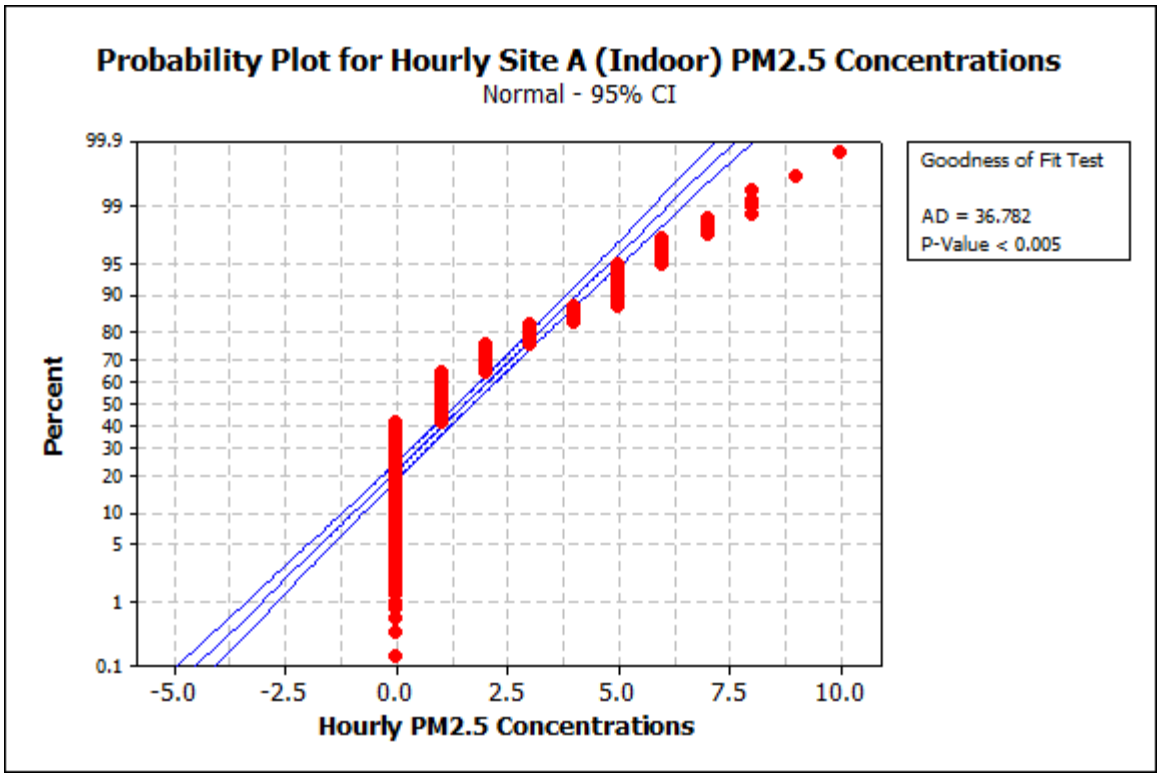

Figure F-3: Cumulative probability distribution plot and Anderson-Darling statisitic for Site A – indoor, Winter

Table F-8: Winter Site B indoor hourly distribution identification for $PM_{2.5}$ concentrations

Distribution	Anderson Darling Co-efficient	P-value
3-Parameter Loglogistic	4.424	*
Loglogistic	4.695	<0.005
3-Parameter Lognormal	5.898	*
Lognormal	5.978	<0.005
3-Parameter Gamma	9.264	*
Gamma	11.413	<0.005
3-Parameter Weibull	11.642	<0.005
Largest Extreme Value	12.269	<0.010
Weibull	15.878	<0.010
Logistic	22.359	<0.005
2-Parameter Exponential	25.5	<0.010
Normal	33.444	<0.005
Exponential	42.172	<0.003
Smallest Extreme Value	52.236	<0.010

* *p*-values not available

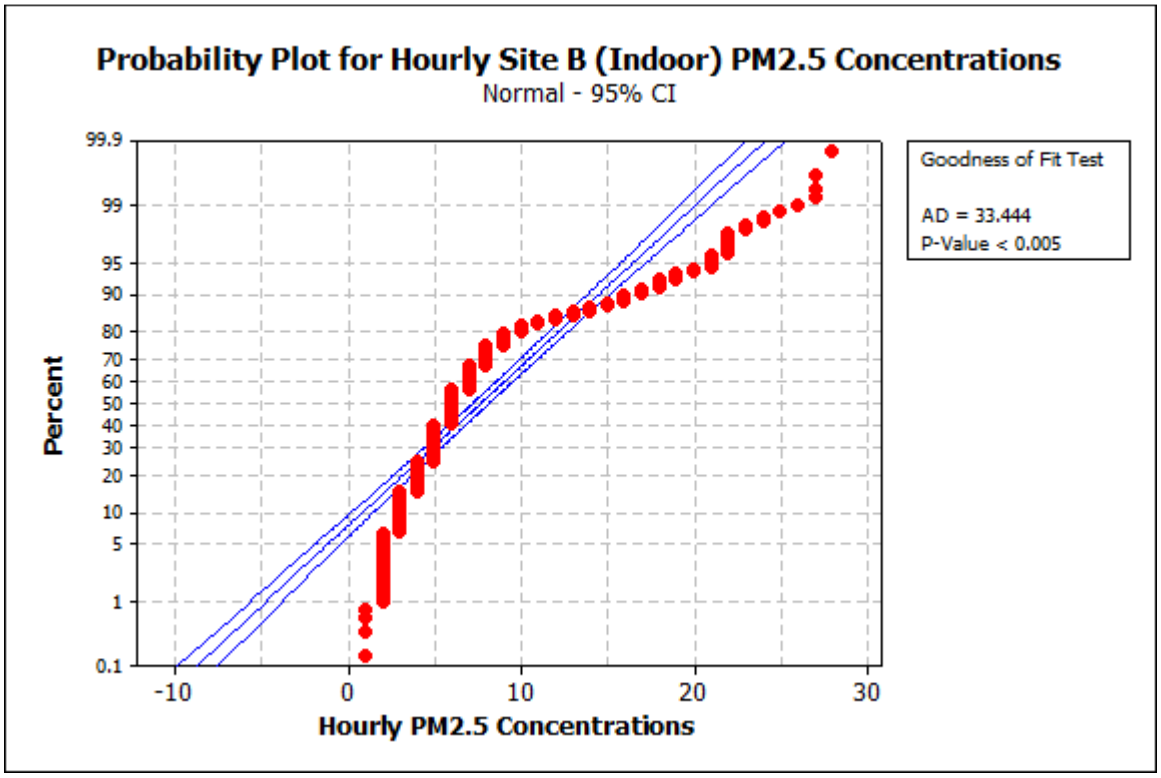

Figure F-4: Cumulative probability distribution plot and Anderson-Darling statistics for Site B – indoor, Winter

APPENDIX G

Firefighter Day – $PM_{2.5}$ Production and Elimination Rates

Episode 2:

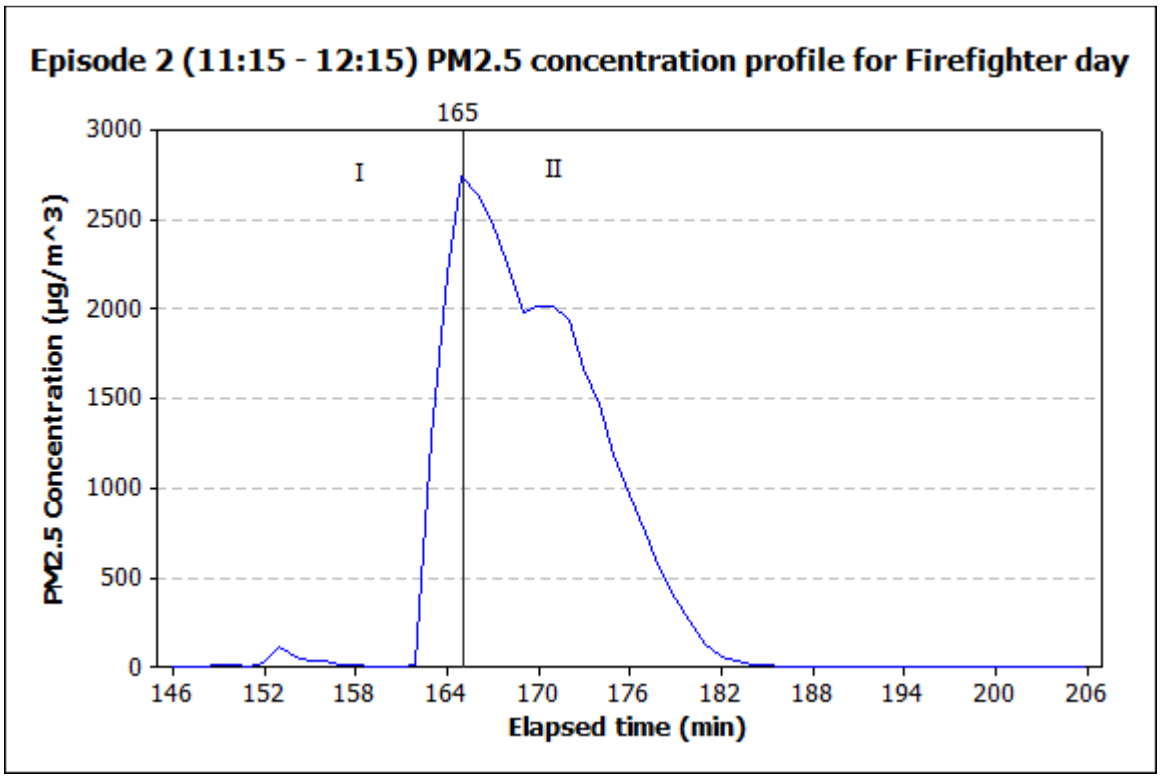

Figure G-1: Episode 2 $PM_{2.5}$ concentration profile

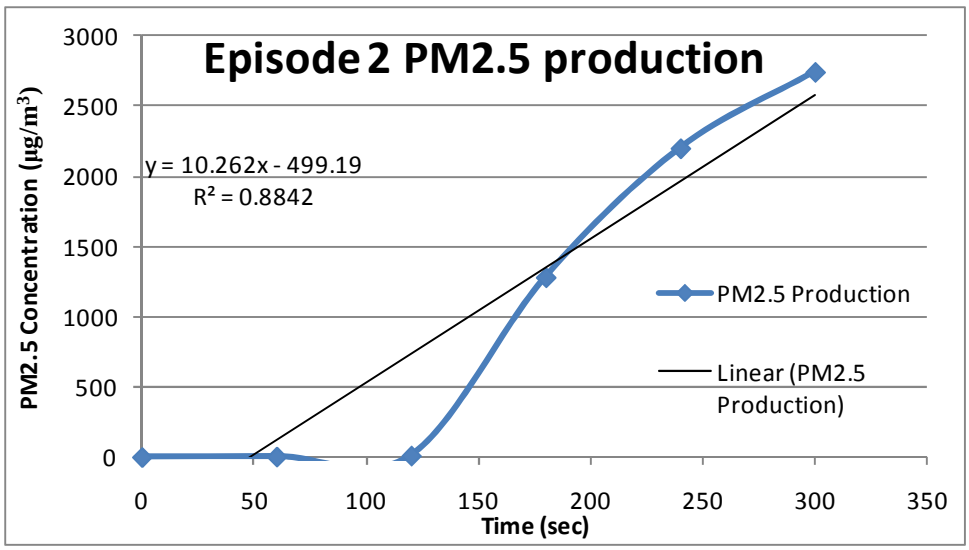

Figure G-2: Episode 2 $PM_{2.5}$ production profile

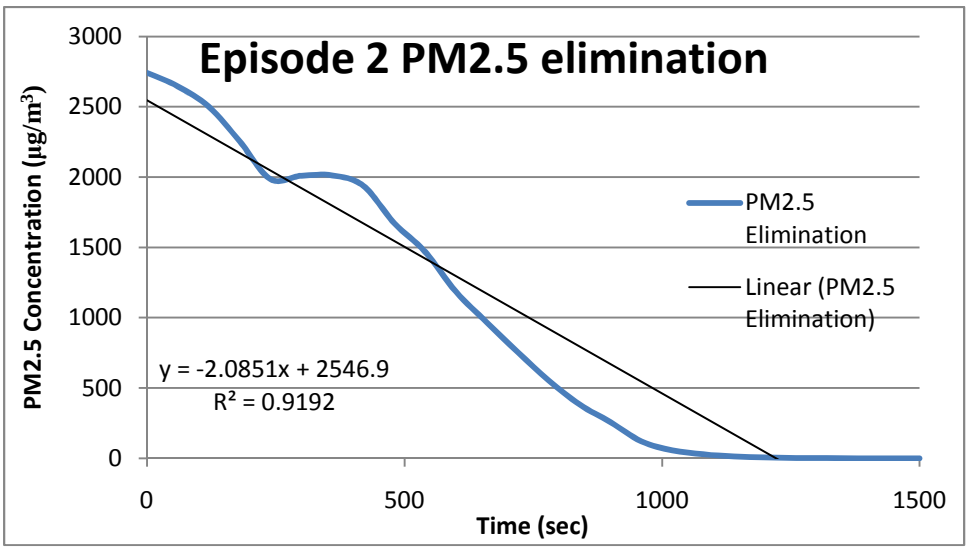

Figure G-3: Episode 2 $PM_{2.5}$ elimination profile

Episode 4:

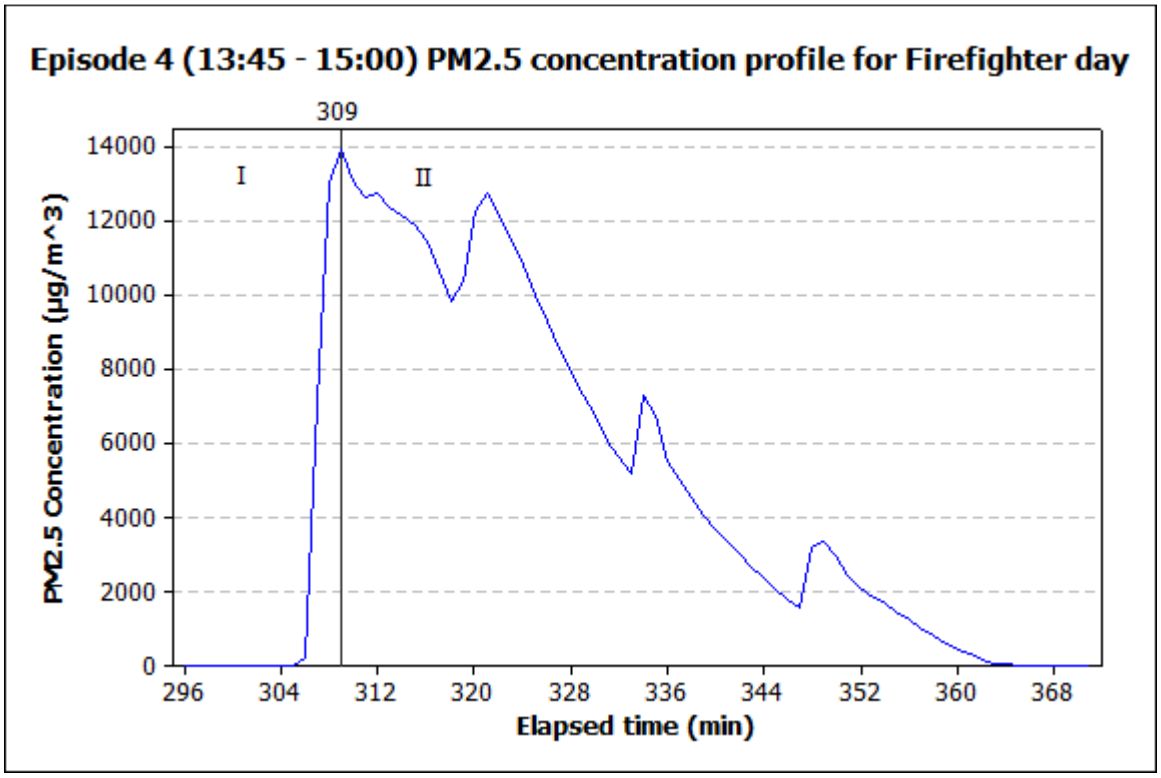

Figure G-4: Episode 4 $PM_{2.5}$ concentration profile

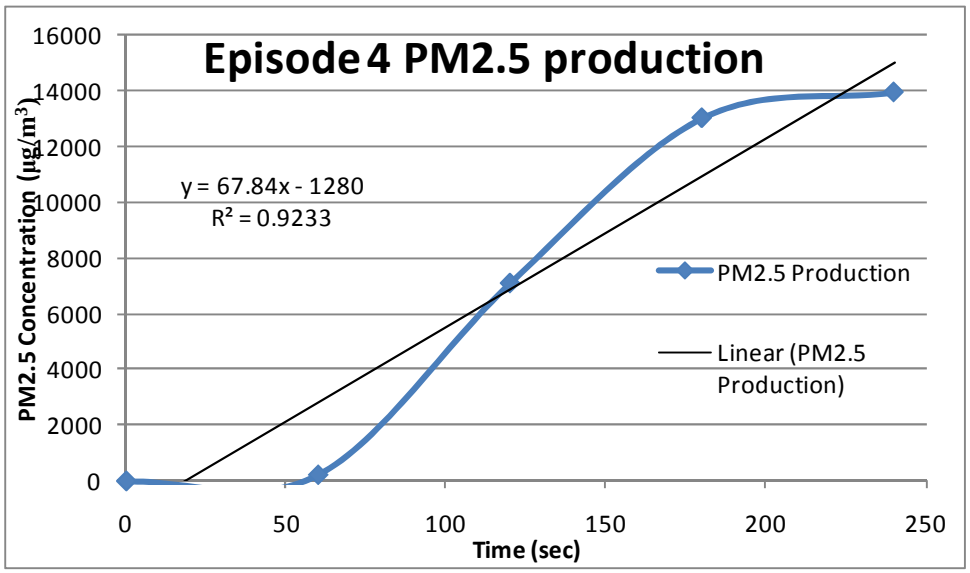

Figure G-5: Episode 4 $PM_{2.5}$ production profile

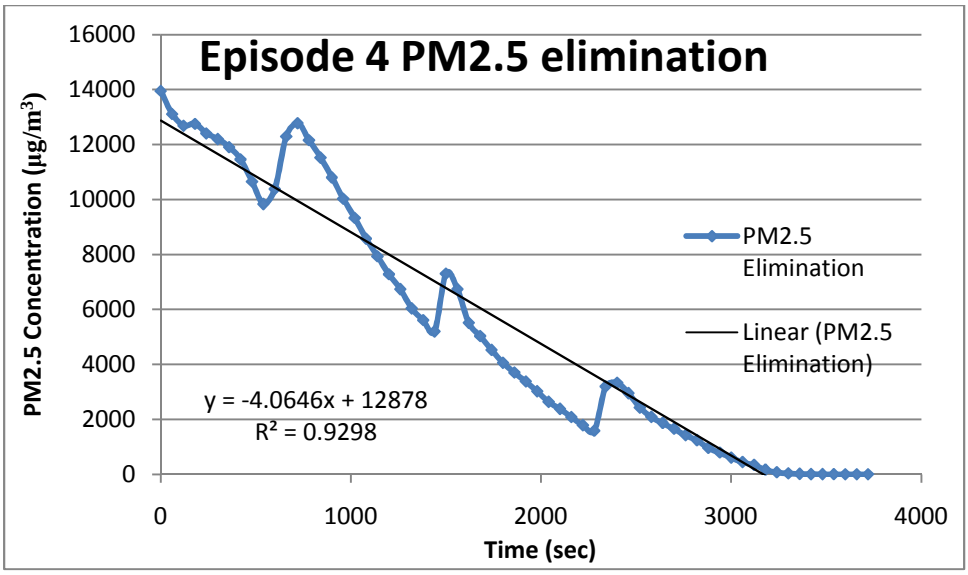

Figure G-6: Episode 4 $PM_{2.5}$ elimination profile

Episode 5:

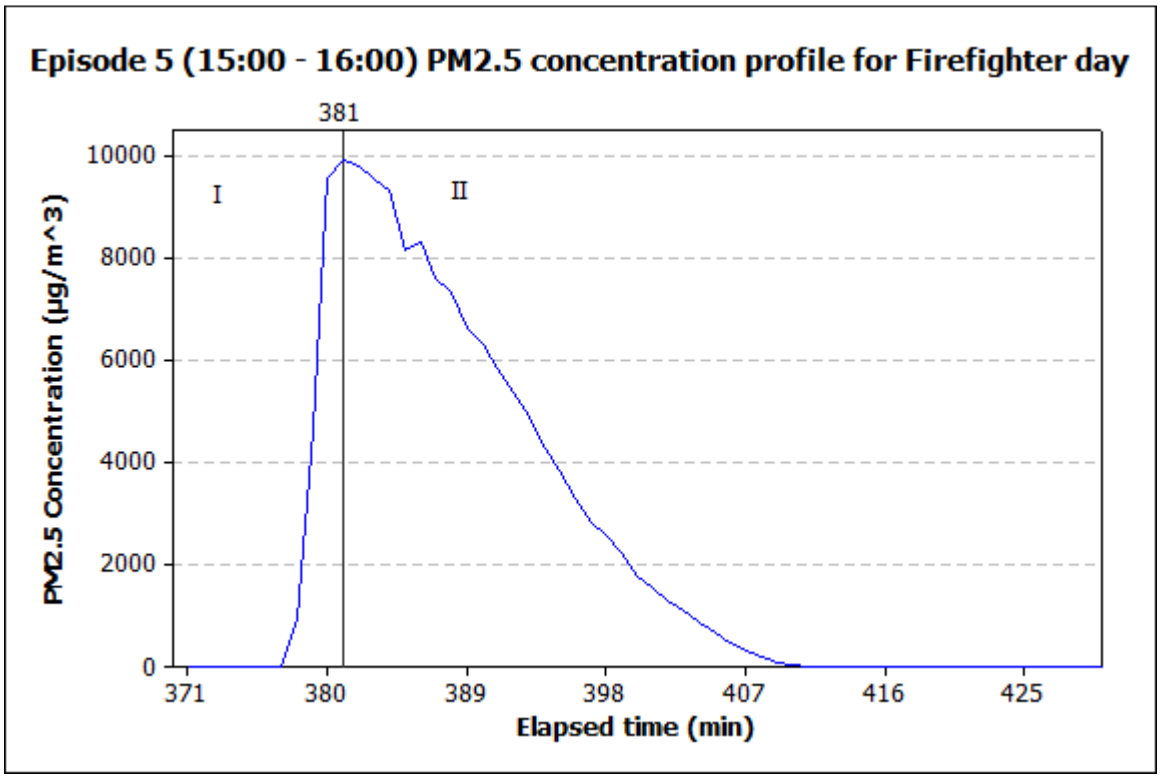

Figure G-7: Episode 5 $PM_{2.5}$ concentration profile

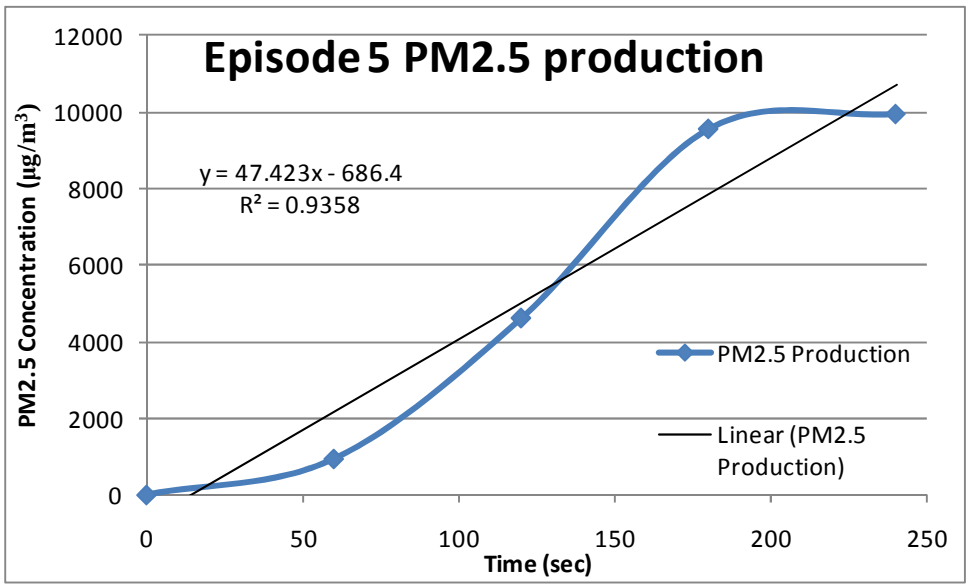

Figure G-8: Episode 5 $PM_{2.5}$ production profile

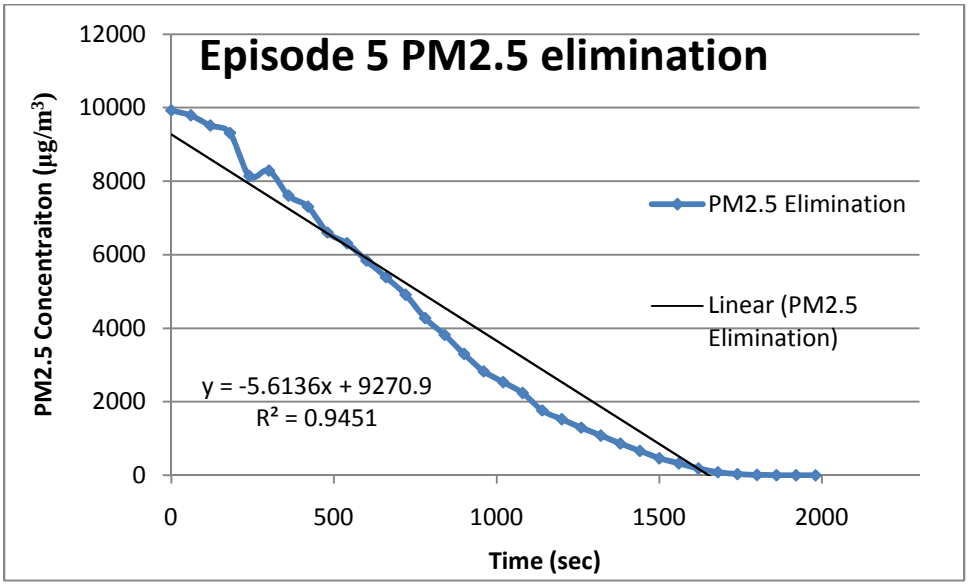

Figure G-9: Episode 5 $PM_{2.5}$ elimination profile

APPENDIX H

Regression Modeling Results

Table H-1: Regression coefficients for Site A hourly indoor $PM_{2.5}$ ($\mu g/m^3$)

Predictor	Coefficient	SE Coefficient	T-value	P-value
Constant	0.8627	0.3126	2.76	0.006
$(PM_{2.5})_{Outdoor}$	0.23886	0.01257	19.01	$p<0.001$
S=4.04058; R-Sq= 50.5%; R-Sq (Adj)= 50.4%;				

Table H-2: ANOVA results for rank predictor model of indoor $PM_{2.5}$ Site A

Source	Degree of freedom	Sum of squares	Adjusted mean squares	F-value	P-value
Regression	1	5899.5	5899.5	190.75	$p<0.001$
Residual Error	354	5779.5	16.3		
Total	355	11679.0			

Table H-3: Regression coefficients for Site B hourly indoor $PM_{2.5}$ ($\mu g/m^3$)

Predictor	Coefficient	SE Coefficient	T-value	P-value
Constant	7.1324	0.6701	10.64	$p<0.001$
$(PM_{2.5})_{Outdoor}$	0.32197	0.02035	15.82	$p<0.001$
S = 9.74410; R-Sq=41.3%; R-Sq (Adj)=41.1%;				

Table H-4: ANOVA results for rank predictor model of indoor $PM_{2.5}$ Site B

Source	Degree of freedom	Sum of squares	Adjusted mean squares	F-value	P-value
Regression	1	23776	23776	250.41	$p<0.001$
Residual Error	356	33801	95		
Total	357	57577			

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