Assessment of Personal Exposure to Particulate Matter Based on a Space-time Method for a Student Residing near a Large Urban Campus

THESIS

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Abstract

Particulate matter (PM) is a mixture of pollutants that have been associated with various adverse health effects. Since concentration levels of PM vary across space and time, the association between exposure to particle pollution and health on both spatial and temporal scales has been a cause of concern.

In this study, we conducted time and space resolved personal monitoring to demonstrate the capability and explore models and methods of analysis to advance ability to examine both PM’s health threat as well as source contribution. In addition, we examine the possible sources that may account for rapid increases in exposure. At the same time, geospatial monitoring was used to record time and location of the subject during monitoring. Perceived surrounding changes and human activities were recorded by voice recorder and activities diary. The monitoring data of personal PM exposure were collected around and on the campus of The Ohio State University. To simplify the geographic data, microenvironments were applied, which divided the study areas into five categories: indoor at home, outdoor, indoor on campus, in transit and others, respectively. Further statistical analyses were conducted to test our hypotheses on personal exposure in those microenvironments. Significant differences of personal exposure levels have been observed between different microenvironments, as well as between some locations in the same microenvironment. Some personal
activities, such as cooking and cleaning, were found to increase personal exposure. Additionally, geo-visualization was applied to present the convenience of personal exposure on a space-time scale, which can help to understand the impact of personal habits and activities on personal exposure.

Results in this study demonstrated the significant variation of personal exposure levels across different microenvironments, as well as the significant increase of personal exposure levels associated with some activities. With space-time integrated personal monitoring PM data, a map was generated and visually showed the small-scale temporal and spatial variability of personal exposure.
This is dedicated to my beloved parents.
Vita

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Major Field:  Environmental Health Science
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Chapter 1: Introduction

1.1 Overview

Particulate matter (PM) is a tiny mass dispersed in the air in the form of solid and/or liquid particles. It comprises both organic and inorganic components, such as sulfates, ammonium, soil, pollen, aerosols, and dust particles (Dockery and Pope, 1997).

Particulate matter can be divided into several categories based on their different behaviors in the atmosphere and the respiratory system. Therefore, as shown in table 1, particulate matter is characterized by the aerodynamic diameter, which is the diameter of the specifically defined sphere (unit-density) with the same aerodynamic behavior (WHO, 2000), and simply mentioned as particle size.

<table>
<thead>
<tr>
<th>EPA Description</th>
<th>Particle Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supercoarse</td>
<td>$d_{pa} &gt; 10 \mu m$</td>
</tr>
<tr>
<td>Coarse</td>
<td>$2.5 \mu m &lt; d_{pa} \leq 10 \mu m$</td>
</tr>
<tr>
<td>Fine</td>
<td>$0.1 \mu m &lt; d_{pa} \leq 2.5 \mu m$</td>
</tr>
<tr>
<td>Ultrafine</td>
<td>$d_{pa} \leq 0.1 \mu m$</td>
</tr>
</tbody>
</table>
From a health perspective, particles of 10-micrometer diameter or smaller raise much concern, because particles of this size are considered respirable, which can pass through the nose and throat and go into the lungs, and then, even into the blood stream. In that case, inhalation of these small particles can cause harmful effects on the respiratory and cardiovascular systems (USEPA, 2008). The severity of these effects depends on the PM’s size, amount, and chemical composition, which substantially vary over space and time (WHO, 2000).

1.2 Statement of Problem

Despite significant improvements, particulate air pollution continues to pose serious environmental and health risks, especially in developing countries. Generally speaking, in order to adequately explore the impact of PM on health, it is necessary to have the best possible estimates of both exposure and dose. As the most prevalent way to monitor regional pollution levels, ambient, community-based PM measurements were suggested to be likely to cause misclassification of exposure and bias in estimates of the association between exposure levels and health effects (C. Boudet et al., 2001; USEPA, 2008). Also, epidemiological evidence emphasized the importance of peak episodic exposures (lasting for one hour or less) on health impacts (Michaels and Kleinman, 2000).

These considerations highlight why it is necessary to understand the precise microenvironments in which higher PM concentrations occur, and the length of time that people stay in these microenvironments in their daily lives (Greaves, 2008). In this way, personal exposure data, which are largely associated with the behavior and
activities of individuals, can provide much more valuable information in environmental health studies.

1.3 Purposes

This study is designed to characterize personal exposure of a student residing near a large, urban campus (The Ohio State University – OSU), by obtaining continuous personal PM data using a miniature aerosol nephelometer (personal DataRAM-1000), and simultaneous geospatial data using a portable GPS device. One key purpose of this study is to demonstrate one integrated method for space and time-resolved personal monitoring. The approach of microenvironments was taken to statistically analyze personal exposure in different microenvironments, which was expected to demonstrate the significant impact of microenvironments on personal exposure levels. As personal activities and surrounding changes (e.g. heavy vehicles, pedestrians smoking, crowd density, cooking, cleaning) were noted by voice recorder and activity diaries, this study is also aimed to demonstrate the great potential of some activities and changes to increase personal exposure levels.

1.4 Hypotheses

The hypotheses to be tested in this study include:

(1) There is a significant statistical difference in the mean concentration of PM between four defined different microenvironments: in-transit, outdoor, indoor at home, indoor on campus. The mean PM concentration of indoor at home is expected to be the highest of these four microenvironments.

(2) There is a significant statistical difference in the mean concentration of PM
between different locations within the same microenvironment.

(3) There is a significant statistical difference in the mean concentration of PM between the indoor and outdoor microenvironments during the same sampling day (with the outdoor area being defined as a circle 100 meters in diameter, and the core of the circle serving as the entrance point to the indoor microenvironment). Under the examination of a one-sided t-test, indoor PM concentrations will be significantly higher than outdoor PM concentrations at the 5 percent level of alpha.

1.5 Objectives

This work will evaluate personal exposure to particulate matter, emphasizing the variability of exposure levels over space and time. Objectives of this study are to demonstrate the significance of microenvironments in personal exposure, to explore the influence of personal activities on personal PM exposure, and to develop methods and models for the simplified representation and visualization. Moreover, we expect that the use of the geo-visualization system will allow us to explore the inherent structure and pattern of the PM exposure to better evaluate the source contribution and health threat.
Chapter 2: Literature Review

A literature review has been conducted to help identify external factors speculated to influence personal PM exposure, and induce variability of exposure level. In addition, we reviewed previous procedures to determine how to conduct the space-time paths on personal exposure. After a thorough review, we focused on the possible combinations of approaches that would effectively integrate PM concentrations with their location and the time of day. This would allow us to uncover the geographical and temporal characteristics of peoples’ daily activities for personal exposure measures.

2.1 Particulate Matter Sources

Both natural process (e.g., volcanoes) and man-made sources (e.g., coal burning, traffic, and power plants) can emit particulate matter (WHO, 2000). Man-made sources tend to be the most common contributors to particle pollution (WHO, 2000). In addition, the majority of man-made particle pollution is concentrated in limited areas, where there are high-density populations (Lindskog, 1983). Therefore, most epidemiologic studies focus on man-made sources.

The most common outdoor, man-made source of particle pollution, especially in towns and cities, is road dust. According to a National Summary of Particulate Matter Emissions by the US EPA (2005), road dust contributed most to the national PM$_{2.5}$
emissions and almost 50% of national PM$_{10}$ emissions. Generally, concentrations of particulate matter along roads increase with the degree of urbanization and traffic density (Han and Naecher, 2006). Moreover, as a major contributor of road dust, studies have shown that diesel exhaust particulate (DEP) accounts for 90% of airborne PM in some large cities (Health Effects Institute, 1995; Riedl and Diaz-Sanchez, 2005).

Meanwhile, since most of our time is spent indoors, especially for children, the elderly, and those of ill health (Byrne, 1998; Wallace, 2000; Robinson and Thomas, 1991), indoor PM levels are crucial factors for determining personal exposure. Indoor PM levels are associated with both indoor sources of PM and the movement of PM between outside and indoor environments.

The predominant sources that elevate indoor particle concentrations include cooking, cigarette smoking and wood burning (Tuckett et al., 1998; Long et al., 2000; Jones, 1998). For example, in a study by Spengler, et al. (1981), one smoker was found to be able to raise fine particles up to 20 μg / m$^3$ (24-h mean) in a household. These indoor sources are related to combustion processes, which mainly result in the increase of smaller particle concentrations, with the majority of them lying in the sub-micrometer range (Ozkaynak et al., 1996; Wallace, 1996).

Another indoor source of PM concentration increases is the re-suspension of particles from reservoirs (e.g., the surfaces of textiles and furniture) (Miguel et al., 1995; Byrne, 1998). Re-suspension can be caused by dusting, vacuuming, floor sweeping, opening of doors, and so on (Jones et al., 2000).
One apparent characteristic that these indoor sources share is that they are apt to emit high-concentrations of ultrafine and coarse particles. These kinds of particles can cause indoor PM concentrations to increase to several times those of background levels (Long et al., 2000; Ferro et al., 2004b). For this reason, continuous monitoring methods are vital to capturing the temporal variability of indoor sources.

2.2 Health effects

Both short-term and long-term exposure to PM can result in adverse health effects, chronic or acute (USEPA, 2004). Generally, according to the US Environmental Protection Agency (EPA), long-term exposure to PM has been linked to a wide range of respiratory and cardiovascular health problems (USEPA, 2008). Also, numerous epidemiologic studies have implicated PM levels in ambient air as a likely contributor to mortality and morbidity from respiratory illnesses, pulmonary function impairments, cardiovascular diseases, and cancer (Pope et al., 2002; Krewski et al., 2000; Heinrich et al., 1999, 2000, 2002b; McConnell et al., 1999; Ferro et al., 2004a; Gauderman et al., 2002, 2004; Zemp et al., 1999).

Although the health effects of short-term PM exposure have not been clearly understood (Ferro et al., 2004b), it is likely that a great number of chronic health effects are linked to repeated short-term exposure to increased particulate levels (Schwartz, 2001).

Multiple epidemiological studies show an increased daily mortality from respiratory and cardiovascular disease during and shortly after high ambient particle episodes (USEPA, 2003; Samet et al., 2000; Wichmann et al., 2000; Mar et al., 2000,
A Harvard University study found that short-term exposure to greatly increased levels of particle pollution could trigger heart attacks in susceptible people (Peters et al., 2001). One-hour and eight-hour maximum PM$_{10}$ concentrations have been demonstrated to be relevant to asthma symptoms in asthmatics (Delfino et al., 1998).

A number of short-term community health studies also conclude that short-term increases in particle levels are relevant to increased hospitalization; doctor visits; and emergency visits for respiratory and cardiovascular causes. Furthermore, short-term studies exploring statistical correlations of particle pollution levels and observed human health impacts cannot derive a no-effect concentration (NEC) or a threshold from available data (Schwartz, 2001; USEPA, 2008).

In total, sufficient evidence has been found demonstrating that both long-term and short-term exposure to particulate matter implies serious health effects.

2.3 Temporal and Spatial Variability of Particle Pollution

Many epidemiologic studies have been done investigating exposure assessment of air pollution and its effect on health. These studies have relied on the data from nearby monitoring sites. These studies assumed that, to a large extent, this kind of data could represent the individual exposure level of the population in question, or at least, could reveal some important factors that caused the health effects. Although it could be a good indicator of the average personal exposure levels of the population living near the monitoring site, data from outdoor monitoring sites have proved to be poorly correlated with the true personal exposure levels in many studies (Kramer et al., 2000).
Moreover, even though the outdoor monitoring data can provide useful insight into the relationship between air pollution and health effects, a reliable statistical conclusion on the relationship could not be reached. It is because variations in pollution concentrations exist in both the time and space dimensions, especially in urban areas. However, in health outcome studies, it is essential to take variability of pollution concentrations into consideration during the study design step. Otherwise, exposure characterization errors and exposure misclassification could be induced and result in biased effect estimates that are far away from the truth.

Several factors have been identified in various studies that contribute to these variations. First, there are multiple sources, man-made and natural, with various compositions (Kim et al., 2005), while both of sources and compositions are changing in space and time. In particular, traffic-related sources have been attracting rising concern, for they have been identified as being of high spatial variability within small distances from emission sources (Evans et al., 2000; Goswami et al., 2002; Lawless et al., 2001). As a consequence, most studies focus on the variation in urban areas with high population density and traffic volumes. In addition, meteorological factors (e.g., wind speed, precipitation, and humidity) and the topography of study areas (e.g., street canyon) also play very important roles in the variation of PM concentration levels. For example, a study by Monn, et al. (1997), found that precipitation could significantly influence the PM<sub>10</sub> levels by decreasing airborne particles. Moreover, in the same study, statistically higher concentration levels were measured during dry periods, compared to rainy periods. Meanwhile, one study conducted near streets
found that, the orientation and aspect ratio of one street would act together with other factors to change the pollution concentration (Micallef and Colls, 1998).

As mentioned by Micallef and Colls (1998), in the street canyon environment, concentration levels of PM$_{10}$ vary in the vertical scale. There was an obvious tendency for the particles to decrease in concentration with the rising height of monitoring sites. In another study set near roads (Monn et al., 1997), the lowest site, at 1.8 meters in height, was particularly set to represent exposure levels of pedestrians. This site measured the highest PM$_{10}$ levels, which was caused by increasing turbulence and by re-suspended particles generated from traffic (Monn et al., 1997). Since most air monitoring systems are higher than 2 meters (Monn et al., 1997; Micallef and Colls, 1998), the pollutant data from these monitoring sites is not suitable for modeling human exposure levels.

In the Particulate matter sources section, we mentioned that the difference between indoor and outdoor concentrations could significantly contribute to variations in person exposure levels. In urban outdoor environment, variations in concentration at a given height are significantly influenced by vehicle-generated turbulence, environmental variables, and variation in traffic flow (Micallef and Colls, 1998). In the study near roads by Monn, et al. (1997), the nearest site to street and the site 15m away from the street have the largest difference in monitored concentration levels, while no statistical difference was found between sites at further distances. In a dense urban area with street canyons, however, it is common to see substantial spatial variability in the short-term observations (Levy and Hanna, 2011).
Concerning the temporal variation, there is always significant variation in PM concentration levels on the scale of seasons, days, hours, or even minutes. For example, the study along roads found that the measured PM values were higher in winter than in summer (Monn et al., 1997). Neff (1997) concluded that wintertime highs were primarily due to higher emissions and regional meteorology, with frequent short-term atmospheric inversions in winter. Specifically, a diurnal pattern of PM concentration levels has been observed in several studies. Chow et al. compared the pattern between urban areas and rural areas. PM$_{2.5}$ concentrations were lowest during the period from 3:00 am to 3:00 pm, which then increased and stayed at the highest levels through midnight, while a reverse pattern was observed at two other sites set in rural areas (Chow, et al., 1999). The similar diurnal pattern with two peaks was observed in three studies set in Ohio, in Mecklenburg, North Carolina and in Santiago, Chile, respectively (Aneja, et al., 2006; Ieesuck, et al., 2002; Perez et al., 2000). One peak appeared in the early morning due to rush hour, while the other appeared in late afternoon that may be caused by rush hour and cooling of the surface after sunset (Aneja, et al., 2006; Ieesuck, et al., 2002; Perez et al., 2000).

On the other hand, the temporal variations also included the variation of spatial correlations, more specifically, the seasonal variation of spatial correlation. These variations may result from the seasonal meteorology and changes in human activity. Therefore, there is no simple way to determine the exact pattern or tendency of the seasonal variation. For example, higher variations were observed in means of PM concentration measured by different monitoring sites during wintertime in a study.
along roads (Monn et al., 1997) and a study in urban areas (Aneja et al., 2006). Comparatively, another study set in New York observed significant differences in means of PM concentration for all of their monitoring sites in the summer, and none in the winter (Maciejczyk et al., 2004).

The literature has focused on the pattern of PM$_{10}$ variability, as many approaches have been taken to deal with the variability observed at the monitoring sites (Levy and Hanna, 2011). Due to the complexity of the contributing factors to variation, it is hard to precisely define the homogeneity or heterogeneity of PM concentrations in relatively limited study areas, which are always set at regional or urban scales in health studies.

In summary, various sources and meteorological conditions, as well as the topography, will influence PM$_{10}$ concentrations at the defined location and time of the study, which result in the temporal and spatial variation of PM concentration levels. Fixed monitoring sites cannot accurately reflect these variations and are not conducted at a height that is suitable for monitoring human exposure levels. Significant difficulties are posed by the discordant patterns in the variations in PM concentration. In particular, more attention should be paid to assessing true human exposure levels.

2.4 Personal Exposure Measurements

2.4.1 Theoretical Background

It has been summarized that nearly half of recent studies conducted on the individual level cannot conclude significant correlations between personal exposure...
levels and outdoor pollution concentrations (Branis, 2010). In addition, multiple studies show that personal exposure/ambient concentration ratios have substantial intra- and inter-personal variability (Williams et al., 2000a, 2000b; Liu et al., 2002). This is because actual personal exposure is a dynamic measurement. First, as we have discussed, PM concentrations in the environment, vary in time and space due to the multiple combinations of PM sources. Also, people are moving among these microenvironments every day with unpredictable time-activity patterns. For example, indoor sources, including personal activities, can result in vastly differing levels of personal exposure.

On the other hand, numerous stationary county-based and community-based air monitor sites exist to provide data for scientific and regulatory purposes. As a result, debates about whether it is suitable to substitute ambient air monitoring data for personal exposure levels have been ongoing, with no clear result. In general, in epidemiologic studies, it has been most common to conduct assessment of morbidity and mortality due to air pollution using ambient air monitoring data (Dockery and Pope, 1994; Katsouyani et al., 1997).

However, according to various studies, which use ambient pollutant data as a surrogate for personal exposure levels, it has been demonstrated that at least one of these essential prerequisites must exist for this method to be tenable: 1). the collected pollutant data on the same individuals is longitudinal, repeated over time. Studies have shown that this measurement could strengthen the personal-outdoor PM correlations (Williams et al., 2001, 2000b). 2). for pooled analyses that use average
exposure concentrations for multiple individuals on a single day, longitudinal correlations with the ambient site concentration are high. Associations were strongest for fine particle sulfate, which was followed by \( \text{PM}_{2.5} \) mass, and less strong, but still significant, for \( \text{PM}_{10} \) mass (Evans et al., 2000; Samet et al., 2000; Landis et al., 2001).

3). there is limited indoor activity and few indoor sources (Evans et al., 2000), which can strongly relate the personal exposure to the ambient air. However, this seems not to be the situation of most people.

In summary, thanks to the large study populations and specific purposes (e.g. air quality control), ambient air data is both efficient and effective. However, actual personal exposure is much more complex than the ambient air change. Exploring true personal exposure has its own unique significance. It is thought that investigating personal exposure will help us to understand what we can be actually exposed to and how we can be exposed, as well as the possible and feasible ways to reduce the exposure. Moreover, as described in the Health Effects section, an exposure peak of one hour or less is more relevant to the health effects of personal exposure (Michaels and Kleinman, 2000). Long-term exposure is, in essence, multiple instances of short-term exposure. Therefore, we can conclude that understanding the effects of every variety of short-term exposure, which may occur in indoor environment, outdoor environment or from activities, is an effective way to connect the effects and risks with particulate pollution.

### 2.4.2 Different Measurement Methods

There are direct and indirect personal exposure measurements. Both direct and
indirect measurements are described and compared in table 2. The direct approaches can measure and determine the individual exposure levels by a biological marker or by a personal sampler, while the indirect approaches would measure exposure levels by static measurement equipment or use models to measure and estimate the exposure levels (Ott, 1982; Lioy, 1995).

<table>
<thead>
<tr>
<th>Table 2. Summary of Personal Exposure Measurements</th>
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<tbody>
<tr>
<td>(Lioy, 1995; Monn, 2001; Briggs, 2000)</td>
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<tr>
<td></td>
</tr>
<tr>
<td><strong>Approaches</strong></td>
</tr>
<tr>
<td>Direct/internal</td>
</tr>
<tr>
<td>Direct/external</td>
</tr>
<tr>
<td>Indirect/external</td>
</tr>
<tr>
<td>Model approach</td>
</tr>
<tr>
<td>Human activity information, e.g. questionnaire, diaries</td>
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</tbody>
</table>

The direct approach is assumed to provide the most accurate estimation of the real personal exposure levels (Briggs, 2000). There are two main direct approaches: biological monitoring and personal monitoring. To some extent, they share several
characteristics. First, both of them can be applied to assess the relationship between exposure and health risks. Thus, they have the same ultimate goal - to estimate the dose. However, biological monitoring measures uptake, while the latter one helps to explore the intake (Dor et al., 1999; Scherer, 2005; Branis, 2010). However, even though biological monitoring can provide better estimates of the relationship between adverse effects and dose caused by being exposed to one or several pollutants, it cannot indicate the spatial and temporal variation of the exposure, which, can only be explored by external approaches.

There are many types of instruments used to monitor personal exposure. They are worn by human subjects to sample and measure personal exposure to specific pollutants (Monn, 2001). For particulate matter, the most widespread division of different personal monitoring approaches is based on two types of instruments: time-integrated and continuous.

With time-integrated devices, the sampled medium will pass through a filter, which removes the desired pollutants at a known rate over a specific period of time (Briggs, 2000). After exposure, the filter is weighed or analyzed to give an indication of the individual’s time-averaged exposure for that period of time (Adams et al., 2009; Briggs, 2000; Branis, 2010; USEPA, 2004). Continuous monitoring devices are designed to continuously monitor and directly display the concentration of a chemical or the magnitude of a condition (USEPA, 2004). This data is stored and can be downloaded for further analysis. The details about these two approaches are displayed in Table 3.
Table 3. Comparison of Time-integrated and Continuous Monitors

(Adams et al., 2009; Monn, 2001; Branis, 2010; USEPA, 2004)

<table>
<thead>
<tr>
<th></th>
<th>Time-integrated</th>
<th>Continuous</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time resolution</td>
<td>Integrated, day, hours</td>
<td>Continuous, seconds to minutes</td>
</tr>
<tr>
<td>Measurement techniques</td>
<td>Gravimetry; Beta meter</td>
<td>Nephelometer; Photoelectric aerosol sensor (PAS); Tapered element</td>
</tr>
<tr>
<td>Type of data</td>
<td>Average exposure</td>
<td>Real-time exposure</td>
</tr>
<tr>
<td><strong>Pros</strong></td>
<td>Can be used for detecting classes or families of chemicals; Ability to detect extremely low concentrations.</td>
<td>High time resolution; Fast response time; Provide good measurement of rapid change in pollutant concentration; Direct reading output at location; Long-lasting battery</td>
</tr>
<tr>
<td><strong>Cons</strong></td>
<td>Long monitor duration needed; Inability to record spatial and temporal characteristics;</td>
<td>Lack sufficient sensitivity and selectivity; Strongly impacted by excessive levels of temperature and relative humidity</td>
</tr>
</tbody>
</table>

Since the pros and cons are relative, the advantages of one approach reflect the disadvantages of the other. Time-integrated approaches cannot indicate exactly when exposure occurs. It would be particularly labor- and resource- consuming to detect acute exposure events (i.e., concentration peaks) with time-integrated monitoring equipment because the consecutive short-term samples would be collected every 15 minutes, or an even shorter duration. In addition, the exposure peaks are often mixed
with periods of low exposure during the specific sampling interval (Adams et al., 2009). Comparatively, continuous approaches can be a much more efficient and effective choice, as they collect the real-time exposure with direct-reading data. Since some occasional acute events are important indoor sources which can largely increase indoor pollutant levels for a short interval, the merits of continuous approaches should be considered first (USEPA, 2004).

As continuous monitors are mainly nephelometers, which are usually used together with a pre-classifier (impactor or cyclone), they can be used to detect the concentration levels of particles with specific size range (e.g. PM$_{2.5}$, PM$_{10}$) (Branis, 2010). However, it is very difficult for continuous monitors to assess the presence of classes or families of chemicals, while time-integrated approaches are able to obtain qualitative and quantitative analytical parameters for multiple components of particles.

However, the main disadvantage of direct approaches is their cost, which makes them difficult to utilize for large-scale research. For this reason, the microenvironmental modeling approach is a widely used indirect approach to personal exposure measurements. The microenvironmental modeling approach is widely applied for certain situations, when an individual spends ignorable time intervals in specific locations during the day. In this approach, a microenvironment is assumed to be a three-dimensional space where the distribution of a pollutant is relatively stable and the concentration of that pollutant is relatively regular (Branis, 2010; Monn, 2001). The variance of concentration within this defined space is significantly lower
than that of normal surroundings. In a basic exposure assessment, exposure is calculated by multiplying the level of a specific agent in the exposure medium by the duration of that exposure (USEPA, 1992; Ott, 1982). Furthermore, with a microenvironment monitoring approach, the exposure refers to the total of the time-weighted average levels of the specific agent from the microenvironments the subject has occupied over a given period of time, namely T (Mage, 1985; Monn, 2001; Ott, 1982). This average is determined using the equation,

\[ E = \sum C_i t_i / T \]

\( E \) is the total exposure for an individual over the duration of the study time. \( C_i \) is the concentration of studied agent in microenvironment \( i \), while \( t_i \) is the duration the individual spent in the microenvironment \( i \). \( i \) is the number of microenvironments the subject has visited during the studied period, and \( T \) is the total studied duration.

Obviously, this formula assumes that besides the studied agent concentration in those microenvironments as the individual is present, we should know exactly how long the individual spends in each defined microenvironment. Therefore, microenvironments (MEs) are generally used with reliable time-activity/time-budget diaries to describe the behavioral patterns of the subject (Monn, 2001). However, as mentioned by Monn (2001), when we apply microenvironments in relatively large-scale surveys, it will call for a lot of effort and money to measure and get data for all of the specific microenvironments. The most feasible way is to adopt an approach in which the most similar microenvironments are classified into Micro-Environmental Types (MET). The following list has been identified to cover
the majority of regular movements of an adult in daily life (Jantunen et al., 1998; Monn, 2001).

- Outdoors (around home, in study areas)
- Indoors at home (kitchen, living room, etc.)
- In transit (car, bus, etc.)
- Others (shopping mall, restaurant, super market, etc.)
- Workplace

2.5 GIS and Geo-visualization

GIS, namely, the Geographic Information System, is an integrated system to deal with geographically referenced data by the whole process from recording, analyzing, to presenting (Foote and Lynch, 2009). It has been playing an important role in multiple scales of health research, whether this is the prediction of disease prevalence on a global scale, explanation of disease patterns on a social scale, detection of clustering on regional scales (Martens, 1998; Dunn et al., 1995; Gatrell and Senior, 1999).

From the environmental health perspective, GIS has also been widely applied in studies related to exposure, ranging from solely locating a group of subjects, to using proximity to pollution source as exposure subrogation (Jones et al., 2006; Comba et al., 2003), to integrating environmental monitoring data into the analysis of health effects of environmental pollutants (Jerrett et al., 2003; Nuckols et al., 2004). For the latter, it used to mostly refer to ecologic studies (Nuckols et al., 2004). In recent years, increasing concern has been expressed over on using GIS in estimating pollutant
levels at individual level (Gauvin et al., 2002; Guilliver and Briggs, 2005). The change from place-based to people-based exposure measurements is largely due to the zoning scheme and spatial scale that would largely affect the analytical results from place-based measurements (Kwan and Weber, 2003, 2008). Further details about this change have been discussed by Kwan (Kwan, 2009).

Generally, GIS data can be analyzed in three areas: visualization, exploration, and modeling (Gatrell and Senior, 1999; Bailey and Gatrell, 1995). However, the first two directions serve each other mutually. So, in most cases, they are mentioned together. This kind of exploratory visualization is called Geo-Visualization, which not only simply supports information assessment and traditionally presents geospatial data, but also provides the visual exploration and interactive spatial data analysis (Kraak, 2003; Bailey and Gatrell, 1995; MacEachren and Kraak, 2001). Therefore, there are primarily three parts in geo-visualization: cartography, Exploratory Data Analysis (EDA), and Visualization. By cartography, attribute data such as mortality, household income, is related with according locations measured by GIS (Jerret et al., 2003). Then, EDA is used to uncover the inner trends or relations. A number of techniques of EDA can be applied to explore these data sets, such as brushing and overlaying. Lastly, maps are supposed to be generated to visually activate thinking on the geospatial trends or relationships (Kraak, 2003). However, as geo-visualization cannot exclude the possibility of ascribing casual phenomena as non-causal relationships, it is always used to generate hypotheses, rather than to test them (Jerret et al., 2003).
Chapter 3: Methods and Materials

3.1 Objectives

This study was designed to assess individual exposure to particulate matter, not only in terms of concentration and duration, but also in terms of activity patterns. Its aim was to derive a simplified representation for visualizing the potential correlations in personal habits, activities, and exposure; and to demonstrate the significance of microenvironments in personal exposure. Moreover, we expect to explore the inherent structure and pattern of the PM distribution in the study area with the application of a geo-visualization system.

3.2 Study Design

Area sampling was located on and near the campus of The Ohio State University. The main process of this study was to utilize the space-time method to assess and evaluate personal exposure to particulate matter in daily life. Moreover, in order to simplify and statistically analyze the geographical information, microenvironments were applied to classify the sampling areas. Concentration levels of particulate matter were measured by continuous-recording and direct-reading personal monitoring equipment (personal DataRAM-1000, pDR: Thermo Scientific, Franklin, MA, US). Geographic data and activity information were obtained by simultaneously recording with a global positioning system (GPS) device, recording activities in activity diaries,
and using a voice recorder.

All of this equipment was set in a rucksack, which was carried by the investigator during the sampling period. When the investigator stayed at the same place (libraries, car, classroom etc) for a period of time the rucksack was put on a chair or table next to the investigator. When the investigator was at home, there was natural ventilation (with half of the windows open). Cars were mechanically ventilated.

Parametric statistical analyses were performed using STATA software to test statistical differences according to the hypotheses of this study. Google Earth and ArcGIS were utilized to generate the maps which visualized the PM concentration along the investigator’s routes. Microenvironments we applied in this study are as follows in Table 4:

<table>
<thead>
<tr>
<th>Microenvironments</th>
<th>Included location</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 In transit</td>
<td>(1) Car</td>
</tr>
<tr>
<td></td>
<td>(2) Shuttle</td>
</tr>
<tr>
<td></td>
<td>(3) COTA bus</td>
</tr>
<tr>
<td>2 Outdoor</td>
<td>(4) Around Home</td>
</tr>
<tr>
<td></td>
<td>(5) On campus</td>
</tr>
<tr>
<td>3 Indoor at home</td>
<td>(6) Kitchen; bedroom; living room</td>
</tr>
<tr>
<td>4 Indoor on campus</td>
<td>(7) Science and Engineerin Library</td>
</tr>
<tr>
<td></td>
<td>(8) Thompson Library</td>
</tr>
<tr>
<td></td>
<td>(9) Classrooms</td>
</tr>
<tr>
<td></td>
<td>(10) Ohio Union</td>
</tr>
<tr>
<td>5 Others</td>
<td>(11) Restaurant; mall; etc.</td>
</tr>
</tbody>
</table>
3.3 Equipment Description and Sampling

3.3.1 PM Concentration Sampling

Particulate matter concentrations were recorded using a personal DataRAM (pDR-1000AN Monitor) from Thermo Scientific (Franklin, MA, US). The DataRAM is a passive sampling, light-scattering nephelometer, which can measure real-time particulate concentrations with a range of 0.001 to 400 mg/m$^3$. The particulate size it responded to ranged from 0.1 to 10μm.

Although DataRAM was factory calibrated, to ensure maximum accuracy of instrument measurement, it is still important to zero DataRAM in relatively clean environment before initiating a measurement run. Therefore, a zero check was performed at the beginning of every sampling day according to the manufacturer’s instructions.

3.3.2 GPS Receiver

The GPS equipment we used in this study was a “BT-335” (GlobalSat, Chino, CA), which can record time, date, speed, altitude and location (in the form of longitude and latitude) at the pre-set intervals. The data it records can be saved in a variety of formats, including KML, which can interface with Google Earth. The geodetic datum it applied was “WGS-84”-- a new World Geodetic System.

The BT-335 is difficult to use for recording in indoor environments, so, it is necessary to start the device outdoors or near a window, where the signal can be easily tracked. In order to maintain the synchronization of the DataRAM and BT-335, it is important to estimate the duration needed for a specific BT-335 to start recording.
outdoors. For example, the BT-335 used in this study needed 7 seconds to start recording at a fixed point near a window. Meanwhile, the DataRAM needed 2 seconds to respond and start recording. In this study, we dealt with this problem by:

1. Starting the BT-335 near a window, making sure it works normally. When GPS status light-emitting device (LED) starts blinking, it means the GPS position is fixed.

2. Turn off the BT-335.

3. Set up the DataRAM, but remain at the last step prior to starting (when the screen shows the “LOG INTERVAL” and “TAG #”).

4. Start the BT-335, wait 5 seconds, then quickly press “ENTER” on the DataRAM.

3.4 Data analysis

3.4.1 Data Arrangement

The PM concentration data was matched with GPS recording location. In cases of mechanical misclassification by the GPS, any movement associated with location transfer was double-checked referring to the information from activity diaries. PM concentration information and geographical information were both required in this study. Only the 10-second interval time points with both PM and geography information, could be adopted in data analysis. Any odd data collected due to a malfunction of the equipment (e.g., continuously repeated sequence of data) was excluded from the data analysis. Any lack or indeterminacy of information would invalidate the recording session. Even without a signal, DataRAM is capable of recording the 10-second-interval data compared to BT-335. For BT-335, loss of the
satellite signal is a common phenomenon in campus buildings. In most situations, it can be easily made up by gathering information from the activity diaries and voice recorder using the time-based rule. However, this kind of geographical information can only be used for the microenvironment approach analysis.

In the map-forming step, we strictly filtered the data points to make sure that all points expressed in the map corresponded to GPS data and PM data. If the information did not correspond, we had to adjust the GPS data to match the stable data from DataRAM. For example, when exiting a building, the BT-335 resumed tracking the signal and started recording the 10-second intervals, but was not simultaneous with the DataRAM recording points. This problem will be further explained in the Discussion section.

3.4.2 Statistical Analysis

Descriptive statistics, which include the mean, standard deviation, minimum and maximum measurements, were used in the analysis or discussion of the data. Due to large quantity of independent samples in this study, we can assume that data in this study is nearly normally distributed. Therefore, parametric tests were applied in statistical analyses of this study with a significant level of 0.05. To detect the statistical difference among more than 2 independent samples (not including 2 groups), ANOVA parametric analyses were used (e.g., comparison among 4 microenvironments; comparison among 3 subtypes in transportation). Otherwise, a t-test was applied to compare 2 independent samples (e.g. comparison between 2 subtypes in microenvironment 2).
In the case of an ANOVA rejecting the null hypothesis, further analyses were conducted on the comparison of every combination of 2 samples using the Bonferroni test. The Bonferroni test was used to identify whether the PM concentration in any of the four microenvironments were statistically different from each other. In one Bonferroni test, multiple tests and comparisons were conducted. To avoid type I errors (assuming an effect where there isn’t one), the alpha value would be changed and adjusted. To make sure the differences were statistically significant, a lower p value should be set, a process known as Bonferroni correction. This correction simply divides the alpha value by the number of tests in a Bonferroni test to get a lower alpha value for the whole set of the $k$ comparisons.

For hypothesis (3) (indoor concentration v. outdoor concentration), the outdoor concentrations were defined as the average of outdoor concentration before entering the indoor environment and after going out of the indoor environment. Furthermore, outdoor concentration levels in this hypothesis were determined by averaging the concentration measured in the area no farther than 100-meters away from the entrance to the indoor environment. At this point, t-test analyses were applied to test every comparison between indoor concentration and outdoor concentration.
Chapter 4: Results

4.1 Overview

Personal exposure to PM was monitored over space and time. It was intended to sample for 10 days in both February and March. However, as we have mentioned that precipitation and wet weather would largely influence the ambient PM level, 9 groups of data were deleted from this study analysis due to specific weather conditions (snow or rain during sampling days), which did not accord with the interests of this study. The investigator’s activity area is almost entirely around the OSU campus and at home. According to the recorded locations during our sampling days, several microenvironments have been identified and classified.

4.2 Summary of the Results

As shown in Table 5, more than 40,000 data points were collected in this study. These data were generally analyzed to identify the mean, minimum, maximum measurement, standard deviation and 24-hour time-weighted average for each sampling day.

Furthermore, the hypotheses were tested separately using parametric analysis. The visualized path-time maps were generated and discussed below.
Table 5. Summary Statistics by Sampling Day

<table>
<thead>
<tr>
<th>Sampling day</th>
<th>Date</th>
<th>N</th>
<th>Mean</th>
<th>S.D</th>
<th>Min</th>
<th>Max</th>
<th>24-h time-weighted average (μg/m³/day)¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Feb 7</td>
<td>1632</td>
<td>0.03668</td>
<td>0.06721</td>
<td>0.003</td>
<td>0.984</td>
<td>* 6.929</td>
</tr>
<tr>
<td>2</td>
<td>Feb 16</td>
<td>4595</td>
<td>0.0219</td>
<td>0.03664</td>
<td>0.001</td>
<td>0.374</td>
<td>* 11.65</td>
</tr>
<tr>
<td>3</td>
<td>Feb 23</td>
<td>1612</td>
<td>0.01832</td>
<td>0.01507</td>
<td>0.001</td>
<td>0.282</td>
<td>3.418</td>
</tr>
<tr>
<td>4</td>
<td>Feb 24</td>
<td>7054</td>
<td>0.0329</td>
<td>0.03524</td>
<td>0.005</td>
<td>0.751</td>
<td>*** 26.86</td>
</tr>
<tr>
<td>5</td>
<td>Apr 1</td>
<td>4953</td>
<td>0.05318</td>
<td>0.1796</td>
<td>0.004</td>
<td>8.02</td>
<td>** 30.49</td>
</tr>
<tr>
<td>6</td>
<td>Apr 3</td>
<td>5011</td>
<td>0.11145</td>
<td>0.4934</td>
<td>0.004</td>
<td>8.02</td>
<td>*** 64.64</td>
</tr>
<tr>
<td>7</td>
<td>Apr 10</td>
<td>4838</td>
<td>0.01783</td>
<td>0.01886</td>
<td>0.001</td>
<td>0.722</td>
<td>* 9.982</td>
</tr>
<tr>
<td>8</td>
<td>Apr 13</td>
<td>3477</td>
<td>0.06976</td>
<td>0.1134</td>
<td>0.005</td>
<td>0.874</td>
<td>* 28.08</td>
</tr>
<tr>
<td>9</td>
<td>Apr 14</td>
<td>3883</td>
<td>0.0174</td>
<td>0.01944</td>
<td>0.004</td>
<td>0.343</td>
<td>* 7.819</td>
</tr>
<tr>
<td>10</td>
<td>Apr 17</td>
<td>3498</td>
<td>0.04395</td>
<td>0.114</td>
<td>0.007</td>
<td>1.431</td>
<td>** 17.80</td>
</tr>
<tr>
<td>11</td>
<td>Apr 18</td>
<td>2916</td>
<td>0.02004</td>
<td>0.00968</td>
<td>0.01</td>
<td>0.155</td>
<td>6.763</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>43469</td>
<td>0.04262</td>
<td>0.1878</td>
<td>0.001</td>
<td>8.02</td>
<td>21.44</td>
</tr>
</tbody>
</table>

¹ default unit of concentrations for this study were set at mg/m³; only different units would be indicated.

* noticed activity that significantly increased the PM concentration levels during monitoring, including frying, cooking, sweeping floor, vacuuming, and smoking, which will be further referred to in sections to follow.

4.2.1 Difference of Personal Exposure by Microenvironment

4.2.1.1 Comparison of PM between 4 Microenvironments

Table 6. Summary Statistics by Microenvironment

<table>
<thead>
<tr>
<th>Microenvironment</th>
<th>N</th>
<th>Mean</th>
<th>S.D</th>
<th>Min</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.In transit</td>
<td>3301</td>
<td>0.03927</td>
<td>0.04721</td>
<td>0.007</td>
<td>1.187</td>
</tr>
<tr>
<td>2.Outdoor</td>
<td>2437</td>
<td>0.03067</td>
<td>0.01837</td>
<td>0.009</td>
<td>0.199</td>
</tr>
<tr>
<td>3.Indoor at home</td>
<td>20721</td>
<td>0.06705</td>
<td>0.2684</td>
<td>0.003</td>
<td>8.02</td>
</tr>
<tr>
<td>4.Indoor on campus</td>
<td>14364</td>
<td>0.01064</td>
<td>0.01068</td>
<td>0.001</td>
<td>0.43</td>
</tr>
<tr>
<td>5.Others</td>
<td>2626</td>
<td>0.04401</td>
<td>0.03328</td>
<td>0.005</td>
<td>0.722</td>
</tr>
<tr>
<td>Total</td>
<td>43469</td>
<td>0.04262</td>
<td>0.1878</td>
<td>0.001</td>
<td>8.02</td>
</tr>
</tbody>
</table>
The division of microenvironments was determined based on the GIS and activity diaries. As shown in Table 6, the microenvironment with the highest concentration, in which the investigator had stayed for the longest duration, was at home (0.06705 mg/m$^3$). Additionally, the highest individual reading was 8.02 mg/m$^3$, which was also at home and measured during a noticed activity (frying). The mean PM concentration for the 5 microenvironments was 0.04262 mg/m$^3$. The largest standard deviation existed in microenvironment 3 (indoor at home). To a large extent, this was because most short-term activities, which could noticeably increase the PM concentration, happened at home. However, as we were not interested in microenvironment 5, the following analyses were conducted without examining the data collected there.

<table>
<thead>
<tr>
<th>Source</th>
<th>SS</th>
<th>df</th>
<th>MS</th>
<th>F</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Between groups</td>
<td>27.4366</td>
<td>3</td>
<td>9.1456</td>
<td>248.42</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Within groups</td>
<td>1502.724</td>
<td>40819</td>
<td>0.0368</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

ANOVA test comparison of 4 independent samples
Test at a significance level of $\alpha=0.05$

As shown in Table 7, a comparison of PM concentration among microenvironments using an ANOVA test indicated that the mean PM concentration was statistically different among the four microenvironments ($p<0.001$).
The results of further analyses using the Bonferroni test are displayed in Table 8. Within these comparisons, the mean PM concentrations were significantly different between pairs of microenvironments (p<0.001), with the exception of microenvironment 1 (in transit) and microenvironment 2 (outdoors) (p=0.140).

4.2.1.2 Comparison by Locations in the same Microenvironment

**Microenvironment 1**

Except for microenvironment 3, there were never fewer than 2 locations included in any microenvironment studied: 3 locations in microenvironment 1; 2 locations in microenvironment 2; 4 locations in microenvironment 4. These three groups of locations were analyzed individually.

As shown in Table 6, the mean PM concentration for three locations in microenvironment 1 was 0.03927 mg/m$^3$. Mean PM concentrations for location 1 (car), location 2 (shuttle), and location 3 (COTA bus) were 0.02703 mg/m$^3$, 0.09129 mg/m$^3$ and 0.02881 mg/m$^3$, respectively. These are displayed graphically in Figure 1.
The comparison among the 3 locations in microenvironment 1 by ANOVA test (Table 9) showed that mean PM concentration was statistically different between these three transportations ($p<0.001$).
Table 10. Comparison by Locations in Microenvironment 1

<table>
<thead>
<tr>
<th>Transit A v.Transit B</th>
<th>Calculated p-value</th>
<th>Mean difference (A-B)</th>
<th>Mean Microen A</th>
<th>Mean Microen B</th>
</tr>
</thead>
<tbody>
<tr>
<td>car v.shuttle</td>
<td>&lt;0.001</td>
<td>-0.06425</td>
<td>0.02703</td>
<td>0.09129</td>
</tr>
<tr>
<td>car v.COTA bus</td>
<td>0.333</td>
<td>-0.001772</td>
<td>0.02703</td>
<td>0.02881</td>
</tr>
<tr>
<td>shuttle v.COTA bus</td>
<td>&lt;0.001</td>
<td>0.06248</td>
<td>0.09129</td>
<td>0.02881</td>
</tr>
</tbody>
</table>

Bonferroni test comparison of 3 independent samples
Test at a significance level of $\alpha=0.016$

In additional, the Bonferroni tests compared paired locations (Table 10). The mean PM concentration was statistically different between car and shuttle ($p<0.001$), and between shuttle and COTA bus ($p<0.001$). Meanwhile, the mean PM concentration was not statistically different between car and COTA bus ($p=0.333$).

Microenvironment 2

Two defined locations were included in microenvironment 2 (outdoors): outdoors around home and outdoors on campus. As shown in Figure 2, mean PM concentration of outdoor around home was higher than that of outdoor on campus. The mean of the measured outdoor PM concentration was 0.03067 mg/m$^3$, as shown in Table 6. The mean concentration for the outdoor environments around home was 0.03242 mg/m$^3$, while that of the outdoor environment on campus was 0.03031 mg/m$^3$. A t-test was used to test two independent samples here. The result, displayed in Table 11, showed that two locations in the microenvironment were statistically different from each other ($p=0.0224$).
Figure 2. Mean PM Concentrations of Outdoor Locations

Table 11. Comparison of PM by Locations in Microenvironment 2

<table>
<thead>
<tr>
<th>Location</th>
<th>Mean</th>
<th>df</th>
<th>t</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 (outdoor around home)</td>
<td>0.03242</td>
<td>2435</td>
<td>2.289</td>
<td>0.0224</td>
</tr>
<tr>
<td>5 (outdoor on campus)</td>
<td>0.03031</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

T test comparison of 2 independent samples
Test at a significance level of $\alpha=0.05$

Microenvironment 4

Microenvironment 4 includes some indoor locations on campus: the Science and Engineering Library (SEL), Thompson Library, classrooms, and the Ohio Union. As displayed in table 7, the mean PM exposure level for the intervals the investigator spent in those four locations was 0.01064 mg/m$^3$. This was the lowest concentration among the five microenvironments. As roughly shown in Figure 3, mean PM
concentrations in SEL and in classroom were higher than those in Thompson Library and in Ohio Union. Exactly, mean PM concentrations by locations in microenvironment4 ranged from 0.00796 mg/m$^3$ in Thompson Library (location 8) to 0.0117 mg/m$^3$ in SEL (location 7).

![Figure 3. Mean Concentrations of Locations in Microenvironment 4](image)

As displayed in Table 12, the ANOVA test indicated that a statistical difference of mean PM concentration existed between locations (p<0.001). More details were explored through the Bonferroni test (see Table 13), which showed that, except for location 8 (Thompson Library) and location 10 (Ohio Union) (p=0.333), and location 7 (SEL) and location 9 (Classroom) (p=0.016), mean PM concentrations were statistically different between any other pair of locations.
Table 12. Comparison of PM Concentration by Locations in Microenvironment 4

<table>
<thead>
<tr>
<th>Source</th>
<th>SS</th>
<th>df</th>
<th>MS</th>
<th>F</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Between groups</td>
<td>0.03776</td>
<td>3</td>
<td>0.01259</td>
<td>114.23</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Within groups</td>
<td>1.56237</td>
<td>14181</td>
<td>0.00011</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

ANOVA test comparison of 4 independent samples
Test at a significance level of $\alpha$=0.05

Table 13. Comparison of PM Concentration by Locations in Microenvironment 4

<table>
<thead>
<tr>
<th>Location A v. location B</th>
<th>Calculated p-value</th>
<th>Mean difference (A-B)</th>
<th>Mean Microen A</th>
<th>Mean Microen B</th>
</tr>
</thead>
<tbody>
<tr>
<td>7 v.8 (SEL v. Thompson)</td>
<td>&lt;0.001</td>
<td>0.00374</td>
<td>0.01170</td>
<td>0.00796</td>
</tr>
<tr>
<td>7 v.9 (SEL v. Classroom)</td>
<td>0.016</td>
<td>0.00067</td>
<td>0.01170</td>
<td>0.01102</td>
</tr>
<tr>
<td>7 v.10 (SEL v. Ohio Union)</td>
<td>&lt;0.001</td>
<td>0.00366</td>
<td>0.01170</td>
<td>0.00804</td>
</tr>
<tr>
<td>8 v.9 (Thompson v. Classroom)</td>
<td>&lt;0.001</td>
<td>-0.00306</td>
<td>0.00796</td>
<td>0.01102</td>
</tr>
<tr>
<td>8 v.10 (Thompson v. Ohio Union)</td>
<td>0.333</td>
<td>-0.00008</td>
<td>0.00796</td>
<td>0.00804</td>
</tr>
<tr>
<td>9 v.10 (Classroom v. Ohio Union)</td>
<td>&lt;0.001</td>
<td>0.00298</td>
<td>0.01102</td>
<td>0.00804</td>
</tr>
</tbody>
</table>

Bonferroni test comparison of 2 independent samples
Test at a significance level of $\alpha$=0.008

4.2.1.3 Comparison between Indoor and Outdoor Environment

This section focuses on comparisons between mean PM concentrations of the indoor locations and those of the outdoor environment around specific indoor locations. Comparisons were conducted using a t-test. The results are shown in Table 14. For those indoor locations the investigator had stayed in during sampling days, the
mean indoor PM concentration was significantly different from that of the outdoor environment.

Table 14. Comparison of PM between Indoor and Outdoor

<table>
<thead>
<tr>
<th>Sampling day</th>
<th>Indoor location</th>
<th>PM concentration</th>
<th>I/O</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Indoor</td>
<td>Outdoor</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Thompson (morning)</td>
<td>0.00656</td>
<td>0.03429</td>
<td>0.1913</td>
</tr>
<tr>
<td></td>
<td>Thompson (evening)</td>
<td>0.006904</td>
<td>0.0328</td>
<td>0.2105</td>
</tr>
<tr>
<td>3</td>
<td>SEL (afternoon)</td>
<td>0.008599</td>
<td>0.03558</td>
<td>0.2417</td>
</tr>
<tr>
<td>4</td>
<td>Classroom (morning)</td>
<td>0.01226</td>
<td>0.05411</td>
<td>0.2267</td>
</tr>
<tr>
<td></td>
<td>SEL 1st floor (evening)</td>
<td>0.01618</td>
<td>0.05351</td>
<td>0.3023</td>
</tr>
<tr>
<td>5</td>
<td>Thompson (morning)</td>
<td>0.009138</td>
<td>0.03127</td>
<td>0.2923</td>
</tr>
<tr>
<td></td>
<td>SEL (afternoon)</td>
<td>0.005037</td>
<td>0.0205</td>
<td>0.2457</td>
</tr>
<tr>
<td>6</td>
<td>SEL (morning)</td>
<td>0.006178</td>
<td>0.02422</td>
<td>0.2551</td>
</tr>
<tr>
<td>7</td>
<td>SEL (afternoon)</td>
<td>0.003594</td>
<td>0.02628</td>
<td>0.1368</td>
</tr>
<tr>
<td></td>
<td>Thompson 11th floor (evening)</td>
<td>0.01027</td>
<td>0.02589</td>
<td>0.3965</td>
</tr>
<tr>
<td>8</td>
<td>Classroom (afternoon)</td>
<td>0.008842</td>
<td>0.02377</td>
<td>0.372</td>
</tr>
<tr>
<td>9</td>
<td>SEL 1st floor (afternoon)</td>
<td>0.01623</td>
<td>0.02841</td>
<td>0.5713</td>
</tr>
<tr>
<td></td>
<td>Ohio Union (afternoon)</td>
<td>0.00804</td>
<td>0.02346</td>
<td>0.3427</td>
</tr>
<tr>
<td></td>
<td>SEL (evening)</td>
<td>0.009307</td>
<td>0.02089</td>
<td>0.4456</td>
</tr>
<tr>
<td>10</td>
<td>SEL (afternoon)</td>
<td>0.01022</td>
<td>0.01902</td>
<td>0.5374</td>
</tr>
<tr>
<td>11</td>
<td>SEL (evening)</td>
<td>0.01399</td>
<td>0.04613</td>
<td>0.3011</td>
</tr>
</tbody>
</table>

4.2.2 Activities Contributing to Elevated PM Concentration

Five kinds of human activities have been noticed to significantly increase the PM concentration. Three of them were identified as particle sources that can directly emit the particulate matter. These included frying, cooking and smoking. The other two activities were floor sweeping and vacuuming, which are related to the re-suspension of particles. The increased PM concentrations related to these activities are separately shown in Figure 4.
Figure 4. Elevated PM Concentration due to Different Personal Activities

Table 15. Summary of the Results of Significantly Elevated PM Concentration due to Noted Activities in this Study

<table>
<thead>
<tr>
<th>Activities</th>
<th>N</th>
<th>Peak value</th>
<th>Ratio¹</th>
<th>Increased concentration (24-h mean) (μg/m³/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Mean</td>
<td>S.D</td>
<td>Mean</td>
</tr>
<tr>
<td>Cooking</td>
<td>5</td>
<td>0.1172</td>
<td>0.03763</td>
<td>6.545</td>
</tr>
<tr>
<td>Frying</td>
<td>7</td>
<td>1.951</td>
<td>1.043</td>
<td>116.4</td>
</tr>
<tr>
<td>Sweeping floor</td>
<td>1</td>
<td>0.141</td>
<td>1.043</td>
<td>116.4</td>
</tr>
<tr>
<td>Vacuuming</td>
<td>1</td>
<td>1.431</td>
<td>55.84</td>
<td>116.4</td>
</tr>
<tr>
<td>Smoking</td>
<td>1</td>
<td>0.142</td>
<td>4.733</td>
<td>116.4</td>
</tr>
<tr>
<td>Smoking¹</td>
<td>1</td>
<td>0.142</td>
<td>4.733</td>
<td>116.4</td>
</tr>
</tbody>
</table>

¹Ratio: peak value to background value.
²enter the room with a smoker who just finished a cigarette 40 minutes ago.
As indicated in Table 15, frying (mean peak value: 1.951 mg/m$^3$) and vacuuming (peak value: 1.431 mg/m$^3$) can suddenly increase PM concentration to particularly high levels. Additionally, ratio of peak concentration caused by one activity to the background level was calculated to indicate significantly elevated concentration level due to that activity. Increases were observed over the background concentration by about 5, 115, 10, 54 and 3 times during cooking, frying, floor sweeping, vacuuming and smoking, respectively. To thoroughly assess the impact of these activities on personal exposure, in terms of both elevated concentration and lasting duration, the increased 24-hr averaged concentration was calculated. Surprisingly, the mean of daily increased concentration due to every frying was 13.93 µg /m$^3$/day, with a largest value adding up to 51.04 µg/m$^3$/day of PM concentration per frying. The high-mean peak concentrations due to these activities can exceed the US EPA PM$_{2.5}$ 24-h standards of 35 µg/m$^3$.

4.2.3 Geo-Visualization with Spatial and Temporal Information
As the above figure (Figure 5) depicts, this approach involves a model within a GIS (ArcGIS): time–activity based exposure model. With the “WGS-84” datum (Geography Coordinate System), “state plane” was applied to this area as a projected coordinate system. With this model, geospatial, temporal, and numerical information were combined and presented at each point in the map—to show the exposure profiles visually. With this representation, the subject’s movement is quite clear throughout the interval while still gaining a sense of the timing and magnitude of measured
personal PM levels. Details of the PM levels are provided in Figure 6. They show that there was an interval with elevated PM level around 19:36, when the subject was around the OSU Medical Center. According to the documents of the voice recorder, the building around that point was under construction. Besides this, the PM levels along the roads on campus were relatively stable and lower than other roads, such as Olentangy River Road.

Figure 6. Time-series of Personal PM Exposure Levels
Chapter 5: Discussion

5.1 Overview

Data collected in this study were used to test three hypotheses: comparison of PM concentration by microenvironment (4 microenvironments), comparison of locations in the same microenvironment, comparison of PM concentration between indoor and outdoor environments. Several personal activities were included in statistical analysis to explore their potential to increase PM exposure levels, and further to demonstrate the variability of personal exposure due to these activities. Moreover, geo-visualization was applied to visualize the temporal and spatial information together. In essence, in order to present a space-time method of the personal exposure assessment, the continuous PM concentration data and corresponding GPS data were combined with the microenvironmental approach. This new approach was adopted to statistically analyze the relationships between PM concentration from different perspectives, with geo-visualization techniques to visualize the PM distribution in both space and time dimensions.

5.2 Summary of Results

The study indicated that, with the exception of microenvironment 1 (in transit) and microenvironment 2 (outdoors), statistical differences existed between all other microenvironments. Further analysis suggested that among the three kinds of
transportation, PM concentration levels in a COTA bus and a car were not significantly different from the outdoor environments (both outdoor around home and outdoor on campus) \((p=0.333)\). Some studies conducted to compare personal exposure levels in difference transport microenvironments have come to the similar conclusion (Gulliver and Briggs, 2004; Morabia et al., 2009). Comparison of the PM concentration levels between in-shuttle and outdoor environments showed a statistical difference \((p<0.001)\).

This statement coincided with the test result for the second hypothesis: that the PM concentration levels in a car \((0.02703 \text{ mg/m}^3)\) and in a COTA bus \((0.02881 \text{ mg/m}^3)\) were not statistically different from each other, but they were both statistically different from the PM levels in a shuttle \((0.09129 \text{ mg/m}^3)\). This phenomenon is explainable. The car and COTA bus were either mechanically (by an HVAC system) or naturally (with most of the windows open) ventilated. The shuttle with sealed windows, however, did not have an HVAC system, and was ventilated only with a small air fan.

In addition, a parametric statistical analysis of the data for other comparisons showed the statistical difference of PM levels between the locations in the same microenvironment and between the outdoor environment and indoor, except for Thompson Library and the Ohio Union \((p=0.333)\), and SEL and classroom \((p=0.016)\) in microenvironment 4. Details of these locations and buildings can be found in the Appendix A (Table 17). At least, from the year of construction, Thompson Library and the Ohio Union are much closer to each other, compared to other locations.
The elevated concentration level due to one activity largely was different from another same activity. Simply put, source strengths varied. For activities those were related to re-suspension of particles, for example, vacuuming, the elevated level could largely depend on vigor of activity, dust loading and materials of furnishings (Ferro et al., 2004a). Collected data in this study is limited to observe the difference of elevated PM levels due to re-suspension of particles with different settings. The largest rise of concentration level caused by frying occurred on April 3rd, which resulted in a concentration of 51.04 µg/m³ (24-hr mean) in the apartment. The 24-hr adjusted exposure level of that day (64.64 µg/m³) far exceeded the EPA guidelines for the 24-hr exposure level. On the other hand, frying also occurred on the same day, adding 1.094 µg/m³ (24-hr mean) of particles, the smallest level increased measured as a result of this activity. Many factors may explain the difference between these two cases, such as the frying temperature, the procedure, and the materials (He, et al., 2004).

In the geo-visualization, there is one prerequisite for the data to form the map: the GPS data and the PM data should correspond point to point. Except for the tips discussed earlier to control the synchronization of the equipment, there may be still some inevitable situations that disturb the GPS recording so that it cannot be matched to the stable PM level data. For those GPS points, we assumed that between 2 recording points (10-s intervals), the subject was moving linearly at the same speed, so we can simply get the geographic data at the same point with the PM level data. However, the geographic data the “BT-335” recorded followed spherical coordinates,
which cannot be used to calculate the distance on the flat level. Therefore, the map projection was necessary, not only in order to present the personal movement on a flat level, but also to get the plane coordinates for the calculation of the point adjustment.

5.3 Limitations

There are several limitations to this study. As a study intended to develop a space-time method for personal exposure assessment, it is reasonable that the emphasis lies in the application of the method, with further analyses based on that. However, the number of subjects in this study should still be counted as the main limitation. Monotonous data sources could result in bias. For example, it is quite possible that significant variability of PM level exists in a library. When calculating the average concentration of this building, it is important to try to figure out under what circumstances the investigator would be exposed to a lower concentration. This kind of variability may be ignored by the monitoring data from one subject. Another problem related with the study design is in the division of the microenvironments into categories. We did not apply any scientifically justified microenvironment definitions, which might cause misclassification.

In terms of measurement and equipment, it was identified that high relative humidity (RH) affected pDR measurements outdoors, even when a heater was used (Wu, et al., 2005). Therefore, a humidistat should be used with pDR in further studies. Moreover, due to limitations with the instrument, PM< 0.1μm cannot be quantified. As a result, PM levels could be higher than what we read from the pDR.
As mentioned above, size, number and chemical composition of particulate matter all determine the severity of its effect on health due to exposure to particle pollution. In this study, the chemical composition of particulate matter was not analyzed. It is beneficial to know the chemical composition, which also varies over space and time. However, we do not adjudge this to be an important limitation of this study. As we discussed in the Health Effect section, very well-done studies have found the correlations between PM$_{2.5}$ and PM$_{10}$ concentrations and adverse health effects, as well as mortality. These indicate that, to some extent, the concentration of particulate matter itself can be an indicator of adverse impacts and worth investigating.

Meteorological data was measured by monitoring station around the OSU campus airport. However, this data was not accurate enough for this study. Variability in the relative humidity and temperature between different locations called for the specific measurement of those locations. One of the main objectives in this study is to compare the PM concentration in different environments. However, in order to explain this difference, or explore it more deeply, precise meteorological data is a predominant factor to consider. Therefore, it would be beneficial to get data of the temperature and relative humidity in every studied location to further explore those differences.

5.4 Recommendations for Future Studies

1. Repeat this study for more subjects; compare investigator PM exposure with different lifestyles to further demonstrate the potential factors that impact personal exposure.
2. Repeat this study with several continuous monitoring days, to compare the exposure level when the investigator (and surroundings) are motionless to other situations.

3. Repeat this study to explore the personal exposure levels with different cultures of cooking in a typical American-style house with an open kitchen.

4. Repeat this study with a fixed monitor at home to compare the difference of two PM concentration monitors.

5. Design a large study to monitor elevated PM levels due to personal activities in different indoor settings to explore source strengths of different personal activities, and to demonstrate their ability to statistically increase personal exposure levels.
Chapter 6: Conclusions

The conclusions for hypotheses tests in this study are as follows:

1. There were differences of the PM concentration between: in transit and indoor at home (p<0.001), in transit and indoor on campus (p<0.001), outdoor and indoor at home (p<0.001), and indoor at home and indoor on campus (p<0.001). The mean concentration levels of microenvironments during monitoring were measured in the following rank order (highest to lowest): indoor at home, in transit, outdoor, and indoor on campus.

2. Within the same class of microenvironment, we further observed concentration differences by subtype (p<0.001). For transportation, differences were observed by type of transportation in the following rank order (highest to lowest): car and shuttle (p<0.001), and COTA bus and shuttle (p<0.001); For outdoor, difference was observed between outdoor around home and outdoor on campus (p=0.0224); For indoor on campus , differences were observed by indoor locations on campus in the following rank order (highest to lowest): SEL and Thompson (p<0.001), SEL and Ohio Union (p<0.001), Thompson and classroom (p<0.001), and Ohio Union and classroom (p<0.001).

3. There were statistical differences of PM concentration between indoor and outdoor environments at SEL, Thompson Library, the classroom, and the Ohio
Union (p<0.001).

4. For microenvironments, no difference of PM concentration was observed between in transit and outdoor (p=0.140); For subtypes, no difference of PM concentration was observed between car and COTA bus (p=0.333) within microenvironment 1 (in transit), as well as between Thompson and the Ohio Union (p=0.333) and between SEL and classroom (p=0.016) within microenvironment 4 (indoor on campus).

It is hoped that future developments in personal exposure monitoring may lead to more accurate exposure assessments, and subsequently, epidemiologic studies with less measurement bias and more accurate results.
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Appendix A: Additional Tables
Table 16. Meteorological Conditions for each Sampling Day

<table>
<thead>
<tr>
<th>Sampling day</th>
<th>Mean Temperature (°F)</th>
<th>Avg. Relative Humidity (%)</th>
<th>Avg. Wind Speed (MPH)</th>
</tr>
</thead>
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<tr>
<td>1</td>
<td>30.6</td>
<td>92</td>
<td>6.13</td>
</tr>
<tr>
<td>2</td>
<td>44</td>
<td>61</td>
<td>8.15</td>
</tr>
<tr>
<td>3</td>
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</tr>
<tr>
<td>Location</td>
<td>Flooring Material</td>
<td>Year Built</td>
<td>Construction</td>
</tr>
<tr>
<td>---------------------------</td>
<td>----------------------------</td>
<td>------------------------</td>
<td>------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Science &amp; Engineering Library</td>
<td>Carpet &amp; Concrete &amp; Wood</td>
<td>1991</td>
<td>Steel frame; Masonry skin</td>
</tr>
<tr>
<td>Thompson Library</td>
<td>Granite &amp; Cork flooring; Italian Marble Staircase; Carpet in limited areas</td>
<td>Newly Renovated, Re-opened in 2009</td>
<td>Two skylights consisting of laminated glass; Reinforced concrete and steel frame with limestone exterior; Atriums and open study/gathering environment created;</td>
</tr>
<tr>
<td>Ohio Union</td>
<td>Wood &amp; Carpet</td>
<td>Newly Renovated, Re-opened in 2010</td>
<td>Operable windows; Atrium and open area; LEED certified, according to U.S. Green Building Council</td>
</tr>
<tr>
<td>Home (Apartment)</td>
<td>Tile in washing room and kitchen &amp; Carpet in other areas</td>
<td>N/P</td>
<td>Open kitchen</td>
</tr>
</tbody>
</table>