Pedestrians' Exposure to Air Pollution: PM2.5, The case for International District, Seattle

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Abstract

Pedestrians are always near to vehicular traffic and street-side activities, chief sources of outdoor air pollution, and are directly exposed to it. Different activities produce pollutants, which affects pedestrians directly. In this thesis, it was tried to find the level of exposure and sources of PM2.5, one of the six 'criteria pollutants' designated by United States Environmental Protection Agency, along a roadways in a busy mixed use area in International District, Seattle, which has a good connectivity to transit. The aim of this experiment is to find out sources of PM2.5 emission that affects pedestrians directly while walking, and its level/concentration. The data was collected while walking with the help of a backpack nephelometer, in both winter (Dec 31st, 2014- Jan 9th, 2015) and spring (March 21st - March 30th , 2015) seasons, for 3 times a day, 20 days total to find out pollution levels at different times of a day and seasonal trends . Field collected data was also compared with the nearby fixed-site monitoring stations to understand the difference, if any, between the data recorded and the actual level of pollution pedestrians are exposed to. The result shows that winter is more polluted than spring, and in morning pollution level is much higher than other times of the day. The reasons behind the pollution have been identified as vehicular traffic, construction activity and roadside smoking, along with weather condition. A linear regression model was fit to observe whether the pollutant level at near road are similar to monitoring station data, and was also subjected to ANOVA test. However, it has been acknowledged that several factors may affect the difference between the two, which could not be fitted exactly in a linear model, rather than providing a probabilistic scenario.

Acknowledgements-

The author expresses enormous gratitude to Professor Christine Bae and Professor Qing Shen for their support, advice and guidance. The author is enormously indebted to Mr. Matthew Harper and Puget Sound Clean Air Agency for helping him at every queries. The author would also like to thank Professor Don Miller and Ms. Heather McAuliffe for guidance and advice. Also, to Professor Alon Bassok for teaching R, without which tool it could not be done.

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1. Introduction & Research questions

It is no new knowledge that air pollution affects human kind greatly. In small geographic scale or in individual level, it can cause subtle diseases like nausea to critical ones like cancer. In global scale, air pollution is cited as primary reason for climate change, attributing to accumulation of greenhouse gases (GHG), and stratospheric ozone layer depletion.

Walking is the global mode of individual transportation. Every able bodied person walks, to access facilities within convenient distance. It is the only mode that is convenient to people of all economic classes as well as the one mode that necessarily need no capital to initiate, which is a required condition for even cycling.

Concentrating upon the case for the United States, it is often observed from the past decades' statistics and data, that as for commuting, walking is not the preferred one, except for fiscal constraints (US Census, 2010, US Community Survey, 2007). The most frequent mode of commute is driving, single-occupancy vehicle as the largest proportion. From the data we get that only 2.9% of the commuters surveyed walks to their job.

However, it should be noted that walking is also an essential mode while using some other modes of transportation to commute. People using transit to commute does walk to the nearest transit stops from home, walks at the interchanges as well as from transit center/stop to office/businesses. They are also as likely to get affected by air pollution as they are walking as the people use only walking as their commute medium.

Here's the arguments in favor of why vulnerability to air pollution is more for pedestrians than other mode of transportation-

● to travel the same distance, pedestrians are most exposed group to urban pollution, if considered time wise.

● though people in some countries occasionally use masks to cover from pollution, still most of them do not have anything to protect from inhaling the polluted air. Whereas, people travelling through mass transit or cars are not that directly exposed to the air, as they are in a controlled environment.

Added to the fact, historically, most of the researches done on air quality standards is based on analyzing data from monitoring stations, which are stationary, often located far from the pedestrians' path and other polluting street-level or on-road sources, while in reality pedestrians' path and some common pollutant sources(vehicles, construction sites, combustion etc.) are often situated side by side. There's opportunity to study whether the exact exposure level, as experienced by the pedestrians is getting recorded in the monitoring stations measuring ambient air quality of an area.

To estimate the pollutant exposure level to pedestrians, and to determine how exact the exposure level is getting measured by the monitoring station quantified pollutant level, following questions was raised as the main study goal for this research-

- What are the level of pedestrian exposure to air pollution? What are possible sources?
- Where are the nodes in an area heavily used by pedestrians where people are affected by severe level of pollutants present in the air? What are possible sources?
- Does these pollutant quantity gets reflected in the data collected at the monitoring stations? If yes, up to which extent (is there a correlation?)

2. Literature review

2.1 Particulate matter and origin

Atmospheric particulate matter or particulate matter (PM) or particulates is the small solid particles present in Earth's atmosphere. The term aerosol commonly refers to the particulate/air mixture, as opposed to the particulate matter alone. Sources of particulate matter can be man-made or natural. The major natural activity responsible for airborne particulate matter includes volcanic eruption, wildfire, landslide and seismic activity, though activities far less in scale and magnitude like waterfalls, pollination etc. can also increase particulate matter concentration in the nearby area(WA State Dept. of Health, 2014). Human activities, responsible for pollution majorly include different combustion activities, from burning of wood and other stuffs, as well as vehicular emissions, industrial emissions, or activities concerning changing landform like earth excavation, construction etc. Fine particulate matter are also likely to be produced by various types of airborne gases (EPA, 2008). They have impacts on climate and precipitation that adversely affect human health. Among various types of particles include suspended particulate matter (SPM), Respirable Suspended Particle (RSP; particles with diameter of 10 micrometers or less), fine particles (diameter of 2.5 micrometers or less), ultrafine particles, and soot (EPA website, 2015).

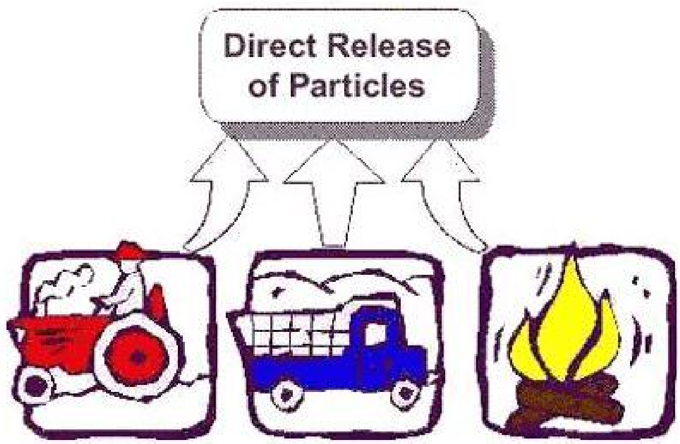


Figure 1 Particulate matter origin- direct, P.C- Bay Area Air Quality Management Dist.

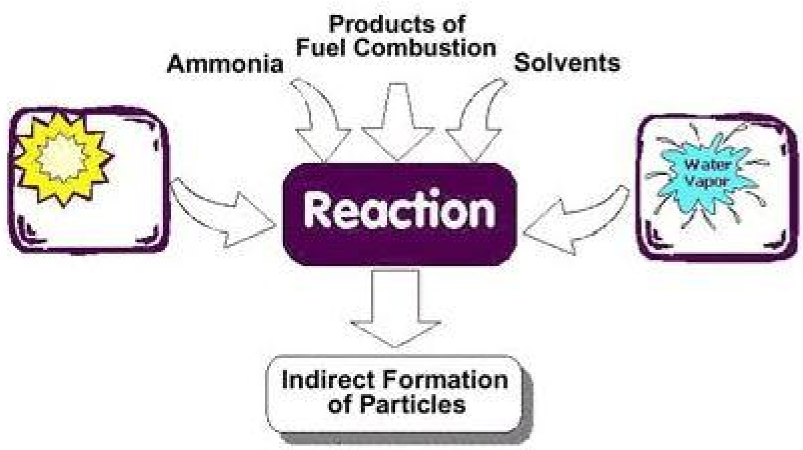


Figure 2Particulate matter origin- indirect P.C- Bay Area Air Quality Management Dist.

The International Agency for Research on Cancer (IARC) and World Health Organization(WHO) has designate airborne particulates a Group 1 carcinogen, or reagents that are definite to have a causal relationship with different types of cancer, especially lung cancer(IARC Press releases, 2013; IARC, 2013). The IARC collected data shows that worldwide, 223,000 lung cancer deaths have been caused by air pollution (IARC, 2013).

Particulate matters are one of the deadliest air pollutants due to their ability to penetrate deep into the lungs and blood streams unfiltered, causing permanent DNA mutations, heart attacks, and premature death (WHO, 2005). In 2013, a study involving 312,944 people in nine European countries revealed that there was no safe level of particulates and that for every increase of 10 μg/m^3 in PM10, the lung cancer rate rose 2.2%. The smaller PM2.5, and ultrafine particles were particularly deadly, with a 36% increase in lung cancer per 10 μg/m^3 as it can penetrate deeper into the lungs. Smaller particles can pass through the smaller airways. They are the most harmful, as they can infuse in the blood once inhaled inside. It can pass through the semipermeable membrane of human lungs alveoli and get into blood circulation, and hence major organs of our body.

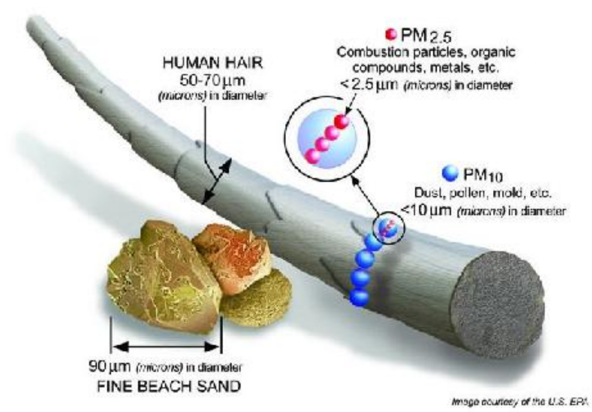


Figure 3 Size comparison of particulate matter- EPA

2.2 Pedestrian's exposure to particulate matter

Studies historically measured data available from the static monitoring station but a few have been done by measuring air pollution while being mobile. Two major studies have covered some aspects of the rationale. Study in London, by dynamic measuring, assigning four volunteers in a 12 day exercise to measure PM2.5, UFP and Carbon Monoxide gas present in the air (Kaur et.al, 2005). They found the levels of personal exposure varies significantly from the data obtained from the monitoring site, opposite sidewalks does not match with each other, as well as morning time measurement shows higher concentration than evening. A study in Seattle area to measure bicyclist's exposure to air pollution (Hong and Bae, 2012), measuring black carbon (size 0.1- 10 µm), showed similar trend, where personal monitoring values were greater than the monitoring station values and showed a trend of higher concentration at morning, as well the monitoring station values shows similar behavior to individual exposure/measurement, though there is difference between the two values at the same time. However, studies of pedestrians' exposure to air pollution is scarce, though a growing momentum has been observed in recent studies to measure specific groups as targeted individual and effect of pollution on them(EPA, 2014, Moore et.al., 2013).

2.3 Hazardous effect of particulate matter

Several epidemiological studies has been done to quantify PM2.5's effect on human health. Researchers quantified the studies in short- term and long term PM2.5 exposure, both have shown that it has causal relationship with several type of syndromes and diseases (WHO, 2004, EPA, 2009). With the concentration of PM2.5 level, the more people gets affected, i.e., it has a positive correlation short term exposure have been identified having causal relationship with the broad categories of Asthma, cardiovascular diseases and mortality (Chimona & Gessner et. al, 2007, Lisabeth et.al., 2008, Fung et.al., 2006, Pope et.al., Ito et.al, 2007). These studies, along with others shows that even when the mean concentration for a 24 hour time is below 15 $\mu g/m^3$ concentration, hence exposure and dose have a positive correlation with increase of mentioned health hazards.

Long term exposure to PM2.5 was found positively correlated with asthma, cardiovascular diseases and mortality, as well as reproductive and developmental malfunctioning, and cancer (Miller et. al., 2007, Kim et. al., 2004, etc.). In a mean concentration of 10.7- 29 $\mu g/m^3$, the risk factor increases to an average of 1.2 for all studies conducted for each 10 μg/m^3 increase in concentration. Chen et.al, 2005, found that Coronary Heart Disease (CHD) mortality rate increases for females, but not much in male subjects.

Experiments and researches have also found that PM2.5 has a causal relationship with visibility, climate, and materials, as well as a likely relationship with ecological effects. (US EPA, Integrated Science Assessment for Particulate Matter, 2009)

2.4 Studies in Seattle area

Few studies have been done in Seattle area to estimate pollution, both by Puget Sound Clean Air Agency (PSCAA) and individual researchers. Researches and evaluation done by PSCAA have estimated the type of pollutants present in the area for central Puget Sound area. In a 2009 study, it has been found that the winter time concentration of particulate matter is much higher than the summer time, and concluded that one major factor may be wood smoke emitting from the heating system. It concludes that the particle pollution in the area is mostly contributed by diesel particulate matter (PSCAA, 2009). Bassok et.al., 2009, estimated pollution in the FAPS(Freeway Air Pollution Shed, Bae et.al., 2007) in the International District, Seattle by mobile monitoring and found that the pollution level vary within the study area to great extent. However, no studies related to only pedestrian's exposure in the area have been found. Evaluation of Air quality in the area have shown that the major sources in the area are vehicular pollution, generating diesel particulate matter as found analyzing data from the monitoring stations (PSCAA, 2010, 2014). However, in residential areas wood burning have significant impact on ambient air quality (PSCAA, 2010). To evaluate global trends of PM2.5 and its effect on human, WHO have specified that the effect and exposure level is space dependent, and several small climatic factors are instrumental. Thus, it could be concluded that though, most of the studies show a positive causal relationship of air pollution and health hazards, they cannot be put down to an empirical formula, rather should be judged at the local or regional level to get a better picture of the pollution and effects (WHO, 2004).

3. Conceptual framework

3.1 Particulate matter and PM2.5

One of the component of common air pollutants is particulate matter, or sometimes called aerosol. They are divided into three separate categories by the size,

1. PM10- Particulate matters having a diameter of 10 µm to 2.5 µm.
2. PM2.5- Particulate matter having a diameter of 2.5 µm to 1.0 µm.
3. Ultrafine Particles (UFP) - particulate matter present having a diameter of less than 1.0 µm.

In another terminology, PM10 is often called course particles, and PM2.5 as fine particles. PM2.5 is a hazardous pollutant, designated as one of the criteria pollutant by the United States Environmental Protection Agency (EPA). EPA defines particulate matter as the particles suspended in air, in the size range of 2.5 or smaller diameter. By the Clean Air Act of 1990, EPA has established National Ambient Air Quality Standard (NAAQS), to monitor six common pollutants, which includes particulate matter. In recent times, EPA also designated PM2.5 as cancerous, after the research published by International Agency for Research on Cancer(IARC) and adopted by World health Organization(WHO) in 2013 (IARC Press Release, Oct 17, 2013).

3.1 Concept of exposure

A concept of exposure science need to be clarified to understand how external factors and human body plays a role in the scenario. The concept of exposure is defined by International Programme on Chemical Safety (IPCS), 2004 is,” ..contact between an agent and a target..” where agent has been defined as a chemical, biological or physical entity, and target as the individual, body or organism coming in contact.

The concept of exposure and its effects are different. Exposure occurs when the agent and the target is close or in physical contact, but that does not imply the target is being harmed due to exposure with the agent. The concept of ‘dose’ clarifies the situation, which could be defined as the amount of exposure to an agent that reacts with the human body (EPA, 2009). Epidemiological studies conduct research about the effect of agents inside the body once inserted in high dose (both in short time or over a longer time period). Exposure science on the other hand, does not deal with internal physical processes or diseases, but does quantify the exposure level, from both the perspective of concentration of agents and targets. From the results found of both type of studies and the researches done at the junction of the two, we can safely assume that exposure does control dose in both spatial and temporal pattern, and also considers the target population who are being exposed to agents. EPA also relates activity patterns to exposure level, as different types of physical activities result in different breathing rate and other physiological processes (EPA, 2003). The figure below depicts a comprehensive relationship in consideration for health hazard between the two, and estimates how they are interrelated.

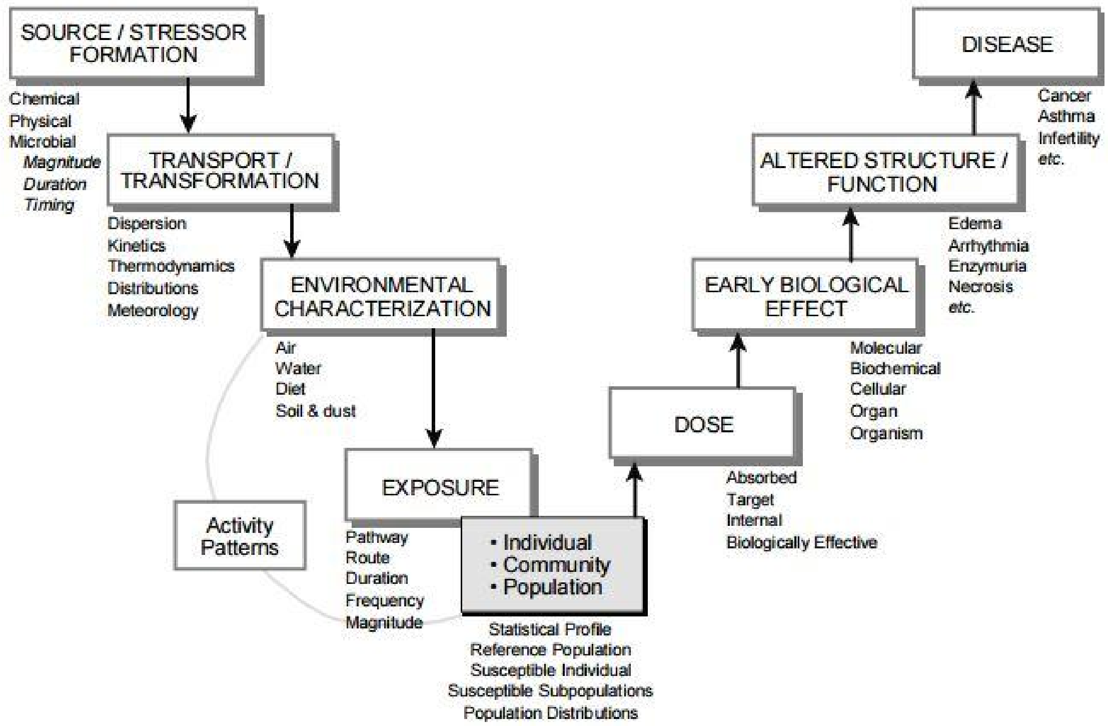


Figure 4: Scientific elements of human health risk assessment, (EPA 2003)

3.2 Concept of Pedestrians' Exposure

The term pedestrian generally refers to people in the state of on foot outdoors, walking on the street. Sometimes it may be contradicted with the fact that they should be in motion, but though that is the general notion, from the exposure point of view, anybody in the outdoors, walking, running or static at one point of time could be termed as pedestrian. In fact, people standing stagnantly at a position, or moving slowly than usual average walking speed is more exposed than people passing by, because the time spent in a polluted microclimatic environment is much more, which increases the cumulative exposure to pollutants.

As pedestrians pass by several types of human activities present on or beside sidewalks, they are affected by the pollution emitted by those activities. The breathing rate becomes factual in calculation the dose from exposure, and adds to the cumulative intake of air pollutants.

Immunity system of individual are also an important factor because resistive power of a human body decides how much cumulative dose can overpower the immune system and diseases can appear. In this regard, scientific studies show that children and aged people are more prone to suffer by same amount of dose than healthy individual due to less immunity. Elder people are also more prone to be in health hazard due to their reduced speed of moving, loss of muscle and more importantly because of the deterioration of their immune system (EPA 2014).

Figure 5 Report of pollution level experienced by pedestrians, cyclists, auto-commuters, Delhi, Source- Hindustan Times, February 2015

3.3 Types of Ambient air monitoring

Ambient air quality monitoring is done by FRM (Federal Regulated Methods), which was initially evaluation of year-long data. However, in recent times with the advancement of technology, 24 hour FRM and instantaneous monitoring is also possible. The problem with most of the FRM, though rated as the gold-standard measurement(EPA, 2015), is that they need time, sometimes 6-8 weeks to be analyzed once data have been collected(MARAMA, 2014). Thus, instant monitoring is not possible. New method which has been found statistically significant in comparison to FRMs, have been categorized as FEM (Federal Equivalent Method). However, none of the methods target a specific population by characteristics like commute mode share etc., while people of different mode share experience different level of pollution in the ambient air. Activities in different mode also plays a key role as some modes are more exercise oriented, (e.g., biking and walking) than other modes, hence pollution exposure and doses are different for each mode (BIgazzi, 2013).

PSCAA does monitor ambient air quality by fixed site monitors within its regional network of monitoring stations.

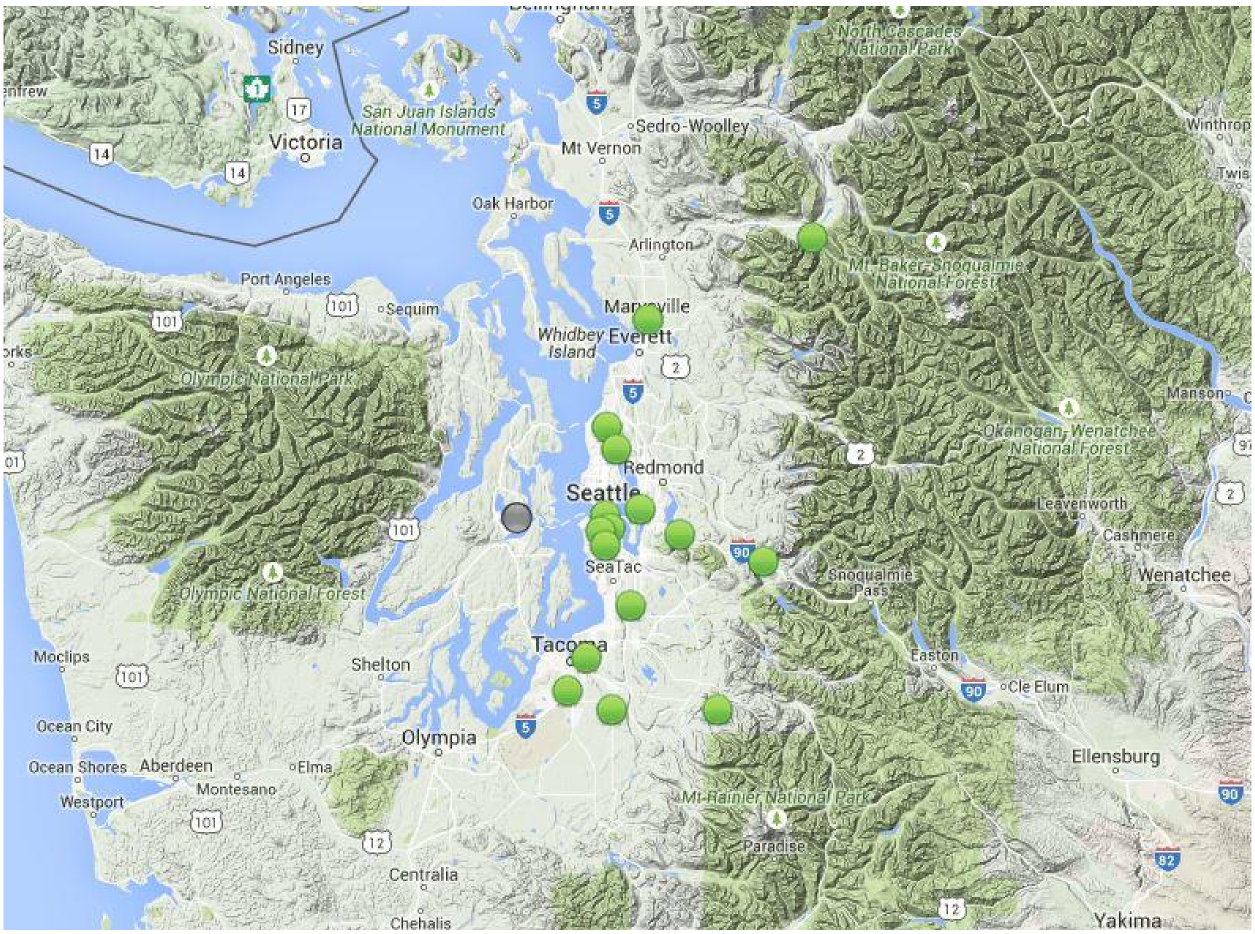


Figure 6 Monitoring Station Network of PSCAA

The monitoring stations consists of several types of monitor, and they measure ambient air quality by direct or indirect measurement. Direct measurement include directly quantifying the pollutant present in the air, e.g., carbon filters, while indirect measurements are measurement of certain properties of some element that has a significant correlation with pollutant quantity present in the air. Nephelometer, used at various sites to monitor air quality is such an indirect method that measures light scattering, rather than particulate matter concentration. High correlation between light scattering and density of fine particles in the air have made it possible to estimate particulate matter concentration in a given area by measuring light scattering observation (WA State Dept. of Ecology, 2008). Duwamish river valley within the PSCAA network use nephelometer to estimate level of pollution. PSCAA's Weller St. Station, located near the freeway I-5, monitors PM2.5 value by direct measurement. It is unconventional in the sense that this is one of the few near road monitoring station, while the ambient air quality standard have been historically measured by monitoring station distant from the direct exposure to pollutants.

The problem with near road static monitoring is that it quantifies pollution perfectly from a certain type of emitter but different kind of activities could not be registered simultaneously due to excessive dominance of one. Different on-road or roadside activities produce different type and amount of pollutants, but dominance of one particular factor can affect understanding of the comprehensive picture of the area as a whole. While evaluating the data from one such station, it was found that the pollution level shows little deviation with time, compared to other monitoring stations, indicating that within short time-span, similar traffic flow results in such flat graphs, and other activities are being dominated by the traffic related air pollution. Similarly, a major problem with fixed site monitoring is that it is often far from the pollutant sources and could not quantify pedestrians' exposure at the truest level. Often seen is that the exposed population or target is nearer to various pollutant sources than fixed site monitors, and experience a different level of exposure to pollutants.

3.4 Mobile monitoring

To estimate spatial variability of pollutant concentration, mobile monitoring have been often used in an area. The process integrates air quality monitoring device with a vehicle, and collects pollutant quantity data, matching it with spatial coordinates /GPS to locate potential Hot-spots, or areas with higher concentration of pollutants. PSCAA have used mobile monitoring in Tacoma for air quality evaluation in 2009, and using it since in different places to estimate spatial variability of pollutants in a geographic region (PSCAA, 2014, Harper, 2015, T&E class presentation).

3.5 Personal monitoring

With the advancement in technology air quality sensors have become smaller and lighter so that it be carried by individuals. A personal monitoring methodology is similar to mobile monitoring in many ways, except for the fact that personal monitoring devices are often smaller than used in mobile monitoring. Another difference between personal monitoring and mobile monitoring is that the portable monitoring devices used for air quality measurement can be kept at areas of interest for longer hours, but personal monitoring is generally small time evaluation, and continuously dynamic, as the user is.

Several types of personal monitoring device became available nowadays, often within modest price range. These includes Micro-Aeth, Aircasting devices, and others. Smartphones and GPS devices, which are readily available could be easily coordinated with the personal monitoring devices that collects the data and maps it spatially to indicate areas of higher pollution concentration.

3.6 Choice of Monitoring

The experiment requires behavior mimicking pedestrian to quantify the exposure. Pedestrians being dynamic, exposure level cannot be mimicked by any fixed monitoring site. Another comprehensive option could be to install several monitoring device in the designated route in certain intervals and getting continuous air quality data to get a comprehensive picture. However, neither that kind of resource nor permission could be availed for such kind of study. The ultimate choice, thus was personal monitoring, as it mimics pedestrians' behavior best.

An assumption made in the conceptual framework and used in the experiment is that the pedestrians are commuters or behave like commuters, and use sidewalks than alternative walking trails or alleyways as the environment of the experiment was determined to be a dense urban neighborhood.

3.7 Difference between author's method vs. EPA and State methodology

As mentioned, the major difference between the two is the choice of monitoring type. Personal monitoring was preferred for the experiment for several reasons including pedestrians do not stay on road all the time, neither they are static. Also, they experience different levels of air pollutants from different sources while walking, as the built environment, infrastructure level and demography varies within the entire route.

Another difference between the two was the method of identification of various sources. With available technology and resources, a rigorous network and years of study, SLAMS(State and Local Air Monitoring Stations) and State Department of Ecology have extensive knowledge of which pollutant are emitted by which sources and their chemical characteristics. To identify sources of pollutants within this experiment, the author needed to gather some evidence that does not include rigorous chemical analysis, rather than determines sources probabilistic by evidence. Photographic evidence seemed perfect for that type of an analysis, to record and understand human activities along sidewalks that essentially worsens the air quality in nearby microenvironment.

Two methods also differ in spatial scale. EPA and State are spread over a larger area consisting of urban, suburban and rural and preserved lands. The scale of this experiment is much smaller and limited to a particular neighborhood with interesting characteristics that may produce interesting results, but effective as it should be well used by pedestrians, and have reasons for commuting by walk.

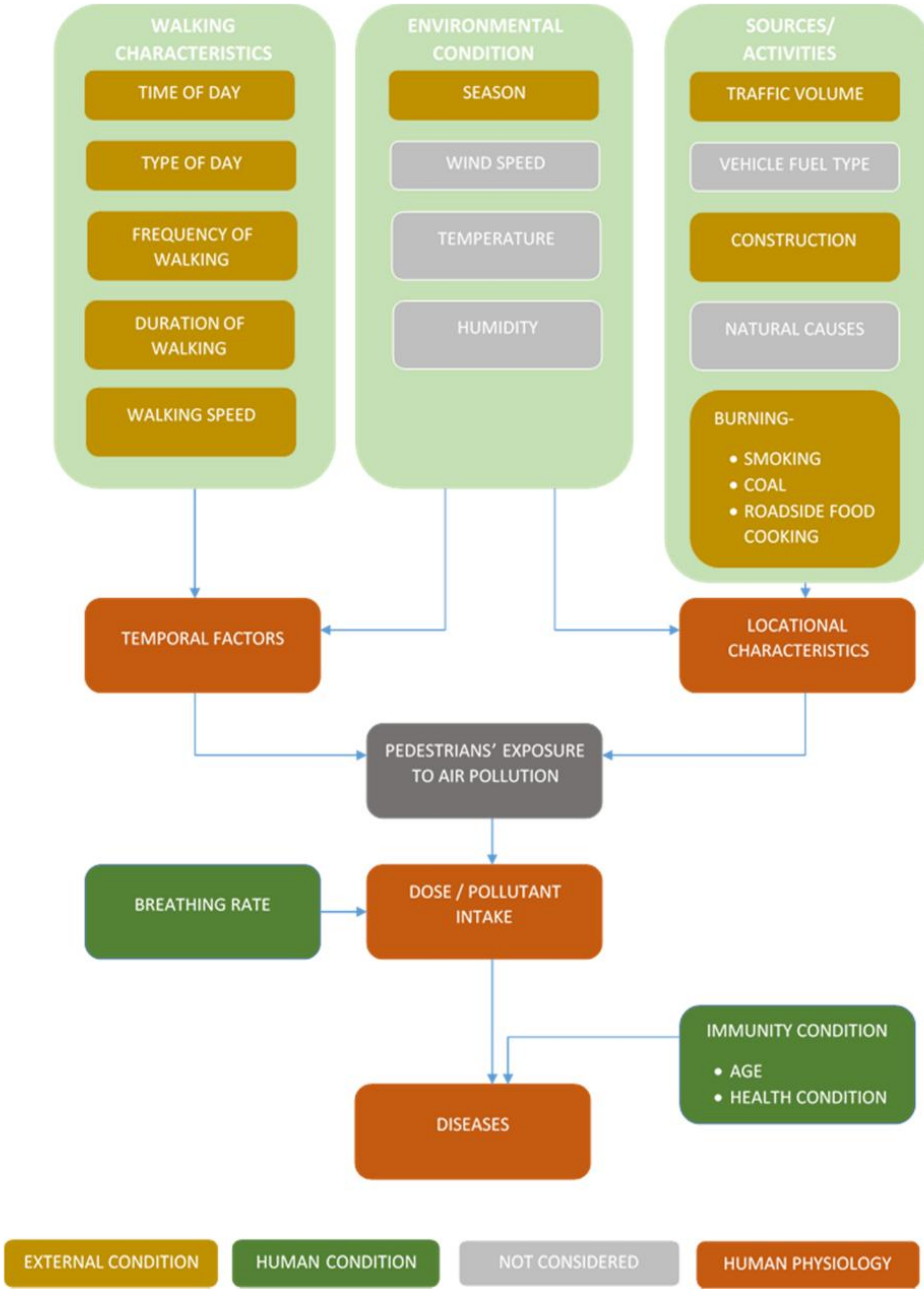


Figure 7 Conceptual framework of pedestrians' exposure to air pollution

4. Methodology

4.1 Site Selection

To obtain solutions for the queries, near-road pollution exposure data needed to obtain, as mentioned before. The writer compared several factors among the potential places accessible to him, those represent a unique feature that can be regarded as a point of high pedestrian activity for commuters. The initial shortlist consisted three places,

1. Westlake Station and Third Avenue, Downtown Seattle.

2. University District and University Way NE, U-district, Seattle

3. Areas surrounding International District tunnel station, Seattle.

Upon careful consideration, International District has been selected due to several reasons, which includes-

1. Transportation and Transit variability- The area is unique within Seattle considering all the transit option it provides. International District tunnel station is connected t Westlake Station/Downtown Seattle to SeaTac International Airport through Link Lightrail, whose stations produce a lot of commuters who commute to Seattle every day. SoundTransit buses are used by people residing within the four central Puget Sound counties, namely King, Kitsap, Snohomish and Pierce. People from Pierce county and southern King county commutes through buses that stops at International District Station. Several routes served by King County Metro also passes through the transit tunnel. King Street Railway station is located next to transit tunnel, which is served by Amtrak and Sounder Train, moving people and freight to and from central Puget Sound area. On Surface, the area is served by several routes served by King County Metro, as

well as several long distance inter-city buses. One nearby lane have bike lane, and lots of car-commuting traffic within the area (2013 Annual Average Daily Traffic at S. Jackson St. - 13700, SDOT, 2015). It is evident that the area is well served by transit and cars, which brings people within the neighborhood who use the roadways to commute within transit centres and respective offices.

2. Mix of several land-use- The area, being adjacent to downtown Seattle, combines a lot of different land-use altogether that makes it diverse and unique. The building mix consists of multifamily apartments, small scale ground level commercials with residential upper floors, hotels and restaurants, art galleries, parklets, transit centres, parking lots etc. A part of the area has been designated as Pioneer Square Historic District, and the main entrance to Centurylink Field is within one block. Presence of several offices and commercials have made this area a well-commuted space.
3. Demographics- International District is one of the most racially diverse neighborhood within city of Seattle. Also, it is distinct in the way that people of several economic levels live here. The area has several homeless shelters, as well as pricy apartments and multi-

stories those serves people of different economic capacity.

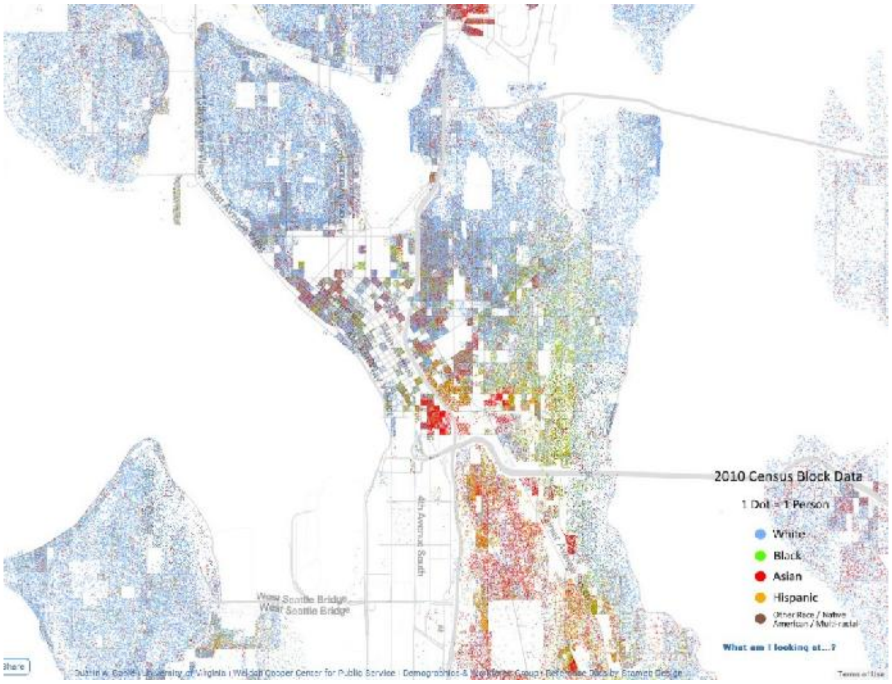


Figure 8 Racial Segregation of Central Seattle, P.C- Weldon Cooper Center, University of Virginia

4. Location of Fixed site monitoring station- The Puget Sound Clean Air Agency have several monitoring sites all over the central Puget Sound area. Among the three chosen locations, International District area is the only area that has a near road monitor at 10th and Weller Street junction, from where data of PM2.5 pollutant could be obtained for comparison and analysis. The Duwamish valley monitoring station is also closest to the

International District than the other two location. These features gave a unique

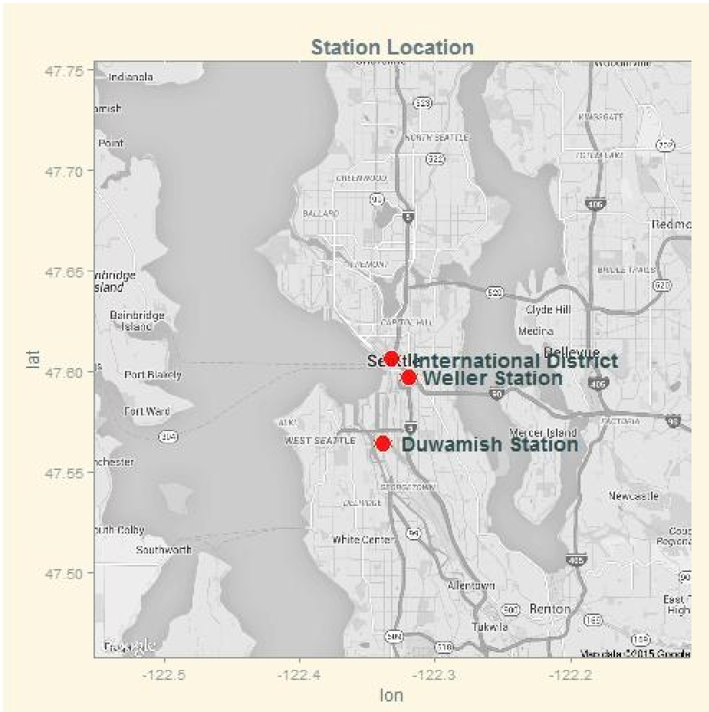


Figure 9 Location of international District, Weller St and Duwamish stn.

opportunity for comparison which was absent for the other two locations.

Considering the above mentioned arguments, a circular path was selected starting and ending on the plaza over International District tunnel station. The path starts at centre of the station, turns west to move into South Jackson Street, towards 1st Avenue South and then northbound to Pioneer square Junction, east Yesler way, south-east towards 2nd Ave South Extension, towards east at South main Street, southwards to 6Th Ave South and back to South Jackson Street taking a westbound turn to International District Tunnel Station. The total length of the trip was around 1.2 Miles. Each trip took approximately 24 minutes in average to complete.

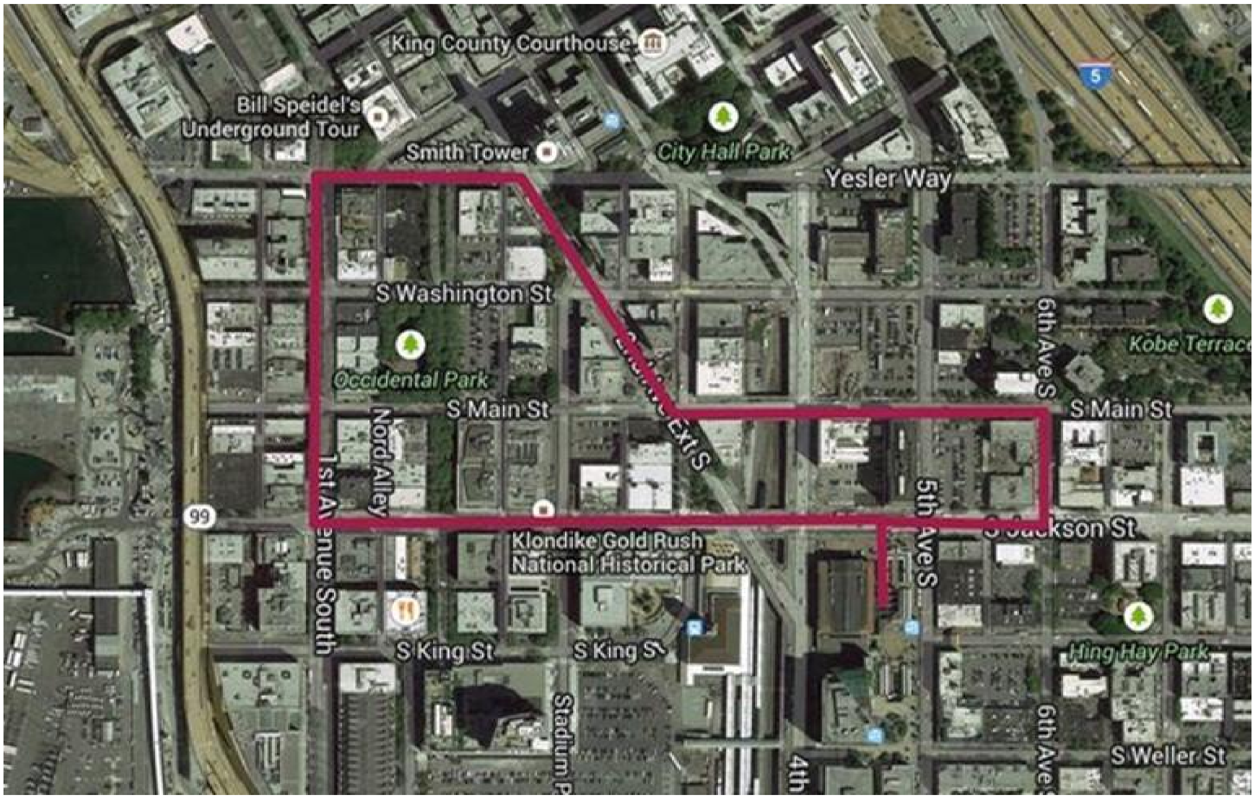


Figure 10 Route for the experiment

4.2 Instrument-

To obtain field data, several instruments have been used, as listed below-

1. **Backpack nephelometer-** Though Nephelometer does not measure PM2.5 directly, they quantify the particles present by light scattering. M903 nephelometer, which has been used for the data collection. It is manufactured by Seattle based Company Radiance Research, and has been used earlier by the Puget Sound Clean Air Agency. Mr. Matthew Harper of PSCAA have improvised the nephelometer to carry it within a conventional backpack to measure the light scattering value along the road. The instrument, in its portable system gets power from a 12 Volt rechargeable battery. An Adriano board has been fixed with the nephelometer, increasing capacity of the unit to monitor Carbon

Figure 11Backpack Nephelometer

Monoxide by fixing corresponding sensor. The circuit board is also designed to include a Bluetooth sender through which it sends the value collected to an android application named Aircasting (www.aircasting.org), developed by Habitatmap, along with humidity, Carbon Monoxide and temperature measurements. However, the Carbon Monoxide sensors was not functional for the particular set used, and temperature and humidity measurement was unreasonable as the sensors were inside the backpack rather than in direct connection with the environment.

2. **Samsung GT 8262 Android 4.1.0 cell phone**- The Aircasting application was installed in the device, which collected the data sent from the backpack nephelometer through Bluetooth. The cell phone GPS sensor was also instrumental to map the data spatially and collecting instantaneous spatial coordinates that helped in spatial analysis of the pollutant quantity.

Figure 12Android cellphone, with Aircasting and GoPro application

3. **Aircasting Application for android** has been another crucial software for data collection.

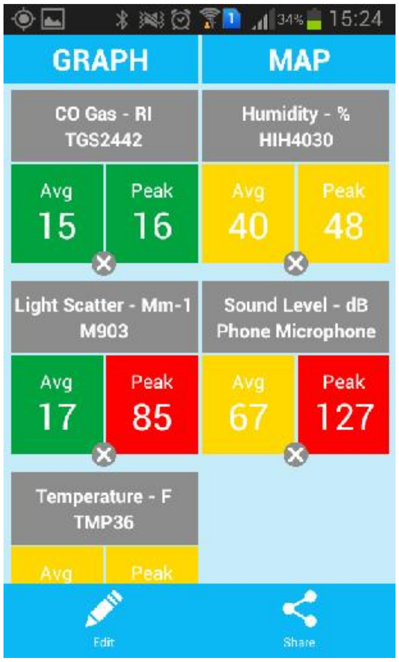


Figure 14Aircasting application- session summary

Figure 13Aircasting application- crowdmap

This application, when used in an android based cell phone, can record data, and integrate it with the spatial coordinates of data collection as mentioned above. Data of individual sessions could be downloaded in comma separated values (.CSV) format for further analysis which has been adopted for this project. If the user wants, he or she can share the data in a crowd sourced map, in www.aircasting.org/crowdmap, where people can check the data shared by others to get a general assessment of air quality of certain places within United States.

4. **GoPro Hero4 camera mounted on forehead-** To understand what kind of human activities are responsible for air pollution and to observe surrounding built environments. The camera has been used to take videography of each data collection session. The video was later checked in accordance with the csv data file to check where and how PM2.5 quantity gets a sudden peak.

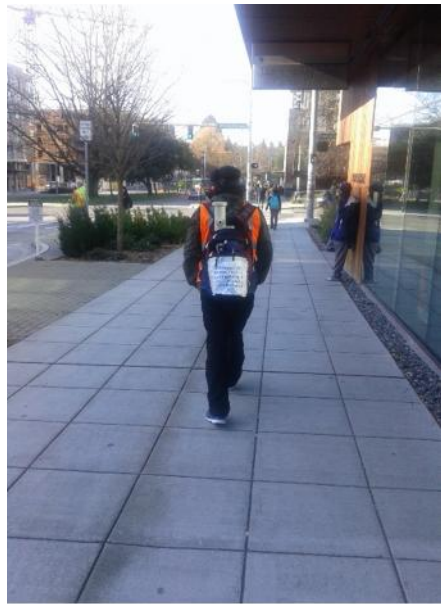
5. **The GoPro application** installed in cell phone helped to control the camera hands free with ease. It also helped earmarking still frames within a video for later analysis.

4.3 Data Collection Timing

A pilot study was conducted on December 9th 2014 and University Way NE, between 40th and 50th St. to check whether the method is suitable and convenient. Three trips, in a day was performed to check whether the instrument could be carried in such frequency throughout the days of collection. Finding the results satisfactory, the writer proceeded to the main data collection.

Data collection trips were conducted in two seasons to observe seasonal variation of air pollution: winter data collection was between 12/31/14 to 01/09/15, and spring data collection was between 03/21/15 to 03/30/2015, to fit in the academic breaks. For the time of day variation, air sampling was conducted three times a day timed initially at 8:30 a.m., 1:30 p.m., and 5:30 p.m., as to mimic probabilistically the most possible hours of walking for commuters. It was assumed that as the area has a lot of offices in the vicinity, people will commute around 8:30 to their offices, and return at around 5:30 to go home. The 1:30 data collection was considered assuming office workers' break. Though, due to delay of transit routes from UW campus to the International District, some of data collection sessions started later than the time initially planned, so the data collection time should be considered as between 8:30-9:30 in the morning, 1:30 p.m-2:30 p.m. in the afternoon, and 5:30-6:30 p.m. in the evening for all days, though each trip took approximately 25 minutes within that time span.

Figure 15 safety vest and GOpro camera location



4.4 Externalities faced

On the first day of data collection, the main externality faced was getting apprehended by Transit Tunnel Security guards at the International District Transit Tunnel. The Security present at site was sceptical about the backpack instrument, and requested for a permission or authorization letter from the Sound Transit authority as well as the King County Metro. The institutions requested an authorization letter as well as an insurance certificate from Office of Risk Management, University of Washington. The UW insurance certificate were issued with letter of recommendations from Professor Christine Bae and Professor Christopher Campbell, chair of the Department of Urban Design and Planning (See Appendix 1). The documents were sent to Ms. Jennifer Ash, King County Metro before the winter data collection was resumed on December 31st, 2014. According to Ms. Ash's recommendation, the collector wore a construction vest while walking for data collection as well to keep a photo identification proof and permission letter from the faculty (Committee Chair Professor Christine Bae), with him all the time during collection. Professor Bae also contacted Local police offices of West Prescient, Seattle to inform them beforehand before resuming the collection. The Police recommend to post a notice of the activity

("Neighborhood Air Sampling-UW Graduate Student") on the backpack (See Figure 16). No other such incident took place afterwards.

4.5 Biases

It cannot be claimed that the data is bias free and complete to be generalized. Several reasons are responsible for the biases that have been considered as follows,-

1. Spatial bias- Air pollutants vary place to place within small microclimatic zones. The measurement was done while walking, so the pollutant quantity of a particular place was available for a particular point, rather than getting the general trend of that particular point. The collection was repeated due to that particular reason as much as possible to get a general estimate within an area.
2. The EPA and Washington State Department of Ecology recommend to use M903 nephelometer at a position distant from the road, 10 meter from the nearest lane for each 1,000 average daily traffic, and in no condition at a distance less than 10 m. from the vehicle lane (Dept. of Ecology, 2008). Following this particular recommendation was not possible due to the thesis argument itself. The general notion of EPA and the state Dept. of Ecology was to measure ambient air quality for the general environment, but as the target group for the experiment were pedestrians, a group being exposed to near-road pollution deviation from the methodology recommended was necessary. Mr. Harper, himself have tried backpack-neph and car-neph during different air quality monitoring evaluation for PSCAA.
3. Air pollution at one place depends upon several climatic factors, including wind speed, direction etc. Wind speed was not considered as a factor for this experiment as it was

assumed that whatever the speed is, people are exposed at some level of pollution at all time, and the target should be estimating that level as well as the major pollutant sources rather than its relationship with wind speed. Nonetheless, wind-speed is a determinant factor in an area to quantify the ambient air quality level.

4. Time wise, the experiment was limited to certain specific hours of certain days. While, EPA considers and recommends State and Local Monitoring Agencies (SLAM) for constant monitoring to get the estimate of pollutants. All fixed site monitors within PSCAA network does measure air pollutant constantly. Even during air quality monitoring in other areas, mobile monitors were also kept static constant monitoring for several days in most of the evaluations done by PSCAA and in other areas (PSCAA, 2010).To be noted, the writer tried to mimic behavior of the commuters, assuming that they will be the most frequent pedestrians within the timespan the collection trip is conducted. Each road segment consists of two foots for pedestrians, while the collector used the same route and same footpaths. The difference between the two footpaths on both side of a particular road segment could vary widely, as the distance between is considerable and the pollutant content possibly be different. The stark difference between air quality of two footpaths were also found in a London based study on pedestrian's exposure (Kaur et.al., 2005).
5. **Residence time of the nephelometer**- it was observed for the instrument to take around thirty seconds from air intake to send the information to the cell phone. Meanwhile the collector have already moved some steps, and so the location where the pollutant quantity is different from where it actually is. Initially it was considered

whether the instrument should be checked in a smoke chamber to get the time accurately. Lately, the controlled environment measurement to estimate residence time was excluded. The nephelometer collects data once per second but the monitoring station data obtained has a frequency of once per minute. Field data obtained from the session was summarized for each minute, taking the most frequent value (Mode) within each minute as the data ranged over a minute. Thus, each sixty data-points from the field data, collected in the sixty seconds of a minute was summarized to one data-point. It was assumed that the lag has been taken care of as the residence time is less than sixty seconds, so data from one minute cannot influence when summarized.

6. **Conversion factor-** As mentioned, the instrument measures light scattering quantity rather than actual PM2.5 quantity, one of the Federal Equivalent Method rather than reference or direct measurement procedures. The relationship between light scatter (Rayleigh scattering, in this case) is statistical, not accurate for all the points. However, the r square value lies in the range of .90 -.92 (conversation with Mr. Harper, and, which means that more than 90% of all the PM2.5 concentration could be explained by the light scatter value obtained from nephelometer, when compared to a more sophisticated Federal Reference Method to compare.
7. **Spatial coordinates-** While plotting the measurement spatially it was noted that due to interference of several wavelengths and connection time-out, sometimes GPS position recorded is not exact as it should be, rather they deviate from the path taken. However, this anomaly was almost mitigated when summarizing the frequency from per second to per minute.

4.6 Data cleaning

Several steps were taken to compare among the data, especially while comparing with the two fixed monitors at Duwamish valley (hence Duwamish data) as well as 10th Ave South (Hence Weller data) at several occasions.

The major challenge was faced while comparing was the different frequency of data collection. Backpack nephelometer, with the help of Aircasting application collects data at each second. The recorded data of Duwamish Station and Weller station have a frequency of once each minute.

To mitigate this difference while comparison, field data was summarized in tabular format to get the maximum, minimum, mean, median and mode for the 60 rows of data collected within a particular minute. The whole process was computed in R, a free statistical software. Most of the comparison and lots have been developed thorough this software.

To estimate the location of the converted data, it was considered to adopt the center point of the sixty location points, and their mean, which will provide the central location of the total path traversed within the minute.

Another challenge faced was the bug present in the Aircasting application. The program, though spaces data correctly within the map while viewed in the cell phone or other electronic devices, renames the Latitude and Longitude fields oppositely. For a position in Seattle, such positions become unplottable in the conventional coordinate system globally followed. After recognizing this bug, their names have been altered, and evaluated that it puts the coordinates in accurate spatial positions.

4.7 Obtaining PM2.5 value

As from the conversation with Mr. Harper and from research it was found that Nephelometer (Here in case, type M903, prepared by Radiance Research, Seattle) measures light scattering coefficient, in the unit of inverse mega-meter (value/10^{-6} m). As mentioned earlier, light scattering have been used for several decades to measure PM2.5 concentration in ambient air for several decades, but the relation may differ from place to place due to several environmental factors. From the continuous data obtained from different monitoring station of PSCAA for long time in the past and comparing them with PM 2.5 concentration by different direct measurement instruments, it was concluded by the PSCAA that in central Puget Sound area, they follow a linear correlation which is,-

PM2.5 = (27.6 * bscat +2.6),

where, PM2.5= Concentration of PM2.5 in µg/m^3,

bscat= Rayleigh light scattering extinction coefficient value obtained from nephelometer in inverse mega meter (10^{-6} m^{-1}).

(Obtained from email communication with Mr. Matthew Harper, dated March 2nd and March 10th, 2015).

For practical purpose, the backpack nephelometer and + android application records values in the unit of 10^{-4} m^{-1}, so, for converting field data obtained from the Aircasting application, the equation has been modified into,-

PM2.5 = (0.276 * bscat +2.6),

Where, PM2.5= Concentration of PM2.5 in μg/m^3,

bscat = Rayleigh light scattering extinction coefficient value obtained from nephelometer in inverse kilo meter (10^{-4} m^{-1}).

4.8 Data analysis

After summarizing the data for each minute, several columns were added as identification factors, that provides information about the time and season of the data collected. The column TOD was added to understand 'Time of Day', whether the collection phase for that particular information was Morning (8:30-9:30 a.m.), Midday (1:30- 2:30 p.m.) or Evening (5:30-6:30 p.m.). The indicator 'Daytype' was added to estimate whether that particular date was Holiday (Weekend or Federal Holiday), or normal 'Weekday'. Another column, 'Timestamp' was added in the format of 'YYYY:MM:DD HH:mm' as an temporal indicator to join data files with monitoring station data obtained and comparison among the three.

Comparison among morning, afternoon and evening levels

To check whether PM2.5 quantity varies widely at different daytime, converted values of PM2.5 was sorted in three groups by the TOD to estimate any trends or interpolation that could be drawn upon from the Field data. Separate comparison was done for winter and spring assuming the seasonal difference may influence or damp the variation present at one particular season, even the activities and number of people present, hence different activities would be different.

Comparison between winter and spring- seasonal variation

The two season during data collection gave the opportunity to check the seasonal variation of PM2.5 present in the air, or how the quantity do varies with the seasonal changes. To compute changes, Field data was divided in two sets by the field season, and plotted against one another. Comparison between morning, midday and evening has been done too for two different season to check if individual season brings different characteristics to the same hours.

Comparison between weekdays and holidays.

Assuming activities, traffic, construction related activities and other sources of pollution, population on the street hence activities would be different in normal weekdays and holidays, a comparison has been done to estimate which type of day is better for pedestrians, or what is the ambient air quality at the specific hours. The challenge faced while plotting the two against each other was that they were inconclusive as number of holidays, including weekends were different from the number of weekday data collected. While there were a total of seven holidays, 12 days were normal weekdays, spanning over the two sessions. To compute difference, they were tabulated, with the calculating the maximum, minimum, median and standard deviation to get a better estimate of where they lie.

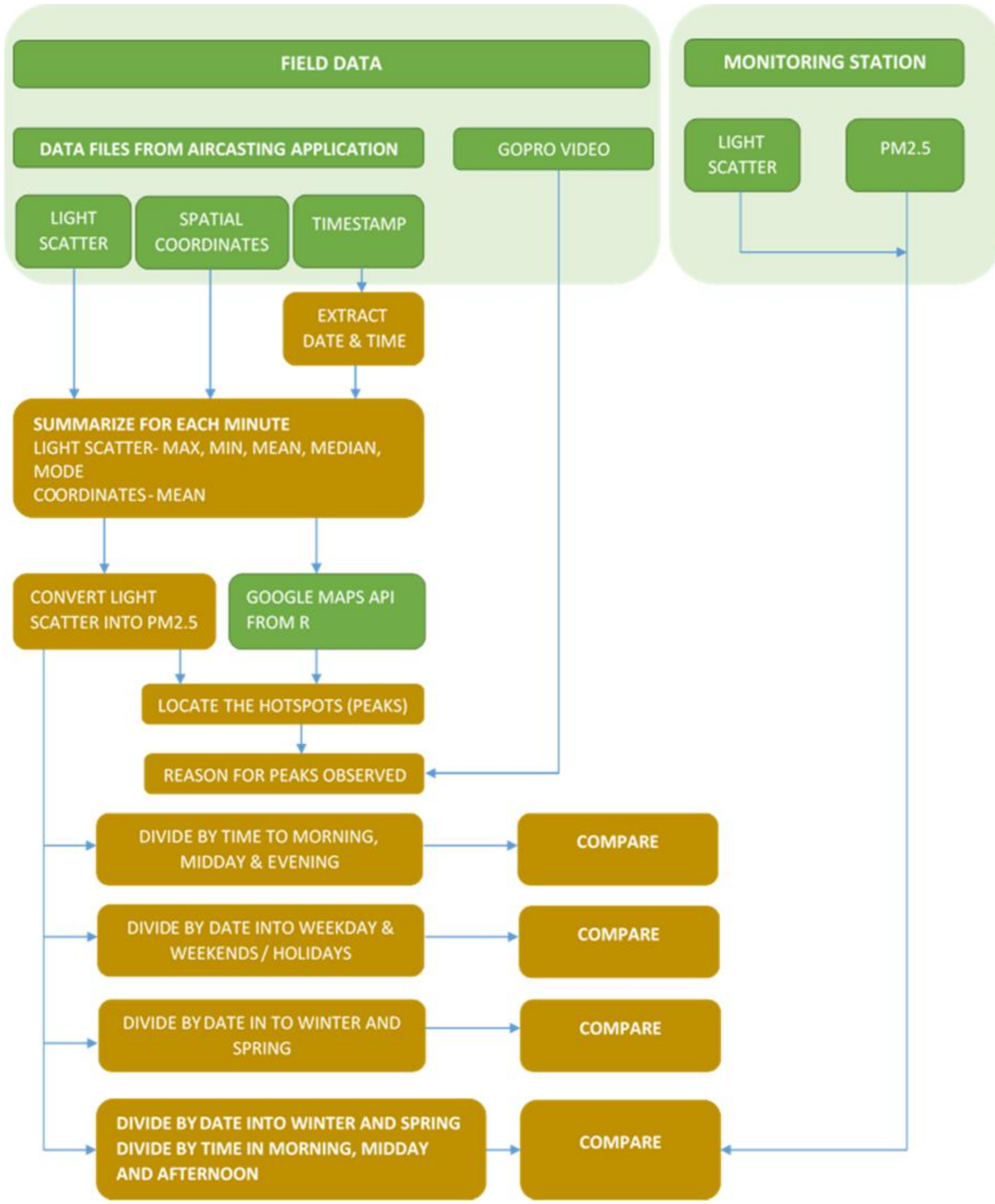


Figure 16 Methodology chart of the experiment

Comparison between field data and data obtained prom PSCAA

To get an estimate of how accurately the monitoring stations measure the pollutant as experienced by the pedestrians, the three PM2.5 level data were plotted against each other, each for the three specific hours of three seasons. Linear relationship between Weller data and Field data, as well as that between Duwamish data and Field data has been established to get an estimate what could be estimated level of pollution a pedestrian can experience while he is somewhere in the experiment route. To understand whether any two of the datasets have any relation with each other, they were also subjected to ANOVA test and pairwise t-test.

Comparison if peaks due to smoking is removed

From the initial estimate and analysis, as well as while finding the reason for peaks shown in the PM2.5 quantity graphs, it was established that passive smoking could be cited as the most important factor to increase the PM2.5 quantity in the ambient air quality. Upon careful observation of the videos, several points were located where people was seen smoking, and those minutes were removed from the summarized dataset, to check whether the estimate will be if in a condition smokers could be removed. While it was not quantified the rate at which smoking increases the pollutant quantity in vicinity, it was concluded that the data collector will be a safe distance from the point where smoking could affect the measurement.

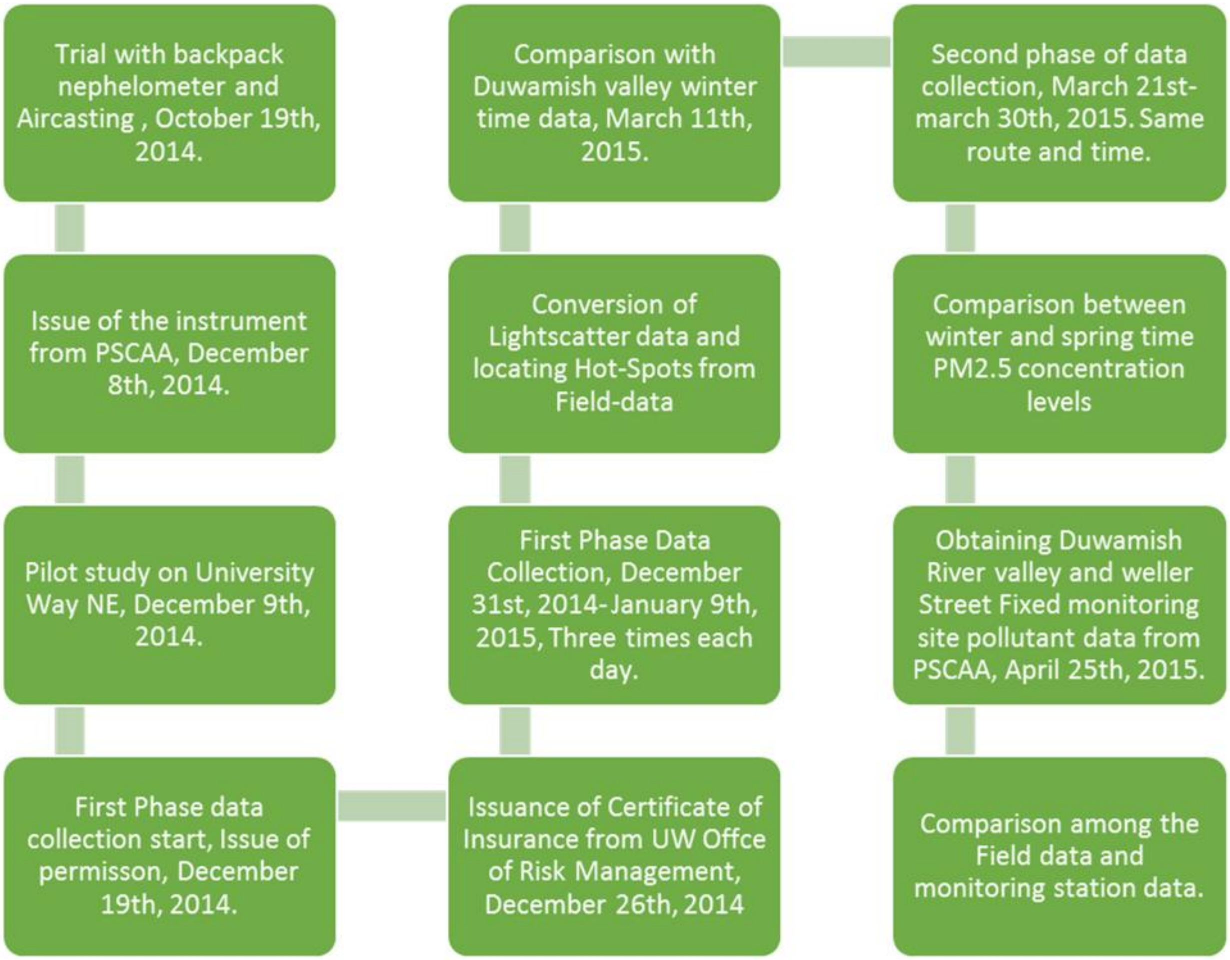


Figure 17 Timeframe of the experiment

6. Results

6.1 General Observations

To estimate the condition and how PM2.5 concentration level vary with times, Pollution level values have been compared by dividing in parts. General description and limits of the sessions have been tried to estimate by dividing the values in quartiles. Minimum, median, mean, and maximum values have been also calculated to find out the range for each division.

6.2 Comparison among morning, midday and evening concentration levels- winter and spring

Table 1 PM2.5 Concentration in winter (μg/m^3)

Time	Minimum	First quartile	Median	Mean	Third quartile	Maximum
Morning	4.245	16.410	21.380	25.000	38.480	57.770
Midday	6.243	11.080	15.440	19.680	28.310	57.770
Evening	4.623	11.720	14.390	17.100	20.610	57.770

Morning time data shows that in average, less than 25% of the minutes have pollutant level lesser than the specified 3 year average PM2.5 level specified by EPA (12 μg/m^3 ,98th percentile) as well as more than a quarter of the minutes have PM2.5 concentration more than a 24 hour limit specified by EPA and State Department of Ecology (35 μg/m^3) and sometimes more. The instrument, having the upper limit due to battery condition, showed that the peak value that could be reached have exceeded in some cases. This implies that in a probable way, more than 75% time of walking, people in the area will be exposed to a higher concentration of PM 2.5 than specified limits.

While comparing with the winter mornings, Midday values generally tend to show a lower PM2.5 concentration. The median at 15.4 μg/m^3, implies that at more than 50% time pedestrian will be exposed to an environment that has higher PM2.5 concentration than the 3 year EPA standard, but the higher quartile values are lower than that of corresponding morning PM2.5 concentration, implying that the peak concentrations of PM2.5 are generally less than morning. Reasons may lie in the inversion effect, implying that the dense and heavier air particulate matters gets concentrated at near-ground level due to less movement among the air molecules in cold winter morning, as seen in the Seattle area than the comparatively warmer midday hours, or due to less human activity as it does not corresponds to the conventional commuting hours, so street activities might be less.

Observation noted here is that evening time concentration tend to be lesser than both morning and afternoon while moving to the higher quartiles, though they shows similar trends in lower quartiles. The third quartile here lowers down to 20.6 µg/m^3, much less than both morning hours and midday hour. It bolsters the inversion and cold winter morning effect, as with daylight air becomes warmer and the particulate matters gets dispersed, until much late hours at night.

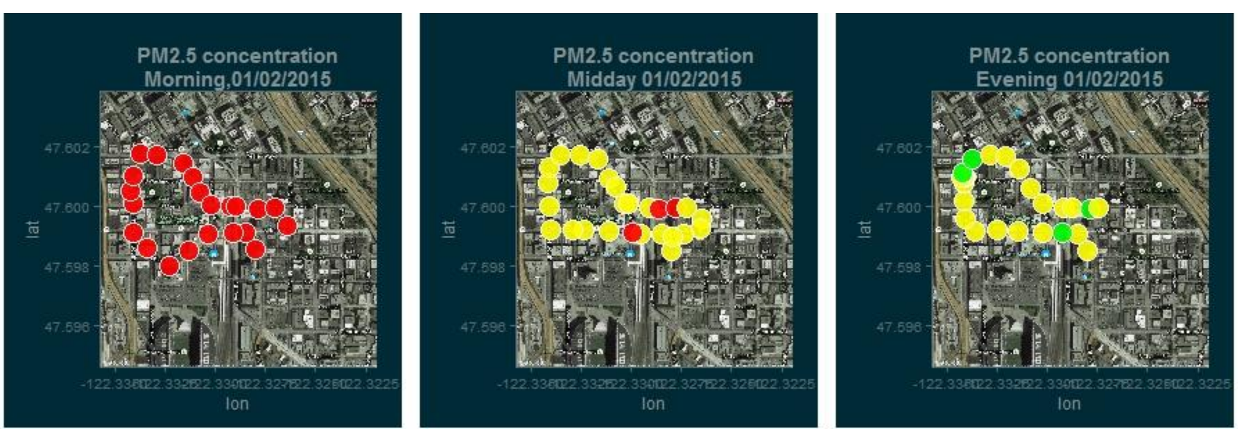


Figure 18 PM2.5 Concentration in different spatial coordinates, green- less than 12ug/m3, yellow- between 12-35 ug/m3 and red- greater than 35ug/m3, January 2nd, 2015

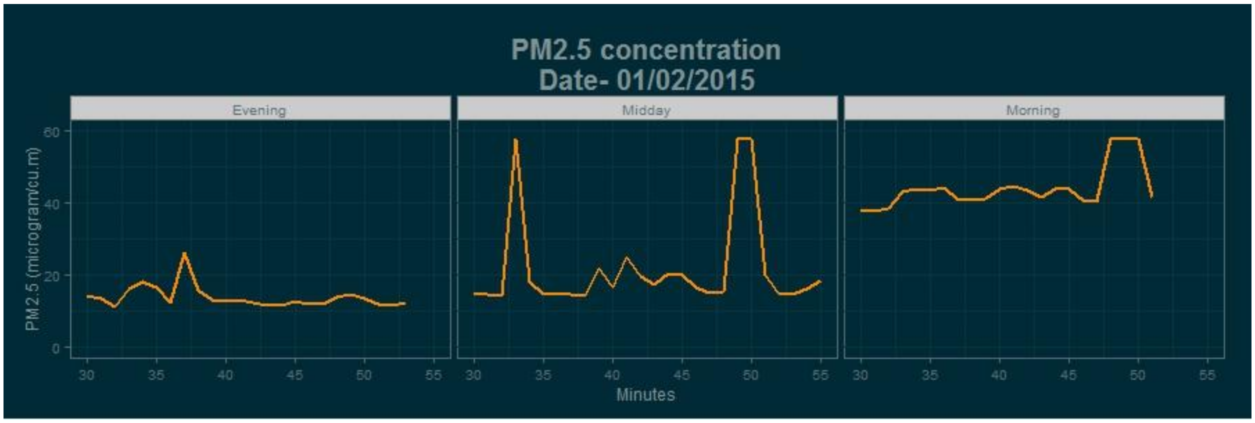


Figure 19 PM 2.5Concentration at three sessions, January 2nd, 2015

Figure 21 PM2.5 concentration at different spatial coordinates, Green dots- less than 12 ug/m3, yellow dots- between 12 and 35 ug/m3, January 5th, 2015.

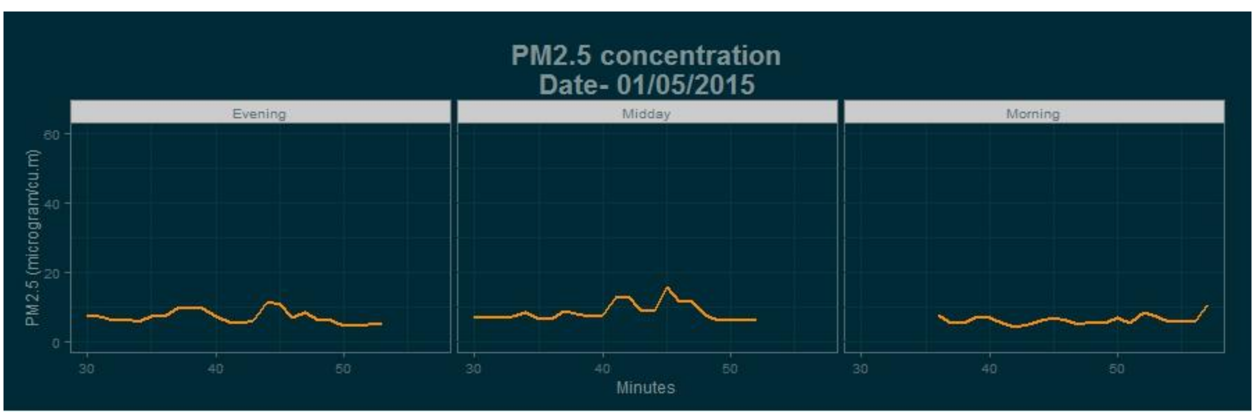


Figure 22 PM2.5 Concentration at three sessions, January 5th, 2015.

Table 2 PM2.5 Concentration in spring (μg/m³)

Time	Minimum	First quartile	Median	Mean	Third quartile	Maximum
Morning	5.702	7.509	8.562	10.520	11.290	27.500
Midday	4.460	6.781	8.131	8.606	9.911	29.980
Evening	4.193	6.661	7.916	8.581	10.130	23.560

Mornings in spring shows specific peaks rather than a continuous polluted environment. General trend show that even more than 75% times, pollutant quantity is lower than EPA 3-years average limit, which is a drastic shift than that of morning winters, which showed the opposite trends. The maximum peak reached is also much lower than corresponding winter observations. Maximum concentration have never reached the peak limitation of the device, and are limited to 27.5 μg/m^3, lesser than the EPA designated 24-Hr value.

Midday sessions of spring PM2.5 concentration follows the morning trend for the spring, with third quartile being at 9.91 μg/m^3, much lower than corresponding winter concentration. The maximum again shows the peak similar to morning times, which tended to be result of microclimatic phenomenon like smoking, which, while counted from the video, has been checked to create 89 peaks in all the sessions together

Evening time pollutant quantity is also within EPA specified limit to much extent. Third quartile is also lower than 12 μg/m^3, and the maximum peak in these hours is also lower.

6.3 Comparison between winter and spring

Table 3 Quartile wise comparison of PM2.5 concentration between winter and spring (μg/m^3)

Time	**Minimum**	**First quartile**	**Median**	**Mean**	**Third quartile**	**Maximum**
Winter	4.245	11.690	17.110	20.630	24.980	57.770
Spring	4.193	6.889	8.239	9.091	10.290	29.980

Comparing winter and spring time PM2.5 concentration, a huge difference between the two is noted. While in winter, PM2.5 concentration level is much higher, almost double for each quartile than corresponding spring concentration. Even the maximum value at winter have reached the peak limit of the instrument multiple time, while it was never the case during spring. The result definitely implies that pedestrians are exposed to a much higher concentration of PM2.5 in winter. From the statistical analysis, it has been also observed that the overall mode of PM2.5 concentration in winter is 57.7 μg/m^3, whereas, in spring the mode is 6.99 μg/m$^{3.}$ (Method of mode calculation- Most likely value, Bickel's modal skewness- .438).

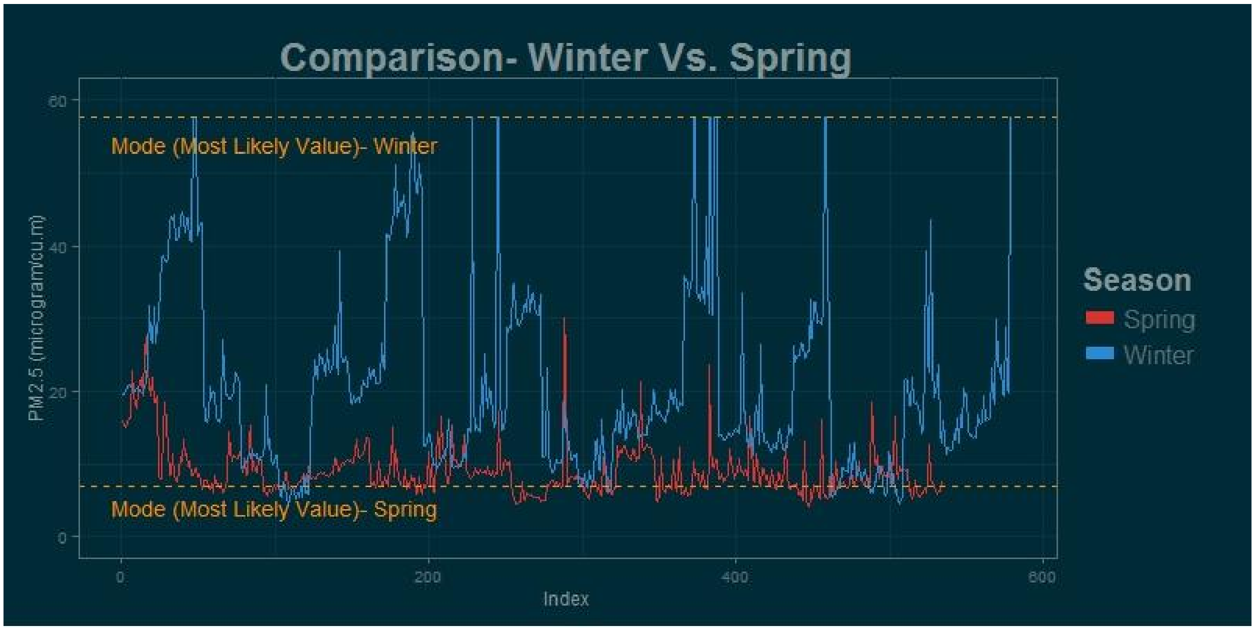


Figure 20 Comparison between Winter and Spring (µg/m^{3})

To search for the reason, activities were checked from the videos taken while measurement. Activities didn't show any significant difference from each other, giving no prominent reason for the seasonal difference.

The possible reason lies in the weather conditions. Spring time experience more windy weather. Higher temperature and more sunny days, which dilates the air and therefore displaces air frequently than winter.

On the other hand, during winter the air is much more stationary, humid and displacement is less. So, concentration of PM2.5 gets accumulated at near road levels, which can definitely be the reason for significant difference. High humidity and rain combine suspended articulate matters in bigger particles and they tend to concentrate at near ground level.

6.4 Comparison between holidays and weekdays

Table 4 Quartile wise comparison of PM2.5 in holidays and weekdays winter (μg/m³)

Time	Minimum	First quartile	Median	Mean	Third quartile	Maximum
Weekday	4.245	13.310	18.060	22.050	24.940	57.770
Holiday	5.432	10.650	14.900	18.260	24.950	57.770

In winter, concentration between holiday and weekday does not vary much and somewhat similar. In fact, some of the highest pollutant concentration have been found on January 1st, morning. Weekdays show a higher concentration in general, as the lower quartiles are higher, possibly due to higher concentration of on road traffic. But as seen, the highest quartiles are almost similar to each other, when compared. To perform the most likely value for both holidays and weekdays, overall mode has been determined, which differs much than the quartile wise comparison. Mode (most likely value) for weekday is of 57.7 μg/m³, but that of holiday is only 11.26 μg/m³. However, it should be noted that the number of sessions of data collection for comparison is different (8 for holiday and 20 for weekday), so, we can draw this conclusion, but cannot be assured.

Table 5 Quartile wise comparison of PM2.5 in holidays and weekdays, spring (μg/m³)

Time	Minimum	First quartile	Median	Mean	Third quartile	Maximum
Weekday	4.838	7.024	8.454	9.432	10.290	27.500
Holiday	4.193	6.511	7.700	8.458	10.260	29.980

Even in spring, concentration of PM2.5 does not vary much between holidays and weekdays. The quartiles show somewhat similar result in general. Testing the overall mode for the two groups also shows that they are somewhat similar (5.43 μg/m³ for holidays and 8.45 μg/m³ for weekdays). It could be concluded that concentration of PM2.5 does not vary much between weekdays and holidays at least in the seasons, winter and spring, but their most likely value does differ, ranging five times in winter, but less than two times in summer. This suggest that more research needs to be done to find out the big seasonal differences between the weekday and the holiday.

6.5 Locating the hotspots, areas/segments having high concentration

Converting the data summarized by minutes and putting them spatially it has been seen that the hot-spots with high PM concentration value is not uniformly distributed, in both aspects of seasonal variation and diurnal variation. PM2.5 concentration limit to locate hot-spots have been determined at 35 $\mu g/m^3$, EPA specified 24-hr level. However, spring time PM2.5 concentration level never crosses the limit, maximum PM2.5 concentration observed in spring being 29 $\mu g/m^3$. The points were divided in two groups, between 35-50 $\mu g/m^3$, and more than 50 $\mu g/m^3$.

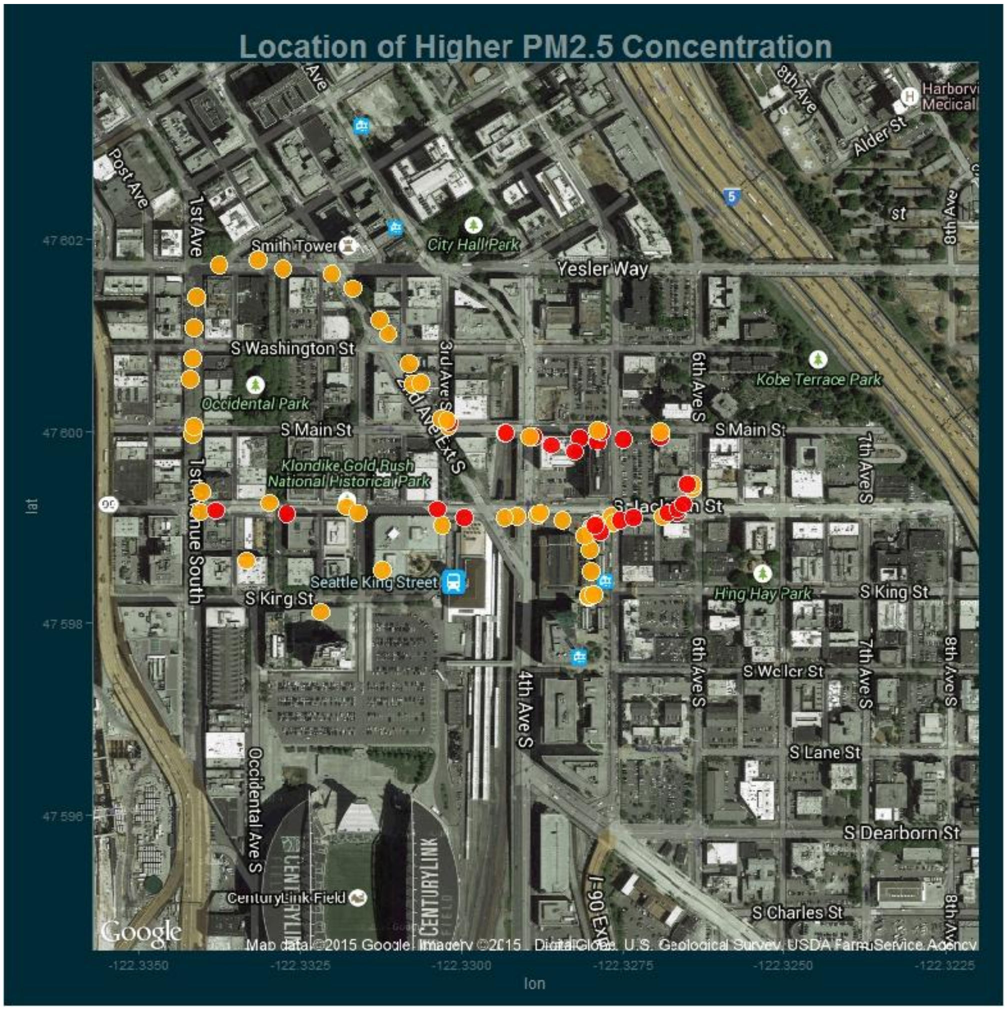


Figure 21 Points where concentration of PM2.5 >35 ug/m^3, orange- between 35 and 50, red >50 ug/m^3.

Summarized data for winter, converted to minute level had 580 rows, i.e., total time of data selected for analysis was 580 minutes in the collection span. Out of them, 76 minutes shows the mode to be greater than EPA 24-hour level, approximately 13% of the total winter data collection time.

Observation from the date and time of day shows that these minutes are not evenly distributed, spatially or temporally. Out of them 53 observation have been noticed in the morning, 16 in midday time and 8 in the evening time measurement. This also corresponds to other studies where it has been seen that the morning time air pollutant concentration in is generally higher than other times of the day, due to climatic factor and other human activities. The result is also similar to PSCAA study of Tacoma by mobile monitoring which found a huge difference between summer time and winter time particulate matter concentration in the air (21 $\mu g/m^3$ in winter vs. 10 $\mu g/m^3$ in summer). Though day to day comparison have not been done due to the short span of data collection, observably, majority of morning high PM2.5 concentration minutes corresponds to particularly Friday mornings. In fact, a separate analysis for individual sessions reveals that during entire span of those particular sessions, morning of January 2nd and January 9th, 2015, air quality in International District, at least in the area of study, have violated EPA 24-hour limit. While it is wrong to interpolate a result from only two sessions, more rigorous study may be required to understand weekly variation pattern, if any, present.

Spatial inspection from Figure 24, putting the hotspots shows that they are not evenly distributed along the path, rather, some of them are concentrated at one area. These definitely intrigues to find the reason behind these hotspots, which will be discussed later in this chapter.

Observation shows that most of the potential hotspots are concentrated at South Jackson Street, east of the International District Tunnel Station, 2nd Ave Ext. South, as well as at 6th Ave South. Other hotspots, present in other road segments, corresponds to a lower level of average concentration in general as seen.

6.6 Sources of PM2.5

Several factors has been identified as the potential sources of pollutants and data files has been checked locating the pollutant quantity on the map, and checking video of the corresponding session. From observation it has been found that there are three major sources of pollutants that adds PM2.5 in the route-

1. Vehicular emission- Video has been checked to see the general trends of traffic volume, though not numerically quantified. Generally it has been observed that both South Jackson Street (AADT- 13700), 1st Avenue and occasionally, 5th Avenue has higher traffic volume than the rest of the segments. Observation from vehicular emission is hard to differentiate from other factors, as it does not shows a peak, rather it can be assume that high traffic volume affects the air quality for the whole area, and shows a higher

value of PM2.5 concentration overall. Individual effect of different type of vehicles need more rigorous monitoring to understand the difference of emissions.

Figure 22Traffic- S Jackson St, King St. junction, 01/09/15

2. Construction activities- Only one construction site has been observed located at the route, at the junction of South Main Street and 5th Avenue south, where construction work was going on during data collection, both in winter and spring. The effect of the construction site has been found variable, i.e., it does show peaks sometimes, but most of the time it does not affect the value. It should have been mentioned that due to construction, the footpath adjacent to the construction site was closed in winter, so, to maintain the same data collection procedure, the collector have to use the other for all sessions.

Figure 23 Construction site at 5th Ave s and South Main St.

3. Smoking- Observed in person and while matching the videos with corresponding session data have showed that individual peaks have been created in near smoking areas. Pedestrians have been found smoking in different locations all over the route, but majorly, at 2nd Ave Ext S, on the railway tunnel bridge in South Main street, and at the tunnel station itself, majorly in the east side entrance, and the junction of South Jackson St. and 5th Ave S. These are the areas where smokers are almost static, conversing with each other, while other smaller peaks have been observed while coming across someone walking and smoking. It should be noted that almost all peaks could be related to smoking except some, but smoking, by itself has not been responsible for crossing EPA 24-hr. limit. Considering the observations of the Hotspot analysis, it could be incurred that smoking have definitely made the condition worse.

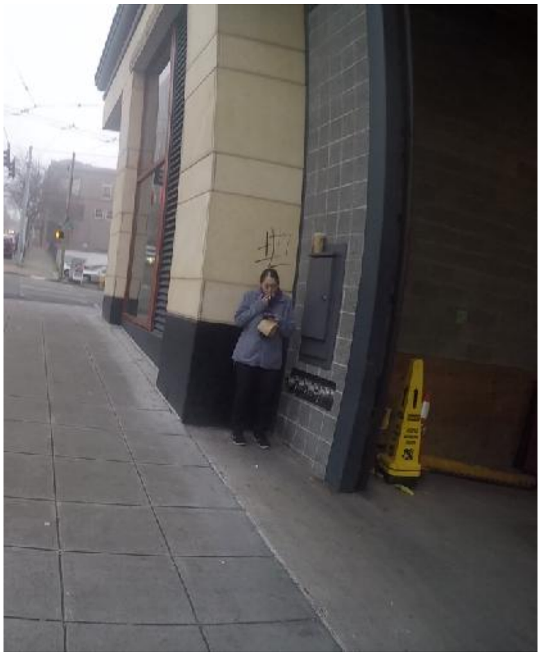


Figure 24walking and smoking , South Jackson St

Figure 25Smoking, South Main St.

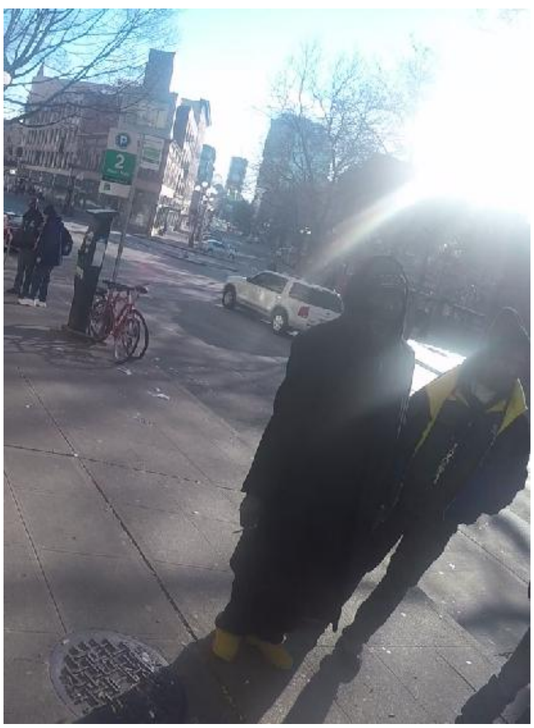


Figure 26Smoking, 2nd Ave Ext. S

6.7 Comparison between fixed site monitors and field data

The research question to answer how much monitoring station data can predict pedestrian's exposure in the experiment area has been tried to study by plotting field data and monitoring station data altogether and to check predictability. Two monitoring sources data shows different pattern when plotted, PM2.5 measurement from Weller St. monitoring station, which is a near road station does show a more consistent value over the sessions than that of Duwamish valley monitoring site or even the Field data obtained and converted. The possible reason for such observation could be explained assuming that during the hours of measurement, Weller station have experienced same level of traffic related air pollutants due to busy hours on I-5. Vehicle pollution being the most dominant factor for the station, the level of pollutant exposure experienced at Weller was same at the same rate of traffic volume.

To understand the relationship in a more comprehensive way and with temporal variability data collected at different time of the day have been plotted separately with corresponding monitoring station data. The general pattern observed is that the field data of PM2.5 concentration is higher than the monitoring stations for winter, but is similar to Duwamish station monitoring site air quality for spring.

Monitor	Minimum	First quartile	Median	Mean	Third quartile	Maximum
ID Field PM2.5	4.245	11.733	17.115	20.688	25.046	57.770
Weller PM2.5	5.10	10.70	14.80	15.47	19.30	31.00
Difference (Field-Weller)	-.855	1.033	2.315	5.218	5.746	26.770
Duwamish PM2.5	3.969	10.897	15.097	18.991	27.179	49.018
Difference (Field-Duwamish)	.276	0.836	2.018	1.697	-2.133	8.692

Figure 27Summary, Field and monitoring station data, winter (µg/m^3)

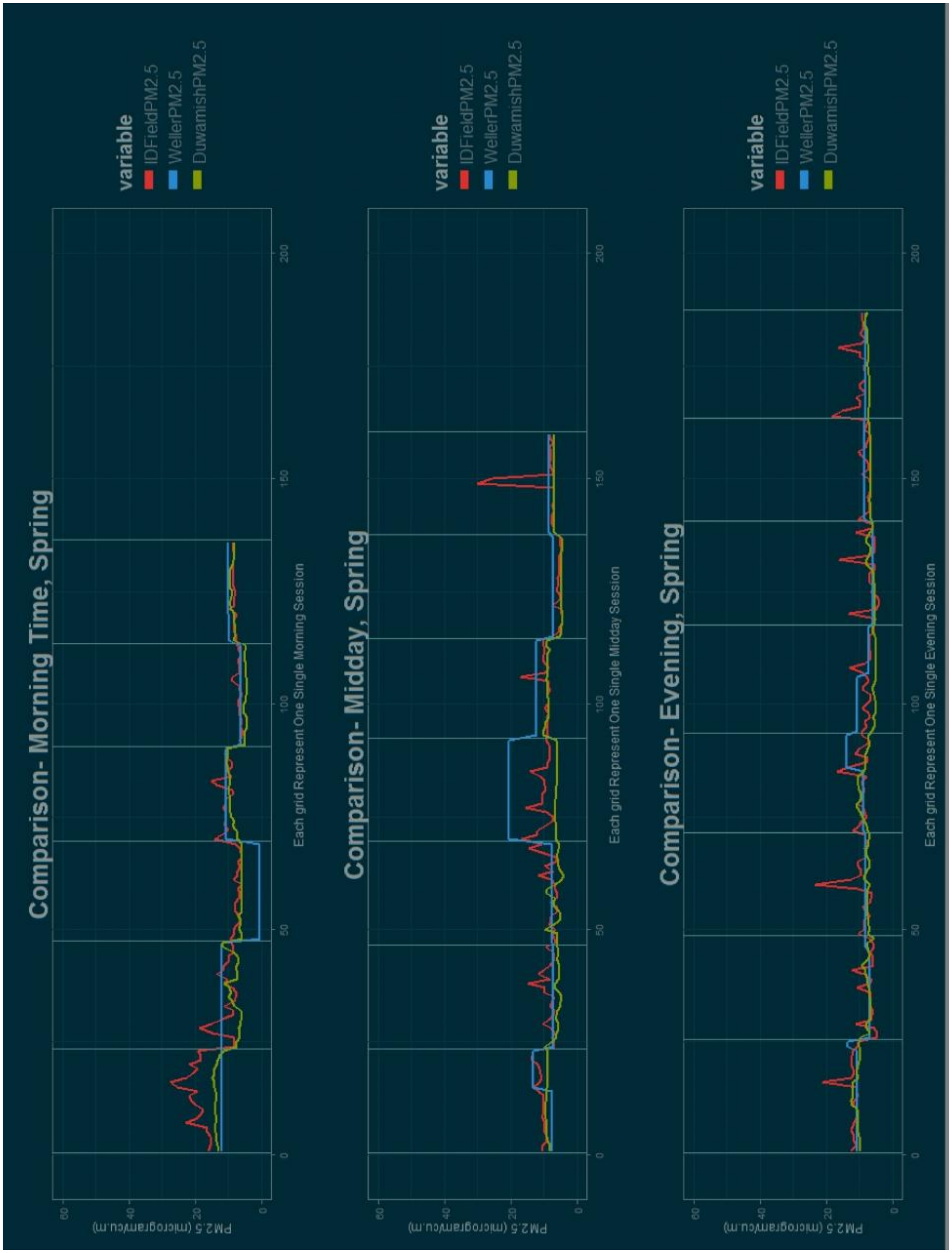


Figure 28Winter time comparison, field and station data

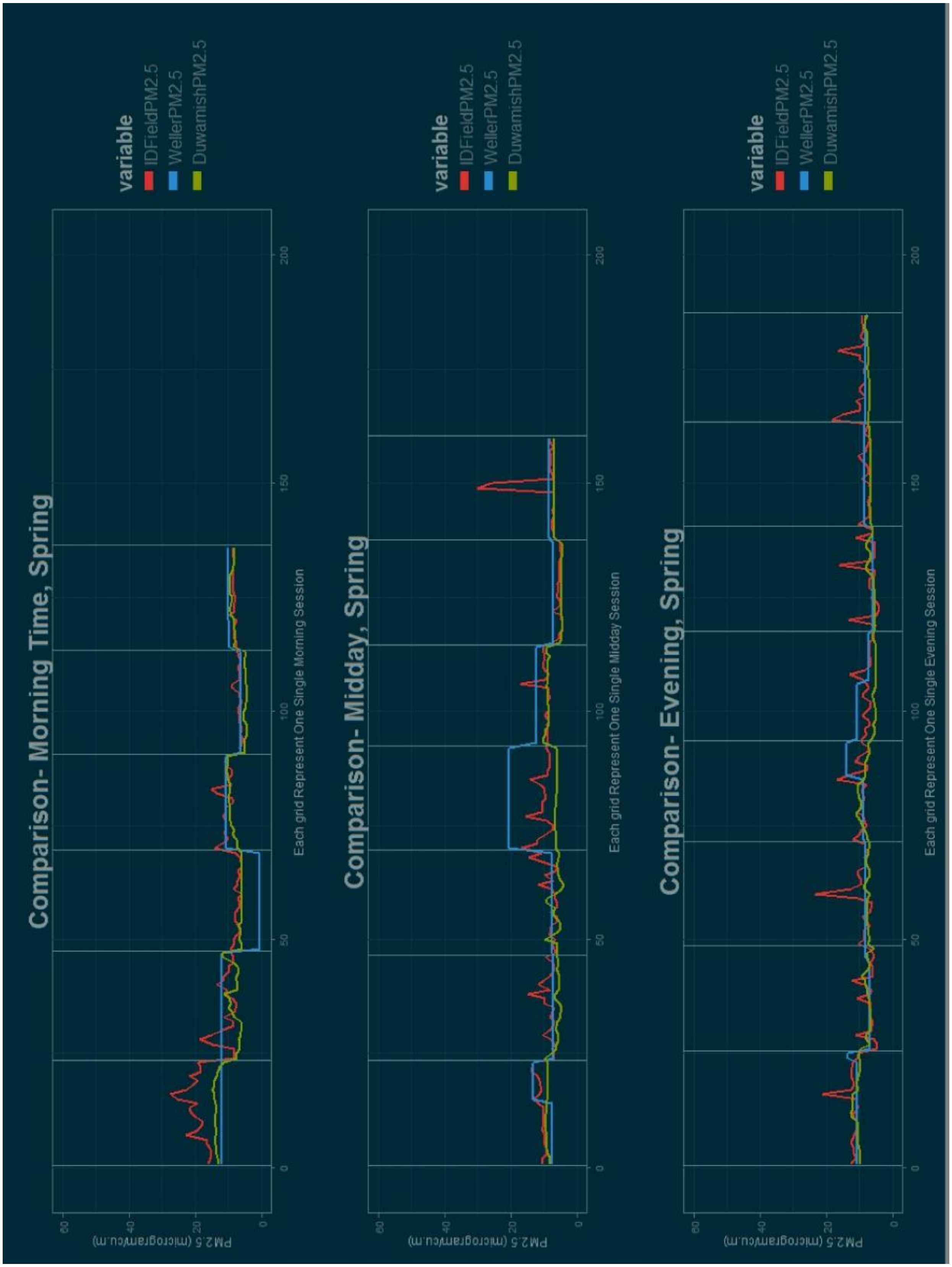


Figure 29 Spring time comparison, field and station data

To check whether the field data and data from the monitoring station have any linear relationship, Field data was fitted in a model separately for winter and spring with the two station monitoring data. In all cases, the p value is significant, rejecting the null hypothesis. Winter time linear model with Duwamish station data produce an intercept of 4.44 and coefficient .703, with adjusted r square value at .54, explaining that a considerable part of the field data could be explained from the Duwamish valley monitoring station data. The relationship is not so strong for spring, where an intercept of 4.08 and coefficient of .374 shows an adjusted r square value of .374. However, it is still a better model than when tried to fit with Weller station data, which, for winter produce a coefficient of .307 and 9.11 as the value of intercept, adjusted r square being .3817. The worst linear model is the comparison with Weller station data for spring, which, though having significant p value, have an adjusted r square of merely .125, with intercept of 5.84 and coefficient of .3613.

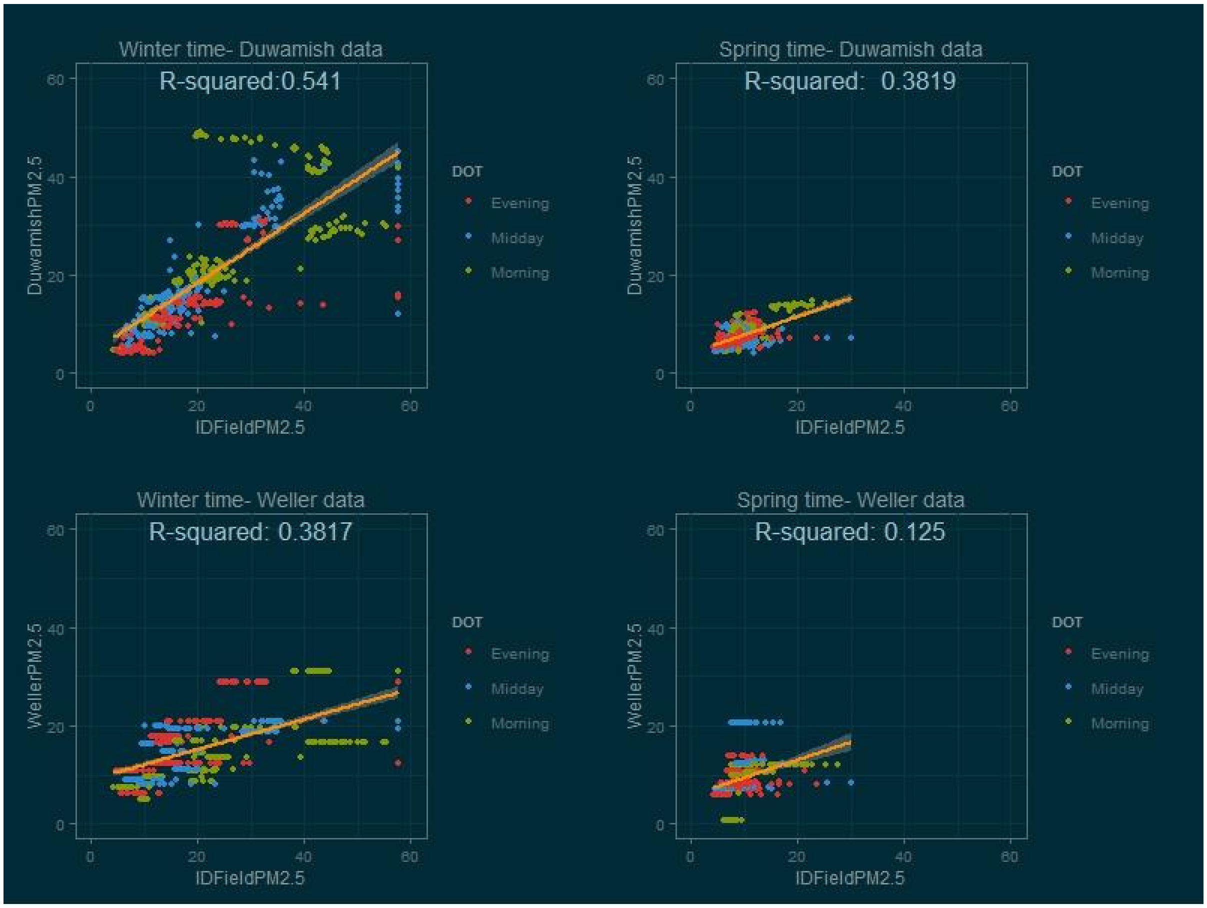


Figure 30Linear relationship between Field data and monitoring station data.

The lower r square values, and gradual decrease from winter to spring depicts that there is variability from the monitoring station data, and pedestrians' accurate exposure to PM2.5 concentration cannot be predicted correctly from the monitoring station value, at least in spring. However, the small number of observations considered for the experiment relative to continuous monitoring as done in the monitoring station, these values may not depict the exact picture that exists, but within the time frame of the experiment it is the general conclusion.

For a more rigorous analysis to analyse whether one of the data could predict the other, the three different monitoring data was subjected to analysis of variance or 'ANOVA' test, to check whether the difference in behaviour with time does corresponds to intra, or inter group variability. The result of the test, with a significant p-value of the order 10^{-8}, and an F-statistics value of 24.39. The critical F-statistics value for 95% interval, 2.99, being way below the F-statistics extracted, the null hypothesis is rejected to imply that the data from monitoring stations and field data are different from each other.

To check whether any of the monitoring station data and their influence and linear relationship with the field data obtained, the three dataset were put under a pairwise t test, with 'bonoferroni' method being used for the p-value adjustment. The highest p-value (.0157), among the four pairs was between Weller station and Duwamish station. Duwamish station data matches maximum with Field data, with a p-value of .001, but Weller station data and field data pair have a p-value of the order 10^{-11}, implying that they does differ significantly from each other, though being spatially the nearest pair.

6.8 Removing the smoking peaks

Observations from the videos suggest that approximately 89 peaks, from both winter and spring have been caused by smoking. These peaks were removed manually to get a clear trend and whether the relationship between better between Field data and monitoring station data.

The linear relationship becomes better for the Weller station data significantly, increasing adjusted R square to .48 form .38 for winter, and .35 from .125 for spring. However, such increase has not been seen when compared to the Duwamish station data, for which r square increases to .58 for winter, and .43 for the spring.

7. Discussion

7.1 Situation according to EPA standard

It could be concluded that pedestrians' exposure to PM2.5 in Seattle, especially the places where the experiment has been done is not too polluted during the data collection period. However, it should be kept in mind that PM 2.5 does not cause irritation or does not provide any instantaneous syndrome to someone, and functions more by accumulation over time. The longer a person is exposed to higher concentration to PM2.5 pollutant, more health risk him or her into. Studies have shown that with each increase in 10 $\mu g/m^3$ increases health hazard risk by 22%. Even a lower concentration of PM2.5 exposure over a long time is potentially dangerous. EPA have historically cut the upper limit of PM2.5 concentration of safe level, 3 year and 24-hour standards, from the time they have designated PM2.5 as a criteria pollutant, and expected that they will cut it down further, which implies that even according to the standard exposure time should be considered hazardous.

As it has been seen that the pollutant level exceeds the 24 hour safety limit standard several times, more studies are much needed to estimate pedestrians' exposure levels over only the winter. Seattle and nearby area winter are moderate and temperate compare to many other cities, though rainy, weather condition does not become severe to abandon walking as a preferred mode of commute. By extrapolation we see that concentration exceeds 76 times out of 584 observations, or 13% of the time. That extrapolates that pedestrians will experience higher level of pollutant 13% of the time they are on street, and the probability has a higher chance even from that as measurements were taken mostly in the commuting hours to get an estimate.

7.2 Difference/similarity between data obtained from PSCAA monitoring sites and field data.

From the comparison we see that there's no good correlation between the data obtained from the field and fixed site monitoring station data. It has also been clear that the field data obtained is generally higher than the value observed at the monitoring station, most of the times except for some outlying incidents. The same trends had been observed by other researchers previously (Kaur, 2005).

Analysing the location and neighborhood of the fixed site monitoring stations may provide a clearer picture for the difference.

Weller street monitoring station is a near freeway/road monitoring station that effectively measures pollution from vehicular emissions on the freeway, I-5. Traffic volume and traffic speed are greater in the freeway than the neighbourhood streets (13,700 vs. 40,000-80,000, WSDOT and SDOT, 2015), so, the pollution level tend to be higher due to excessive vehicular emission on the freeway. Though it is also considered that vehicles moving at slower speed and periodic stops at junctions tend to emit higher amount of pollutants in the adjacent year, the stark difference between the traffic volumes subdue that effect. People, in the United States and also in Seattle try to avoid residing near freeway due to excessive air and noise pollution. Resemblance with the data, even getting higher value than that type of a monitoring station certainly clarifies that even being a mixed-use neighbourhood with mostly residential and commercial activity, the area has higher concentration of pollutants than there should be.

Similar conclusion could be drawn for the Duwamish station. This one, is located in an industrial valley with several pollutant emitting sources nearby, as well as from the freight trucks passing through the industrial area. The field data collected shows a trend to be higher than that of Duwamish valley monitoring site, which concludes that even though with less fixed and industrial level pollution emitting sources, International District experiences a higher level of PM2.5 concentration. The result recommends that identifying potentially hazardous area and separating them than others to limit exposure to pollution cannot be achieved by only zoning designations, as it has been in the past. To evaluate pollution concentration at specific areas, more empirical studies need to be done, both by fixed site as well as mobile or personal monitoring, to get a better estimate of the air quality for an area, at least if pedestrians' exposure is considered. PSCAA has been instrumental in innovating ways of mobile monitoring, using several portable light carry instruments including M903 nephelometer converted into car-nephelometer or backpack-nephelometer(used for this experiment), as well as Micro-Aeth, and Aircasting instruments. A growing momentum have been observed from EPA also. EPA, understanding its limitation of funding and instruments, are encouraging common mass to measure pollutant while different activity of mode of commute. EPA has released a report recently suggesting types of air monitors to purchase and the recommended ways to collect pollution data that could be matched with EPA standards, calling individuals curious and inquisitive to measure air-pollution as 'citizen scientists'(EPA Air sensor Guidebook, 2014).

7.3 Who is getting affected

Environmental condition essentially brings upon the topic of environmental justice. Bae et. al., 2007, introduced the term FAPS and showed how poor residents are clustered near Freeway emissions in Seattle. However, observed in the area is somehow different from the general notion of the economically weaker section getting more affected due to the activities from the rich.

It is true that the area is not vehicle free, instead, a lot of vehicles have been observed during the data collection phase. However, as mentioned in the result chapter, vehicular pollution, in the experiment area does not provide sudden peaks in a spot, or sudden concentration of pollutants as experienced, which was the case for smoking.

During the collection phase as well as from the videography taken it has been seen that it's mostly people of lower economic capabilities are the people who are smoking and has been subjected to passive smoking. People gathered in front of the charitable homeless shelters on 2nd Ave extension south, 6th Main Street as well as at the plaza over International District Tunnel Station are the people being affected by staying near the smokers. One pattern observed is that while different people is involved in smoking at different time, they are almost always in close proximity to each other, which increases the chance of getting affected by passive smoking continuously. The area does not contain any designated smoking spot for public use, or there's no strict rule to abide by, which is necessary to separate smoke related or pollution and people inhaling it up to larger extent.

7.4 What planning level policy recommendation could facilitate to mitigate the current situation?

Of the activities cited as the major sources for pollutants, neither construction activity nor vehicular traffic could be mitigated easily. With the rapid growth in Seattle nowadays, construction activity is more likely to increase rather than mitigated. Strict regulations could be established for construction within the city, alike to all developers to keep pollutants from being spread out, e.g. higher fences and barriers, or to use more sophisticated instruments for earth removal or tearing down. However, those recommendations also incurs extra cost for construction, and Seattle, already facing a shortage of affordable housing, may become more pricy due to such recommendations. Through the cost benefit analysis should be performed before such recommendations take place, i.e., comparing the health benefits for such recommendations to the additional cost required.

The third reason, smoking, gives better opportunities to mitigate. As observed, passive smoking certainly increase health hazards, and the experiment area does include lot of potential hot spots, where smoking worsens the air quality. From planning and policy perspective, designated smoking area could be established all over the city at reasonable distance from each other and banning smoking elsewhere, at least in outdoor. Another extension of this policy could be to create designated smoking spots distant from the normal route for pedestrians wherever possible. One such example could be part of the parklet present in the junction of Yesler way and 2nd Ave Ext. South, as the whole segment of 2nd Ave Ext. South are frequented by smokers.

Seattle, being famous for neighborhood level planning, can also recommend neighborhood level air quality study by citizen scientists, and may put that as a recommended policy within neighborhood comprehensive planning elements. Periodic evaluation by mobile monitoring, as discussed earlier has become cheaper and such small funds could be arranged, if good political will persists. Neighborhood leaders can take active responsibility or outsource among willing neighborhood residents for such evaluation. Though the statement is author's own view on this subject, but frequent discussion with officials from PSCAA have established this conception that the agency is more than willing to help and train people willing to conduct individual assessment.

Several studies has been conducted with city officials or regional agencies collaborating with the universities present in the area. College of Built Environment and College of Environment of University of Washington have been instrumental in such studies. In future, responsibilities for neighbourhood level monitoring could be distributed among several agencies and universities collaborating. Universities and colleges can play both educational and environmental opportunities within different neighbourhood.

7.5 Further possibilities and opportunities for expansion.

The results obtained from the data necessarily recommends more rigorous research and experiment to quantify PM2.5, and other pollutant exposure at various points. They could be targeted towards a specific population, area, or time, to understand air pollution and air quality at places in a more distinct manner. Similar studies should be conducted in areas frequented by pedestrians, e.g. Downtown Seattle, University District among others. Also, more extensive studies are required within the same experiment area to understand seasonal, diurnal and activity related variation of PM2.5 concentration.

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Appendix A - Example of Minute Summarized data file, January 2nd, 2015.

	Minutes	Center_lat	Center_long	Maximum	Minimum	Mean	Median	Mostfreq	time	IDFieldPM2.5
1	30	47.598555	-122.32798	130.11	127.76	128.7868421	128.74	128.54	Morning	38.07704
2	31	47.599092	-122.328452	129.33	126.98	128.1658621	128.15	127.57	Morning	37.80932
3	32	47.599121	-122.329078	148.29	129.91	139.1615517	139.2	129.91	Morning	38.45516
4	33	47.599085	-122.330363	150.44	146.53	148.0232759	147.7	147.12	Morning	43.20512
5	34	47.598523	-122.331285	150.44	147.7	149.3165517	149.56	150.05	Morning	44.0138
6	35	47.597987	-122.332269	150.24	147.51	148.5674576	148.48	148.09	Morning	43.47284
7	36	47.598588	-122.333363	151.81	142.82	148.2898276	148.975	151.03	Morning	44.28428
8	37	47.599108	-122.334062	143.21	137.54	138.9489655	138.32	138.32	Morning	40.77632
9	38	47.600094	-122.334067	140.47	137.73	138.692931	138.51	138.32	Morning	40.77632
10	39	47.600533	-122.334187	148.09	138.71	142.3054237	140.27	139.49	Morning	41.09924
11	40	47.601024	-122.334092	150.24	145.75	148.107069	148.48	149.27	Morning	43.79852
12	41	47.601758	-122.333766	153.37	145.94	150.7022414	151.61	152.2	Morning	44.6072
13	42	47.601716	-122.332923	151.22	146.53	148.4375862	148.29	148.29	Morning	43.52804
14	43	47.601461	-122.331626	148.68	140.47	143.0584483	142.23	142.23	Morning	41.85548
15	44	47.600986	-122.331099	151.61	141.06	147.1394915	148.09	149.27	Morning	43.79852
16	45	47.600479	-122.330793	153.18	147.9	150.6656897	150.44	149.46	Morning	43.85096
17	46	47.600058	-122.330208	150.44	138.12	143.8363793	143.79	138.51	Morning	40.82876
18	47	47.599978	-122.32924	188.95	136.36	149.5267241	139.885	137.73	Morning	40.61348
19	48	47.59998	-122.32899	199.9	194.43	199.7517241	199.9	199.9	Morning	57.7724
20	49	47.599898	-122.327895	199.9	199.9	199.9	199.9	199.9	Morning	57.7724
21	50	47.599949	-122.32702	199.9	146.53	171.6884483	167.74	199.9	Morning	57.7724
22	51	47.599352	-122.326433	146.53	140.08	142.1713793	141.84	140.86	Morning	41.47736
23	30	47.59849	-122.327988	47.02	43.89	45.49298246	45.65	44.48	Midday	14.87648
24	31	47.599085	-122.328495	45.45	44.09	44.75	44.77	44.28	Midday	14.82128
25	32	47.599086	-122.329516	157.87	42.72	74.315	52.985	42.91	Midday	14.44316
26	33	47.599099	-122.329965	199.9	117.6	170.4887931	177.03	199.9	Midday	57.7724
27	34	47.599137	-122.331101	114.86	47.02	70.76711864	67.16	56.4	Midday	18.1664
28	35	47.599193	-122.332376	46.82	41.54	43.08172414	43.11	43.7	Midday	14.6612
29	36	47.599186	-122.332915	45.85	43.7	44.98568966	45.06	45.65	Midday	15.1994
30	37	47.599199	-122.334024	44.67	42.33	43.37189655	43.5	43.89	Midday	14.71364
31	38	47.600006	-122.334068	56.21	42.52	45.40491525	44.28	42.91	Midday	14.44316
32	39	47.600773	-122.334125	70.28	56.01	66.44775862	67.645	70.09	Midday	21.94484
33	40	47.601318	-122.334073	62.46	50.34	55.20275862	54.84	50.73	Midday	16.60148
34	41	47.601703	-122.333497	81.62	50.34	66.48413793	67.84	81.23	Midday	25.01948
35	42	47.60171	-122.332541	78.1	56.6	65.76965517	62.755	62.46	Midday	19.83896
36	43	47.601591	-122.331654	56.6	53.86	54.69254237	54.45	54.45	Midday	17.6282
37	44	47.600933	-122.331098	64.61	54.84	60.76396552	61.68	64.42	Midday	20.37992
38	45	47.600633	-122.330736	63.83	56.99	60.70413793	60.995	63.25	Midday	20.057
39	46	47.600108	-122.330316	62.66	49.56	54.73413793	54.155	50.34	Midday	16.49384
40	47	47.600082	-122.330135	49.95	44.87	46.75966102	46.43	45.45	Midday	15.1442
41	48	47.599934	-122.329119	138.71	45.26	74.7162069	63.44	47.02	Midday	15.57752
42	49	47.599914	-122.328642	199.9	142.03	180.6039655	179.765	199.9	Midday	57.7724
43	50	47.599947	-122.327825	199.9	106.06	167.0093103	181.035	199.9	Midday	57.7724
44	51	47.599941	-122.327214	103.91	46.82	65.96482759	63.145	63.83	Midday	20.21708
45	52	47.599584	-122.326468	46.63	42.72	43.85169492	43.89	43.89	Midday	14.71364
46	53	47.599258	-122.326537	49.56	43.89	46.57293103	46.04	44.28	Midday	14.82128
47	54	47.599088	-122.327362	57.58	49.17	50.99586207	49.76	49.56	Midday	16.27856
48	55	47.59897	-122.327904	59.14	57.38	58.12	57.97	57.58	Midday	18.49208
49	30	47.598519	-122.327986	49.56	43.11	46.8954386	47.41	43.11	Evening	14.49836
50	31	47.599043	-122.328492	43.11	34.7	39.70034483	40.57	40.57	Evening	13.79732
51	32	47.599116	-122.329224	37.05	30.79	32.98881356	32.55	31.38	Evening	11.26088
52	33	47.599124	-122.33023	51.91	36.85	44.98241379	47.02	49.17	Evening	16.17092
53	34	47.599179	-122.331472	57.18	50.15	54.68034483	55.13	56.01	Evening	18.05876
54	35	47.599204	-122.332466	51.32	42.72	49.09172414	50.15	50.54	Evening	16.54904
55	36	47.599181	-122.333602	87.68	35.68	47.29389831	39.39	36.27	Evening	12.61052
56	37	47.599556	-122.33406	90.42	54.64	75.84103448	77.125	86.51	Evening	26.47676
57	38	47.600202	-122.334134	53.67	45.06	48.65051724	47.9	47.61	Evening	15.74036
58	39	47.600803	-122.33417	44.87	38.03	40.54344828	39.98	38.22	Evening	13.14872
59	40	47.600961	-122.334094	38.42	36.66	37.3037931	37.24	37.05	Evening	12.8258
60	41	47.600987	-122.334161	38.61	36.66	37.81389831	37.83	37.83	Evening	13.04108
61	42	47.600999	-122.33426	37.05	33.33	35.18293103	35.29	35.48	Evening	12.39248
62	43	47.601097	-122.334192	33.92	32.55	33.08431034	33.14	33.14	Evening	11.74664
63	44	47.601605	-122.333762	33.53	31.77	32.60206897	32.36	32.36	Evening	11.53136
64	45	47.601726	-122.332832	38.03	33.53	36.00762712	36.46	36.85	Evening	12.7706
65	46	47.60166	-122.332059	36.07	34.31	34.96465517	34.9	34.9	Evening	12.2324
66	47	47.601264	-122.331392	37.44	34.31	34.96862069	34.7	34.51	Evening	12.12476
67	48	47.600618	-122.330839	51.12	37.24	43.3137931	41.35	41.54	Evening	14.06504
68	49	47.600098	-122.330176	50.93	41.94	46.59741379	46.53	44.28	Evening	14.82128
69	50	47.599959	-122.329185	41.94	37.44	39.76169492	39.78	39.78	Evening	13.57928
70	51	47.599964	-122.328775	38.42	32.75	35.58896552	35.97	34.12	Evening	12.01712
71	52	47.599898	-122.327859	35.09	32.55	33.5487931	33.33	33.33	Evening	11.79908
72	53	47.599933	-122.327478	36.66	34.9	35.76241379	35.68	35.68	Evening	12.44768

Appendix B- Certificate from Office of Risk Management, University of Washington

UNIVERSITY OF WASHINGTON

OFFICE OF RISK MANAGEMENT

EVIDENCE OF GENERAL AND AUTOMOBILE LIABILITY COVERAGE

Regarding: Pedestrian exposure to air pollution in Seattle study in the Transit tunnels and streets during Winter and Spring Quarter (Jan-May) 2015

Covered Entity: The University of Washington – **Department of Urban Design and Planning**

Term: 07/01/2014 through 06/30/2015

Limits: Coverage is unlimited per occurrence and in the aggregate

Policy Number: Not applicable; this is a statutorily self-insured program

Form: Occurrence

Conditions: Coverage applies to the negligent acts or omissions of the University of Washington and its employees, students, and agents acting in the course and scope of their University duties. The term "agent" includes volunteers to authorized University programs.

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Date Issued: January 6, 2015

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