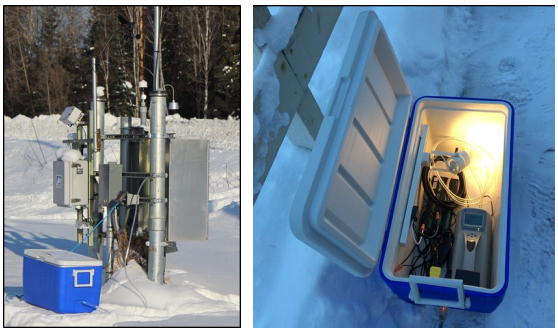
Center for Environmentally Sustainable Transportation in Cold Climates

Near-Roadway Air Pollution: Evaluation of Fine Particulate Matter ($PM_{2.5}$) and Ultrafine Particulate Matter ($PM_{0.1}$) in Interior Alaska



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This report presents a study of fine ($PM_{2.5}$) and ultrafine ($PM_{0.1}$) particles in the Fairbanks North Star Borough (FNSB) in Interior Alaska, with specific emphasis on the relationship of ultrafine particles (UFPs) to vehicular traffic. Chapter 1 provides a summary of published literature on particulates in air from vehicular emissions. Chapter 2 provides a novel and robust GIS-based data analysis approach to $PM_{2.5}$ data collected by the FNSB. This analysis approach is convenient for identifying hotspots, as well as locations where $PM_{2.5}$ changes either abruptly or continuously or does not change at all. The results reveal that average on-roadway $PM_{2.5}$ concentrations are higher in North Pole than in Fairbanks, and mean levels are higher in stationary background monitoring data than in mobile monitoring on-roadway data. Not surprisingly, significant negative correlations were found between temperature and $PM_{2.5}$. Chapter 3 presents the results from the data collection campaign to measure UFPs at roadside locations in Fairbanks and North Pole and investigate the relationship of UFPs with traffic and meteorological parameters. Multilinear predictive models were developed for estimation of UFPs and $PM_{2.5}$ based on weather and traffic parameters. Overall, this study improves our understanding of on- and near-roadway particulates in a cold-climate region.

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METRIC (SI*) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4		mm
ft	feet	0.3048		m
yd	yards	0.914		m
mi	Miles (statute)	1.61		km
		AREA		
in^2	square inches	645.2	millimeters squared	cm^2
ft^2	square feet	0.0929	meters squared	m^2
yd^2	square yards	0.836	meters squared	m^2
mi^2	square miles	2.59	kilometers squared	km^2
ac	acres	0.4046	hectares	ha
		MASS (weight)		
oz	Ounces (avdp)	28.35	grams	g
lb	Pounds (avdp)	0.454	kilograms	kg
T	Short tons (2000 lb)	0.907	megagrams	mg
		VOLUME		
fl oz	fluid ounces (US)	29.57	milliliters	mL
gal	Gallons (liq)	3.785	liters	liters
ft^3	cubic feet	0.0283	meters cubed	m^3
yd^3	cubic yards	0.765	meters cubed	m^3

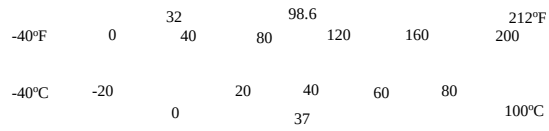
Note: Volumes greater than 1000 L shall be shown in m^3

		TEMPERATURE (exact)		
ºF	Fahrenheit	5/9 (ºF-32) ºC temperature temperature	Celsius	
		ILLUMINATION		
fc	Foot-candles	10.76	lux	lx
fl	foot-lamberts	3.426	candela/m^2	cd/cm^2
		FORCE and PRESSURE or STRESS		
lbf	pound-force	4.45	newtons	N
psi	pound-force per square inch	6.89	kilopascals	kPa

These factors conform to the requirement of FHWA Order 5190.1A *SI is the symbol for the International System of Measurements

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	Miles (statute)	mi
		AREA		
mm^2	millimeters squared	0.0016	square inches	in^2 m^2
meters squared		10.764	square feet	ft^2 km^2
kilometers squared		0.39	square miles	mi^2 ha
hectares (10,000 m^2)		2.471	acres	ac
		MASS (weight)		
g	grams	0.0353	Ounces (avdp)	oz
kg	kilograms	2.205	Pounds (avdp)	lb mg
megagrams (1000 kg)		1.103	short tons	T
		VOLUME		
mL	milliliters	0.034	fluid ounces (US)	fl oz
liters	liters	0.264	Gallons (liq)	gal
m^3	meters cubed	35.315	cubic feet	ft^3
m^3	meters cubed	1.308	cubic yards	yd^3
		TEMPERATURE (exact)		
ºC	Celsius temperature	9/5 ºC+32	Fahrenheit temperature	ºF
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/cm ^{2}	candela/m^2	0.2919	foot-lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	pound-force	lbf
kPa	kilopascals	0.145	pound-force per square inch	psi



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EXECUTIVE SUMMARY

Particulate air pollution in the form of fine ($PM_{2.5}$) and ultrafine ($PM_{0.1}$) particles has become a global concern, especially in urban areas with high population and vehicular traffic. Considerable research has been carried out to understand the underlying processes that impact particulate pollution, but most studies have been conducted in warmer regions such as California. The Fairbanks North Star Borough (FNSB) in Interior Alaska provides an interesting example of a relatively small- to mid-sized northern locality (population ~100,000) with persistent air quality issues and extremely cold climatic conditions for a major part of the year. Since December 2009, the FNSB has been designated a nonattainment region by the U.S. Environmental Protection Agency for the federal $PM_{2.5}$ standard. As part of their remediation efforts, the borough and state have undertaken increased monitoring by using an on-roadway monitoring vehicle (sniffer vehicle) and stationary near-roadway sites for air quality measurements beyond what is required for regulatory compliance. The goal of this project was to analyze the data collected by the borough's mobile monitoring vehicle (years 2012–15) to shed light on the $PM_{2.5}$ issues faced by the FNSB. Ultrafine particle (UFP) concentration levels were measured at four road weather information system (RWIS) sites in the FNSB region, and $PM_{2.5}$, traffic data, and weather data were collected at those locations.

In the first part of the study with mobile monitoring, data were categorized in nine different groups based on their mean and standard deviation values to determine the spatiotemporal distribution of $PM_{2.5}$. This novel way of grouping data allows identification of locations with consistently poor and consistently better air quality, by going beyond the simple analyses of means and accounting for variability and standard deviation in the data. In addition to hotspot identification, analysis found that average on-roadway $PM_{2.5}$ concentrations are higher in North Pole (27.2 $\mu g/m^3$) than in Fairbanks (12.9 $\mu g/m^3$), and that average concentrations are higher in

the background stationary monitoring data (29.4 μg/m^3) than in the mobile monitoring data (20.0 μg/m^3) for the study period. Not surprisingly, significant negative correlations (R^2=0.49 for Fairbanks and R^2=0.31 for North Pole) were found between temperature and $PM_{2.5}$. Temporal distribution of the data suggests that $PM_{2.5}$ levels increase gradually in the months of October and November, peak during the months of December, January, and February, and quickly plummet from March onwards.

In the latter part of the study, data on UFP measurements were collected at each of the RWIS sites in the FNSB for four days between March 1 and 18, 2017, for five continuous hours each day. Among other parameters, $PM_{2.5}$ concentrations, temperature, relative humidity, wind speed, and traffic volume data were collected. Data were analyzed to develop correlations between UFPs and other parameters, to compare data from this study with other studies, and to determine current roadside UFP concentration levels in Interior Alaska. Fairbanks roadside locations showed higher mean UFP counts (41,700 particles/cm^3) than in North Pole (22,100 particles/cm^3). Similarly, Fairbanks roadside locations showed higher $PM_{2.5}$ concentrations and traffic counts (6.3 μg/m^3; 15 vehicles/min) than in North Pole (4.6 μg/m^3; 10 vehicles/min), both being well below the on-roadway and background $PM_{2.5}$ concentrations estimated in the first part of this report. Multilinear predictive models were developed for estimation of UFPs and $PM_{2.5}$ based on weather and traffic parameters. This first study of UFPs in Alaska improves our understanding of near-roadway UFPs in cold regions.

CHAPTER 1.0 BACKGROUND AND LITERATURE REVIEW

1.1 Introduction

In urban areas, road traffic is one of the main sources of particulate matter (PM) in the atmosphere. Exposure to PM can have harmful effects on human health. A better understanding of traffic-related PM would give us more opportunity to research health risks related to PM. Size distribution of PM is also important because different-sized particles have different effects on human health. Since strategies for removing particulates from the environment are often based on particulate size, better knowledge of size distribution could help select more appropriate strategies for a specific environment.

1.2 Particulate Matter

It is well-established that airborne PM has adverse impacts on human health, making it an important subject of research. Particulate matter is commonly classified according to three modes: ultrafine (nucleation mode, diameter less than 0.1 μm), fine (mainly accumulation mode, diameter between 0 and 2.5 μm), and coarse (diameter between 2.5 and 10 μm) (Taiwo et al. 2014). Generally, fine and ultrafine PM is formed and released from high-temperature processes such as vehicular exhaust, oil and coal combustion, biomass burning, industrial processes, and chemical reactions in the atmosphere (Harrison et al. 2003). Coarse particles evolve from attrition processes, including mechanical abrasion of crustal material and re-suspension of road and soil dust, sea spray, volcanic eruptions, and brake and tire wear from vehicles (Allen et al. 2001).

The U.S. Environmental Protection Agency (EPA) includes PM in its list of Criteria Air Pollutants, considering its impact on public and human health. Under the National Ambient Air Quality Standards (NAAQS), the EPA has established safe ambient levels for PM, which are 35

$\mu g/m^3$ (24 hr average) and 150 $\mu g/m^3$ (24 hr average) for $PM_{2.5}$ and PM_{10}, respectively. There is no standard yet for $PM_{0.1}$, and regulations are still under consideration (Kumar et al. 2014).

1.3 Particulate Matter in the Fairbanks North Star Borough

In the last decade or so, Fairbanks, Alaska, has experienced some of the highest measured PM concentrations in the United States. The topography of Fairbanks contributes to temperature inversions and low mixing height. The city is surrounded on three sides by hills, which results in the entrapment of air pollution for days, sometimes weeks. Fairbanks also has low wintertime temperatures. The combination of topography and low air temperatures forms a perfect recipe for poor air quality. Since 2006, Fairbanks has frequently exceeded the federal $PM_{2.5}$ standard, and in 2009, Fairbanks was declared a nonattainment area. Prior to being designated a nonattainment area for $PM_{2.5}$, Fairbanks faced many air pollution-related problems, for example, nonattainment of the carbon monoxide standard for many years, although the city overcame this problem in 2004. The Fairbanks North Star Borough (FNSB) has initiated programs to identify specific sources of $PM_{2.5}$ in ambient air, and established monitoring sites for collecting hourly $PM_{2.5}$ concentrations.

1.4 Roadside Particulate Matter

Vehicular traffic emissions have three components: (1) vehicle exhaust; (2) emissions from brake, tire, and road wear; and (3) re-suspension from wheel-generated turbulence (Amato et al. 2013). The latter two components are considered non-exhaust emissions.

1.4.1 Exhaust emissions

Exhaust emissions from motor vehicles, also referred to as “tail pipe emissions,” contain fine and ultrafine particles (UFPs) because motor vehicles produce carbonaceous aerosols (Pant and Harrison 2013), and emission happens at high temperature through the tail pipe. Engine age, type, and maintenance play a role in the variation of PM emissions from motor vehicles (Pant and

Harrison 2013). In addition, type and condition of the engine, fuel composition and additives, operating conditions, and emission control devices cause variation in PM emission (Amato et al. 2013). Studies show that PM emission varies in vehicles with different fuel systems; for example, diesel vehicles emit a greater mass of PM and a larger number of UFPs than gasoline vehicles emit (Rose et al. 2006). Most research and resulting policy have focused on exhaust emission. As a result of improved engine operations and controlled tail pipe emissions, a huge reduction of PM has occurred over the past 30 years (Allen et al. 2006), but other vehicle-related sources are less studied.

1.4.1 Non-exhaust emissions

Non-exhaust emissions mainly contribute to coarse particles ($PM_{2.5-10}$). Even though PM from exhaust emissions are reduced, a zero emission vehicle still can produce PM from tire wear, road wear, brake wear, and re-suspended road dust (Allen et al. 2006, Pant and Harrison 2013). Rexeis and Hausberger (2009) have estimated that PM concentration due to non-exhaust emissions will amount to 90% of total PM by the end of this decade. Non-exhaust emissions are becoming more important, and further research is needed to improve our understanding of PM sources and constituents.

1.4.1.1 Tire wear

The rolling shear forces between tire tread and the road surface are the main cause of tire wear particles (Rogge et al. 1993). Tire use predominantly produces coarse ($PM_{2.5-10}$) particles. Tire debris enters the atmosphere due to turbulence caused by wind speed and traffic density within the air column above the street. The settling velocity of that debris varies based on the PM size (Rogge et al. 1993). Microscopic analysis shows that tire wear particles generally elongate on rough surfaces (Gunawardana et al. 2012). For example, tires wear more on asphalt pavements than on concrete pavements. Tire tread is also a potential source of airborne particles because tire

tread contains natural rubber copolymers such as styrene-butadiene rubber and polyisoprene rubber, and zinc (Zn) (Pant and Harrison 2013). Tire type impacts the magnitude of emissions too. Hussein et al. (2008) have reported that studded tires cause more emissions than summer and friction tires (winter tires).

1.4.1.2 Brake wear

Brake wear refers to abrasion between brake lining material and brake discs. Grinding and condensation of brake pad materials are responsible for coarse-range and fine-range particle emissions, respectively. Garg et al. (2000) have reported that the condensation of brake pad materials releases PM directly into the atmosphere and is a source of trace metal concentration. Each daily rush hour is a potential time for release of high brake-wear-related emissions because at that time, people operate vehicles in stop-and-go mode (Grieshop et al. 2006). Freeway exit sites contribute higher brake wear emissions than do other types of roadside sites (Abu-Allaban et al. 2003).

1.4.1.3 Road dust

Road dust is composed of coarse-sized particles from traffic, wood burning, industrial emissions, and other sources (Kupiainen et al., 2005). It is hard to tell whether road dust is crustal, re-suspended, or direct emission because of the spatial and temporal variation of its composition. Researchers have discussed re-suspended dust more than any other type of road dust. Various factors associated with traffic, road, and meteorological parameters influence the amount of re-suspended road dust. Etyemezian et al. (2003) found that season and roadway travel speed significantly affect emission amounts. Heavy traffic shows a strong correlation with re-suspension of road dust (Thorpe et al. 2007). People think that precipitation reduces re-suspended dust from the road, but research does not support that notion. Street washing experiments conducted in Spain have not proven effective in controlling PM re-suspension (Karanasiou et al. 2012).

1.5 Spatial Variation of Particulate Matter

Three common approaches are used in measurement and quantification of spatial variation of PM in urban areas: (1) measurements as a function of distance from a major road; (2) measurements at a major road as well as at side streets; and (3) measurement at specific and predefined locations within a city (Morawska et al. 2008).

1.5.1 Particle concentration and distance from the road

Several studies have been done on the effect of distance from the road on particle concentration, and these studies have generally followed the same procedures and considered the same areas, i.e., undisturbed by barriers like buildings or hills and showing the same shape of the dispersion function. Changes to size distribution and particle number were the main concentration of the studies; however, a few studies tried to correlate particle concentration with pollutants emitted from vehicles. As a result, all of these studies show that concentration of PM decreases with distance from the road, up to a certain point, around 300 m, after which concentration and size distribution levels reach the local background (Hitchins et al. 2000, Zhu et al. 2002).

On-road and roadside particle concentrations range between 10^4 and 10^6 particles cm^{-3} and show correlation with vehicle flow characteristics. The higher speed of a vehicle contributes to greater particle concentration and smaller particle size. But less variation was observed in particle volume compared with particle number size distributions (Kittelson et al. 2004). Virtanen et al. (2006) showed that total concentrations at roadsides are dominated by nucleation mode particles and increase with higher traffic rates, and that the effect of traffic rate is stronger on particles smaller than 63 nm than on larger particles. Harrison et al. (1999) reported that, on the road, significant numbers of particles are in the 3–7 nm size range, with a mode below 10 nm, and are attributable to homogeneous nucleation processes.

1.5.2 On-road and urban background concentration

A number of studies monitored the concentration of particle characteristics in urban sites located at various orientations in relation to urban traffic, or from mobile laboratories around the city. Most commonly, the aims of such studies were to compare the differences between local hotspots and urban background locations, rather than to provide a comprehensive characterization of the relationship between the concentrations and the distance from a particular street or traffic flow. Particle size distribution is much more stable at background urban sites, where it is likely to be unimodal; closer to traffic, particle size distribution is multimodal and changes rapidly (Harrison et al. 1999, Morawska et al. 2004). Near traffic, the nanometer fraction of UFPs dominates the total particle number concentrations, and their contribution decreases with distance from traffic (Kittelson et al. 2004).

1.5.3 Particle concentration in different environments

Studies show that different environments contribute to different particle concentration levels. Studies have been done on the environment of eight categories: on-road, roadside (with different distance from the road), road tunnel, street canyon, urban, urban background, rural, and clean background (Morawska et al. 2008). Figure 1.1 represents a comparison of mean and median concentrations for different environments.

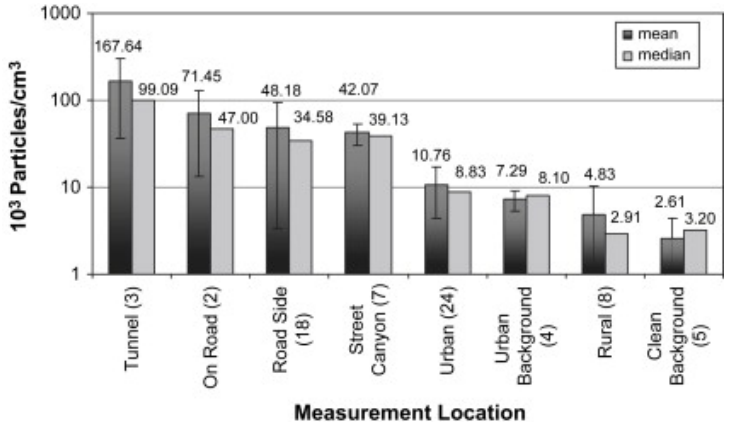


Figure 1.1 Number concentrations of particles at different locations (Ref.: Morawska et al. 2008).

1.6 Factors Affecting PM Concentrations

Wind speed, temperature, and relative humidity are the most important factors affecting PM, and are briefly discussed below.

1.6.1 Wind speed

Wind speed is responsible for dispersion and dilution, and thus causes atmospheric mixing. Wind also causes re-suspension of particles. Studies found a direct correlation of UFPs with wind. Charron and Harrison (2003) found that when the relationship between larger particle concentration and wind speed is U-shaped, UFP concentration decreases. Since wind speed increases the coagulation rate, causing better air mixing and particle loss due to deposition, Hussein et al. (2005) presented UFP concentration by a decreasing exponential function of wind speed. Hussein et al. (2005) found a linear decreasing trend with wind speed and provided an explanation that, in summertime, mixing of aerosol particles occurs within a bigger volume so the changes of particle concentration with wind speed are smaller. Also, road traffic may cause mixing despite otherwise static conditions.

1.6.2 Temperature

Temperature plays an important role in variation of particle number concentration. Especially in wintertime, people burn wood to keep their houses and buildings warm, producing particles most likely to be ultrafine. Charron and Harrison (2003) found that particles in the size range of 11–30 nm in a roadside environment peaked during the early morning, showing an inverse association with air temperature. On the other hand, Kim et al. (2002) showed that during the warmer months, some increase in particles smaller than 100 nm occurs in the afternoon, linked to an increase in temperature. However, most of the literature suggests an inverse relation of temperature with particle number concentration. Olivares et al. (2007) found that when the temperature decreased from +15°C to -15°C, the particle number more than doubled, and they

mentioned that variation was pronounced with particles smaller than 40 nm, while variation of particles larger than 100 nm was not so statistically significant.

1.6.3 Relative humidity

Relative humidity shows a daily anti-correlation with temperature, but a positive correlation with ambient particle concentration. Condensation of volatile compounds onto pre-existing aerosol changes the particle size, and thus changes particle numbers. Also, studies show that nucleation mode particles are largely influenced by relative humidity. Hussein et al. (2005) found that in southern Finland the high number concentration of particles larger than 100 nm during warmer summer temperatures was partly due to the growth of aerosol particles in the presence of condensable vapors emitted from the surrounding boreal forest.

1.6.4 Temperature inversion

A temperature inversion, which is a mix of several meteorological conditions, that exacerbate poor air quality by trapping accumulated pollutants in the atmosphere closer to the ground. In this condition, the air is stable, little vertical mixing occurs, and wind speed is lower; thus, pollution concentration increases. For example, Janhaïl et al. (2006) showed that morning temperature inversions in Goteborg, Sweden, resulted in significantly elevated concentrations of traffic-related pollutants, including UFPs, but there was no impact of inversion on PM_{10} concentrations.

1.6.5 Precipitation

In general, precipitation has a washout effect on the environment, which ultimately helps remove particles from the atmosphere. Charron and Harrison (2003) found an opposite effect in relation to particles below 150 nm, with an increase of particle numbers during rain with >0.4 mm raindrops. In addition, the highest particle numbers were measured just 1 hour after a rain event.

The possible explanation for this phenomenon is an effect of reduced temperature during precipitation events.

1.7 Chemical Composition of Particulate Matter

Atmospheric PM is made up of diverse chemical substances including water-soluble ions, trace metals, and organic compounds (Taiwo et al. 2014). Water-soluble ions constitute a significant portion of PM mass (Yin and Harrison 2008) and therefore play an important role in aerosol chemistry. Sulfate and nitrate are formed mainly from the oxidation of SO_2 and NO_x. Sodium, magnesium, and chloride are the main components of sea spray; potassium arises from biomass burning or soil, and Ca from construction, soil, and steelworks emissions (Oravisjärvi et al. 2003, Pandolfi et al. 2010). Several anthropogenic, geogenic, and biogenic activities are responsible for emissions of trace metals to the atmospheric environment and hence play important roles in determining size distributions (Allen et al. 2001). Each source has a characteristic size distribution reflective of its source. Here, the only chemical composition of traffic-related PM will be discussed.

1.7.1 Exhaust particles

Exhaust particles contain submicron-sized primary particles and micrometric secondary particles (S-N-organics) formed in the atmosphere by condensation of gaseous compounds on existing nuclei (Amato et al. 2013). Elemental carbon, adsorbed organic material, inorganic salts, and traces of metallic compounds are the main components of gasoline- and diesel-originated exhaust particles, although particles emitted from engines operated with gasoline and diesel are different from each other by size and chemical composition.

Diesel engines contribute more fine and ultrafine particles than gasoline engines in both mass basis and number basis concentration (Rose et al. 2006). Gasoline engines release a higher

fraction of organic carbon (OC), while diesel engines emit more elemental carbon (EC) (Watson 1994, Weingartner et al. 1997). Zhu et al. (2010) reported that $PM_{2.5}$ emissions from diesel and gasoline vehicles are rich in different fractions of EC and OC. Vehicles are also a major source of n-alkanes, and diesel engines are known to emit more n-alkanes than gasoline engines emit (Rogge et al. 1993)

Studies show that elemental markers used for vehicular emissions include copper (Cu), manganese (Mn), iron (Fe), zinc (Zn), barium (Ba), tin (Sn), nickel (Ni), molybdenum (Mo), and antimony (Sb) (Birmili et al. 2013, Lough et al. 2004). Metals can be emitted from various exhaust-related sources including fuel and lubricant combustion, catalytic converters, particulate filters, and engine corrosion (Lough et al. 2004), but many appear to arise from non-exhaust sources. Nickel (Ni) and vanadium (V) have been reported present in emissions due to oil combustion (Pey et al. 2010).

1.7.2 Non-exhaust emission

Non-exhaust emissions come from tire wear, brake wear, road wear, and road dust, as discussed earlier. Different types of PM can have different chemical compositions.

1.7.2.1 Tire wear

Minimal research has been done on the chemical composition of tire wear. Rogge et al. (1993), who presented some of the most detailed information on tire tread debris, suggested benzothiazole as a possible tracer for tire wear products in the atmosphere, although this conclusion was drawn from analyses of only one tire. More recently, Kumata et al. (1997) suggested that 2-(4-morpholinyl) benzothiazole, an impurity found in vulcanizing agents used in tire manufacturing, may have potential use as a molecular marker for tire abrasion products. In a later study, Kumata et al. (2002) reported the presence of benzothiazole compounds in street runoff, concluding that tire wear and contaminated road dust are the likely source.

Hildemann et al. (1991) detected several metals at substantial concentrations. Aluminium (Al), calcium (Ca), Cu, Fe, titanium (Ti), and Zn were particularly prevalent. However, the dynamometer tests were performed on tires from a vehicle driven for 7200 miles on normal roads, so contamination of the tire tread with road dust may have affected concentrations. Adachi and Tainosho (2004) reported the presence of other metals in tire wear debris that may contribute substantially to airborne metal loadings, including manganese (Mn), Fe, cobalt (Co), Ni, Cu, cadmium (Cd), and lead (Pb). Camatini et al. (2001) identified rubber particles from tire wear experiments in the laboratory by the presence of sulfur (S) and Zn using SEM-EDX analysis.

1.7.2.2 Brake wear

Modern brake lining materials are composites of many ingredients including chemicals. Particle emissions from the braking process vary in chemical composition. Several studies have been done to determine the metal content of brake linings and wear particles. Metals such as Fe, Cu, Pb, and Zn are ubiquitous and have been repeatedly reported in high concentrations in brake lining materials. Hildemann et al. (1991) found brake dust particles predominantly composed of Fe compounds, silicon compounds, organics, magnesium (Mg), and barium (Ba). In a more comprehensive assessment performed by Garg et al. (2000), Fe, Cu, Sb, and Ba were found to be most abundant.

1.7.2.3 Road dust

Particles emitting from a wide variety of sources deposit on the road surface. Exhaust particles, de-icing salt, and biogenic and geogenic materials may all be carried from nearby locations and deposited on the ground. These deposited materials or particles are referred to as road dust. The diversity of sources is so huge that Miguel et al. (1999) reported at least 20 different road dust sources from which the presence of allergens has been derived. Deposited materials are re-suspended through the abrasion of traffic and cause PM emissions. Typically, road composition

is dominated by elements and compounds associated with crustal materials. Therefore, local geology can have an effect on the composition of road dust, varying with location. Variation with season can also be pronounced, especially in regions where road salting procedures and studded tire use is common in winter months (Schauer et al. 2006). Analysis of road dust samples conducted by Hildemann et al. (1991) in Pasadena reported the composition as 27% SiO_2, 11% Al_2O_3, 9% Fe_2O_3, 4% Ca, and 17% organics. Etyemezian et al. (2003) reported organic carbon as an important constituent of many soil and road dust samples as are Ca and Fe.

1.8 Impacts of PM on Human Health

The World Health Organization estimates that PM air pollution contributes to approximately 800,000 premature deaths each year, ranking it the 13th leading cause of mortality worldwide (Anderson and Thundiyil 2012). However, many studies show that the relationship is deeper and far more complicated than originally thought. Ultrafine particles ($PM_{0.1}$) especially can have more adverse effects on human health than coarse and fine particles (Russell and Brunekreef 2009). Ultrafine particles easily penetrate deep into the respiratory system and reach a large surface area, which increases their reactivity, leading to adverse health effects (Betha et al. 2014). People subjected to long-term exposure to PM have significantly more cardiovascular incidents and a higher mortality rate.

1.8.1 Exposure to PM

Being able to understand the sources of PM does not mean a similar understanding is available for how individuals (or even populations) are exposed. An individual's exposure may not be similar to ambient measurements and the corresponding emissions, since people move from one environment to another and spend a lot of time in buildings and vehicles (Russell and

Brunekreef 2009). In general, exposure means concentrations experienced in an environment over time (Morawska et al. 2008)

1.8.2 Exposure to ultrafine particles

Few studies have investigated human exposure to UFPs. In winter, people spend a lot of time on roadways traveling to or from work, and UFPs are strongly associated with traffic-related emissions. A roadside study by Kaur et al. (2006) showed that various modes of transport resulted in different exposures, with average personal UFP count exposure (10^4 particles cm^{-3}) of 4.61 (walking), 8.40 (cycling), 9.50 (bus), 3.68 (car), and 10.81 (taxi). Gouriou et al. (2004) found that particle concentrations in exposed car passengers may present high peaks, up to 10^6 particles cm^{-3}.

1.8.3 Health effects

Particulate matter is associated with a wide variety of cardiovascular and respiratory health issues, with responses to exposure being both acute (e.g., increased hospital admittances for respiratory disease or premature mortality from cardiovascular disease) and chronic (reduced longevity in cities with higher PM levels). There are also indications of reproductive and developmental effects.

1.8.3.1 Cardiovascular effects

Studies suggest that PM significantly affects the cardiovascular system. Research on this topic has focused on both the long-term effects of PM exposure and the acute effects of increases in ambient PM on cardiovascular mortality. Brook et al. (2010) found that for any increase in mortality caused by PM, two-thirds of the effect was accounted for by cardiovascular diseases.

As for short-term effects, time-series studies estimate that a 10 $\mu g/m^3$ increase in mean 24-hour $PM_{2.5}$ concentration increases relative risk (RR) by 0.4% to 1% for daily cardiovascular mortality (Pope and Dockery 2006). Short-term PM exposure is also associated with triggering

myocardial infarction (MI). Peters et al. (2001) reported on a study of 772 Boston area patients with MI; elevated concentrations of $PM_{2.5}$ increased the risk of MI within a few hours and one day after exposure.

Many studies have been conducted through the years to understand the long-term exposure effect of PM. One of the well-known studies is the "Harvard Six Cities study," a cohort study, published in 1993, that followed 8111 patients for 16–18 years. The study showed a 29% (95% CI, 8–47%) increase in mortality rate for the most polluted cities compared with the least polluted cities (Dockery et al., 1993). Particulate pollution was associated with lung cancer and cardiopulmonary disease. Pope et al. (1995) conducted a cohort study of 552,000 patients in 151 areas and found a 17% increase in all-cause mortality and a 31% increase in cardiopulmonary mortality between the most polluted and the least polluted cities.

1.8.3.2 Respiratory effects

While much of the interest in PM has focused on the cardiovascular system, many studies evaluated the association between PM exposure and respiratory illness. Researchers have evaluated endpoints including respiratory symptoms, medication use, lung function, health-care utilization, and mortality (Anderson and Thundiyil 2012). Studies suggest that PM levels may affect lung function and development. Gauderman et al. (2004), who followed 1759 patients over 8 years, found that children who lived in communities with the highest PM concentrations were five times more likely to have low FEV1(forced expiratory volume in 1 second), an assessment of the normality of lung function, than those in communities with the lowest PM concentrations. Studies also found that children with better lung function were susceptible to asthma when exposed to higher levels of $PM_{2.5}$ (Islam et al. 2007).

Several studies have demonstrated an association in adults between respiratory hospitalization and ambient PM (Medina-Ramon et al. 2006). Even with short-term exposure,

effects are stronger for stronger patients (Arena et al. 2006). Peng et al. (2009) found in their study of 12 million Medicare enrollees in 108 counties a significant increase in respiratory hospitalizations with increasing $PM_{2.5}$ levels in the eastern U.S., suggesting that morbidity may be related to specific chemical constituents of PM, which differ across the nation since they did not find a consistent effect of PM in the western U.S.

CHAPTER 2.0 WINTERTIME ON-ROADWAY $PM_{2.5}$ MOBILE MONITORING IN FAIRBANKS AND NORTH POLE, ALASKA

2.1 Introduction

Airborne particulate matter (PM) contributes to increasing mortality rates from respiratory and cardiovascular disease (Brunekreef and Holgate 2002). With an aerodynamic diameter of less than or equal to 2.5 microns, $PM_{2.5}$ has a tremendous effect on human health, visibility, and climate condition, making it an important subject of research and study (Wang and Ogawa 2015), and with urbanization and industrialization, $PM_{2.5}$ pollution has become a global concern. Many studies have been done in major cities in the U.S. and Europe regarding PM concentrations and associated health effects (Dockery et al. 1993, Katsouyanni et al. 2001, Le Tertre 2002). Research indicates that cities with large populations and traffic volume continuously show higher concentrations of $PM_{2.5}$ (Huang et al. 2015, Pant et al. 2015). However, many cities with small populations can still show higher concentrations of $PM_{2.5}$ due to reasons such as topography and extreme weather conditions. The city of Fairbanks, Alaska, with a population of only 31,644 (U.S. Census Bureau, 2017) is one of those locations.

In the case of the Fairbanks North Star Borough (FNSB), which includes the cities of Fairbanks and North Pole, topography contributes to extreme temperature inversions and low mixing height during peak winter days, typically during the months of November through February. Naturally, cold winter periods are also associated with higher residential heating emissions, along with inversions and low temperatures that trap particulates close to the ground. During this period, Fairbanks experiences poor air quality for days, sometimes weeks (Ward et al. 2012a). Because it exceeded the federal $PM_{2.5}$ 24-hour National Ambient Air Quality Standard, the FNSB was designated a $PM_{2.5}$ nonattainment area in 2009 (Leelasakultum and Molders 2011). Since 2009, several air quality monitoring and control programs have been initiated by the FNSB in partnership with the Alaska

Department of Environmental Conservation and the U.S. EPA. One such program is the on-roadway mobile monitoring of $PM_{2.5}$ concentration levels in commercial and residential areas during the winter months, typically October to March. The mobile monitoring vehicle makes one to two trips almost every day to monitor adverse air quality hotspots within the FNSB. This method provides wider spatial and temporal coverage than what is possible by regulatory mandated monitoring, and the $PM_{2.5}$ data obtained supplements the background data collected by the stationary air quality monitors for regulatory purposes.

There are several reports in the literature wherein data obtained from stationary air quality monitoring stations are used to estimate the spatial distribution of $PM_{2.5}$ concentrations (Blanchard et al. 2014, Zhao et al. 2014, Tunno et al. 2017). These studies generally use a small number of fixed locations to represent the spatial variability of the whole study area. For a smaller area this procedure may be representative, but for larger cities where monitoring stations are sparsely distributed, it may be problematic. In several recent studies, mobile monitoring is being used for particulate data collection, in part because of the availability of inexpensive mobile monitoring devices. Most of these studies collect mass concentrations of $PM_{2.5}$ and focus on the chemical composition and size distribution of PM (Kozawa et al. 2012, Westerdahl et al. 2005), or on understanding human exposure to $PM_{2.5}$ (Panis et al. 2010); but few, if any, have considered mobile monitoring data to determine the spatial variation of $PM_{2.5}$ (Table 2.1).

In this work, a new method is developed to broadly understand the spatiotemporal variability of $PM_{2.5}$ concentrations by focusing on the study area, more specifically the sampling route driven by the mobile monitoring vehicle. The total route was divided into many small segments to precisely understand place-to-place variation of $PM_{2.5}$ concentrations.

Table 2.1 Summary of studies related to spatial distribution of $PM_{2.5}$ using mobile monitoring data

Reference	Sampling Year	Location	Pollutants Measured	Sampling Duration
Tran et al. 2012	2008–2009	Fairbanks, AK	$PM_{2.5}$	N/A
Weijers et al. 2004	1999–2000	Amsterdam, Netherlands	UFP, $PM_{2.5}$	3 days
Poppel et al. 2013	2010	Flanders, Belgium	UFP, $PM_{2.5}$, BC	10 days
Zwack et al. 2011	2007	Brooklyn, NY	$PM_{2.5}$, UFP, PAHs	~50 hours
Patton et al. 2014	2009–2012	Boston, MA	$PM_{2.5}$, NO, NOx, CO, BC, pPAH	340–1124 hours
Pirjola et al. 2006	2003–2004	Helsinki, Finland	$PM_{2.5}$, PM_{10}, UFP, CO, NO, NOx	N/A
Larson et al. 2007	2004–2005	Vancouver, B.C.	$PM_{2.5}$, levoglucosan	N/A

2.2 Data and Methods

2.2.1 Mobile monitoring vehicle

The raw $PM_{2.5}$ data were collected by the FNSB Air Quality Division using a mobile monitoring vehicle (MMV). The MMV is equipped with an aerosol monitor (*personal* DataRAM™ pDR-1500; Thermo Fisher Scientific, Waltham, MA) and a GPS (Garmin Ltd.) to measure the $PM_{2.5}$ concentrations and the vehicle position, respectively. The aerosol monitor was set inside the vehicle with an ambient air inlet probe located above the vehicle, approximately 2.5 m above the roadway. Sample air was drawn into the aerosol monitor at a rate of 1.52 L/min during the measurement. The MMV was driven on predetermined routes in Fairbanks and North Pole, shown in Figure 2.1, typically from October to March, for two to three hours each day. This study considers data from three consecutive winter seasons (October 2012 to March 2013, October 2013 to February 2014, and October 2014 to March 2015) for a total of 210 days. Though there was a fair amount of commonality in the routes driven by the vehicle between years, some variation in spatial coverage does exist. The raw data obtained consist of latitude, longitude, timestamp, and $PM_{2.5}$ concentration at 2-second resolution. Figure 2.1 shows the merged routes for the three sampling seasons of the data.

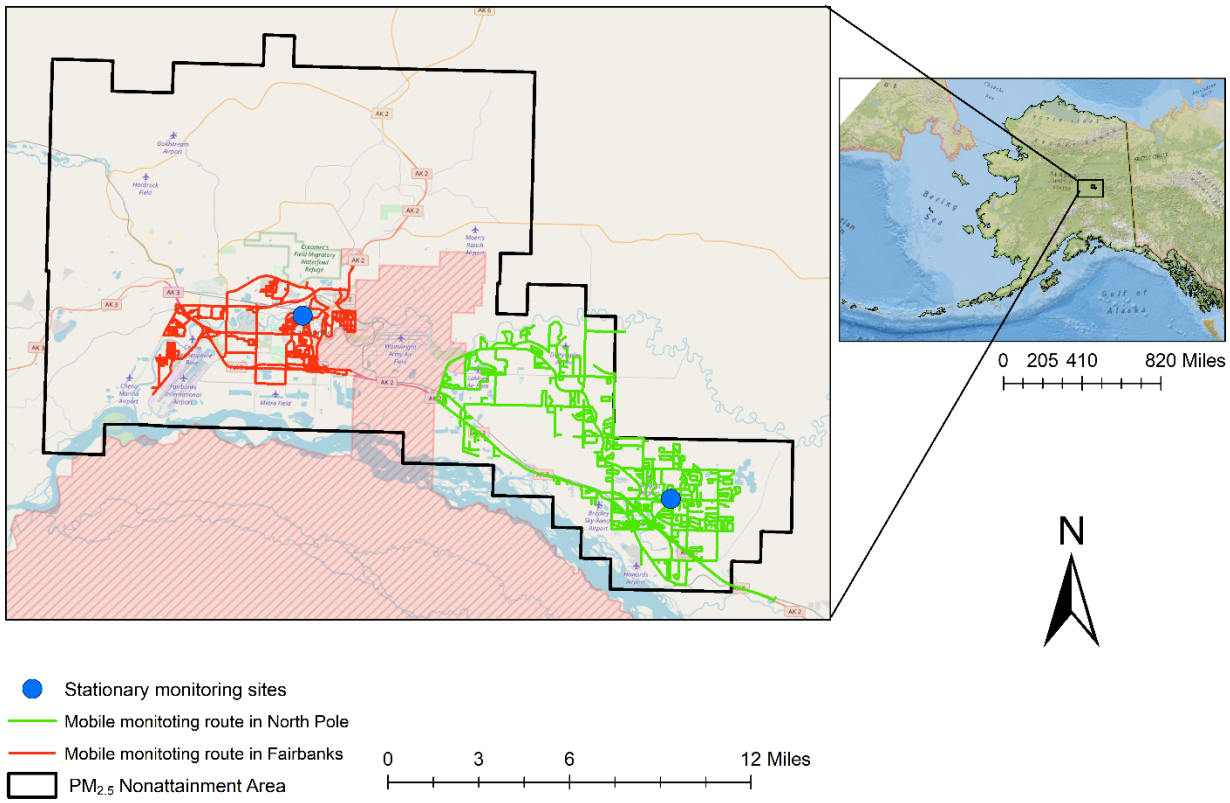


Figure 2.1 Study area showing sampling route of the mobile monitoring vehicle and the stationary monitoring sites in the nonattainment area of the Fairbanks North Star Borough

2.2.2 Vehicle route

The MMV was not driven the same route consistently in every month of the sampling periods. It was necessary for the analysis to cover all routes used by the MMV during a sampling period, to not ignore any potential hotspots. Using ArcGIS (ver. 10.3.1, Esri, Redlands, CA), a single comprehensive route was created by considering and merging all different routes covered by the MMV over the three-year sampling period. The types of roads with corresponding length were arterial (58.32 km), local (26.13 km), major (44.08 km), and minor (39.98 km) for the city of Fairbanks.

2.2.3 Route segmentation

MMV measurements are all instantaneous data at varied spatial locations. In order to assess the variability of PM2.5 with time at given location (on the route), the comprehensive Fairbanks and North Pole route (shown in Figure 2.1) was divided into 1137 segments of varied lengths. In ArcGIS,

initially the route was divided so that each segment was of equal length. In doing so, 773 segments of equal length (213 m) were created. A majority of those segments were further divided and spatially discontinuous, although during the spatial analysis they were considered a single entity. As a result, the spatial distribution of the data would not be accurate. To rectify this problem, segmentation was accomplished by focusing on the continuity of each segment. Each $PM_{2.5}$ data point was joined to one of the segments based on location. After that, each segment was assigned the average of all coinciding $PM_{2.5}$ readings for each respective day. Additionally, the monthly and annual mean and standard deviation of $PM_{2.5}$ were calculated for each segment.

2.2.4 Categorization

For monthly data, all segments were divided into nine categories based on three levels each for the mean and standard deviation of the $PM_{2.5}$ data. Both the mean and standard deviation of $PM_{2.5}$ data were divided into three levels by considering the 25^{th} and 75^{th} percentile values of the $PM_{2.5}$ data as the cutoff points. Values less than or equal to the 25^{th} percentile were considered low, between the 25^{th} and 75^{th} percentiles, medium, and above the 75th percentile, high. A similar approach was used for the yearly average $PM_{2.5}$ data. Table 2.2 lists those nine categories along with the ranges for monthly and yearly means for the two cities. Each of the nine categories represents a unique air quality condition. For instance, low mean with low standard deviation (LM-LSD) represents consistently good air quality condition. On the other hand, high mean with low standard deviation (HM-LSD) denotes consistently poor air quality condition. Furthermore, high mean with medium standard deviation (HM-MSD) and high mean with high standard deviation (HM-HSD) can be considered poor air quality conditions of chronic and episodic concern, respectively.

Table 2.2 Categorization schemes of the road segments based on the mean and standard deviation of the $PM_{2.5}$ concentration

Category	Category Name	Description	Area	Monthly Values		Yearly Values	
				Mean	Standard Deviation	Mean	Standard Deviation
1	LM-LSD	Low Mean – Low Standard Deviation	Fairbanks	0–6.5	0–4.1	0–8.4	0–2.1
			North Pole	0–10.6	0–4.6	0–19.1	0–11.6
2	LM-MSD	Low Mean – Medium Standard Deviation	Fairbanks	0–6.5	4.1–11	0–8.4	2.1–6.2
			North Pole	0–10.6	4.6–23.9	0–19.1	11.6–33.9
3	LM-HSD	Low Mean – High Standard Deviation	Fairbanks	0–6.50	>11	0–8.4	>6.2
			North Pole	0–10.6	>23.9	0–19.1	>33.9
4	MM-LSD	Medium Mean – Low Standard Deviation	Fairbanks	6.5–16.5	0–4.1	8.4–16.2	0–2.1
			North Pole	10.6–42.3	0–4.6	19.1–44.8	0–11.6
5	MM-MSD	Medium Mean – Medium Standard Deviation	Fairbanks	6.5–16.5	4.1–11	8.4–16.2	2.1–6.2
			North Pole	10.6–42.3	4.6–23.9	19.1–44.8	11.6–33.9
6	MM-HSD	Medium Mean – High Standard Deviation	Fairbanks	6.5–16.5	>11	8.4–16.2	>6.2
			North Pole	10.6–42.3	>23.9	19.1–44.8	>33.9
7	HM-LSD	High Mean – Low Standard Deviation	Fairbanks	>16.5	0–4.1	>16.1	0–2.1
			North Pole	>42.27	0–4.6	>44.8	0–11.6
8	HM-MSD	High Mean – Medium Standard Deviation	Fairbanks	>16.5	4.1–11	>16.2	2.1–6.2
			North Pole	>42.27	4.6–23.9	>44.8	11.6–33.9
9	HM-HSD	High Mean – High Standard Deviation	Fairbanks	>16.5	>11	>16.2	>6.2
			North Pole	>42.27	>23.9	>44.8	>33.9

2.2.5 Other data

Publicly available 24-hour average temperature data were obtained from the Fairbanks International Airport station and the Eielson Air Force Base station, both of which are proximal to the sampling route of the MMV (Weather Underground 2017). For the spatial analysis, publicly available shapefiles representing roads and streets in the borough were obtained from the FNSB Geographic Information System (GIS 2017). Mobile monitoring data were also compared with the stationary monitoring data in order to investigate the correlations between roadside and background concentrations of $PM_{2.5}$. Two stationary monitoring sites, NCORE in Fairbanks and the fire station in North Pole, were considered sources of stationary data. These data are publicly available from the EPA website (U.S. EPA 2017) with a 24-hour resolution. Table 2.3 shows all the data used in this study.

Table 2.3 Summary of raw data used

Data Name	Data Type	Resolution/Accuracy	Source
Mobile $PM_{2.5}$	Spatial	2 sec/± 40 (m)	FNSB
Stationary $PM_{2.5}$	Tabular	24 hr	EPA
Temperature	Tabular	24 hr	Weather Underground
Road layer	Spatial		FNSB GIS

2.3 Results

2.3.1 Spatial distribution of $PM_{2.5}$ concentrations

2.3.1.1 Fairbanks, Alaska

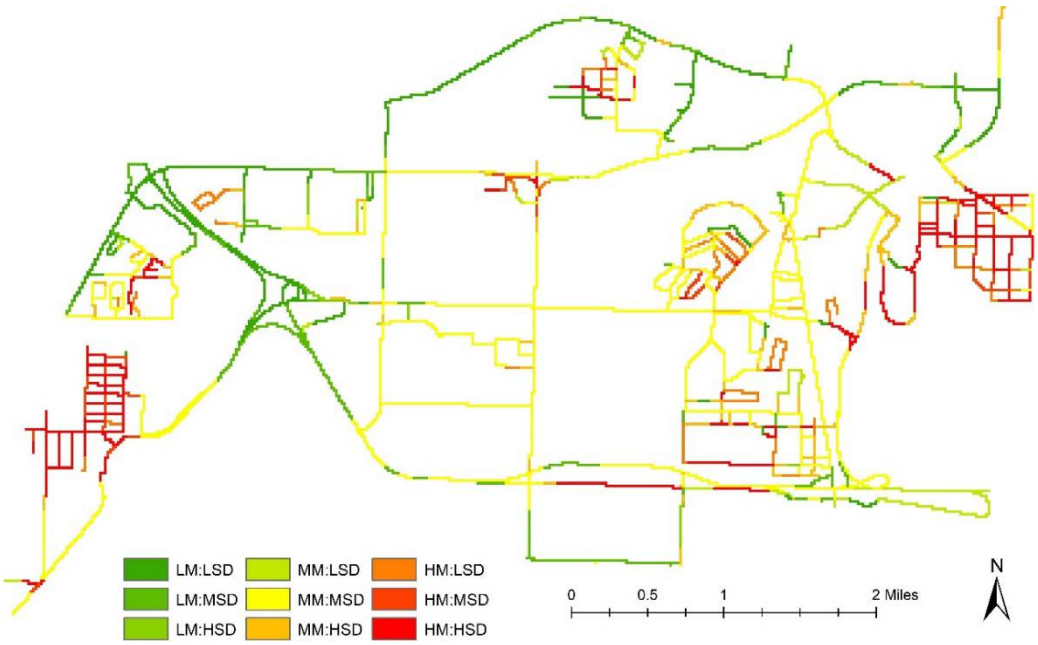
Figure 2.2a represents the spatial variation of average $PM_{2.5}$ concentrations over Fairbanks for the entire three-year study period. The first observation is that air quality in the eastern and southwestern parts of the study area is undoubtedly worse than in other parts of the study area. The northern and northwestern regions exhibit minimum $PM_{2.5}$ levels, and the central region shows medium levels. The second observation is that higher concentrations of roadside $PM_{2.5}$ were measured

on streets near residential areas, where street density seems higher. The least concentrations were measured on highways.

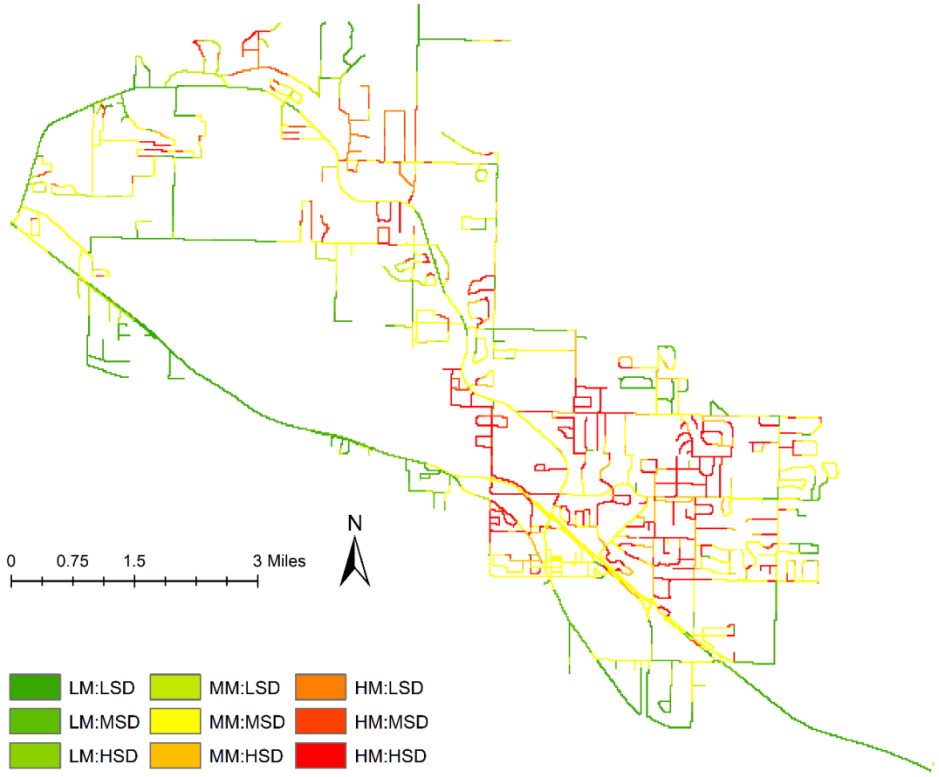
A separate analysis of yearly $PM_{2.5}$ averages (Figure 2.3) indicated a similar trend in spatial distribution. For year-to-year variation in mean $PM_{2.5}$ concentrations, however, there is statistically significant evidence that the mean values of $PM_{2.5}$ are different for each year (p-value<0.05, ANOVA). The mean values of $PM_{2.5}$ for the 2012–13, 2013–14, and 2014–15 seasons are 13.27 $\mu g/m^3$, 16.49 $\mu g/m^3$, and 12.19 $\mu g/m^3$, respectively. Although the 2013–14 period shows a higher mean $PM_{2.5}$ value, it contains five months of data (October 2013 to February 2014), while the other two years contain six months of data (October to March). Improved air quality in the month of March, owing to favorable meteorological conditions, may be a contributor to lower seasonal averages for the 2012–2013 and 2014–2015 seasons. Considering this, it would be insightful to consider monthly variability of $PM_{2.5}$ concentrations in the dataset.

The monthly averages of $PM_{2.5}$ data presented in Figure 2.4 reveal that the overall trend of monthly variations in $PM_{2.5}$ concentration was similar each year of the study period. At the beginning of wintertime in October, air quality in Fairbanks starts to deteriorate and reaches its worse condition in the middle of winter, around December to January, and improves at the end of the season, around March. It seems that meteorological conditions play an important role in this.

For 2012–13, the lowest monthly mean concentration of $PM_{2.5}$ (9.2 $\mu g/m^3$), as well as the highest monthly mean temperature, was found in October. The mean concentration of $PM_{2.5}$ increased from October to December, along with a drop in mean temperature. The PM concentration suddenly dropped in January, then increased through March. In this period, mean temperature values showed an inverse relation with the value of $PM_{2.5}$.



(a)



(b)

Figure 2.2 Spatial distribution of $PM_{2.5}$ concentration in (a) Fairbanks and (b) North Pole for the time period 2012–2015 (winter months only)

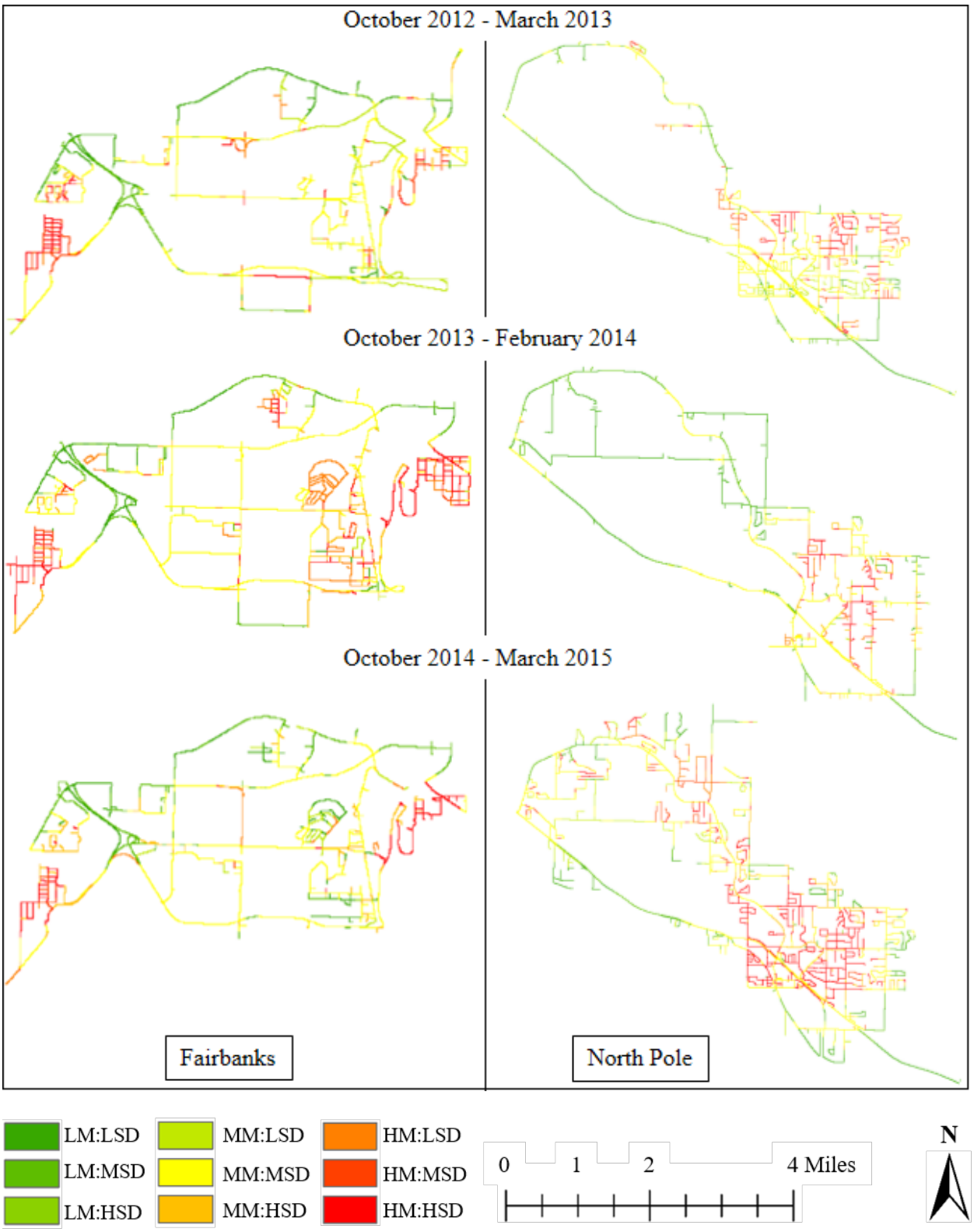
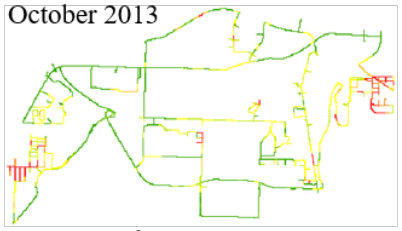
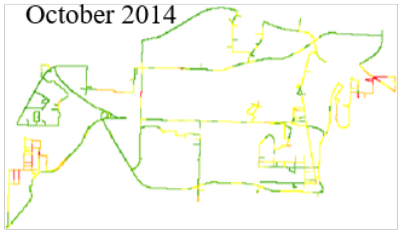
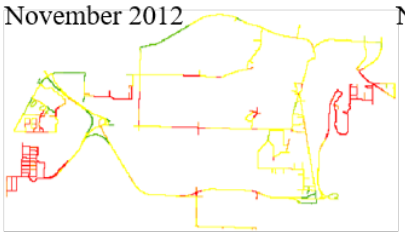
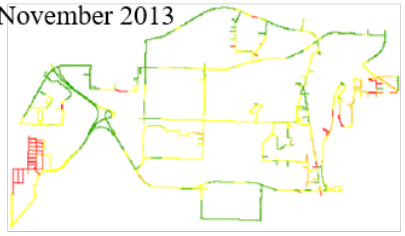
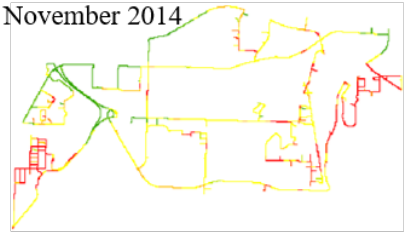
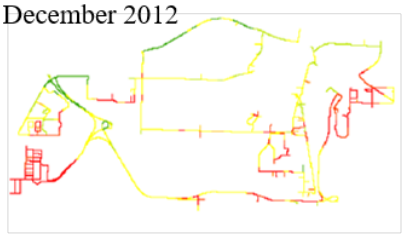
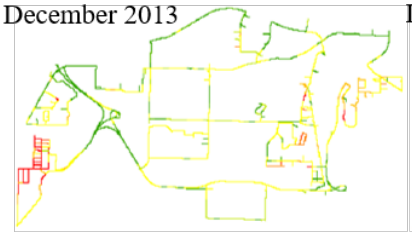
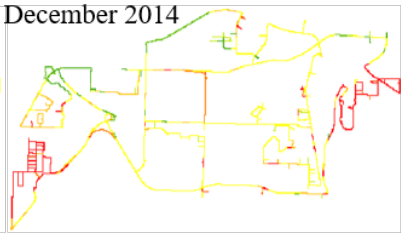
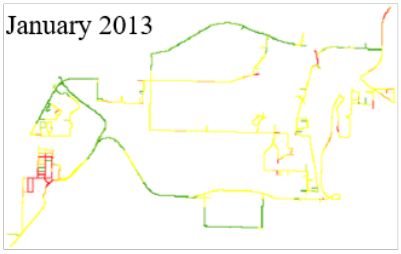
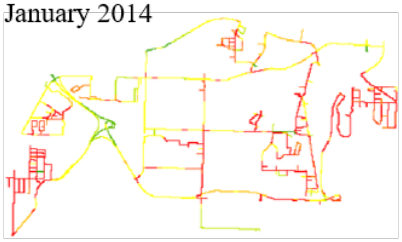
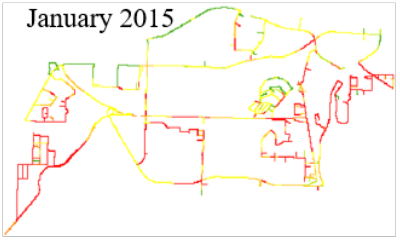
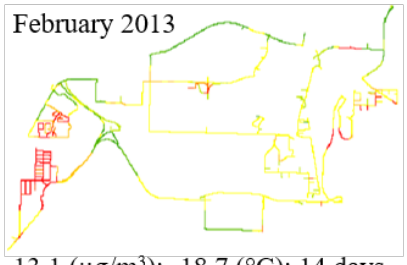
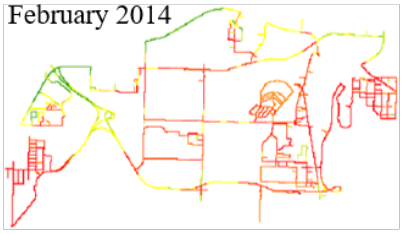
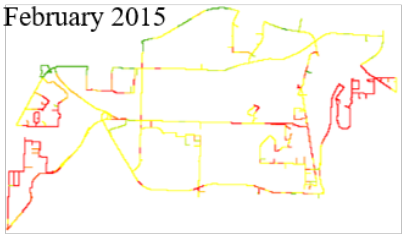


Figure 2.3 Yearly average concentrations of $PM_{2.5}$ in the study area

2012-2013	2013-2014	2014-2015
October 2012 	October 2013 	October 2014 
9.2 (µg/m³); -5.2 (°C); 8 days	9.6 (µg/m³); 2.5 (°C); 9 days	7.3 (µg/m3); -3.6 (°C); 12 days
November 2012 	November 2013 	November 2014 
14.9 (µg/m³); -22.4 (°C); 20 days	9.5 (µg/m³); -14.3 (°C); 10 days	13.9 (µg/m³); -11.6 (°C); 12 days
December 2012 	December 2013 	December 2014 
15.7 (µg/m³); -27.1 (°C); 12 days	9.1 (µg/m³); -20.3 (°C); 9 days	14.2 (µg/m³); -13.1 (°C); 9 days
January 2013 	January 2014 	January 2015 
10.2 (µg/m³); -19.1 (°C); 12 days	18.8 (µg/m³); -13.5 (°C); 11 days	16.9 (µg/m³); -21.2 (°C); 15 days
February 2013 	February 2014 	February 2015 
13.1 (µg/m³); -18.7 (°C); 14 days	22.5 (µg/m³); -20 (°C); 18 days	16.1 (µg/m³); -17.1 (°C); 12 days

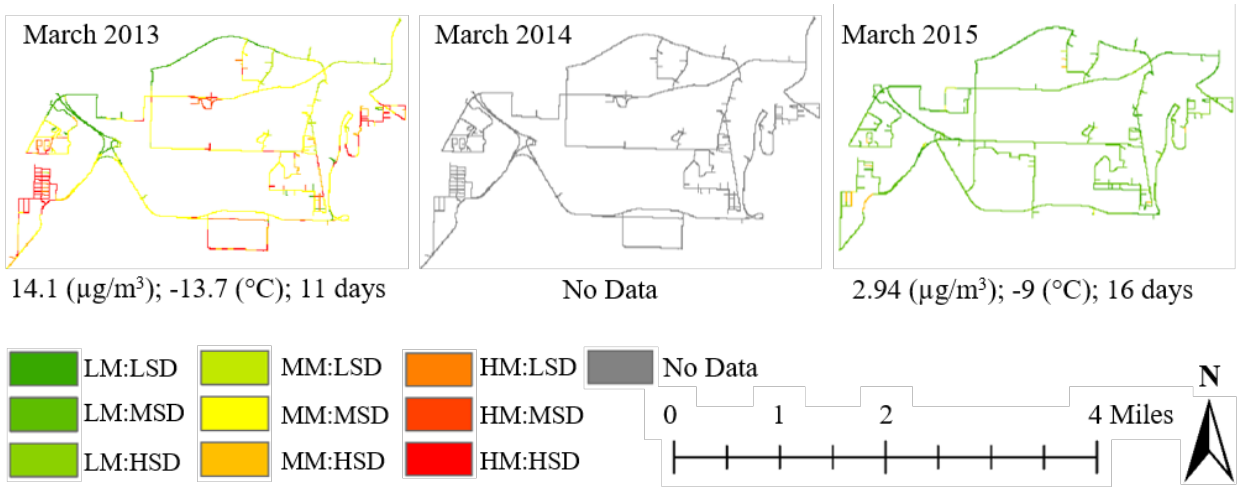


Figure 2.4 Monthly mean $PM_{2.5}$ concentration in Fairbanks. The numbers below each map represent the consecutive monthly average of $PM_{2.5}$, the monthly average temperature, and the number of days the MMV was driven during that month.

Table 2.4 presents mean $PM_{2.5}$ concentrations in one of the nine categories for every month during the three-year sampling period and the percentage of the mobile monitoring route in each category. For this allocation, each road segment was attributed to each of the nine categories based on mean $PM_{2.5}$ values over that segment. This approach is helpful in classifying the sampling area based on air quality.

2012–13 study year. During 2012–13, the percentage of road segments in the LM-LSD category (suggesting consistently good air quality) was highest in October (29.2%) and lowest in November (4.9%). Figure 2.4 shows that during this time most of the segments were on the Parks Highway, Mitchell Expressway, and College Road. On the other hand, the percentage of road segments associated with HM-LSD deviation was very low during this period, with the highest value in March (4.2%) and the lowest value in October (0.8%). This implies that not many areas experience consistently poor air quality, and that hotspots are episodic and shifting, which is further supported by a high percentage of segment length in HM-HSD category (6.3–23.9% in 2012–13). As for the categories with medium values of mean $PM_{2.5}$ concentration (6.5–16.5 µg/m^3), most of the segments in this sampling area are in those categories and most of them (30.5–56.8%) are in category 5 (MM-

MSD). Figure 2.4 indicates that central and downtown Fairbanks represent the segments in this category.

2013–2014 study year: As evident in Figure 2.4, during 2013–14, the monthly mean of $PM_{2.5}$ concentration was highest in February (22.5 µg/m^3) and lowest in December (9.1 µg/m^3). The month of December had the lowest mean value of $PM_{2.5}$ and the lowest monthly mean temperature for this study year. As for the temporal trends of $PM_{2.5}$ concentration, starting from October, the mean concentrations decreased through December and increased through February. The highest mean value of $PM_{2.5}$ was measured in February, and the MMV was driven more days in February than in other months in this time period. In addition, the MMV was driven on more route segments than in other months, which suggests that in February more area was included in the data collection process. Figure 2.4 depicts the central region of the study area, which experienced episodic poor air quality conditions in February. The road segments associated with this condition were mainly Airport Way, Johansen Expressway, Peger Road, and the roads in the downtown area.

Table 2.4b shows that in October most of the segments were in category 1 (38.8%), which helps in understanding the lower mean value of $PM_{2.5}$ concentrations in this month. From October to January, the number of segments associated with category 1 decreased and then increased in February, implying that the percentage of the area associated with consistently good air quality was higher in October and then dropped through January. Figure 2.4 indicates that segments of College Road, the Mitchell Expressway, and the Parks Highway primarily belong in this category. However, the percentage of segments in category 7, which describes air quality as consistently poor, increased from October to February. A similar trend of change can be seen for category 9, with the highest value of percentage of segments in February (31.3%).

2014–15 study years. For the period 2014–2015 with respect to Figure 2.4, the highest monthly concentration of $PM_{2.5}$ was 16.9 µg/m^3 and the lowest was 2.94 µg/m^3, observed in January

and March, respectively. While monthly mean $PM_{2.5}$ concentration increased from October to January and then decreased through March, monthly mean temperature showed the opposite trend in change. As with the past two years, the central region of the study area exhibited an episodic plunge in air quality, which happened in January for this time period (Figure 2.4). Furthermore, as with the previous two years, the eastern and western parts of the study area were noted to have consistently high mean concentrations of $PM_{2.5}$ this year (2014–15).

In Table 2.4c it can be seen that the segments associated with category 1 and category 2 had the highest percentages, 32% and 61.7%, respectively, in March, which indicates an overall low mean $PM_{2.5}$ concentration in this month. Segments associated with category 9 also had a high percentage (37.7%) in January, which suggests an episodic condition of poor air quality this month.

Table 2.4 Monthly comparison of segments associated with each level of air pollution for (a) October 2012–March 2013 (b) October 2013–February 2014 (c) October 2014–March 2015 for the city of Fairbanks

		Percentage of segment length	Mean $PM_{2.5}$ ($\mu g/m^3$)	Percentage of segment length	Mean $PM_{2.5}$ ($\mu g/m^3$)	Percentage of segment length	Mean $PM_{2.5}$ ($\mu g/m^3$)	Percentage of segment length	Mean $PM_{2.5}$ ($\mu g/m^3$)	Percentage of segment length	Mean $PM_{2.5}$ ($\mu g/m^3$)	Percentage of segment length	Mean $PM_{2.5}$ ($\mu g/m^3$)
Category		October, 2012		November, 2012		December, 2012		January, 2013		February, 2013		March, 2013	
Low	1	29.2	3.3	4.9	4.7	7.5	5.6	16.5	4.5	8.6	4.4	13.5	4.6
mean	2	14.7	5.4	2.7	5.9	0.3	5.9	7.0	5.6	9.4	5.2	1.1	5.6
	3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Medium	4	11.8	10.9	4.1	9.4	10.9	9.6	4.5	9.3	9.0	10.2	10.6	9.1
mean	5	30.5	8.8	52.7	11.7	44.5	12.4	56.8	10.3	46.6	11.2	42.4	12.0
	6	5.2	13.6	6.4	13.5	1.8	14.7	7.0	14.0	7.8	14.1	8.0	14.7
High	7	0.8	29.9	2.4	31.9	0.9	23.2	1.5	21.7	1.9	21.6	4.2	31.2
mean	8	0.4	27.2	4.2	20.4	10.2	19.6	0.3	18.3	3.1	27.9	4.0	21.7
	9	7.3	33.4	22.7	24.3	23.9	25.8	6.3	22.2	13.6	26.6	16.1	25.0

(a)

Category		October, 2013		November, 2013		December, 2013		January, 2014		February, 2014		March, 2014	
Low	1	38.8	4.5	25.7	4.0	25.6	4.7	1.5	3.6	6.1	5.3		
mean	2	5.7	5.1	8.8	5.6	6.7	5.6	3.2	4.8	0.9	6.1		
	3	0.1	5.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0		
Medium	4	15.0	8.5	8.5	9.0	8.4	7.8	6.7	11.1	7.0	10.1		
mean	5	25.7	9.3	40.3	9.0	45.4	9.1	32.5	12.0	16.1	12.5	No Data	
	6	4.9	13.5	6.2	12.2	5.6	13.7	7.3	14.7	1.0	12.9		
High	7	1.4	25.9	1.2	31.7	2.0	27.4	3.6	30.3	10.3	29.6		
mean	8	1.6	28.8	2.4	20.8	0.9	21.7	10.4	24.5	27.2	21.5		
	9	6.8	34.4	7.0	27.7	5.5	22.8	34.8	26.3	31.3	33.0		

(b)

Category		October, 2014		November, 2014		December, 2014		January, 2015		February, 2015		March, 2015	
Low	1	24.5	3.4	12.0	3.7	4.6	4.0	6.8	3.8	4.1	4.8	32.0	1.3
mean	2	24.4	5.3	6.3	5.3	6.1	5.1	2.0	5.7	1.2	5.6	61.7	3.3
	3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.4	5.5
Medium	4	3.7	9.4	1.7	9.6	2.8	8.4	4.7	10.6	6.4	9.4	1.1	9.1
mean	5	35.7	8.5	44.3	12.2	48.4	11.6	30.2	11.4	47.6	12.3	0.5	8.2
	6	8.8	12.7	8.6	13.9	12.4	13.8	13.6	14.3	5.2	12.6	2.3	8.9
High	7	0.3	21.9	1.2	28.9	3.4	27.0	2.1	31.5	2.5	30.9	0.0	0.0
mean	8	0.0	0.0	5.5	18.3	1.2	25.7	2.9	22.1	7.9	19.0	0.0	0.0
	9	2.6	21.7	20.3	24.2	21.0	22.9	37.7	24.5	25.2	25.4	0.0	0.0

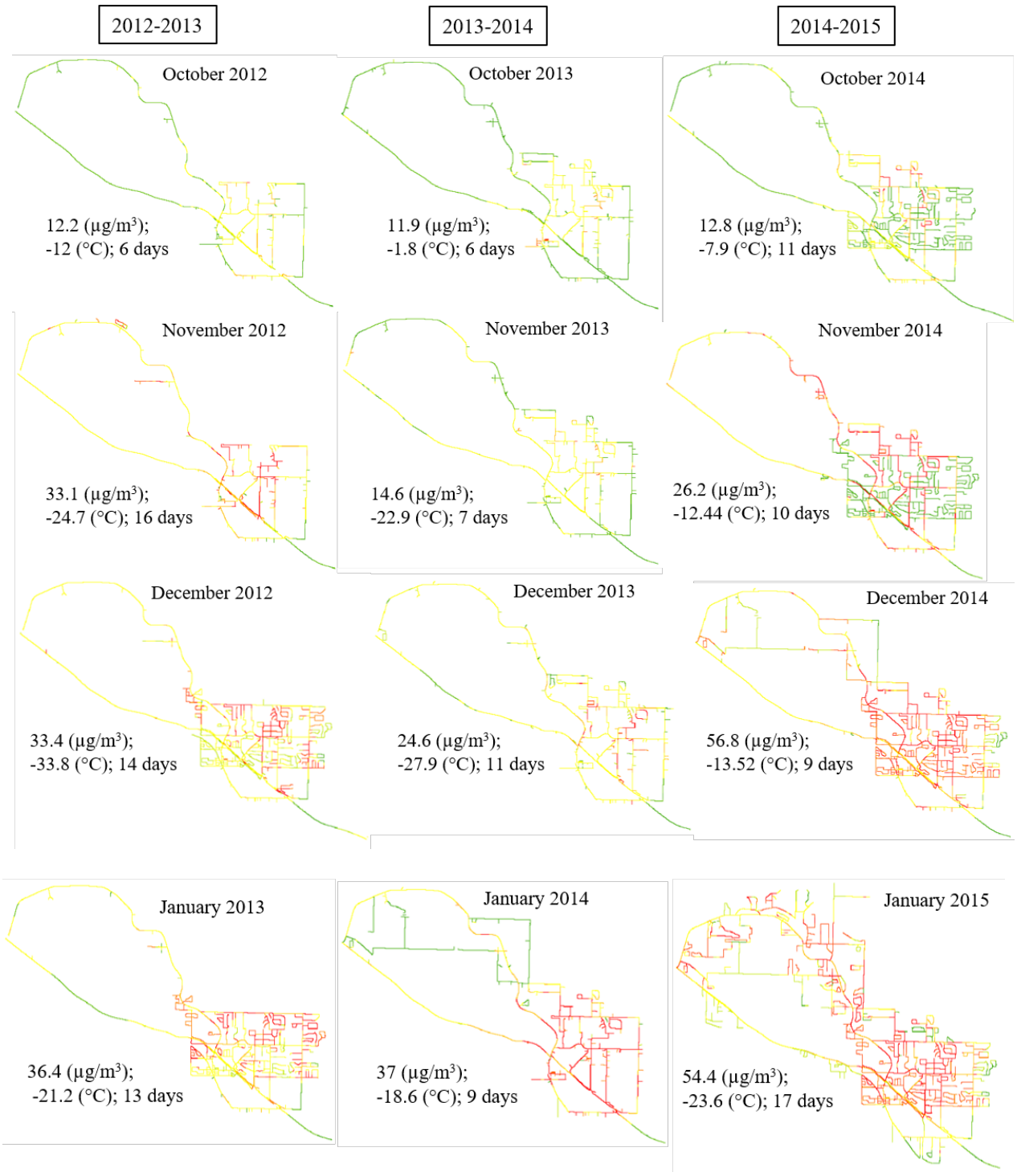
(c)

2.3.1.2 North Pole, Alaska

Figure 2.2b represents the spatial distribution of three years (2012–15) of aggregated average $PM_{2.5}$ concentrations in the North Pole study area. It is evident here that the southeastern part of the study area, which is close to the North Pole fire station, has the poorest air quality; the western part, which includes the Richardson Highway and part of Badger Road, is least polluted. In Figure 2.3, the spatial distribution of yearly average $PM_{2.5}$ data suggests similar trends and results.

Looking at monthly averages for finer temporal resolution (Figure 2.5), we found that $PM_{2.5}$ concentrations increased from October to January and decreased from January to March. The lowest value of mean $PM_{2.5}$ concentration was found in March; the highest was found in January. The southeastern side of the study area shows chronically poor air quality. In this region, the monthly mean $PM_{2.5}$ usually exceeded 42.27 $\mu g/m^3$ from November to January. Not unexpectedly, during the study period, monthly mean temperature showed an inverse correlation with monthly mean $PM_{2.5}$ concentrations.

2012–13 study year. Table 2.5a shows that segments from category 2 (LM-MSD) were highest (44.1%) in percentage in March and lowest (1.2%) in December, implying that for most of the area, the air quality was good in March. In each month, most of the segments were in category 5 (MM-MSD), except for October and March. In January, after category 5, the second highest value of the percentage of segments (16.2%) belonged to category 9 (HM-HSD) with a mean $PM_{2.5}$ of 74.6 $\mu g/m^3$. This was also the highest category 9 share over the entire year, indicating that January experienced frequent episodic instances of poor air quality. It is clear from the map (Figure 2.5) that the southeastern side of the study area accounted for these episodic conditions.


2012-2013
2013-2014
2014-2015
October 2012
12.2 (µg/m³);
-12 (°C); 6 days
October 2013
11.9 (µg/m³);
-1.8 (°C); 6 days
October 2014
12.8 (µg/m³);
-7.9 (°C); 11 days
November 2012
33.1 (µg/m³);
-24.7 (°C); 16 days
November 2013
14.6 (µg/m³);
-22.9 (°C); 7 days
November 2014
26.2 (µg/m³);
-12.44 (°C); 10 days
December 2012
33.4 (µg/m³);
-33.8 (°C); 14 days
December 2013
24.6 (µg/m³);
-27.9 (°C); 11 days
December 2014
56.8 (µg/m³);
-13.52 (°C); 9 days
January 2013
36.4 (µg/m³);
-21.2 (°C); 13 days
January 2014
37 (µg/m³);
-18.6 (°C); 9 days
January 2015
54.4 (µg/m³);
-23.6 (°C); 17 days

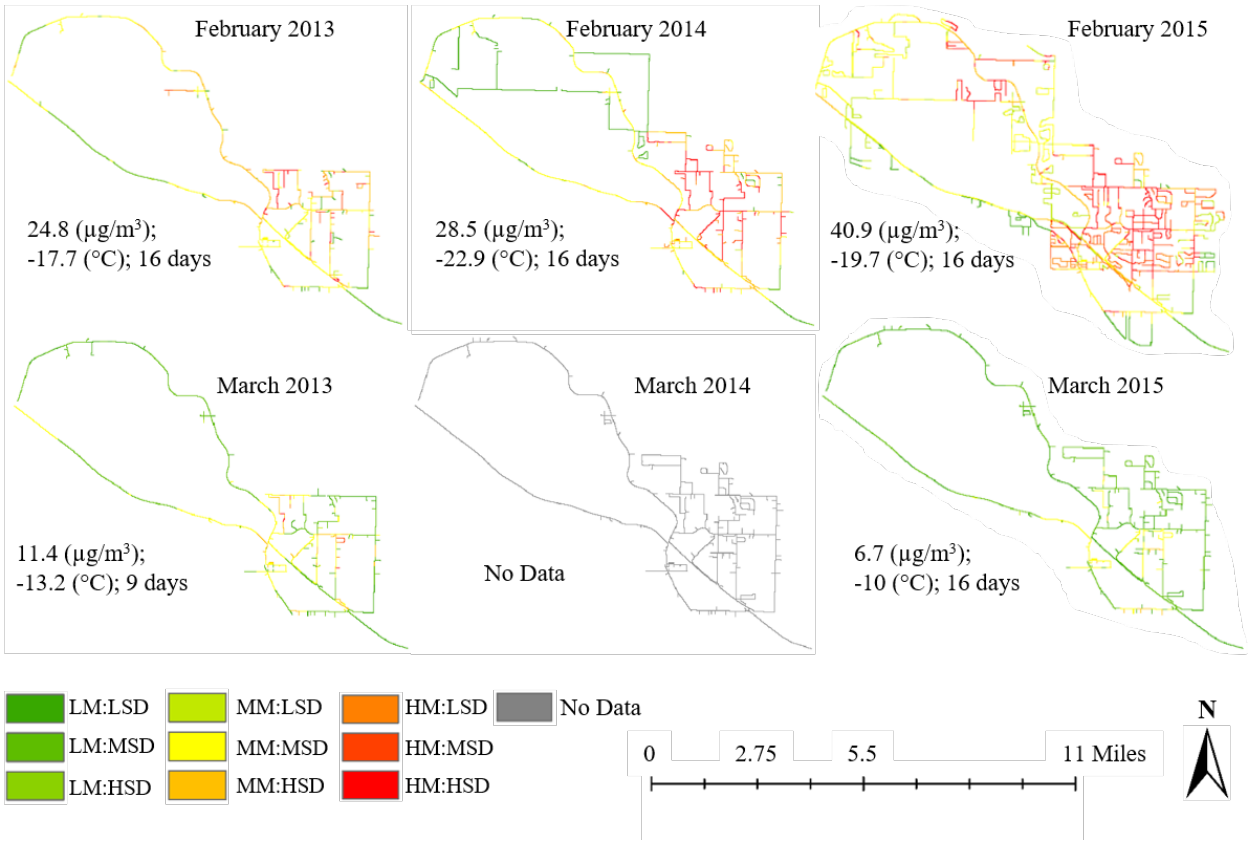


Figure 2.5 Month-to-month variation in mean $PM_{2.5}$ concentration in North Pole. The text, written below each map, represents consecutively the monthly average of $PM_{2.5}$ concentration, the monthly average temperature, and the number of days the MMV was driven.

2013–14 study year. Figure 2.5 shows that the highest concentration of monthly $PM_{2.5}$ was found in January and the lowest in October. The southeastern side of the study area had a chronic situation of poor air quality from December to February and an episodic situation in January. During this year, most of the segments (27.4–63.5%) were in category 5 (MS-MSD) except for January (21.5%). The highest percentage of segments associated with category 9 (HM-HSD) were again found in January (34.8%) followed by February, which suggests the episodic condition of high $PM_{2.5}$ concentration in these two months. The percentage of segments associated with category 1 (LM-LSD) were highest in October (23.1%), gradually decreased through December (5.1%), and then increased by February (22.5%).

2014–15 study year. It can be seen in Figure 2.5 that the highest value of monthly mean $PM_{2.5}$ concentration was found in December (56.8 μg/m^3) followed by January (54.4 μg/m^3) and the lowest was found in March (6.7 μg/m^3). Similar to the previous two years, the southeastern side of the study area exhibited higher concentrations of $PM_{2.5}$ during 2014–15, with especially chronic poor air quality from November to February. The northern and eastern regions of the study area only showed episodic conditions of poor air quality. As for temperature, the monthly mean value dropped from October to January and rose from January to March. With reference to Table 2.5c, the highest percentage of segments associated with category 9 (HM-HSD) was found in December (21.9%) followed by January (21.2%). These values suggest episodic conditions of poor air quality in the study region during these months. Conversely, many segments in the study area showed consistent air quality.

Table 2.5 Monthly comparison of segments associated with each level of air pollution for (a) October 2012–March 2013 (b) October 2013–February 2014 (c) October 2014–March 2015 for the city of North Pole

		Percentage of segment length	Mean $PM_{2.5}$ ($\mu g/m^3$)	Percentage of segment length	Mean $PM_{2.5}$ ($\mu g/m^3$)	Percentage of segment length	Mean $PM_{2.5}$ ($\mu g/m^3$)	Percentage of segment length	Mean $PM_{2.5}$ ($\mu g/m^3$)	Percentage of segment length	Mean $PM_{2.5}$ ($\mu g/m^3$)	Percentage of segment length	Mean $PM_{2.5}$ ($\mu g/m^3$)
Category		October, 2012		November, 2012		December, 2012		January, 2013		February, 2013		March, 2013	
Low	1	6.0	2.1	3.3	3.7	2.1	4.8	1.5	3.4	5.7	3.1	17.0	2.8
mean	2	42.2	7.4	3.1	6.0	1.2	6.9	5.3	7.6	14.0	7.7	44.1	6.7
	3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Medium	4	3.2	23.8	2.7	26.6	16.3	22.8	4.5	25.6	1.8	25.7	0.8	18.7
mean	5	41.1	15.1	48.8	23.1	52.6	27.8	44.8	22.7	36.8	16.5	27.2	15.9
	6	7.1	24.8	19.2	35.6	3.4	35.4	12.8	30.5	29.6	27.2	8.9	24.9
High	7	0.2	50.8	3.2	70.1	3.1	58.2	6.0	63.6	2.1	68.7	0.5	53.7
mean	8	0.0	0.0	4.5	70.0	11.4	58.5	8.9	59.9	2.8	89.3	0.9	56.0
	9	0.2	46.3	15.3	55.7	9.8	59.7	16.2	74.6	7.1	73.6	0.5	47.5

(a)

Category		October, 2013		November, 2013		December, 2013		January, 2014		February, 2014		March, 2014	
Low	1	23.1	3.5	8.9	2.9	5.1	3.8	19.8	1.3	22.5	3.2		
mean	2	33.0	7.4	28.3	7.9	6.4	8.4	2.4	6.4	4.6	8.2		
	3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0		
Medium	4	3.2	21.2	2.3	26.1	5.5	25.1	1.6	21.3	1.0	18.5		
mean	5	34.2	16.0	54.4	17.0	63.5	21.9	21.5	24.0	27.4	20.7	No Data	
	6	4.3	27.9	4.6	30.2	10.0	35.0	15.5	36.2	22.6	33.9		
High	7	1.4	74.7	0.9	54.3	1.6	63.0	3.2	89.5	1.5	88.6		
mean	8	0.4	65.6	0.5	60.6	1.9	69.1	1.8	106.2	1.4	86.8		
	9	0.4	51.9	0.0	0.0	5.9	577.4	34.1	61.6	19.1	61.8		

(b)

Category		October, 2014		November, 2014		December, 2014		January, 2015		February, 2015		March, 2015	
Low	1	36.4	3.3	39.8	0.3	3.5	5.9	4.1	4.7	6.7	2.7	40.6	3.1
mean	2	16.9	7.9	4.5	5.5	0.4	8.0	2.1	6.7	2.0	7.4	41.7	6.0
	3	0.0	0.0	0.1	7.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Medium	4	7.3	15.9	0.6	30.1	9.4	28.4	10.9	22.8	13.2	23.5	0.7	23.4
mean	5	23.8	15.7	16.3	25.4	20.5	26.1	19.9	26.2	29.2	24.0	14.8	14.4
	6	12.5	28.3	11.5	34.2	8.8	35.4	13.3	34.4	12.2	34.2	2.1	20.8
High	7	0.0	0.0	1.1	76.8	16.0	77.0	7.9	102.1	7.4	63.2	0.0	0.0
mean	8	0.1	172.4	3.0	62.7	19.5	92.4	20.5	91.6	11.6	81.7	0.0	0.0
	9	3.0	56.9	23.1	64.7	21.9	71.7	21.2	71.5	17.6	70.6	0.0	0.0

(c)

2.3.2 Correlation between mobile and stationary monitoring data

A box-plot comparison between mobile and stationary monitoring data is presented in Figure 2.6. In Fairbanks, for the three years considered, the mean value of daily $PM_{2.5}$ concentrations from the stationary monitoring site was always higher than the mean value from the mobile monitoring. Similarly, in North Pole, the mean $PM_{2.5}$ values from MMV data were lower than the stationary data except for the 2014–2015 time-period. Furthermore, the mean values for both stationary and mobile monitoring of $PM_{2.5}$ for North Pole were equal to or mostly higher than for Fairbanks.

The stationary data shown in Figure 2.6 uses daily average (of the 24-hr data) while the mobile monitoring was done only during a part of the day. Since we know there are clear diurnal variations in hourly PM2.5 values there may be concerns that the differences between stationary and mobile PM2.5 in Figure 2.6 are due to data collected over different times of the day. To address that, we also considered (for December and January 2014; Figure 2.7) hourly data from stationary sites and only used temporally matched stationary site data (same hours as MMV was driven) for comparison with MMV data. As can be seen in Figure 2.7, similar trends hold true and PM2.5 values for stationary data are higher than those for MMV data.

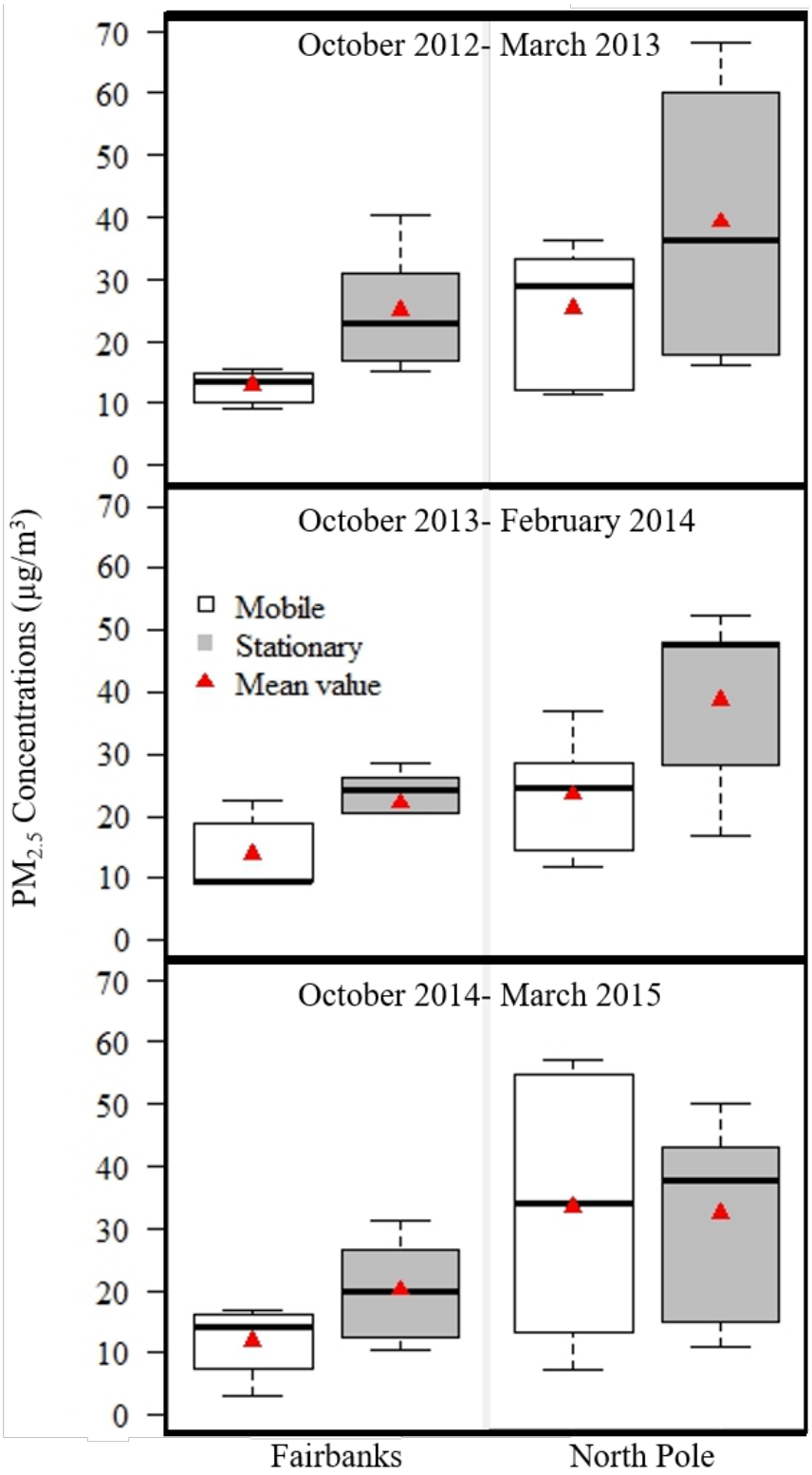


Figure 2.6 Daily average concentration of $PM_{2.5}$ data. Only the MMV operating days are considered. The box represents the 25th, 50th, and 75th percentiles; whiskers extend at most to 1.5 interquartile ranges

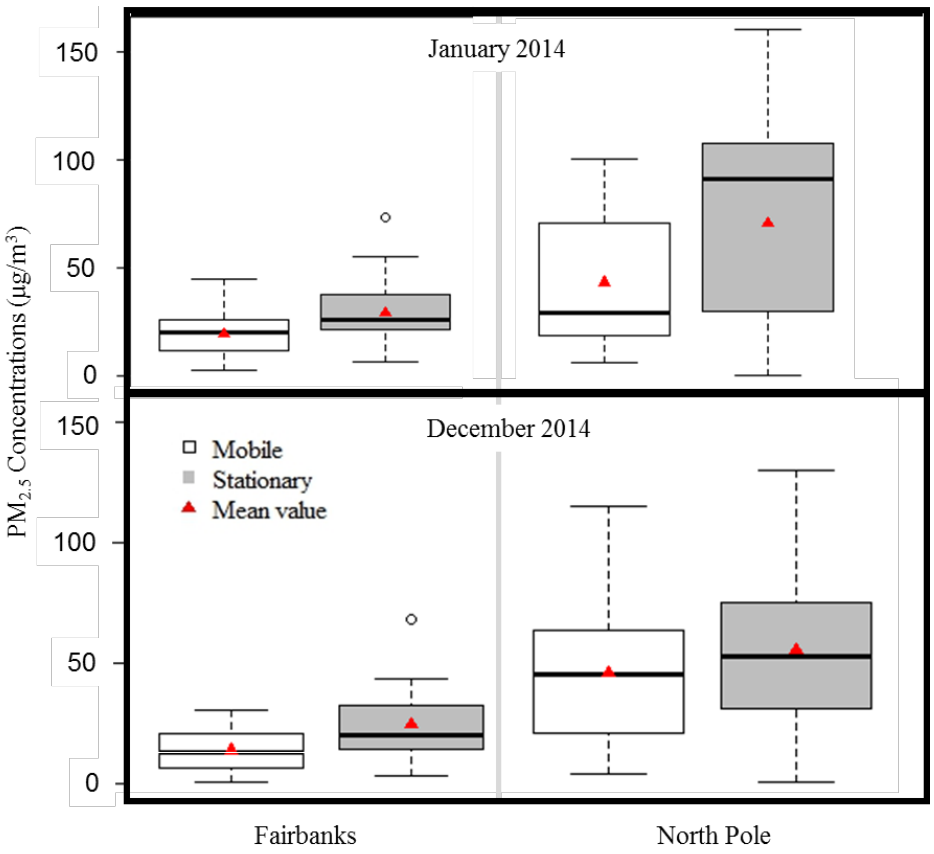
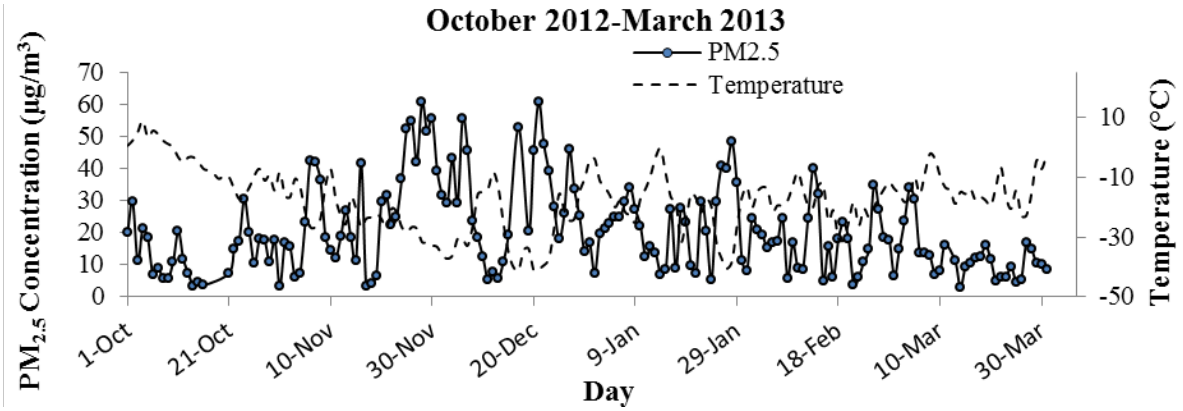


Figure 2.7 Average concentrations of hourly $PM_{2.5}$ data. Only the MMV operating days (during the hours that the MMV was driven) are considered for MMV as well as stationary data. The boxes represents the 25th, 50th, and 75th percentiles; whiskers extend at most to 1.5 interquartile ranges.

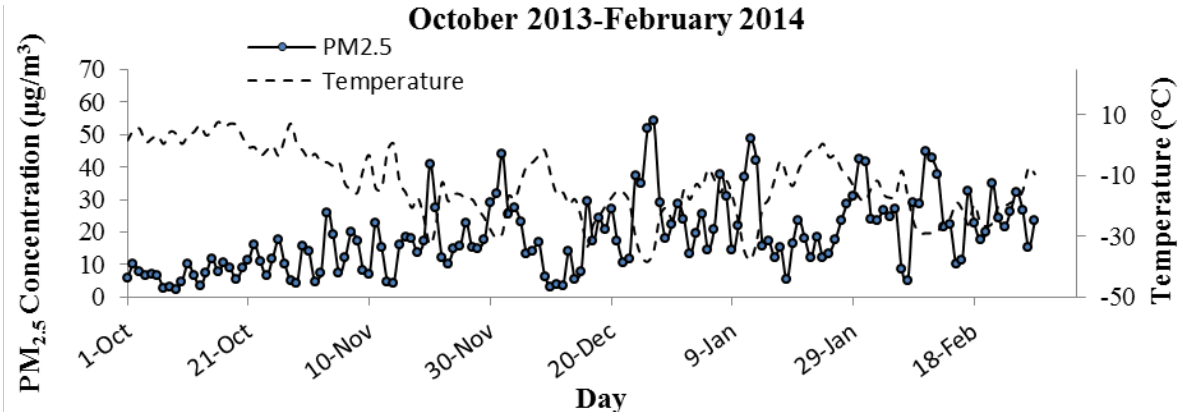
2.3.1 Correlation between temperature and $PM_{2.5}$

Figure 2.8 shows the correlation between daily average concentrations of stationary $PM_{2.5}$ and temperature data in Fairbanks. The Pearson correlation coefficient value between temperature and $PM_{2.5}$ data is -0.70. In every measured period, it is visible that whenever temperature decreased, the concentration of $PM_{2.5}$ increased. More specifically, in the beginning (October of each year) and ending (March of each year except for the 2013/2014 season) of the winter season, when temperature was high, $PM_{2.5}$ concentrations were low. At mid-winter (December to February), when the temperature dropped below -20°C, the $PM_{2.5}$ concentration reached its highest level. Similarly, the North Pole stationary $PM_{2.5}$ data shown in Figure 2.9 indicate a negative correlation with temperature data (Pearson correlation coefficient = -0.55). The regression models between temperature and $PM_{2.5}$

concentrations, showed a negative correlation for both Fairbanks (R^2 = 0.49, p-value <2.2e^{-16}) and North Pole (R^2=0.31, p-value <2.2e^{-16}) data.



(a)



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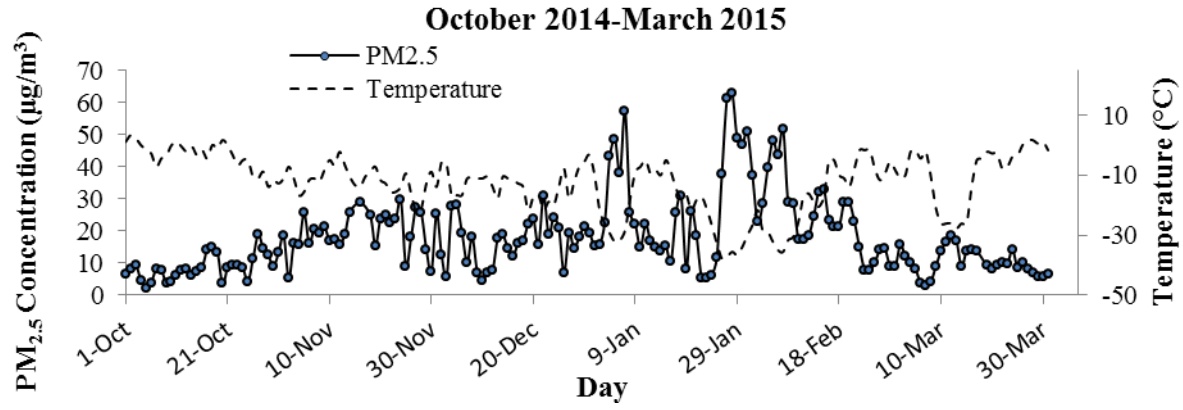
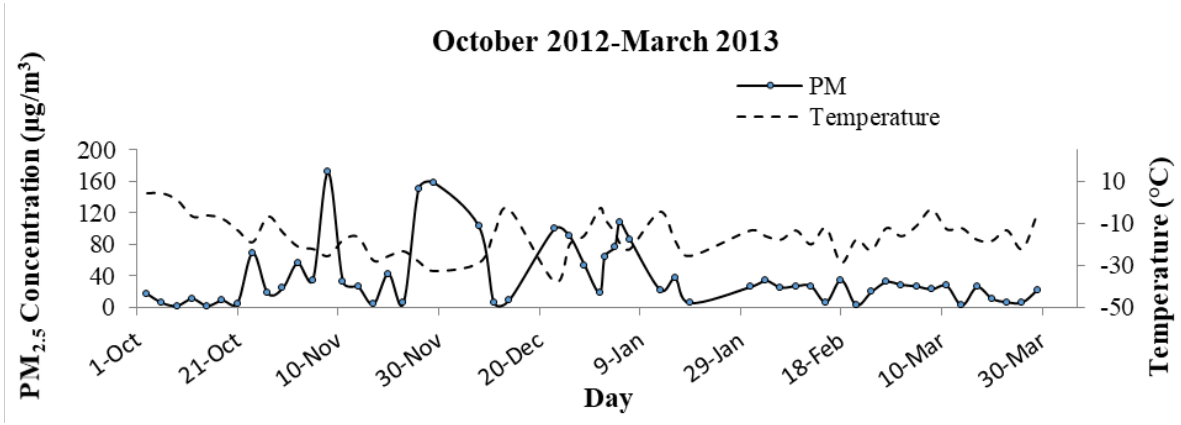


(c)

Figure 2.8 Daily average $PM_{2.5}$ concentration from the stationary monitoring sites and temperature vs. time in Fairbanks for the measured periods in (a) 2012–2013, (b) 2013–2014, and (c) 2014–2015



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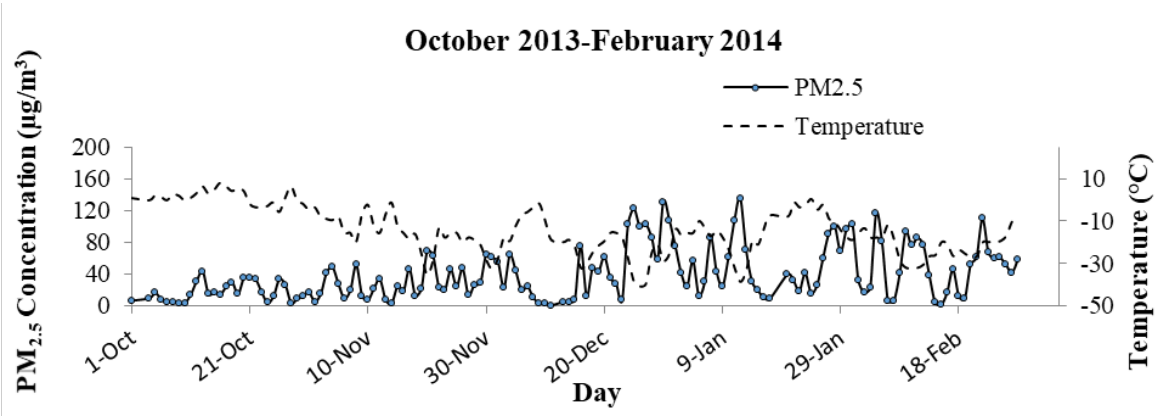

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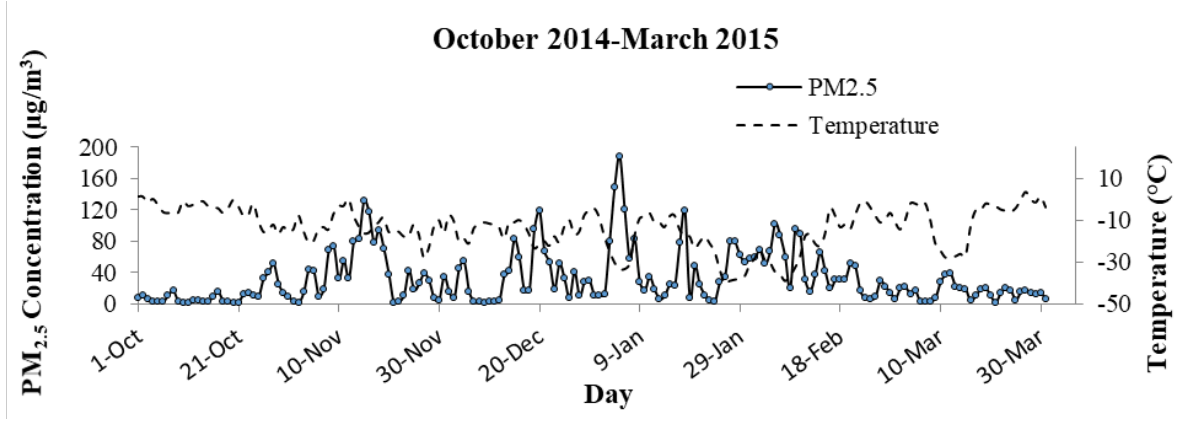

(c)

Figure 2.9 Daily average $PM_{2.5}$ concentration from stationary monitoring sites and temperature vs. time in North Pole for the measured periods in (a) 2012–2013, (b) 2013–2014, and (c) 2014–2015

2.4 Discussion

This work explores on-roadway air quality, which is important to understand since people spend a significant amount of time driving and have high potential for exposure to on-road PM.

While the results show that yearly average concentrations of $PM_{2.5}$ are higher in North Pole than in Fairbanks (for both mobile and stationary monitoring, Figure 2.6 and Figure 2.7), the $PM_{2.5}$ values for North Pole had a lower temperature correlation (-0.55) than Fairbanks (-0.70), indicating that factors beyond temperature may contribute to higher $PM_{2.5}$ levels in North Pole. Also, for both Fairbanks and North Pole, daily average $PM_{2.5}$ concentrations of stationary monitoring data (background concentrations) were higher than the $PM_{2.5}$ concentrations from mobile monitoring (on-road concentrations)—on average, 73.5% higher in Fairbanks and 39.2% higher in North Pole. Considering only time-matched stationary data, though, as in Figure 2.7, the difference may be lower; which needs more investigation. On-roadway concentrations closely reflect traffic-associated emissions and stationary concentrations reflect the background concentrations, since by design the stationary monitors are set up away from any major sources to capture the general background. This observation suggests that traffic-associated emissions may not be a major source of $PM_{2.5}$ concentrations, and that there are other contributing sources. If traffic was one of the major sources, the roadside concentrations of $PM_{2.5}$ would be expected to be generally higher than the background stationary data.

Various previous studies have considered the contribution of traffic to overall $PM_{2.5}$, and some have compared that contribution with emissions from residential areas. For example, a nationwide source apportionment study (Thurston et al. 2011) that used 273 U.S. EPA chemical speciation monitoring network (CSN) sites for years 2000–2005 found motor vehicle traffic-generated $PM_{2.5}$ to be a significant source, and highest in California. This study, however, excluded Alaska and Hawaii.

In another study (Janssen et al. 1997), $PM_{2.5}$ concentration at street location was reported to be higher than the corresponding background location in Arnhem and Wageningen, Netherlands.

These studies suggest that roads and locations close to or within residential areas have higher concentrations of $PM_{2.5}$, and this is in line with findings from the $PM_{2.5}$ source apportionment study for Fairbanks (Ward et al. 2012), which indicated that residential wood burning during the winter months accounts for 60–80% of $PM_{2.5}$. Also, roads in residential areas typically have lower speed limits and less traffic volume. Therefore, one might expect less air movement and less mixing, in other words, more stagnant air in which the PM can accumulate. Wood and coal are regularly used as fuel for indoor heating in both Fairbanks and North Pole, and Fairbanks has two coal-fueled power plants, though secondary sulfates (produced from coal combustion and distillate fuel oil) exhibited much lower contributions (8–20%) in the model. Notably, the contribution from automobiles was found to be lower than 7%.

A master route or a comprehensive route is constructed by combining all possible routes used by the MMV as sampling routes. This process was done separately for Fairbanks and North Pole. Both master routes are then divided into small segments to calculate the variation between two consecutive segments. Importantly, data were neither interpolated nor extrapolated to estimate $PM_{2.5}$ concentrations for areas where the MMV was not driven or samples were not collected.

In one of the approaches currently used by the FNSB, daily $PM_{2.5}$ concentration maps are developed for both Fairbanks and North Pole, applying the natural neighbor interpolation method on data collected by the MMV. The areas are divided into four categories of air quality based on EPA 24-hour levels, namely “good” (represents $PM_{2.5}$ concentrations 0–11 $\mu g/m^3$), “moderate” (12–35 $\mu g/m^3$), “unhealthy for sensitive groups” (36–55 $\mu g/m^3$), and “unhealthy” (56–150 $\mu g/m^3$). Overall, this approach is questionable due to the use of spatially variable mobile monitoring data, as opposed to longer-term stationary data. While our approach utilizes the same MMV datasets, we chose to

represent only the actual roadway locations where the MMV was driven and $PM_{2.5}$ data were collected in order to avoid extrapolations and associated errors.

The Pearson correlations between temperature and daily average $PM_{2.5}$ concentrations were -0.70 and -0.55 for Fairbanks and North Pole, respectively. Figure 2.8 and Figure 2.9 indicate the negative relationship between $PM_{2.5}$ and temperature during the study period for both Fairbanks and North Pole. These correlations suggest a strong influence of temperature on $PM_{2.5}$ concentrations. Tran and Mölders (2011) and Eliminir (2005) found similar trends in Fairbanks, Alaska, and Cairo, Egypt, respectively. Increased $PM_{2.5}$ concentrations during colder temperatures are not unexpected, as colder temperatures warrant increased residential heating, and higher fuel combustion leads to higher particulate emissions. Additionally, vehicular emissions tend to rise with falling temperatures, as the associated events of idling vehicles and cold starts become more prevalent in winter. All of these factors affect the overall concentration of $PM_{2.5}$. Conversely, in their study in Nagasaki, Japan, Wang and Ogawa (2015) found a positive correlation between temperature and $PM_{2.5}$ concentration. Furthermore, Tai et al. (2010) reported a positive correlation between temperature and $PM_{2.5}$ throughout the U.S.

Most studies that map regional PM focus on average concentrations, ignoring the variability in the data. Herein, we accounted for variability by creating categories using standard deviation such that the data on monthly average and yearly average concentrations of $PM_{2.5}$ were divided into three categories based on standard deviation. The three categories for standard deviation are low standard deviation (LSD), medium standard deviation (MSD) and high standard deviation (HSD). The LSD category represents the values of standard deviation that ranged from the minimum to the 25^{th} percentile; the MSD and HSD categories represent the 25^{th} to 75^{th} percentiles, and greater than the 75^{th} percentile, respectively. The average value of $PM_{2.5}$ within the LSD category indicates a chronic situation, since the data have less variability. Low standard deviation regions could be used to identify

places that have consistently good and poor air quality. Data in the HSD category indicate abrupt and episodic values with high variability; thus, this category could be used to identify places that have acute episodic events of good/poor air quality. Overall, this is a novel approach that can lend new insight into air quality datasets.

2.5 Conclusions

The $PM_{2.5}$ data from mobile (on-roadway) and stationary monitors, and temperature data were collected in Fairbanks for three consecutive winter seasons. Mobile monitoring data were used to obtain spatial distribution of on-road $PM_{2.5}$ in Fairbanks and North Pole. To get spatio-temporal distribution of on-roadway $PM_{2.5}$, monthly and yearly geospatial analyses were done. Based on the mean and standard deviation of $PM_{2.5}$ values, nine different categories were established. The categories with good air quality were more frequent in the beginning of the winter season, while the categories with poor air quality were most frequent in the middle of the winter season. The analysis of stationary $PM_{2.5}$ data showed a significant difference between stationary and mobile data, stationary data being generally higher. This result suggests that the background stationary concentrations were probably not a result of on-roadway vehicular emissions. Furthermore, temperature data were analyzed with stationary concentrations of $PM_{2.5}$, which demonstrated that temperature had a negative correlation with $PM_{2.5}$ for both Fairbanks and North Pole.

CHAPTER 3.0 MEASUREMENT OF ULTRAFINE PARTICULATES IN FAIRBANKS AND NORTH POLE, ALASKA

3.1 Introduction

Ultrafine particulates (UFPs, having aerodynamic diameter less than or equal to 0.1 μm) are ubiquitous in urban environments and can have significant health impacts (Aalto et al. 2005, Simon et al. 2017). Because of their small size, UFPs can penetrate deeper into human lungs and mix with the blood stream. In urban areas, the major sources of UFPs are traffic-associated emissions, industrial operations, and residential outputs (Abernethy et al. 2013).

The UFPs that originate from vehicular emissions are often investigated by evaluating on-roadway and roadside concentrations of UFPs (Simon et al. 2017, Zwack et al. 2011). Zhu et al. (2002) mentioned motor vehicles as the primary direct emission source of UFPs in the urban environment. Some of the highest concentrations were noted near highways and major roadways (Karner et al. 2010, Simon et al. 2017). Concentrations of UFPs can vary significantly based on proximity of the source, and the highest concentrations are often measured within 100 m of the source, decreasing gradually to background levels at locations farther than 300 m from the source (Abernethy et al. 2013). Since people often spend a considerable amount of time on the road, especially in urban areas, the potential for exposure to on-roadway UFPs is high, even inside the vehicle cabin.

Recent studies indicate that UFPs can be more toxic than $PM_{2.5}$ with the same chemical composition (Zhu et al. 2002); however, UFPs are not yet regulated by the EPA. The National Ambient Air Quality Standards (NAAQS), provided by the EPA (μg of particles per cm^3 of air), include regulations for mass concentrations of $PM_{2.5}$ and PM_{10} (particulate matter ≤ 0 μm). On a mass basis, UFPs are often overlooked due to their significantly lower mass concentrations

compared with $PM_{2.5}$. When considered in terms of number concentrations (number of particles per cm^3 of air), however, UFPs represent 80% of the particles in an urban area (Zhu et al. 2002).

In December 2009, the Fairbanks North Star Borough (FNSB) was declared in nonattainment by the U.S. EPA for $PM_{2.5}$ (particulate matter with aerodynamic diameter $\leq$2.5 μm). In April 2017, the FNSB was re-classified as a serious nonattainment area. During winter months, the level of particulate concentrations increases due to local wood burning for heating and to extremely low temperatures that result in temperature inversions and entrapment of pollutants near the ground for days (Ward et al. 2012a), a condition further exacerbated by the valley-like topography of the FNSB area. Most of the limited air quality studies related to $PM_{2.5}$ in the FNSB focus on evaluation of $PM_{2.5}$ sources and influences of weather parameters on $PM_{2.5}$ concentrations (Tran and Mölders 2011, Ward et al. 2012a). To our knowledge, there are no reported data on UFP concentrations for Interior Alaska, and in general, most research studies that measure traffic-related UFPs in the United States are conducted primarily in warm weather regions. The goal of the research reported in this chapter was to determine the ranges of traffic-related UFP data in Interior Alaska, as well as investigate correlations between UFPs and $PM_{2.5}$.

3.2 Materials and Methods

3.2.1 Study area and sampling locations

Study Area. Ultrafine particulate monitoring was done at roadside locations in Fairbanks and North Pole, two cities in Interior Alaska within the FNSB. The city of Fairbanks spans an area of 84.7 km^2, of which 11% is classified residential and 5% and 4% are classified commercial and industrial, respectively (GIS 2017). The city of North Pole spans an area of 10.43 km^2, of which approximately 27% is classified residential and 8% and 18% are classified commercial and industrial, respectively (GIS 2017). Four sampling locations were selected: two in Fairbanks and two near North Pole, though technically outside the city limits of North Pole but were considered

representing North Pole in the analyses here. All four sites are part of the Alaska Department of Transportation and Public Facilities (ADOT&PF)-maintained Road Weather Information System (RWIS) sites, which were already monitoring weather/meteorological (temperature, wind speed, relative humidity) and other air quality parameters (CO, SO_2 and $PM_{2.5}$) (Figure 3.1). The air quality monitors were deployed and operated primarily by the Alaska Department of Environmental Conservation (ADEC). The ADOT&PF uses the RWIS sites to provide real-time road conditions and weather information by deploying video cameras and other sensors.

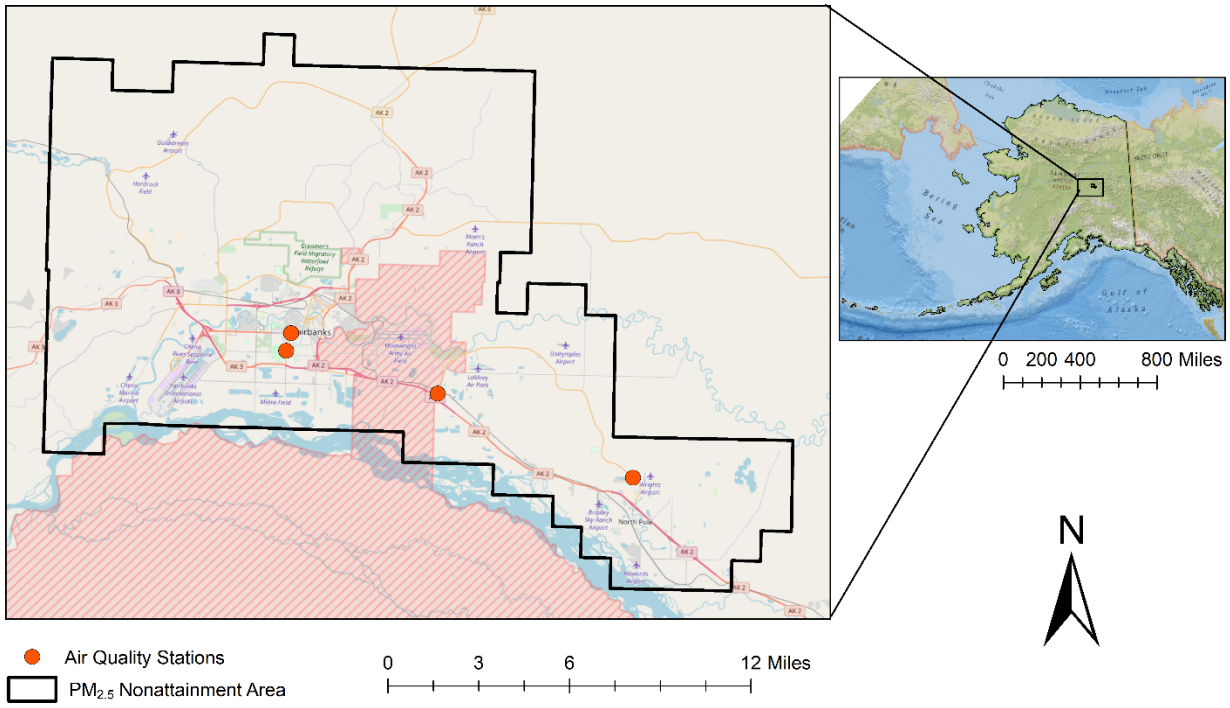

Figure 3.1 RWIS sites with air quality monitors in the FNSB

Sampling Locations. **Station 1** is located beside the intersection point of Airport Way and Cowles Street in Fairbanks (LAT: 64.836836, LONG: -147.739594, z: 158 m). This site is located at the middle of small residential, commercial, and recreational areas. The main infrastructure near this station consists of Lathrop High School (located approximately 300 yards from the sampling location), Noel Wien Public Library, and the Shoppers Forum Mall. Students from Lathrop High School regularly use this intersection for crossing the road. **Station 2** (Lathrop St.) is located at

the tee section between Lathrop Street and 21st Avenue (LAT: 64.828386, LONG: -147.74473, z: 158 m). The average annual daily traffic on Lathrop Street in 2017 was 6744 vpd (vehicles per day). This location is surrounded mostly by residential houses and recreational facilities. The monitoring station is positioned right beside the parking lot of the Big Dipper Ice Arena; Fairbanks Memorial Hospital is nearby. **Station 3** (East Badger) is one of the two RWIS sites on Badger Road, near Alvira ave. in North Pole. This site is in the middle of a residential area (LAT: 64.772, LONG: -147.353088, z: 175 m). The average annual daily traffic on Badger Road close to this station in 2017 was 7683 vpd. The speed limit for this road is 50 mph. **Station 4** (West Badger) is located on Badger Road, where Old Richardson Highway meets Badger Road, on the right side of the Richardson Highway entering ramp (LAT: 64.809943, LONG: -147.573772, z: 167 m). The average annual daily traffic on this section of Badger Road in 2017 was 11,733 vpd. In addition to the sites just described, measurements were conducted at three background locations (away from a major roadway), mostly within residential areas. These locations were, on average, 100 m away from city roads, namely Farmers Loop Road, Fairbanks Street, and College Road.

3.2.2 Data collection

A hand-held condensation particle counter (CPC) (Model 3007, TSI Inc.) was used to measure UFP number concentrations (Figure 3.2). This portable instrument is widely used to measure UFP concentrations in roadside mobile monitoring studies (e.g., Knibbs et al. [2009], Fruin et al. [2008]). According to the CPC manufacturer, the particle size measurement range is 0.01 µm (50% efficiency) to >1.0 µm, with +-20% accuracy and <9 s response time for 95% response (TSI Inc. 2012). For this study, the sampling interval of the CPC was set to 1 second, and prior to each use, the CPC was checked for zero count.

Figure 3.2 Handling of ultrafine particle counter during data collection process: (a) Condensation particle counter (CPC), Model 3007, TSI Inc.; (b) CPC housed in a cooler along with the temperature data logger and a 12V light bulb to keep the inside warm; (c) Measuring ultrafine particle concentration at RWIS station

The sampling period was March 3, 2017, to March 18, 2017. Data were collected at each of the four locations for four days, and each day for five hours. Table 3.1 presents the sampling time and corresponding locations in detail. During this sampling period, average ambient air temperatures were around -20°C. The CPC, however, does not operate below 10°C; thus, it was housed in a custom-designed temperature-controlled chamber during outdoor sampling (details on the temperature-controlled chamber are provided in Appendix A). A temperature data logger was used to monitor the temperature inside the chamber. The average temperature in the chamber measured between 16°C and 20°C during the sampling period.

Table 3.1 Detailed schedule of data collection of ultrafine particulate matter

Date (2017)	Start Time	Duration	Stations
3-Mar	5:13 PM	5 Hours	Lathrop St. and 21st Ave.
4-Mar	9:14 AM	5 Hours	Badger Rd. and Elvira Ave.
5-Mar	10:56 AM	5 Hours	Airport Way and Cowles St.
5-Mar	4:45 PM	5 Hours	Lathrop St. and 21st Ave.
11-Mar	2:19 PM	5 Hours	Badger Rd. and Elvira Ave.
12-Mar	10:42 AM	5 Hours	Lathrop St. and 21st Ave.
12-Mar	4:28 PM	5 Hours	Airport Way and Cowles St.
13-Mar	11:18 AM	5 Hours	Badger Rd. and Elvira Ave.
14-Mar	10:56 AM	5 Hours	Airport Way and Cowles St.
15-Mar	9:22 AM	5 Hours	Lathrop St. and 21st Ave.
15-Mar	3:34 PM	5 Hours	Badger Rd. and Old Richardson Hwy.
16-Mar	7:15 AM	5 Hours	Badger Rd. and Old Richardson Hwy.
17-Mar	12:12 PM	5 Hours	Badger Rd. and Old Richardson Hwy.
17-Mar	6:02 PM	5 Hours	Airport Way and Cowles St.
18-Mar	9:54 AM	5 Hours	Badger Rd. and Old Richardson Hwy.
18-Mar	3:37 PM	5 Hours	Badger Rd. and Elvira Ave.

Each of the selected RWIS sites included an AQM60 (Aeroqual Limited, New Zealand) air monitoring station, operated and maintained by ADEC (Figure 3.3). The $PM_{2.5}$ data were measured using a nephelometer housed in the AQM60 air monitoring station. The monitor is optimized and manufacturer-calibrated for use in low-temperature conditions. Specifically, the $PM_{2.5}$ nephelometer in AQM60 can measure in the range of 0–2000 $\mu g/m^3$, with a resolution of 0.01 $\mu g/m^3$ and an accuracy of $<\pm$ (2 $\mu g/m^3$ + 5% of reading). According to ADEC, the internal temperature of AQM60 was set at 15°C. Throughout the sampling duration, the temperature was stable, between 14°C and 16°C. When the outside temperature starts to rise, however, so does the AQM internal temperature.

Figure 3.3 RWIS site equipped with AQM60 air quality monitor (rectangular box outlined in red) with other road weather monitoring devices

By matching the period of UFP data collection, synchronized traffic counts and meteorological parameters (wind speed, temperature, and relative humidity (RH)) were obtained from the RWIS monitoring sites. Table 3.2 shows all the parameters collected at each station, with corresponding time resolution.

Table 3.2 Resolution of the overall collected data

Stations	Data
Station 1: Airport Way and Cowles St.	UFP (1-s); $PM_{2.5}$, RH, TEMP (5-min); Traffic Volume (1-min); Wind Speed (10-min)
Station 2: Lathrop St. and 21st Ave.	UFP (1-s); $PM_{2.5}$, RH, TEMP (5-min)
Station 3: Badger Rd. and Elvira Ave.	UFP (1-s); $PM_{2.5}$, RH, TEMP (2-min); Traffic Volume (1-min); Wind Speed (10-min)
Station 4: Badger Rd. & Old Richardson Hwy.	UFP (1-s); $PM_{2.5}$, RH, TEMP (2-min); Traffic Volume (1-min); Wind Speed (15-min)

3.2.3 UFP data correction

The concentration range for the CPC is 0–100,000 particles/cm^3, but the measured concentrations often exceeded this range at different sampling stations. The data with higher concentrations (than the recommended range) may be erroneous due to particle coincidence effects. To correct such data, Westerdahl et al. (2005) developed and recommended the use of the following relationship:

$$y = 38456e^{0.00001x} \text{ for } x > 100{,}000 \text{ particles/ cm}^3$$

where x is the UFP concentration measured by the CPC and y is the corrected or actual concentration of UFP. No correction was made for the CPC data below 100,000 particles/cm^3.

3.2.4 Data preparation and statistical analysis

Referring to Table 3.2, the time resolutions were different for different variables. Before we performed any statistical analysis, it was necessary to align all the variables on the same scale and with the same time stamps. Thus, the data were scaled to 1-min resolution, and later, data were arranged in 5-min. 10-min, and 15-min resolution scale.

After getting the raw data of all the variables with different resolutions (Table 3.2), the resolution was modified to 1-min, 5-min, 10-min, and 15-min for UFP concentrations, and other variables were synchronized with those resolutions. For each resolution, the mean traffic count, mean weather parameters (wind speed, temperature and relative humidity [RH]) and several percentiles (10^{th}, 25^{th}, 50^{th}, 75^{th}, and 90^{th} percentiles), mean and standard deviation of UFP number concentrations were calculated. For exploratory data analysis, summary statistics of the data were computed, and the data were plotted as boxplots to visually depict the data and detect any outliers. We used Q-Q plots to select a suitable transformation for the response variable (i.e., the UFP number concentrations, Figure 3.4) to normalize the data. After trying different transformation functions, we found that log-transformation was suitable for the UFP data. Statistical analyses for

the raw data and processed data were done using R software, version 3.4.1 (R development Core Team, Vienna, AT, 2009).

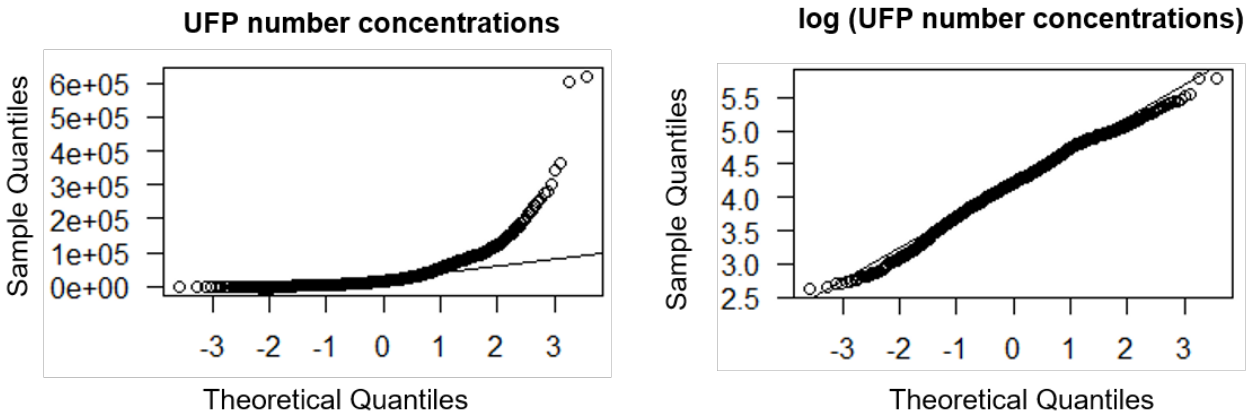

Figure 3.4 Q-Q plots of UFP number concentrations (1 min average data) and log transformed data

3.2.5 Predictor variable selection

A three-step method was employed to select optimal predictive variables.

Step 1: In Step 1, correlation analysis and scatter plots were generated to rule out variables that are irrelevant. If the correlation coeffient of the variables with the log-transformed UFP concentrations was less than 0.05 and the scatter plots did not show any clear pattern, the variable was not considered a potential predictor variable. The variables thus selected were considered for Step 2.

Step 2: In Step 2, multicolinearity of independent variables was assessed. Variance inflation factors (VIFs) were used to avoid multicollinearity. A value of VIF less than 10 was considered an indication of weakly correlated variables, and a value of VIF greater than 10 was considered a highly correlated variable. Up to this step all the selected variables (wind speed, traffic count, temperature, relative humidty, location, and $PM_{2.5}$) were found eligible for modeling.

Step 3: In Step 3, the selected predictor variables from Step 2 were further assessed by iteratively using a backward-selection approach. In R, the drop1() function and *F*-test were used in the process, and the variables with *p* values ≥ 0.05 were left out of the model.

3.2.6 Multilinear regression modeling

For multiple linear regression with predictor variables, we used the ordinary least-squares method to fit the model. The *stats* package of R is used in this regard. The equation for the linear regression is:

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \ldots\ldots\ldots + \beta_n X_n + \varepsilon \quad (1)$$

where Y is the response variables and $X_1, X_2, \ldots\ldots X_n$ are the predictor variables, β_0 is the model intercept, $\beta_1, \beta_2, \ldots\ldots \beta n$ are the linear coefficient for the respective predictor variables, and ε is the normal random error term ($\varepsilon \sim N(0, \sigma^2)$).

3.2.7 Regression diagnostics

Preliminary model validation and evaluation were carried out using various methods. The model fit was assessed by plotting fitted (or modeled) versus observed data values. The normality of the predictor variables was assessed via histograms or Q-Q plot residuals. For homogeneity, standardized residuals were plotted against fitted values to check if the spread was random and equally spread everywhere. The independence of different predictor variables was assessed by plotting residuals versus predictors in the model, to check if the residuals were uniformly spread. Models were also checked for influential observations (e.g., Cook's distance function; Cook's distance values <0.5 are acceptable).

In addition to these evaluations, model performance was assessed by training the models with a random 75% subset of the data set and by testing model predictions against the 25% of UFP measurements not used for model building. This process was repeated 10 times, and the results were averaged (2-fold, 10-repeat cross-validation) (Max and Kuhn 2008). The cross-validated R^2 (CV-R^2) was obtained after fitting linear regression models between CV-predicted and observed values.

3.3 Results

Roadside Particulate Concentrations. The average roadside UFP number and mass concentrations of $PM_{2.5}$ were 31,891 cm^{-3} and 5.3 $\mu g/m^3$, respectively. Summary statistics of one-minute averaged concentrations of all the variables collected during the sampling period are provided in Table 3.3.

Table 3.3 Summary statistics of the data

Statistics	UFP Conc. (#/cm^3)	$PM_{2.5}$ (µg/m3)	Temp. (°C)	RH (%)	Wind Speed (m/s)	Traffic Volume
Minimum	422.90	0.00	-21.61	21.20	0.00	0.00
1st Quartile	9741.80	2.21	-10.03	28.52	0.45	7.00
Median	23282.20	3.27	-5.82	33.60	0.89	10.00
Mean	31891.80	5.33	-6.65	34.90	1.05	11.69
3rd Quartile	41099.70	5.71	-2.65	39.60	1.34	15.00
Maximum	618634.80	117.75	4.00	61.40	4.47	43.00

Data distributions of UFP concentrations (Figure 3.5) show that UFP number concentrations were higher for stations at Cowles and Lathrop (in Fairbanks) than for those at Badger East and Badger West (proximal to North Pole); though it must be noted that the data were collected at different times of the day (Table 3.1) which could introduce variability as there are known diurnal variations in particulate matter. Station-wise, the highest mean concentrations of UFP (41,684 #/cm^3) were observed at *S*tation 1, near the traffic signal between Airport Way and Cowles Street. Owing to the traffic signal, it is expected that *S*tation 1 would experience frequent vehicle stops/starts and *vehicle* idling. Vehicles do not usually stop at the other stations; thus, higher UFP concentrations at Station 1 could, in part, be attributed to traffic signal-related vehicular emissions. Lowest average UFP concentrations (13,400 #/cm^3) were measured at Station 3 *(Badger East).*

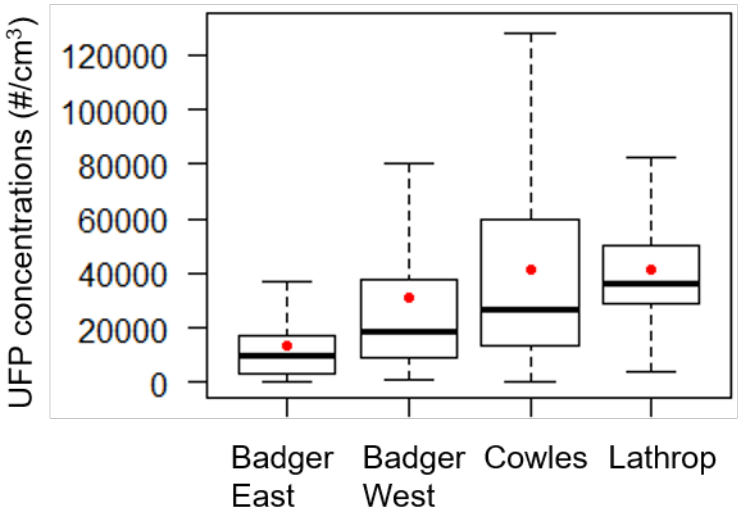

Figure 3.5 Distribution of UFP measurements at different locations at the four stations in Fairbanks and North Pole. Boxes represent 25th, 50th, and 75th percentiles; whiskers extend at most to 1.5 interquartile ranges. Red point depicts mean value

Interestingly, the distribution of roadside $PM_{2.5}$ data shows the same trend of distribution as UFP concentrations (Figure 3.6). Roadside $PM_{2.5}$ concentrations were higher for the stations in Fairbanks than those near North Pole, which indicates a probable correlation (Pearson coefficient = 0.23) between roadside ultrafine and $PM_{2.5}$ concentrations. Again, however, caution should be exercised in comparing values across stations as the data were collected at different times of the day and the differences in particle counts could potentially be an artifact of diurnal particulate matter variability. Furthermore, like UFP concentrations, the highest mean $PM_{2.5}$ value (7.8 µg/m^3) was observed at Station 1; the lowest was observed at Station 3.

$PM_{2.5}$ concentrations at monitoring stations from previous years. The distribution of $PM_{2.5}$ data from two winter seasons, 2015–16 and 2016–17, is shown in Figure 3.7. Station 3 showed the highest ranges of $PM_{2.5}$ concentration in both seasons: 0–103 µg/m^3 in 2015–16 and 0–90 µg/m^3 in 2016–17. Overall, stations in North Pole showed higher $PM_{2.5}$ concentrations than stations in Fairbanks. Data collected in March 2017 showed a higher concentration of $PM_{2.5}$ (Figure 3.6) at Station 1 (Cowles) relative to other stations, but when data were averaged for the

whole season, Station 1 showed a lower concentration of $PM_{2.5}$ relative to other stations. Note that the $PM_{2.5}$ means are higher for the annual averages.

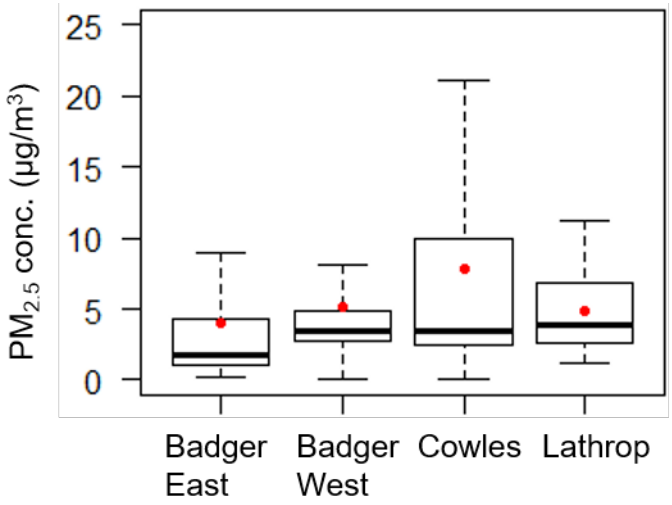

Figure 3.6 Distribution of $PM_{2.5}$ concentrations at different locations in Fairbanks and North Pole. Box represents 25th, 50th, and 75th percentiles; whiskers extend at most to 1.5 interquartile ranges. Red dots denote mean value

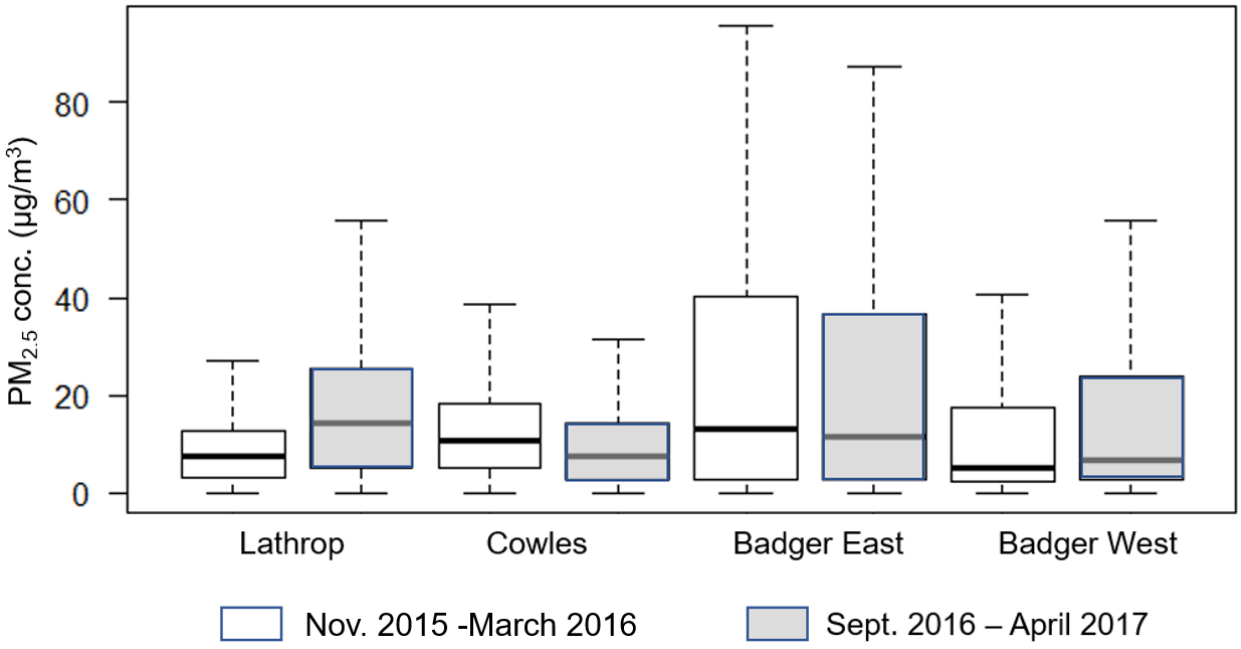

Figure 3.7 Distribution of $PM_{2.5}$ concentrations in two different years (2015–16 and 2016–17)

Data distribution of other variables. Figure 3.8 shows the data distribution of meteorological parameters (temperature, wind speed, and relative humidity) and traffic count

during the sampling period (3–18 March 2017; Table 3.3). Data show very low wind speeds measured at the sampling locations, with 71% of the wind speed observations <1 m/s and 89% <2 m/s. The highest average traffic counts (15/min) were found at Station 1 (Cowles), and the lowest average traffic counts (8/min) were found at Station 4 (Badger West). The lowest temperature (-21.6°C) was recorded at Station 2, and the lowest relative humidity (21.2%) was measured at Station 4, while the highest temperature (4°C) and relative humidity (61.4%) were measured at Station 3. Data show that 90% of the temperature measurements were below 0°C.

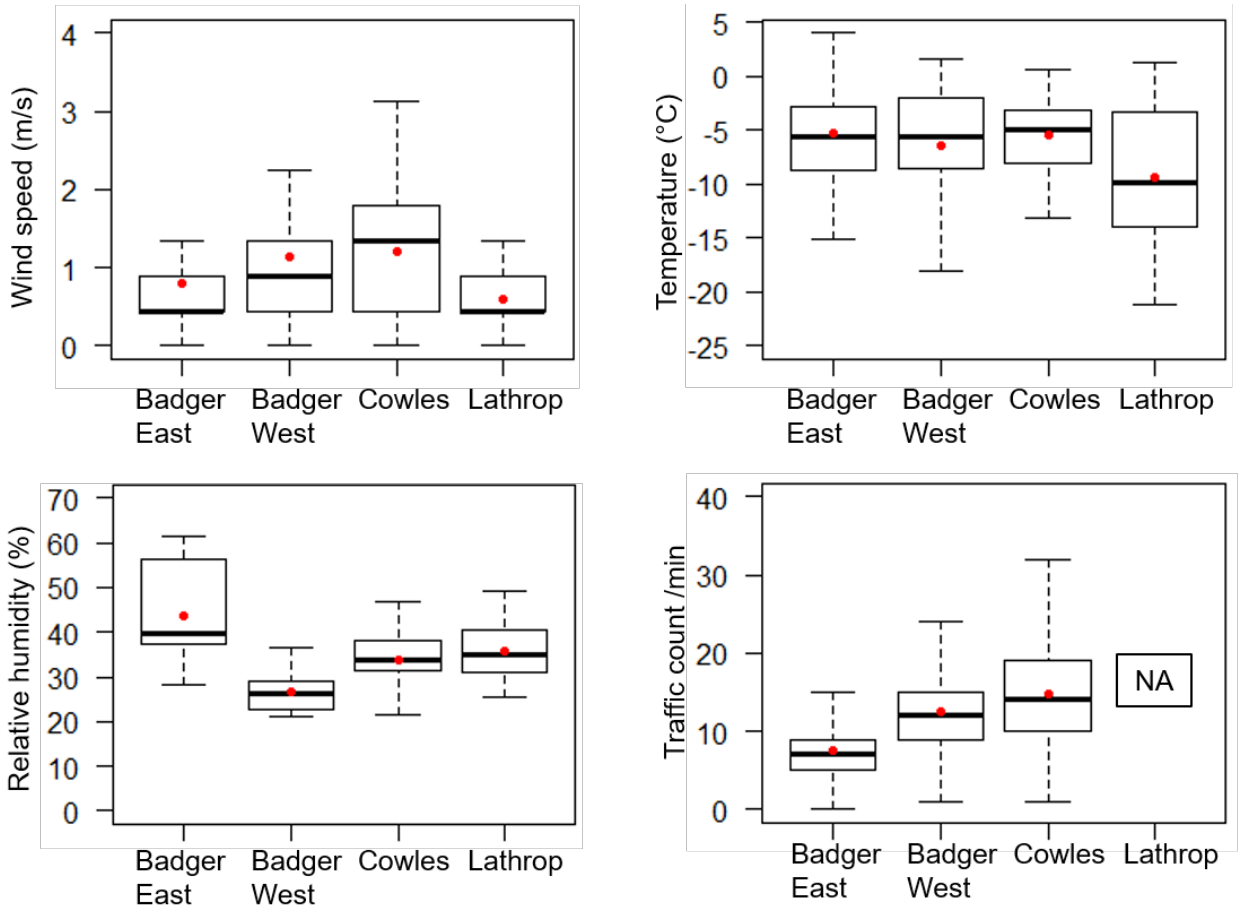

Figure 3.8 Distribution of meteorological parameters and traffic count at different locations in Fairbanks and North Pole. Box represents 25th, 50th, and 75th percentiles; whiskers extend at most to 1.5 interquartile ranges. Red point illustrates mean value

UFP Modeling Results. Multiple linear regression (MLR) models were fitted using 1-min, 5-min, 10-min, and, 15-min time resolution UFP data; log-transformed percentiles (10th, 25th, 50th,

75th, and 90th percentiles), mean and standard deviation of the UFP number concentrations were used as dependent variables and thus seven models were developed for each time resolution. Weather parameters (temperature, wind speed, and relative humidity) and location were the most important predictors for UFP. Table 3.4 lists the models, including the linear coefficients and *p*-values for each predictor variable and the model *R*-square value for each model. Model results for the 1-min resolved UFP data in Table 3.4(a) show that wind speed, relative humidity, and location were significant in all seven models. Traffic count was not significant in any of the models. While $PM_{2.5}$ was significant for higher percentile models (75th and 90th), it was not significant for lower percentiles models (10th and 25th) and the 50th percentile model. Models show that all the weather parameters were negatively correlated with the response variables in each case but one, where wind speed was positively correlated in the standard deviation model. The R^2 value of these models ranged from 0.18 to 0.41, with the highest R^2 for the10th percentile model and the lowest R^2 for the standard deviation model. The value of R^2 continuously dropped for higher percentile models. Furthermore, the R^2 value of the mean model (0.28) was close to the R^2 value of the 50th percentile model. Location was also a significant predictor in the seven models. Location was treated as a categorical variable in the model with two factors: North Pole (Location@NP in Table 3.4) and Fairbanks. North Pole includes Stations 3 and 4; Fairbanks includes Stations 1 and 2. Model results present the coefficient of North Pole relative to Fairbanks. Thus, in the models, negative coefficient values for North Pole suggest that UFP concentrations are higher for the stations in Fairbanks than those near North Pole.

Table 3.4 Results of the models for log-transformed UFP concentrations. Data resolution: (a) 1-min (b) 5-min (c) 10-min (d) 15-min

Model parameters	Mean		10th Percentile		25th Percentile		50th Percentile		75th Percentile		90th Percentile		Standard deviation	
	linear coefficient	p- value	linear coefficient	p- value	linear coefficient	p- value	linear coefficient	p- value	linear coefficient	p- value	linear coefficient	p- value	linear coefficient	p- value
Intercept	4.810	2.00E-16	4.609	2.00E-16	4.663	2.00E-16	4.759	2.00E-16	4.875	2.00E-16	5.016	2.00E-16	4.734	2.00E-16
PM2.5	0.003	0.0214	-	-	-	-	-	-	0.004	0.0027	0.005	0.00127	0.010	2.90E-08
Traffic count	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Wind speed	-0.147	2.00E-16	-0.257	2.00E-16	-0.230	2.00E-16	-0.187	2.00E-16	-0.131	2.00E-16	-0.091	2.00E-16	0.077	2.19E-07
Temperature	-0.023	2.00E-16	-0.032	2.00E-16	-0.030	2.00E-16	-0.028	2.00E-16	-0.022	2.00E-16	-0.019	2.00E-16	-	-
Relative Humidity	-0.008	1.79E-10	-0.005	4.15E-05	-0.006	1.80E-06	-0.007	1.48E-08	-0.009	3.53E-12	-0.011	2.23E-16	-0.032	2.00E-16
Location @ NP	-0.451	2.00E-16	-0.465	2.00E-16	-0.450	2.00E-16	-0.439	2.00E-16	-0.428	2.00E-16	-0.449	2.00E-16	-0.482	2.00E-16
R^2	**0.28**		**0.406**		**0.37**		**0.306**		**0.242**		**0.208**		**0.18**	

(a)

Model parameters	Mean		10th Percentile		25th Percentile		50th Percentile		75th Percentile		90th Percentile		Standard deviation	
	linear coefficient	p- value	linear coefficient	p- value	linear coefficient	p- value	linear coefficient	p- value	linear coefficient	p- value	linear coefficient	p- value	linear coefficient	p- value
Intercept	4.865	2.00E-16	4.386	2.00E-16	4.612	2.00E-16	4.724	2.00E-16	4.886	2.00E-16	5.112	2.00E-16	5.102	2.00E-16
PM2.5	-	-	-	-	-	-	-	-	-	-	0.007	0.01921	0.013	0.00052
Traffic count	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Wind speed	-0.120	1.46E-09	-0.287	2.00E-16	-0.256	2.00E-16	-0.195	2.00E-16	-0.124	1.23E-09	-0.053	0.0131	0.100	4.90E-04
Temperature	-0.023	1.28E-11	-0.033	2.00E-16	-0.033	2.00E-16	-0.029	3.43E-16	-0.023	2.76E-11	-0.014	0.00025	-	-
Relative Humidity	-0.008	0.000558	-	-	-0.006	0.0316	-0.007	0.00562	-0.008	0.0007	-0.012	4.97E-06	-0.031	2.00E-16
Location @ NP	-0.438	2.00E-16	-0.482	2.00E-16	-0.473	2.00E-16	-0.429	2.00E-16	-0.407	2.00E-16	-0.395	2.00E-16	-0.472	1.55E-14
R^2	**0.295**		**0.484**		**0.445**		**0.369**		**0.271**		**0.212**		**0.24**	

(b)

Model parameters	Mean		10th Percentile		25th Percentile		50th Percentile		75th Percentile		90th Percentile		Standard deviation	
	linear coefficient	p- value	linear coefficient	p- value	linear coefficient	p- value	linear coefficient	p- value	linear coefficient	p- value	linear coefficient	p- value	linear coefficient	p- value
Intercept	4.885	2.00E-16	4.392	2.00E-16	4.425	2.00E-16	4.732	2.00E-16	4.918	2.00E-16	4.961	2.00E-16	4.685	2.00E-16
PM2.5	-	-	-	-	-	-	-	-	-	-	0.020	8.93E-06	0.022	0.00014
Traffic count	-	-	-	-	-	-	-	-	-	-	-	-	0.021	0.0314
Wind speed	-0.107	5.87E-05	-0.273	2.00E-16	-0.225	5.99E-14	-0.178	8.56E-10	-0.117	2.96E-05	-	-	-	-
Temperature	-0.022	1.29E-06	-0.034	4.89E-11	-0.032	6.91E-11	-0.029	1.48E-09	-0.023	9.21E-07	-	-	-	-
Relative Humidity	-0.009	0.0081	-	-	-	-	-0.007	0.0549	-0.009	9.08E-03	-0.009	0.0061	-0.024	8.41E-06
Location @ NP	-0.432	1.81E-13	-0.540	3.16E-16	-0.508	1.40E-15	-0.477	2.67E-14	-0.421	4.31E-12	-0.325	1.56E-07	-0.248	0.00757
R^2	**0.303**		**0.499**		**0.464**		**0.397**		**0.293**		**0.207**		**0.255**	

(c)

Model parameters	Mean		10th Percentile		25th Percentile		50th Percentile		75th Percentile		90th Percentile		Standard deviation	
	linear coefficient	p- value	linear coefficient	p- value	linear coefficient	p- value	linear coefficient	p- value	linear coefficient	p- value	linear coefficient	p- value	linear coefficient	p- value
Intercept	4.550	2.00E-16	0.638	2.00E-16	4.433	2.00E-16	4.520	2.00E-16	4.933	2.00E-16	4.946	2.00E-16	5.215	2.00E-16
PM2.5	0.022	8.86E-05	-	-	-	-	-	-	-	-	0.027	4.03E-07	0.025	0.00034
Traffic count	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Wind speed	-0.072	0.0267	-0.033	2.61E-12	-0.246	3.81E-11	-0.180	1.37E-07	-0.118	0.00039	-	-	-	-
Temperature	-	-	-0.004	2.70E-07	-0.031	2.53E-07	-0.026	5.77E-06	-0.020	0.00029	-	-	-	-
Relative Humidity	-	-	-	-	-	-	-	-	-0.008	0.03802	-0.009	0.018	-0.030	8.46E-09
Location @ NP	-0.374	2.99E-07	-0.058	8.31E-09	-0.503	5.13E-10	-0.458	1.66E-09	-0.440	5.44E-09	-0.339	7.98E-06	-0.356	0.00037
R^2	**0.327**		**0.486**		**0.486**		**0.418**		**0.311**		**0.286**		**0.25**	

(d)

- indicates not used in the model due to lack of statistical insignificant.

Similar to the seven models in Table 3.4(a), more MLR models were fitted using 5-min, 10-min, and 15-min resolution data, seven models from each category (21 in total). Model outputs for 5-min resolution data are presented in Table 3.4(b). As with 1-min resolution models, weather parameters were significant in all the models except temperature and relative humidity, which were not significant in the standard deviation model and the 10^{th} percentile model, respectively. Again, traffic count was not found statistically significant in any of these models. $PM_{2.5}$ was only significant in the 90^{th} percentile and standard deviation models, and showed a positive correlation with response variables. Relative to 1-min resolution data, 5-min data increased the model R^2 by 5%, 19%, 20%, 21%, 12%, 2%, and 33% in the mean, 10^{th}, 25^{th}, 50^{th}, 75^{th}, 90^{th} percentiles and standard deviation models, respectively. The 10^{th} percentile models showed the highest R^2 value, and the 90^{th} percentile models showed the lowest R^2 value. Location was found to be a significant predictor in these models, with negative correlations at the North Pole locations.

Table 3.4(c) lists the results of MLR models using 10-min resolution data. Here, traffic count was found significant in the standard deviation model. Among weather parameters, wind speed and temperature were significant in all the models except the 90^{th} percentile and standard deviation models. On the other hand, relative humidity was significant in all but the 10^{th} and 25^{th} percentile models. Similar to the 5-min resolutions models, $PM_{2.5}$ was only significant in the 90^{th} percentile and standard deviation models. Relative to 5-min data, 10-data increased the model R^2 value by 3%, 3%, 4%, 8%, 8% and 6% in the mean, 10^{th}, 25^{th}, 50^{th}, and 75^{th} percentiles and standard deviation models, respectively, and decreased the R^2 value by 2% in the 90^{th} percentile model. These values indicate that the rate of increment of R^2 values was higher when resolution increased from 1 min to 5 min than when resolution increased from 5 min to 10 min. However, similar to 5-min models, the highest R^2 value was found in the 10^{th} percentile model and the lowest R^2 value was found in the 90^{th} percentile model.

Models with 15-min resolution data are presented in Table 3.4(d). The R^2 value of most of the models increased, except for the 10th percentile and standard deviation models—3% and 2%—which decreased respectively relative to the 10-min models. However, the number of predictor variables changed in those models. For example, relative humidity was only significant in the 75th and 90th percentiles and standard deviation models; $PM_{2.5}$ was significant in the mean, 90th percentile, and standard deviation models; temperature was not significant in the mean models and (along with wind speed) in the 90th percentile and standard deviation models.

Overall, among all the predictor variables, location was the important and statistically significant predictor in all 28 models, while traffic count was significant in only one model, where standard deviation was used as a response variable and 10-min resolution data were used (Table 3.4[c]). Meteorological predictors were also significant in the models, but were not consistent in all the models.

Additional UFP models. Four additional MLR models were fitted using only the mean value of 1-min resolution of the log transformed UFP concentrations. A summary of these models is listed in Table 3.5. These models were fitted to investigate other predictor variables, and they were compared using R^2 values. Additionally, traffic count data were no longer used in these models, since they were insignificant in previous UFP models. Days of the week (weekdays and weekend are considered as the factor of this categorical variable), distance of the monitoring stations from Fairbanks International Airport (FAI), and the local power plant in Fairbanks (PP; Aurora Energy LLC) were used as the new predictor variables. Distances from two locations were not used in the same model because their inclusion led to high levels of collinearity among them.

Model results show that the R^2 value of Models 1 and 2 are 0.34 and 0.33, resepectively. The R^2 value in Model 2 decreased when $PM_{2.5}$ was not included, and relative humidity was found insignificant in the model. Thus, it seems that wind speed, temperature, location, and sampling

days are the important predictors in the models. Note that all the predictors except $PM_{2.5}$ show a negative correlation with Log(UFP).

In Models 3 and 4, FAI and PP distances were added, respectively. The R^2 value increased by 35% and 32% in Models 3 and 4, respectively, as compared with Model 1, indicating that this approach might be able to help explain the ultrafine concentrations in the study area. But this was just a preliminary evaluation and more comprehensive work would be needed to draw clear conclusions. For example, other major sources (e.g. UAF power plant, Eielson Air Force Base power plant; and other air fields) will need to be included in the analyses and the results compared with other on-the-ground measurements. It was interesting to note that after adding these distance predictors in the model, $PM_{2.5}$ and temparature were no longer significant in the model, and the correlation of relative humidity and location with the response variable changed from negative to positive. Furthermore, adding these variables in the model decreased the wind speed coefficient and increased the coefficient of day of week.

$PM_{2.5}$ Modeling Results. Table 3.6 summarizes all of the models in which $PM_{2.5}$ was used as the response variable. The raw $PM_{2.5}$ data were transformed to $(PM_{2.5}+5)^{-1.25}$ to make the data normally distributed. Comparing Models 1 and 2, adding UFP as a predictor variable increased the model R^2 by 10%, but day of week (weekday vs. weekend) was found to be insignificant in the model, with the non-inclusion of UFPs. The R^2 value further increased by 9% in Model 3 compared with Model 1 after including traffic count in the model, which was also significant in the model (p<0.05). The R^2 values in Models 3 and 4 increased by 16% after including PP distance and FAI distance, respectively. Again, however, the analyses including the distances needs more work to draw any significant conclusions.

Table 3.5 Summary of UFP models where Log (UFP) is the response variable

	UFP model 1		UFP model 2		UFP model 3		UFP model 4	
	linear coefficient	P-value	linear coefficient	P-value	linear coefficient	P-value	linear coefficient	P-value
Intercept	4.6771	2.00E-16	4.6642	2.00E-16	4.3970	2.00E-16	4.1100	2.00E-16
$PM_{2.5}$	0.0062	4.00E-10	[a]-		-	-	-	-
Wind speed (m/s)	-0.1704	2.00E-16	-0.1792	2.00E-16	-0.1865	2.00E-16	-0.1920	2.00E-16
Temperature (°C)	-0.0152	2.00E-16	-0.0164	2.00E-16	-	-	-	-
RH (%)	-0.0016	0.0295	-	-	0.0207	2.00E-16	0.0205	2.00E-16
Location @NP	-0.3822	2.00E-16	-0.3883	2.00E-16	0.4742	2.00E-16	0.4093	2.00E-16
Day @weekend	-0.1948	2.00E-16	-0.2099	2.00E-16	-0.1202	2.00E-16	-0.1003	4.31E-14
FAI airport distance (m)	[a]-		[a]-		-6.59E-05	2.00E-16	[a]-	
Power plant distance (m)	[a]-		[a]-		[a]-		-6.36E-05	2.00E-16
R^2	**0.3407**		**0.3346**		**0.4611**		**0.4504**	

a-': data are not included in the model.
-': variable was not significant in the model

Table 3.6 Summary of the $PM_{2.5}$ models where $(PM_{2.5}+5)^{-1.25}$ is the response variable

	$PM_{2.5}$ model 1		$PM_{2.5}$ model 2		$PM_{2.5}$ model 3		$PM_{2.5}$ model 4		$PM_{2.5}$ model 5		$PM_{2.5}$ model 6	
	linear coefficient	P-value	linear coefficient	P-value	linear coefficient	P-value	linear coefficient	P-value	linear coefficient	P-value	linear coefficient	P-value
Intercept	0.0789	0.00	0.0699	0.00	0.0532	2.00E-16	0.04	2.00E-16	0.1043	2.00E-16	0.0870	2.00E-16
UFP	0.0000	2.00E-16	[a]-		0.0000	2.00E-16	[a]-		0.0000	1.11E-05	0.0000	1.11E-05
Wind speed (m/s)	0.0083	2.00E-16	0.0100	2.00E-16	0.0073	2.00E-16	0.0086	2.00E-16	0.0080	2.00E-16	0.0080	2.00E-16
Temperature (°C)	0.0022	2.00E-16	0.0023	2.00E-16	0.0032	2.00E-16	0.0035	2.00E-16	0.0022	2.00E-16	0.0022	2.00E-16
RH (%)	0.0002	4.35E-06	0.0002	2.46E-06	0.0010	2.00E-16	0.0010	2.00E-16	-0.0009	2.00E-16	-0.0009	2.00E-16
Location @NP	-0.0018	0.00746	0.0015	0.0178	0.0062	5.45E-08	0.0101	2.00E-16	-0.0378	2.00E-16	-0.0383	2.00E-16
Day @weekend	-0.0022	0.00226	-	-	-0.0077	3.68E-16	-0.0083	2.00E-16	-0.0119	2.00E-16	-0.0119	2.00E-16
FAI airport distance (m)	[a]-		[a]-		[a]-		[a]-		[a]-		3.38E-06	2.00E-16
Power plant distance (m)	[a]-		[a]-		[a]-		[a]-		3.29E-06	2.00E-16	[a]-	
Traffic count/minute	[a]-		[a]-		2E-04	0.0231	2E-04	0.0176	2.05E-04	0.0085	2.05E-04	0.0085
R^2	**0.4425**		**0.402**		**0.485**		**0.4559**		**0.5626**		**0.5626**	

a-': data are not included in the model.
-': variable was not significant in the model

All the predictor variables were found to be significant in predicting $(PM_{2.5}+5)^{-1.25}$. Additionally, weather parameters, traffic count, and distance were found to be positively correlated with the transformed response variable, which ultimately suggests an inverse correlation between $PM_{2.5}$ concentrations and the predictor variables. In contrast, weekend factor showed a negative coefficient in the models, and relative humidity showed a negative coefficient only when distance was used in the model as the predictor variable.

3.4 Discussion

UFP Comparisons. To put the UFP measurements in context, UFP levels measured were compared against various global measurements, especially since there were no known previous measurements of UFP in the study area.

Compared with larger cities—e.g., Los Angeles—the UFP levels observed in Fairbanks and North Pole are relatively low. While data were collected at the roadside at approximately 3 m from the center of the road, Zhu et al. (2002) collected their data at 17 m from the center of the road (I-710, Los Angeles), and UFP concentrations in their study were 5–10 times higher than in this study. However, it should be mentioned that Zhu et al. (2002) collected data in the fall, while we collected data in the winter.

In a recent study in the metropolitan Los Angeles area, Li et al. (2013) found the average on-road UFP concentrations (35,010 particles/cm^3) very similar to this study, although the current study represents roadside particulate data. Li et al. (2013) collected their data in the month of March, though average temperature and weather conditions during March are significantly different in Los Angeles compared with Interior Alaska. Furthermore, UFP concentrations in the current study were found in agreement with near-roadway UFP concentrations from other locations—e.g., Minneapolis (Hankey and Marshall 2015), Basel (Ragettli et al. 2014), and New York (Zwack et al. 2011).

Meteorological predictors. Temperature, wind speed, and relative humidity were strong predictors in both the UFP and $PM_{2.5}$ models. Overall, most of the models showed that log(UFP) and $PM_{2.5}$ increase with linear decrease in those parameters. While most studies are in agreement with the negative wind speed correlation with UFPs and $PM_{2.5}$, temperature has been shown to have a positive correlation (Zwack et al. 2011, Li et al. 2013). A possible explanation for this apparently anomalous finding is that most studies reported in the literature collected data in the summertime, when particulates are formed through photochemical conversion and air temperature plays an important role (Li et al. 2013). Similar to the current study, though, Patton et al. (2014) found a negative correlation between temperature and UFPs, and they collected their data between September and August in Somerville, Massachusetts. In another study in three Canadian cities (Toronto, Vancouver, and Montreal), Weichenthal et al. (2014) showed that wind speed and temperature are in negative correlation with in-vehicle $PM_{2.5}$ and UFP.

Traffic Predictor. One of the predictors that we expected to have physical interpretability in the model was traffic count, but in the UFP models, traffic count was not found to be a significant predictor. In previous similar studies, however, traffic count showed a negative correlation with UFPs (Zwack et al. 2011, Patton et al. 2014). For $PM_{2.5}$ models, increasing traffic counts were significantly associated with decreasing $PM_{2.5}$ concentrations, which is opposite of what Zwack et al. (2011) found in their study.

Multiple factors could explain these findings. Sampling occurred only for five hours at a sampling station on a sampling day, leading to a narrow range of traffic count. Moreover, traffic count may not be a good predictor to interpret vehicular emissions in the model. Vehicle speed can be a possible predictor in that case. Since data were collected using stationary monitoring devices, slow moving vehicles may contribute a higher number of UFPs and $PM_{2.5}$ concentrations than faster moving vehicles. Higher pollutant concentrations at Station 1 indicate that as well.

Model Comparisons. For the UFP mean model, the R^2 was found to be 0.28. Zwack et al. (2011) found a similar R^2 value (0.24) in their study in Brooklyn, New York. However, they found traffic count to be significant in their model, probably because they collected their data via mobile monitoring (carried monitoring devices on walking routes), while this study used stationary data in the models.

Results of the model indicate that, overall, the value of R^2 increased as the resolution of data decreased from 1 min to 15 min. Furthermore, higher R^2 values were consistent with the model where the 10^{th} and 25^{th} percentiles of log-transformed UFP concentrations were used as the response variable. This result indicates that UFP concentration values lower than the 25^{th} percentile are better explained by the predictor variables than the mean values or values higher than the 75^{th} and 90^{th} percentiles.

Limitations. This study has some limiting factors that could influence the interpretability and generalizability of the findings. First, data were collected only in the winter months. It would have been ideal to sample each of the four seasons, at various times of the day, to fully understand the correlation between weather parameters and air pollution. Second, the sampling period involved low wind conditions, skewed data, which may have influenced the model. Third, data were collected at four fixed locations. Most of the studies related to near-roadway UFPs and $PM_{2.5}$ involved on-road mobile monitoring to interpret traffic-related UFPs and $PM_{2.5}$ (Zwack et al. 2011, Li et al. 2013, Weichenthal et al. 2014, Weichenthal et al. 2016, Patton et al. 2014). Thus, to fully characterize the traffic and air quality relationship, on-road mobile monitoring would have been an ideal solution. Fourth, previous regression modeling studies showed that traffic speed and wind direction are highly significant in the model for predicting UFPs (Patton et al. 2014, Simon et al. 2017, Li et al. 2013). However, these variables, which were not recorded in the current study, could have helped develop more robust models. It seems reasonable to conclude that the models

presented here are location- and weather-sensitive and not immediately transferable to other locations in the U.S. (or elsewhere), and even only applicable for winter months.

Despite these limitations, this study provides key insights on UFP concentration levels in Fairbanks and North Pole, and could inform future exposure studies and public policy decisions. Furthermore, this study can be considered an initial approach using regression modeling. These models can be used as reference for studies on particulate matter air quality in the Fairbanks North Star Borough, as well for other cities with similar cold weather conditions.

3.5 Conclusions

Roadside number concentrations of ultrafine particles (UFPs) were collected for the first time at four RWIS monitoring stations in Fairbanks and North Pole, Alaska. Descriptive statistical analyses of UFPs are presented, and the data are compared with similar studies conducted at other locations globally. To do the MLR modeling analysis, we collected data for other predictor variables and incorporated them in the models to investigate statistical correlations with UFPs. A variety of statistical models consistently found significant correlations between UFPs and weather parameters. Traffic count did not show significant correlation with UFPs. Similar to UFP models, $PM_{2.5}$ models were generated. These models showed high correlation with weather parameters and traffic count. Overall, this work provides useful information about roadside particulate air pollutants in a cold climate region, which can be used as a basis for hotspot identification, improved monitoring, as well as for future studies investigating health risks associated with roadside air pollutants.

CHAPTER 4.0 REFERENCES

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