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Metro Vancouver Near-Road Air Quality Monitoring Study

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SERVICES AND SOLUTIONS FOR A LIVABLE REGION

Metro Vancouver Near-Road Air Quality Monitoring Study

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Executive Summary

Regional air quality in Metro Vancouver has improved steadily over the past several decades, in part because of stricter vehicle emission standards and the AirCare vehicle emissions inspection and maintenance program that have reduced major air contaminants that cause smog and harm health. Despite local improvements in vehicle emissions, Canada's urban areas, population and use of vehicles continue to grow. Around 10 million Canadians, 32% of the total population, now live within 250 metres of a major roadway and in range of vehicle emissions. This percentage is higher in Metro Vancouver, where over one million people, nearly half the population, live within 250 metres of a major road. Canadian scientific data indicates clearly that exposure to traffic-related air pollutants (TRAP) is a significant public health issue in Canada.

Metro Vancouver partnered with Environment and Climate Change Canada and the University of Toronto to conduct a two-year Near-Road Air Quality Monitoring Study in the Metro Vancouver region. The study consisted of establishing two monitoring stations in Vancouver equipped with instrumentation capable of measuring TRAP and meteorology. A near-road monitoring station was established in East Vancouver on a busy truck route (Clark Drive) that traverses a densely populated community while a background station was established nearby, but located away from traffic emissions. This report provides an analysis of data collected during the study from May 2015 to December 2017.

The Metro Vancouver study was part of a larger national study that included establishing two similar near-road monitoring stations in Toronto. Together the Metro Vancouver and Toronto studies will inform national guidelines for near-road monitoring across Canada. The national guidelines will incorporate lessons learned in locating a near-road monitoring site, determine contaminants to be monitored, and evaluate the use of additional air quality instrumentation not routinely used in air quality monitoring networks.

The primary focus of this report is to provide a description of the monitoring stations, instrumentation and an analysis of the monitoring results. Data collected at the Vancouver near-road monitoring station are also compared with the background station in Vancouver, other network stations in Metro Vancouver and two near-road monitoring stations in Toronto. This report also provides recommendations to reduce traffic-related emissions, reduce exposure to TRAP and track air quality improvements in the near-road environment.

The Vancouver near-road site (NR-VAN) experienced higher concentrations of TRAP including nitrogen dioxide (NO_2), nitric oxide (NO), carbon monoxide (CO), black carbon (BC), fine particulate ($PM_{2.5}$), and ultrafine particles (UFP) compared with other monitoring sites in the region. Higher concentrations were more frequent at the NR-VAN site and there were exceedances of Metro Vancouver's air quality objectives at the near-road monitoring site that were not measured at the other regional monitoring sites. Vehicles emit air contaminants from the combustion of fuel, as well as from brake and tire wear.

The amount by which average concentrations were higher at the near-road site compared with the background site was established for each contaminant, and referred to as the near-road contribution. Vehicle traffic was responsible for an increase of over 5 ppb or 1.4 times more NO_2 at the near-road monitoring station compared with the nearby background station. Fine particulate matter ($PM_{2.5}$) was 2.2 $\mu g/m^3$ greater or 1.4 times more at the near-road station, which is significant since it is more than a quarter of the annual $PM_{2.5}$ objective. Considerable black carbon was also attributed to vehicle sources in the near-road environment with an increase of 1.2 $\mu g/m^3$ or 2.8 times more black carbon. More than half of the additional $PM_{2.5}$ measured at the near-road site was black carbon. While there are no provincial, federal or Metro Vancouver objectives for black carbon, it is a contaminant that has been identified as a health concern as well as having potential climate change impacts. This study presents the first ultrafine particle monitoring results in the region and found nearly twice the amount of UFP in the near-road environment. The near-road site also experienced higher average volatile organic compounds (VOC) than the background site, but lower for most VOC species when compared with a station located near an oil refinery tank farm. Higher concentrations of ethylene, benzene and 1,3-butadiene were measured at the near-road site, which was thought to be influenced by emissions from a gas station adjacent to the site.

Concentrations at the near-road site were higher on weekdays compared with weekends for all TRAP. Lower concentrations on weekends can be explained by large reductions of heavy-duty vehicle traffic. Traffic volumes were found to be highest on weekdays with a negligible reduction on Saturdays (0.3%) and relatively small reduction on Sundays (12%) for light-duty vehicles, and considerable 51% reduction on Saturdays and 72% reduction on Sundays for large heavy-duty vehicles. The greater truck traffic on weekdays is thought to play a key role in near-road contributions. The reduction in contaminant levels on Saturdays can almost entirely be attributed to the reduction in trucks, indicating the disproportionate influence of these vehicles. Sunday was found to have considerably lower truck traffic and lowest concentrations of any day.

The influence of traffic emissions was examined by investigating contaminant concentrations associated with various wind directions observed at the Vancouver near-road station (NR-VAN). The highest peak concentrations were associated with calm wind conditions, although since these conditions occurred relatively infrequently they did not result in a large influence on *average* contaminant concentrations. When winds were not calm, the highest concentrations for most contaminants were measured when the wind was blowing from a nearby major intersection, with five times higher average NO, two times higher CO, NO_2, and UFP, and almost three times higher BC compared with times the wind was blowing from the sector that was not associated with a major roadway. The sector associated with the roadway directly adjacent to the monitoring station was associated with the highest average UFP levels. The upwind sector that was not associated with a major roadway experienced the lowest concentrations, which were similar to those measured at the background station.

Correlation between traffic volume and contaminant concentrations was found to be low when all vehicle types were considered. However, when individual vehicle types were considered separately a strong relationship was found between large heavy-duty vehicles and elevated NO_x, UFP and BC levels. Higher concentrations of NO_x, UFP and BC were found when the proportion of large heavy-duty vehicles using Clark Drive was the highest. The relationship indicates that the highest measurements of UFP and BC are more closely linked with large heavy-duty vehicles, and less so for light-duty vehicles. The traffic volume at the highway site in Toronto was more than ten times greater than the Vancouver truck route site but both measured similar TRAP concentrations. As a result, overall traffic volume may not be as important a factor influencing TRAP measurements as previously thought and that truck route designation and/or proportion of heavy-duty trucks may be more important.

Both the truck route (NR-VAN) in Vancouver and the highway (NR-H401) in Toronto were found to experience considerably higher concentrations of TRAP compared with the downtown near-road station (NR-TOR) in Toronto. Of the three sites, NR-VAN was found to have the highest concentrations of NO, NO_2 and BC, while NR-H401 had the highest concentrations of $PM_{2.5}$ and UFP. There were a number of factors that make it challenging to directly compare TRAP concentrations measured at the three near-road sites operated as part of the study, including: the proportion of heavy-duty trucks to overall traffic volume; the environment immediately surrounding the stations; road configuration and meteorology. For example: the NR-VAN station was downwind of traffic emissions more often than at NR-H401 station due to the road configuration and wind patterns; there was less dispersion and lower winds at NR-VAN compared with NR-H401 due to the surrounding urban environment; the NR-VAN station monitoring station air intake was twice as close to the roadway compared with NR-H401 resulting in 1.6 times less dilution at NR-VAN compared with NR-H401. These factors in combination resulted in higher relative concentrations measured at the NR-VAN site compared with NR-H401.

Key findings of the study are:

- Local traffic strongly influences local air quality
- Highly polluting heavy-duty diesel trucks make a disproportionate contribution
- Vehicle fleet mix matters more than traffic volume
- Wind patterns, street configuration and the built environment considerably influence pollutant levels

To further understand the impacts of traffic-related air pollutants and track changes, Metro Vancouver is committed to continue air quality monitoring at the Vancouver near-road monitoring station. A key recommendation of this study is to develop a program to reduce emissions and exposure to traffic-related air pollutants. This program would draw from a range of strategies, including land use policy, infrastructure design, and transportation management, and would require support from multiple levels of government, from individual municipalities to the provincial level. A key strategy of the program will be increased education about the health impacts of traffic-related air pollution and transportation decisions.

Acknowledgments

Several study partners contributed to this near-road monitoring study. Environment and Climate Change Canada's National Air Pollution Surveillance (NAPS) program contributed monitoring equipment, study guidance and coordination. The Southern Ontario Centre for Atmospheric Aerosol Research (SOCAAR) at the University of Toronto led by Dr. Greg Evans provided project direction, coordination, and operation of NR-TOR site. Dr. Michael Brauer, Dr. Perry Hystad and Alejandro Cervantes provided land-use regression modelling to assist with siting of the Vancouver near-road and background sites. The Ontario Ministry of the Environment, Conservation and Parks conducted operation of the NR-H401 station and contributed to project coordination and troubleshooting. Environment and Climate Change Canada West operated the carbon dioxide and EC/OC analyzers and a traffic camera at NR-VAN.

Several government partners contributed to the Lower Fraser Valley Air Quality Monitoring Network including: Fraser Valley Regional District, Environment and Climate Change Canada and BC Ministry of Environment and Climate Change Strategy. Other partners acknowledged for providing funding to the monitoring network are: Vancouver Airport Authority, Parkland Refining (BC) Ltd., Trans Mountain Pipeline LP, and Vancouver Fraser Port Authority.

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List of Acronyms

AADT	Annual Average Daily Traffic
BC	Black Carbon
BG-VAN	Vancouver background monitoring station
CAAQS	Canadian Ambient Air Quality Standard
CBD	Central Business District
CO	Carbon Monoxide
CO_2	Carbon Dioxide
DPM	Diesel Particulate Matter
EC/OC	Organic carbon and elemental carbon
EMME	Transportation computer model
GIS	Geographic Information System
HEI	Health Effects Institute
H/W	Height to width
ICBC	Insurance Corporation of British Columbia
IARC	International Agency for Research on Cancer
LFV	Lower Fraser Valley
LUR	Land-Use Regression
NAPS	National Air Pollution Surveillance
NO_X	Nitrogen oxides
NO_2	Nitrogen dioxide
NO	Nitric oxide
NR-VAN	Vancouver near-road monitoring station
NR-H401	Toronto Highway 401 near-road monitoring station
NR-TOR	Toronto College Street near-road monitoring station
O_2	Oxygen
O_3	Ozone
PM	Particulate matter
$PM_{2.5}$	Fine particulate matter
RETE	Reducing Exposure to Traffic Emissions

RI	Relative impact
SOCAAR	Southern Ontario Centre for Atmospheric Aerosol Research
TRAP	Traffic-Related Air Pollutants
UFP	Ultrafine particles
US EPA	United States Environmental Protection Agency
VOC	Volatile organic compounds

1. Introduction

In this section an overview is provided along with a description of traffic-related air pollutants, air quality objectives and standards, the study objectives and monitoring scope and discussion of regional trends.

1.1 Overview

Emissions from motor vehicles are one of the largest sources of air contaminants. Multiple traffic-related compounds have been identified with adverse health effects. Living near a major roadway has been identified as a risk factor for a number of respiratory symptoms and cardiovascular problems. Approximately 10 million Canadians live in areas where they are exposed to traffic-related air pollution, about 32% of the total population (Brauer et al., 2013a). In Metro Vancouver, over one million people or nearly half of the population resides near a major roadway.

In 2011, a study commissioned by the federal National Air Pollution Surveillance (NAPS) program summarized the current understanding of air quality near major roadways (SOCAAR, 2011). The study included a review of existing monitoring studies, an analysis to determine the population living near major roadways, and recommendations on the establishment of near-road monitoring stations. One of the outcomes of the study was for NAPS to pursue studies conducted in two of Canada's most populated cities, Toronto and Vancouver.

Metro Vancouver, in partnership with NAPS and the University of Toronto, conducted a Near-Road Air Quality Monitoring Study in the Metro Vancouver region. The study consisted of establishing two monitoring stations equipped with air quality monitoring instruments capable of measuring traffic-related air pollutants. A near-road air quality monitoring station (NR-VAN) was established on Clark Drive in East Vancouver on a busy roadway that traverses a densely populated community. A background air quality station (BG-VAN) was established three kilometers away at Sunny Hill Children's Hospital and was located away from traffic routes for comparative purposes. Monitoring commenced at both monitoring stations on May 1, 2015. The Sunny Hill background station operated for 16 months while the Clark Drive near-road monitoring station continues to operate.

Information from the study will be used to determine public exposure to air contaminants. Together the Metro Vancouver and Toronto studies will inform national recommendations established for near-road monitoring across Canada. The recommendations will incorporate guidance on locating a near-road monitoring site, determine contaminants of concern to be monitored, and evaluate the use of additional non-standard air quality instrumentation. This report is focused on the Metro Vancouver stations, equipment and instruments used, analysis of results and recommendations.

In 2010, the federal National Air Pollution Surveillance (NAPS) program commissioned the Southern Ontario Centre for Atmospheric Aerosol Research (SOCAAR) at the University of Toronto to assess existing information on near-road monitoring and develop recommendations on the design of a near-road network for Canada (SOCAAR, 2011). In 2012, NAPS and the University of Toronto launched a study in collaboration with Metro Vancouver and the Ontario Ministry of the Environment, Conservation and Parks. Three years of planning and development led to the creation of three new near-road monitoring stations in Vancouver and Toronto described in this report. A report was prepared by SOCAAR to inform development of the national near-road monitoring program (SOCAAR, 2019).

The Vancouver study purposes are to:

1. inform the development of recommendations for near-road monitoring;
2. characterize air quality near major roadways; and
3. determine public exposure to traffic-related air pollutants.

This report includes the following objectives:

- determine air pollution increment in near-road environment;
- understand how near-road air quality differs from background and other locations;
- improve overall population exposure estimates to air contaminants;
- investigate relationship of traffic volume and type to air contaminant concentrations;
- evaluate the seasonality of the near-road environment;
- compare near-road environment with regional air quality stations; and
- inform development of actions and strategies to reduce exposure.

Regional air quality in Metro Vancouver has improved steadily over the past several decades, in part because of stricter vehicle emission standards and the AirCare vehicle emissions inspection program that have reduced major air contaminants that cause smog and harm health. Despite local improvements in vehicle emissions, Canada's urban areas, population and use of vehicles continue to grow.

1.2 Traffic-Related Air Pollutants (TRAP) and Health Impacts

Motor vehicles emit traffic-related air pollutants (TRAP) as a result of the combustion of fuel (mainly gasoline and diesel) and brake and tire wear. These air pollutants can cause adverse human health effects. People who live, work, or play near major roads (roads with an average daily traffic volume of 15,000 or more) are exposed to higher concentrations of traffic-related air pollution.

In Canada 10 million people (32% of the population) live within 250 m of a major road, and in BC the proportion is slightly higher (37% of the population). Residential location is considered a reasonable proxy for an individual's overall exposure to TRAP and this data tends to be the most available and analyzed (Brauer et al., 2012). In addition, school and work locations are important determinants of exposure to TRAP. Some sub-populations are at increased risk such as people with long commutes in traffic and people exercising or engaging in active transport (e.g. cycling) in proximity to TRAP (Brauer et al., 2012).

It is well known that concentrations of traffic-related air pollutants decrease with distance from roadways. Numerous near-road air pollutant monitoring studies show that elevated concentrations of traffic-related pollutants such as ultrafine particles (UFP), black carbon (BC), nitrogen oxides (NO_x), and carbon monoxide (CO) generally occur within 50 m and background levels are reached between 150 and 500 m from the road. A simplified graphic is provided in Figure 1.1 that depicts a generalized concentration profile near and away from the roadway. The figure highlights that the highest concentrations are present on the roadway and decrease as you move further away from the traffic emissions.

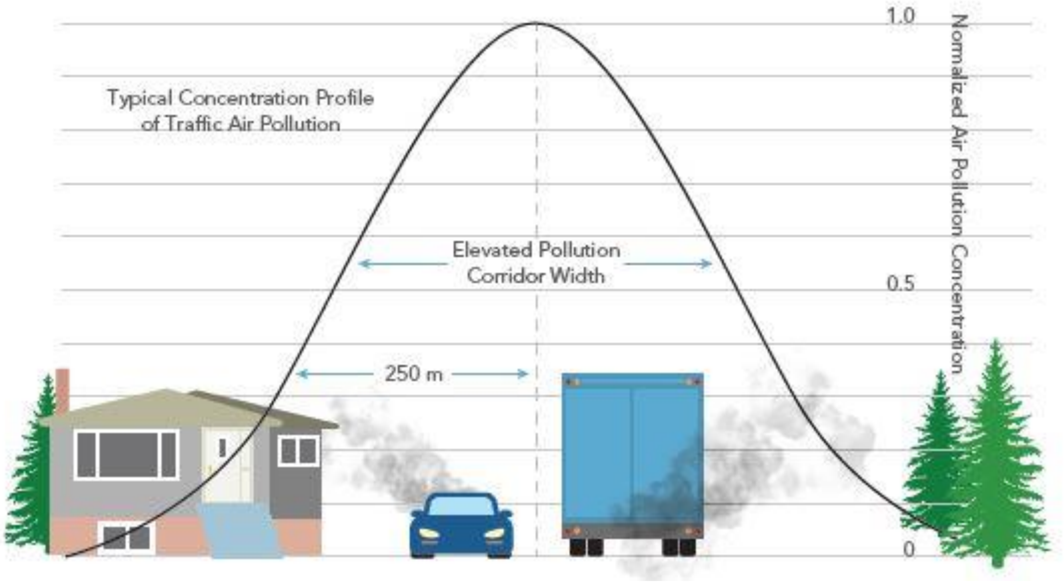


Figure 1.1: Typical near-road TRAP profile.

The Health Effects Institute (HEI) commissioned an international panel to critically review the body of existing evidence and literature on health effects of exposure to TRAP (HEI, 2010). The institute compiled and analyzed information on TRAP and their health effects, and used a series of criteria from the United States Surgeon General to assess the health evidence and health outcomes. They concluded that exposure to TRAP is a public health concern deserving of public attention. A subsequent Canadian study (Brauer et al., 2012) updated HEI's findings to include Canadian studies, and concluded that there is a causal relationship between exposure to TRAP and exacerbation of asthma, as well as onset of childhood asthma. The authors stated that evidence also suggests the potential for causal relationships between exposure to TRAP with cardiovascular mortality and morbidity, non-asthma respiratory symptoms and impaired lung function, and lung cancer. The study concludes that **Canadian scientific data clearly indicates that exposure to TRAP is a significant public health issue in Canada.**

A recent study found that Canada has the third highest overall rate of traffic-related childhood asthma (per 100,000 children) cases behind only Kuwait and the United Arab Emirates, among 194 countries analyzed (Achakulwisut et al., 2019). The high rate in Canada is influenced by traffic-related pollution levels and overall asthma rates.

A study by Anenberg et al., 2019 estimated that air emissions from transportation in Canada are responsible for 1,400 deaths and 12 billion (USD) dollars of health damages. The study employed models on vehicle emissions, air pollution, and epidemiological models to determine the impacts of transportation emissions on air quality and public health. The study examined the transportation sector as a whole, evaluating specific subsectors: on-road diesel vehicles, on-road non-diesel vehicles, shipping, and non-road mobile sources that include agricultural and construction equipment and rail transportation. On-road diesel vehicles were estimated to be responsible for 37% or 518 deaths and on-road non-diesel vehicles 28% or 392 deaths in Canada. The health burden was likely underestimated in the study since only two traffic-related air pollutants, $PM_{2.5}$ and O_3, were considered and the methodology excluded other important health impacts including noise, physical activity effects, road injuries, resuspension of road dust, release of particles from brake and tire wear, evaporative emissions, and fuel life-cycle emissions.

Specific components of TRAP are associated with particular health impacts (Stantec, 2013). For example, particulate matter aggravates respiratory and cardiovascular diseases, reduces lung function, increases respiratory symptoms, and can lead to premature death. There is also further evidence both short-term exposure and chronic long-term exposure can affect heart attack rates (Mustafic et al., 2012). Black carbon health impacts are closely linked with diesel and linked with cancer risk (Health Effects Institute, 2010). Diesel vehicles (e.g., heavy-duty trucks) are considered the most critical source of TRAP; diesel-exhaust particles are the most harmful vehicle related contaminants and a harmful human carcinogen (BC Ministry of Environment, 2012). Although diesel engines are more fuel-efficient than gasoline engines, they emit considerably more particulate matter per vehicle or per litre of fuel burned. Particulate matter (PM) emissions from heavy-duty diesel vehicles are 10 times greater than from light-duty gasoline vehicles (Dallmann and Harley, 2010).

Measurement of a number of key contaminants can be used to represent exposure to overall traffic emissions. Several of these contaminants were monitored continuously: carbon monoxide (CO), nitrogen oxides (NO_X), ground-level ozone (O_3), fine particulate ($PM_{2.5}$), and black carbon (BC). Non-continuous daily samples were collected on filters and/or in canisters. The samples were analysed at a federal laboratory for a selection of volatile organic compounds (VOC) and chemicals contained within $PM_{2.5}$. The near-road and background monitoring sites in Vancouver also measured ultrafine particles (UFP) which are not routinely measured in the region. The near-road monitoring study was the first time UFP has been measured in Metro Vancouver, due to the availability of new monitoring technology and emerging interest in the health effects of these particles.

1.2.1 Nitrogen oxides (NO_x)

Oxides of nitrogen (NO_x) include nitric oxide (NO) and nitrogen dioxide (NO_2). Both are produced by the high temperature combustion of fossil fuels or biomass. Common NO_X sources include boilers, building heating systems and internal combustion engines. In the Lower Fraser Valley (LFV), transportation sources account for approximately 63% of NO_X emissions, with stationary and area sources contributing the remainder. NO is predominant in combustion emissions, and rapidly undergoes chemical reactions in the atmosphere to produce NO_2. NO_2 is a reddish-brown gas with a pungent, irritating odour. Nitrogen oxides play a key role in the formation of smog (ground-level ozone) and secondary $PM_{2.5}$.

NO_2 has direct and indirect effects on human health and the environment. There is strong evidence that NO_2 causes respiratory effects and contributes to early mortality at ambient concentrations commonly found in Canada, particularly for the young, elderly and those with pre-existing respiratory conditions. Health Canada estimated that 1,300 deaths per year in Canada can be attributed to acute exposure to concentrations of NO_2 above background levels (Health Canada, 2017). The scientific evidence indicates that NO_2 is a non-threshold contaminant, meaning that exposure even at low concentrations can cause health effects.

In addition, NO_2 can damage ecosystems through acid rain and eutrophication (when bodies of water become overly enriched with minerals and nutrients). Secondary $PM_{2.5}$ formed by reactions of NO_X with other air contaminants also impairs visual air quality which can result in economic losses for tourism and impact recreational activities.

1.2.2 Carbon monoxide (CO)

Carbon monoxide (CO) is an odourless gas. Carbon monoxide is produced by the incomplete combustion of fuels containing carbon. The principal source within Metro Vancouver is motor vehicle emissions with a large percentage coming from the transportation sector.

When inhaled, CO reduces the body’s ability to use oxygen. Health effects associated with relatively low-level, short-term exposure to CO include decreased athletic performance and aggravated cardiac symptoms. Long-term exposure to low concentrations may cause adverse effects in people suffering from cardiovascular disease.

1.2.3 Ground-level ozone (O_3)

A primary component of smog, ground-level ozone is not directly emitted into the atmosphere, but is created when NOx and volatile organic compounds react in the presence of sunlight. Close to emission sources, ozone is quickly consumed by NO. As a result, ozone concentrations are expected to be lower in areas like the near-road environment which contain significant combustion sources of NO.

Ground-level ozone has been linked with a broad spectrum of human health effects. Because of its reactivity, ozone can injure biological tissues and cells. Exposure to ground-level ozone for even short periods at relatively low concentrations has been found to significantly reduce lung function in healthy people during periods of exercise. This decrease in lung function is generally accompanied by other symptoms including tightness of the chest, pain and difficulty breathing, coughing and wheezing.

There is strong evidence that ozone adversely affects human health even at low concentrations, particularly for the young, elderly and those with heart and lung conditions. Health Canada estimated that 3,600 deaths per year in Canada can be attributed to acute and chronic exposure to concentrations of ozone above background levels (Health Canada, 2017). The scientific evidence indicates that ozone is a non-threshold contaminant, meaning that exposure even at low concentrations can cause health effects.

In addition, ozone is also a short-lived climate forcer and contributes to climate change. Because it is a very strong oxidant, ozone can also damage ecosystems and vegetation, reduces crop yields and damages buildings and materials.

1.2.4 Fine particulate matter ($PM_{2.5}$)

The term '$PM_{2.5}$', or fine particulate matter, refers to airborne particles with an aerodynamic diameter of 2.5 micrometres (µm) or less. Fine particulate matter is emitted from a variety of sources including industry, transportation, heating and non-road engines. Some fine particulate may be directly related to specific sources (e.g., black carbon or diesel particulate matter from diesel fuel combustion), but studies indicate that a considerable proportion of ambient fine particulate is also created in the atmosphere by the reaction of other air contaminants.

Exposure to fine particulate is one of the major air quality and health issues in Metro Vancouver. $PM_{2.5}$ are small enough to be breathed deeply into the lungs, resulting in impacts to both human respiratory and cardiovascular systems. Short-term exposure to airborne particles at the levels typically found in urban areas in North America is associated with a variety of adverse effects. Particulates can irritate the eyes, nose and throat and cause coughing, breathing difficulties, reduced lung function and an increased use of asthma medication. In addition, it is a major cause of visibility degradation.

For fine particulate matter, there is robust scientific evidence of health effects at very low concentrations and no evidence of an exposure threshold: that is, any incremental increase in $PM_{2.5}$ concentration is associated with an increased risk of adverse health outcomes. Health Canada estimated that 9,500 deaths per year in Canada can be attributed to chronic exposure to above-background concentrations of fine particulate matter, $PM_{2.5}$ (Health Canada, 2017).

1.2.5 Black carbon (BC)

Black carbon (BC) is carbonaceous material formed by the incomplete combustion of fossil fuels, biofuels, and biomass, and is emitted directly in the form of fine particles ($PM_{2.5}$). Non-road engines (primarily diesel fueled), heavy duty vehicles, rail and marine vessels are significant sources of BC emissions. Other significant sources in the region include agricultural burning, open and prescribed burning, wildfires and residential heating.

In many cities Diesel Particulate Matter (DPM) is a significant contributor to $PM_{2.5}$ levels. In 1998, following a 10-year scientific assessment process, California Air Resources Board identified DPM as a toxic air contaminant based on its potential to cause cancer and other health problems, including respiratory illnesses, and increased risk of heart disease. Subsequent to this action, research has shown that DPM also contributes to premature deaths (CARB, 2011). In 2012, the International Agency for Research on Cancer (IARC), which is part of the World Health Organization, classified diesel engine exhaust as carcinogenic to humans, based on sufficient evidence that exposure is associated with an increased risk for lung cancer (IARC, 2012). In Metro Vancouver, DPM is responsible for around two-thirds of the lifetime cancer risk associated with air pollution (Sonoma, 2015 and Metro Vancouver, 2009).

Formed during incomplete combustion, black carbon is the solid fraction of $PM_{2.5}$ that strongly absorbs light and converts that energy to heat. When emitted into the atmosphere or deposited on ice or snow, black carbon can enhance global temperature change, melting of snow and ice, and change precipitation patterns (International Council on Clean Transportation, 2009). Black carbon can be used as an indicator for diesel fuel combustion and wood smoke.

1.2.6 Volatile Organic Compounds (VOC)

Volatile Organic Compounds (VOC) refers to a combination of organic chemicals. A large number of chemicals are included in this group but specific compounds are generally present at relatively low concentrations in air compared to other common air contaminants. Gaseous VOC present in the air can originate from direct emissions and from volatilization (i.e., changing into the gas phase) of substances in the liquid or solid phase. Locally, some VOC can be contaminants found in urban smog and are also precursors of other contaminants present in smog such as ozone and fine particulates. VOC species have a range of photochemical reactivity, and thus potential to lead to ground-level ozone formation (e.g., ethylene). Other VOC, such as benzene, can pose a human health risk.

1.2.7 Ultrafine Particles (UFP)

Ultrafine particles (UFP) consists of a combination of suspended solids and liquid droplets having aerodynamic diameters less than 0.1 microns (100 nanometers). These particles are measured based on their numbers (units of $\#/cm^3$) in the atmosphere rather than fine particulate matter that is measured based on its mass ($\mu g/m^3$). There are several sources of UFP, including the manufacturing and combustion sources as well as precursors for secondary particle formation. It is generally recognized that smaller particles are more harmful to human health. Unlike larger particles, UFP can penetrate pulmonary tissue, enter the bloodstream, and circulate throughout the body.

1.3 Air Quality Objectives and Standards

Air quality objectives and standards are used as benchmarks to characterize air quality. Metro Vancouver's ambient air quality objectives are shown in Table 1.1. The objective or standard is achieved if the ambient concentration is lower than (i.e., better than) the objective. Table 1.1 contains two sets of objectives for CO, NO_2 and O_3. The values in brackets labelled with an asterisk denote more stringent objectives that were adopted by Metro Vancouver's Board in November 2019. Air quality measurements presented in this report were collected before the more stringent objectives were adopted and are compared to objectives in effect at the time of measurement. There are no regional, provincial or federal objectives or standards for black carbon or ultrafine particles.

Table 1.1: **Metro Vancouver's ambient air quality objectives.**

Air Contaminant	Averaging Period	Ambient Air Quality Objective[a]	
		µg/m³	ppb
Carbon monoxide (CO)	1-hour	30,000 (14,900*)	26,200 (13,000*)
	8-hour[b]	10,000 (5,700*)	8,700 (5,000*)
Nitrogen dioxide (NO_2)	1-hour	200 (113*[c])	106 (60*[c])
	Annual	40 (32*)	21 (17*)
Sulphur dioxide (SO_2)	1-hour	183	70
	Annual	13	5
Ozone (O_3)	1-hour	161	82
	8-hour	128[b] (122*[d])	65 (62*[d])
Inhalable particulate matter (PM_{10})	24-hour	50[b]	
	Annual	20	
Fine particulate matter ($PM_{2.5}$)	24-hour	25[b]	
	Annual	8 (6[e])	
Total reduced Sulphur (TRS)	1-hour (acceptable)	14	10
	1-hour (desirable)	7	5

*Metro Vancouver's Board adopted more stringent air quality objectives in November of 2019.

[a] Except where noted, Metro Vancouver objectives are "not to be exceeded", meaning the objective is achieved if 100% of the validated measurements are at or below the objective level.

[b] Achievement based on rolling average.

[c] Achievement based on annual 98th percentile of the daily maximum 1-hour concentration, averaged over three consecutive years.

[d] Achievement based on annual 4th highest daily maximum 8-hour average concentration, averaged over three consecutive years.

[e] Metro Vancouver's annual $PM_{2.5}$ planning goal of 6 µg/m³ is a longer term aspirational target to support continuous improvement.

2. Study Design

In this section a description of the monitoring stations is provided, the study periods for various analyses and monitoring methods are described and a discussion of population near major roads in Metro Vancouver is provided.

2.1 Monitoring Sites

Two monitoring stations were established in Vancouver equipped with air quality monitoring instruments capable of measuring traffic-related air pollutants in 2015. A near-road monitoring station was established on Clark Drive (NR-VAN) while a background air quality station (BG-VAN) was established approximately three kilometers away at Sunny Hill Children's Hospital on Slocan Street, both stations located in East Vancouver. The near-road monitoring station was located alongside a busy roadway that transects a densely populated community. The background station was located away from heavy traffic routes for comparative purposes and was established to measure typical levels experienced in Vancouver (Figure 2.1) away from traffic emissions.

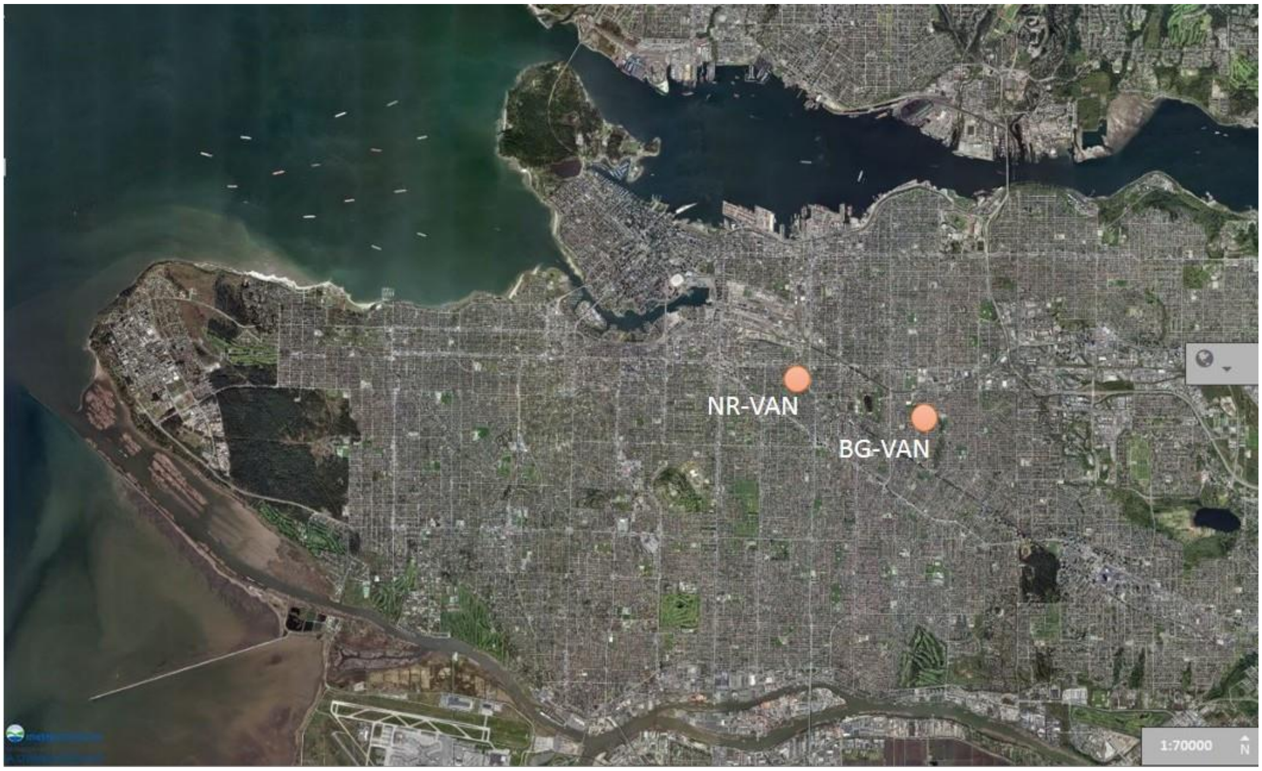


Figure 2.1: Near-road monitoring station (NR-VAN) on Clark Drive and background monitoring station (BG-VAN) at Sunny Hill Children's Hospital in East Vancouver.

2.1.1 Clark Drive Near-Road Monitoring Station

This subsection includes a site description, rationale for site location, and further description of the Clark Drive near-road monitoring station design.

2.1.1.1 Site Description

The Clark Drive near-road monitoring station (NR-VAN) is located in East Vancouver between 11th and 12th Ave on Clark Drive. The location was selected based on the high traffic volume experienced at this location, the truck route designation of Clark Drive and dense population of the surrounding neighbourhoods. The near-road site is adjacent to Clark Drive which is aligned north-south. Clark Drive has 6 travel lanes with about 33,000 vehicles per day. Within 100 metres of the station there is another major road to the south, 12th Avenue, which is aligned east-west. Within 250 metres there is a third major roadway to the north (East Broadway) that is aligned east-west. A discussion of the rationale for the siting of the station is provided in Section 2.1.1.2.

The station is located in a neighbourhood that is predominately zoned as two family dwellings (RT-5). Portions of Clark Drive are zoned as commercial (C-1 and C-2) while the Broadway corridor, an arterial road near the station, is comprised of multiple dwelling (RM-4) zoning. There is a park to the northwest of the station and two gas stations, one located adjacent to the station property to the south and one across Clark Drive to the southeast. The location in relation to the surrounding neighbourhood is shown in Figure 2.2.

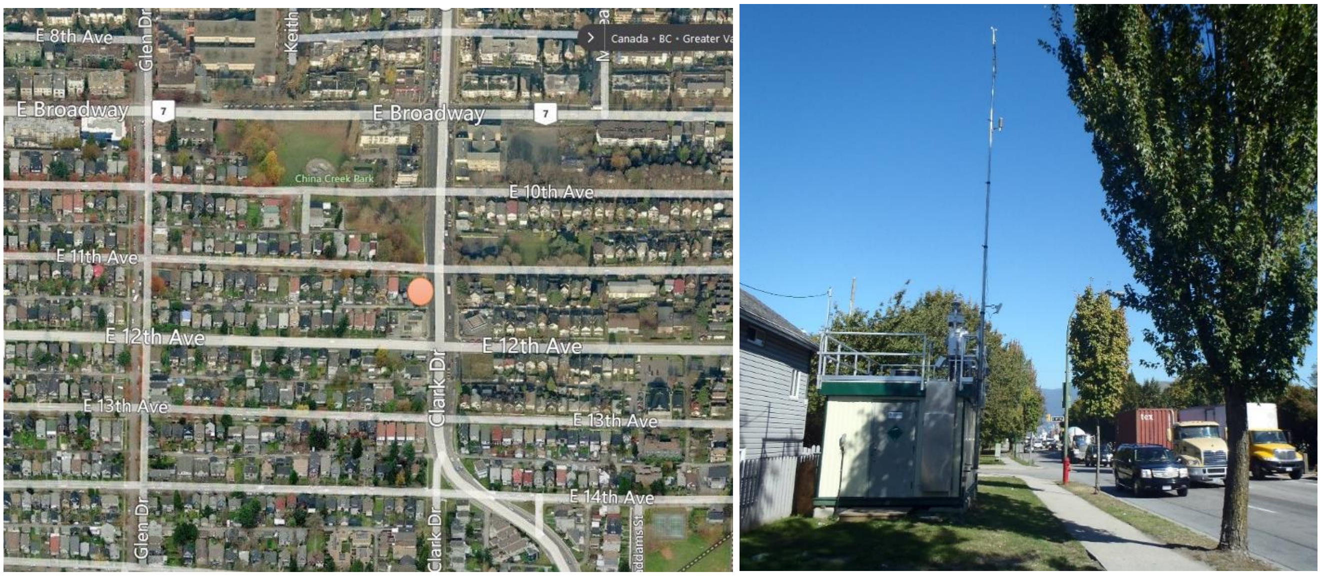


Figure 2.2: Map and photo showing near-road monitoring station in East Vancouver on Clark Drive (NR-VAN).

The station is composed of a shelter and meteorological tower (shown in Figure 2.2). The shelter is 3 metres by 6 metres (10 by 20 feet) and the tower is 12 metres tall mounted to the side of the shelter. The roof of the shelter is flat and served as a mounting platform for the integrated sampling equipment. The inside of the shelter was air conditioned and housed the continuous air quality monitors, data logging computer and communications equipment. The shelter is attached to a foundation and power is provided to the station via underground cabling. The exterior of the shelter includes a ladder on the south side with a locking restraint to prevent access by non-authorized personal. The rooftop includes a safety railing.

2.1.1.2 Location Selection

To aid in identifying candidate locations suitable for a near-road monitoring station within the region, an analysis was performed to examine traffic volumes and population densities throughout the region. Metro Vancouver identified areas of the region with high traffic volumes and population densities using a Geographic Information System (GIS). Output from a transportation computer model (EMME), used to predict travel demand patterns, was obtained from TransLink and imported into GIS. The model output was used to identify the top 25% busiest roads in the region. Roads with a “separated roads” designation (e.g., Highway 1 and Highway 99) were excluded since they were thought not to represent the common arterial roadways that transverse Metro Vancouver. In Figure 2.3a the road network’s traffic volume is shown with the top 25% of busy roads coloured from green (lower traffic volumes) to red (higher traffic volumes).

To determine the population density near these busy roadways in the region, the population was summed within a 200 m roadway buffer, and divided by buffer area to identify population density close to the top 25% of busy roads. Figure 2.3b shows the population density with red representing the highest density (i.e., population per square kilometer) and green representing the lowest density.

Finally, to determine where the busiest roads were that traversed dense populations a third figure was produced whereby traffic volume was multiplied by population density to get the “exposure-weighted” traffic volumes. These are shown in Figure 2.3c where red represents a busy roadway through a dense population.

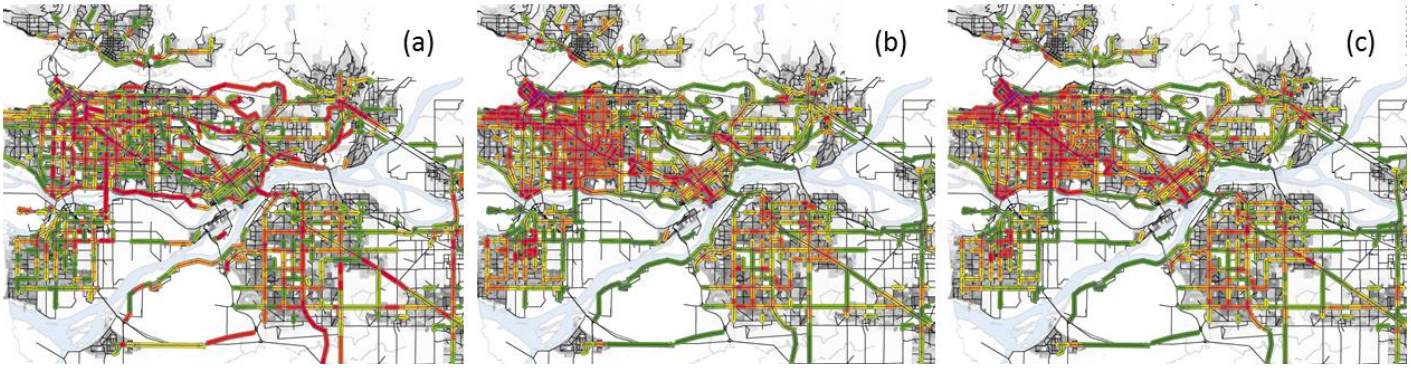


Figure 2.3: (a) Traffic volume identifying the top 25% of busy roads in the region, (b) population density along the roads in the region, and (c) traffic volume weighted by population density. Green denotes the 1st decile, yellow the 5th decile, and red the 10th decile.

As shown in the figures, the City of Vancouver has the greatest number of highly trafficked roadways and some of the highest traffic volumes on major roadways that traverse densely populated neighbourhoods. While a location for the near-road monitoring study was sought in the City of Vancouver, it is anticipated that measurements collected in this study will be representative of major roadways in other Metro Vancouver municipalities and the results will assist in understanding the public's exposure to air contaminants in other municipalities. Section 2.4 explores the population near major roadways in more depth.

Using the "exposure-weighted" traffic volume figure as a guide (Figure 2.3c), aerial photos were reviewed to identify candidate locations for the near-road monitoring station. In total, 35 sites were short-listed and site visits were conducted for each of these sites.

The Clark Drive site was identified as the most suitable site for near-road study given it was located on a key traffic corridor, a truck route, in a densely populated neighbourhood and met siting criteria including access to power, within 20 m of the roadway, good exposure, and sufficient space for an air monitoring shelter.

Prior to finalizing the monitoring location, a suite of Land-Use Regression (LUR) models were utilized to confirm that the location selected was representative of the high concentrations of TRAP in the region (Brauer et al., 2013a). Five LUR models were developed to include consideration of black carbon, fine particulate, ultrafine particles, nitrogen dioxide and nitric oxide and identified areas were the highest concentrations were predicted. Further, the five LUR models were merged to identify areas where the highest concentrations from each model overlap. The overlap of the five LUR models is shown in Figure 2.4 where pink denotes the area where all five models are predicted to have the highest 10% of concentrations.

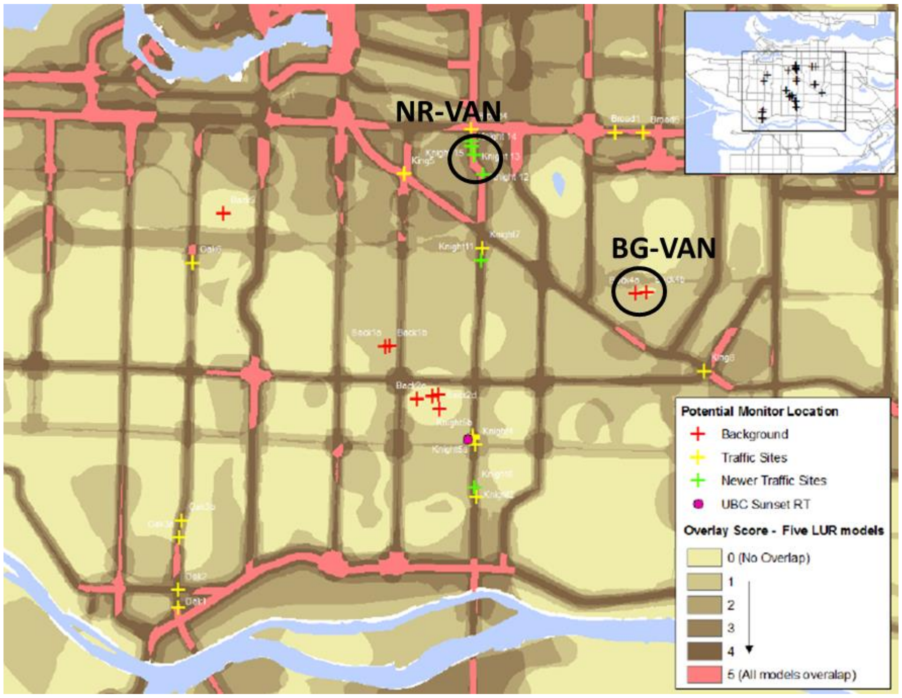


Figure 2.4: Overlay of five land-use regression models showing the intersection of the top decile concentrations from all models.

2.1.1.3 Station Design

The monitoring station is located on a 25-foot wide empty lot adjacent to Clark Drive. The station was sited using guidance from the Design of a Near-Road Monitoring Strategy (SOCAAR, 2011) and located within 20 metres of the roadway. The distance from the roadway is relatively close with the monitoring inlets a distance of 5.7 metres away from curb lane (Figure 2.2).

There are two instrument racks inside the station along with two long benches lining the north and east walls (Figure 2.5a). One instrument rack houses the station computer and internet communications hardware. The second instrument rack has the O_3, CO, and NO_x analyzers and the multi-gas calibrator. The VOC sampler and particulate instruments including two UFP monitors, 7-channel black carbon unit, EC/OC analyzer and continuous $PM_{2.5}$ analyzer are located on the two benches. The CO_2 instrument is mounted on the wall above the bench. The meteorological data logger (Campbell Scientific CR800) is also mounted on the wall. The equipment used at the station is provided in Table 2.1 along with the measurement heights.

The inlets protruding from the roof are all located in line with the roadway so that the inlets are all the same distance from Clark Drive. The layout of exterior equipment and inlets is shown in Figure 2.5b. Integrated samplers (two dichotomous particulate matter samplers and one $PM_{2.5}$ speciation sampler) are on the roof. Two sets of meteorological instrumentation are operated at the station. A meteorological mast is attached to the side of the shelter and extended twelve metres from ground level. Standard network instruments were mounted on the tower while an “all-in-one” meteorological sensor was mounted at inlet height on a short post attached to the shelter roof railing.

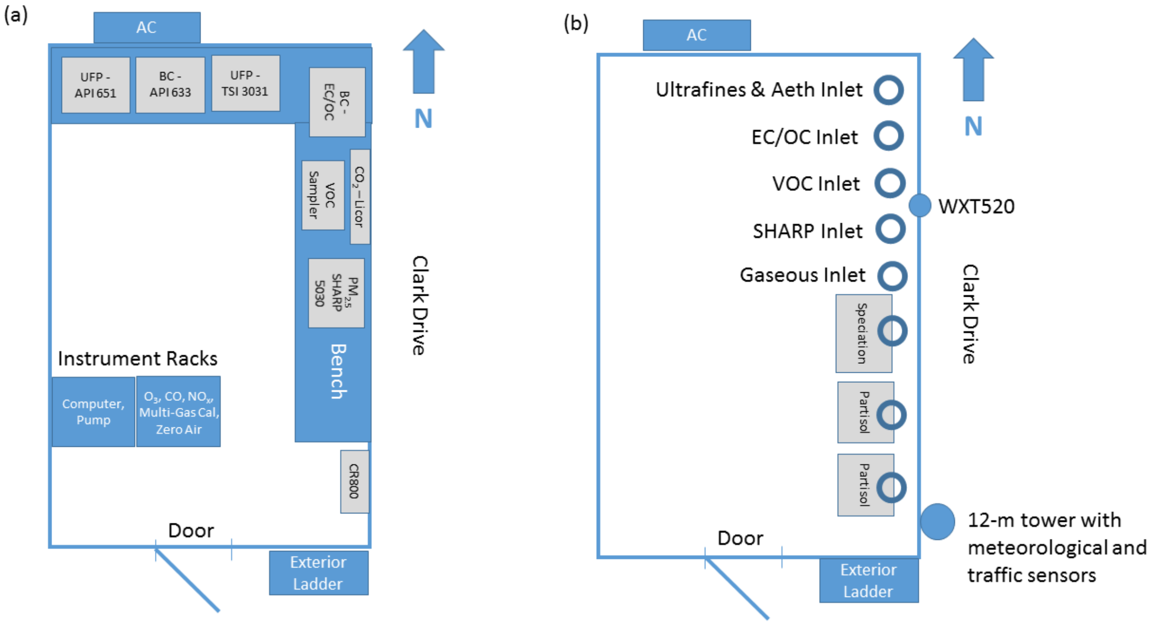


Figure 2.5: Interior (a) and exterior (b) layout of Clark Drive shelter.

Table 2.1: Air quality parameters measured at Clark Drive station (NR-VAN).

Parameter	**Instrument/ model**	**Inlet**	**Inlet/ Instrument height (m)**	**Instrument location/mount**
Continuous Analyzers				
UFP Size Distribution	TSI 3031	Stainless steel Inlet tube	4.8	Bench
UFP Particle Counter	API 651		5.0	Bench
Black Carbon	Aethalometer Magee API 633-7		4.8	Bench
EC/OC	Sunset Labs		4.8	Bench
PM$_{2.5}$ Mass	SHARP 5030		5.0	Bench
NO$_x$	Thermo 42i	Teflon gas Inlet	4.8	Rack
CO	API 300EU			Rack
O$_3$	Thermo 49i			Rack
CO$_2$	Li-Cor 840-A			Wall mounted
Integrated Samplers				
PM$_{2.5}$ Speciation	Met-One SASS		5.0	Roof
PM Dichot (2)	Partisol 2000i-D		4.9	Roof
VOC	Summa Canisters		4.7	Roof
Meteorological and Traffic Instrumentation				
Traffic sensor	Wavetronix-HD Count Station		4.9	
Wind speed	Met One 010C		12.3	Tower mounted
Wind direction	Met One 020C		12.3	
Air temp and RH	HMP155		9.9	
Wind speed Wind direction Air temp and RH Pressure	Vaisala WXT520		5.0	Mounted off short post on railing

2.1.2 Sunny Hill Background Site

This subsection includes a description of the Sunny Hill background monitoring site and further description of the station design.

2.1.2.1 Site Description

A background monitoring station (BG-VAN) was established at Sunny Hill Children's Hospital in East Vancouver. The background station was sited to measure air quality at a nearby site to Clark Drive but located away from traffic emissions. The station was located in a predominately residential neighbourhood with the exception of the hospital property in which the station was situated. The location in relation to the surrounding neighbourhood is shown in Figure 2.6. The air quality shelter was located on the northwest corner of the property on a grassy opening in a treed area of the hospital. Since the site was surrounded by tall trees and posed challenges for measuring representative winds, a second site was used where a meteorological tower was deployed on a nearby roof. The free-standing 10-metre tower was situation on the roof of the hospital approximately 110 metres away from the air quality shelter.

The nearest street, Slocan Street, is a bike route and a quiet residential street with traffic calming measures along the corridor. A land-use regression model was used to verify that the location was in fact removed from traffic influences (Figure 2.4).

Figure 2.6: Map and photo of background air quality monitoring station (square) and meteorological tower (circle) in East Vancouver (BG-VAN) at Sunny Hill Children's Hospital.

2.1.2.2 Station Design

The air quality shelter was supplied by NAPS and consisted of a portable trailer with the dimensions of 8 feet by 12 feet (shown in Figure 2.6). The roof of the shelter was flat and served as a mounting platform for the integrated sampling equipment. The inside of the shelter was air conditioned and housed the continuous air quality monitors, data logging computer and communications equipment. The equipment used at the station is provided in Table 2.2 along with the measurement heights.

Table 2.2: Air quality parameters measured at the background station at Sunny Hill Hospital (BG-VAN).

Parameter	Instrument/ model	Inlet	Inlet/ instrument height (m)	Instrument location/mount
Continuous Analyzers				
UFP Size Distribution	TSI 3031	Stainless steel Inlet tube	5.4	Bench
UFP Particle Counter	API 651		5.4	Bench
Black Carbon	Aethalometer Magee API 633-7		5.4	Bench
PM$_{2.5}$ Mass	SHARP 5030		5.8	Bench
NO$_x$	Thermo 42i	Teflon gas Inlet	5.4	Rack
CO	API 300EU			Rack
O$_3$	Thermo 49i			Rack
Integrated Samplers				
PM$_{2.5}$ Speciation	Met-One SASS		5.6	Roof
PM Dichot	Partisol 2000i-D		5.6	Roof
VOC	Summa Canisters		4.7	Roof
Meteorological Instrumentation				
Wind speed	Met One 010C		18	Mounted on tower on hospital roof
Wind direction	Met One 020C		18	
Air temp and RH	HMP155		16	
Precipitation	OTA KEIKI OTA 34-T tipping bucket		8	On hospital roof
Wind speed	Vaisala WXT520		5.4	Air quality shelter (mounted off short post on roof)
Wind direction				
Air temp and RH				
Pressure				

2.1.3 Metro Vancouver Comparison Sites

Metro Vancouver operates an extensive ambient air quality monitoring network with 31 air quality monitoring stations located throughout the Lower Fraser Valley (Metro Vancouver, 2019). The monitoring network collects air quality data from Horseshoe Bay to Hope every hour of the day, seven days a week. It provides the means to track air quality trends, measure the performance of air management programs, identify problem areas, inform the development of new policies and actions, and provide data to the public. Operated by Metro Vancouver, the monitoring network is one of the most comprehensive in the world. Current air quality information is available at Metro Vancouver's website www.airmap.ca. Several network sites were selected due to their proximity to the near-road station and used for comparison in this study. These include Vancouver-Downtown, Burnaby-Kensington Park, North Vancouver- Second Narrows, Port Moody, Burnaby South, Burnaby-Burmount, North Burnaby, North Vancouver-Mahon Park and Richmond-Airport. A description of these stations is provided in Table 2.3 and their locations are shown in Figure 2.7.

Table 2.3: Existing air quality monitoring network stations used in the study.

ID	Site Name	Site Characteristics and Description
T1	Vancouver-Downtown	Located in the Robson Square Complex in downtown Vancouver, this station is situated in an area of dense traffic surrounded by mixed multiple-story and high-rise residential and commercial buildings.
T4	Burnaby-Kensington Park	This station, located in North Burnaby, is situated in a mixed neighbourhood which includes residential, industrial, commercial, and park land-use which is typical of other surrounding areas.
T6	North Vancouver-Second Narrows	Located in the District of North Vancouver near Second Narrows Bridge in a commercial and industrial setting situated on an active works yard adjacent to many nearby emission sources.
T9	Port Moody	Located in Rocky Point Park within an area that has experienced a reduction in industrial sources and an increase in mobile and residential sources over the last two decades.
T18	Burnaby South	Located at Burnaby South Secondary School, this monitoring station is established in a residential area on the top of the south slope of Burnaby.
T22	Burnaby-Burmount	This site is located on the southern slope of Burnaby Mountain adjacent to a residential neighbourhood to the south and a petroleum products storage tank farm to the northeast.
T24	North Burnaby	This site is located in a park adjacent to a petroleum products storage tank farm and product distribution center of an oil refinery and the neighbouring community.
T26	North Vancouver-Mahon Park	This station measures air quality in the residential areas of central North Vancouver. On bench-land above the harbour and away from major traffic corridors, this station is situated so as to represent air quality for a wider region along the North Shore.
T31	Richmond-Airport	Located at Vancouver International Airport on Sea Island in Richmond, this station is near the east end of a major take-off runway, between airport operations and the residential community of Burkeville to the east.

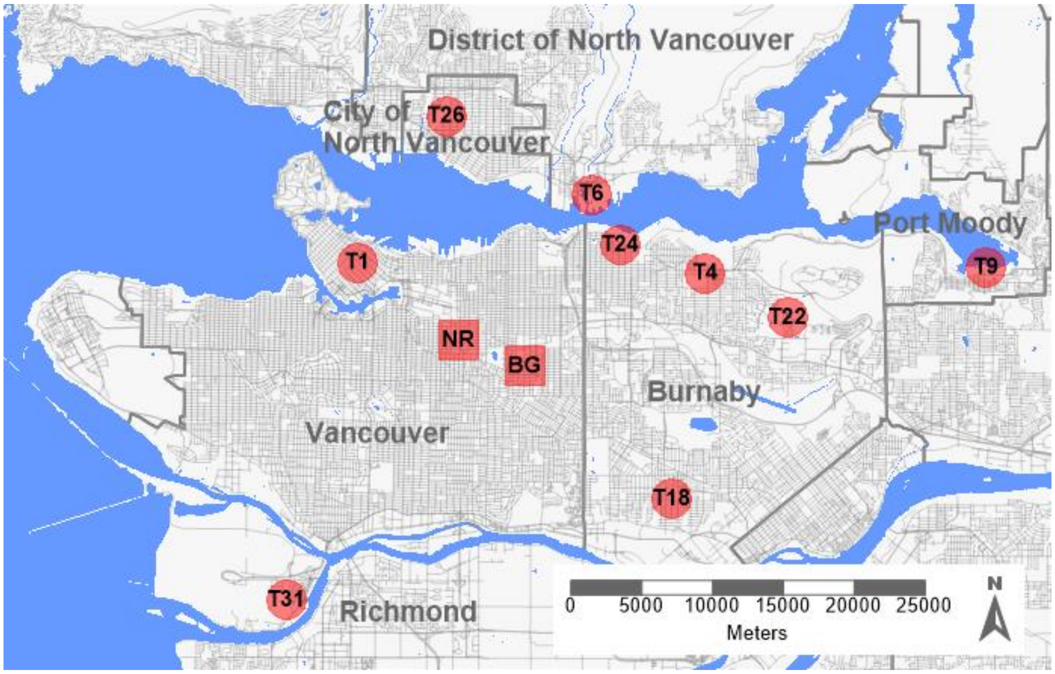


Figure 2.7: Location of near-road study sites (square) and network stations (circle).

2.1.4 Other Near-Road Stations in National Study

The near-road monitoring study conducted in Toronto consisted of the establishment of two near-road monitoring stations. A near-road monitoring station (NR-H401) was established by the Ontario Ministry of Environment on Highway 401 in Toronto, Ontario. The area surrounding the site can be described as open terrain. The station was located 14 metres from the roadside. The highway has 18 lanes with about 365,000-410,000 vehicles per day. Highway 401 has been described as the busiest highway in North America with some of the highest measured traffic volumes. The station location is shown in Figure 2.8.

The other near-road monitoring station was established at the University of Toronto in a building located on College Street (NR-TOR). The monitoring equipment was housed in a room in the building. The inlets were located 15 m from the roadside and 3 m above ground level. The monitoring site was located within a street canyon with four story buildings to the north and buildings varying between 3 -5 stories to the south. College street at the monitoring site is a four lane roadway that experiences traffic volumes ranging from 16,000 to 25,000 vehicles per day. The station location is shown in Figure 2.8.

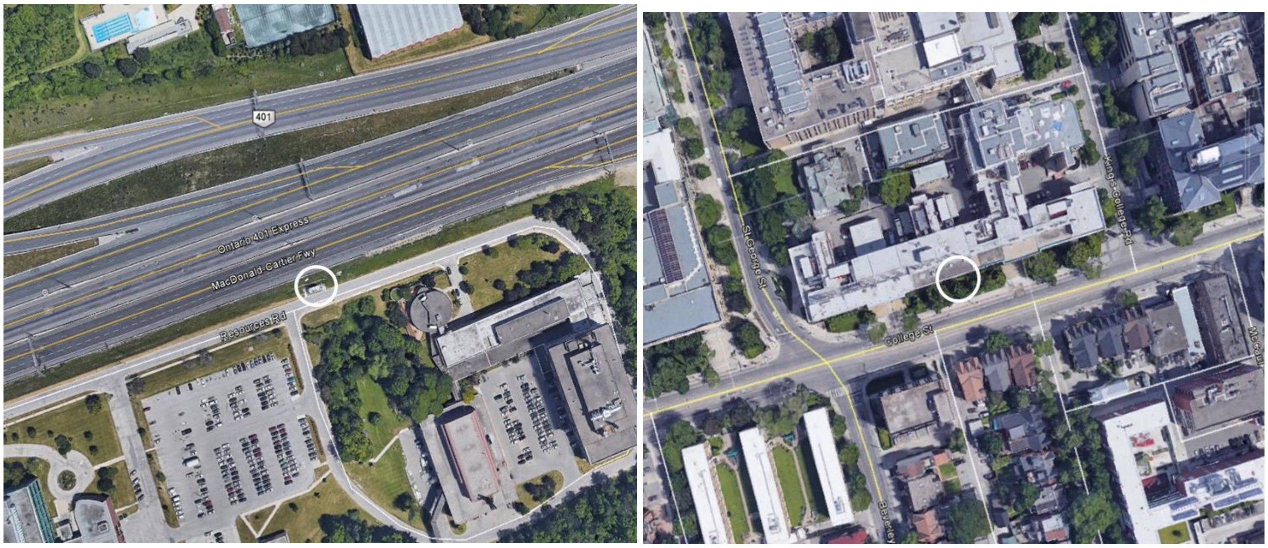


Figure 2.8: Location of near-road study sites, NR-H401 (left) on Highway 401, and NR-TOR (right) on College Street in Toronto, ON.

2.2 Study Period

Monitoring began May 1, 2015 at both the near-road (NR-VAN) and background (BG-VAN) monitoring stations in Vancouver. The background station was operated on a temporary basis for 16 months until August 31, 2016. The station was decommissioned in early September 2016 while the near-road station continues to operate. This report primarily uses data collected during the study period from May 1, 2015 to December 31, 2017.

2.3 Monitoring Methods

Numerous air contaminants were measured at the near-road and background air quality monitoring stations along with the comparison stations (Table 2.5). Table 2.4 provides the specific dates used for each type of analysis.

Table 2.4: Study periods used for various analyses presented in this report.

Analysis Description	Report Section	Date
Comparison of NR-VAN and Metro Vancouver Comparison Sites	5.1 to 5.6	May 1, 2015 to December 31, 2017
Pollution roses, polar plots, wind sector analysis	6.2 and 6.3	
Traffic results and correlation	3.4 and 6.4	March 9, 2016 to December 31, 2017
VOC Comparison	5.7	July 11, 2015 to December 31, 2016
Comparison of NR-VAN and BG-VAN	6.1	May 1, 2015 to August 31, 2016
Comparison of NR-VAN, and NR-H401, NR-TOR	6.5.1	May 1, 2015 to March 31, 2017

Table 2.5: Contaminants measured at study sites and comparison sites.

Stations		Air Quality Monitors									
		Continuous							Integrated		
		Gases				Particles					
ID	Name	NO_x	CO	O_3	CO_2	$PM_{2.5}$	BC	UFP	VOC	SP	D
T1	Vancouver-Downtown	√	√	√							
T4	Burnaby-Kensington Park	√	√	√		√					
T6	N. Vancouver-2nd Narrows	√	√	√		√	√				
T9	Port Moody	√	√	√		√	√		√		√
T18	Burnaby South	√	√	√		√	√		√	√	√
T22	Burnaby-Burmount								√		
T24	Burnaby North								√		
T26	N. Vancouver-Mahon Park	√	√	√		√					
T31	Richmond-Airport	√	√	√		√	√		√		
NR-VAN	Vancouver-Clark Drive	√	√	√	√	√	√	√	√	√	√
BG-VAN	Vancouver-Sunny Hill	√	√	√		√	√	√	√	√	√
NR-H401	Toronto-Highway 401	√	√	√	√	√	√	√	√	√	√
NR-TOR	Toronto-College Street UoT	√	√	√	√	√	√	√	√	√	√
Total Monitoring Units		**11**	**11**	**11**	**3**	**10**	**8**	**4**	**9**	**5**	**6**

NO_X = nitrogen oxides; CO = carbon monoxide; O_3 = ozone; CO_2 = carbon dioxide; $PM_{2.5}$ = fine particulate matter; BC = Black Carbon. UFP = Ultrafine Particles; VOC = volatile organic compounds; SP = particulate speciation; D = dichotomous particulate; √ = monitored at this location.

2.3.1 Routine Continuous Measurements

Numerous contaminants were measured at NR-VAN and BG-VAN and employed routine continuous monitors which provide data in real-time every minute of the day. The routine continuous monitors used in this study measured carbon monoxide (CO), nitrogen oxides (NO_x) which include nitrogen dioxide (NO_2) and nitric oxide (NO), ground-level ozone (O_3), fine particulate matter ($PM_{2.5}$) and black carbon (BC). The routine continuous instrumentation is described in Table 2.1 and Table 2.2.

2.3.2 Non-Routine Continuous Measurements

Several non-routine continuous analyzers were utilized in this study. Ultrafine particles (UFP) were measured for the first time in the region. Two different monitors were used to measured UFP. The API 651 UFP analyzer was used to measure total particle count and the TSI 3031 was used to measure particle counts of various size fractions. A side by side comparison, conducted by study partners, of the two API 651 were found to have close agreement while a co-located test of the TSI 3031 demonstrated considerable disagreement between co-located instruments. As a result of the poor agreement of TSI 3031 instruments, the TSI 3031 measurements are not shown in this report. UFP concentrations presented in this report were measured with the API 651 monitor.

While black carbon has been measured in the region for many years, this study was the first to employ the Magee Scientific AE33 7-channel aethalometer. The AE33 aethalometer was the primary black carbon monitor used in this study, however it was determined that the incorrect data channels were logged at NR-VAN and BG-VAN. The AE33 includes three sets of channels, two of which are uncompensated (BCn1 and BCn2) and one for the final result (BCn). The BCn2 channels were logged rather than the BCn channels resulting in -2% to -11% error on average. The error was found to be greater for individual hours with a range of -23% to +42%. Raw data was collected and used to determine the error, however not enough raw data was available to recover the entire study period. Therefore, BC data used in the analysis for the calculation of peak levels are not provided for NR-VAN and BG-VAN. Average BC levels are reported. The BC levels reported for the Metro Vancouver comparison sites and the Toronto near-road sites were not affected.

Data from two analyzers operated by Environment and Climate Change Canada during the study at NR-VAN are not included in this report. They were the Sunset Labs EC/OC analyzer and Li-Cor 840-A CO_2 analyzer. The non-routine continuous instrumentation is included in Table 2.1 and Table 2.2.

2.3.3 Integrated Sampling

Non-continuous 24-hour (daily) samples of volatile organic compounds (VOC) and particulate were collected at NR-VAN and BG-VAN as well as several of the Metro Vancouver comparison sites. Particulate speciation samples were collected to determine the chemical composition of $PM_{2.5}$ and dichotomous particulate samples were used to measure the coarse and fine faction of particulates as well as metals.

Non-continuous samples were collected in accordance with the National Air Pollution Surveillance (NAPS) program. A sampling frequency of every third day was used at NR-VAN and BG-VAN and every sixth or twelfth day at the other Metro Vancouver comparison sites. After collection, samples were transported to and analyzed in a federal laboratory in Ottawa to determine contaminant concentrations. These detailed data can be used to help determine the emission sources contributing to the contaminants in the air. Table 2.1 and Table 2.2 includes the integrated sampling equipment at NR-VAN and BG-VAN, respectively.

2.3.4 Meteorology

Two sets of meteorological instruments were operated at NR-VAN and BG-VAN. At NR-VAN a pneumatic tower was attached to the shelter and extended to a height of 12 metres. Standard instrumentation was mounted on the tower and logged with a Campbell Scientific CR800 datalogger. Wind measurements were taken at the top of the tower (at 12.3 m height) and air temperature and relative humidity sensor (housed in a radiation shield) were mounted at approximately 8 m height to avoid the radiative influences of the shelter's black roof. A second set of meteorological parameters were measured near the height of the inlets with an all-in-one Vaisala WXT520 mounted off the roof railing (at a height of 5 m).

At BG-VAN, because the station was surrounded by tall trees, a more desirable location for measuring representative winds was sought. A free-standing 10-metre tower was deployed on the roof of the nearby hospital building approximately 110 metres away from the station (Figure 2.6). At this height meteorological observations would better represent wind patterns in the neighbourhood. Wind measurements were taken at a height of 18 m while air temperature and relative humidity was measured at 16 m to avoid the influence of the roof. Standard instrumentation was mounted on the tower and logged with a Campbell Scientific CR800 datalogger. Table 2.1 and Table 2.2 provides the meteorological instrumentation and observation heights at NR-VAN and BG-VAN, respectively.

2.3.5 Data Acquisition

Measurements of air quality, traffic and meteorological data were collected automatically on a continuous basis. These data were collected by a station computer using Envista Ultimate data logging software. Data from the study sites (NR-VAN and BG-VAN) were transmitted to a data cloud managed by a contractor, DR DAS, supplier of data acquisition system software to most air quality agencies in Canada (located in Ohio). These data were stored in an electronic database available remotely to the study participants. Data from the air quality monitoring network stations (i.e., Metro Vancouver comparison sites described in Section 2.1.3) were transmitted to Metro Vancouver's Head Office in Burnaby, and stored in the network database.

3. Traffic

This section includes a description of the regional vehicle fleet, road configuration at the near-road monitoring station, traffic counting instrumentation and results of traffic count measurements.

3.1 Description of vehicle fleet

In the LFV, light-duty vehicles are the dominant vehicle type based on 2015 vehicle registration data from the Insurance Corporation of British Columbia (ICBC). Shown in Figure 3.1a, light-duty vehicles account for 94% of all vehicles on the road in the region with 47.0% classified as passenger cars and 47.3% classified as other 2-axle 4-tire vehicles which include pickup trucks, sport utility vehicles, and cargo vans calculated using regional vehicle registration data. The remaining 6% of vehicles in the region are motorcycles (2.6%) and heavy-duty vehicles including buses, refuse trucks, cement mixers and other single unit trucks (2.1%) and combination trucks (1.0%) that are defined as any truck-tractor towing at least one trailer.

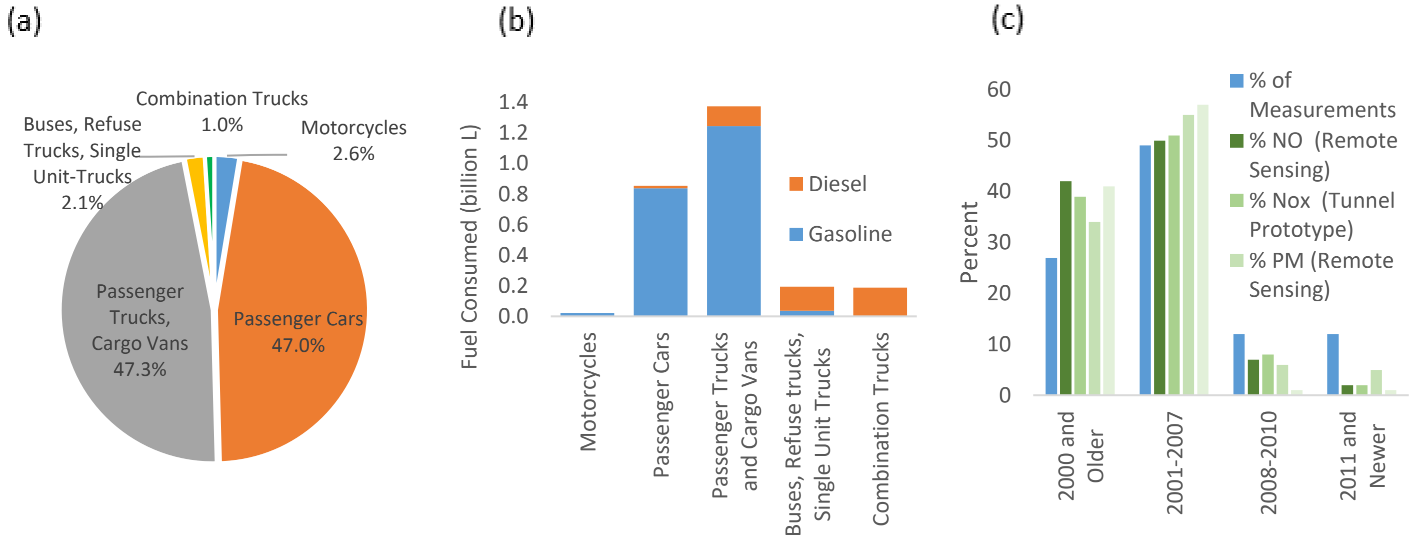


Figure 3.1: Regional (a) vehicle type distribution, (b) fuel consumed by vehicle type and (c) distribution of emissions based on vehicle age.

Fuel usage differs between vehicle types, which in turn can lead to different emissions. According to 2015 ICBC data and US EPA (2016), passenger cars and other 2-axle 4-tire vehicles in the LFV are primarily fueled by gasoline: 93% of the fuel consumed by these vehicle types is gasoline, and 7% is diesel, as seen in Figure 3.1b. For single-unit and combination trucks, the trend is reversed: 76% and 100% of fuel consumed by single unit trucks and combination trucks, respectively, is diesel.

Vehicle age can influence emission levels. A 2013 study commissioned by Metro Vancouver titled "Remote Sensing Device Trial For Monitoring Heavy-Duty Vehicle Emissions" found that heavy-duty vehicles with the model year 2007 or older had higher NO_x and PM emissions compared to newer models. Vehicles in this age category accounted for 76% of heavy-duty vehicles counted but contributed 90% of NO_x and up to 98% of PM emissions.

Another report prepared from the same study, titled "Remote Sensing Device Survey of Light-Duty Vehicle Emissions in the Greater Vancouver Regional District", found similar results for light-duty vehicles: the oldest vehicle category of 1991 and older had the lowest number of vehicles observed in the study, but it had the highest percentage of "high emitter" vehicles. Most high emitters had model years 1992-2005 and were seven to twenty years old at the time of the study (Figure 3.1c).

3.2 Road Configuration

The configuration of the Clark Drive roadway directly adjacent to the monitoring station is comprised of six travel lanes and a seventh left turn lane. The four closest lanes to the station travel southbound while the three furthest lanes travel northbound (Figure 3.2). Clark Drive is a truck route and one of the primary routes for goods travel to and from south of Vancouver. Clark Drive to the north is an entry point to the Port while Clark Drive to the south within several blocks realigns with Knight street and further south connects to the Knight Street Bridge which is a major transportation route to the other major Port in the region (Delta Port) and United States. Table 3.1 describes each lane.

Located within 75 m of the monitoring station is a major intersection where Clark Drive and East 12th Avenue intersect. The intersection results in stop and go traffic near the monitoring station. East 12th Avenue is another major commuter corridor, four lanes in width and does not allow truck traffic due to the narrow lane widths further to the west the avenue.

Table 3.1: Clark Drive (NR-VAN) configuration of lanes.

Lane number	Lane name	Traffic Direction	Description	Items of note	Stopping restrictions
1	SB-Curb	Southbound	The curb lane closest to the station.	Anecdotally it was noticed that trucks occasionally parked and/or idled in this lane while drivers used the gas station.	No stopping Monday to Friday 3 pm – 6 pm.
2	SB-Middle	Southbound	Through lane to travel southbound		
3	SB-Centre	Southbound	Through lane to travel southbound		
4	SB-Left turn	Southbound	Left-hand turn lane for traffic turning on to 12th Ave. Must turn left at 12th Ave.		
5	NB-Left	Northbound	Through lane to travel northbound		
6	NB-Centre	Northbound	Through lane to travel northbound		
7	NB-Curb	Northbound	The curb lane furthest from the station.	Bus stop at this location. The bus frequency ranged from every 5 minutes to 30 minutes.	No stopping Monday to Friday 7 am – 9:30 am.

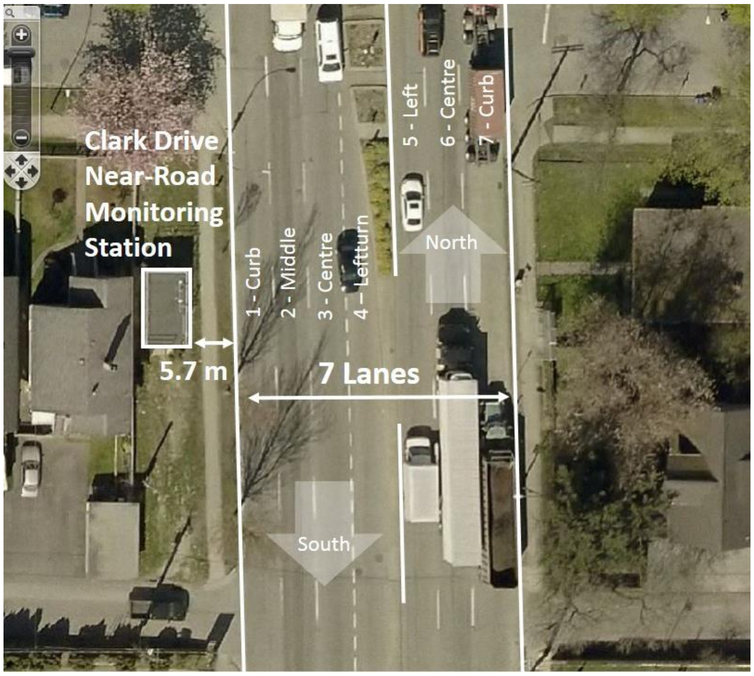


Figure 3.2: Plan view of the Clark Drive near-road monitoring station (NR-VAN).

3.3 Traffic Measurements

Traffic measurements were made with a Wavetronix HD traffic sensor at NR-VAN. The instrument was mounted on the tower to give a clear line of sight to the roadway and each lane on Clark Drive.

The Wavetronix HD traffic sensor was deployed in August of 2015. Following the deployment of the sensor, data appeared to be providing reasonable values. However, a firmware update of the instrument that was applied shortly after deployment is thought to have resulted in the instrument shifting into an erroneous state for considerable period of time. As a result, erroneous data was invalidated from the start of the study until March 2016. Therefore, traffic data is not available in 2015 and the traffic data record starts on March 9, 2016.

The traffic sensor was configured to measure traffic counts (i.e., volume) for each lane. The sensor was also configured to measure counts of vehicles of various lengths. The lengths were categorized based on three categories to allow differentiation of vehicle types (e.g., light-duty passenger vehicles vs heavy-duty trucks). The vehicle length range of each category are given in Table 3.2. The vehicle length classifications were recommended by a representative of the instrument manufacturer as standard vehicle lengths used in other deployments around the Province.

Table 3.2: Vehicle length classifications.

Vehicle length (m)	Vehicle types	Vehicle classification
1-7.6	Passenger cars and trucks, cargo vans	Light-duty
7.6-15	Buses, refuse trucks, cement mixers and single-unit trucks (short- and long-haul)	Small heavy-duty
15-36.5	Combination-unit trucks (short- and long-haul)	Large heavy-duty

3.4 Traffic Results

The distribution of daily traffic volume at NR-VAN by lane is provided in Figure 3.3 as a boxplot while the maximum and average 24-hour totals are tabulated in Table 3.3. The boxplot conveys statistical information including the average (dot), median (line), 75th percentile (top of box), 25th percentile (bottom of box), 95th percentile (upper whisker), and 5th percentile (lower whisker). The daily average of 32,600 was calculated using available data which can be thought of as the annual average daily traffic (AADT), typically calculated using 365 days in calendar year. The effect of the allowance of parking on the two outside lanes is evident in traffic counts where these lanes measured the lower traffic volumes compared with other lanes. Lane 1 is the closest lane to the monitoring station. Lane 4 also recorded lower traffic volumes as a left turn lane that starts several meters before the monitoring station (Figure 3.2).

The traffic sensor was used to determine the vehicle type based on the vehicle length. Three classifications were defined including: 1. light-duty (passenger cars, passenger trucks and cargo vans), 2. small heavy-duty (buses and small trucks including refuse trucks, cement trucks and other single-unit trucks) and 3. large heavy-duty (large trucks including combination trucks). The vehicle length classification gives insight into the percentage of various vehicle types (provided in the bottom of Table 3.3). The majority of vehicles that passed NR-VAN were light-duty vehicles (82% of total vehicles). Small heavy-duty vehicles made up 12% and large heavy-duty vehicles made up 6% of total vehicle traffic.

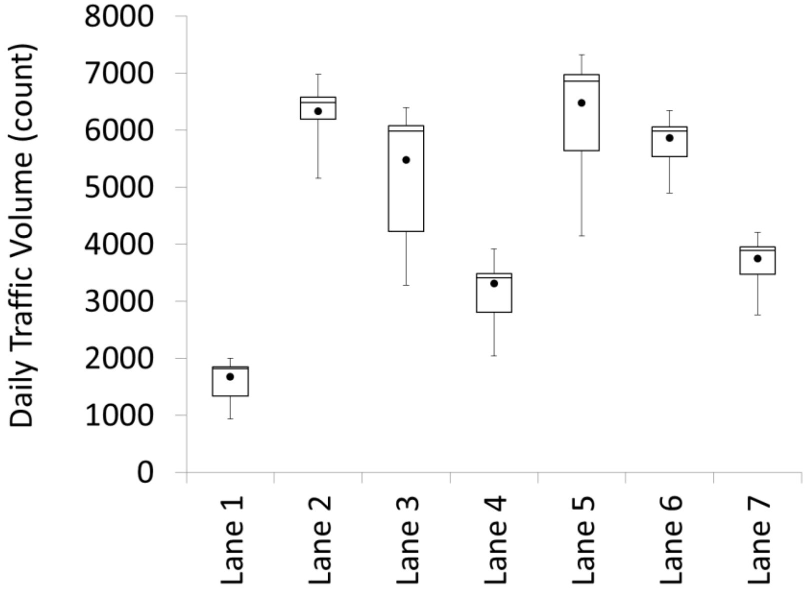


Figure 3.3: Traffic monitoring results at NR-VAN.

Table 3.3: Daily traffic volume on Clark Drive by lane and vehicle length.

	Daily Maximum (count)	Daily Average (count)	Percentage of Total by lane	Percentage of Total by class
Lane 1	2,468	1,680	5%	
Lane 2	7,489	6,022	18%	
Lane 3	7,126	5,595	17%	
Lane 4	4,823	3,286	10%	
Lane 5	8,398	6,554	20%	
Lane 6	7,145	5,902	18%	
Lane 7	4,796	3,554	11%	
Total (all vehicles)	**39,564**	**32,592**	**100%**	**100%**
Light-duty (passenger cars, passenger trucks, and cargo vans)	32,373	26,698		82%
Small heavy-duty (buses, refuse, cement and single unit trucks)	5,287	3,784		12%
Large heavy-duty (combination Trucks)	3,408	2,110		6%

The traffic sensor measurements of 12% small heavy-duty vehicles and 6% large heavy-duty vehicles was greater than the regional fleet makeup, which was estimated (in Section 3.1) to be 2% small heavy-duty and 1% large heavy-duty vehicles. This part of Clark Drive, a truck route near the Port, experienced about six times more truck traffic than the regional average.

The seasonal pattern for traffic is shown for the three vehicle classifications in Figure 3.4. The monthly averages are shown in black while the range of 25th – 75th percentiles are shown in dark grey and the range of 5th – 95th percentiles shown in light grey. The seasonal pattern of light-duty vehicles (Figure 3.4a) is not entirely clear as there is apparent year to year differences in total traffic. For example, March 2016 shows higher average traffic than March 2017. There doesn't appear to be any seasonal pattern with larger trucks (Figure 3.4c) with traffic total relatively constant throughout the year.

Figure 3.5 provides the distribution of daily traffic volume by day for the three vehicle classifications. Examining all classifications together indicates that weekdays experienced greater daily traffic than the weekend (Figure 3.5a). On average the least traffic was experienced on Sunday. The volume of light-duty vehicles was similar on weekdays and Saturday with slightly lower traffic experienced on Sunday (Figure 3.5b). In contrast there was a considerable difference in the volume of large trucks (Figure 3.5d) on weekdays compared with Saturday and Sunday. Sunday experienced the lowest volume of large trucks with approximately half the amount of trucks compared with Saturday.

A series of diurnal plots are shown in Figure 3.6 for traffic volumes broken into direction and vehicle classification. Total traffic, southbound and northbound are shown in Figure 3.6 plots (a) to (c). Weekday total displays the highest volume with the role of "rush hour" evident in the plots. Traffic travelling northbound toward the central business district (CBD) peaks in the morning while traffic flowing southbound away from the CBD peaks in the afternoon (Figure 3.6b). The resultant diurnal traffic patterns display a peak in the afternoon due to the greater number of lanes in the prominent commuter traffic direction with four lanes southbound and three lanes northbound (Figure 3.6a).

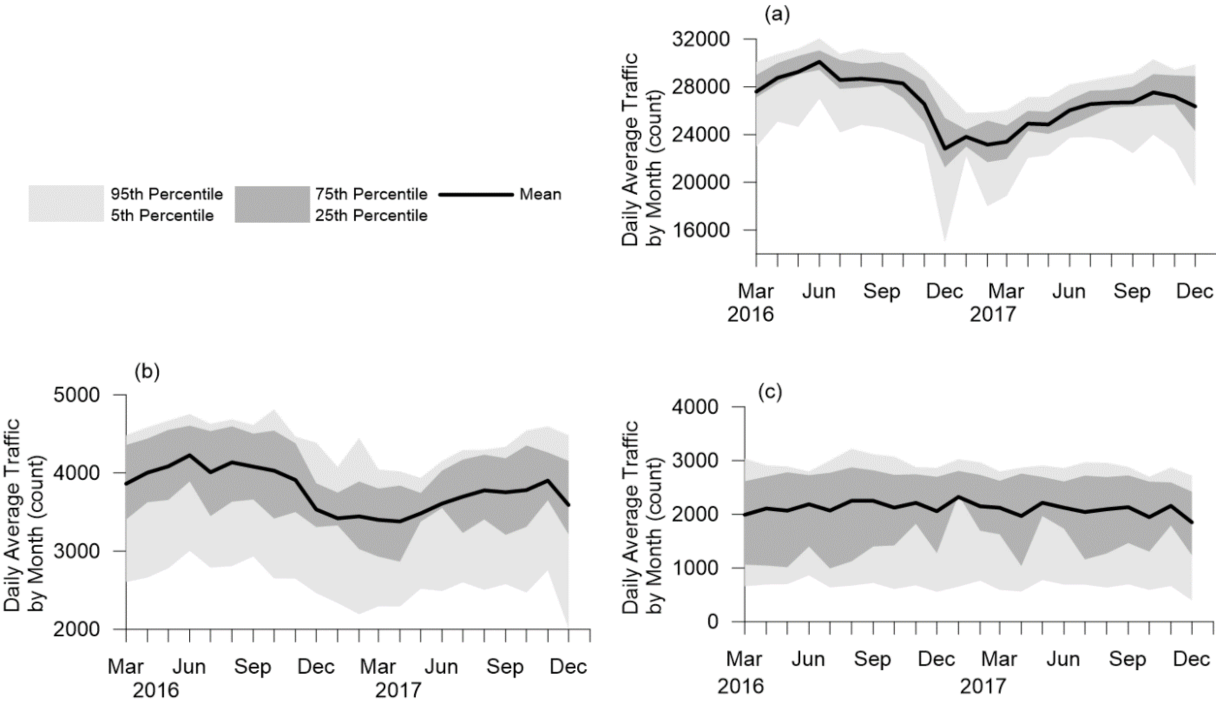


Figure 3.4: Monthly daily average traffic for (a) light-duty, (b) small heavy-duty and (c) large heavy-duty.

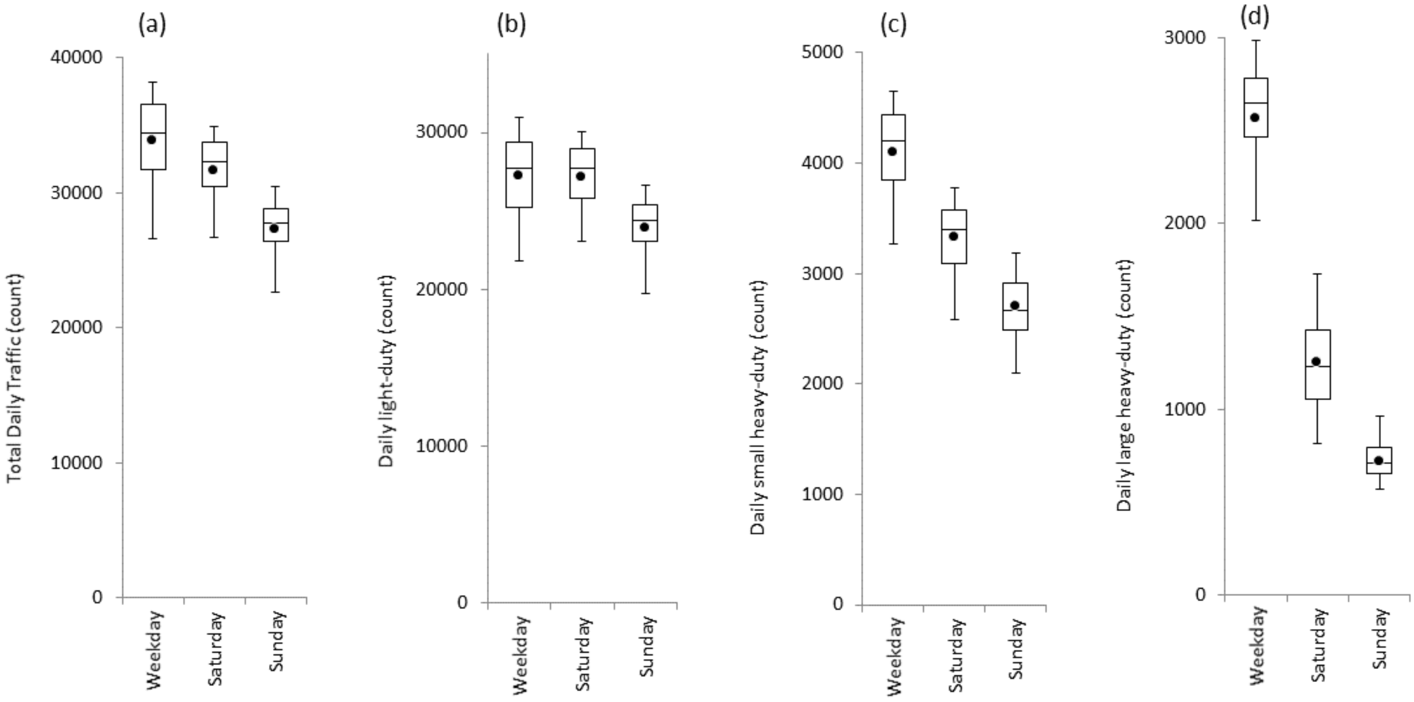


Figure 3.5: Average number of total vehicles and vehicle types on weekdays and weekends.

Daily traffic patterns for each vehicle classification are shown in Figure 3.6 plots (d) to (f) while the ratio of each vehicle classification is provided in Figure 3.6 plots (g) to (i). Light-duty vehicle traffic (Figure 3.6d) appears similar to the total traffic pattern which was to be expected since this vehicle classification makes up the majority of traffic with vehicle class/total traffic ratios greater than 0.8 (Figure 3.6g) indicating that these vehicles make up 80% of the total. Traffic volumes for small heavy-duty vehicles (Figure 3.6e) shows a rapid increase on weekdays in the morning followed by a relative plateau and a decrease in the evening. Weekends show a less rapid increase to midday followed by a decrease. The ratio of small heavy-duty vehicles increased rapidly at the start of the workday on weekdays with little to no difference between summer and winter (Figure 3.6h). Traffic volumes for large heavy-duty vehicles were considerably greater during the week (Figure 3.6f). A slight drop midday is evident in the large truck traffic volumes that was not present in the other two vehicle classifications. It is thought that this relative drop was due to truck drivers taking a lunch break. The percentage of large heavy-duty vehicles was greatest during the day on weekdays and much lower on weekends (Figure 3.6i).

Calendar plots are provided in Figure 3.7 showing the daily total traffic in 2017 for light-duty and large heavy-duty vehicles, respectively. In general, Fridays experienced the highest count of light-duty vehicles and lowest on statutory holidays. Similar traffic counts were measured on weekdays for large heavy-duty vehicles with considerably less traffic on Saturday while Sunday experienced the least amount of traffic.

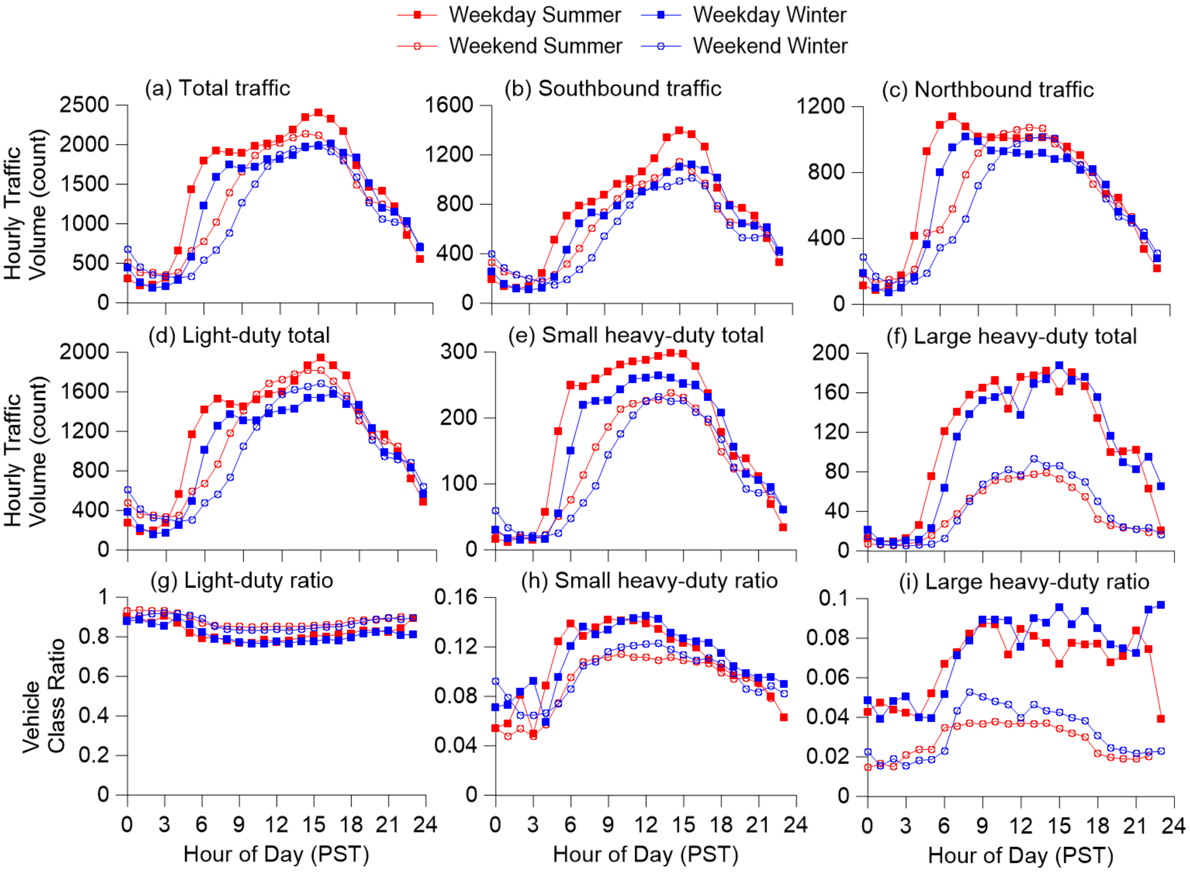


Figure 3.6: Diurnal patterns in traffic given by all vehicle type (a), traffic by direction (b and c), light-duty (d), small heavy-duty (e), large heavy-duty (f) and the ratio of each vehicle classification to total (g, h and i).

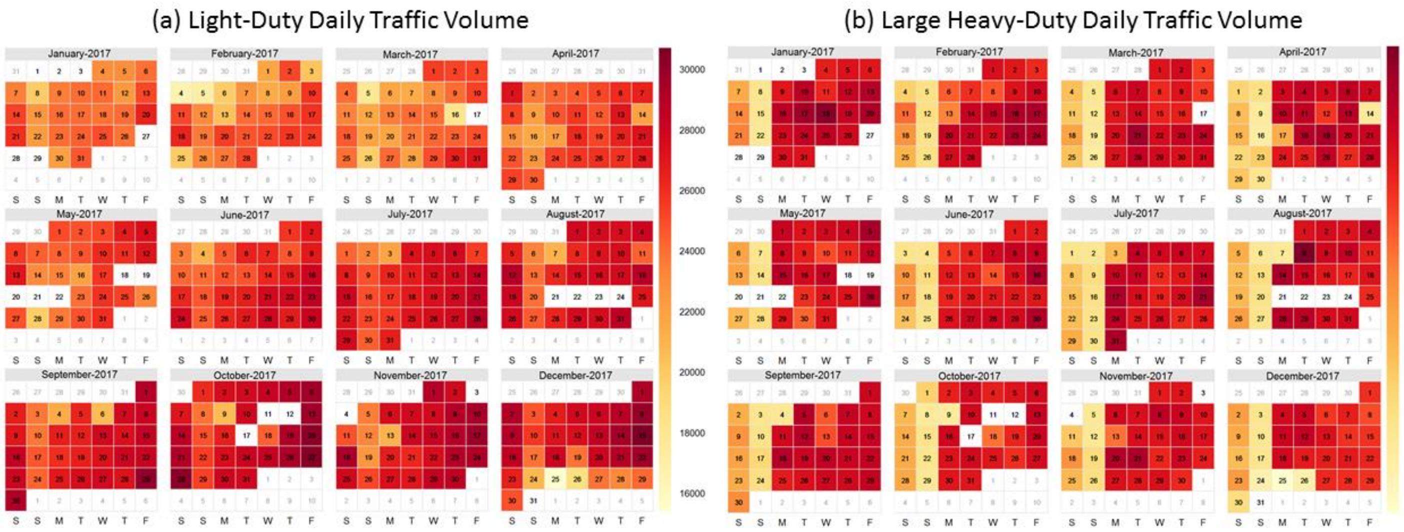


Figure 3.7: Calendar plot for 2017 showing daily count of light-duty vehicles (a) and large heavy-duty (b).

4. Meteorology

Meteorology is important in understanding air quality patterns, as the state of the atmosphere can affect pollutant dispersion and resulting ground-level concentrations. Meteorology was observed at the study sites to allow for a characterization of meteorological patterns throughout the region and to assist with the linkage between pollutant emission sources and ambient concentrations.

Wind patterns vary throughout the region. The distributions of wind frequency at the near-road monitoring station (NR-VAN) is provided in Figure 4.1. The distributions are shown as a “wind rose”, which is a bar chart in a polar format. The direction of the bar indicates the direction from which the wind is blowing, the colour indicates the wind speed class and the length of the bar indicates the frequency of occurrence.

Figure 4.1 shows the observed annual wind rose for the period of May 1, 2015 to December 31, 2017. The pattern shows the predominant winds in the area. The NR-VAN site exhibited a predominant south-southeast wind with a smaller component from the east, and very little wind from either the north or southwest. The dominant winds were predominantly blowing from the direction of the major roadways near the monitoring station. Although there are variations seasonally and throughout the day, a predominant easterly wind is typical of the coastal regions of Metro Vancouver.

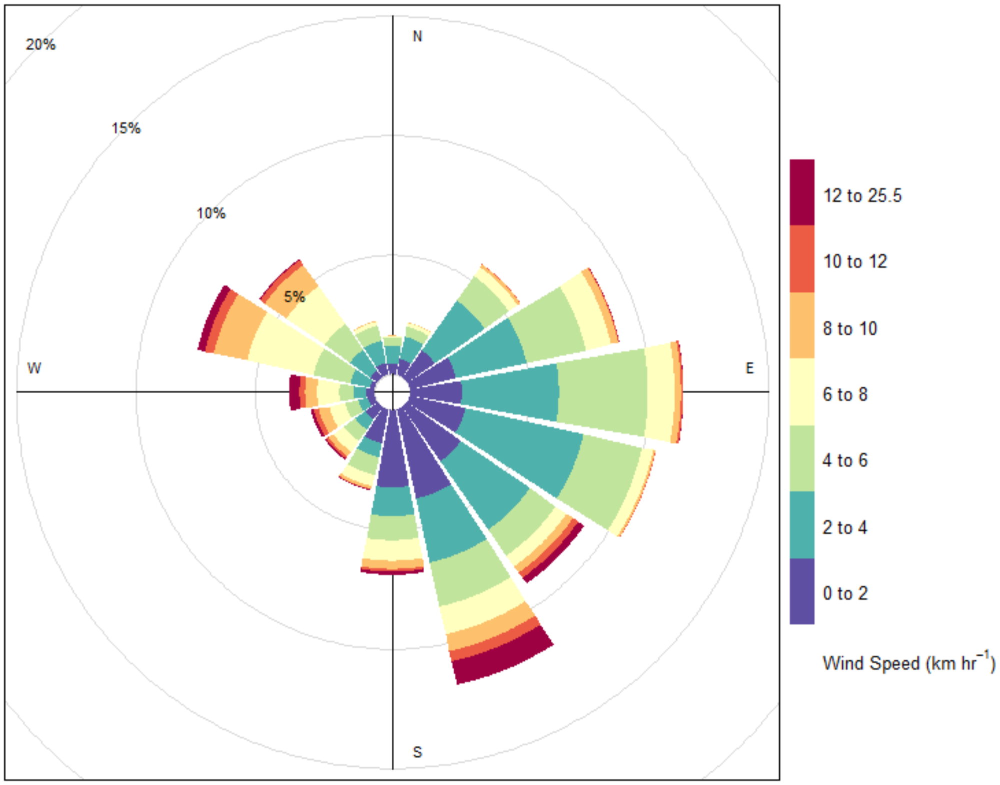


Figure 4.1: Wind rose at NR-VAN (observed from 12-m height).

Figure 4.2 illustrates the seasonal variation of air temperatures observed at Port Moody a study site where climate normals are available from a nearby Environment and Climate Change Canada station. The hourly maximum and minimum, and average temperatures are given for the study period years of 2015, 2016 and 2017. Also shown in Figure 4.2 are the 30-year climate normal (1981-2010) for Environment Climate Change Canada's Port Moody station.

The temperatures observed in 2015 suggest that on average May, June, and July were considerably warmer than the 30-year average (climate normal). Comparisons of the two full winters measured show that average temperatures during the 2015/16 winter was warmer than normal while 2016/17 was colder than normal.

The monthly total precipitation is shown in Figure 4.3 for the background station (BG-VAN), Port Moody and Richmond-Airport along with climate normals for Environment Canada's Port Moody and Richmond-Airport stations. Compared with the climate normals the spring and early summer of 2015 was considerably drier but with a near-normal winter in 2015/16. The year 2016 experienced a relatively normal amount of precipitation with the exception of a drier April. In 2017 January and the summer months were drier than normal while March and April were wetter than normal.

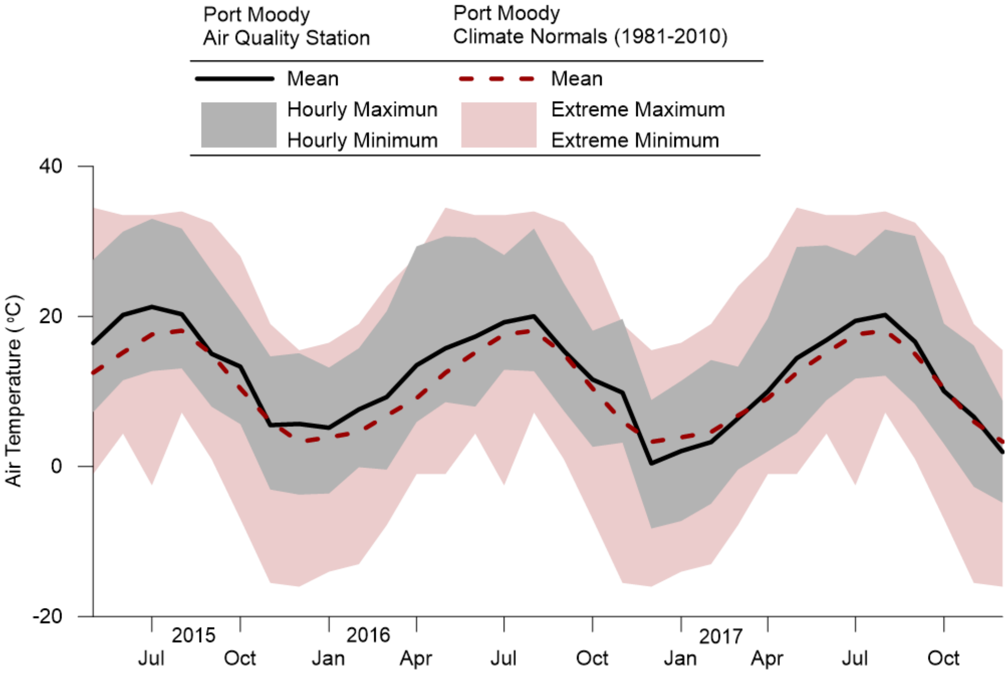


Figure 4.2: Monthly 1-hour mean, minimum and maximum air temperature at Port Moody compared with climate normals.

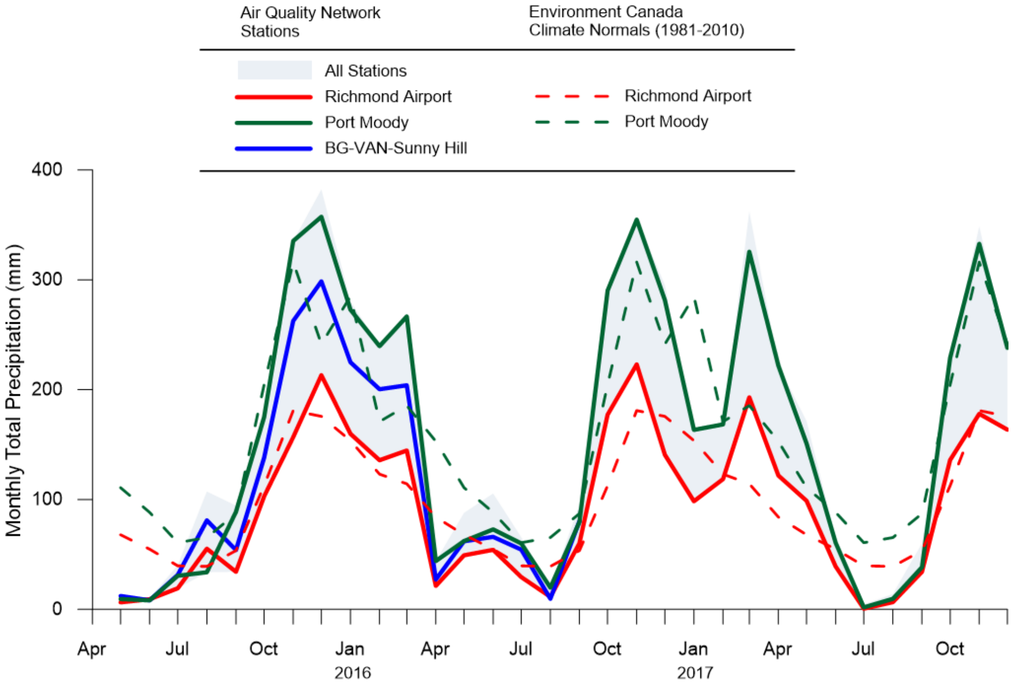


Figure 4.3: Monthly total precipitation (mm).

5. General Monitoring Results

This section summarizes results contaminant concentrations measured at NR-VAN, BG-VAN and the comparison sites in Metro Vancouver. The results include an investigation into statistics, seasonal and diurnal trends, frequency of contaminant concentrations and comparison to Metro Vancouver ambient air quality objectives.

5.1 Nitrogen Oxides

Nitric oxide (NO) and nitrogen dioxide (NO_2) are produced by the high temperature combustion of fossil fuels, and are collectively referred to as NO_X. Nitric oxide generally predominates in combustion emissions but rapidly undergoes chemical reactions in the atmosphere to produce NO_2. Nitrogen dioxide is a reddish-brown gas with a pungent, irritating odour. It has been implicated in acute and chronic respiratory disease and in the creation of acid rain. It also plays a major role in ozone formation, and as a precursor to secondary particulate formation ($PM_{2.5}$), both of which can affect visual air quality in the region.

A boxplot is provided in Figure 5.1a which shows measured NO_2 levels during the study period (May 1, 2015 to December 31, 2017). The boxplot conveys statistical information including the mean (dot), median (line), 75th percentile (top of box), 25th percentile (bottom of box), 95th percentile (upper whisker), and 5th percentile (lower whisker). The NR-VAN site experienced higher concentrations compared with the BG-VAN site and other comparison sites in Metro Vancouver. The near-road station (NR-VAN) experienced 1.4 times more NO_2 compared with the background station (BG-VAN). The Vancouver-Downtown site also experienced elevated NO_2 concentrations and is also located near a major roadway. Figure 5.1b shows the maximum 1-hour and average concentrations during the study period. The 1-hour NO_2 concentrations were below (i.e., better than) the 1-hour Metro Vancouver objective at all times during the study period. Average levels for the study period were also below Metro Vancouver's annual objective with the exception of NR-VAN which was found to just meet the objective during the study period.

Annual averages calculated for each calendar year revealed that an exceedance of the annual objective occurred in 2017 (Table 5.1). The NR-VAN station was the only station to exceed the Metro Vancouver's annual objective (21 ppb). A value of 22.1 ppb was measured in 2017 while a value of 20.8 ppb was measured in 2016. All data collected in 2015 was used to calculate an average in 2015 with a value of 19.3 ppb, although this year did not meet the data completeness requirements of 75%. All other stations measured annual averages below the air quality objective (i.e., better than).

NO_2 concentrations are dominated by emissions from transportation sources, which is indicated by the locations of the highest concentrations. The highest concentrations are measured in more densely trafficked areas near busy roads. Lower concentrations were observed where traffic influences were less pronounced.

The federal government has adopted a more stringent Canadian Ambient Air Quality Standard (CAAQS) for annual and 1-hour NO_2, that came into effect January 1, 2020. The annual NO_2 CAAQS has a numerical value of 17 ppb and 12 ppb for the years 2020 and 2025, respectively. While regional-scale emission inventory forecasts indicate that emissions of nitrogen oxides will decrease in the future, it is thought that near-road environments may be challenged to achieve the NO_2 CAAQS given the abundance of nitrogen oxides in this environment. Additional work may be needed to reduce NO_2 concentrations in near-road environments.

Measured NO and NO_x concentrations demonstrated a considerable difference between the near-road site (NR-VAN) and comparison sites (Figure 5.2). The effect of fresh traffic emissions was apparent at NR-VAN where the near-road station experienced 3.5 times more NO and 2.2 times more NO_x than the background station on average.

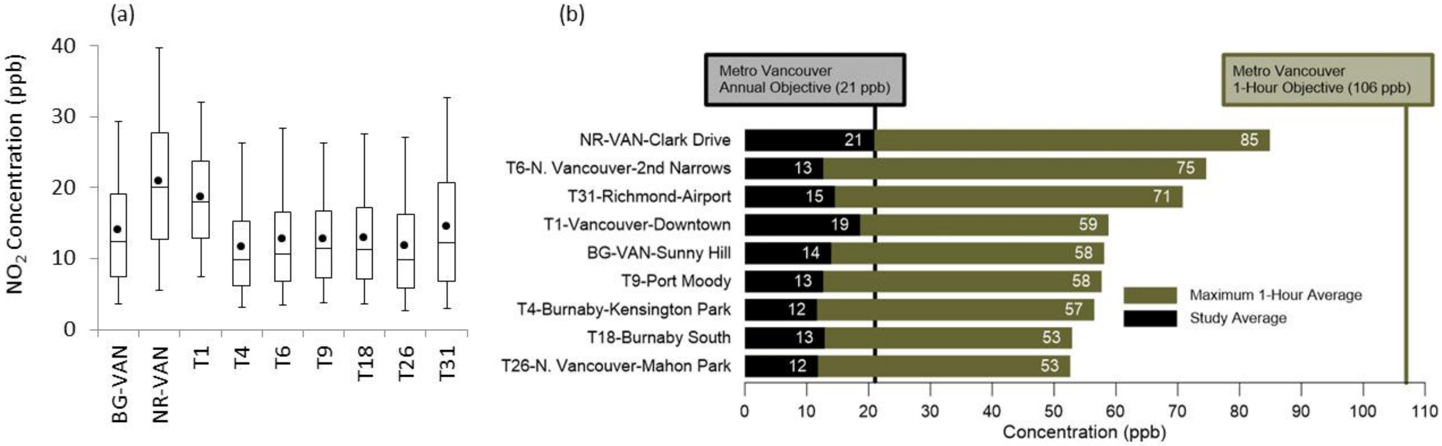


Figure 5.1: Nitrogen dioxide monitoring results during study period.

Table 5.1: Annual average nitrogen dioxide by year.

Station	2015	2016	2017
NR-VAN-Clark Drive	19.3*	20.8	**22.1**
BG-VAN-Sunny Hill	13.7*	14.1*	-
Vancouver-Downtown	18.3	18.5	19.1
Burnaby-Kensington Park	11.8	11	12.2
N. Vancouver-2nd Narrows	12.6	12	13.3
Port Moody	12.6	12	13.5
Burnaby South	13.8	12.2	13.5
N. Vancouver-Mahon Park	12.2	10.9	12.7
Richmond-Airport	14.2	14.3	15.9

*Did not meet data completeness criteria and average was calculated from all data available within the year.

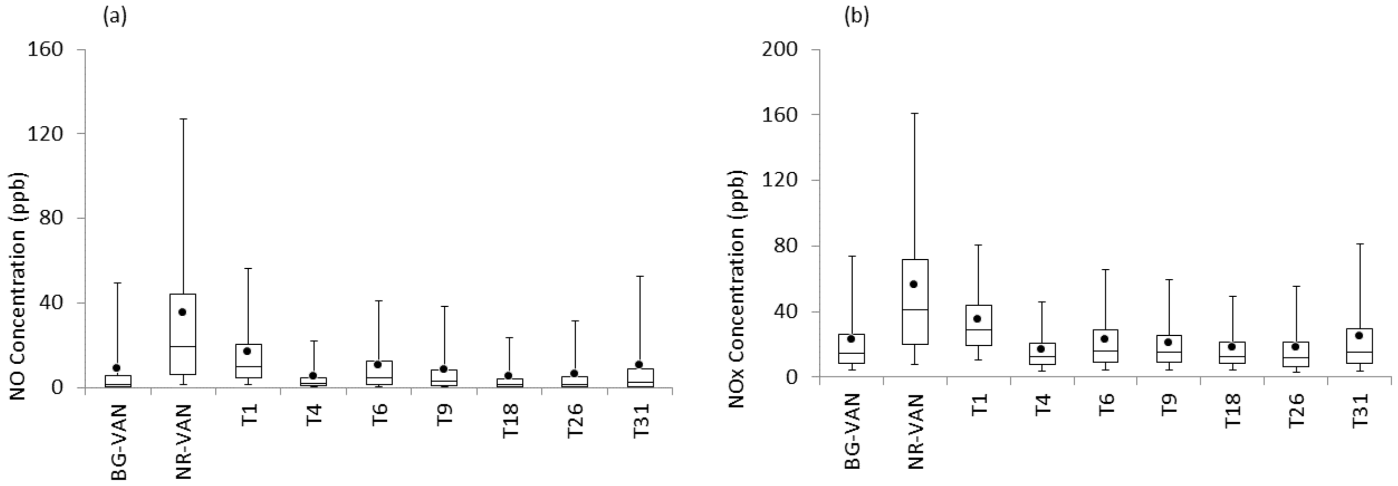


Figure 5.2: Nitrogen oxide (a) and nitrogen oxides (b) monitoring results.

The seasonal pattern for NO_2 is shown by monthly averages and the monthly maximum 1-hour concentrations in Figure 5.3. On average, NO_2 concentrations were higher in the winter and lower in the summer. This seasonal pattern is typical of the region and is the result of lower atmospheric mixing heights in winter along with increased residential, commercial and industrial heating. There is a known relationship with vehicle NO_x emissions for both gasoline and diesel vehicles where emissions increase when ambient outdoor temperatures decrease, which may also play a role in the higher concentrations during the colder winter. The NR-VAN site shows a higher average during winter of 2016/17 which was considerably colder than the winter of 2015/16. On average the winter of 2016/17 was 3°C colder than 2015/16.

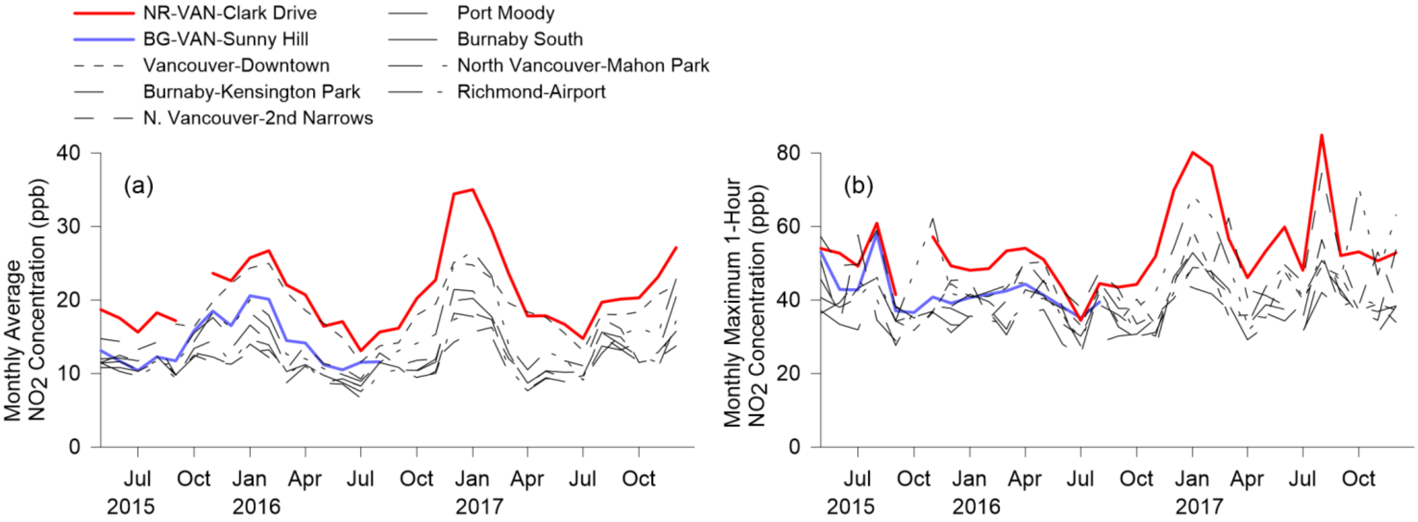


Figure 5.3: Monthly average (a) and short-term peak (b) nitrogen dioxide.

There was little to no discernable seasonal pattern for the peak 1-hour NO_2 levels although the influence of significant regional wildfire smoke was pronounced in August 2017 and to a lesser degree in August 2015.

The values in Table 5.2 represent the frequency distribution (or count) of how many hourly average measurements were in specified ranges, respectively. Both Vancouver-Downtown and NR-VAN experienced the lowest frequency of concentrations less than 5 ppb, and NR-VAN experienced the greatest frequency of elevated concentrations.

A series of diurnal plots are shown in Figure 5.4 and Figure 5.5 that demonstrate the differences between weekdays and weekends along with differences between summer and winter. Most stations exhibit higher concentrations on weekdays compared with weekends and a peak (i.e., higher relative concentrations) in the morning along with a peak in the afternoon. Higher concentrations corresponded relatively well with traffic volume patterns and the morning and afternoon commutes. In the summer the evening peak occurred later and was higher than concentrations in the morning.

Table 5.2: Frequency distribution of hourly nitrogen dioxide.

NO_2 Conc. (ppb)	BG-VAN-Sunny Hill	NR-VAN-Clark Drive	Vancouver-Downtown	Burnaby-Kensington Park	N. Vancouver-2nd Narrows	Port Moody	Burnaby South	N. Vancouver-Mahon Park	Richmond-Airport
0 to 5	1327	895	199	3745	2969	2571	2761	4373	3548
5 to 10	3146	2885	2697	7944	7386	6995	7189	7201	5821
10 to 15	2627	3421	4714	5294	5475	5986	5388	4660	4134
15 to 20	1973	3884	5108	2894	3192	3875	3406	3088	3209
20 to 25	1370	3766	4338	1603	1889	1973	2153	1922	2636
25 to 30	754	3068	2640	800	900	976	1099	972	1748
30 to 35	341	2026	1216	352	493	352	457	444	939
35 to 40	126	1222	377	174	221	91	192	143	460
40 to 45	20	565	85	57	118	24	53	39	221
45 to 50	5	272	17	19	41	2	12	10	97
50 to 55	4	119	2	6	11	1	4	1	19
55 to 60	1	57	2	1	6	1			5
60 to 65		24			4				4
65 to 70		15							1
70 to 75		3			1				1
75 to 80		1							
>=80		3							
Missing Data	11730	1198	2029	535	718	577	710	571	581
Completeness	50%	95%	91%	98%	97%	98%	97%	98%	98%

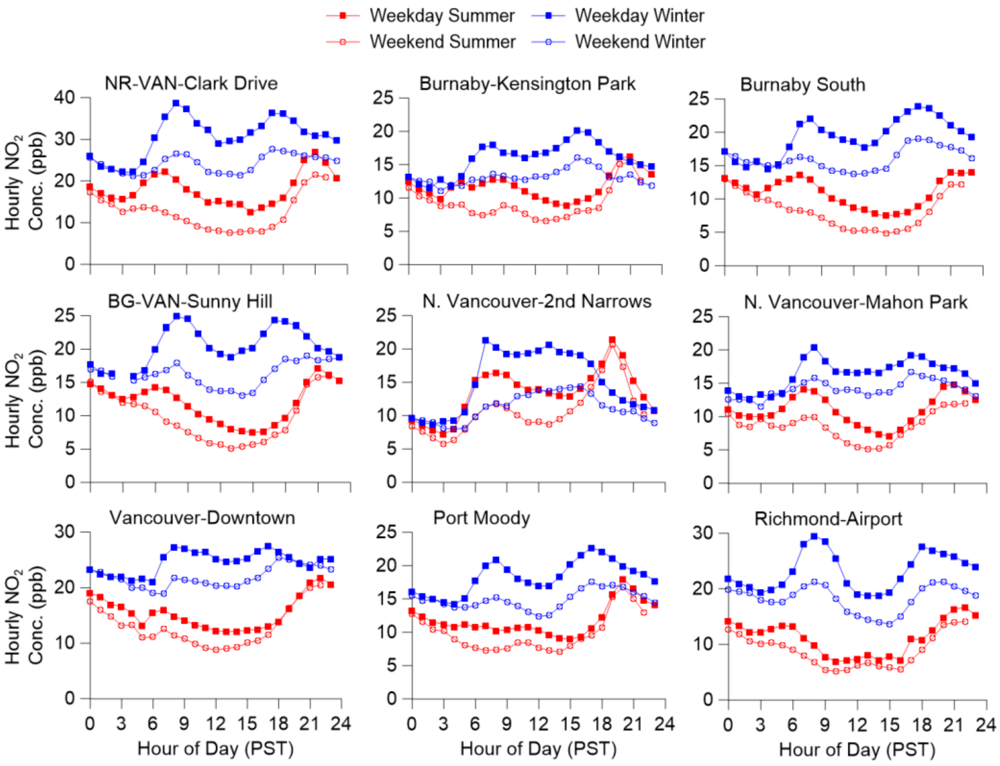


Figure 5.4: Diurnal trends nitrogen dioxide.

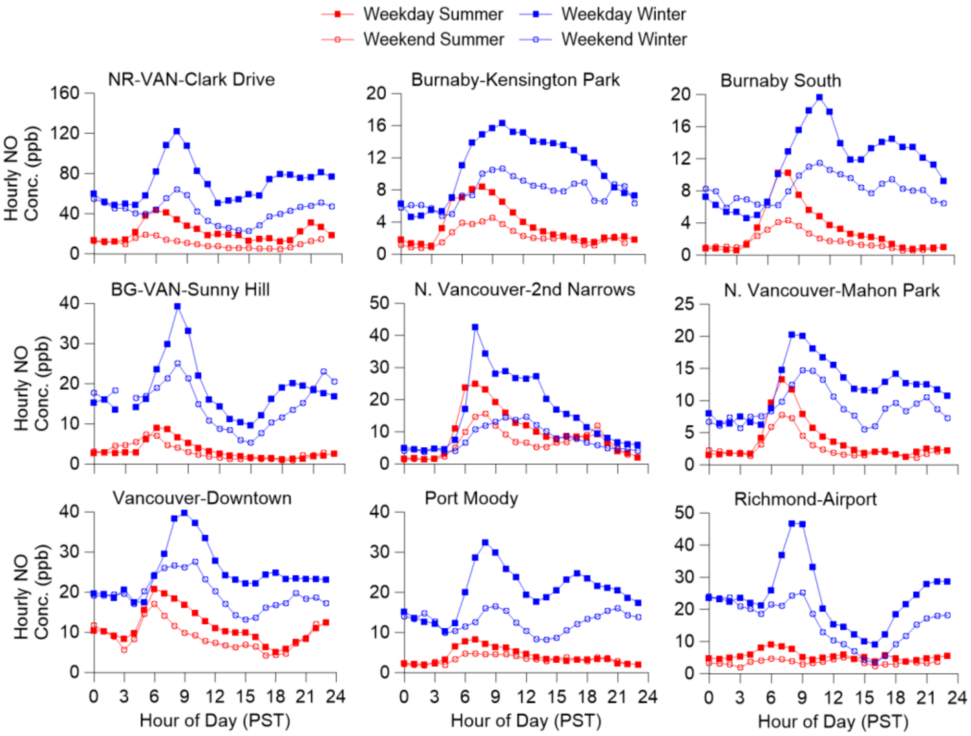


Figure 5.5: Diurnal trends nitric oxide.

5.2 Ozone

Ozone (O_3) is termed a secondary contaminant because it is not usually emitted directly into the air. Instead, it is formed from chemical reactions involving contaminants identified as precursors, including NO_X and reactive VOC. The levels of O_3 measured depend on the emissions of these precursor contaminants.

Nitrogen oxide (NO_X) emissions are dominated by transportation sources. About 60% of the emissions come from cars, trucks, ships, rail and planes. Other sources include non-road engines, boilers and building heating systems. The main contributors to VOC emissions are chemical products use (industrial, commercial and consumer products such as paints, varnishes and solvents), natural sources (trees and vegetation), cars and light trucks and non-road engines.

The formation of O_3 occurs readily during hot and sunny weather conditions with peak levels observed in the summer. Under these conditions, the highest levels generally occur downwind of major precursor emissions, and are observed in eastern parts of Metro Vancouver and in the Fraser Valley Regional District (FVRD). Metro Vancouver and the FVRD adopted the Regional Ground-Level Ozone Strategy in 2014, which provides strategic policy direction for ozone management in the LFV based on local scientific research. Research indicates that a spatial understanding of the ratio of concentrations of nitrogen oxides (NO_X) and volatile organic compounds (VOC), two precursor contaminants that react to form ozone, is key to determining which precursors to reduce in order to maintain and improve air quality in our region.

Figure 5.6a illustrates the results of O_3 monitoring during the study period in boxplot format while the average and maximum 1-hour and 8-hour averages are shown in Figure 5.6b.

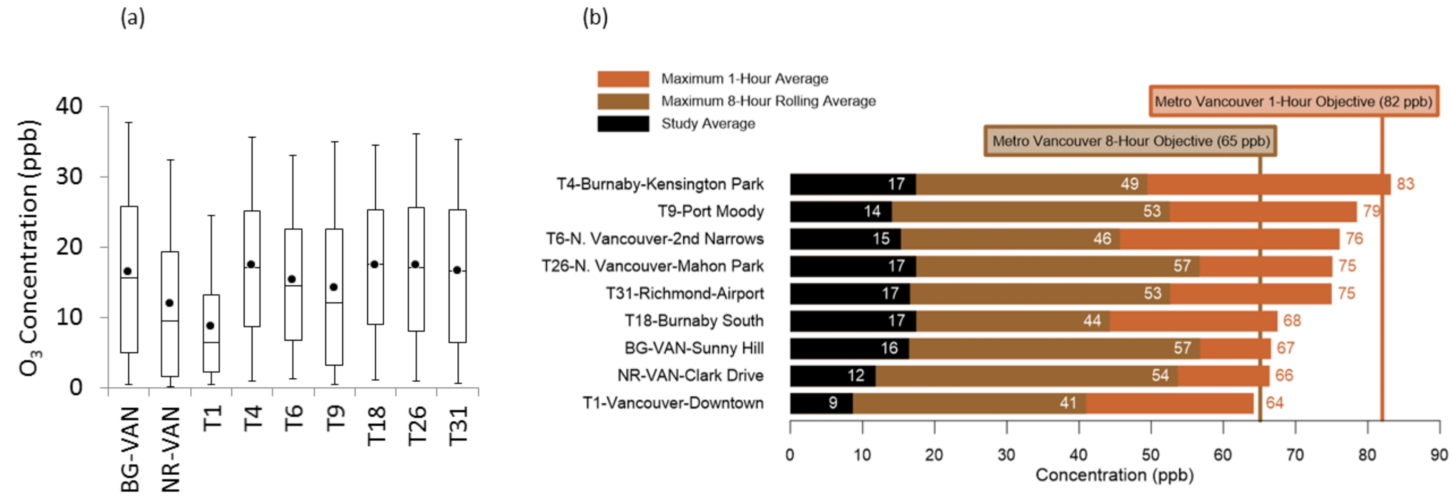


Figure 5.6: Ground-level ozone monitoring results during the study period.

During the study period there were no exceedances of the 1-hour and 8-hour Metro Vancouver objectives with the exception of Burnaby-Kensington Park where the 1-hour objective was exceeded due to enhanced ozone from wildfire smoke in 2017. It is rare for ozone to be elevated in the western portion of the LFV. Burnaby-Kensington Park last exceeded the 1-hour ozone objective of 82 ppb in 1990 when higher precursor concentrations were more prevalent in the region.

The highest ozone concentrations typically occur in the eastern parts of Metro Vancouver and in the FVRD (not shown). The lowest annual O_3 averages (Figure 5.6) occur in highly urbanized areas due to O_3 scavenging. Ozone scavenging occurs in locations where higher levels of NO_x are found such as urban areas or near busy roadways. In these areas, emissions containing NO_x react quickly with O_3 to form NO_2 (nitrogen dioxide) and O_2 (oxygen) thus decreasing O_3 concentrations. As a result, the NR-VAN station experienced some of the lowest ozone levels in the region with levels 0.8 times lower than the background station.

The seasonal variation evident in Figure 5.7 was typical of historical ozone patterns in the LFV with higher values in spring and summer, and lower values during fall and winter. Spring exhibited the highest average O_3 concentrations (Figure 5.7a) while the highest short-term hourly concentrations (Figure 5.7b) occurred in the summer. The enhancement of ozone in the summer due to the presence of wildfire smoke was evident in August 2017 when elevated ozone levels occurred throughout the LFV, including the western parts of the region.

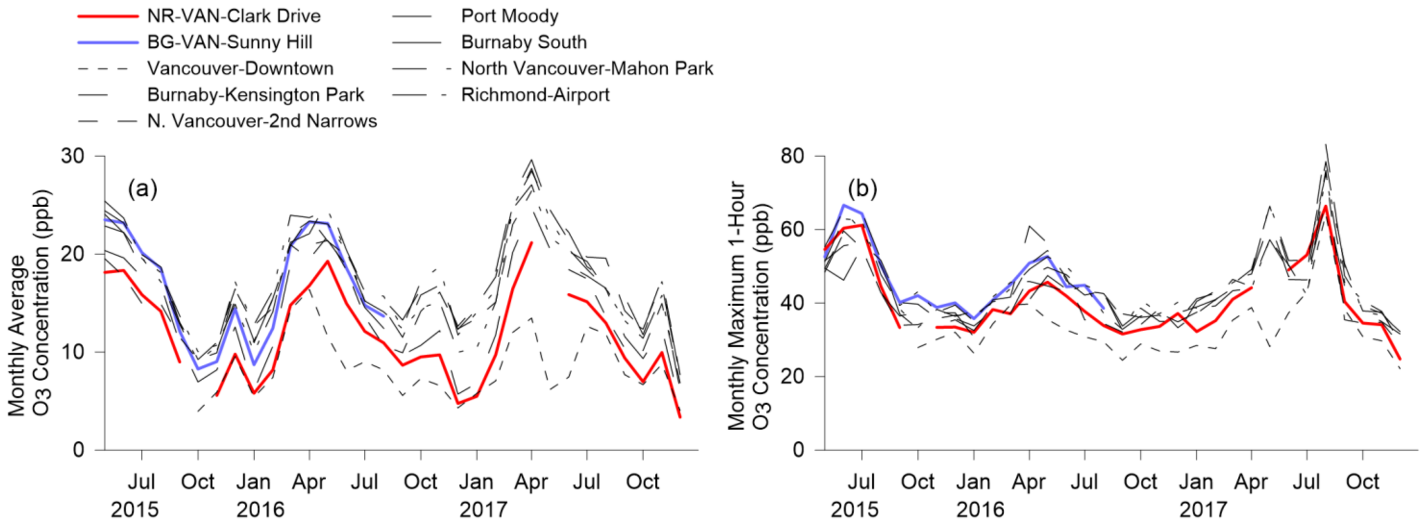


Figure 5.7: Monthly average (a) and short-term peak (b) ground-level ozone.

The frequency distribution for hourly average concentrations is shown in

Table 5.3. The frequency distributions in these tables show how often various O_3 levels are reached. It can be seen that Vancouver-Downtown and NR-VAN exhibited the greatest frequency of measurements in the lowest concentration range (0-4 ppb) due to the abundance of NO_x.

A series of diurnal plots are shown in Figure 5.8 for each O_3 monitoring station. The diurnal plots illustrate the weekday/weekend differences along with summer/winter differences. Most of the stations exhibited similar diurnal patterns. In summer, O_3 concentrations were low through the night and began to increase near sunrise with the highest (peak) concentration experienced in the afternoon. The NR-VAN site shows a greater weekday/weekend effect than other sites. This was expected due to the role NO_x emissions play in the formation of ground-level ozone. Similarly, emissions of nitrogen oxides were greater during the week resulting in less ozone compared with the weekend. Winter showed an afternoon peak although it was greatly attenuated compared with the summer.

Table 5.3: Frequency distribution 1-hour ground-level ozone.

O_3 Conc. (ppb)	BG-VAN-Sunny Hill	NR-VAN-Clark Drive	Vancouver-Downtown	Burnaby-Kensington Park	N. Vancouver-2nd Narrows	Port Moody	Burnaby South	N. Vancouver-Mahon Park	Richmond-Airport
0 to 4	2632	7566	7950	2935	3458	6338	2826	3381	4538
4 to 8	1109	2526	4274	2377	3156	2676	2228	2290	1881
8 to 12	1052	2293	3109	2526	2900	2340	2514	2386	2181
12 to 16	1126	2298	2278	2868	2945	2305	2764	2595	2474
16 to 20	1175	2129	1685	2939	2864	2131	2908	2869	2654
20 to 24	1180	1759	986	2778	2487	1991	2900	2588	2498
24 to 28	1026	1290	613	2446	1884	1773	2718	2444	2447
28 to 32	865	940	341	1806	1491	1461	1928	1957	1885
32 to 36	700	622	119	1232	834	943	1150	1211	1294
36 to 40	426	318	42	560	350	524	513	653	636
40 to 44	213	143	12	273	134	228	187	292	230
44 to 48	87	41	7	100	40	86	47	117	55
48 to 52	29	21		42	10	35	20	53	12
52 to 56	9	10	2	15	4	16	6	27	3
56 to 60	7	6	2	6	3	11	7	14	7
60 to 64	6	4	2	8	1	5	6	4	4
64 to 68	3	1	1	2	2	2	1	4	1
68 to 72				2		3		2	1
72 to 76				2	1	3		4	2
76 to 80				1	1	2			
80 to 84				2					
>=84									
Missing Data	11779	1448	1984	495	847	538	687	525	605
Completeness	50%	94%	92%	98%	96%	98%	97%	98%	97%

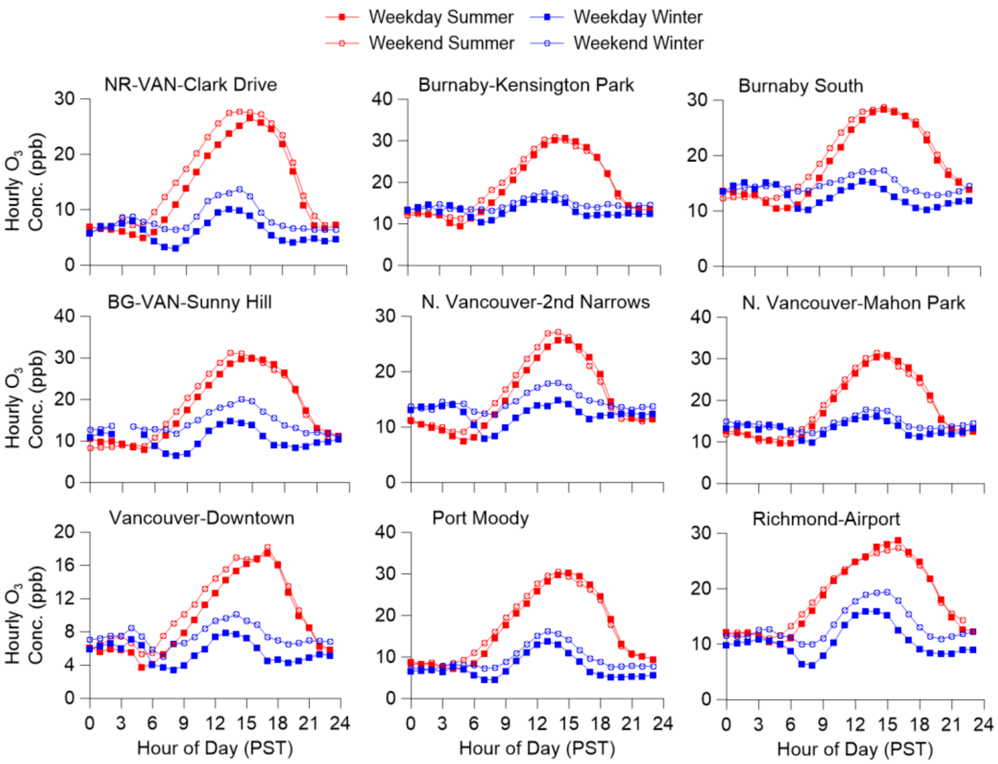


Figure 5.8: Diurnal trends ground-level ozone.

5.3 Carbon Monoxide

The principal sources of carbon monoxide (CO) are non-road engines and motor vehicles. In the Lower Fraser Valley (LFV), over 91% comes from mobile sources which include cars, trucks, buses, planes, trains, ships and non-road engines. Other sources contributing to measured CO levels are building heating, commercial and industrial operations, and smoke from wildfires.

Figure 5.9 illustrates the results of CO monitoring during the study period in a boxplot (a) and bar chart (b) format that provides the value of the maximum 1-hour and 8-hour average as well as the study average for each CO monitoring location.

The Vancouver-Downtown and NR-VAN stations experienced similar average concentrations and were the highest of the study sites. The NR-VAN site measured the highest peak 1-hour and 8-hour levels. The NR-VAN station experienced a similar median to Vancouver-Downtown but higher average and peak levels. The NR-VAN station measured 1.4 times more CO compared with background station on average. Measured CO levels at all sites were well below any Metro Vancouver, federal or provincial objective or standard. At these concentrations carbon monoxide is not considered a health concern, however it is a useful contaminant to measure to identify local emission sources such as vehicle traffic.

The seasonal pattern for CO are plotted as monthly average and maximum 1-hour concentrations in Figure 5.10. Overall, average CO concentrations were higher in the winter compared with the summer. This seasonal pattern is typical of the region and is due to lower atmospheric mixing heights along with increased residential, commercial and industrial heating in the winter. The NR-VAN site measured considerably more CO during the colder winters of 2016/17 and 2017/18 compared with the milder winter of 2015/16. The comparison sites did not experience any noticeable difference between the winters, perhaps suggesting that traffic emissions are susceptible to differences in winter temperatures.

Wildfire smoke impacts are evident in the monthly maximum 1-hour measurements at all monitoring stations in July 2015, where a peak can be seen at all stations (Figure 5.10b).

The frequency distribution for hourly concentrations is shown in

Table 5.4. The lowest number of hours where 0-130 ppb concentrations were measured occurred at the Vancouver-Downtown site followed by NR-VAN. The NR-VAN site experienced the most frequent number of hours in the upper concentration ranges.

A series of diurnal plots are shown in Figure 5.11 for CO. Most stations exhibit higher winter concentrations on weekdays compared with weekends, with many stations showing a peak in the morning that corresponds relatively well with morning traffic patterns. Stations including NR-VAN, BG-VAN, N.Vancouver-2nd Narrows, N.Vancouver-Mahon Park and Richmond-Airport all show a peak (rapid increase and decrease) in concentrations on weekday mornings in winter where weekend mornings do not show the same pattern. Diurnal trends of carbon monoxide measured at the near-road station indicate a strong influence of traffic emissions.

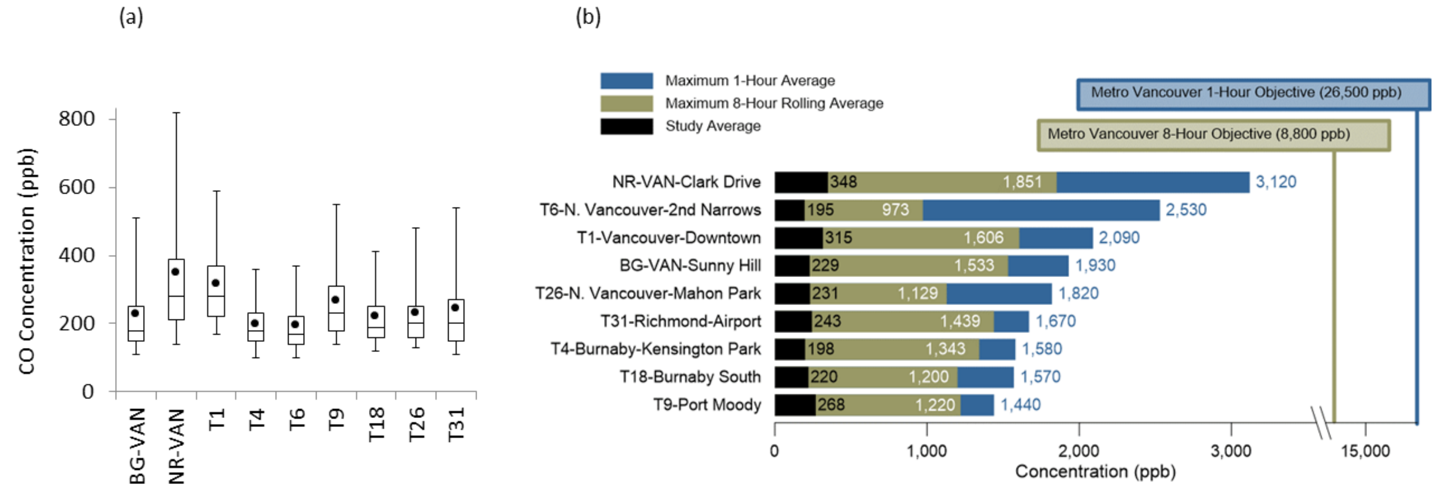


Figure 5.9: Carbon monoxide monitoring results during study period.

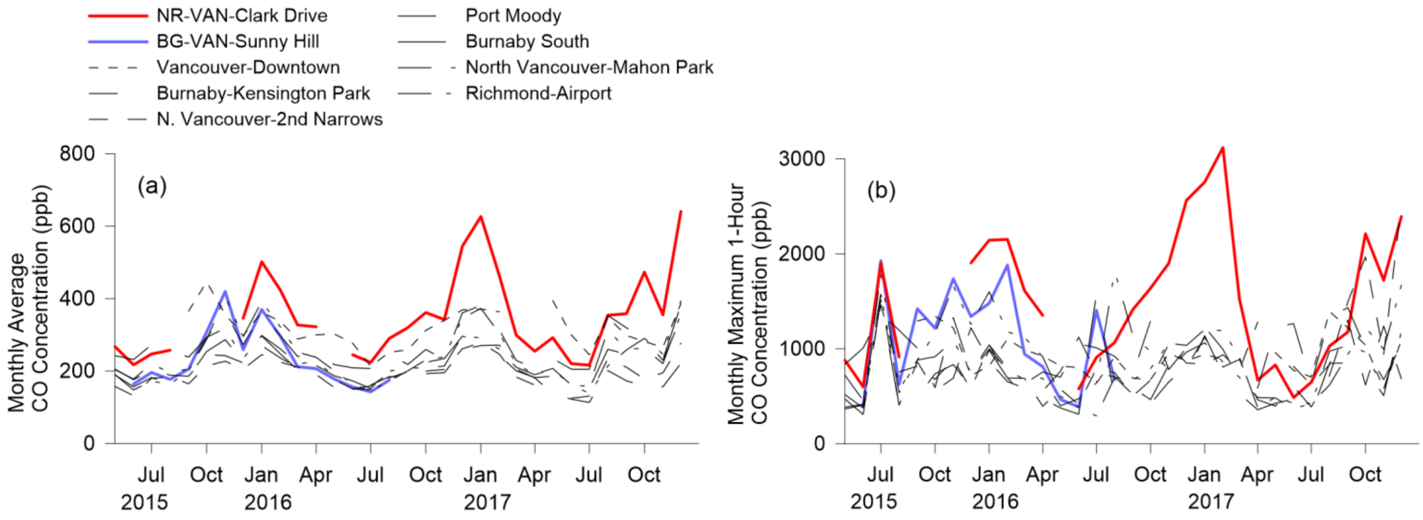


Figure 5.10: Monthly average (a) and short-term peak (b) carbon monoxide.

Table 5.4: Frequency distribution hourly carbon monoxide.

CO Conc. (ppb)	BG-VAN-Sunny Hill	NR-VAN-Clark Drive	Vancouver-Downtown	Burnaby-Kensington Park	N. Vancouver-2nd Narrows	Port Moody	Burnaby South	N. Vancouver-Mahon Park	Richmond-Airport
0 to 130	1504	498	137	3526	4305	593	1886	1400	2679
130 to 260	7346	8654	8495	15659	14489	13791	15738	16162	13734
260 to 390	1492	6680	8258	2744	2507	5226	3597	3467	3861
390 to 520	436	2328	2648	563	607	1789	937	1052	1234
520 to 650	205	1019	937	141	206	857	274	512	540
650 to 780	102	629	412	44	62	326	97	194	312
780 to 910	95	356	160	15	26	118	33	92	173
910 to 1040	64	237	69		9	43	16	54	113
1040 to 1170	36	155	23	6	4	20	9	15	62
1170 to 1300	23	125	19	5	2	14	4	3	26
1300 to 1430	15	91	5	2	4	5	2	1	20
1430 to 1560	4	68	1	2	2	1	2		6
1560 to 1690	3	63	1	1			1		7
1690 to 1820	2	29	3					1	
1820 to 1950	3	24						1	
1950 to 2080		12			1				
2080 to 2210		10	1						
2210 to 2340		1							
2340 to 2470		3							
>=2470		5			1				
Missing Data	12094	2437	2255	716	1199	641	828	470	657
Completeness	48%	90%	90%	97%	95%	97%	97%	98%	97%

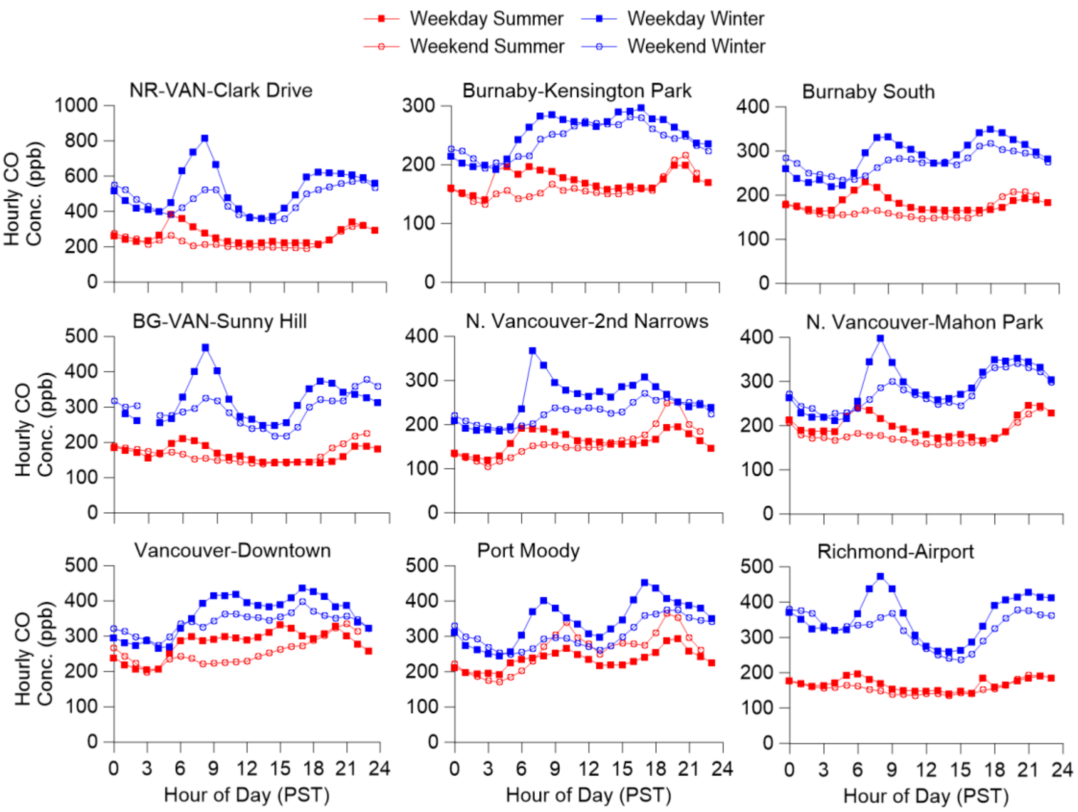


Figure 5.11: Diurnal trends carbon monoxide.

5.4 Fine Particulate Matter (PM$_{2.5}$)

Emissions of PM$_{2.5}$ are dominated by residential wood burning, heating, transportation, industrial sources and non-road engines. In addition to these local sources, PM$_{2.5}$ can be transported long distances in the air from sources such as large forest fires in other parts of western Canada, the US or more distant.

Scientific investigations in the LFV indicate that a considerable proportion of ambient PM$_{2.5}$ is also formed by reactions of NO$_X$ and SO$_2$ with ammonia in the air (mainly from agricultural sources in the LFV). Fine particulate produced in this manner is called secondary PM$_{2.5}$ and accounts for a significant percentage of PM$_{2.5}$ in summer. Therefore, emissions of precursor gases of secondary PM$_{2.5}$ are also important sources in the region.

Figure 5.12 illustrate the results of PM$_{2.5}$ monitoring during the study period. A boxplot of hourly values is provided in Figure 5.12a while the maximum 24-hour rolling average as well as the study period average is shown in Figure 5.12b. Two of the summers during the study experienced active wildfire seasons with fires mainly burning outside the region. Heavy smoke was transported by these wildfires into the region. Unprecedented levels of PM$_{2.5}$ were encountered throughout the region when high levels of PM$_{2.5}$ were measured in the summers of 2015 and 2017. Given the influence of wildfire smoke, days impacted by wildfire smoke were removed from the analyses provided here to more clearly show differences between the near-road and comparison sites under more normal conditions.

After removing wildfire effects, all stations were below Metro Vancouver's 24-hour PM$_{2.5}$ objective with the exception of the near-road station (Figure 5.12b). The NR-VAN station exceeded the objective on two days in 2015 (November 29 and 30) and five days in 2017 (October 29, 30 and 31; November 1 and 12). With wildfire effects removed, the study period average (May 1, 2015 to December 31, 2017) was below the Metro Vancouver annual objective of 8 µg/m^3 at all stations and below the planning goal of 6 µg/m^3 at all but one station, NR-VAN. Metro Vancouver's planning goal is a longer term aspirational target to support continuous improvement. On average, the NR-VAN station experienced 1.4 times more $PM_{2.5}$ than the background station.

The annual average for each station by year is presented including wildfire effects in Table 5.5. The near-road monitoring station was the only station to exceed the annual average objective, which occurred in both 2015 and 2017 when wildfire smoke impacted the region during summer. Since the near-road station started operation late in the year in 2015, the year did not meet the 75% data completeness criteria typically used to calculate an annual average.

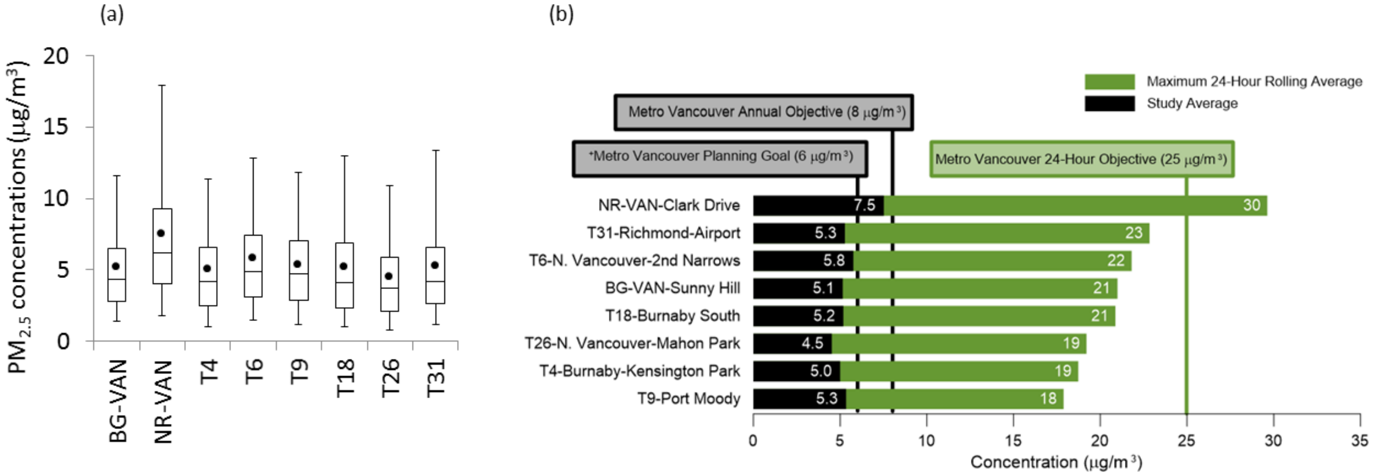


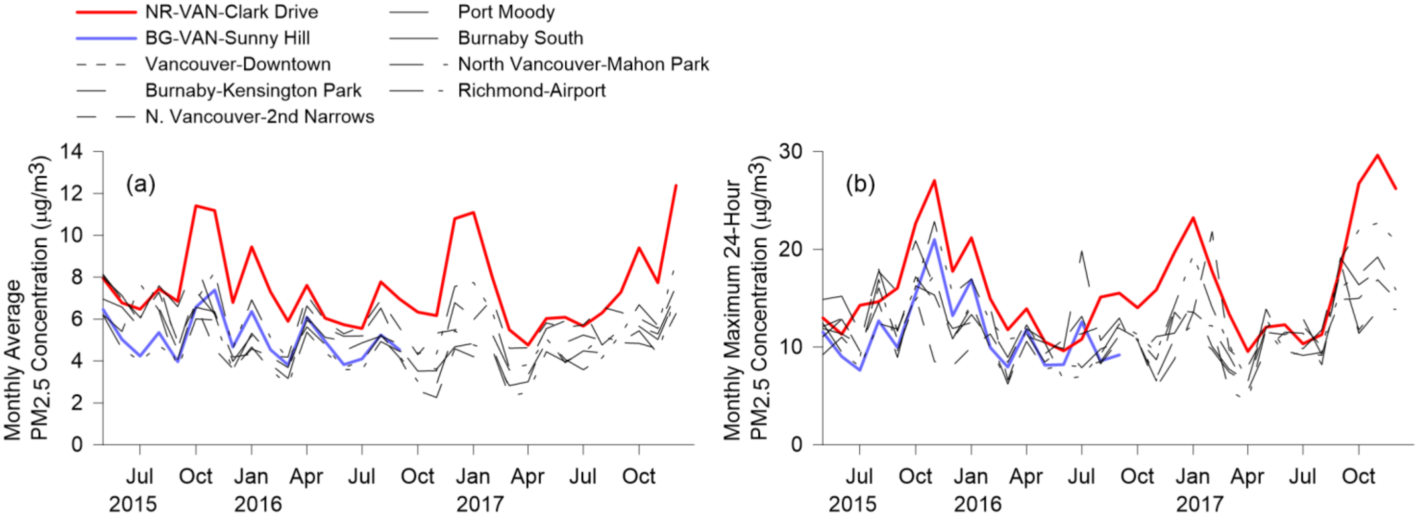
Figure 5.12: Fine particulate matter monitoring results (with wildfire effects removed).

Table 5.5: Annual average fine particulate matter by year (wildfire effects included).

Station	2015	2016	2017
NR-VAN-Clark Drive	**8.8***	7.1	**8.8**
BG-VAN-Sunny Hill	6.1*	4.8	-
Burnaby-Kensington Park	6.6	4.5	6.4
N. Vancouver-2nd Narrows	6.2	5.4	7.7
Port Moody	6.3	4.9	7.1
Burnaby South	7	4.6	6
N. Vancouver-Mahon Park	5.5	4.1	6.3
Richmond-Airport	6	5	6.2

*Did not meet data completeness criteria and average was calculated from all data available within the year.

Seasonally, $PM_{2.5}$ levels are historically higher in the summer with the highest values typically experienced during the dry summer months (Figure 5.13), due to the secondary formation of $PM_{2.5}$ and smoke from wildfire activity. However, when wildfire effects were removed (as was done for Figure 5.13) there was little to no seasonal pattern in average $PM_{2.5}$ levels at the study sites. The NR-VAN site experienced greater averages in October and November in 2015, December 2016, January and December 2017. The highest peak levels experienced a similar pattern with the elevated concentrations generally occurring in fall and winter.



Note: Due to extreme wildfire smoke that impacted the region, wildfire smoke effects have been removed.

Figure 5.13: Monthly average (a) and short-term peak (b) fine particulate matter.

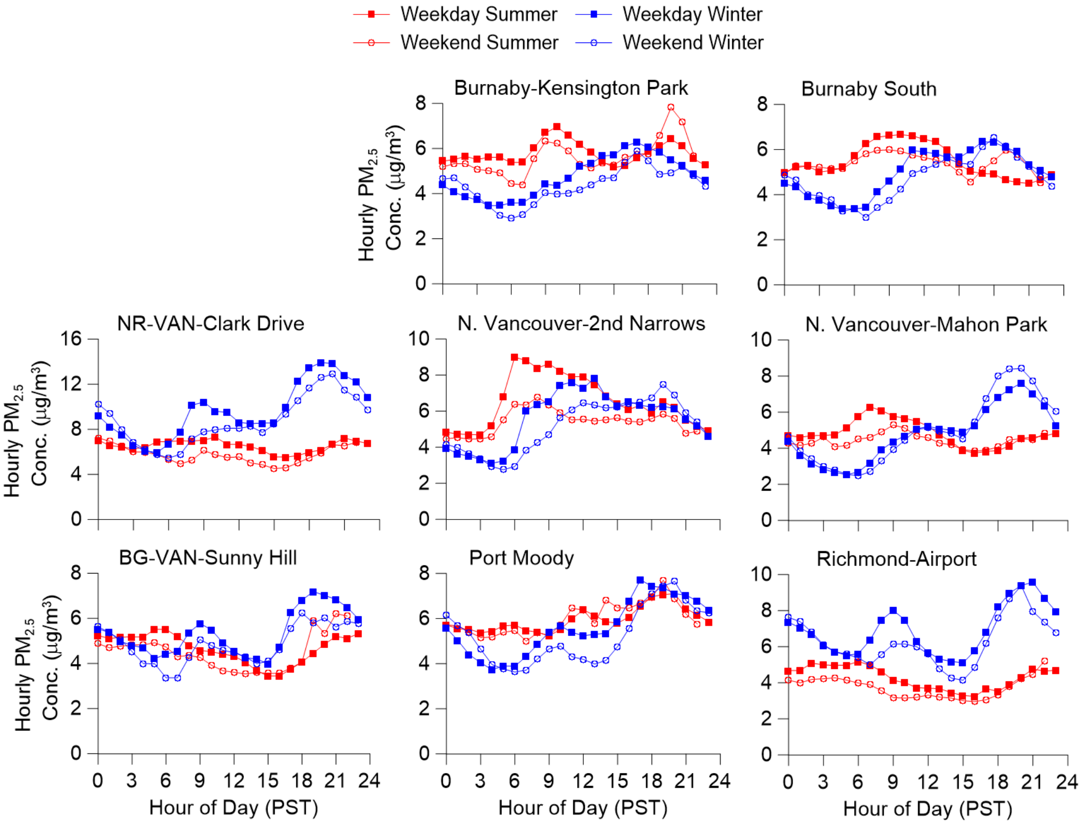
Table 5.6 provides the frequency distribution of $PM_{2.5}$ concentrations for the study period. Wildfire days have been included in the table. The dominant wildfires during the study period occurred in 2015 when heavy smoke was transported from the northwest of Vancouver. The stations NR-VAN and BG-VAN were among the most impacted in the region during the wildfire event. The NR-VAN site exhibited the lowest frequency of lower concentrations (0-5 $\mu g/m^3$), indicating a nearby source of PM emissions from traffic.

A series of diurnal plots are shown in Figure 5.14 for $PM_{2.5}$ with wildfire effects removed. In general, the summer exhibited little diurnal variation while the winter displayed higher $PM_{2.5}$ concentrations in the evenings compared with the daytime. The evenings in winter were likely elevated due to reduced atmospheric mixing depths coupled with regional and local emission sources such as residential wood burning.

Table 5.6: Frequency distribution 24-hour rolling average fine particulate matter.

Note: Wildfire days have been included in this table.

$PM_{2.5}$ Conc. ($\mu g/m^3$)	BG-VAN-Sunny Hill	NR-VAN-Clark Drive	Burnaby-Kensington Park	N. Vancouver-2nd Narrows	Port Moody	Burnaby South	N. Vancouver-Mahon Park	Richmond-Airport
0 to 5	6911	5072	12921	9252	11319	12572	14281	13073
5 to 10	4540	12537	8200	10827	9411	7674	6625	7746
10 to 15	516	2578	1179	1335	1210	1675	824	1535
15 to 20	106	814	132	93	87	207	119	472
20 to 25	36	366	52	62	59	66	57	130
25 to 30	2	136	35	33	30	87	24	53
30 to 35	1	62	42	35	40	77	25	60
35 to 40	1	57	29	26	30	48	47	19
40 to 45	2	47	49	40	43	49	34	1
45 to 50	1	38	59	65	49	23	48	3
50 to 55	2	43	80	61	60	6	59	3
55 to 60	1	2	35	71	56	7	82	3
60 to 65	2	2	6	17	5	12	26	3
65 to 70	1		6	13	4	8	21	4
70 to 75	1	2	4	12	4	1	1	7
75 to 80	1	2	6		3	2	2	
80 to 85	2	1	10		9	3	2	
85 to 90	1	2	2		9	11	1	
90 to 95	2	1	2		4		3	
95 to 100	2	2	2		7		4	
100 to 105	2	2	4				4	
105 to 110	1	2	2					
110 to 115	2	2	7					
115 to 120	3	4						
120 to 125	6	4						
>=125								
Missing Data	11279	1646	560	1482	985	896	1135	312
Completeness	52%	93%	98%	94%	96%	96%	95%	99%



Note: Due to extreme wildfire smoke that impacted the region, wildfire smoke effects have been removed.

Figure 5.14: Diurnal trends fine particulate matter.

5.5 Black Carbon (BC)

Black carbon (BC) is carbonaceous material formed by the incomplete combustion of fossil fuels, biofuels, and biomass, and is emitted directly as a component of fine particulate matter ($PM_{2.5}$). BC is a major component of "soot", a complex light-absorbing mixture that also contains some organic carbon. Black carbon contributes to the adverse impacts on human health, ecosystems, and visibility associated with fine particulate matter ($PM_{2.5}$).

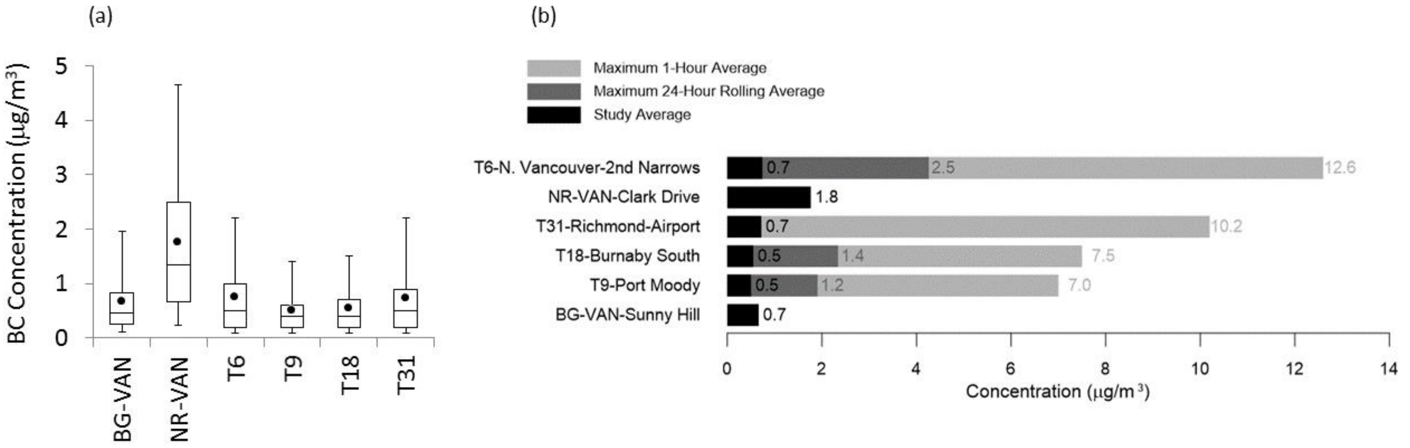
Although BC has a very short residence time in the atmosphere (about a week), it is a strong absorber of solar radiation. As a result, BC is considered a "short-lived climate forcer" and has climate change implications.

Mobile sources are the largest contributors of BC emissions in the LFV, emitting over 80% of the BC emissions in the region. Non-road engines (primarily diesel fuelled), heavy-duty vehicles, diesel rail locomotives and marine vessels are significant sources of BC emissions. Other significant sources in the region are biomass burning activities, including agricultural burning, open and prescribed burning, wildfires and residential heating.

Figure 5.15 illustrates the results of BC monitoring for the study period in a boxplot (a) and bar chart (b) format. Figure 5.15b displays the value of the maximum 1-hour and 24-hour average as well as the study average for each station.

There are no provincial, federal or Metro Vancouver objectives for black carbon. While the highest 1-hour peak concentration occurred at N.Vancouver-Second Narrows, the highest average concentrations were measured at the near-road station (NR-VAN). The NR-VAN station measured BC concentrations 2.8 times greater than at the background station on average.

In Figure 5.16 the seasonal BC patterns are shown. There does not appear to be a seasonal pattern, with the highest average values occurring in October 2015, January 2017 and August 2017 at the NR-VAN site. A series of diurnal plots are shown in Figure 5.17 for BC. Considerably more BC was present on weekdays compared with weekend in both winter and summer at NR-VAN. On winter weekdays the morning exhibited the highest peak concentrations with a decline near noon and increase until the evening at NR-VAN. Winter weekends displayed little variation throughout the day.



*Due to a data logging issue peak hourly measurements for NR-VAN and BG-VAN are not shown here.

Figure 5.15: Black carbon monitoring results.

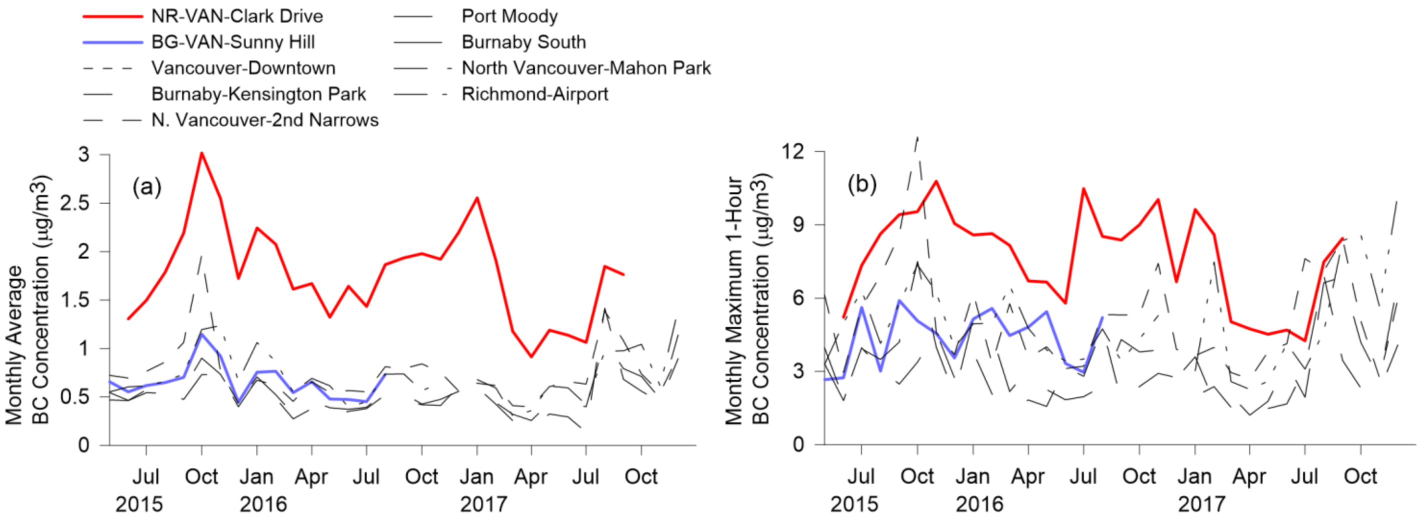


Figure 5.16: Monthly average (a) and short-term peak (b) black carbon.

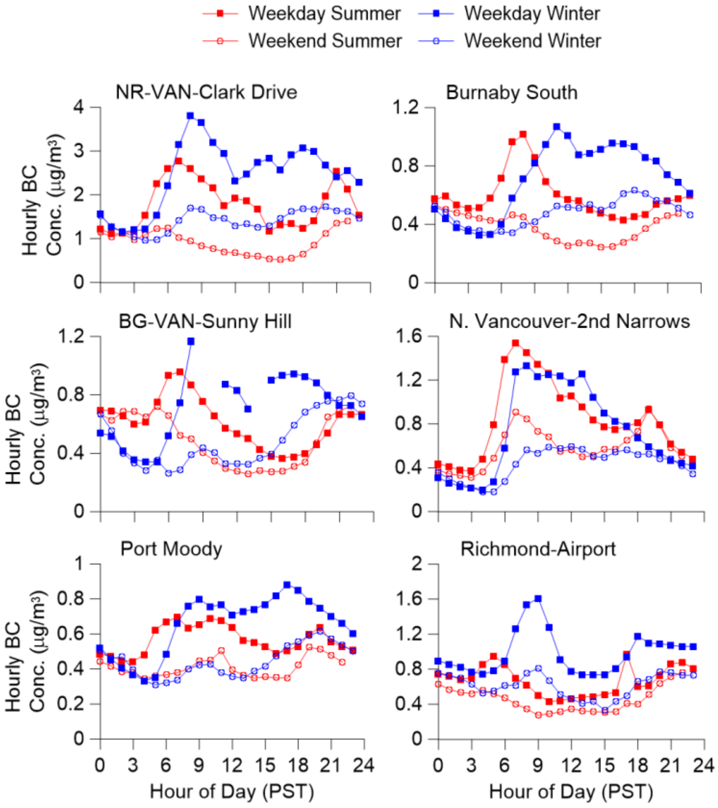


Figure 5.17: Diurnal trends black carbon.

5.6 Ultrafine Particles (UFP)

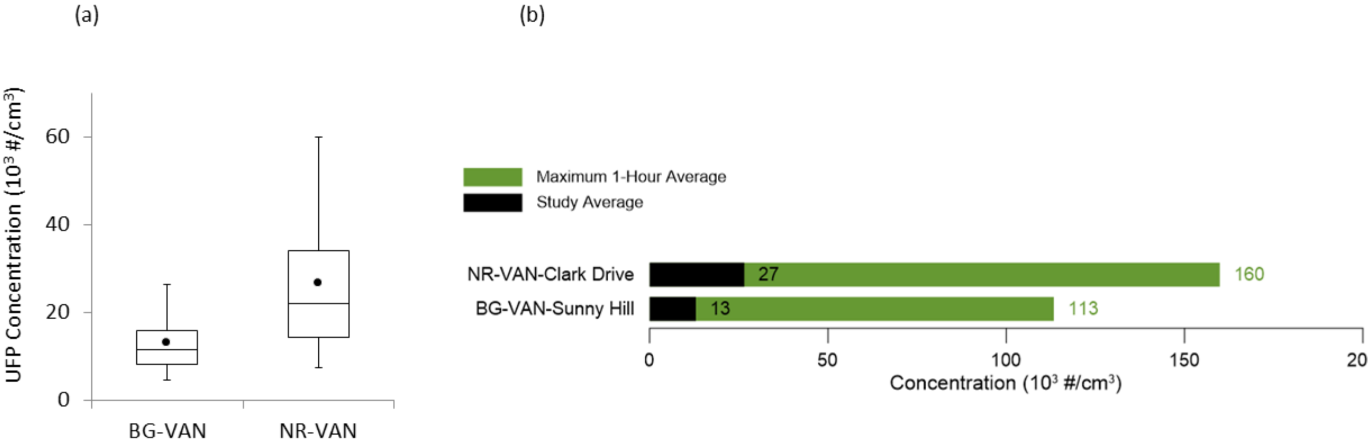
Ultrafine particles (UFP) consists of a combination of suspended solids and liquid droplets having aerodynamic diameters less than 0.1 microns (100 nanometers). These particles are measured based on their number concentration (units of 10^3 #/cm^3) in the atmosphere rather than fine particulate matter that is measured based on its mass concentration (μg/m^3).

Sources of UFP include direct emissions from manufacturing and combustion sources. Ultrafine particles can also be formed from chemical reactions involving contaminants identified as precursors. Health research indicates that smaller particles are more harmful to human health. Unlike larger particles, UFP can penetrate pulmonary tissue, enter the bloodstream, and circulate throughout the body thereby damaging a number of internal bodily systems that may be inaccessible to larger particles.

Ultrafine particles are relatively short-lived in the air, as compared to longer-lived $PM_{2.5}$ particles which may persist in the atmosphere for up to several weeks. The short lifetime for UFP results from their very high number concentrations upon emission. Levels may peak near strong UFP sources such as busy freeways. These exceptionally concentrated UFP rapidly agglomerate (stick together) with each other and with larger particles (e.g. $PM_{2.5}$) to yield particles with diameters larger than 0.1 microns. Agglomeration, dispersion, and advection are the dominant atmospheric processes determining the UFP spatial distribution. Deposition (settling onto surfaces) plays a minor role in the UFP spatial distribution because gravity does not have a strong influence on UFP. Typically, UFP levels decrease exponentially within 500 m of a strong source.

Long-term continuous ultrafine particles monitoring has not been conducted in the region prior to this study. The results from the background and near-road monitoring study are the first collected in the Metro Vancouver region due to availability of new monitoring technology and interest in these particles from a health perspective.

The results of UFP monitoring are shown with a boxplot in Figure 5.18a with the study average and maximum 1-hour averages shown in Figure 5.18b. There are currently no federal, provincial or Metro Vancouver air quality objectives for UFP. On average the near-road station (NR-VAN) measured twice as many ultrafine particles than the background station (BG-VAN).



Note: UFP measurements were only made at the two near-road study sites.

Figure 5.18: Ultrafine particles monitoring results.

Seasonally, UFP levels at NR-VAN followed a similar pattern to NO_2 and CO with higher average concentrations measured in the winter months (Figure 5.19). Due to the shorter data collection period at BG-VAN, it is difficult to discern a seasonal pattern.

Table 5.7 shows the frequency distribution of UFP concentrations for the study period. The near-road monitoring site (NR-VAN) measured a greater frequency of higher concentrations compared with the background site (BG-VAN).

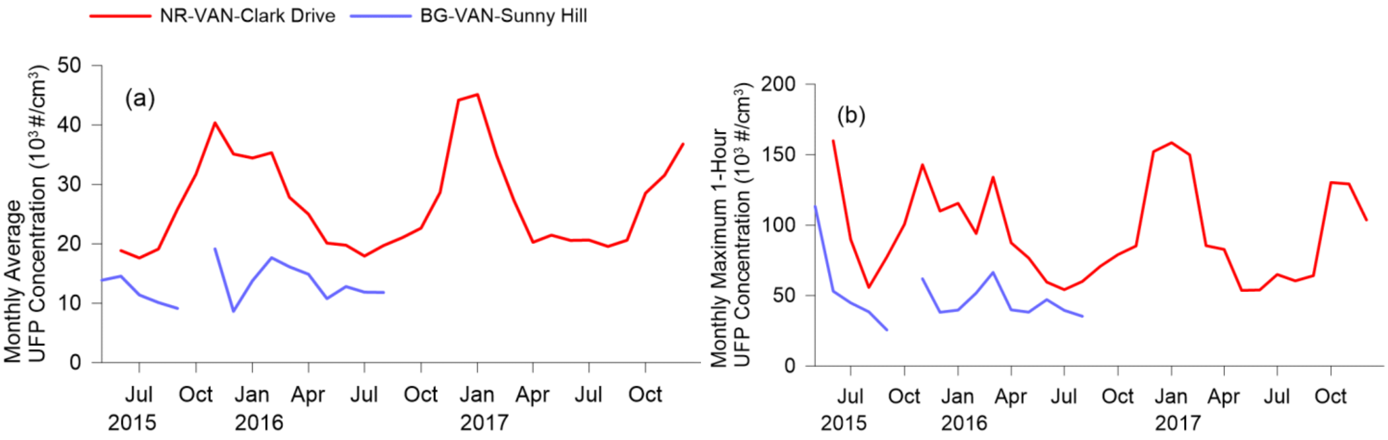


Figure 5.19: Monthly average (a) and short-term peak (b) ultrafine particles.

Table 5.7: Frequency distribution 1-hour average ultrafine particles.

UFP Conc. (10^3 #/cm^3)	BG-VAN-Sunny Hill	NR-VAN-Clark Drive
0 to 5	739	404
5 to 10	3628	1917
10 to 15	3573	3450
15 to 20	1796	3428
20 to 25	844	2845
25 to 30	398	2292
30 to 35	181	1718
35 to 40	73	1296
40 to 45	28	939
45 to 50	10	729
50 to 55	5	540
55 to 60	2	421
60 to 65	1	259
65 to 70	1	208
>=70	1	589
Missing Data	12144	2389
Completeness	48%	90%

Diurnal plots are provided for the two UFP monitoring stations in Figure 5.20. The NR-VAN station exhibited less diurnal variation in summer with consistently higher concentrations compared to the background site. The background site exhibited a peak midday corresponding with a nucleation event. Nucleation events are associated with chemical reactions involving precursor contaminants. Weekdays experienced greater concentrations compared with weekends. Traffic emissions were the dominant source of UFP at NR-VAN.

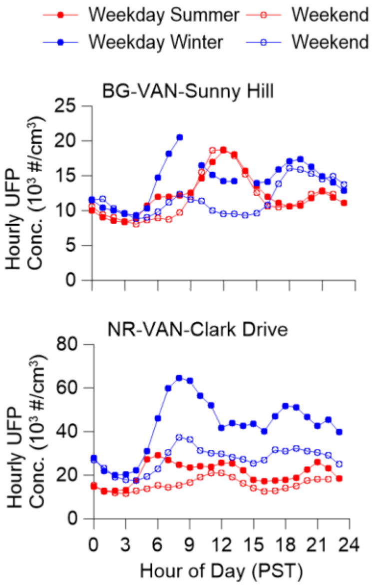


Figure 5.20: Diurnal trends ultrafine particles.

5.7 Volatile Organic Compounds (VOC)

Volatile organic compounds are organic compounds containing one or more carbon atoms that have high vapour pressures and therefore evaporate readily to the atmosphere at normal ambient temperatures and pressures. VOC can originate from direct emissions, volatilization (i.e. changing into the gas phase) of substances in the liquid or solid phase, and formation from precursor contaminants via chemical reactions in the atmosphere. Sources of VOC in the LFV include, but are not limited to, emissions from the combustion of fossil fuels, evaporation from industrial and residential solvents and paints, vegetation, agricultural activities, petroleum refineries, fuel-refilling facilities, the burning of wood and other vegetative materials, and large industrial facilities.

Locally, VOC can be found in urban smog and are precursors to the formation of other contaminants present in smog such as ozone and fine particulates. Some VOC (e.g. carbon tetrachloride) can contribute to depletion of the stratospheric ozone layer and may contribute to climate change. Other VOC (e.g. benzene) can pose a human health risk.

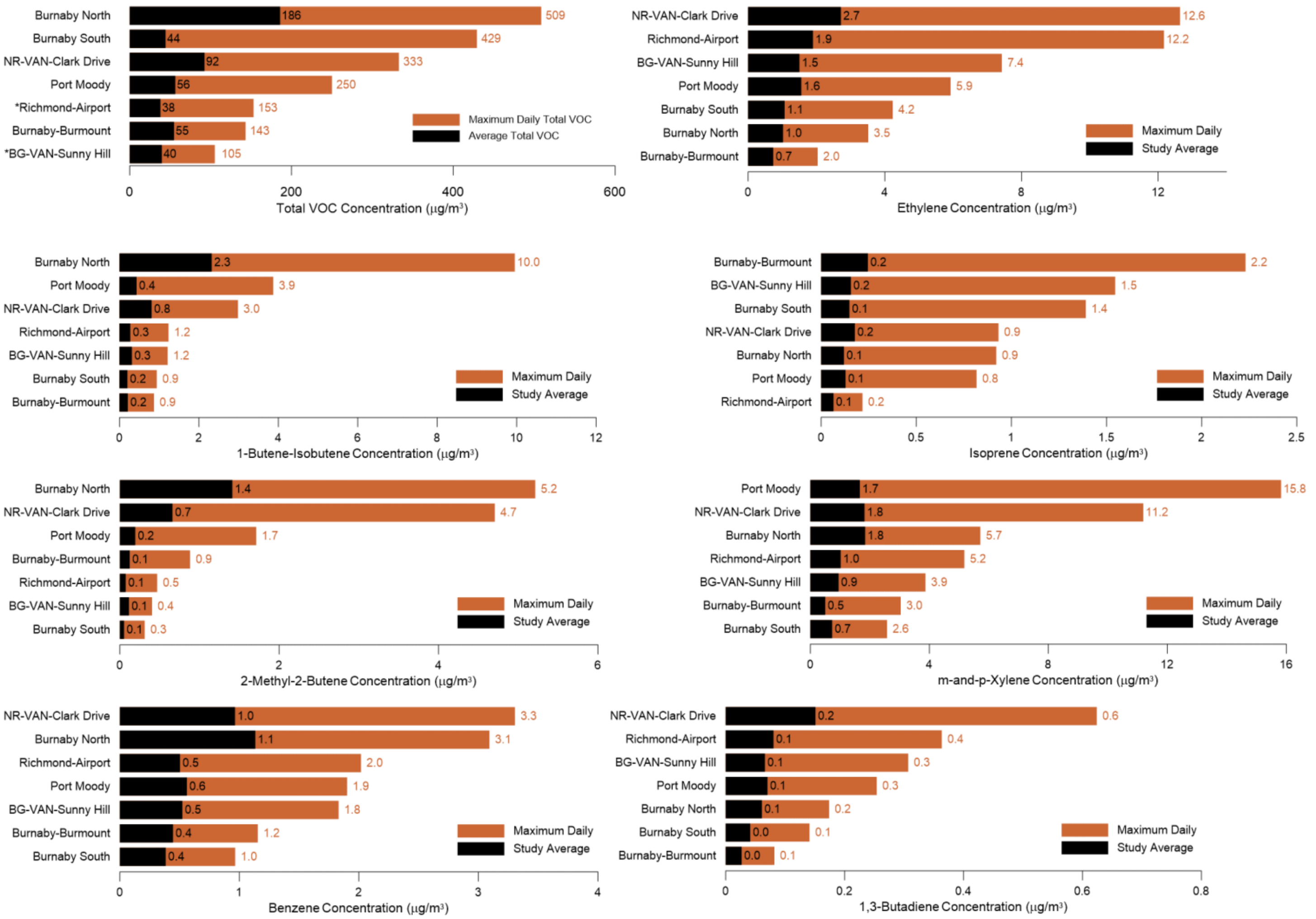
VOC samples were collected at both NR-VAN and BG-VAN along with other sites in the LFV. In cooperation with the federal NAPS program, canister sampling of VOC has been conducted in the LFV since 1988. Canisters sent to the federal laboratory are analyzed for up to 175 species of VOC. While there are many thousands of organic compounds in the atmosphere that meet the definition of a VOC, the NAPS measurement program focuses on VOC that are important precursors in ozone formation and/or are known to have toxic effects. In order to report and track the most important VOC in relation to these two main focus areas, a number of priority VOC, as defined below, have been selected and reported herein.

Figure 5.21 shows the maximum daily total VOC and average total VOC from each VOC monitoring station from July 11, 2015 to Dec 26, 2016. Results for samples collected in 2017 had not been analyzed by the laboratory in time to be included in this report. The data indicates that the highest average total VOC levels were measured at Burnaby North which is located near an oil refinery tank farm. The NR-VAN site experienced the second highest average VOC.

VOC species have a range of photochemical reactivity, and thus potential to lead to ozone formation. In the report *Metro Vancouver VOC Policy Options Review* (SNC Lavalin, 2015), a ranking of VOC is presented based on the reactivity of the VOC species and their relative abundance in the LFV. The top five ranked VOC for ozone formation in the LFV were ethylene, 1-butene/isobutene, isoprene, 2-methyl-2-butene, and m- and p-xylene and measured concentrations are shown in Figure 5.21.

Toxic VOC have been identified as a human health concern due to known acute or chronic health effects. The *Toxic Air Pollutants Risk Assessment* (Sonoma, 2015) commissioned by Metro Vancouver identified high priority toxic VOC in the LFV based on cancer and/or non-cancer health risks associated with measured levels. The study identified high priority VOC including benzene and 1,3-butadiene and measured concentrations are shown in Figure 5.21.

- **Ethylene** is the number one ranked VOC for its ozone producing potential in the LFV. Ethylene, also known as ethene, has the chemical formula C_2H_4. It is a colorless gas with a sweet odour and taste. Ethylene occurs naturally and is also manufactured for a number of uses. Ethylene is degraded in the atmosphere by reactions with hydroxyl radicals, ozone and nitrate radicals and is the number one ranked VOC in the LFV for its ozone producing potential. The highest average and peak concentrations occurred at NR-VAN and Richmond-Airport.
- **1-Butene/isobutene** are emitted both by natural and anthropogenic sources and are the second most important VOC in terms of its ozone producing potential in the LFV. They are colourless gases with a slightly aromatic odour. The highest average and peak concentrations occurred at the Burnaby North station that is adjacent to a tank farm where petroleum products are stored.



*Data completeness criteria were not met at these stations and averages were calculated from all available data during July 11, 2015 to December 26, 2016.

Figure 5.21: VOC monitoring, July 2015 to December 2016.

- **Isoprene** is a priority from an ozone production perspective and is released to the atmosphere by natural sources and during the production of heavy petroleum oils. Isoprene is a colourless, volatile liquid hydrocarbon with the chemical formula C_5H_8 and has a mild aromatic petroleum-like odour. Vapor-phase isoprene is degraded in the atmosphere by reaction with photochemically-produced hydroxyl radicals and thus is of interest due to its ozone producing potential. The highest concentrations occurred at the Burnaby-Burmount station that is adjacent to the Burnaby Mountain tank farm where petroleum products are stored. Interestingly the background station (BG-VAN) measured higher peak and average levels compared with the near-road monitoring station (NR-VAN).
- **2-Methyl-2-butene** is a component of refinery gas and used as an agricultural chemical, fuel and fuel additives, and intermediate in chemical manufacturing. It reacts to form ground-level ozone. 2-Methyl-2-butene is a clear colourless liquid with the chemical formula C_5H_{10} and a petroleum-like odour. The compound is degraded in the atmosphere by reaction with photochemically-produced hydroxyl radicals, ozone, and nitrate radicals. The highest concentrations occurred at the Burnaby North station that is adjacent to the refinery tank farm followed by NR-VAN.
- **Xylenes**, released into the atmosphere as fugitive emissions from industrial sources, vehicle exhaust, and solvents, react to help form ground-level ozone. Xylenes are a family of three aromatic hydrocarbon isomers (ortho-, meta- and para-xylene) with the chemical formula C_8H_{10}. They are colourless liquids that are nearly insoluble in water

and have a sweet odour. The highest daily maximum concentration occurred at Port Moody followed by NR-VAN while the highest average concentrations occurred at NR-VAN and Burnaby North.

- **Benzene** is an aromatic hydrocarbon with a sweet odour at high concentrations and the chemical formula C_6H_6. At ambient temperature it occurs as a volatile, colourless, highly flammable liquid that is somewhat soluble in water. Benzene has been classified by the US EPA as a known human carcinogen and has both acute and chronic inhalation exposure effects. At current ambient concentrations measured in the LFV, it poses a lifetime cancer risk greater than Health Canada's 1 in 100,000 screening threshold (Sonoma, 2015). In the LFV, the primary sources of benzene include gasoline engine exhaust, service station fugitive emissions, and residential wood burning, as well as refinery and tank farm fugitive emissions. The highest peak and average concentrations occurred at NR-VAN and Burnaby North that is adjacent to the refinery tank farm.
- **1,3-Butadiene** is a colourless gas with mild gasoline-like odour with the chemical formula C_4H_6. 1,3-Butadiene has been classified by the US EPA as a known human carcinogen and has both acute and chronic inhalation exposure effects. At current ambient concentrations measured in the LFV it poses a lifetime cancer risk greater than Health Canada's 1 in 100,000 screening threshold. 1,3-Butadiene is found in emissions from gasoline internal combustion engines in on-road vehicles, off-road vehicles, and aircraft. In Metro Vancouver, residential wood burning is also a significant source, and oil refinery emissions have historically contributed to 1,3-butadiene emissions The highest peak and average concentrations occurred at the near-road monitoring station (NR-VAN) followed by the Richmond-Airport station.

Highest levels of VOC were measured near petroleum storage tank facilities. For all VOC presented in this section (except isoprene), NR-VAN had higher measured concentrations than BG-VAN. These elevated levels at NR-VAN were due to traffic emissions in the near-road environment and the presence of two gas stations located within 75 metres of the near-road station.

6. Detailed Near-Road Findings

This section contains the detailed findings from several different types of analyses. The analyses presented in this section include near-road contribution, pollution roses and polar plots, wind sector analyses, contaminant and traffic correlations, and comparison to other near-road monitoring stations.

6.1 Near-Road Contribution

The near-road (NR-VAN) and background (BG-VAN) monitoring stations were established to act as comparison sites, with the aim of isolating the effects of heavy traffic. They were located near to each other to ensure that both were affected similarly by large- or regional-scale air quality influences. NR-VAN was located beside a major traffic route with high traffic volume, while BG-VAN was situated in a residential neighbourhood beside a bike route with very low traffic. Differences in air quality between the two sites can mainly be attributed to traffic emissions.

To calculate the traffic-related air pollution contributed by traffic emissions, or near-road contribution, hourly concentrations measured at the background station (BG-VAN) were subtracted from the near-road monitoring station (NR-VAN) for each hour of the day. This approach has been found to a good way to determine the near-road contribution (Hilker et al., 2019). Figure 6.1 provides the distribution of the hourly near-road contributions for NO_2, NO_x, NO, CO, O_3, $PM_{2.5}$, BC and UFP. The average contribution is provided in Table 6.1 for all days, weekdays, Saturdays and Sundays The percent contribution is also provided, calculated as the near-road contribution divided by the average contaminant concentration at the near-road site. These contributions represent the percentage of contaminants measured at the near-road site thought to be attributable to traffic emissions.

The trend was consistent amongst the contaminants NO_2, CO, $PM_{2.5}$, BC and UFP whereby the greatest near-road contribution was experienced on weekdays while a smaller contribution was experienced on Saturday and least on Sunday. A converse trend is evident with ground-level ozone where the near-road station measured lower levels of ozone compared with the background station. Lower O_3 in the near-road environment was expected due to the O_3 scavenging that occurs where higher levels of NO_x are found near busy roadways.

There was a larger near-road contribution in nitrogen dioxide measurements on weekdays (6.2 ppb) with a smaller difference on Saturday (3.9 ppb) and Sunday (3.1 ppb). A similar trend was apparent with CO, $PM_{2.5}$, BC and UFP where the largest differences occur on weekdays. The average near-road contribution of $PM_{2.5}$ was 2.2 $\mu g/m^3$ which is significant since it is more than a quarter of Metro Vancouver's annual $PM_{2.5}$ objective of 8 $\mu g/m^3$. The contribution results in the annual objective not being achieved at the near-road station during years impacted by wildfire smoke transported into the region.

There was considerably more black carbon in the near-road environment. The near-road site experienced on average 1.2 $\mu g/m^3$ more black carbon than the background site. On average more than half of the additional $PM_{2.5}$ measured at the near-road site was black carbon.

Ultrafine particles were considerably higher in the near-road environment compared with the background station. The contribution was much greater on weekdays compared with weekends. On average the near-road site experienced 11,500 $\#/cm^3$ more UFP with 13,800 $\#/cm^3$ more UFP on weekdays.

It was found that there was a near-road contribution for all contaminants measured (NO_2, NO, NO_x, CO, $PM_{2.5}$, BC and UFP) with the exception of O_3. The contribution was calculated as the average difference between the near-road and background measurements divided by the average near-road concentration and expressed as a percentage. A range of percent contributions were found at the near-road station for each contaminant: NO_2 (28%), NO (71%), NO_x (55%), CO (30%), $PM_{2.5}$ (30%), BC (64%), UFP (46%) and O_3 (-32%). These contributions represent the percentage of contaminants measured at the near-road site thought to be attributable to traffic emissions.

Both the near-road contribution and contaminant concentrations were found to be higher on weekdays compared with weekends for all traffic-related air pollutants. On average, CO and $PM_{2.5}$ near-road contributions were one and a half times higher on weekdays compared with Sunday, NO_2, NO, and NO_x were at least twice as high, while BC and UFP were nearly three times higher.

The lower concentrations on weekends can be explained by the large reductions of heavy-duty vehicle traffic. Traffic volumes were found to be the highest on weekdays with a negligible 0.3% reduction on Saturdays and 12% reduction on Sundays of light-duty and considerable 51% reduction on Saturdays and 72% reduction on Sundays for large heavy-duty. The total traffic volume and greater truck traffic on weekdays is thought to play a key role in near-road contributions. The reduction in contaminant levels on Saturday can almost entirely be attributed to the reduction in trucks indicating the disproportionate influence of these vehicles. Sunday had considerably lower truck traffic and lowest near-road contribution of any day.

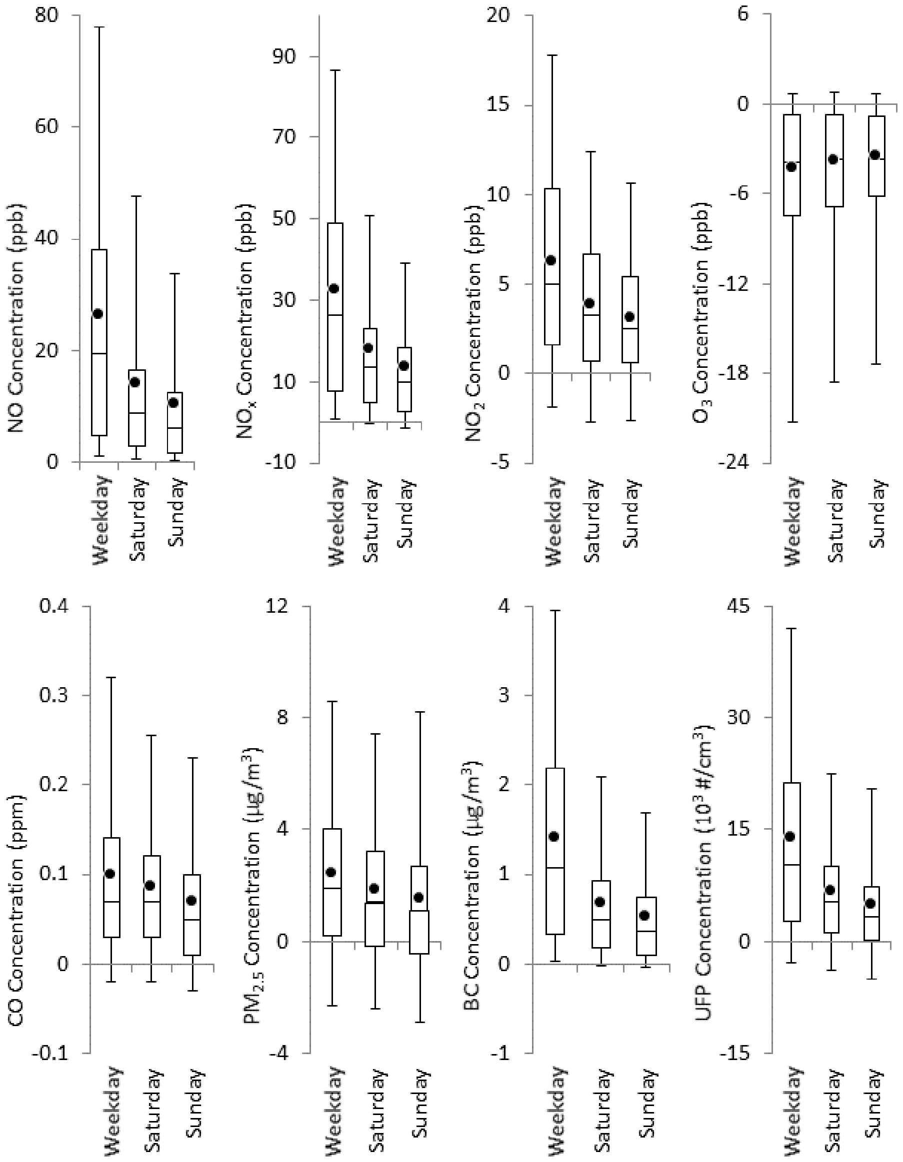


Figure 6.1: Distribution of near-road contribution for various contaminants at NR-VAN.

Table 6.1: Near-road contribution at NR-VAN for various contaminants.

Contaminant	Units	All		Weekday	Saturday	Sunday
NO_2	ppb	5.4	(28%)	6.2	3.9	3.1
NO	ppb	22.3	(71%)	26.4	14.1	10.5
NOx	ppb	27.7	(55%)	32.6	18.0	13.5
CO	ppb	93	(30%)	100	87	69
O_3	ppb	-4.1	(-32%)	-4.3	-3.8	-3.5
$PM_{2.5}$	µg/m^3	2.2	(30%)	2.4	1.9	1.5
BC	µg/m^3	1.2	(64%)	1.4	0.7	0.5
UFP	10^3 #/cm^3	11.5	(46%)	13.8	6.7	5.0

A series of diurnal plots are shown in Figure 6.2 that demonstrate the hourly differences between the near-road (NR-VAN) and background (BG-VAN) station for each hour of the day. The plots are largely thought to be the near-road contribution throughout the day. Most contaminants exhibit a greater near-road contribution on weekdays compared with weekends. For example, a considerable near-road contribution of NO and NO_x was found on weekdays in both winter and summer compared with weekends. Fine particulate matter exhibited a lower near-road contribution in the early morning and increasing contribution during the day in the winter. The near-road contribution of UFP was greater in the winter compared with the summer where a rapid increase in contribution was found in the morning on weekdays. A bimodal peak was found for the near-road contribution of CO on weekdays where the first peak occurred in the morning and the second in the late afternoon.

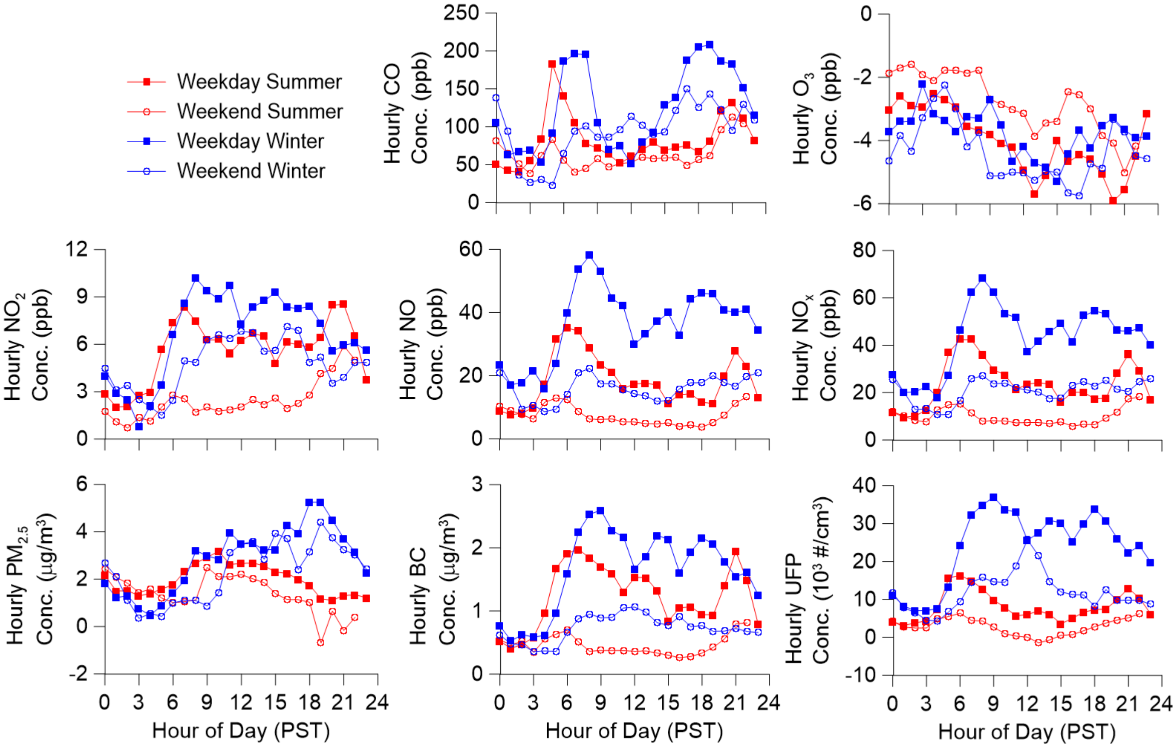


Figure 6.2: Diurnal trend of hourly difference between near-road and background measurements.

The seasonality of the differences between the near-road and background station measurements were examined. Figure 6.3 shows the monthly average of the hourly differences shown in black for various contaminants while the range of 25th – 75th percentiles are shown in dark grey with the range of 5th – 95th percentiles are shown in light grey. Generally, there is little seasonal variation between sites for NO_2. Carbon monoxide and fine particulate matter show a similar seasonal pattern with fall and winter exhibiting the greatest near-road contribution. Higher UFP were measured at the near-road site compared with the background station in winter compared with summer. Ground-level ozone was lower at the near-road site compared to the background site for most of the year with the greatest difference occurring in the spring.

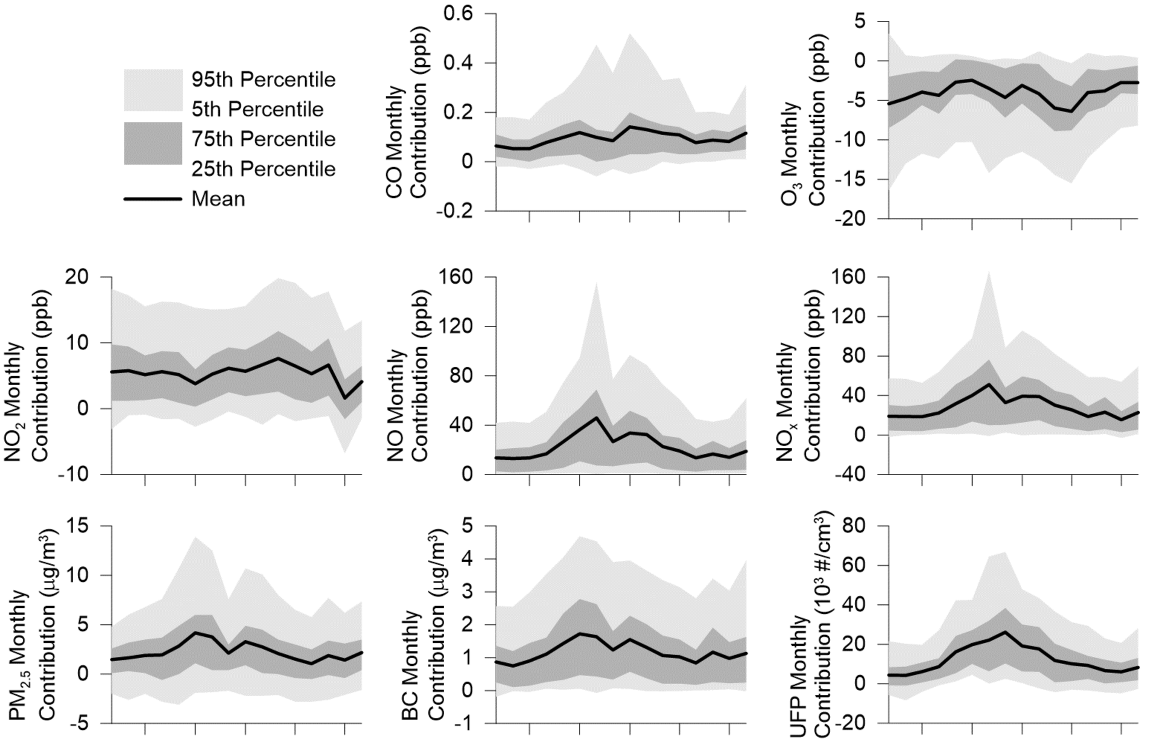


Figure 6.3: Seasonality of near-road contribution for various contaminants.

6.2 Pollution roses and polar plots

To visualize the relationship between winds and contaminant concentrations, pollution roses and polar plots can be used to identify directions from which contaminants may be originating or emitted. Pollution roses pair each hour's wind direction (at 12 m height) with the associated hourly concentration aggregated over the monitoring period. The petals of the pollution rose extend in the direction that wind was blowing from and are colored to represent the frequency of time (represented as a percentage) during which a range of concentrations were measured. The total length of the petal represents the percentage of time that wind was blowing from that direction and the individual colour bands are the subset of the total frequency for this direction.

Because each pollution rose is produced using the same wind direction observations, the length of each of the petals is the same for all figures (with the exception of CO and wind frequency due to different data completeness for these parameters). At the near-road station, one of the predominant wind directions is south-southeast from the intersection of Clark Drive and 12th Avenue. Due to the higher frequency of winds coming from this direction, it allows for more transport of contaminants from the intersection to the station and results in higher average concentrations under these wind conditions, as discussed in Section 3.2.3. A majority of the wind directions measured at the near-road station come from the directions which have significant vehicle traffic and therefore these figures demonstrate that the near-road station likely measures concentrations related to traffic emissions more often than emissions from the residential areas to the west of the station. Figure 6.4 shows pollution roses for various contaminants and includes a wind rose in the bottom right corner.

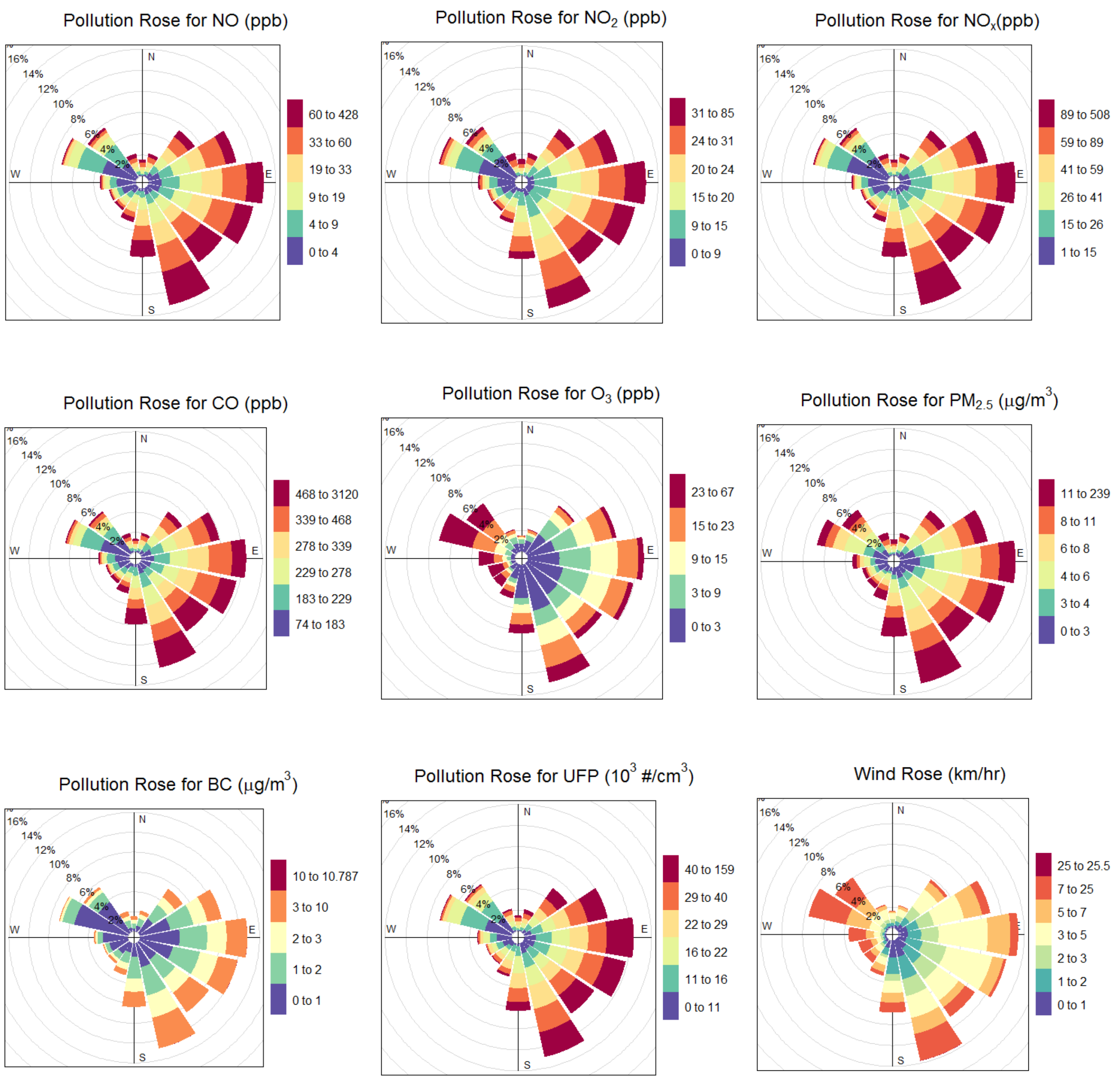


Figure 6.4: Pollution roses and wind rose at NR-VAN.

A majority of the highest NO_x concentrations, above 80 ppb, were measured during times when the winds were blowing from the south-southeast. The top row of plots in Figure 6.4 also shows that the highest concentrations of NO occur when the wind was from the south-southeast. Concentrations of NO_2 are highest when the wind was blowing from Clark Drive and the intersection of Clark Drive and 12th Avenue.

Carbon monoxide concentrations were highest when winds are blowing from the south, south-southeast and south-east, which allowed transport of emissions from Clark Drive and the intersection. The ozone pollution rose has a different pattern than the other contaminants which was a result of ozone scavenging occurring in the area around the monitor.

The highest ozone concentrations were measured when winds were blowing from the northwest and west-northwest, which occurred during summer months.

Similar to nitrogen oxides, the highest $PM_{2.5}$ concentrations were recorded during times when the wind was blowing from the south, south-southeast and southeast, which was the direction of Clark Drive and the intersection of Clark and 12th.

Black carbon concentrations have a strong relationship with winds coming from Clark Drive, with the highest concentrations being recorded when the winds were blowing from anywhere between the northeast and south. Clark Drive, as noted in Section 3.1.9, is a popular route for large trucks, which are also the largest emitters of black carbon.

Finally, the UFP pollution rose shows a more unique pattern than many of the other contaminants in Figure 6.4, with the highest concentration being directly linked to times when the wind would transport emissions from Clark Drive. Black carbon exhibits a similar pattern, but the UFP pollution rose shows a more pronounced set of high concentration. This demonstrates that vehicles can be a major source of UFP in near road environments and UFP can be highly localized.

While pollution roses demonstrate the relationship between wind direction, frequency and pollution concentrations, they do not contain information about wind speed. In order to show this additional information, polar plots are presented in this section. Figure 6.5 shows the average concentrations for each wind speed/wind direction pairing while Figure 6.6 shows a maximum set of concentrations which are determined by finding the maximum recorded value at each wind speed/wind direction pairing.

Polar plots are helpful to visualize the relationship between three variables rather than two provided in the pollution rose. Additionally, because wind speed is integrated into the plot, some generalizations about which sources could be contributing to higher concentrations can be drawn. For example, high concentrations that occur when winds are light may indicate that a source is close to the monitoring location.

The polar plots in Figure 6.5 show higher average concentrations for many contaminants associated with light winds aligned north/south in the same orientation as Clark Drive. The polar plot for ozone highlights the scavenging which occurs near the monitor as a result of nearby NO_x vehicle emissions. The polar plots provided in Figure 6.6 provide the 1-hour maximum concentration associated with each wind speed and direction pairing. The plots show similar patterns to the average concentrations but with more defined high concentrations when the winds are light. This pattern indicates that local emissions result in the highest recorded concentrations at Clark Drive.

Based on the average (Figure 6.5) and maximum (Figure 6.6) polar plots, there appears to be a strong connection between ultrafine particles and Clark Drive, with the highest concentrations to the east of the station under relatively light wind conditions.

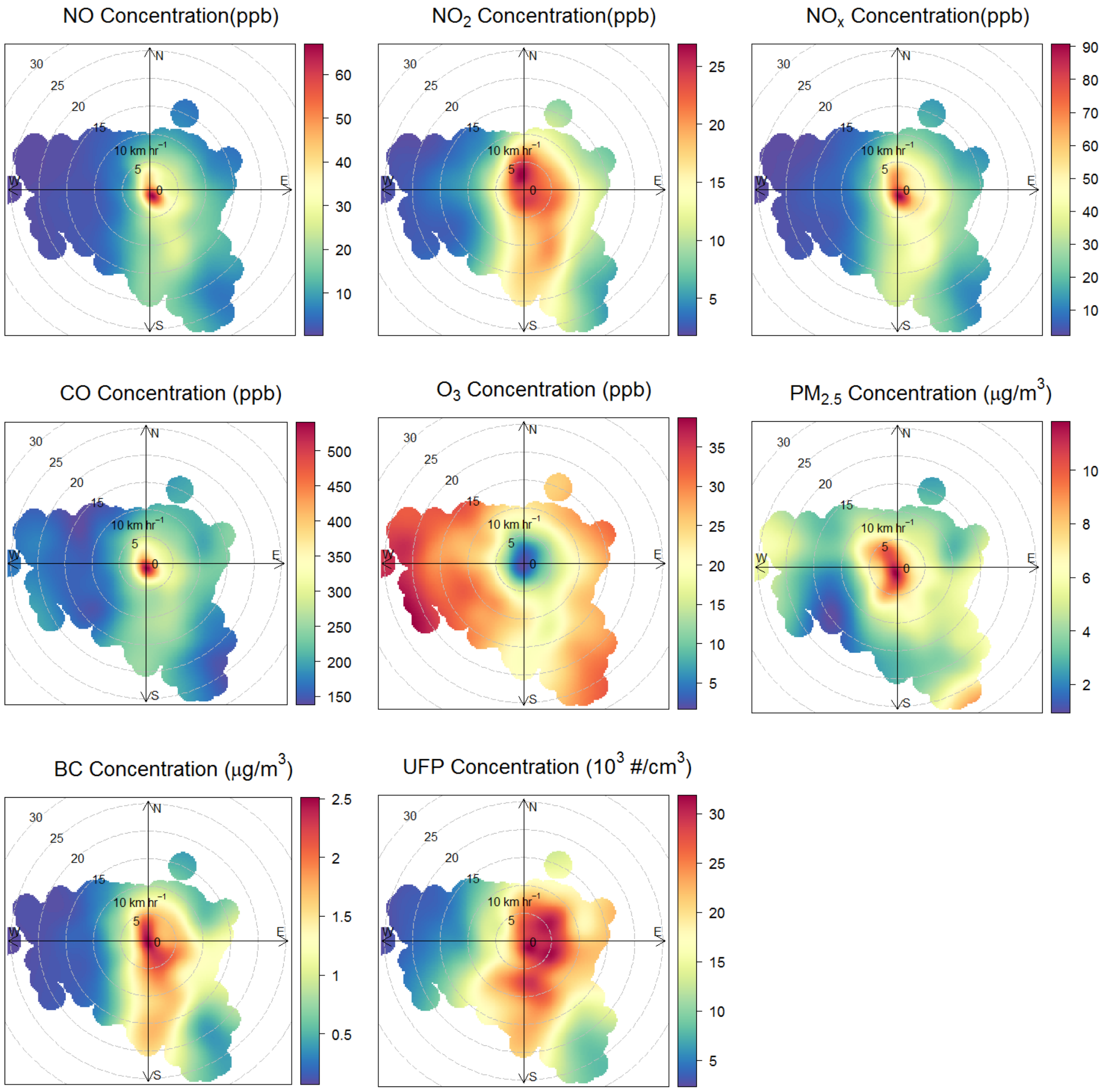
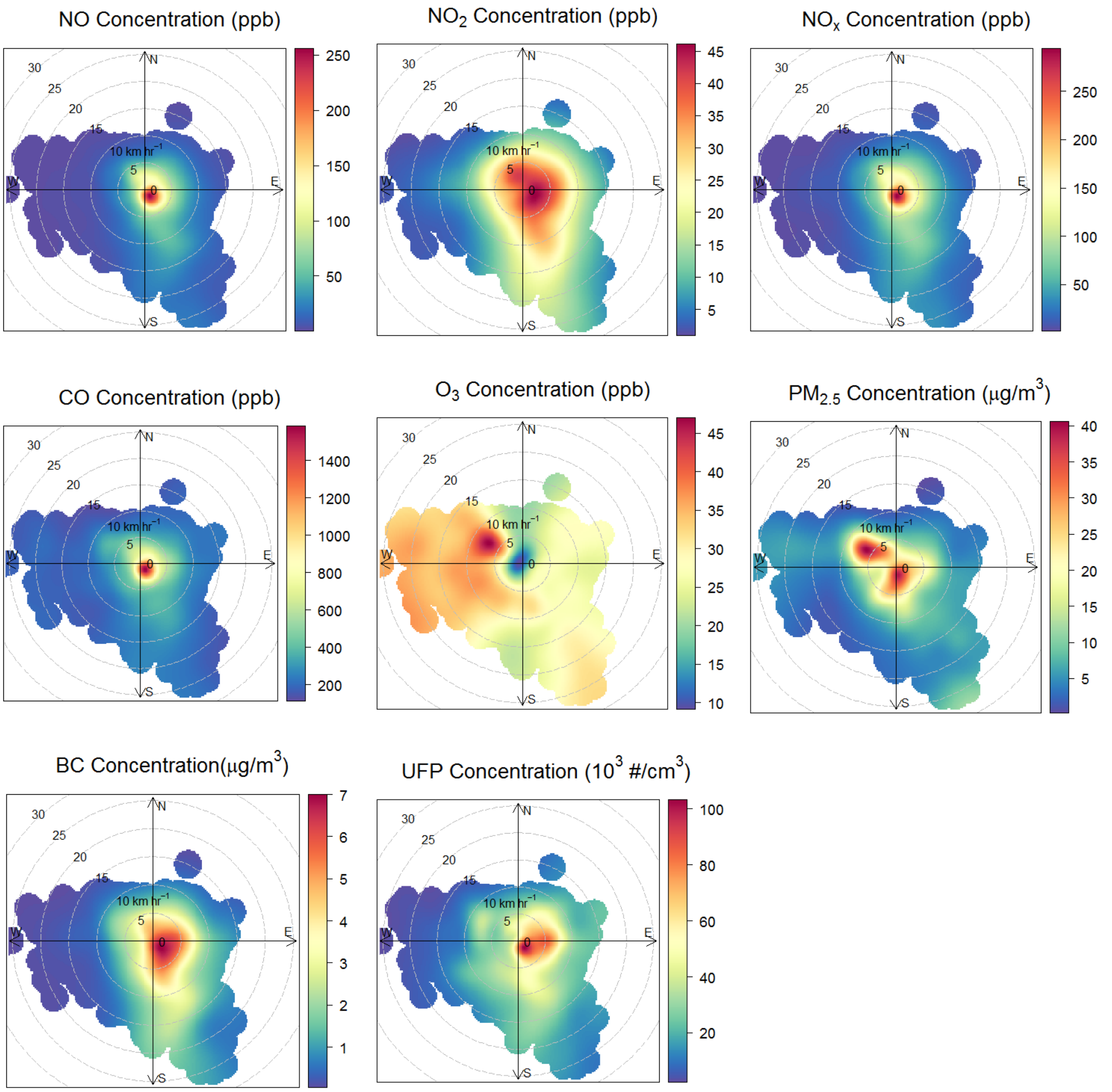


Figure 6.5: Polar plots of average hourly contaminant concentration at NR-VAN.


NO Concentration (ppb)

NO_2 Concentration (ppb)

NO_x Concentration (ppb)

CO Concentration (ppb)

O_3 Concentration (ppb)

$PM_{2.5}$ Concentration (µg/m^3)

BC Concentration(µg/m^3)

UFP Concentration (10^3 #/cm^3)

Figure 6.6: Polar plots of maximum hourly contaminant concentration at NR-VAN.

Fine particulate polar plots indicate that Clark Drive contributed to the ambient concentrations but that there were also contributions from the residential area to the west of the station. This may be a result of residential wood burning in the area. Carbon monoxide shows a very well defined hotspot with both the average and maximum under light wind conditions, indicating a local emission source (i.e., motor vehicles) was the main contributor to measured concentrations.

Ozone exhibits a unique pattern compared to many of the other contaminants presented in this section. Both the average and maximum polar plots show that the highest concentrations were under higher winds from all directions and that under light wind conditions, ozone concentrations tend to be low. This pattern was also indicative of the ozone scavenging which occurred as a result of the chemical reaction with NO_x and ozone.

The polar plots for NO_x, NO_2 and NO show the relationship between the contaminants as well as some key differences in the possible source areas. NO_2 concentrations in the average polar plot show a much larger area of elevated concentrations compared to NO_x and NO. The shape of the elevated NO_2 areas on the polar plot also mimics the orientation of Clark Drive which would indicate that vehicle emissions along Clark Drive contributed to local concentrations, not just the vehicles emitting directly next to the monitor.

6.3 Wind Sector Analyses

Contaminant concentrations from various wind sectors were examined to provide further insight into the near-road contribution. Other near-road studies have found traffic emissions can influence ambient air quality up to a distance of 100 to 500 m (HEI, 2010). At the NR-VAN site there are three major roadways within 250 m of the station with two alignments: east-west and north-south. These roadways include Clark Drive (6 lanes to the east), 12th Ave (4 lanes to the south) and Broadway (6 lanes to the north). Clark Drive and East Broadway are designated truck routes while 12th Avenue is not. These roadways are shaded blue in the wind sector plot shown in Figure 6.7 with the 100 m and 250 m radius from the station shown in black circle.

Wind sectors were defined based on capturing wind angles from specific road segments to better understand the associated concentrations with each sector. Figure 6.7 provides the wind angles for each sector labelled as: north, east, south and west. The north sector includes Clark Drive to the north as well as the Broadway/Clark Drive intersection approximately 250 m away. The south sector includes the wind angle for traffic emissions from the Clark Drive/12th Ave intersection as well as 12th Ave up to 100 m away. The east sector includes the angle between the north and south sections which includes the portion of Clark Drive with traffic emissions closest to the monitor inlets, directly adjacent to the station. The west sector includes the wind sector that does not include any traffic emissions from a major roadway.

Figure 6.7 provides average (bar) and peak (whisker) 95th percentile contaminant concentrations for the near-road station when winds are from each sector and when winds are calm. Also shown in this figure for comparison is contaminant concentrations from the background station (shown as the bar on the right labelled as “BG-VAN”). For all contaminants the highest average concentrations were found when winds were calm. A threshold of 0.5 m/s (the stall speed of the anemometer) was applied to determine when winds were calm. Calm conditions occurred during stagnant conditions and when winds were light. Emission sources emitted close to the near-road station (e.g., traffic emissions) during calm conditions would result in less dispersion compared with windier conditions. The overall effect of emissions released without a strong mechanism to transport and disperse the emissions across a greater volume is for contaminants to increase in concentration without winds to bring in non-polluted air or disperse emitted contaminants.

Traffic is a major source of nitrogen oxides emissions in the region. Elevated average NO and NO_2 concentrations were observed when traffic emissions were downwind of monitoring station. The highest average NO concentration was measured when winds were calm (61 ppb), followed by the south sector (54 ppb), north sector (38 ppb) and east sector (33 ppb). Similarly, the highest peak hourly NO followed a similar trend. The lowest average concentration was measured from the west sector (10 ppb) that represents a direction from which there are no major roadways. The background station experienced even lower average concentrations (9 ppb). The south sector experienced five times higher average NO compared with the sector without the roadways, while the north sector experienced four times and east sector three times, suggesting significant contributions of traffic-related emissions. Interestingly the north sector, which represents the wind sector with the major intersection within 100 metres of the station, has greater average and maximum concentrations compared with east sector which includes traffic emissions emitted directly beside the monitoring station.

Nitrogen dioxide displays a somewhat different trend than NO which likely related to the NO_2 formation reaction and other potential regional NO_2 precursors. The north sector exhibited the higher average and peak concentrations compared with the east and south sectors. It is evident that there was abundant NO from the near-road environment, especially from the east and south sectors. It is known that NO_2 formation takes time and occurs at distance downwind from NOx emission sources such as traffic. It is likely that the higher NO_2 values from the north sector are a result of emissions released in the downtown peninsula where traffic and marine emissions are spatially concentrated and abundant.

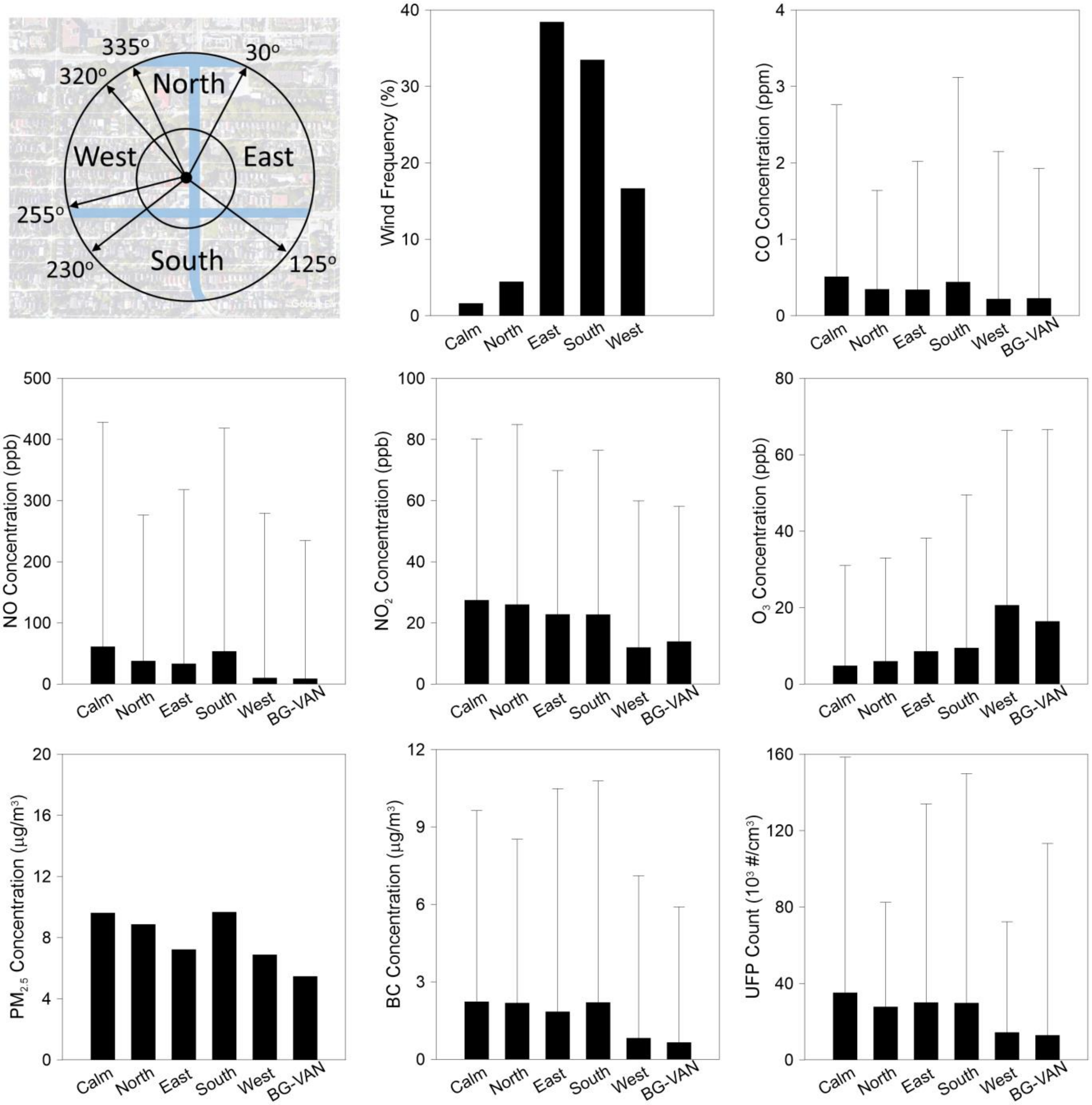
The west sector experienced the highest average and peak concentrations of ground-level ozone of the wind sectors which is to be expected given the role that traffic emissions play in the reaction of ground-level ozone. Nitric oxide emitted from traffic reacts with O_3 to form NO_2 and leads to lower O_3 levels in the near-road environments.

Carbon monoxide follows a similar trend as NO with the same ranking of average concentrations for each wind classification scheme: south, east, and north followed by the west sector. The highest peak concentration was found to occur in the south sector which includes the Clark/12th Ave intersection.

Fine particulate matter at NR-VAN during the study period was influenced by a number of factors including wildfire events, a local bog fire, a near-by structure fire and fireworks. Peak levels of $PM_{2.5}$ cannot necessarily be attributed to near-road traffic emissions and have thus not been shown in Figure 6.7. Average levels with or without these non-traffic related influences removed show similar trends in the wind sector analysis and thus Figure 6.7 was calculated using all available data. Average levels of $PM_{2.5}$ indicate higher concentrations are experienced from roadway north sector (8.9 $\mu g/m^3$), east sector (7.2 $\mu g/m^3$), south sector (9.7 $\mu g/m^3$) and during calm conditions (9.6 $\mu g/m^3$), compared with the non-roadway west sector (6.9 $\mu g/m^3$) and the background station (5.5 $\mu g/m^3$). It is clear that major roadways have a significant influence on $PM_{2.5}$ levels whether it is from vehicle exhaust, brake wear or road dust. The south sector (emissions from the intersection) exhibited the highest average concentration while east sector (traffic emissions directly beside station) exhibited a similar average $PM_{2.5}$ as the west sector without any traffic emissions. This suggests that proximity to major intersections play an important role in average $PM_{2.5}$ concentrations. It is suspected that the stop and start traffic at the intersection plays an important role in higher concentrations.

Ultrafine particles shows similar average concentrations in east and south sectors with little to no difference in the averages between the sectors. The north sector has a slightly lower average while the west sector, without road emissions, shows similar averages as the background station. The highest peak UFP concentrations was associated with calm conditions followed by south, east and then north sectors.

Black carbon exhibited little variability in average concentrations for calm conditions and north, east and south sectors while the west sector (the sector without a major roadway) experienced much lower concentrations. The west sector exhibited a similar average and peak concentration as the background station.



Note: Peak levels of $PM_{2.5}$ cannot necessarily be attributed to near-road traffic and have thus not been shown here.

Figure 6.7: Contaminant concentration by wind sectors (North, East, South, and West) and calm conditions at NR-VAN and from all wind sectors at BG-VAN.

The impact of air contaminants on the NR-VAN station relates to both the wind frequency from a sector and contaminant concentrations in that sector, both shown in Figure 6.7. Relative Impact (RI) of a contaminant on the NR-VAN station from the four sectors were estimated by taking into account both the wind frequency and average concentrations in individual sectors. The following equation was applied to calculate the RI of each sector for individual contaminants:

$$RI_i = \frac{C_i \times n_i}{\sum_{i=1}^{4} C_i \times n_i}$$

where,
RI_i is the relative impact of a sector i on the NR-VAN station for a contaminant;

$[C_i]$ is the average concentration of the contaminant in the sector i; and
n_i is number of times air blowing from the sector i to the NR-VAN station.

Table 6.2 shows that the south sector had the most significant impact on the NR-VAN station for most contaminants due to frequent winds and high concentrations measured from this sector. The RI in this sector that contained the intersection to the south was the highest for TRAP including NO (49%), CO (42%), $PM_{2.5}$ (40%) and BC (41%) and second highest NO_2 (36%) and UFP (37%). The RI in the east sector (with the roadway directly adjacent to this pathway) experienced the highest NO_2 (42%) and UFP (43%) with second highest NO, CO, $PM_{2.5}$ and BC. While calm conditions were associated with the highest average concentrations because these conditions where relatively infrequent the RI associated with them was low with less than 5% for all contaminants. Similarly, the north sector was associated with higher concentrations than the sector upwind of near-road emissions (west sector), however winds were infrequently from the north sector and thus resulted in a relatively low RI for all contaminants. In fact, the RI from the north sector was similar (i.e., within 5%) to west sector for many contaminants including NO, NO_2, CO, BC and UFP.

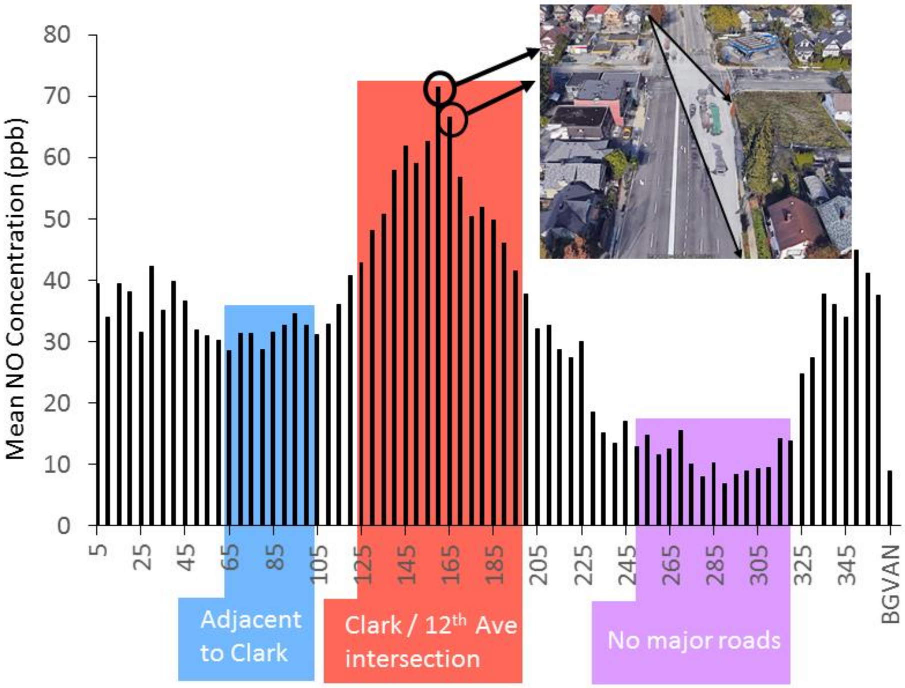
Table 6.2: Relative Impact of individual sectors on the NR-VAN station.

		Relative Contribution						
Sectors	Wind angle	NO	NO_2	O_3	CO	$PM_{2.5}$	BC	UFP
North	335°-30°	4%	5%	2%	4%	5%	5%	4%
East	30°-125°	35%	42%	30%	38%	35%	40%	43%
South	125°-230°	49%	36%	29%	42%	40%	41%	37%
West	255°-320°	4%	9%	29%	9%	13%	7%	8%
Calm		5%	4%	1%	4%	4%	4%	4%
Major roadways	335°-255°	89%	85%	67%	85%	82%	87%	86%
No major roadways	255°-335°	6%	11%	31%	11%	15%	9%	10%

Direct traffic influence of air pollution on the NR-VAN station was further assessed by calculating an RI for the wind sectors associated with major roadways (335°-255°) and an RI for the wind sectors associated with no major roadway (255°-335°). The RI of the major roadways was 89% for NO, 89% for NO_2, 85% for CO, 82% for $PM_{2.5}$, 87% for BC and 86% for UFP, indicating signification contributions of traffic emissions for these contaminants.

Further detailed examination of smaller discrete wind angles reveals additional detail and demonstrates which sectors are associated with various contaminant levels. Note: Three colours are used to outline directions from an intersection (red), roadway beside the station (blue) and no major roadways (purple). The inset orthophoto shows the wind angle associated with the highest concentrations.
Figure 6.8 shows average NO concentrations calculated for five-degree wind angles. The angles associated with the highest concentrations are nearly aligned with Clark Drive road axis and also include the major intersection to the south. Winds coming from the intersection have been highlighted in red in Note: Three colours are used to outline directions from an intersection (red), roadway beside the station (blue) and no major roadways (purple). The inset orthophoto shows the wind angle associated with the highest concentrations.
Figure 6.8 and show the highest average concentrations of all of the wind angles. In particular, the two five-degree wind angles associated with the highest average concentrations are circled in Note: Three colours are used to outline directions from an intersection (red), roadway beside the station (blue) and no major roadways (purple). The inset orthophoto shows the wind angle associated with the highest concentrations.
Figure 6.8 with the angles displayed in the inset orthophoto. The inset shows the potential source area on the roadway which includes the area where vehicles cue at the intersection. It is thought that the emissions of vehicles accelerating

from a stop plays a key role in higher concentrations of TRAP at the monitoring station compared with other emission sources and wind angles. For example, the highlighted wind angles in blue shows the concentrations associated when winds blow from the Clark Drive roadway directly adjacent to the monitoring station which are considerably lower than concentrations measured from the intersection.



Note: Three colours are used to outline directions from an intersection (red), roadway beside the station (blue) and no major roadways (purple). The inset orthophoto shows the wind angle associated with the highest concentrations.

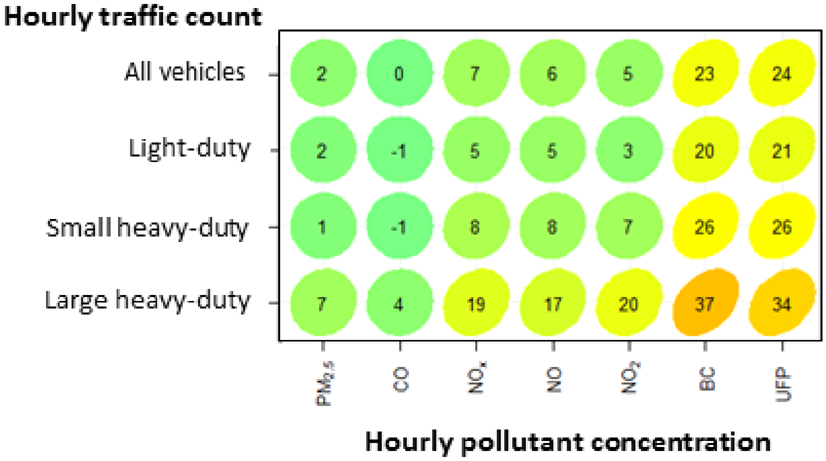
Figure 6.8: Average nitric oxide concentration by five-degree wind sectors at NR-VAN.

It is interesting to compare two different five-degree wind sectors for comparison (shown in Figure 6.9) to examine the role of other factors that influence TRAP at a monitoring location. The wind sector, 235-240°, that contains a major road 125 metres away shows lower concentrations of average NO compared with a wind sector, 335-340° that contains a major road further away (~230 metres). The wind sector with the closer roadway was found to have an average value of 15 ppb compared with the sector with the further roadway with a value of 27 ppb. While distance between a receptor and a major roadway is important there are several other factors that can influence ambient concentrations. These factors include traffic volume, truck route designation and building configuration. The 235-240° wind sector includes traffic emissions from 12th Ave which is a four lane road that restricts truck traffic while the 335-340° sector includes traffic emissions from Broadway (a six land route with truck traffic). Each sector also has a different urban form (i.e., surface roughness) that also is thought to play a key role in the dispersion of TRAP between the emission source and receptor. The pathway of the 235-240° wind sector includes closely spaced 2-3 story buildings while the 335-340° sector pathway is unimpeded and does not include any buildings. It is thought that when winds are blowing from 235-240° that traffic emissions would be mechanically pushed up over the 2-3 story buildings and vertically mixed resulting in lower ground-level concentrations at the monitoring location. The traffic emissions released on Broadway would not be subject to the same vertical mixing when winds are blowing from 335-340° since there are no obstacles to force mechanical mixing of contaminants. It is not known the degree to which three factors: traffic volume, truck designation, and/or surface roughness influence TRAP. However, it can be concluded in this example that distance to roadway is less important than the three factors combined. The role of urban geometry is explored further in Section 6.5.2.2.

Figure 6.9: Two five-degree wind sectors representing differing distances to a major roadway.

6.4 Contaminant and traffic correlations

Emissions from different types of vehicles (i.e., vehicle classification) is known to vary significantly, with light-duty vehicles (passenger cars and trucks) often having lower emissions than heavy-duty vehicles (single unit and combination trucks). The NR-VAN traffic instrument has the ability to categorize the size of passing vehicles for each lane and count hourly traffic. The correlation between hourly contaminant concentration and traffic volume was determined (Figure 6.10) for three vehicle classifications (r value multiplied by 100). Higher positive values indicate a strong positive correlation while values close to zero indicate no correlation. For many contaminants, the correlation between hourly concentrations and traffic count for all vehicles was found to be small. There could be a number of reasons for the weak correlation which could include the role that meteorology plays in local contaminant transport, contaminants being more regionally homogenous or the averaging period smoothing out some higher intra-hour measurements. The classification for large heavy-duty (combination trucks) was found to have highest correlations of the three classifications with black carbon and ultrafine particles having the highest correlations to traffic volume.



Hourly traffic count	$PM_{2.5}$	CO	NO_x	NO	NO_2	BC	UFP
All vehicles	2	0	7	6	5	23	24
Light-duty	2	-1	5	5	3	20	21
Small heavy-duty	1	-1	8	8	7	26	26
Large heavy-duty	7	4	19	17	20	37	34

Figure 6.10: Correlation matrix of hourly traffic volume and contaminant concentration (r value multiplied by 100).

In order to better understand how vehicle type may contribute to recorded concentrations, a series of scatter plots are shown in Figure 6.11. To develop these plots, each hour's vehicle count was expressed as a percentage of the total traffic volume during the same time. The percentages of these three vehicle classes were then plotted against the concentration observed during the hour. A simple linear regression line was then overlaid to help visualize if there was a change in percentages as concentrations increase.

If there was no relationship between vehicle classification and air quality concentrations, then it would be expected that each of the three scatter plots would show a flat line as concentrations increased. If the data shows that there is an increase in the vehicle classification percentage as concentration increases, that could indicate that the vehicle classification contributes more to recorded concentrations. An example of a contaminant which appears to have no relationship with vehicle class (Figure 6.11), which shows that as concentrations increase, all three vehicle classifications remain mostly flat, indicating that higher ozone was not likely associated with a specific vehicle classification. Alternatively, the NO_x plot shows a strong relationship between large trucks and elevated NO_x concentrations (Figure 6.11). The increase in NO_x concentration occurred during times when there is a higher percentage of large heavy-duty vehicles (i.e., trucks) using Clark Drive.

The ultrafine particles plot shows that with higher recorded concentrations, they are often associated with a much higher percentage of small and large heavy-duty vehicles and not with light-duty vehicles (i.e., passenger cars and trucks). This would imply that light-duty vehicles may not be responsible for some of the highest recorded concentrations of UFPs.

Carbon monoxide in Figure 6.11 shows that as concentrations increase, light-duty vehicles have a small decrease in their contribution to these higher concentrations. Likewise, small heavy-duty traffic has almost no change in percentage of traffic makeup as carbon monoxide concentrations increase. Large heavy-duty traffic only shows a modest increase in total traffic percentage with increasing concentrations. Unlike the case of ultrafine particles discussed above, carbon monoxide concentrations do not appear to be overly influenced by a specific class of vehicles instead.

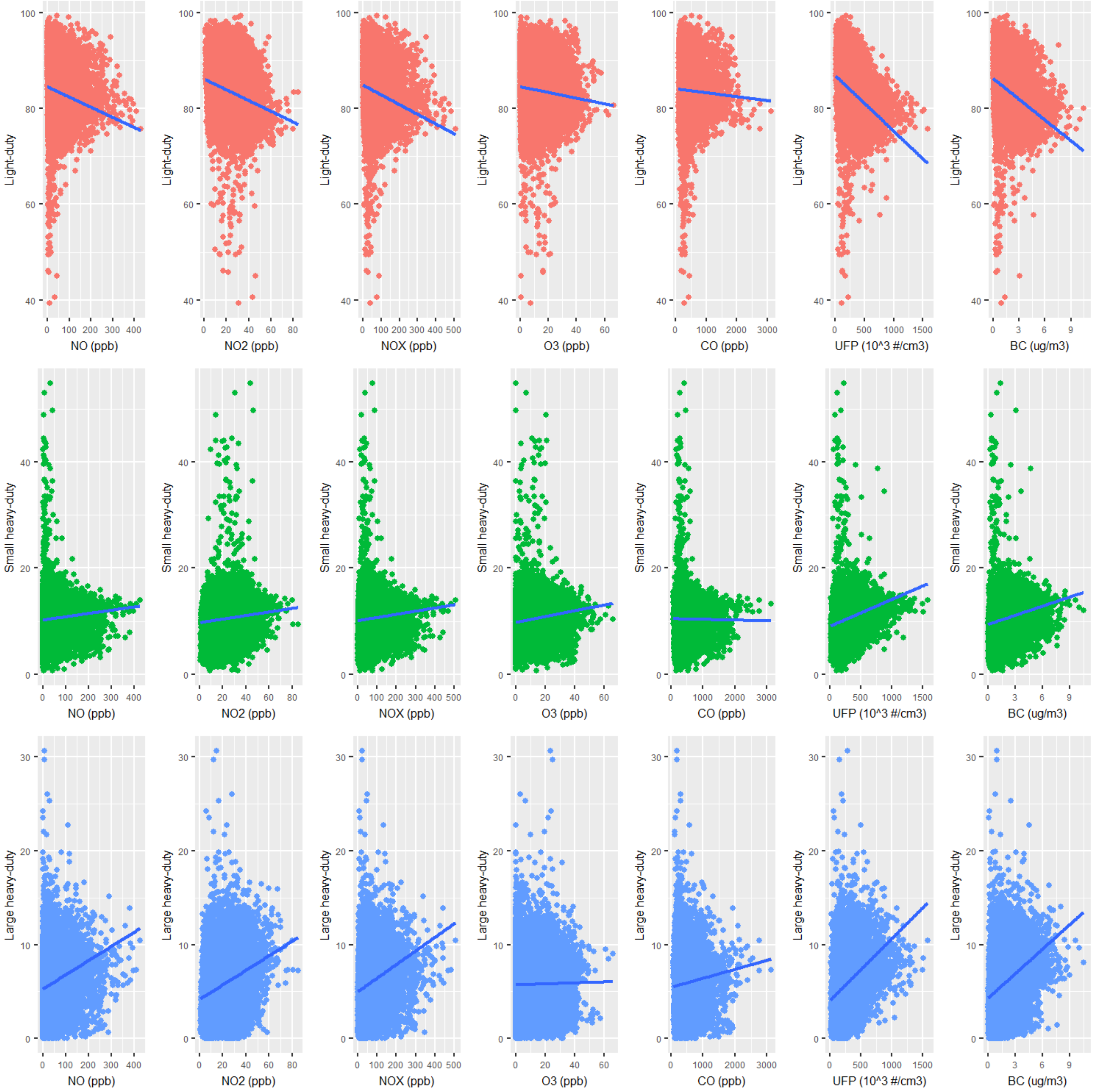


Figure 6.11: Relationship between contaminant concentration and percent total traffic volume by vehicle class.

6.5 Comparison other near-road stations

Comparisons are made in this section between results from the near-road monitoring station in Vancouver and the two in Toronto along with context for the comparisons. These near-road stations represent three different types of roadways and can be used to provide near-road information for a variety of roadway types that can further be used across the country to understand similar near-road environments.

6.5.1 Comparison of three near-road stations

In this section NR-VAN is compared to the other two near-road monitoring stations operated in Toronto. One Toronto site (NR-H401) was located on Highway 401 while the other was located downtown at the University of Toronto campus on College Street (NR-TOR). The NR-H401 site experienced high traffic volume with an AADT of ~400,000, which is thought to have the highest traffic volume in North America, while the NR-TOR site experienced an AADT of ~17,000. In comparison, the NR-VAN which experienced an AADT of ~33,000. Together, the Vancouver and Toronto sites represent a trucking route, highway, and downtown road, and bring into focus the current state of near-road pollution in Canada. Prior to conducting the study, it was expected that air contaminant levels would be strongly correlated to traffic volume and that the NR-H401 site would experience order of magnitude greater concentrations compared with NR-VAN. However, this was not found to be the case. The distribution of TRAP measured at the three near-road sites is shown in Figure 6.12 for a comparative period. The mean, 95th percentile and maximum value for the stations are provided in Table 6.3.

The NR-VAN and NR-H401 sites experienced considerably higher nitrogen oxides (i.e., NO, NO_x, and NO_2) compared with the NR-TOR site both in terms of higher average and peak concentrations. For the comparative period, NR-VAN measured an NO_2 average of 21 ppb while NR-H401 measured 19 ppb and NR-TOR measured 11 ppb. A value of 21 ppb measured at NR-VAN is the same numerically as the Metro Vancouver annual NO_2 objective of 21 ppb. Similarly, higher average and peak levels of CO were measured at NR-VAN and NR-H401 compared with NR-TOR. Carbon monoxide levels at all sites were well below Metro Vancouver's and Ontario's carbon monoxide objectives.

Average and peak ozone concentrations were the lowest at NR-VAN which is not a surprise given the higher amount of nitrogen oxides compared with both NR-H401 and NR-TOR. As discussed earlier, ozone scavenging is prevalent where higher levels of NO_x are found. In these environments, emissions containing NO_x, react quickly with O_3 to form NO_2 (nitrogen dioxide) and O_2 (oxygen) thus decreasing O_3 concentrations.

Of the three sites NR-VAN experienced the lowest 95th percentile (peak) 24-hour $PM_{2.5}$ average compared with NR-H401 and NR-TOR when wildfire effects were removed. The NR-H401 experienced the highest peak and average $PM_{2.5}$ concentrations. All three sites were found to exceed Metro Vancouver's 24-hour $PM_{2.5}$ objective. The NR-VAN and NR-H401 sites experienced higher average BC concentrations compared with NR-TOR while the NR-VAN site measured higher average levels compared with NR-H401.

The highest UFP levels were found at the NR-H401 site compared with NR-VAN and NR-TOR both in terms of the average and peak. The maximum number of UFP per cm^3 was found to be nearly two times higher at NR-H401 compared with NR-VAN. The NR-TOR had the lowest average and peak levels compared with the other two near-road sites.

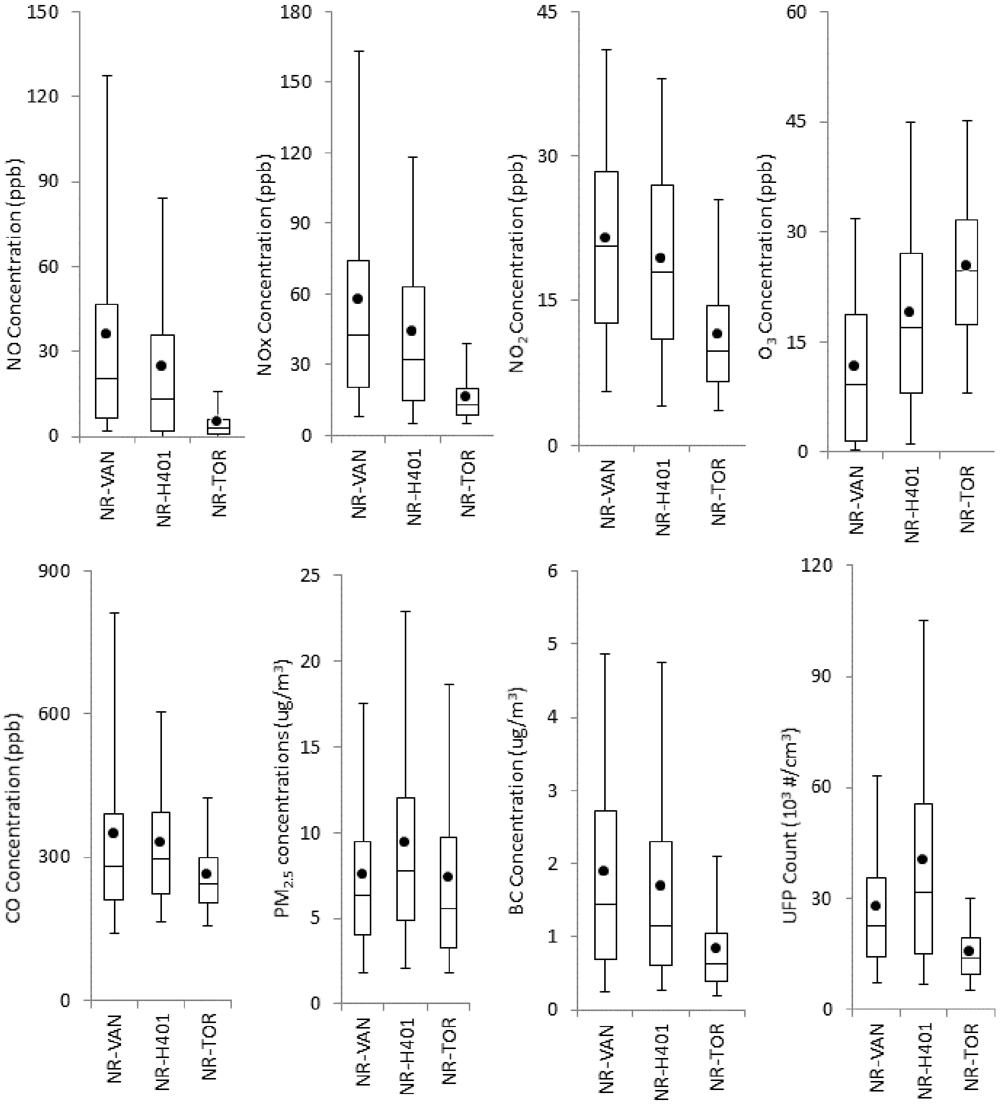


Figure 6.12: Distribution of near-road measurements at three near-road stations.

Table 6.3: Hourly near-road measurement levels at a truck route (NR-VAN), highway (NR-H401), and downtown road (NR-TOR).

		Mean			95th Percentile			Maximum		
	Units	NR-VAN	NR-H401	NR-TOR	NR-VAN	NR-H401	NR-TOR	NR-VAN	NR-H401	NR-TOR
NO	ppb	36	25	5	127	84	16	428	332	115
NO_2	ppb	21	19	11	41	38	25	80	84	53
NOx	ppb	57	44	16	163	118	39	508	397	161
CO	ppb	346	329	263	810	603	424	3120	1617	2395
O_3	ppb	12	19	25	32	45	45	61	87	81
$PM_{2.5}$	µg/m^3	8	9	7	18	23	19	27*	37*	25*
BC	µg/m^3	1.9	1.7	0.8	4.9	4.7	2.1		17	12
UFP	10^3 #/cm^3	27.4	40.0	15.3	63.2	105.3	30.0	159.9	255.5	116.2

*Calculated as a 24-hour rolling average.

6.5.2 Reasons for differences between NR-VAN and NR-H401

The Vancouver near-road monitoring station (NR-VAN) located on an arterial road was found to experience similar concentrations to the near-road station located on an 18-lane highway (NR-H401) in Toronto. This section explores factors that may explain why two near-road sites with an order of magnitude difference traffic volumes would experience similar contaminant concentrations. These factors include frequency of wind direction, average speed of winds, street canyon effect, and proximity to roadway.

6.5.2.1 Frequency of time when monitoring station is downwind from traffic emissions

The NR-VAN monitoring station was found to be downwind of traffic emissions 83% of the time while the NR-H401 station was downwind only 52% of the time. Given this, the NR-VAN station measured a greater frequency of traffic emissions compared with NR-H401. Measuring a greater frequency of traffic emissions at NR-VAN influences the relative average concentration and poses a greater likelihood of capturing more extreme concentrations.

It was relatively simple to calculate the wind angle in which winds were blowing from the highway towards the NR-H401 station given the linear configuration of the highway. Wind angles 254° through 70 ° (inclusive) represented the direction in which traffic emissions were present (Figure 6.13a). When winds were blowing from these angles the monitoring station was downwind of traffic emissions.

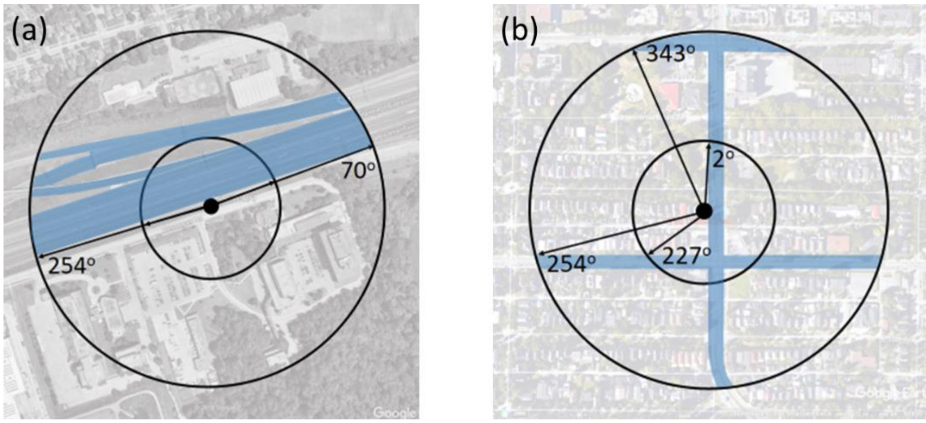


Figure 6.13: NR-TOR (a) and NR-VAN (b) showing major roadways in blue within with 100 m and 250 m radius.

It was more difficult to calculate the wind angles that include major roadways (i.e., traffic emissions) upwind of NR-VAN given that the monitoring station was within 250 metres of several major roadways with two different alignments (east-west and north-south). The NR-VAN site was adjacent to Clark Drive which is aligned north-south. Within 100 metres of the station was also another major road to the south, 12th Avenue, which is aligned east-west. Within 250 metres there was a third major roadway to the north, East Broadway, which is also aligned east-west. These roadways within 250 m of NR-VAN are shown in blue in Figure 6.13b.

Studies have demonstrated that traffic emissions can be detected at 500 metres (HEI, 2010) and therefore it was not necessarily possible to easily quantify which major roadways and road segments were impacting the NR-VAN station. It is well known that as the distance from a receptor to emission source is increased that dispersion also increases and the resultant concentration decreases (assuming there are no terrain or land use effects at play).

To understand the frequency of winds patterns blowing from a major roadway to the near-road stations the wind data was examined. For this analysis distances of 100 m and 250 m were considered to contrast the frequency of wind at the two sites (NR-VAN and NR-H401). Using a radius of 100 m, it was determined that winds blow from major roadways (Clark and 12th Ave) to NR-VAN 73% of the time, while at NR-H401 52% of the time winds blow from a major roadway. Using a 250 m radius the wind angle increases considerable at NR-VAN to include East Broadway to the north and a longer segment of 12th Ave. With a 250 m radius, the wind blows 83% of the time from major roads towards the NR-VAN station while a

250 m radius at NR-H401 has an unchanged frequency of 52%. Comparing the frequency of winds at the two stations reveals that NR-VAN was subject to a greater frequency of TRAP emissions compared with NR-H401. Measuring a greater frequency of traffic emissions at NR-VAN will influence the relative average concentration and potentially pose a greater likelihood of capturing more extreme concentrations from high emitting vehicles (e.g., poorly maintained or older trucks).

6.5.2.2 Wind speed comparison and street canyon effect

During a comparative period only about 1% of the data observed at NR-H401 were classified as light winds with the wind speed of 0.5 m/s or less. On average wind speeds were 2.7 m/s, and had a median of 2.3 m/s and a maximum hourly wind speed of 19.2 m/s (Table 6.4). In contrast, at NR-VAN, 22% of the wind observations were light winds. On average wind speeds were 1.2 m/s with a median of 1.1 m/s and maximum hourly wind speed of 7.1 m/s. On average, for the comparative period, the wind speeds at NR-VAN were less than half the speed compared with NR-H401.

The turbulent diffusion equation that defines the concentration downwind of an emission source relies on wind speed as a variable. As wind speed increases the concentration decreases. The greater frequency of calm conditions at NR-VAN and lower average wind speeds is thought to result in a greater influence of TRAP at NR-VAN compared with NR-H401 per unit of emission. The NR-VAN site has a greater surface roughness (i.e., is more sheltered) and experiences calmer conditions and slower winds resulting in less dispersion of TRAP compared with NR-H401.

Table 6.4: Comparative statistics for winds at NR-VAN and NR-TOR (August 1, 2015 to March 31, 2017).

	Mean (m/s)	Median (m/s)	Maximum (m/s)	N	Light Winds (%)
NR-VAN	1.2	1.1	7.1	11284	22
NR-H401	2.7	2.3	19.2	10869	1.2

Wind and turbulence are vital to the dispersion of air contaminants (Oke, 1987). In areas characterized by low buildings the air exchange between street-level where TRAP are emitted and above roof-level depends upon the height to width ratio (H/W) of the buildings and streets. If the streets are narrow, air exchange is restricted (Figure 6.14a) compared with that in a more open arrangement where the vortex circulation aids street-level flushing (Figure 6.14b).

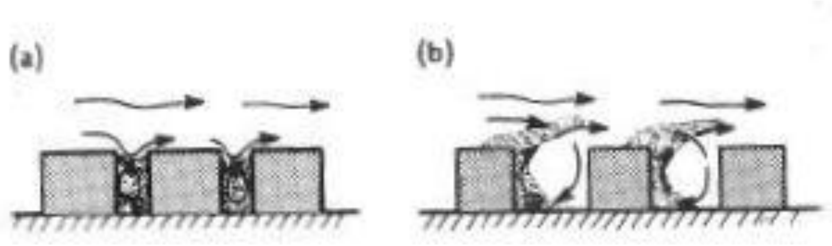


Figure 6.14: The influence of building air flow on pollution dispersion taken from Oke (1987).

High pollution levels have been often observed in urban street canyons due to the increased traffic emissions and reduced natural ventilation (Vardoulakisa et al., 2003). Vardoulakisa classified a street canyon as ‘regular’ with a height to width ratio of 1, a ‘deep’ canyon with a ratio of 2 while an ‘avenue’ canyon was defined as H/W = 0.5.

The NR-H401 site had open exposure with a H/W ratio of approximately 0.02 and thus would not be associated with a street canyon. There were no building obstacles near the highway at the monitoring station on either side of the highway. The site had good natural ventilation and did not experience buildup of contaminants at the monitoring location as a result of building obstacles. Conversely, the NR-VAN station was located directly beside a two-story house. On Clark Drive opposite to the monitoring station was a four-story building with surrounding trees that were slightly taller than the structure. The NR-VAN sites has an estimated H/W ratio of 0.28 and could be characterized as a non-uniform or asymmetric avenue canyon. While the H/W ratio was less than 0.5 the site likely experienced some restriction in airflow at street-level near the monitoring station. The measurement height of air contaminants at NR-VAN occurred within the cavity of the canyon. Therefore, it is suspected that at NR-VAN a restriction in airflow may lead to less dispersion of TRAP in comparison with the NR-H401 site. A restriction in airflow and less dispersion would result in greater ambient concentrations of TRAP per unit emission.

Vardoulakisa et al. (2003) states that the natural ventilation of urban streets is reduced mainly due to the presence of buildings. Within the urban canopy, wind vortices, low-pressure areas and channeling effects may be created under certain meteorological conditions, giving rise in some cases to air pollution hotspots. For example, high concentration levels have been often observed on the leeward side of regular canyons under perpendicular wind conditions.

Urban geometry affects the capacity to disperse contaminants in a city on at least two scales (Oke, 1988). Oke argues that the total array of roughness elements affects the production of mechanical turbulence, the form of the vertical wind profile and the depth of the urban mixing layer. These are local or meso-scale effects. The wake shed by each building and the circulation and turbulence associated with street canyons also produce micro-scale effects in amongst, and just above the buildings. The neighborhood configuration surrounding NR-VAN is that of closely spaced two to three-story buildings. The two scales outlined by Oke are thought to result in two different outcomes for contaminant concentrations measured at NR-VAN. For traffic emissions emitted on Clark Drive the role of the buildings is to restrict dispersion (in the street canyon) and results in greater TRAP measured at NR-VAN compared with no obstacles. Conversely, traffic emissions emitted on 12th Ave, are subject to mechanical turbulence as air is forced over the buildings between the emission source and receptor (i.e., monitor). The mechanical turbulence acts to increase dispersion and lower TRAP concentrations measured at NR-VAN compared with wind directions that do not have building obstacles in the emission receptor pathway. Section 6.3 provides an example of two different wind sectors, one with building obstacles and one without, shown in Figure 6.9.

It can be concluded that road configuration, the local wind regime and urban form play important roles in TRAP concentrations measured at any one location.

6.5.2.3 Proximity to roadway

It is well established that concentrations of traffic-related air pollutants decrease with distance from roadways. A review of near-road air pollutant monitoring studies showed that elevated concentrations of traffic-related pollutants such as ultrafine particles (UFP), black carbon (BC), nitrogen oxides (NO_x), and carbon monoxide (CO) generally occur within 50 m and background levels are reached between 150 and 500 m from the road. There have been near-road monitoring studies conducted in the US, Canada, Finland, Holland, and Australia to characterize the behaviour of traffic-related pollutants at increasing distances from roads. These studies have demonstrated a relationship been contaminant levels and distance to the roadway of the monitoring station. The relationship is known as the distance-decay gradient and is shown in Figure 6.15. Many of these studies showed comparable decay gradients in UFP number concentration as distance from major roadways increases (Table 6.5).

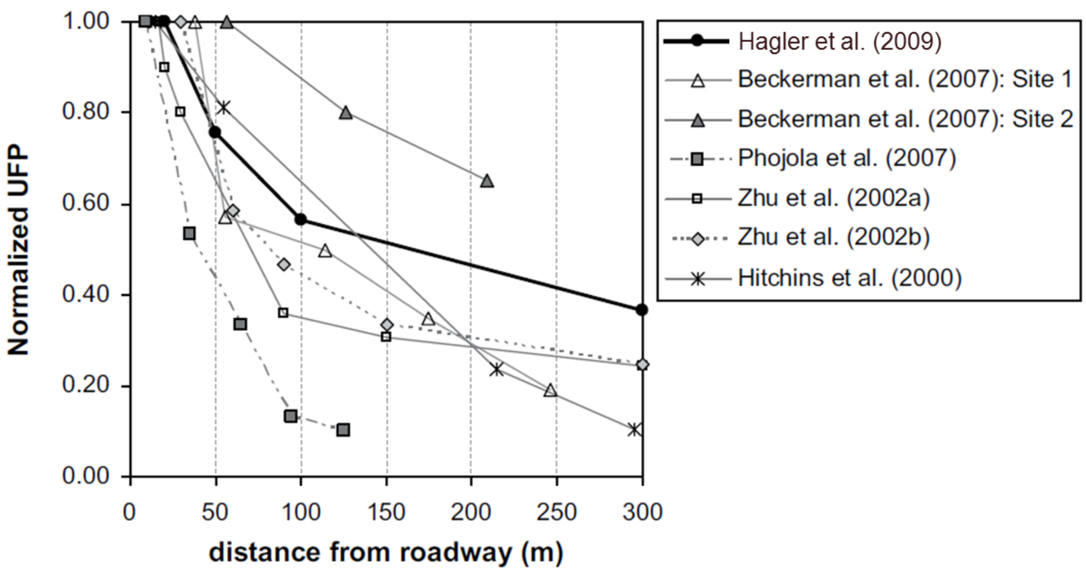


Figure 6.15: Distance-decay gradients from several studies (taken from Hagler et al., 2009).

Table 6.5: Near-road decay gradient of UFP (taken from SOCAAR, 2011).

Location	Road Type	Traffic (Veh/hr)	Distance range (m)	Season	Gradient up to 50m (% / 10 m)	Reference
Helsinki	Highway	3300	0-140	Winter	10	Pirjola et al., 2004
Helsinki	Highway	4800	0-140	Summer	14	Pirjola et al., 2004, 2006
Brisbane	Highway	3400	15-375		5	Hitchins et al., 2000
Brisbane	Arterial	2130	15-280		10	Hitchins et al., 2000
Los Angeles	Highway	12180	17-300	Summer	19	Zhu et al., 2002
Toronto	Highway	16500	38-438	Summer	24	Beckerman et al., 2008
Raleigh	Highway	5200	20-300	Summer	8	Hagler et al., 2009

The stations NR-VAN and NR-H401 were located at difference distances to the roadway and were subject to different levels of dilution of vehicle emissions. The station NR-VAN was 5.7 metres while NR-H401 was 14 metres from the edge of the curbside travel lane. The difference in distance of over 8 metres has an influence in TRAP intensity or concentration level. Using the range of distance-decay gradients reported in Table 6.5 an estimate of the influence was calculated by multiplying the gradient (in %/10 m) by the difference in distance. Using the distance-decay gradients found in the literature it was estimated that a 3 to 20% increase in concentrations could be attributable to proximity of the roadway at NR-VAN compared with NR-H401 assuming a similar emission regime. To illustrate this, a simplified graphic provided in Figure 1.1 depicts a generalized concentration profile near and away from the roadway. The figure highlights that the highest concentrations are present on the roadway and decrease as you move further away from the traffic emissions (i.e., where residents are typically located).

Rather than use the distance decay gradients to calculate the influence of distance to the roadway a more sophisticated approach can be taken. Wang et al. (2018) developed a multiple linear regression model that utilized CO_2 measurements collected at both NR-VAN and NR-H401 and factored in the distance to the roadway. They calculated the dilution factor attributable to 8.3 m closer distance that NR-VAN was to the roadway compared with NR-H401. They found that because of this distance, NR-VAN experienced 1.6 times less dilution compared with NR-H401. The air intake at NR-VAN was twice as close to the traffic emissions compared with NR-H401 and therefore the NR-VAN measured less diluted traffic emissions resulting in higher relative concentrations.

7. Conclusions

In this study, the Vancouver near-road monitoring station results are compared with a nearby background station and comparison sites in Metro Vancouver, the near-road contribution is established and the Vancouver near-road site is also compared with the two near-road monitoring sites in Toronto. In addition to the monitoring results, this report also provides a description of the monitoring stations, equipment employed, and outlines recommendations.

7.1 General Monitoring Results

The near-road monitoring site in Vancouver (NR-VAN) was found to experience higher average and peak concentrations of NO, NO_2, NO_x, CO, $PM_{2.5}$, BC and UFP in relation to comparison sites in the region. Frequency distributions of contaminants showed that NR-VAN exhibited a greater frequency of elevated concentrations compared with other sites. The near-road site exhibited both a lesser frequency of lower concentrations (i.e., less clean air) and a greater frequency of higher concentrations. The lesser frequency of lower concentrations was due to the near-road monitoring station being subject to the same background air quality the region experiences, plus the added traffic emissions resulting in greater TRAP concentrations.

During the study there were exceedances of Metro Vancouver's air quality objectives at the near-road monitoring station that were not present at comparison sites. The annual average of NO_2 exceeded Metro Vancouver's air quality objective (21 ppb) in 2017 and nearly exceeded in 2016. The exceedance of the annual objective can be attributed to the influence of traffic emissions. Vehicle traffic was found to be responsible for an increase of over 5 ppb of NO_2 on average at the near-road monitoring station.

Several wildfires were experienced during the study that resulted in heavy smoke throughout the region. With wildfire effects removed, the near-road, background and comparison sites experienced $PM_{2.5}$ levels below Metro Vancouver's annual objective of 8 $\mu g/m^3$ and all but one station, the near-road station, was below the planning goal of 6 $\mu g/m^3$. When wildfire days were included, it was found that the near-road station exceeded the Metro Vancouver annual objective in both 2015 and 2017 while other stations were below the objective. During the wildfires, all stations exceeded Metro Vancouver's 24-hour $PM_{2.5}$ objective. With wildfire effects removed only the near-road station exceeded the objective on several days in November 2015 and October 2017.

A significant near-road contribution for $PM_{2.5}$ was found (2.2 $\mu g/m^3$) to be more than a third of the $PM_{2.5}$ annual planning goal of 6 $\mu g/m^3$. Also considerable black carbon was attributed to the near-road environment with an average of 1.2 $\mu g/m^3$ greater than the background site. On average more than half of the additional $PM_{2.5}$ measured at the near-road site was black carbon. While there are no provincial, federal or Metro Vancouver objectives for black carbon, it is a contaminant that has been identified as a concern from a health perspective as well as potential climate change impacts.

As expected the near-road monitoring station measured low concentrations of ground-level ozone due to scavenging and did not exceed any air quality objectives or standards. On average the Vancouver near-road station measured approximately 4 ppb less ozone than the background station.

Investigation of 24-hour volatile organic compounds (VOC) samples revealed that average total VOC levels at the near-road monitoring station were half as much as levels at a monitoring station near an oil refinery tank farm. Several individual VOC were investigated that were of concern for their importance as precursors in ozone formation (ethylene, 1-butene/isobutene, isoprene, 2-methyl-2-butene, and xylenes) and known toxic health effects (benzene and 1,3-butadiene). Ethylene and 1,3-butadiene were found to have higher average and peak concentrations at the near-road station compared with the other comparison stations. The near-road station experienced a slightly higher peak but lower average benzene level compared with the refinery station. Given the elevated levels of some VOC at the near-road station and the presence of two gas stations located within 75 metres of the station, it is highly unlikely that all the additional VOC at NR-VAN is attributable to traffic emissions. It was thought that the gas stations are significantly influencing VOC at the near-road station.

This study presented the first ultrafine particles monitoring in the region and found over two times more UFP in the near-road environment compared with the site removed from traffic influences.

It was found that traffic on Clark Drive was made up of 12% small heavy-duty vehicles and 6% large heavy-duty vehicles, which was greater than the regional estimate of 2% small heavy-duty vehicles and 1% large heavy-duty vehicles (estimated in Section 3.1). Clark Drive experienced six times more truck traffic compared with the regional average.

7.2 Near-Road Contribution

The near-road contribution was determined using the subtraction method outlined in Hilker et al., 2019. A range of contributions were found at the near-road station for each contaminant: NO_2 (28%), NO (71%), NO_x (55%), CO (30%), $PM_{2.5}$ (30%), BC (64%), UFP (46%) and O_3 (-32%). The near-road contribution and pollutant concentrations were found to be higher on weekdays compared with weekend days for all traffic-related air pollutants. On average, CO and $PM_{2.5}$ concentrations were 1.5 times higher on weekdays compared with Sunday, NO_2, NO, and NO_x were 2 times higher, while BC and UFP concentrations were nearly 3 times higher. Daily traffic volumes were found to be the highest on weekdays with a negligible reduction (0.3%) of passenger cars and trucks on Saturdays and slightly larger reduction of 12% on Sundays. The traffic volume of large trucks was considerably different on weekdays and weekends where there was a significant reduction of 51% on Saturdays and 72% on Sundays. The total traffic volume and greater truck traffic on weekdays was thought to play a key role in near-road contributions. The reduction in contaminant levels on Saturday can almost entirely be attributed to the reduction in trucks indicating the disproportionate influence of these vehicles. Sunday was found to have considerably lower truck traffic and lowest near-road contribution of any of the days.

The influence of traffic emissions was evident when examining contaminant concentrations associated with various wind directions at the NR-VAN station. The highest average concentrations were associated with calm conditions although these conditions were experienced infrequently and the relative contribution of calm conditions on the average contaminant level was found to be low. Wind patterns were examined and the highest concentrations for most contaminants were found to be associated with the wind directions coming from a nearby intersection located to the southeast. The intersection represents the confluence of two major roadways where vehicles experienced the highest rates of emission associated with accelerating from a stationary position. The southeast wind direction was also the most frequent wind direction, resulting in a considerable effect on the overall air quality experienced at the near-road monitoring station.

Wind angles at NR-VAN were divided into sectors representing various segments of Clark Drive including the Broadway intersection to the north, 12th Avenue intersection to the south, Clark Drive to the east, and the sector associated with upwind conditions that did not include a major roadway. The sector with the closest intersection (12th Ave to the south) was associated with the highest average concentrations of NO, CO, $PM_{2.5}$, and BC and highest maximum concentrations for NO, CO, BC and UFP compared with the other sectors. This sector experienced five times higher average NO, two times higher CO, NO_2 and UFP, and almost three times higher BC compared with the sector without a major roadway. The sector associated with winds blowing from Clark Drive to the east, directly adjacent to the monitoring station, includes traffic emissions that are the closest to the monitoring station. It was found that this sector resulted in the highest average UFP levels and similar but slightly lower peak levels of UFP compared with the sector from the south. Other contaminant levels associated with the eastern sector were found to be relatively high compared with the background station levels.

The sector associated with upwind conditions that did not include a major roadway experienced the lowest average concentrations of all the TRAP including NO, NO_2, CO, $PM_{2.5}$, BC and UFP. Levels measured from this wind sector were similar to these contaminants measured at the background station (BG-VAN).

The direct traffic influence of air pollution on the NR-VAN station was further assessed by calculating a relative impact for a wind sector that includes all the major roadways (within 250 m) and an another wind sector associated with no major roadway. The relative impact of the major roadways on overall concentrations was found to be 89% for NO, 89% for NO_2, 85% for CO, 82% for $PM_{2.5}$, 87% for BC and 86% for UFP, indicating signification contributions of traffic emissions for these contaminants.

7.3 Contaminant and traffic correlation

Overall, little correlation was found between traffic volumes and contaminant concentrations when all vehicle types were considered. A slightly higher correlation was found when large heavy-duty vehicles were considered separately with the highest correlation found for black carbon and ultrafine particles. Consideration of the two near-road stations at a highway site in Toronto and truck route site in Vancouver revealed an order of magnitude difference in total traffic volume but similar TRAP concentrations.

The role of vehicle type on contaminant concentrations was further investigated by applying a simple linear regression to determine the relationship between the ratio of vehicle types and contaminant concentrations. It was found that there was a strong relationship between large heavy-duty vehicles and elevated NO_x, UFP and BC concentrations. Higher concentrations of NO_x were found when the percentage of large heavy-duty vehicles using Clark Drive was the highest. The relationship indicates that light-duty vehicles may not be responsible for some of the highest recorded concentrations of UFP and BC, which are more likely associated with large trucks.

7.4 Comparison of three near-road sites

Three near-road stations with different surrounding environments, traffic volumes and road configurations were compared. The three sites represent a trucking route, highway and downtown road.

The trucking route (NR-VAN) and highway (NR-H401) experienced considerably higher nitrogen oxides (i.e., NO, NO_x, and NO_2), BC and UFP compared with the downtown road (NR-TOR site) in terms of higher average and peak concentrations. Higher levels of NO, NO_x, NO_2 and BC were measured at NR-VAN compared with NR-H401. The NR-H401 experienced higher $PM_{2.5}$ and UFP concentrations. The maximum number of hourly UFP was nearly two times higher at NR-H401 compared with NR-VAN.

The truck route (NR-VAN) had similar TRAP concentrations to the highway (NR-H401) and in some cases the concentrations were higher at NR-VAN (e.g., NO_2, NO_x, NO and BC). This result was unexpected given the order of magnitude difference in traffic volumes experienced at the two sites. Highway 401 experiences considerably greater volumes of traffic (~400,000 AADT) compared with Clark Drive (~33,000 AADT) and thus greater traffic emissions. Further investigation into this result were pursued and it was determined that the differences in the near-road environments of the two stations as well as the individual station siting played key roles in contaminant concentrations measured at the two sites. Investigation into a rationale for this revealed that the differences in micro-meteorology, road configuration and proximity of the sampling equipment to roadway emissions played a role in resultant contaminant concentrations at each site.

It was found that road configuration and unique wind regime at each near-road site played an important role in the resultant contaminant concentrations. During the study period the NR-H401 site was downwind of traffic emissions 52% of the time, influenced by the linear orientation of highway and local winds. In contrast the NR-VAN site, located within 250 m of three major roadways, was downwind of traffic emissions 83% of the time. Given this, the NR-VAN station measured a greater frequency of TRAP emissions compared with NR-H401 and thus was subject to higher relative concentrations on average.

The surrounding environment of the monitoring station, influenced the dispersion of traffic emissions, and also played a key role in the resultant TRAP concentrations measured at each site. The NR-H401 site had open exposure with good natural ventilation with no nearby buildings or obstacles to slow or restrict airflow near the station. Conversely, the NR-

VAN station was located a few feet from a two-story house in a densely built-up neighbourhood. The NR-VAN site had an estimated building height to street width ratio of 0.28 and was associated with some restriction in airflow at street-level where the monitoring inlet was located within the cavity of the street-canyon. Wind speed was found to be considerably lower at NR-VAN and light winds were experienced much more frequently compared with NR-H401. On average, winds were twice as fast at NR-H401 compared with NR-VAN and the maximum wind speed was much higher at NR-H401. Light winds (<0.5 m/s) were measured 22% of the time at NR-VAN while only 1% of the time at NR-H401. Since the NR-VAN site was more sheltered and experienced calmer wind conditions, less dispersion of TRAP occurs compared with NR-H401 and thus NR-VAN resulted in higher relative TRAP concentrations. It was found that road configuration, the micro-meteorology of the site and urban form play important roles in TRAP concentrations measured at any one location.

Another factor investigated to determine the differences between NR-VAN and NR-H401, was the distance of the monitoring station air intake to traffic emissions (i.e., distance to the first lane of traffic). The NR-VAN station was more than twice as close to the roadway compared with NR-H401, which was found to influence TRAP intensity or concentration levels. It was estimated, using distance-decay gradients found in the literature, that a 3 to 20% increase in concentrations could be attributable to proximity of the roadway at NR-VAN compared with NR-H401 assuming a similar emission regime. In Wang et al. (2018) a dilution factor of 1.6 times less dilution at NR-VAN compared with NR-H401 was found. With the air intake at NR-VAN twice as close to the traffic emissions compared with NR-H401, less dilution of traffic emissions at NR-VAN resulted in higher comparative concentrations.

8. Recommendations

Based on the findings of this study, several recommendations are made to reduce traffic-related emissions, exposure to traffic-related air pollutants and track air quality improvements in the near-road environment.

1. **Continue Operation of the Clark Drive Near-Road Air Quality Monitoring Station**

   The near-road monitoring study was intended to inform national recommendations for ongoing monitoring of near-road environments across Canada. The national recommendations will incorporate lessons learned in locating near-road monitoring stations, determine contaminants to be monitored, and evaluate additional non-standard air quality instrumentation. When the guidance is available it is recommended that it is followed and that a near-road monitoring station is operated in the region. ***It is recommended that operation of the Clark Drive Near-Road Monitoring Station is continued and at a minimum follows the national recommendations for near-road monitoring.***

2. **Consider Enhancing Air Quality Monitoring Near Major Roadways**

   The near-road air quality station on Clark Drive was set up to measure some of the highest expected concentrations of TRAP in the region. It was set up on a busy truck route, near a major intersection and close to other high-volume traffic roads. While the measurements taken at the Clark Drive monitoring station may be some of the highest in the region for some contaminants, they may not be representative of the concentrations that the majority of Metro Vancouver's population that live near a major roadway are exposed to. ***It is recommended that additional monitoring resources are utilized to characterize air quality near major roadways in other representative locations in Metro Vancouver.*** The monitoring resources could include a second permanent monitoring station or other more portable monitoring equipment that could be deployed in various near-road locations as specialized studies. Portable monitoring equipment would allow more flexibility and allow other major roadway types to be examined and population exposures to be determined.

3. **Develop a Program to Reduce Emissions of and Exposure to Traffic-Related Air Pollutants**

   The near-road environment at Clark Drive was found to experience more polluted air compared with other sites in the region with exceedances of Metro Vancouver's objectives. Levels of NO, NO_2, NO_x, CO, $PM_{2.5}$, BC and UFP were higher at the near-road site compared with other sites. ***It is recommended that Metro Vancouver develop a program to***

reduce emissions of traffic-related air pollutants and reduce exposure to traffic-related air pollutants. Reduction in traffic emissions may also have co-benefits of reducing impacts of climate change. Considerable work has already been done to identify strategies to reduce exposure to traffic-related air pollution in the region and the program should consider adopting these. A number of examples are listed below that could be considered as elements of such a program. Two key local studies, Brauer et al. (2012) and Stantec (2013), identify policy recommendations to reduce exposure to traffic-related air pollutants.

A study conducted for Health Canada (Brauer et al., 2012) reviewed the scientific evidence of adverse health effects associated with exposure to traffic-related air pollutants and identified potential exposure-mitigation strategies. The study provides detail on several mitigation strategies for reducing exposure to traffic-related air pollution. The authors focus on four key areas:

1. Land-use planning and transportation management: for example, siting of new buildings and roads, road setbacks, spatial and/or temporal limitation of motor vehicle activity (especially heavy-duty diesel vehicles) near densely populated areas, and separation of motorized transportation from active transportation modes.
2. Reduction of vehicle emissions: identifies the importance of controlling emissions at their source, using approaches such as new vehicle emission regulations, fuel quality standards, and inspection and maintenance programs for the existing fleet;
3. Modification of existing structures: includes implementation of outdoor measures such as physical barriers and separation of bicycle lanes, as well as indoor measures such as air filtration;
4. Encouraging behaviour change: for example, by offering alternatives to private vehicles such as car-sharing and improved public transport, and by educating residents about the impact of their transportation choices on regional air quality, as well as exposure to TRAP.

The authors state in a further publication (Brauer et al., 2013b) that in the short term, policies and regulations that target existing infrastructure and vehicles are likely to be the most effective in reducing exposure because they operate at the population level. In the long term, they advocate a focus on land-use planning that incorporates health impact assessments that influence the siting of new buildings or roads where exposure can be minimized.

A comprehensive study titled “Reducing Exposure to Traffic Emissions” (RETE) was conducted in 2013 whereby a consulting team worked closely with Metro Vancouver, TransLink, and the British Columbia Ministry of Environment and was guided by a multi-agency steering committee. The study acknowledged the linkages between exposure to harmful traffic-related air pollutants and adverse health impacts, and identified and evaluated strategies to reduce resident exposure to traffic-related air pollution within British Columbia. Strategies are recommended to shape the community and environment so that residents’ exposure to traffic-related air pollutants is reduced through design and mitigation, as well as recommendations to reduce overall vehicle emissions from traffic. The study recommends strategies that contribute to communities' existing strategies and plans for vibrant, compact communities, and resolve the apparent dilemma that can exist between TRAP exposure reduction and smart growth infill development objectives. The study authors recognize that no particular agency or level of government has the sole mandate and responsibility to reduce exposure to traffic emissions. The study identifies key strategies and roles for various agencies to take action, as well as areas to collaborate such as land use, design, transportation management, and education / outreach strategies to reduce, mitigate and prevent exposure.

The authors assessed numerous strategies in terms of effectiveness at reducing exposure, feasibility and potential to achieve co-benefits. Ultimately they recommended several highly effective and feasible strategies which range in approach from land use, design, and transportation management, to education and outreach. Example strategies provided in the report are shown below (note that there are more strategies contained within the report):

Example Land Use Strategies

- **Adopt policy to require large-scale transportation infrastructure projects and plans involving major roadways to quantify air quality-health benefits and costs through a Health Impact Assessment.** This will allow quantification of air quality health benefits and costs and identify appropriate mitigation measures for areas of concern.

- **Work with health authorities and other relevant agencies to develop a process for assessing health impacts of proposed new communities, infrastructure and transportation services, using an integrated approach that assesses the full range of health impacts, including quantification of air quality health impacts.** Since this recommendation was made, a Health Impact Assessment guidebook (Metro Vancouver, 2015a) and toolkit (Metro Vancouver, 2015b) have been developed and are available to assess overall health implications of proposed new communities, infrastructure and transportation services, including air quality and noise, with input from public health authorities.

- **Work with health authorities and other relevant agencies to develop best management practices that will mitigate exposure in identified higher TRAP exposure areas as part of zoning and development permit processes.** Promote a mix of land uses, siting considerations and designs for sensitive land uses (e.g., daycares), and encourage mitigation through building design and operation, ventilation and filtration.

Example Design Strategies

- **Create barriers between emission sources and higher TRAP exposure areas** such as walls and landscaped boulevards and medians between emission sources and higher TRAP exposure areas.

- **Locate designated pedestrian and cycling routes further away from busy roads (e.g., parallel roads, separated bike paths)** in areas with heavy stop-and-go traffic, while keeping travel time the same. The route could be located outside a higher TRAP exposure area, on a parallel minor road or on a bike path 1 to 2 m further away from vehicle traffic.

- **Update the BC Building Code to require indoor air quality management practices that reduce levels of outdoor contaminants and investigate whether municipalities/regional districts have the authority to require indoor air quality management practices.** In higher TRAP exposure areas, for example, buildings could be required to be well sealed, ventilate with fresh air located away from busy roads, and employ filtration with high efficiency particulate air (HEPA) filters.

Example Transportation Management Strategies

- **Implement parking management strategies that help reduce TRAP** by increasing parking pricing in all areas (not just downtown Vancouver) targeting high exposure areas, support projects that unbundle parking from property, and reduce parking supply.

- **Enhance pedestrian and cycling infrastructure** such as on-street infrastructure and crossings that increase road and path connectivity and provide safe and attractive walking and cycling, end-of-trip and off-street infrastructure, and improved maintenance plans (e.g. snow clearance and salting and/or sanding plans for sidewalks and bicycle paths).

- **Improve transit service quality** such as service frequency and operating hours, reliability and travel time.

- **Implement congestion pricing on provincial and / or arterial roads** to reduce congestion on provincial and arterial roads, and encourage the use of alternative modes of transportation and / or off-peak travel.

- **Designate truck traffic to specific times** encouraging off-hour deliveries to reduce congestion and daytime smog formation with consideration of noise pollution in the evenings.

- **Provide more infrastructure for electric and other cleaner vehicle technologies / fuels for high emitting vehicles** at ports and distribution centres for trucks to encourage truck drivers to plug-in while loading and unloading their vehicles or use other cleaner vehicle technologies / fuels.

4. <u>Develop Education and Outreach Materials</u>

There is an opportunity to disseminate the findings from this study to both the public and stakeholders such as other governments and the transportation sector. The Reducing Exposure to Traffic Emissions (RETE) study outlines several education and outreach strategies that should be adopted. ***It is recommended that fact sheet(s) and workshop modules on reducing exposure to TRAP are developed.*** Building on the findings of this study and other available health information on TRAP, a fact sheet(s), workshop modules, and other education and outreach materials should be developed for the public to inform them of the health impacts of transportation decisions. Specific workshop modules should be developed with and for various stakeholders including transportation planners, the transportation authority, the trucking industry, the Port, and other governments. Strategies recommended in the RETE study were adapted to address the findings of this study and could include:

- **Educate the general public about health impacts of transportation decisions** including benefits of active transportation, adverse effects from motorized transport, and risks of exercising near busy roads and truck routes.

- **Develop a fact sheet and/or workshop module on reducing exposure to TRAP** that highlights the findings of this study and potential exposure reduction strategies and available resources for land-use planning, building and transportation.

- **Where feasible, educate vulnerable individuals regarding the risk of living, working and exercising in higher TRAP exposure areas** whereby the community can use information about the traffic volumes on their streets and then identify their major / busy roadways and communicate that information to vulnerable individuals.

- **Work with the trucking community to inform about exposure to TRAP** including potential fuel savings and health exposure risks of extended idling.

- **Encourage children and parents to walk and bike to school** through Safe / Best Routes to School programs or by parking a few blocks away from the schools and walk the rest of the way.

Metro Vancouver is currently developing an updated air quality management plan, the *Clean Air Plan*, which will identify opportunities for accelerated emissions reductions in our region, including near major roadways. The near-term actions in the *Clean Air Plan* will help protect human health and the environment, while reducing greenhouse gas emissions, through incentives, education and regulations. These emissions reductions align with *Climate 2050*, Metro Vancouver's long-term strategy to support achieving a carbon neutral and resilient region by 2050.

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