Pilot study: using air quality monitoring to track changes in bus fleet emissions on the Golden Mile, Wellington City

Tamsin Mitchell
Environmental Science Department

For more information, contact the Greater Wellington Regional Council:

Wellington
PO Box 11646

T 04 384 5708
F 04 385 6960
www.gw.govt.nz

Masterton
PO Box 41

T 06 378 2484
F 06 378 2146
www.gw.govt.nz

GW/ESCI-T-21/7

May 2021

www.gw.govt.nz
info@gw.govt.nz

Report prepared by:	T A Mitchell	Senior Environmental Scientist, Air Quality	T. Mitchell
Report reviewed by:	Dr N Talbot	Independent consultant and University of Auckland researcher	
Report approved for release by:	L Baker	Manager, Environmental Science	L J Baker **Date**: 21/5/2021
	F Abbott	Manager, Assets & Infrastructure - Metlink	**Date**: 21/5/2021

The report may be cited as:

Mitchell, T.A. 2021. Pilot study: using air quality monitoring to track changes in bus fleet emissions on the Golden Mile, Wellington City. Greater Wellington Regional Council, Publication No. GW/ESCI-T-21/7

Executive summary

Increasing public transport use and active travel modes is key to decreasing traffic congestion and reducing emissions of both CO_2 and harmful pollutants on a per passenger per km basis. Metlink is committed to delivering an environmentally friendly bus fleet across the region by progressively decarbonising the bus fleet whilst increasing patronage. The long term goal is 100% electric fleet on all core services by 2030. As part of this programme the older more polluting buses will be phased out resulting in co-benefits for air quality.

This study focuses on the impact of bus emissions on the Golden Mile which runs through Wellington City's central business district (CBD). The Golden Mile is the city's busiest pedestrian area and the road corridor for most of the city's core bus routes. It is also where the region's highest traffic-related air pollution levels are found, despite having relatively low traffic volumes. Indicative air monitoring shows annual average levels of traffic-related air pollution (nitrogen dioxide) reduced following the introduction of new bus fleet and routes through the city centre. Whilst this monitoring is useful for identifying long term air quality trends it is not necessarily the best measure for identifying real-world local changes in bus emissions on the Golden Mile over time.

This report presents the findings of a 10-week air monitoring study to assess the feasibility of measuring black carbon, a marker of diesel particulate and a short term climate warming agent, at an inner city bus stop. The study confirms that black carbon is a more sensitive indicator of bus emissions than nitrogen dioxide and therefore more useful for evaluating impacts of the bus fleet upgrades and any interventions specifically designed to improve bus travel times and reliability on the Golden Mile arising from Let's Get Wellington Moving projects.

Progressively modernising and electrifying the bus fleet on the Golden Mile is expected to lead to cleaner and healthier air for people who work, visit and live in the CBD. Being able to quantify the real-world improvements in air quality due to changing emissions profile of the bus fleet could help inform future policies and plans associated with active travel and public transport.

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1. Introduction

1.1 Purpose and context

Greater Wellington Regional Council (GWRC) funds and manages the regional Metlink public transport network of buses, trains and harbor ferries. The Metlink network includes more than 90 public bus routes which account for 9% of Wellington's mode share. The proposed draft Wellington Regional Public Transport Plan 2021-31 focuses on three strategic priorities of mode shift, decarbonisation of the public transport fleet and improving customer experience. Decarbonisation of the bus fleet is proposed through progressively increasing the number of electric buses in the fleet from 10 to 108 from mid-2021 (21% of the fleet) with a long term goal of 100% electric fleet by 2030. Bus fleet electrification, as well as reducing CO_2 emissions, will also remove older diesel-powered buses from the fleet which is expected to lead to cleaner and healthier air quality for people who work, visit and live in Wellington city central business district.

Let's Get Wellington Moving (LGWM) is a joint initiative between Wellington City Council, GWRC and Waka Kotahi NZTA that seeks to move more people with fewer vehicles (https://lgwm.nz/). There are a number of early delivery projects, including improvements on the Golden Mile aiming to encourage active transport (walking and biking) and give buses more priority. The Golden Mile, a 2.3 km corridor that runs through inner city Wellington (Figure 1.1), is central to the Wellington bus network with 36,000 people travelling by bus along part of the Golden Mile every weekday. It is also highly pedestrianised with 31,000 people walking along part of it during a typical weekday (https://lgwm.nz/).

With the support of Metlink, GWRC's Environmental Science team established low-cost indicative nitrogen dioxide (NO_2) air quality monitoring sites along the Golden Mile in July 2016. Whilst this monitoring has shown some improvement in air quality in the last three years, levels of air pollution have not reduced commensurate with the reduction in bus movements and fleet upgrades along the Golden Mile introduced in mid-July 2018. The reasons for this discrepancy are not clear and need further investigation to understand whether it is due to higher than expected on-road bus emissions, other sources of air pollution, measurement uncertainty in the indicative monitoring method and/or inter-annual variation in weather patterns.

The purpose of this environmental monitoring study is to evaluate monitoring black carbon as an indicator of ultra-fine diesel particulate to assess whether this pollutant is more strongly associated with bus emissions than the currently monitored indicator (nitrogen dioxide). This report presents the findings of a 10-week air monitoring study that assesses whether fine temporal resolution black carbon measurements can be matched with bus activity data on a section of the Golden Mile. If successful, this monitoring approach could be used to track real-world changes in the bus fleet's emissions profile and the impacts of the LGWM Golden Mile improvements on air quality the over the next 10 years.

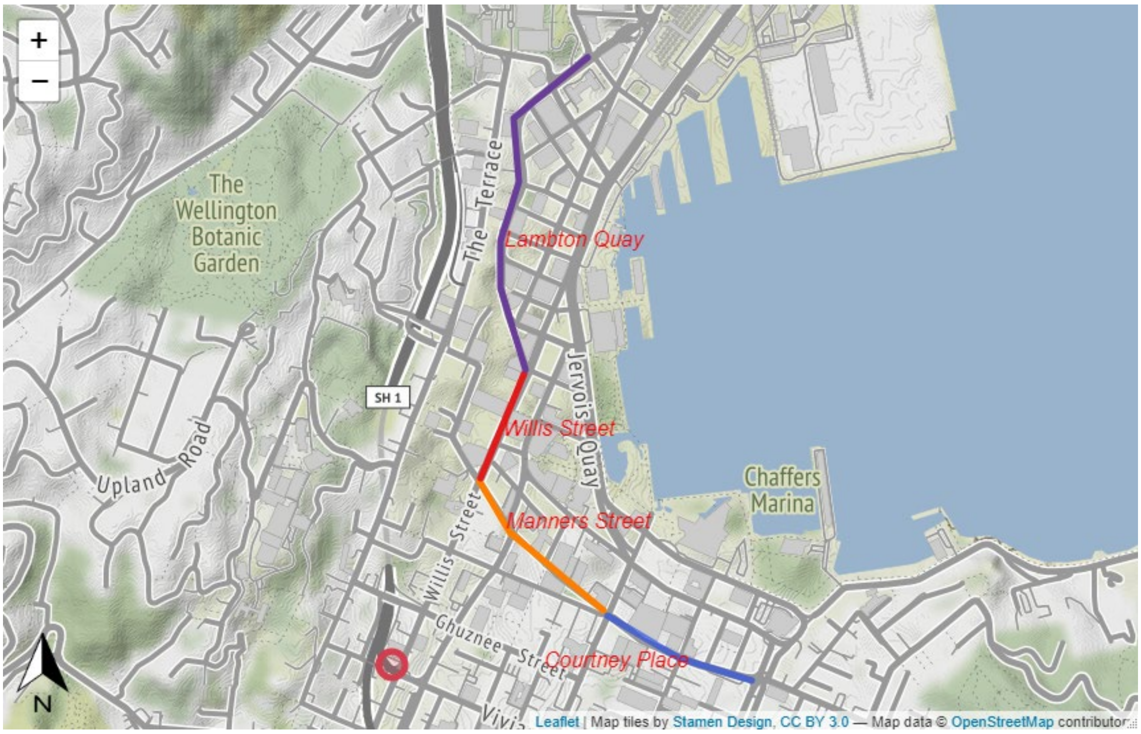

Figure 1.1: Location of the streets that make up the Golden Mile in Wellington City and the location of Wellington Central air monitoring station (red circle)

1.2 Study objectives

(a) Trial a compact kerbside mounted air quality monitoring instrument to measure black carbon concentrations at an inner-city bus stop.

(b) Evaluate whether black carbon monitoring can be used to represent local bus diesel particulate emissions.

(c) Assess whether local black carbon monitoring can be used as an indicator to evaluate the impact of planned bus fleet changes to reduce emissions of harmful pollutants and co-emitted CO_2.

2. Transport-related air pollution impacts and indicators

2.1 Background

By international comparisons most of Wellington City has good air quality, due to wind from the Cook Straight, low population density and virtually no air pollution arising from outside the region or country. However, Wellington City still faces pressures from transport emissions leading to degraded air quality alongside congested roads and inner city built up areas where tall buildings either side of the road restrict the dispersal of emitted pollutants. Sections of the Golden Mile have the poorest air quality in the region and are amongst the highest air pollution levels recorded in the country (Waka Kotahi NZTA, 2020).

To measure pollutant levels in Wellington city, GWRC Environmental Science operate a permanent air quality monitoring station located on the corner of Willis Street and the southbound Urban Motorway (Figure 1.1). This site has been fully operational since 2016 and monitoring results show this location complies with National Environmental Standards and guidelines for air quality (Mitchell, 2020). The Wellington Central air monitoring station provides the air quality statistics used to compare Wellington's air quality with other cities in NZ and overseas.

In complex urban terrain air pollution levels can vary considerably over short distances (Longley et al., 2019). Characterising this variability is necessary to establish representative monitoring sites for reporting regional trends in harmful transport-related emissions (Mitchell, 2017). GWRC (Environmental Science) engaged NIWA to assist with spatial monitoring surveys and modelling to identify representative monitoring sites. The first monitoring survey in summer 2015/2016 showed elevated pollutant levels along the public transport spine through Wellington city (Longley et al., 2016). Therefore, this area was identified as a priority for establishing monitoring sites.

Initiatives to increase walking and biking, increase public transport patronage, decarbonise the bus fleet and improve bus priority provide great opportunities for improving air quality on high pollution streets in Wellington City. Reducing harmful emissions and air pollution is an important component in minimising the impact of transport on the environment and people's health, especially with a growing population and potential for higher personal exposure to traffic emissions during commuting. There is a growing body of evidence that exposure to traffic-related air pollutants is associated with exacerbation of asthma, respiratory symptoms, impaired lung function, and increased risk of cardiovascular disease and premature death (Health Effects Institute, 2010).

2.2 Traffic-related air pollutant indicators

Traffic-related air pollution is a complex mixture of gases and particles with differing chemical, physical and toxicological properties. Trends in traffic-related air pollutants are typically tracked by monitoring fine particulate matter ($PM_{2.5}$), black carbon and nitrogen dioxide. These indicators are discussed below.

2.2.1 Fine particles ($PM_{2.5}$)

Fine particles known as $PM_{2.5}$ (aerodynamic diameter < 2.5 µm) are emitted by vehicle exhaust (primarily diesel) due to incomplete combustion. Most of these exhaust particles are ultra-fine in size (ie, less than 0.1 µm) and therefore do not make up a large fraction of measured $PM_{2.5}$ mass concentrations.

A short-term monitoring study January to February 2020 at Wellington Central air monitoring analysed elemental compositions of $PM_{2.5}$ collected on filters. GNS Science, using a reconstructed mass approach, found that $PM_{2.5}$ was on average made up of 26% black carbon, 26% secondary sulphate, 28% sea salt, 19% soil and 1% smoke (Perry Davy, GNS Science, pers. comm. 9/9/2020). Therefore, the relatively high contribution of non-traffic sources to $PM_{2.5}$ reduce the usefulness of this metric as an indicator for vehicle exhaust particulates.

2.2.2 Black carbon

Black carbon is a sizeable component of fine particle combustion emissions with particle diameters of less than 100 nm. BC is therefore a strong marker of ultra-fine particle combustion emissions from vehicles, especially diesel-powered. Black carbon is also emitted by solid fuel burning (home fires), shipping and aviation.

Although heavy duty vehicles, including buses, are only a small part of the regional vehicle fleet they are high emitters of black carbon and therefore can have a disproportionate impact on local air quality (Rakowaska et. al., 2014). Long term PM speciation monitoring undertaken in Auckland confirms that 90% of black carbon arises from diesel fuelled vehicles and 10% from petrol fuelled vehicles (Davy & Trompetter, 2017). The Auckland study also showed that ambient $PM_{2.5}$ originating from diesel vehicles was composed of 60% to 90% black carbon on a mass basis depending on monitoring site location (Davy & Trompetter, 2017). Therefore, monitoring black carbon at the roadside may be used to evaluate the impacts of interventions, such as fleet composition changes or roadway changes, on traffic emissions (Reche et al., 2011).

A review of the health effects of black carbon particles as a component of PM2.5 concluded that black carbon acts as a universal carrier of a wide variety of combustion-derived chemical constituents of varying toxicity to humans and therefore reducing exposure to black carbon from combustion sources should lead to a reduction in health effects associated with $PM_{2.5}$ (World Health Organization, 2012). Another critical review of health impacts of black carbon from various sources found black carbon was causally related with cardiovascular and lung cancer deaths (Grahame et al., 2014). The role of black carbon as a surrogate for exposure to traffic emissions and attributable health impacts is an ongoing international field of research.

Black carbon contributes to climate change because its dark colour is very good at absorbing heat and in the atmosphere it acts as short-term climate warming agent (Ministry for the Environment, 2018). Therefore, reductions in black carbon can more quickly mitigate changes in the climate compared to carbon dioxide which persists for hundreds to thousands of years in the atmosphere (Ramanathan & Carmichael, 2008).

2.2.3 Nitrogen dioxide (NO2) and nitrogen oxides (NOx)

Nitrogen dioxide (NO_2) is a harmful air pollutant derived from fuel combustion. NO2 is a respiratory irritant that can impair lung function later in life in exposed children and aggravate asthma. There is also an association between NO_2 and increase in death rates and hospital admissions for respiratory disease (US EPA, 2016). NO_2 levels measured at Wellington Central and Upper Hutt monitoring sites meet national guidelines and standards (Mitchell, 2020).

Generally, only a small amount of NO_2 is directly emitted in exhaust emissions. Most NO_2 is formed as a secondary pollutant when nitric oxide (NO) produced during high temperature fuel combustion is rapidly oxidised by ozone (O_3) in outdoor air. The reaction between NO and O_3 continues until either the O_3 is depleted or all NO is converted to NO_2.

Collectively NO and NO_2 are known as NOx. Although all motor vehicles emit NOx, diesel vehicles emit substantially greater amounts of NOx (and particulate matter) per mass of fuel burnt than petrol vehicles due to the engine conditions necessary for diesel combustion (Gentner & Xiong, 2017).

3. Evaluating harmful emissions from road transport

3.1 Regulation of bus emission standards

The quantity of emissions from an individual diesel-powered bus depends, although not entirely, on its exhaust emission control technology determined by which European (EURO) standard the bus has been manufactured to meet. EURO standards for heavy duty vehicles (over 3.5 tonnes) were introduced in 1992 (EURO I) with progressively stringent limits for NOx and PM being required from EURO II to EURO VI. EURO VI (introduced in 2013/14) required a 50% reduction in PM and 80% reduction in NOx over EURO V. In order to meet these limits, diesel particulate filters and specific NOx after treatment technologies are required (EMEP/EEA, 2019[1]). NZTA requires that all existing buses must meet EURO III and all new buses entering an urban fleet must meet EURO V (current national Vehicle Exhaust Emission rule) (NZTA, 2014).

Although there are as yet no regulated emission limits for black carbon, the need to reduce black carbon emissions (as the largest component of diesel particulate matter) is becoming increasingly recognised as necessary to mitigate both adverse health impacts and global warming (Miller & Lim, 2018). The control of black carbon emissions is largely achieved through the regulated PM limit as diesel particulate filters (DPF) required to achieve the PM limit also reduce black carbon (Wiesner et al., 2021). Therefore it is expected that black carbon emissions from EURO VI buses will be significantly lower than older EURO models as the EURO VI are fitted with diesel particulate filters (DPFs) to remove soot particles.

3.2 Metlink bus fleet emissions

The Public Transport Operating Model (PTOM) that came into law in 2013 changed the way public transport is planned and procured. GWRC used this process as an opportunity to start on a pathway to a zero emission bus fleet by incentivising bus providers to use lower emitting (ie, higher EURO standard and electric) buses in their fleet (Kuschel & Cooper, 2017). A bus emissions evaluation model was developed for the PTOM bus operators tender using the best available bus emissions data from testing in Europe as used in COPERT[2] and average bus speeds across the network. In July 2018 major changes were made to Wellington's bus network design and fleets. To track the emissions trends across the new network, Metlink has developed a more accurate prototype bus emissions prediction tool that uses on-road data from each individual bus trip, eg, distance travelled, speed travelled and EURO emissions standard, to calculate the total fleet emissions. The emissions modelling shows a substantial drop in estimated harmful emissions across the whole fleet following the July 2018 network changes (Hamish Clark, Metlink, pers. comm. 18/2/2020).

International research has shown the importance of understanding how harmful emissions actually emitted whilst driving can differ from the

[1] https://www.eea.europa.eu/publications/emep-eea-guidebook-2019
[2] European Union's standard Computer Model to Calculate Emissions from Road Transport..https://www.emisia.com/utilities/copert/

manufacturers type approval (ICCT, 2015). A recent study carried out in Auckland using on-board testing (PEMS[3]) of 32 vehicles (Kuschel et al., 2019), whilst not including buses, found real-world emissions of most pollutants were higher than regulated standards. The study also found differences between COPERT emission factors used in Waka Kotai NZTA's national vehicle emissions prediction model (VEPM) and the real-world emissions and recommends additional testing of heavy duty diesel vehicles to better predict emissions and fuel consumption from this class of vehicles.

The potential discrepancy between emissions factors derived from COPERT and on-road testing in New Zealand support the need to investigate the use of roadside air quality monitoring to track the real-world impacts of a changing emissions profile, particularly at sensitive locations, such as the Golden Mile.

3.3 Using air quality monitoring to detect emission trends

Linking air quality trends at a monitoring site to locally-generated traffic emissions is complex and challenging. Bluett et al. (2016) describe the main long term drivers of air pollutant trends as:

(a) Number of vehicle trips per day past the site

(b) Fleet profile (vehicle age distribution, vehicle type (eg, light duty, heavy duty), fuel type (eg, petrol, diesel)

(c) Driving conditions (congested or free-flowing)

(d) Real-world emissions performance of vehicles (effectiveness of emission control technology and fuel quality).

Using air quality measurements to infer emissions trends is confounded by meteorology which strongly influences the ability of the atmosphere to transport, dilute, transform and remove air pollutants. Therefore, even when traffic emissions remain fairly constant, air pollutant concentrations can vary widely due to changes in weather conditions (Oke, 1978). Evaluating the impact of emissions and any interventions to reduce emissions on air quality is therefore challenging due to the influence of meteorology. Unless accounted for meteorological variation can mask underlying trends in air pollutant emissions (Air Quality Expert Group, 2020). Statistical modelling techniques involving machine learning to account for the impact of meteorology on air pollutant measurements have been shown to assist in revealing underlying changes in traffic emissions, for example, the introduction of London's low emission zone (Grange & Carslaw, 2019).

3.4 Current air quality monitoring of bus emissions on the Golden Mile

From July 2016 Metlink co-funded GWRC's Environmental Science team to undertake air quality monitoring along the Golden Mile to help understand the contribution of bus fleet emissions on air quality and to track any impacts due

[3] Portable Emissions Monitoring System

to fleet upgrades and route changes resulting from the network changes in July 2018. Accordingly, three passive NO_2 monitoring diffusion tube (Figure 3.1) sites were installed on the Golden Mile bus corridor: Courtney Place WEL083, Manners Street WEL082 and Lambton Quay WEL081 (Figure 4.5). The monitoring method for passive NO_2 diffusion tubes in described in section 4.1.4. NO_2 measurements at these sites show a downward trend in air pollutant levels from 2017 to 2019. Most of this decrease occurred over 2018 coinciding with the introduction of the new bus fleet and routes (Figure 3.2). The 2018 step change in NO_2 is not seen at other monitoring sites less directly affected by bus movements such as Wakefield Street and Wellington Central air monitoring station, which both show a steady downward trend.

Figure 3.1: Passive NO_2 diffusion tube installed on Manners Street (WEL082)

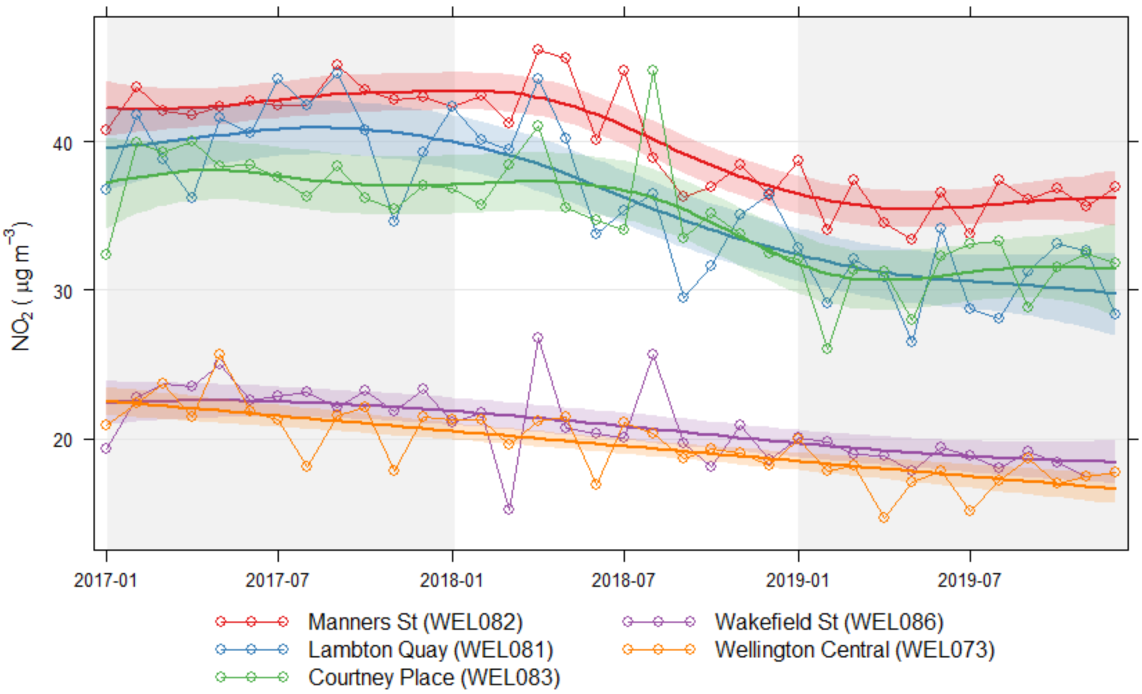

Figure 3.2: Smooth trend (deseasonalised) of monthly NO_2 passive diffusion tube concentrations between 2017 and 2019. Plot created using Openair (Carslaw & Ropkins, 2012).

A non-parametric linear time trend test (Theil Sen, as implemented in Openair Carslaw & Ropkins, 2012) was used to assess trends in NO_2 as a percentage change per calendar year from 2017 to 2019 at different Wellington city roadside sites (Table 3.1). All monitoring sites experienced a three year downward trend in NO_2 (ie, improving air quality). Some sites have improved more than others but the reasons for this cannot be explained without detailed local traffic data. Time trends are sensitive to the start and end date and so these results are a three-year snap shot rather than a definitive long term trend. Three years is also a relatively short time period for assessing air quality trends which are sensitive to inter-annual variation in weather patterns.

Table 3.1: Trends in deseasonalised monthly NO_2 at passive diffusion monitoring sites between 2017 and 2019. The 95% confidence intervals are shown in square brackets.

Location	Site ID	Percent change per year (2017 to 2019)
Manners Street	WEL082	-6.7 [-9.3, -5.5]
Thorndon Quay	WEL084	-7.5 [-10.7, -4.5]
Courtney Place	WEL083	-7.9 [-9.9, -6.2]
Wellington Central air monitoring station	WEL073	-9.0 [-11.5, -6.9]
Newtown	WEL049	-10.0 [-12.9, -8.1]
Basin Reserve	WEL008	-10.7 [-12.3, -8.2]
Lambton Quay	WEL081	-10.9 [-14.7, -8.4]

A more detailed analysis was undertaken for Manners Street (WEL082) to see if observed NO_2 concentrations for three periods with different bus fleet profiles traveling through Manners Street could be correlated with changes in bus numbers and types. Between 2017 and 2019 changes in the amount of NOx (kg) emitted on Manners Street were expected as many of the older EURO III buses were replaced by lower emitting EURO VI models in mid-July 2018. Figure 3.3 compares three six-month periods with different fleet profiles and bus numbers. January to June 2017 was the baseline fleet configuration before the electric trolley buses were removed. January to June 2018 was the transitional fleet that did not include any electric buses. January to June 2019 covers the new fleet and PTOM implementation with fewer buses overall and including a proportion of new EURO VI buses.

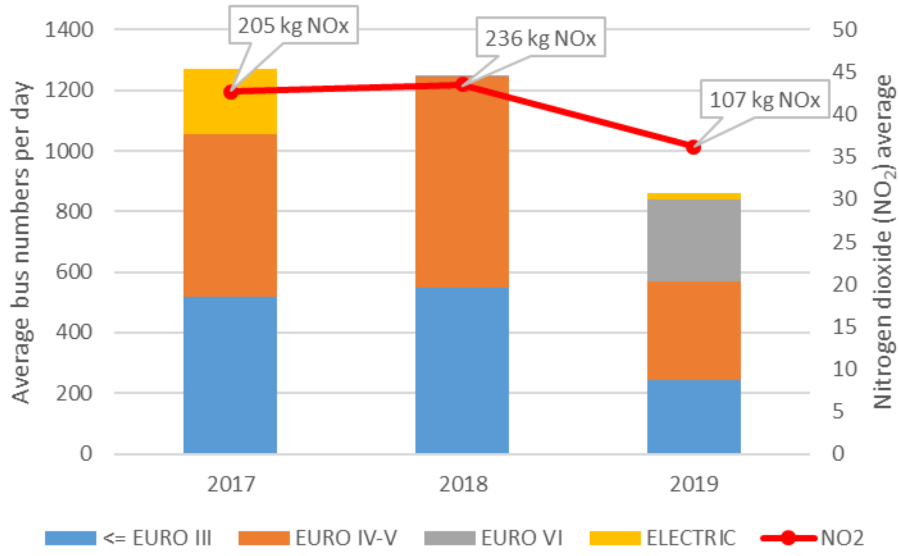

Figure 3.3: Six-month average NO_2 concentration (µg/m^3) measured by passive diffusion tubes at Manners Street (WEL082) compared to average number of daily buses classified by engine technology and estimated bus fleet NOx emissions on Manners Street are shown in the call outs

At face value Figure 3.3 shows that from 2018 to 2019 a 55% reduction in estimated NOx emissions and 31% reduction in bus numbers was associated with a 17% reduction in NO_2. A range of percentage decreases at other NO_2 monitoring sites over the same time period were also observed with the largest percentage decrease of 24% at the Basin Reserve (WEL008) and the smallest percentage decrease of 7.5% at Thorndon Quay (WEL084).

The NO_2 passive diffusion tube monitoring results show that air quality is improving on the Golden Mile, particularly on Lambton Quay, in line with improvements seen at other monitoring sites much less affected by bus traffic such as Wellington Central air monitoring station. The results also show that Manners Street air quality is least improved and still has the highest NO_2 levels of all currently monitored locations in the region. The 2019 annual average measured on Manners Street (WEL082) was 35.9 µg/m^3 - higher than that measured at the heavily trafficked Basin Reserve site (WEL008) of 31.1 µg/m^3.

It is unclear how much of the downward trend in NO_2 on the Golden Mile was due to changes in on-road emissions, fewer buses on the route, measurement uncertainty in the indicative monitoring method and inter-annual variation in meteorology. A further complicating factor is the role of atmospheric chemistry in the local formation of NO_2 which means that the relationship between reductions in NOx emissions and levels of NO_2 are non-linear, ie, reductions in emitted NOx do not result in equivalent reductions in NO_2 (Clapp & Jenkin, 2001).

Ideally NOx concentrations should be monitored alongside NO_2, however this is not currently possible as there are no reliable compact and affordable measurement technologies available. New sensor testing for monitoring traffic impacts is an active area of research being undertaken by NIWA (Longley & Kachhara, 2020).

Black carbon is an inert pollutant strongly associated with diesel emissions and therefore may be a more specific indicator for tracking bus emission trends. With the current technology available, black carbon can be monitored over short time frames (eg, 1 minute to 1 hour) and may be able to be correlated with bus activity data and meteorological variables that affect pollutant dispersion. Black carbon has been used to evaluate change in public transport systems in Spain and Slovenia (Titos et al., 2015) and Chile (Gramsch et al., 2013).

4. Methods

4.1 Monitoring instruments, locations and data considerations

4.1.1 Instrumentation

Black carbon was simultaneously measured at Manners Street and at Wellington Central air monitoring sites (Figure 4.1) using two different aethalometer instruments. Aethalometers collect aerosol particles by continuously drawing sampled air through a spot on a filter tape. The particles are analysed by measuring the transmission of light through one portion of the filter tape containing the sample, versus the transmission through an unloaded portion of the filter tape acting as a reference area. This analysis is done at several optical wavelengths spanning the range from the near-infrared to the near-ultraviolet. The wavelength used to calculate black carbon concentration is 880 nm.

A MicroAeth (MA350 serial number 0051, Aethlabs) was used to measure black carbon on Manners Street. This instrument is compact and designed to be mounted on a fence line or street pole for black carbon monitoring in areas where it is not possible to deploy an air quality station. The MA350 instrument is designed to run on an internal battery for a period of 2-3 days before being recharged using a mains connection for about 12 hours. Therefore, to ensure continuous operation, the instrument was connected to mains power using a DC to AC adapter. Achieving a safe and secure mains connection for the instrument on an inner city street was a non-trivial and expensive exercise involving certified electrical work plus a traffic management plan, permissions of the asset owner and a potentially meter and lines connection fees. Therefore the instrument is suitable for either very brief campaigns (one to two days) running on battery power or longer term operation with a mains connection.

Annual servicing and maintenance of the MA350 instrument currently needs to be undertaken in Australia where the manufacturer’s agent is located. Any instrument repairs need to be undertaken by the US manufacturer. The instrument’s filter tape cartridge has 85 sampling locations and the tape advances each time the instrument is manually stopped for the weekly data download. The tape advance is also automatically triggered during sampling depending on the particulate loading on the filter and the flow rate. Over the 75 day monitoring period 35 filter spots were used. At this filter spot advance rate it is estimated that for continuous monitoring around four filter cartridges per year would be required at total cost of $7,729 depending on exchange rate fluctuations as the tape is manufactured in the US.

A Magee Scientific Aethalometer (AE33, Magee Scientific) was used to measure black carbon at the Wellington Central air monitoring station. This instrument measures black carbon at seven optical wavelengths in near-real time, weighs 20 kg and needs to be housed within a temperature controlled shelter.

Prior to the monitoring campaign the MA350 monitor was collocated with the AE33 monitor at Wellington Central air monitoring station from 13 March to 6 May 2019. At one-hour resolution the instruments showed good agreement (R^2=0.94) although the MA350 underestimated concentrations on average by around 22% compared to the AE33 (Appendix 1, Figures A1.1 and A1.3). The relative difference between the monitoring instruments was dependent on concentration levels – with negative bias of the MA350 increasing at higher black carbon concentrations measured by AE33. These instrument colocation results were not used to adjust the MA350 data to make it equivalent to the AE33 as the period of colocation was relatively brief and did not include the winter period. More investigation is required to better understand the differences in measurement, which may relate to instrument settings, for example, the AE33 has a higher flow rate (2 l/min) and there may be differences in the reference temperature (0^oC or 25^oC) used to convert the volumetric flow to a mass value for reporting black carbon concentrations.

Appendix 1 (Table A1.1) shows the monitoring instrument operating parameters. Meteorological measurements (wind speed, wind direction, temperature, relative humidity, barometric pressure) were obtained from the Wellington Central air quality monitoring station and from Glasgow Wharf site at CentrePort (purchased from Metservice).

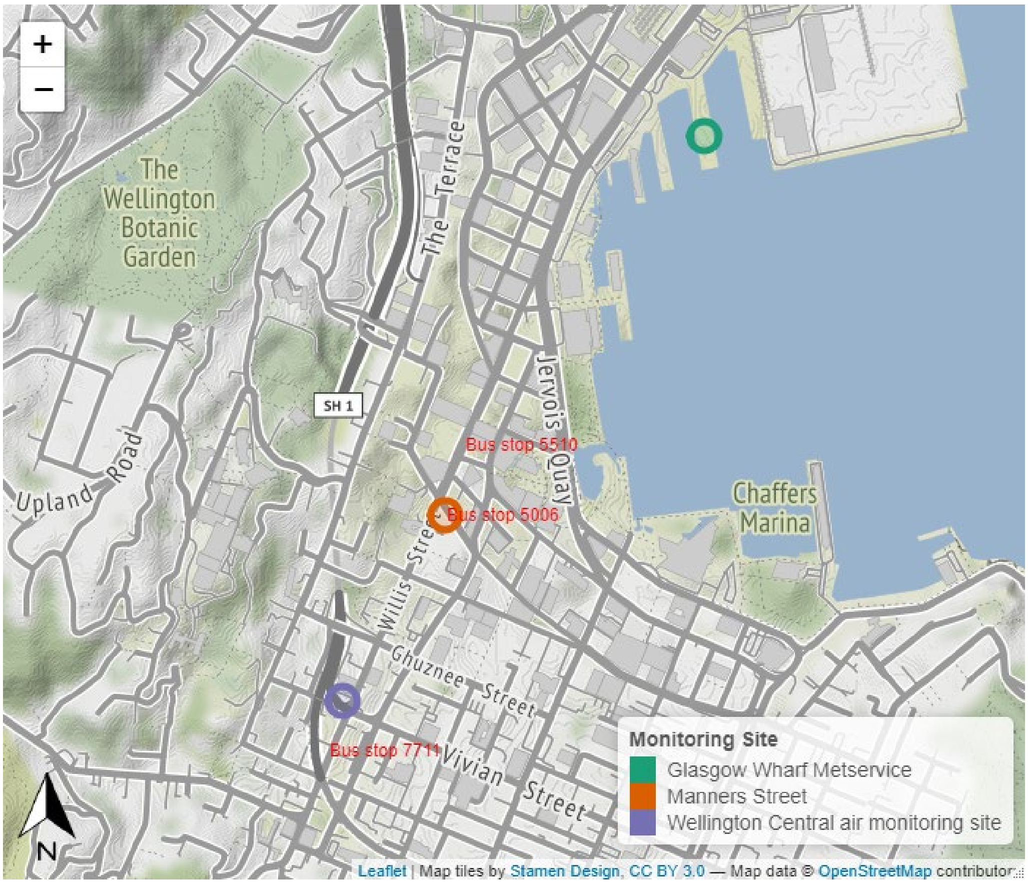

Figure 4.1: Location of monitoring sites and bus stops

4.1.2 Manners Street monitoring site

The MA350 was housed in a weather tight case and mounted behind the Real Time Display (RTD) of bus stop 5006 on Manners Street. The sample inlet was directed towards the street at a height of approximately 3m. This location was chosen because the MA350 requires mains power which could be obtained from the RTD infrastructure already in place.

The monitored bus stop is situated on the 100 m section of Manners Street that is a two-way bus lane running between signalised intersections at Willis Street and Victoria Street. This street section forms a narrow and shallow street canyon approximately 15 m width flanked by multi-storey buildings either side. The road width is 6.5m with pedestrian pavements of 4.7m and 3.8m either side of the road.

The street is also lined with deciduous trees and in summer the canopy may contribute towards restricting the dispersion of bus and traffic emissions on the street (Salmond et al., 2013). There are overhanging building facades that extend to approximately 1.5 m from the kerbside which may further confine emissions on the street.

Bus stop 5006 is adjacent to the northbound bus lane which is restricted to buses, bicycles, motorcycles/scooters and in service taxis. The southbound bus lane is restricted to bus-only traffic between 0700 and 1900 Monday to Friday. Therefore the monitoring location will be primarily influenced by bus traffic and the influence of traffic from surrounding streets is reduced due to the street canyon configuration.

Figure 4.2: Enclosure housing the MA350 black carbon monitor mounted at bus stop 5006 (left) and monitoring sample line inlet (red triangle) and NO2 passive diffusion tube facing the street (right) (lat -41.291029, lon 174.776536)

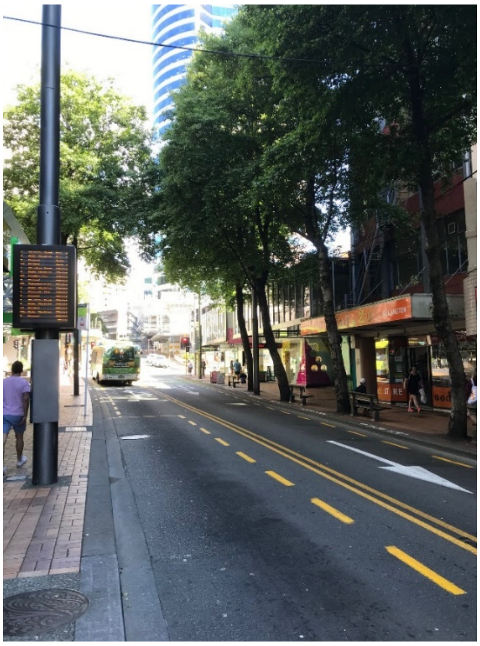

Figure 4.3: Manners Street – west facing, showing location of Bus Stop 5006 and northbound bus (left) and east facing, showing entrance to southbound bus lane

4.1.3 Wellington Central air monitoring site

The Wellington Central air monitoring station is a permanent reference air quality monitoring station located on the corner of the urban motorway and Willis Street (Fig 4.4). The station measurements represent traffic impacts from vehicles on the southbound motorway shortly after exiting the Terrace Tunnel. The Annual Average Daily Traffic (AADT) on this section of the urban motorway is estimated at 20,925 with 3.6% heavy vehicles) based on NZTA traffic counter (01N11074)[4] located on the southbound motorway approximately 220m before the traffic enter the Terrace Tunnel. The site is also influenced by Willis Street and 22 m from a signalised intersection. The site is sheltered from northerly winds by a multi-story building at 222 Willis Street.

[4] https://www.nzta.govt.nz/resources/state-highway-traffic-volumes/

Figure 4.4: Wellington Central air station on the corner of the urban southbound motorway (one-way) and Willis Street (lat -41.293635 lon 174.771876)

4.1.4 Passive NO_2 diffusion tube monitoring

To extend the coverage of traffic-related air pollution monitoring, GWRC's Environmental Science team has progressively established a regional network of passive diffusion tubes to track trends in annual average nitrogen dioxide (NO_2) as an indicator of trends in regional traffic emissions for future Regional Land Transport Plan reporting (Mitchell, 2017). This network is nested within the Waka Kotahi (NZTA) national NO_2 tubes monitoring network framework (NZTA, 2017). Although measurements from passive diffusion tubes are less accurate than continuous measurements made by reference instruments (eg, chemiluminescent method M200E, Teledyne API) at Wellington Central air monitoring station, they are a relatively inexpensive method of extending monitoring coverage and are suitable for determining long term averages (Air Quality Expert Group, 2004).

Passive diffusion tubes are a widely used method to monitor nitrogen dioxide. They consist of a plastic tube approximately 7 cm long with an internal diameter of 1 cm that can be capped at both ends. One end of the tube contains a mesh disc coated with triethanolamine (TEA) which absorbs NO_2. During sampling the bottom cap is removed allowing air to passively enter the tube. After one month of exposure the tube is sealed and is sent to a laboratory for analysis by colorimetry, from which the average concentration of NO_2 during the exposure period can be calculated.

A NO_2 diffusion tube was installed at the Manners Street bus stop (GW001) and was operated on the same monitoring schedule and analysis method as the existing Golden Mile NO_2 monitoring sites for December 2019 and January 2020 (Figure 4.5).

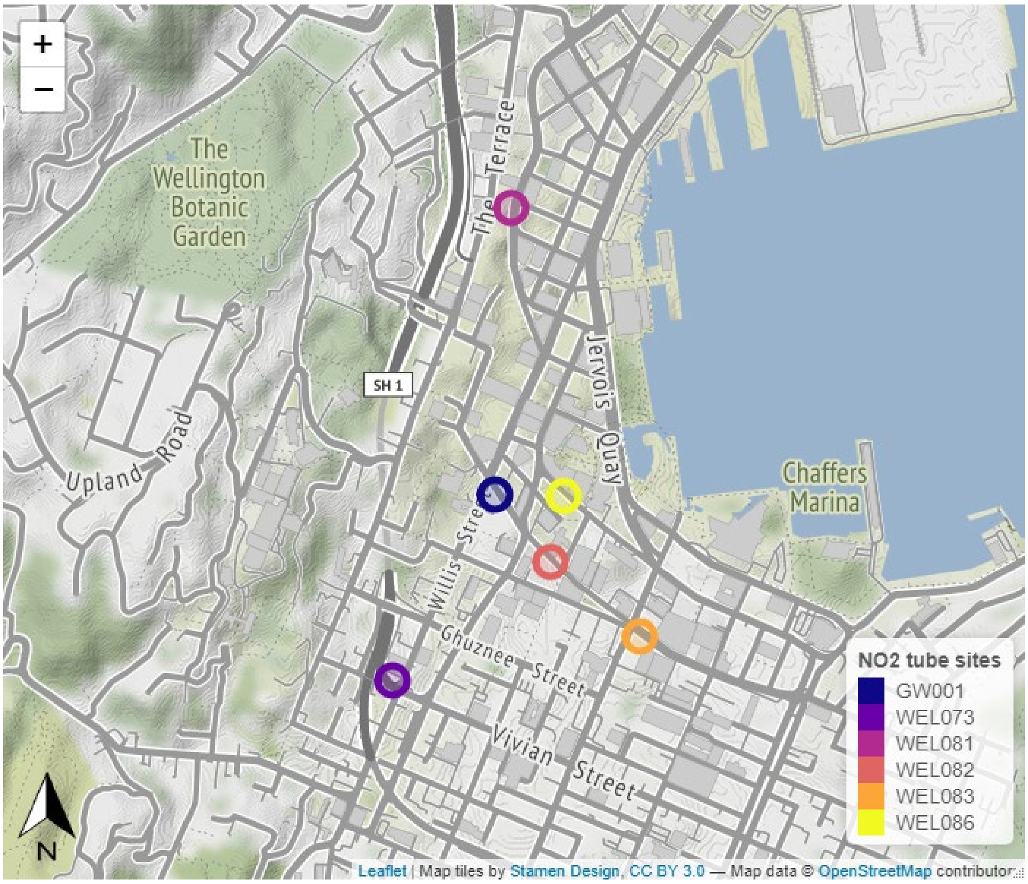

Figure 4.5: Inner Wellington city NO_2 passive diffusion tube monitoring site locations

4.2 Bus activity data and PM emission estimates

During the monitoring period ID numbers of buses identified by engine type that travelled down Manners Street in both directions were obtained from Metlink's Real Time Information (RTI) system. The date and time (hh:mm:ss) for individual buses (identified by unique vehicle ID number) travelling past bus stop 5006 and stop 5510 were binned to the nearest 1-minute resolution in an Excel pivot table provided by Metlink (Arne Brandt, pers. comm. 4/2/2020). The unique vehicle ID number was matched to a look up table of the corresponding bus engine and exhaust treatment technology type, ie, EURO III, EURO IV, EURO V, EURO VI, Electric and Unknown.

A basic validation exercise comparing RTI-identified bus and time stamp to visual observations at bus stop 5006 was carried out on 12 December 2019 (0949 to 1047) and 30 January 2020 (0901 to 1028). This exercised confirmed that the majority of buses were identified by the RTI and were observed within +/- 1 to 2 minutes of their assigned 1-minute time band. The Airport Flyer buses were not counted by the RTI as they are not part of the Metlink bus network. There were also a small number of Metlink buses that were not picked up by the RTI (eg, on 30/1/2020 09:01 to 10:28 eight (12%) Metlink buses were not counted. It was assumed that the non-counts are randomly distributed amongst the bus engine type classifications and that their absence from the dataset would not significantly affect bias the results of the black carbon monitoring. Over the monitoring period 3.3% of northbound buses (Bus Stop 5006) and 3.6% of southbound buses (Bus Stop 5510) were classified as unknown.

PM bus emissions (g/hour) were calculated using the bus activity data, bus type and PM10 emissions factors used in the Metlink Bus Emissions Prediction Model (Hamish Clark, Metlink, pers. comm. 19/2/20220) (Table 4.1). Unlike the bus emissions prediction model, the emissions were not adjusted for passenger weight, bus speed or tare weight. The estimated PM emissions (g/hour) do not include non-exhaust emissions such as brake, tyre or road wear. Nor can they represent driving conditions, frequency of stops and starts, road gradient and other environmental conditions, such as, ambient temperature (Grange et al, 2019).

Table 4.1: Emissions factors g/km (20 km/hr) (provided by Emission Impossible, 2019) used in Bus Emissions Prediction Tool

Bus engine/exhaust after treatment type	**PM10 (g/km)**	**NOx (g/km)**
EURO III	0.23	11.28
EURO IV	0.06	6.77
EURO V	0.06	4.40
EURO VI	0.01	0.80
Electric	0.00	0.00

4.3 Data collation and analysis

Bus activity data were merged with black carbon data from the two monitoring sites (bus stop 5006 and Wellington Central air monitoring station) and were reported in daylight saving time (NZDS). Matched time stamped measurements of monitoring data, bus counts and emissions estimates at stop 5006 and 5510 classified by the engine technology were aggregated at 1-minute, 10-minute, 30-minute, 1-hour and 24-hour resolution using R (R Core Team, 2020). ThesSalmoe files were then used for exploratory data analysis and visualisation using R packages *openair* (Carslaw & Ropkins, 2012).

5. Results

5.1 Pollutant concentrations

5.1.1 Black carbon

Black carbon was measured from 21 November 2019 to 3 February 2020. The measurement period included 44 days on which there were normal weekday bus services (median of 1156 buses per day recorded on Manners Street) and 31 days on which there were reduced services (median of 541 buses per day) due to weekend or holiday schedules. A total of 118,832 1-minute black carbon measurements were obtained for each monitoring location and the summary of these results is shown in Table 5.1. The MA350 monitoring instrument performed well with good data capture. The main disadvantage of this instrument is that it operates ‘off-line’ and therefore required regular field visits to check the instrument and manually download data.

Table 5.1: Summary of black carbon concentrations (µg/m3) Manners Street and Wellington Central air monitoring station (21/11/2019 to 3/2/2020)

Sites	Averaging time	Min	Mean	25%	50%	75%	95%	Max	SD	var
Manners St	1-min	-2.02	2.04	0.23	0.60	2.00	7.99	631.5	7.06	49.9
	1-h	0.00	2.04	0.48	1.22	2.58	6.56	20.03	2.41	5.81
	24-h	0.40	2.04	1.18	1.65	3.03	4.14	4.72	1.16	1.34
Wellington central	1-min	-0.84	0.52	0.18	0.36	0.66	1.53	48.5	0.65	0.42
	1-h	0.00	0.52	0.24	0.41	0.70	1.28	3.27	0.40	0.16
	24-h	0.19	0.52	0.35	0.49	0.68	0.89	1.21	0.21	0.04

The 1-minute black carbon data were very spikey (Appendix 2, Figure A2.1) suggesting it may be possible to identify high black carbon emitting buses individually. However, matching black carbon concentrations to individual bus movements was not possible due to the 1-minute average monitoring data and the +/- 1 to 2 minute uncertainty in geo-locating an individual bus at stop 5006 where the monitor was located.

Travel times for buses on the Golden Mile vary by time of day and bus dwell times at the Manners Street bus stop 5006 average around 12 seconds but can be twice this at times (Burra, 2020). Along Manners Street it is also common to observe four or five buses stopping in a series as they wait for buses ahead to move on or the traffic lights to change. Therefore identifying black carbon emissions from a specific bus is not possible with this monitoring method.

Figure 5.1 shows 24-hour average black carbon at Manners Street stop 5006 and Wellington Central.

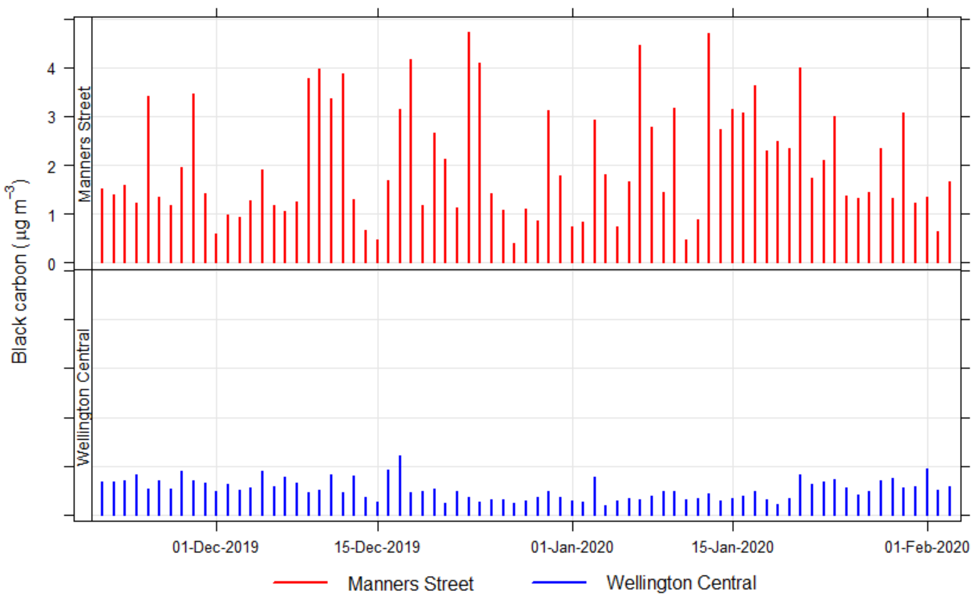

Figure 5.1: Daily black carbon concentrations (24-hour average, midnight to midnight) for Manners Street bus stop 5006 and Wellington Central air monitoring station

5.1.2 Nitrogen dioxide (NO_2)

NO_2 levels measured by passive diffusion tube at the Manners Street monitoring site (GW001) in December 2019 and January 2020 were 3.3 times higher than those measured at Wellington Central. Over the same period black carbon levels at Manners Street were 4.1 and 4.3 times higher than measured at Wellington Central (Table 5.2).

The NO_2 concentration measured at Manners Street bus stop 5006 was, on average, 20% higher than that found at the other GWRC Manners Street site (WEL082) which was 29.2 µg/m^3 (December 2019) and 30.3 µg/m^3 (January 2020). This result was not unexpected as the placement of the NO2 monitoring tube at bus stop 5006 was designed to measure maximum impact of bus emissions and did not meet the method requirement that the tube should be sited to open sky, exposed to freely flowing air with no overhanging vegetation or buildings (NZTA, 2017). The sample tube was sited approximately 2.5 m above ground level and was therefore somewhat confined within the display panels of the RTD system.

Table 5.2: Monthly passive NO2 diffusion tube results compared to average black carbon for the same monitoring periods

	Manners Street (bus stop 5006)		**Wellington Central air monitoring site**	
Month[5]	NO2 tube (µg/m^3)	BC MA350 (µg/m^3)	NO2 tube (µg/m^3)	BC AE33 (µg/m^3)
December 2019	35.8	2.0	10.7	0.5
January 2020	38.7	2.2	12.0	0.5

[5] December (2/12/20219 to 8/1/2019) and January (8/1/2020 to 3/2/2020)

5.2 Bus activity data

The total number of buses and their proportions spilt by emissions standard (EURO designation or electric) both northbound and southbound travelling through Manners Street adjacent to the black carbon monitor were calculated based on information extracted from the RTI system (Figure 5.2).

The relative proportion of buses by EURO standard being operated on the route through Manners Street did not change markedly from day to day, only the total of number of buses varied depending on whether it was a reduced service schedule due to the weekend or the holiday period (Figure 5.3). The variation in average total numbers of buses on Manners Street (based on stop 5506 and 5510) is shown in Figure 5.2.

Estimated PM bus emissions (g/hr) for the buses on Manners Street (northbound and southbound) are shown in Figure 5.3. The PM emissions estimates and the total number of buses follow the same pattern as there is a linear relationship between bus type and emission EFs as the proportion buses classified by engine technology was reasonably invariant from day to day with only the total number of buses varying between normal weekdays and weekends.

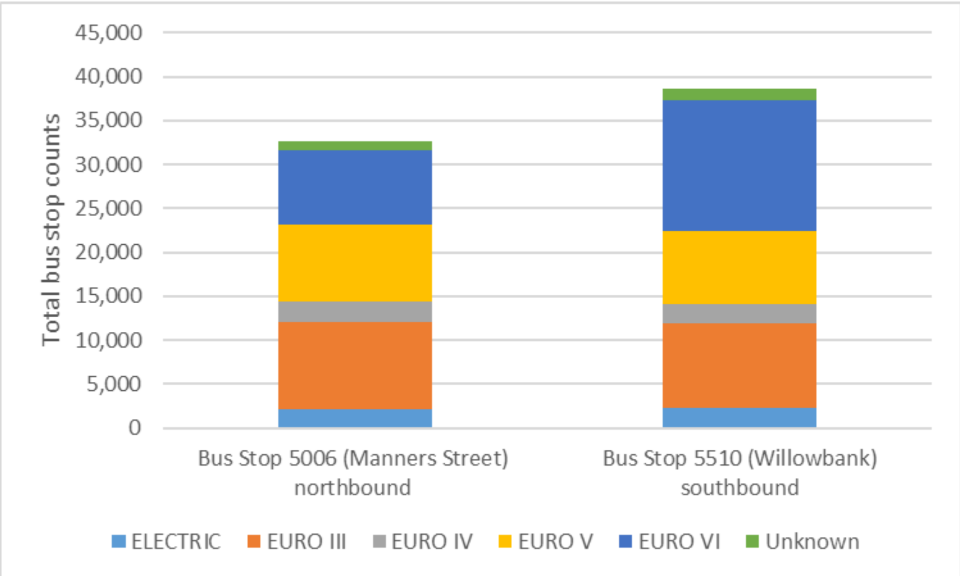

Figure 5.2: Total bus counts by engine technology (EURO standard or electric) by bus stop recorded over the study period 21/11/2019 to 3/2/2020.

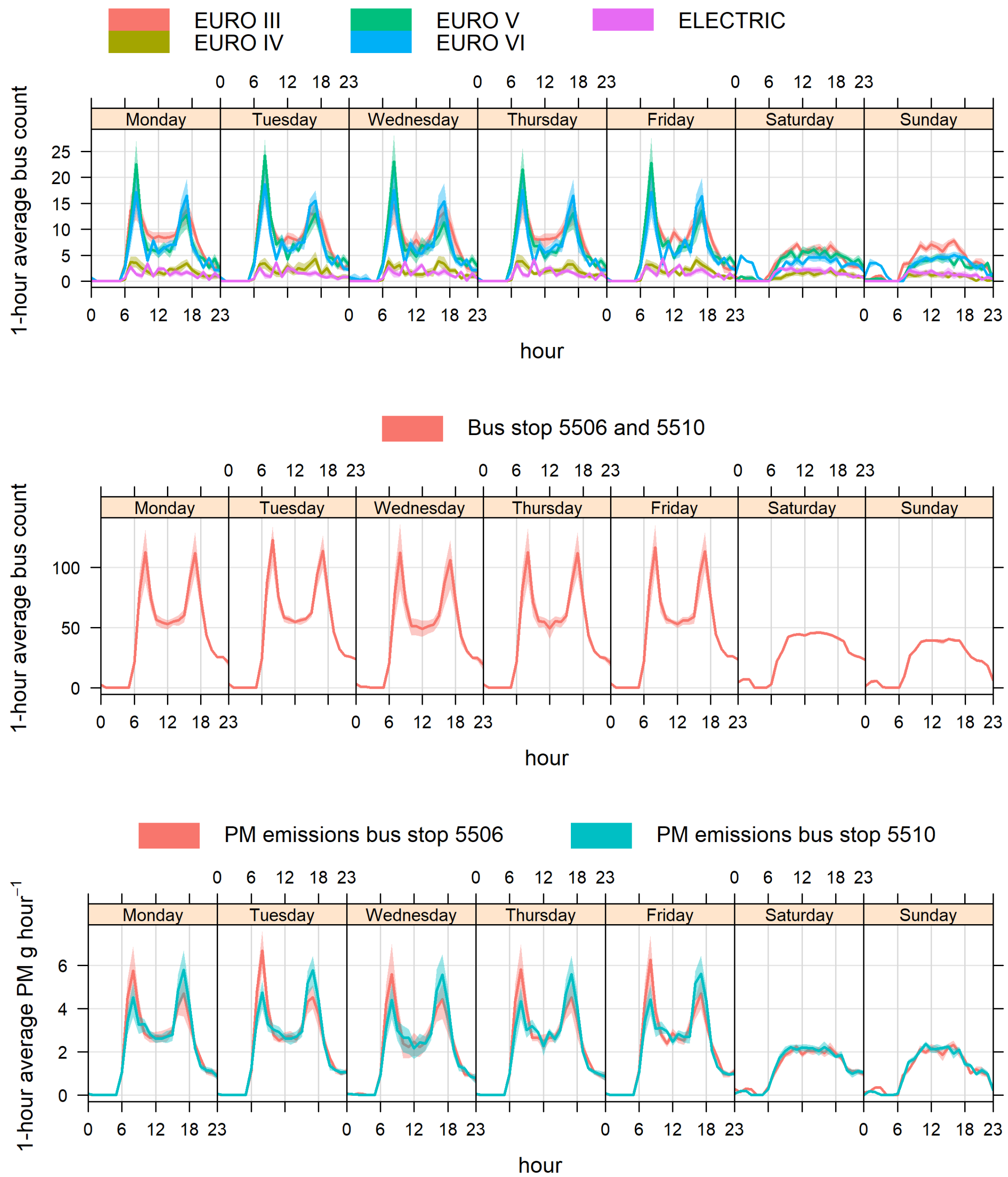

Figure 5.3: Manners Street average hour- weekday variation. Top: northbound bus counts classified by EURO standard at bus stop 5006. Middle: Combined northbound and southbound bus counts (bus stop 5006 and 5510). Bottom: PM emissions (g/hr) calculated from combined northbound and southbound bus counts (bus stop 5006 and 5510).

Correlations between black carbon and bus data were examined at 1-minute, 10 minute, 30 minute and 1-hour resolution. black carbon was moderately correlated with 1-hour bus counts and PM emissions estimates for both bus stops (5006 and 5510), with the strongest correlation found for PM emissions at stop 5006 (r= 0.69), total bus count and EURO III bus counts at bus stop 5006 (r=0.68) (Appendix 3, Figure A3.1). Correlations at other time bases, 1 minute, 10 minute and 30 minute were weaker (not shown).

5.3 Diurnal black carbon concentration

5.3.1 Manners Street

The diurnal profile for 1-hour black carbon measured at Manners Street follows the same pattern as estimated emissions of PM and average hourly total bus counts at bus stop 5006 (Figure 5.4). Reduced black carbon concentrations were observed during the weekends when there were fewer buses spread more evenly during the day, as there was no am or pm peak commuter travel demand on the weekends compared to weekdays.

Average black carbon concentration recorded at the Manners Street site when there were no buses counted by the RTI (ie, from 0100 to 0500 on weekdays and 0300 to 0500 on weekends) was 0.388 µg/m^3 compared to 0.270 µg/m^3 measured at Wellington Central monitoring site. It is not known whether the source of black carbon when buses are not operating is due to other vehicles on the bus-only section of Manners Street, infiltration from traffic on surrounding streets or some combination of the two. Due to the time of year the overnight black carbon is unlikely to be linked to emissions from solid fuel appliances.

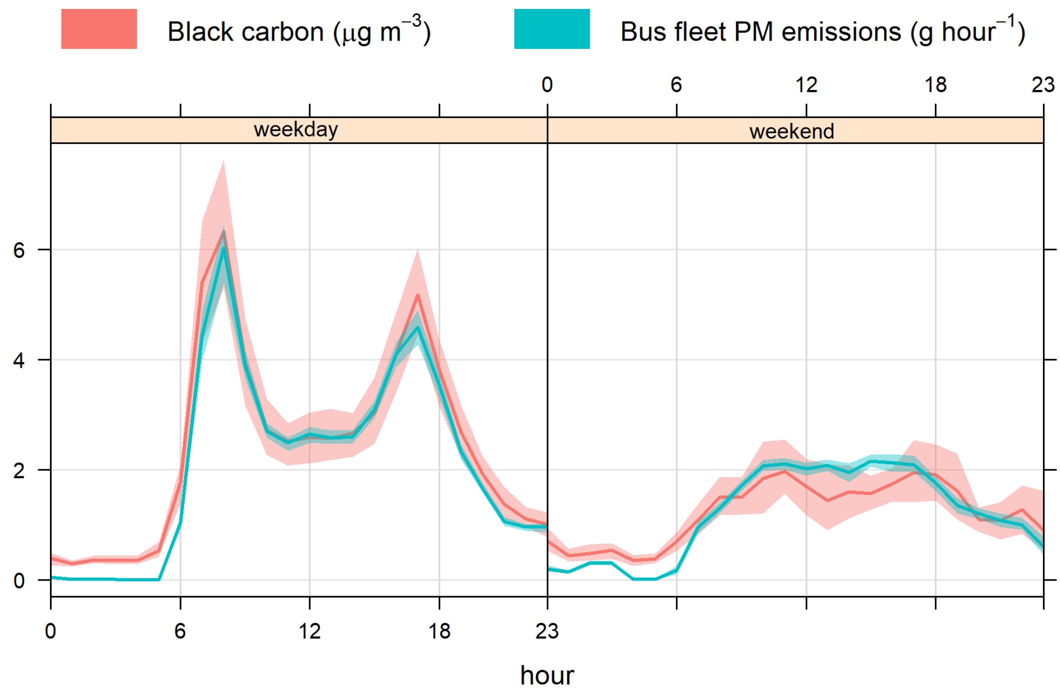

Figure 5.4: Diurnal profile of black carbon and estimated PM bus fleet emissions measured at Manners Street (bus stop 5006) over the monitoring campaign. Weekday profile (left) and weekend profile (right). The solid line is the mean and the shaded area is the 95% confidence interval in the mean.

5.3.2 Wellington central air monitoring station

The diurnal profile of black carbon at Wellington central air monitoring station (Figure 5.5) did not show an afternoon peak (nor for other traffic-related air pollutants measured) which is typical for the summer months. It is likely that the absence of an afternoon/evening pm black carbon peak is due to generally less stable atmospheric conditions in the afternoon (compared to the morning) during spring and summer which favour the dispersion of traffic pollutants. The reason why this ‘afternoon’ effect was not observed at Manners Street is likely due to enhanced sheltering and confinement of emissions within the street canyon during the afternoon.

Wellington central air monitoring station recorded much lower black carbon levels than on Manners Street, despite being next to a road with an AADT of approximately 20,000 during a normal weekday (as measured by NZTA Terrace Tunnel southbound traffic counter). The Wellington Central air monitoring station has a 5m set back from the kerbside and approximately 10m from the road centreline allowing traffic emissions to be dispersed and diluted. One-way northbound buses operate on Willis Street (23 m SE of the Wellington Central monitoring site. This bus fleet was 100% EURO VI over the monitoring period, with an average of 97 buses per day on weekdays and 60 per day on weekends as counted at bus stop 7711 (Hamish Clark, Metlink, pers. comm. 21/09/2020). The impact of these bus movements on black carbon measured at Wellington Central is not known but not expected to be significant given EURO IV are designed to have good exhaust soot control and buses are a small fraction of the traffic on Willis Street.

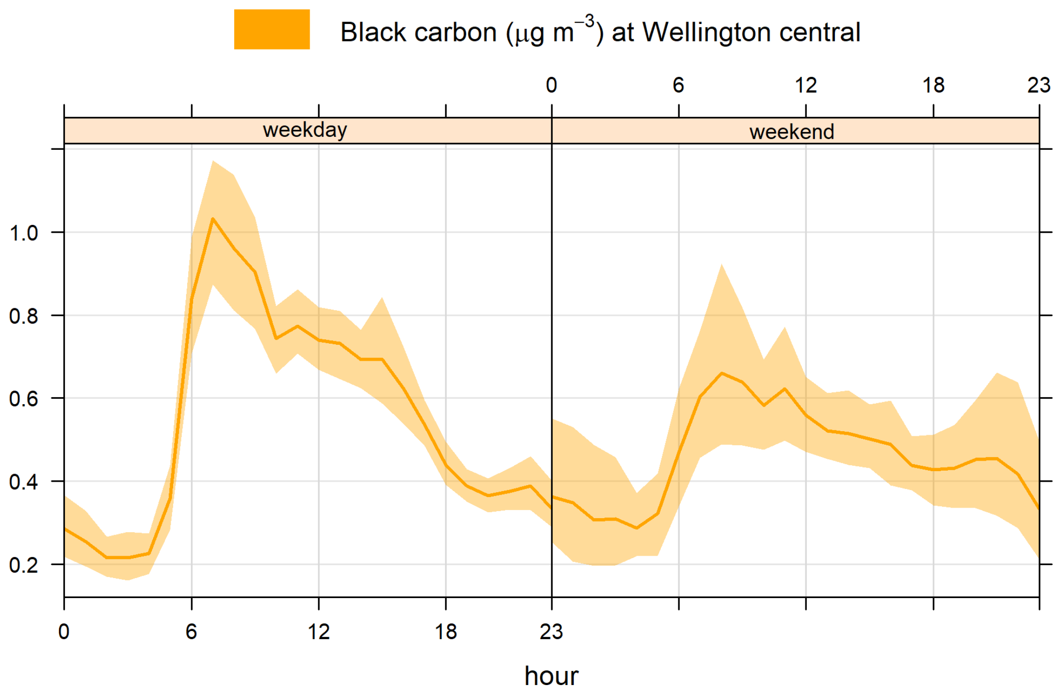

Figure 5.5: Diurnal profile of black carbon (μg/m3) measured at Wellington Central air monitoring station during the monitoring campaign. The solid line is the mean and the shaded area is the 95% confidence interval in the mean.

5.4 Impact of meteorology on black carbon concentrations

This section explores the relationship between meteorological measurements from Glasgow Wharf and Wellington Central air monitoring station and black carbon concentrations at Manners Street.

Wind flows across Wellington are almost always from either N-NW or S-SE but how these winds are experienced locally varies due to funnelling of wind around built-up areas and the sheltering effects of buildings. The Wellington Central monitoring site is sheltered by a nearby multi-storey building (222 Willis Street) which blocks wind from the north to east and north to west quadrants. Therefore wind speeds and wind direction measured at this site will not necessarily represent other parts of Wellington city. Average wind speeds measured at Glasgow Wharf (MetService) are higher than at Wellington Central air monitoring station due to Glasgow Wharf being more exposed to northerly and southerly winds. Wind roses for both sites showing frequency of wind speed and wind direction counts over the monitoring period are presented in Appendix 5 (Figure A5.1).

5.4.1 Variation in hourly black carbon levels with wind speed and direction

Figure 5.6 shows a bivariate polar plot of hourly black carbon concentrations at Manners Street varying by wind speed and wind direction (measured at Glasgow Wharf) using the Conditional Probability Function (CPF) (Uria-Tellaetxe & Carslaw, 2014) to calculate the probability that for a particular wind sector the concentration of hourly BC was greater than 75th percentile, ie, 2.6 µg/m^3. The probability of black carbon concentrations being greater than the 75th percentile was highest when the wind direction recorded at Glasgow Wharf originated from the S to SSW sector and the wind speed was between 5-10 m/s. Linear correlations of black carbon and estimated PM bus emissions also show that the relationship is strongest under S and SW wind directions (Figure 5.7). Conditional Probability Plots for black carbon measured at Wellington Central air monitoring station are difficult to interpret due to highly localised wind effects arising from the blocking of wind from the nearby building.

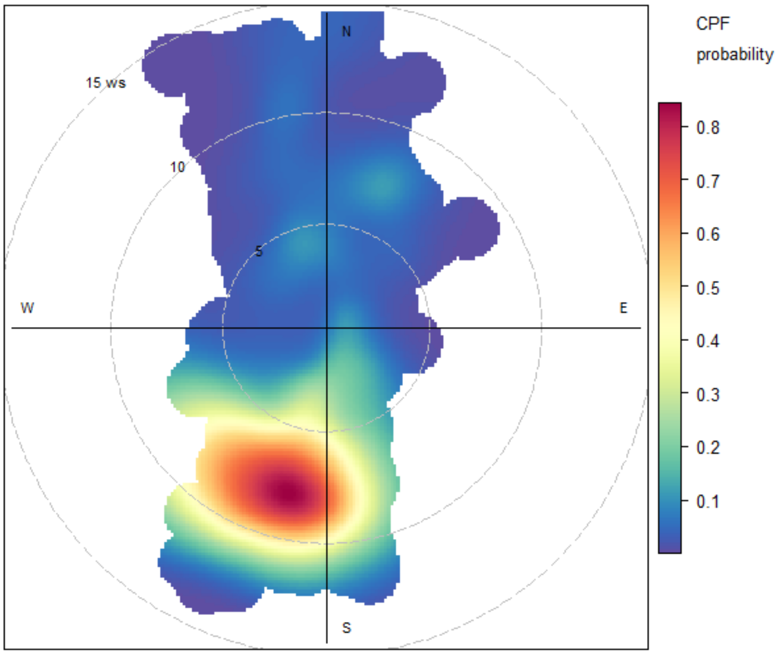

Figure 5.6: CPF polar plot of for 1-hour black carbon concentrations > 75th percentile (2.6 µg/m3) at Manners Street using wind data from Glasgow Wharf. The key shows the probability range from 0.1 to 0.8.

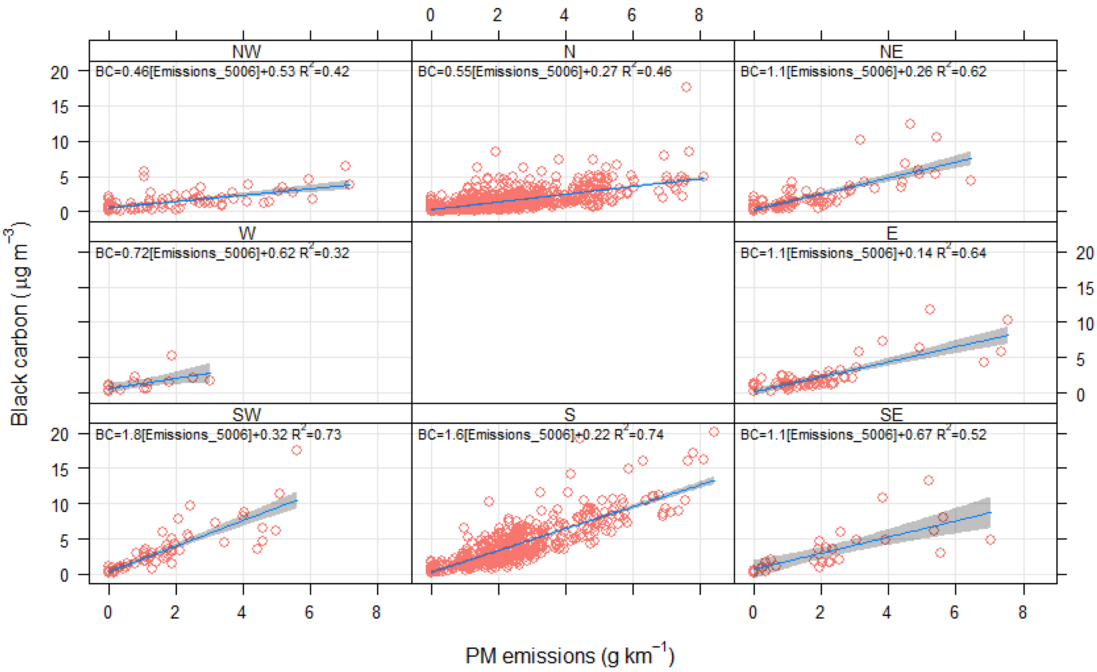

Figure 5.7: Linear relationship between 1-hour black carbon concentrations at Manners Street and estimated hourly PM bus emissions conditioned by wind direction sector as measured at Glasgow Wharf

The CPF polar plot suggest that wind direction is an important factor influencing black carbon concentrations on Manners Street. It is hypothesised that during S-SW conditions wind flow is broadly perpendicular to Manners Street which leads to recirculation of wind within the street canyon causing accumulation of pollutants on the leeward side of the street where the monitor was located (Vardoulakis et al., 2003). Figure 5.8 shows schematic wind flow and accumulation of locally generated pollutants when the wind direction is perpendicular to a generic street canyon. Figure 5.9 shows an aerial view of the Manners Street canyon showing orientation with respect of S-SW wind direction.

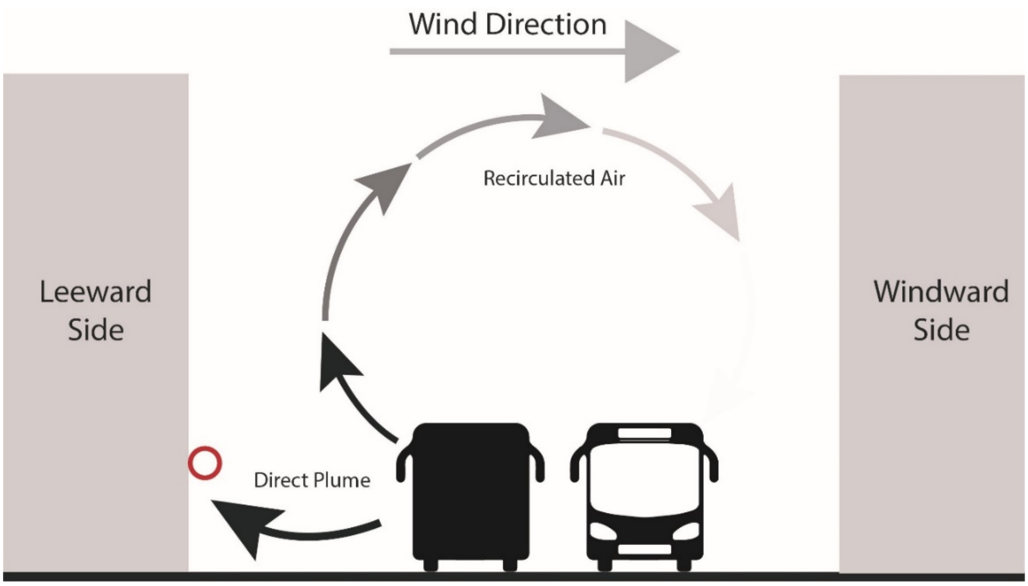

Figure 5.8: Diagram of a typical street canyon showing recirculation of locally trapped emissions when the wind direction is perpendicular to the street. The red circle shows the location of the black carbon monitor. Source: adapted from Wiesner (et al., 2021).

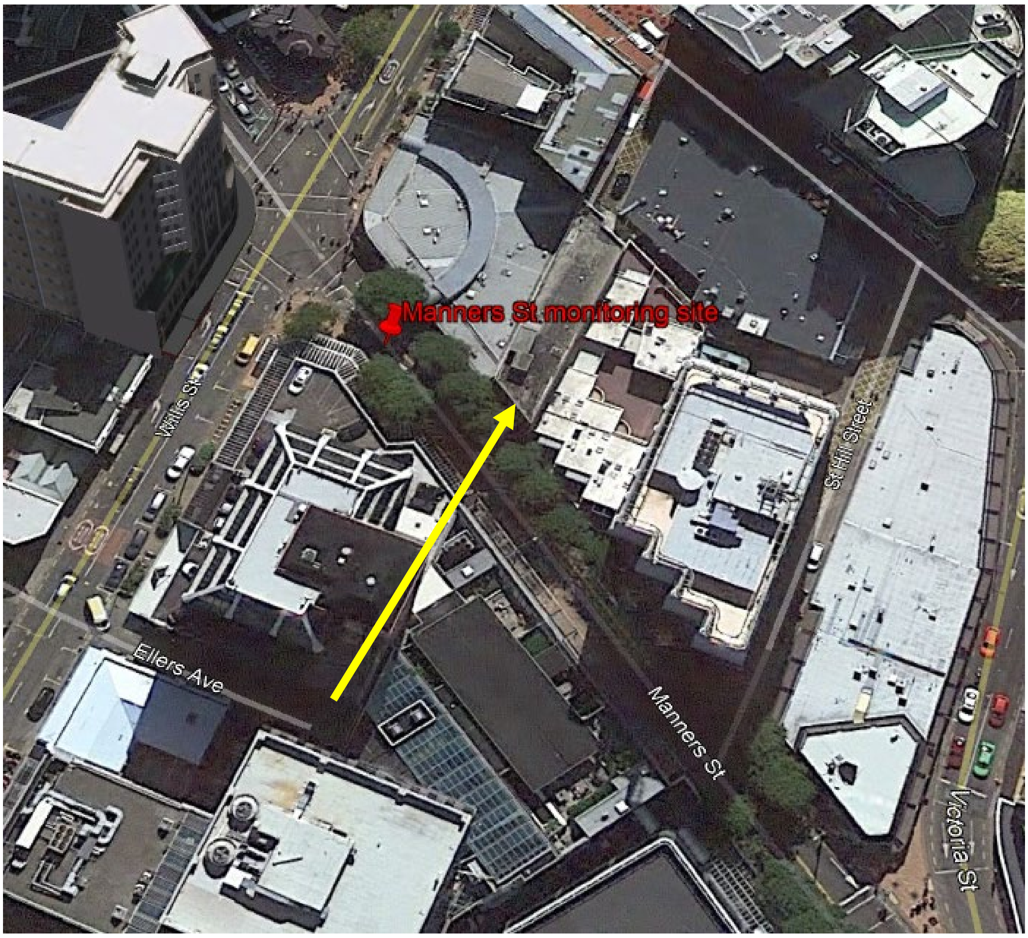

Figure 5.9: Aerial view of Manners Street monitoring location (Google Earth 2021) with S-SW wind direction arrow (yellow) superimposed

5.4.2 Variation in daily black carbon

The calendar plot (Figure 5.10) shows Manners Street 24-hour average black carbon by calendar day over plotted with an arrow that shows vector- averaged wind direction scaled by wind speed. This plot illustrates the variation in daily air pollutant levels which is likely driven by a combination of day of the week (hence bus service levels), other unmeasured levels of traffic activity on surrounding streets (eg, pre-Christmas shopping days may experience more traffic congestion) and the mediating effect of wind direction. Figure 5.11 shows the days with the highest black carbon concentrations were dominated by winds for the S and SW sector (as measured at Glasgow Wharf).

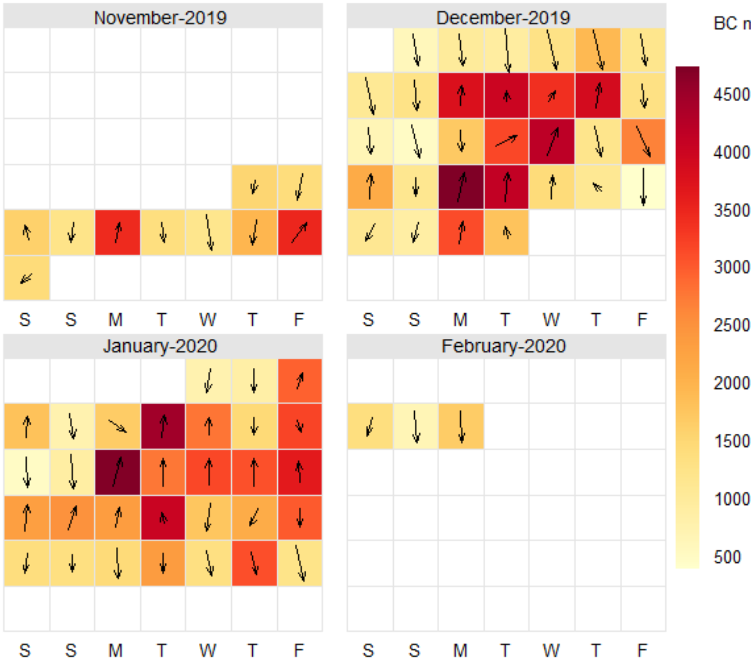

Figure 5.10: Calendar plot showing 24-hour black carbon concentrations measured at Manners Street with the arrow showing vector- averaged wind direction scaled by wind speed as measured at Glasgow Wharf

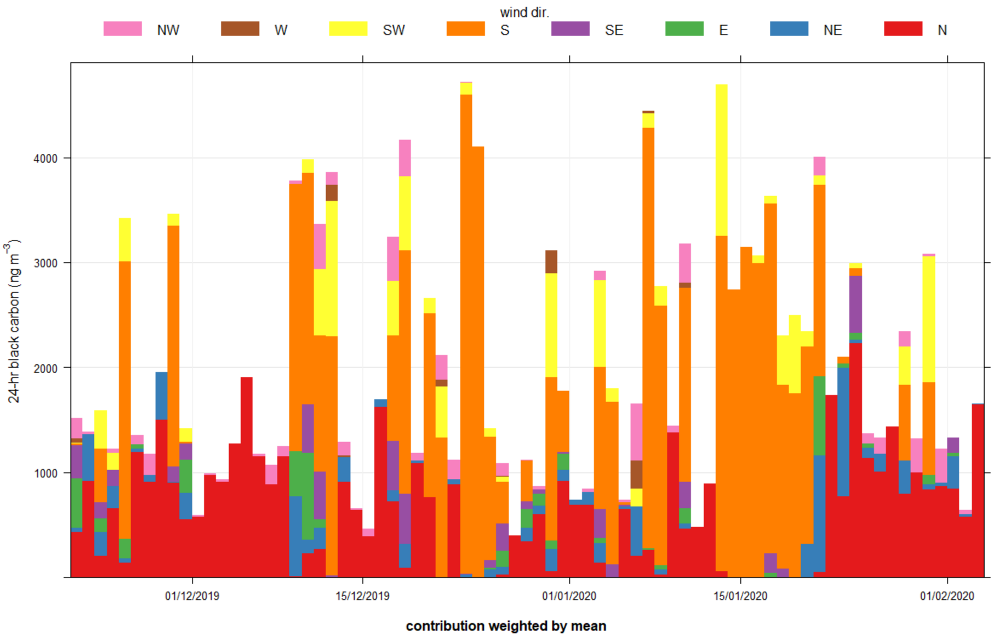

Figure 5.11: 24-hour black carbon concentrations measured at Manners Street apportioned by wind direction sectors

6. Discussion and implications

6.1 Black carbon pollutant levels

Black carbon concentrations were measured over the beginning of summer 2019/20 (December and January) when concentrations of traffic-related air pollutants are typically low compared to the winter period as the atmosphere is more stable leading to poorer dispersion of pollutants. Black carbon may also be elevated during the winter in areas affected by residential wood burning (Davy & Trompetter, 2017). A small amount of wood smoke influence is detected during winter at the Wellington Central air monitoring station.

Black carbon concentrations measured in Manners Street are similar to those reported for the same time of year at peak traffic sites in Auckland (Khyber Pass Road, Queen Street and Penrose – southern motorway) despite having only a fraction of the traffic (Davy & Trompetter, 2017). Although collected using a different monitoring method and purpose, average black carbon from January to February 2018/2019 at Queen Street, Auckland was 2.06 µg/m^3 (Perry Davy, GNS Science, pers. comm. 17/3/2020) which is very similar to the levels recorded at Manners Street.

Upgrading the bus fleet to electric and EURO VI and bus lane priority measures to reduce frequency of stop/starts at intersections should improve air quality along the Golden Mile. Previous long term monitoring in Auckland (Queen Street) to track trends in sources of particulate matter has shown that black carbon concentrations were lowered when buses were re-routed away from the air quality monitoring site (Talbot & Lehn, 2018). Studies overseas used black carbon monitoring in a street canyon to find improvements in air quality arising from renewal of the bus fleet (Titos et al., 2015).

Levels of black carbon measured on Manners Street were considerably higher and more variable than those measured at Wellington Central air monitoring station. The monitoring location in Manners Street was at a bus stop and therefore captures the impact of stop-start driving which results in elevated emissions compared to when the bus is travelling at uniform speeds. The bus stop monitoring site was also impacted by idling emissions as passengers alight and disembark. During the peak weekday commuter travel periods (0700 to 0900 and 1600 to 1700) the residence time of buses on the monitored section of Manners Street may be longer than other times of day as buses queue to get through the traffic lights at the intersection of Willis Street and Manners Street. Bus stops and traffic lights are noted as locations for high black carbon exposure for pedestrians (Targino et al., 2018).

The Wellington central air monitoring site is located approximately 10 m from the roadside therefore emissions from the traffic are relatively dispersed and diluted compared to Manners Street. Therefore black carbon measurements at Wellington central air monitoring station are more representative of ambient concentrations whereas those at Manners Street represent direct emissions from bus exhaust. Therefore, Wellington Central monitoring station is a useful 'contrast' site to track any reduction in traffic-related particulate matter from the general fleet. Ideally another black carbon monitoring site in an inner city street canyon that is not a on a bus route should be used as a control site.

6.2 Black carbon as an indicator for tracking bus fleet emissions

6.2.1 Meteorological effects on black carbon

The short pilot study demonstrates the potential for using ambient black carbon measurements at a bus stop for tracking long term changes in composite bus fleet emissions. The study showed that 1-hour aggregated black carbon measurements at the Manners Street bus stop 5006 corresponded to bus movements and emissions estimates derived from bus activity data.

The relationship between black carbon and bus activity was strongly affected by wind direction, with the highest black carbon concentrations found during south to south west (S-SW) wind flows. Under this wind regime bus emissions may be confined within the street section (canyon) due to local recirculation. There may be other interactions between wind direction and black carbon concentrations along street corridors with a different orientation elsewhere on the Golden Mile. It is recommended that MetService data from the Kelburn weather station which is exposed to the predominant NW wind flows be purchased to further explore the impact of wind direction on black carbon concentrations in Manners Street and at Wellington Central air monitoring station.

A longer period of monitoring data is needed to develop a robust relationship between black carbon concentrations and meteorological conditions. These data would allow statistical modelling to account for the variability in black carbon concentrations due to changes in weather. Accounting for meteorology can greatly assist both the identification of when an emissions change occurred as well as the magnitude of the change (Air Quality Expert Group, 2020). This approach was used in London to show decreases in roadside NO2 concentrations were consistent with a retrofit of EURO III buses with selective catalytic reduction technology (Barratt & Carslaw, 2014).

A longer period of monitoring with the MA350 black carbon instrument is needed to fully evaluate whether it is practical for a semi-permanent deployment at the bus stop or whether a shorter period, for example, annual 3-month summer and/or winter campaigns could provide sufficient data for evaluating long term trends in bus emissions.

6.2.2 Comparing black carbon measurements to bus emissions prediction tool outputs

Further work is required to explore whether the Metlink prototype Bus Emissions Prediction Tool can be used to predict hourly or daily PM and/or NOx emissions for Manners Street based on the existing model inputs. If so, it may be possible to compare longer term black carbon measurements that have been corrected for meteorological or street canyon dispersion effects to long term changes in PM emissions (as the fleet is upgraded) predicted by the bus emissions model. The purpose of this comparison would be to confirm that predicted emissions reductions are actually being achieved on-road, ie, the modelled emissions and observed black carbon measurements are following the same trend. A method to account for black carbon emissions from non-exhaust sources (brake, tyre and road wear) will need to be considered.

6.3 Impact of bus fleet versus other traffic sources on air quality

6.4 Health impacts

Although this pilot study was not designed to provide information on impacts of traffic and bus emissions on exposure and health, it is useful to provide some context of how the results may be interpreted in relation to air quality standards and guidelines.

6.4.1 Black carbon

There are currently no health-based guidelines for ambient black carbon or reference monitoring methods. Therefore the air monitoring data collected during this study are appropriate as an indicator of bus and traffic emissions but are not able to be used to determine health effects. It is noted that any lowering of black carbon concentrations through emissions improvements should lead to a reduction in adverse health effects associated with tail pipe emitted PM2.5 (World Health Organization, 2012; European Environment Agency, 2013).

6.4.2 Nitrogen dioxide (NO_2)

Standards and guidelines for NO_2 are shown in Table 6.1. NO2 tube monitoring results cannot be directly compared to the World Health Organization annual average guideline of 40 µg/m^3 because it is not a reference monitoring method. Compared to the reference method the NO_2 tube monitoring method is less accurate and typically overestimates concentrations by 33% (Kuschel & Sridhar, 2020). However, as the relationship between annual average NO_2 measured by both monitoring methods are strongly correlated it is possible to adjust NO_2 tube results to reference equivalent using a linear regression equation based on co-located measurement method sites in Auckland, Wellington and Christchurch (Appendix 6, Figure A6.1). Using this equation, annual average NO2 measured at WEL082 in 2019 (Manners/Cuba Street) is adjusted down from 35.9 µg/m^3 to 30.2 µg/m^3 which is below the World Health Organization guideline of 40 µg/m^3. Without site-specific co-location data, caution should be used in applying a regression equation relationship developed from other sites. The magnitude of the overestimation may depend on the local site dispersion characteristics and the NO_2/NOx ratio, which is a measure of the relative availability of NO and O_3 at the site (Kirby et al., 2001). The NO contribution will vary by fleet composition, for example, relative proportions of diesel and petrol vehicles.

Table 6.1: Standards and guidelines for NO_2 measured by reference instruments

Standard/Guideline	Numerical value	Averaging time (12-month period)
National Environmental Standard[6]	200 µg/m^3	1-hour (10th highest)
National Ambient Air Quality Guideline[7]	100 µg/m^3	24-hour (maximum)
World Health Organization (2006)	40 µg/m^3	Annual
Regional target (PNRP)	132 µg/m^3	1-hour (maximum)
Regional target (PNRP)	66 µg/m^3	24-hour (maximum)

NZ has a short term environmental standard for NO_2 (1-hour) and a daily guideline (24-hour average). The PNRP has a policy of managing air quality so that it is within the "acceptable" range which is up to 66% of the national standard and guideline. Applying regression equations developed by NIWA (2014) using data from Auckland monitoring (1987 and 2008) to estimate short term NO_2 values from annual average data, suggests that 2019[8] concentrations on Manners Street (WEL082) would likely meet the 1-hour standard (estimated 98 µg/m^3) and 24-hour guideline (estimated 65 µg/m^3) but could be close to exceeding the "acceptable" target for the PNRP 24-hour guideline (Table 6.1).

Due to the Manners Street bus stop 5006 measuring 'peak emissions', it is not recommended to use these data for estimating likely compliance with ambient air quality standards and guidelines. The NO_2 passive tube monitoring results from the other CBD locations (Manners Street (WEL082), Lambton Quay (WEL081) and Courtney Place (WEL083, Wakefield Street (WEL086) provide a useful indicator of trends in traffic-related air quality in highly pedestrianised inner city locations. Results from these sites suggest that short-term and long term standards for NO_2 would be met.

It is not possible to estimate exposure to traffic-related air pollution (NO_2) and black carbon based on CBD monitoring sites as people do not spend their entire time at a single location. A large-scale study would be needed to investigate the relative importance of different microenvironments (eg, place of residence, workplace and commute) to daily and long term exposure to traffic related air pollution (Lim et al., 2015).

[6] NES-AQ (2004). Resource Management (National Environmental Standards for Air Quality) Regulations 2004
[7] Ambient air quality guidelines: 2020 update. Ministry for the Environment, ME 438.
[8] The 2020 NO2 passive diffusion tube annual average was not available at the time of writing. 2020 saw reduced concentrations due to the impacts of COVID-19 travel restrictions on vehicle traffic and public transport.

6.5 Study limitations

This pilot study produced a small dataset for analysis and included public holidays (ie, Christmas, New Year and Wellington Anniversary Day) and school holidays and therefore may not be representative of annual average conditions. Resources did not permit a control site on a non-bus impacted street canyon which would help determine the relative impact of bus emissions compared to other traffic emissions on black carbon levels. Fine-grained traffic count and vehicle profile data from surrounding streets were not available to definitively assess the potential impact of non-bus traffic on black carbon levels in Manners Street.

7. Conclusions

This study found that black carbon monitoring at an inner city bus stop could be used to represent diesel particulate emissions from a cohort of buses travelling through a street section of the Golden Mile. As the monitoring period was relatively short (ie, 10 weeks) and there were no changes to the bus fleet profile over this time, it was not possible to assess the impact of different fleet mixes (eg, proportion of electrics) on black carbon levels. Therefore the black carbon monitoring represents a December 2019 to January 2020 baseline of bus fleet diesel particulate emissions.

Assessing the impact of electrification and changes to the bus fleet profile on real-world levels of particulate emissions requires long term monitoring of black carbon concentrations on the Golden Mile, either continuous or repeated monitoring campaigns as resources allow. Successfully using black carbon measurements to evaluate the impact of fleet upgrades on particulate emissions involves controlling for local meteorological effects in the street canyon and accounting for other non-bus emissions sources of black carbon.

Whilst there are no ambient regulatory guidelines or targets for black carbon to minimise health or climate effects, a reduction in black carbon will be correlated with a reduction in traffic-derived harmful $PM_{2.5}$ and ultrafine particulate. Therefore the decarbonisation of the bus fleet and measures to reduce bus start/stop frequency through bus priority lanes will have co-benefits for air quality and positive impacts on liveability and amenity in inner city Wellington.

8. Recommendations

(a) Continue black carbon and NO_2 passive monitoring on Manners Street so that a multi-year dataset is available for future analysis.

(b) Investigate whether additional black carbon or finely resolved NOx monitoring can be installed on another street canyon in the CBD that is not on or near a bus route to act as a control site.

(c) Continue to review the availability of low cost compact sensors suitable for monitoring roadside NOx.

(d) Explore the feasibility of calculating a composite bus fleet black carbon emission factor using inverse dispersion modelling as a complementary measure for tracking changes in emissions.

(e) Investigate ability to output modelled PM emission predictions from the Metlink prototype bus emissions predictions model for bus movements on Manners Street to compare to trends in meteorologically-normalised black carbon concentrations.

Acknowledgements

This pilot study could not have been undertaken without the support and contributions of the following people and organisations:

- Darren Li and Rhys Evans (GWRC Environmental Science) for installing and maintaining air quality monitoring equipment.
- Arne Brandt (Metlink Operations), Hamish Clark and Chris Vallyon (Metlink Strategic Insights) for providing bus activity data and outputs from the bus emissions prediction tool.
- Raymond Malcolm (Metlink Assets & Infrastructure) permission for use of RTD infrastructure and power for the monitoring instrument.
- Gustavo Olivares (NIWA) for the loan of the MA350 and technical advice on instrument operation and settings.

In addition I would like to thank Nick Talbot for an insightful peer review which has significantly improved this report.

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Appendix 1: Aethalometer settings and colocation results

Table A1.1: Aethalometer instrument settings and specifications

	MA350 (Manners Street)	AE33 (Wellington Central air monitoring station)
Flow rate	150 ml/min	2 L/min
Time base	60 seconds	60 seconds
Dual spot compensation	Yes	Yes
Measurement resolution	0.001 µg/m3	0.001 µg/m3
Limit of detection	0.03 µg/m3 (5 min time base, 150 ml/min, Single Spot)	< 0.005 µg/m3 (1-hour)
Flow control	Mass control (corrected to 25°C)	Mass control (corrected to 0°C)

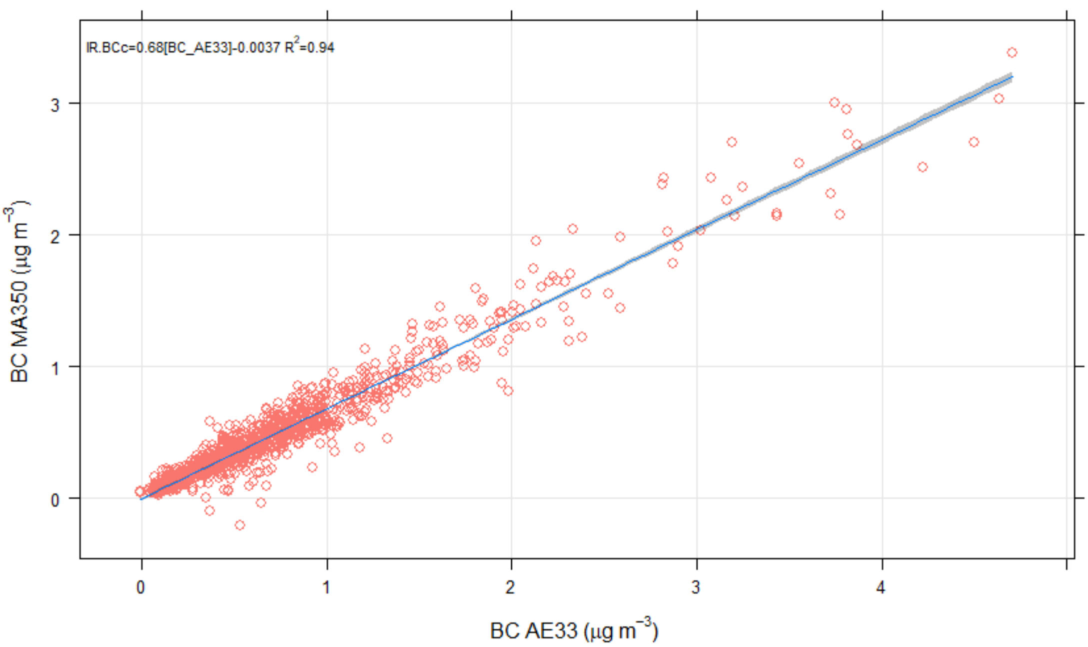


Figure A1.1: Correlation plot black carbon (1-hour average) MA350 and AE33 aethalometer colocation at Wellington Central air monitoring station 13/3/2019 to 6/5/2019. y = 0.68x -0.0037, R^2=0.94

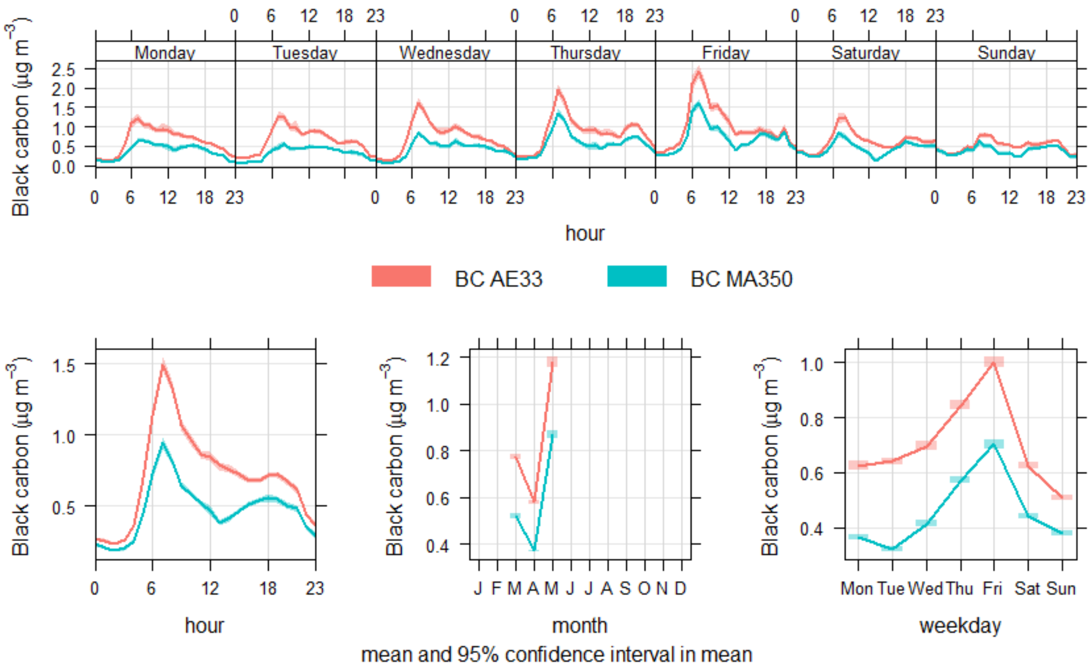


Figure A1.2: Time variation of black carbon MA350 and AE33 aethalometer colocation at Wellington Central air monitoring station 13/3/2019 to 6/5/2019

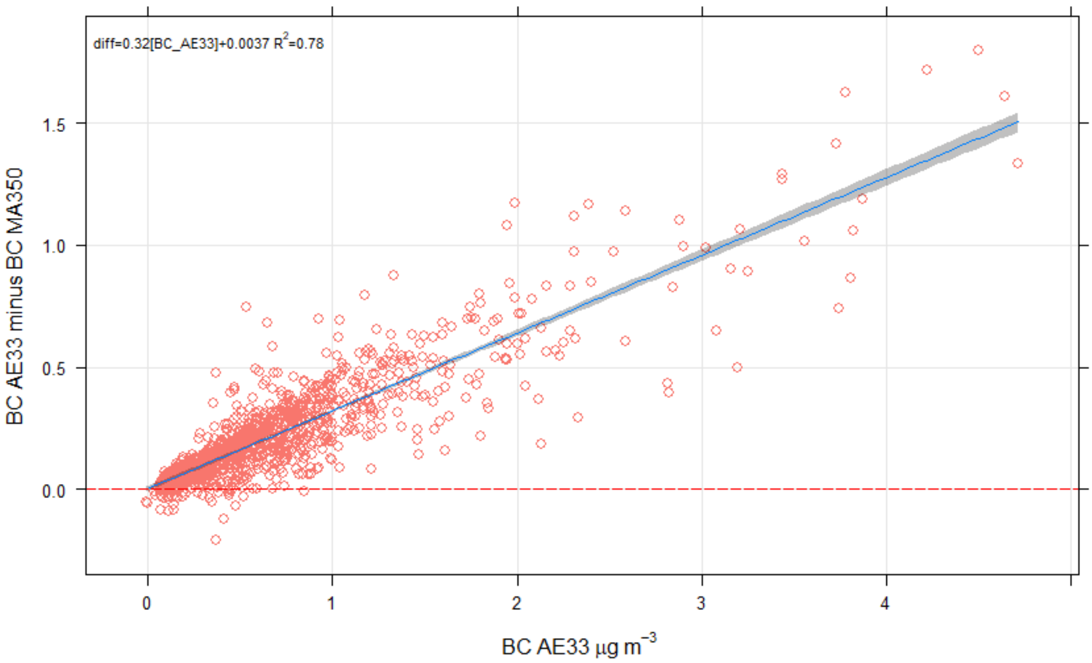


Figure A1.3: Regression of difference in 1-hour black carbon AE33 and MA350 aethalometer colocation on AE33 at Wellington Central air monitoring station 13/3/2019 to 6/5/2019

Appendix 2: Black carbon (1-minute average) at Manners Street

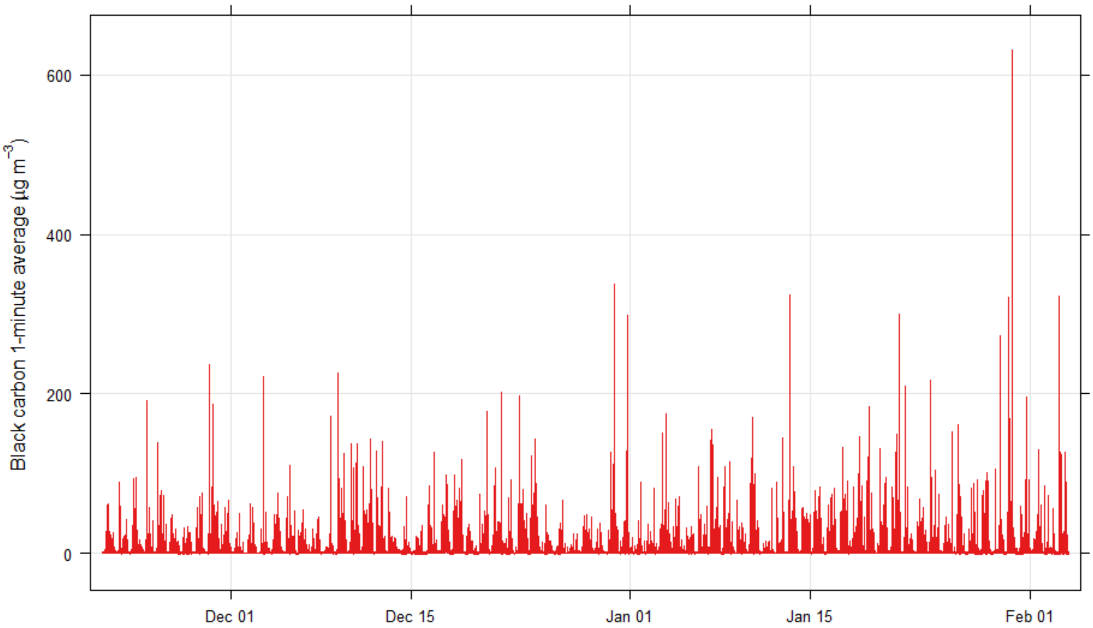


Figure A2.1: Black carbon (MA350) 1-minute average (µg/m3) Manners Street bus stop 5006, 21/11/2019 to 3/2/2020

Appendix 3: Correlation matrix black carbon and bus counts

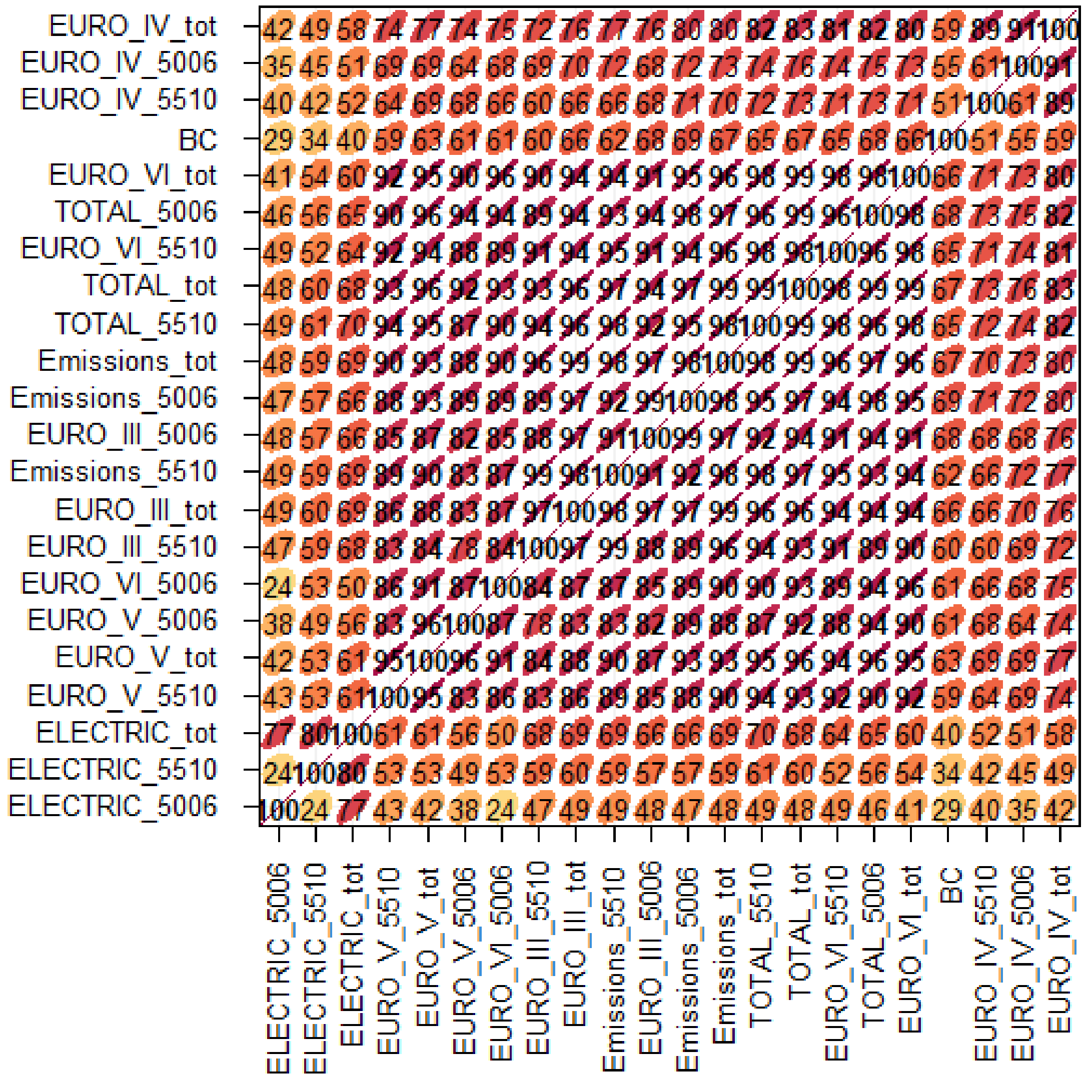


Figure A3.1: Black carbon (MA350) 1-hour average correlation matrix and bus activity data

Appendix 4: Black carbon and traffic counts at Wellington Central

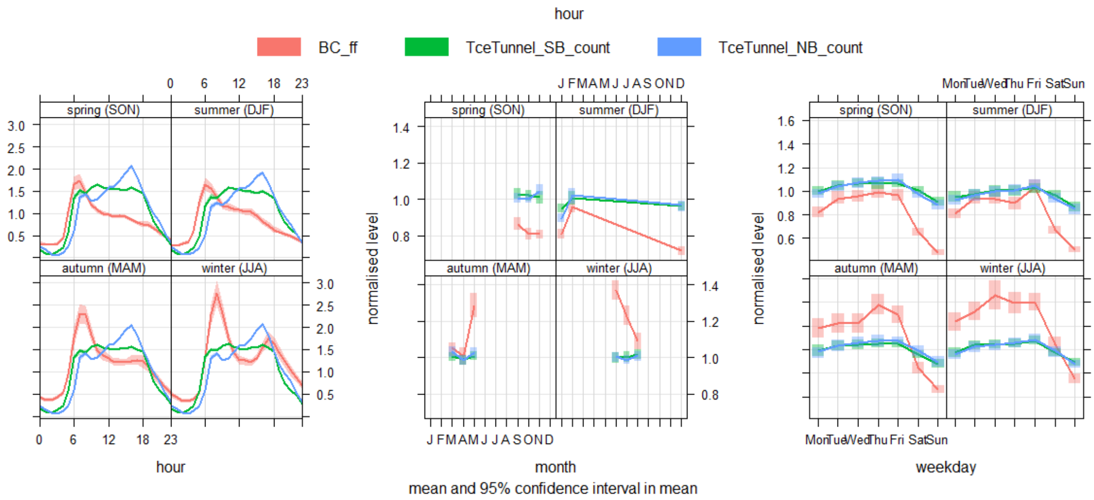
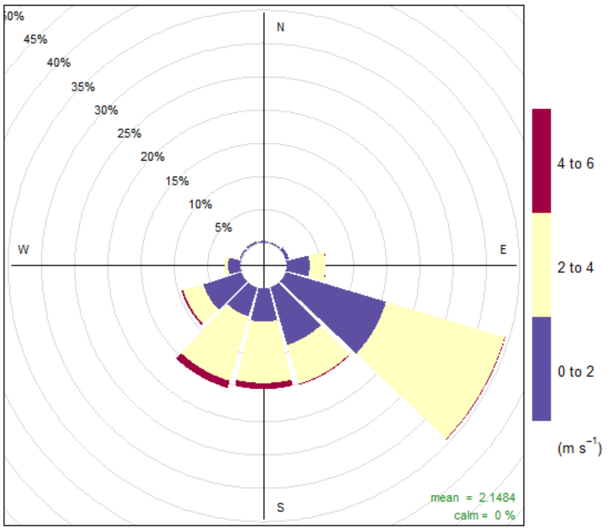
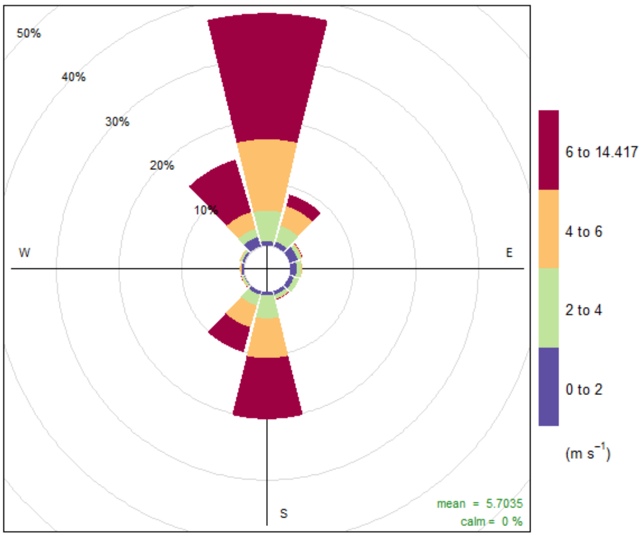


Figure A4.1: Time variation black carbon at Wellington Central air monitoring station compared to NZTA traffic counts at Terrace Tunnel Southbound (ID: 01N11074) and Terrace Tunnel Northbound (ID: 01N21074) (2018 to 2019)

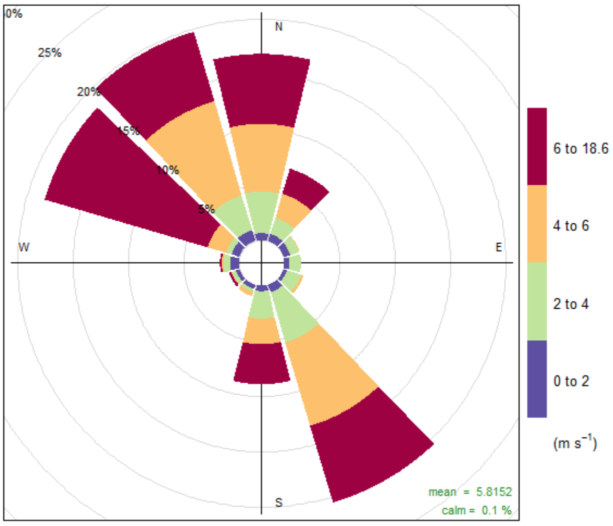
Appendix 5: Wind roses



Wellington central (GWRC)



Glasgow Wharf (MetService)



Kelburn (MetService)

Figure A5.1: Wind roses based on 1-hour wind speed and wind direction measurements 21/11/2019 to 3/2/2020. The wedge points towards the direction the wind originates from.

Appendix 6: Relationship between NO_2 monitoring methods

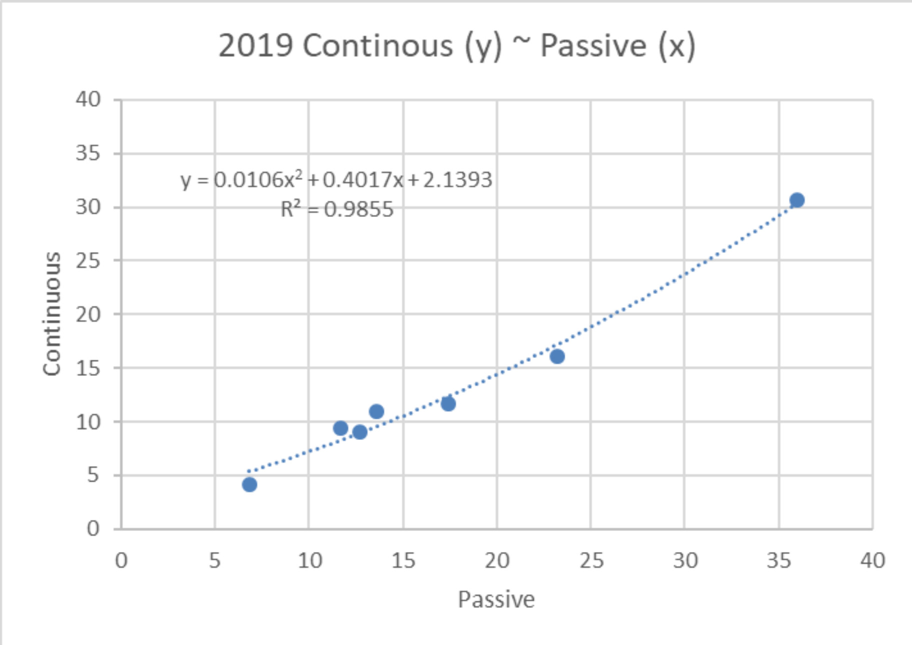


Figure A6.1: Linear regression of NO2 annual average by continuous monitoring reference method on passive diffusion tube method. Data from Auckland, Christchurch and Wellington for the 2019 calendar year (NZTA).