Metlink bus fleet decarbonisation impacts on air quality

Wellington City Golden Mile 2022/23 update

Tamsin Mitchell & Hamish Clark

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

Upper Hutt
PO Box 40847

T 04 526 4133
F 04 526 4171
www.gw.govt.nz

GW/KI-T-23-22

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

Report prepared by:	T Mitchell H Clark	Senior Air Quality Scientist Transport Analyst	
Report reviewed by:	D Gordon	Team Leader, Land, Air and Climate	
Report approved for release by:	E Harrison F Abbott	Manager, Knowledge Manager, Metlink Assets & Infrastructure	 **Date:** 17 April 2024  **Date**: 17 April 2024

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Executive summary

The Golden Mile is the main throughfare through Wellington City's business, shopping, and entertainment precinct that runs from Courtney Place through to Lambton Quay and the Wellington railway station. Almost 90% of Wellington City's bus routes travel the Golden Mile, with 22,000 passengers boarding at bus stops each day.

Monitoring 2016 to 2021 showed the Golden Mile had the highest levels of traffic-related air pollution in the region. The main reason for poor air quality was the high frequency of diesel buses travelling through 'street canyons' where dispersion of traffic emissions is restricted by multi-story high rise buildings either side of the street.

This study updates an earlier study that was based on a shorter monitoring period (Mitchell & Clark, 2023). In this report, three-year monitoring trends in diesel particulate (black carbon) and harmful nitrogen dioxide exhaust gas (NO_2) from the bus-only lane on the Golden Mile were compared to trends at the Wellington Central air monitoring station next to the urban motorway. Air pollution trends were compared to changes in the composition of the bus fleet travelling the Golden Mile. These bus fleet changes are part of Metlink's public bus decarbonisation programme, aiming for all core routes to be fully electric by 2030.

Key findings:

- Annual average black carbon concentrations measured on the Manners Street bus-only lane reduced by 50% between 2020/21 and 2022/23, compared to a 6% reduction at Wellington Central air monitoring site beside the southbound urban motorway.

- Annual average NO_2 concentrations measured on the Manners Street bus-only lane reduced by 29% between 2020/21 and 2022/23, compared to a 2.5% reduction at Wellington Central air monitoring site.

- Over this same period the proportion of electric buses on Manners Street increased from 5% to 52% with a corresponding decrease in proportion of diesel buses.

- Metlink's electrification of bus fleet operating on the Golden Mile has significantly improved local air quality. This improvement reduces exposure to harmful air pollutants for all travel modes on the Golden Mile, pedestrians, bus users, cyclists, and motorists.

Contents

1. Traffic-related air pollution in Wellington city

Traffic exhaust contains pollutants that are harmful for human health and greenhouse gases (CO_2, methane, and nitrous oxide) that contribute to global warming and climate change.

The air pollution health impacts from motor vehicles in Wellington City's territorial authority area are estimated to result in; 60 premature deaths, 266 hospitalisations, 473 cases of childhood asthma including 28 hospitalisations[1] and 16,059 restricted activity days[2]. These health impacts have an been to have an estimated social cost of $279.8 million per year (Kuschel et al., 2022).

Levels of air pollution from traffic are high in Wellington CBD compared to other parts of the region. The highest levels are found on the Golden Mile, a 3 km corridor through the main business, shopping, and entertainment area. Almost 90% of Wellington City's bus routes travel the Golden Mile, with 22,000 passengers boarding at bus stops each day, and around two-thirds of all journeys being to or from the Golden Mile. Pre-COVID, the Golden Mile had nearly 30,000 pedestrians on a typical weekday (LGWM, 2020)[3].

Greater Wellington is aiming to reduce public transport emissions by accelerating decarbonisation of the bus fleet, with a target for all core routes to be electrified by 2030 (Regional Public Transport Plan, 2021). Metlink began replacing diesel buses for electric buses on the Golden Mile from September 2021 which led to an improvement in air quality in 2021/22 (Mitchell & Clark, 2022).

This report compares a further year of air monitoring data collected in 2022/23 to ongoing changes in the fleet profile operating on Manners Street in the Golden Mile based on two air pollutant indicators, nitrogen dioxide (NO_2) and black carbon particulate.

NO_2 is formed when motor vehicle NOx emissions are oxidised. Diesel powered vehicles emit substantially greater amounts of NOx (and particles) per mass of fuel burnt than petrol vehicles due to the high temperature engine conditions needed for diesel combustion (Gentner & Xiong, 2017).

Black carbon is a measure of the ultrafine soot particles formed during combustion which make up a significant fraction of tailpipe $PM_{2.5}$ from diesel vehicles (Davy & Trompetter, 2018). Black carbon is therefore a roadside indicator of diesel particulate. While there are no air quality health guidelines for black carbon yet, it is a useful indicator of harmful combustion particulate (World Health Organization, 2021) and for evaluating the effects of vehicle fleet changes (Reche et al., 2011)

[1] https://www.stats.govt.nz/indicators/human-health-impacts-of-pm2-5-and-no2/
[2] A restricted activity day is one in which a person due to exposure to air pollution does not feel well enough to go to work, school or undertake their normal activities.
[3] More recent count data could not be found.

2. Bus fleet emissions profile

Wellington region has a highest per capita use of public transport in New Zealand (NZ) and in 2022/23 there were 34 million passenger boardings (Greater Wellington, 2023). Although public transport is only a small contributor to regional emissions compared to private vehicles, diesel buses can have a disproportional impact on air quality along high frequency bus routes through streets flanked by high rise buildings. An Auckland CBD study found peak NO_2 concentrations were linked to bus stop density (Miskell et al., 2015).

The most significant factor influencing diesel bus emissions is the European emission standard (EURO) that the vehicle was manufactured to meet. Overtime EURO emission limits for heavy vehicles have become more stringent (Figure 2.1). On-road testing shows that heavy-duty vehicles built to EURO IV and EURO V frequently do not meet their specified emission limits. However, EURO VI vehicles have delivered a step change in reducing NOx emissions compared to previous standards (Metcalfe & Kuschel, 2022).

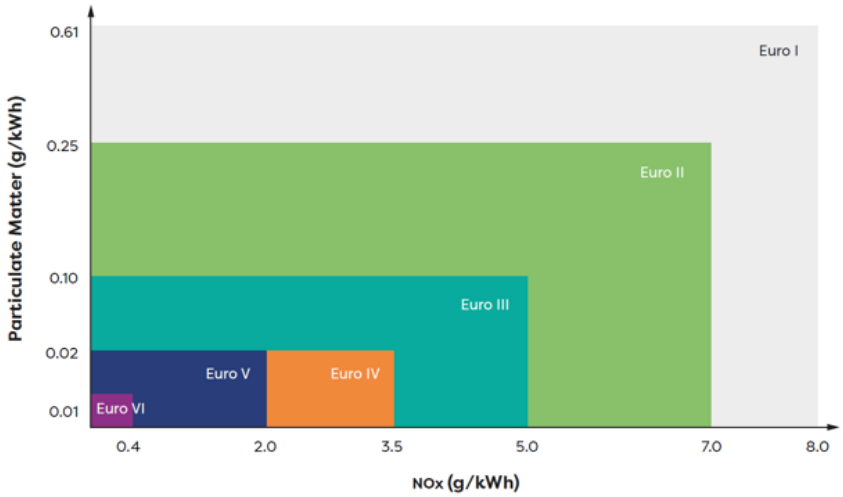

Figure 2.1 Development of European heavy-duty legislated emission limits. Source: https://www.aecc.eu/legislation/heavy-duty-vehicles/

In mid-2018 Metlink rolled out major changes to bus routes and replaced the oldest and most polluting buses with newer models manufactured to meet more stringent EURO emission limits. This fleet change resulted in a downward step change in modelled harmful emissions across the network (Mitchell & Clark, 2022).

A breakdown of the fleet in-service kilometres (kms) by bus types (2022/23) for the network shows a quarter of all kms were undertaken by electric buses. Although 3% of kms were travelled by EURO III buses, they produced 32% of the fleet modelled NOx emissions and 53% of particulate matter emissions. Deploying electric and buses that meet the latest EURO emission standards will substantially reduce harmful emissions from the network, with co-benefits for reduced exposure to air pollution on high frequency inner city streets for all commuters, whether that is driving, cycling, walking, or taking public transport.

3. Air monitoring sites and datasets

The study analyses trends in black carbon (diesel particulate) and NO_2 passive tube measurements on an inner-city bus-only lane (Manners Street) on the Golden Mile between July 2020 and June 2023. Over this period, bus fleet operating on Manners Street changed from predominately diesel-powered to just over 50% electric. To evaluate the impact of bus fleet decarbonisation on the Golden Mile, air quality trends on Manners Street were compared to Wellington Central air monitoring reference site (Figure 3.1), which was not affected by bus fleet electrification. Monitoring methods used in this study and datasets are in Appendices A1 and A2.

3.1 Monitoring site descriptions

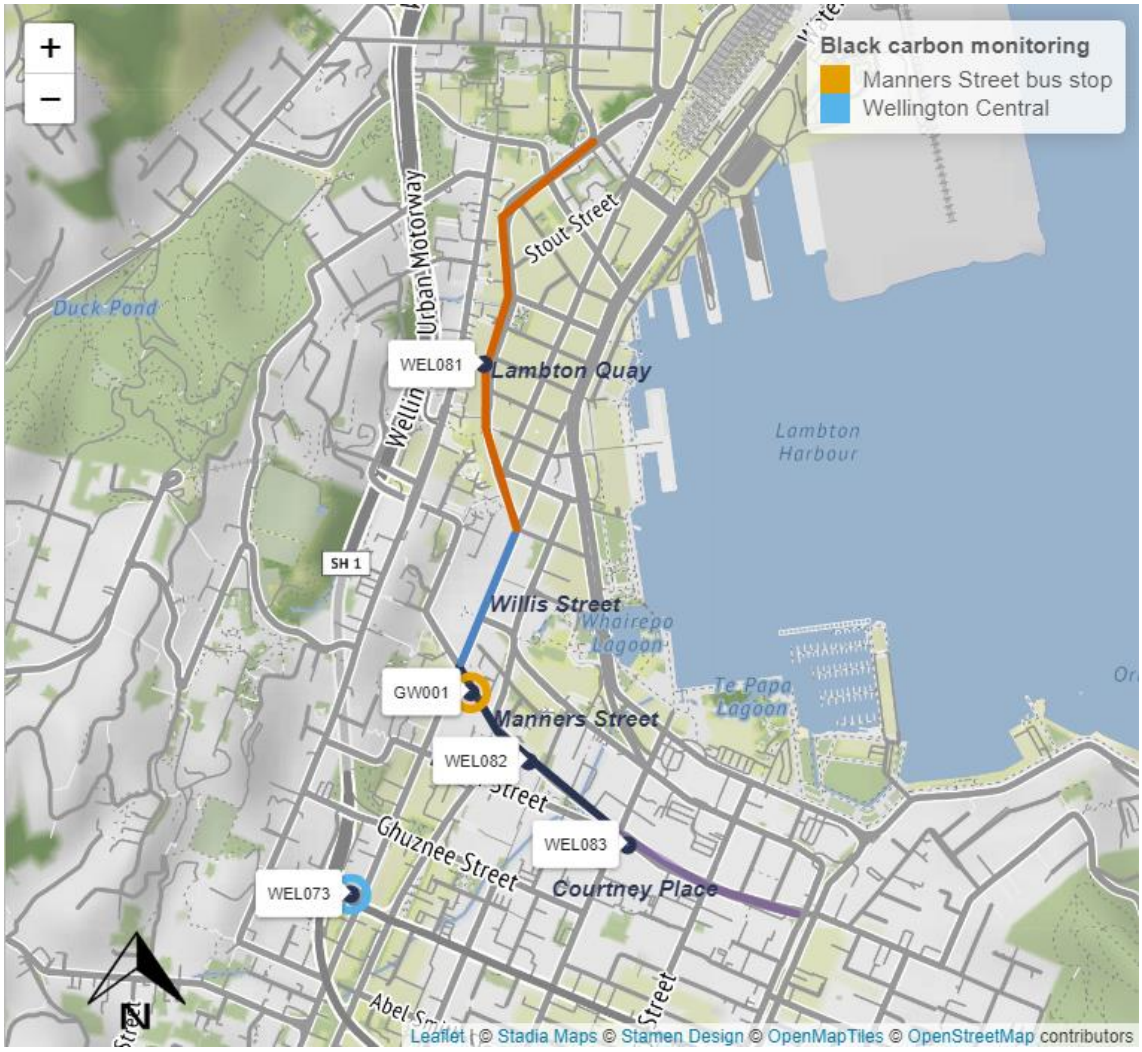

Figure 3.1. Golden mile from north to south (Lambton Quay, Willis Street, Manners Street, Courtney Place) and location of the Manners Street and Wellington Central black carbon monitoring sites and passive diffusion tube NO_2 sites with IDs.

Site description Manners Street, Golden Mile

Black carbon and NO_2 tube monitoring was carried out on Manners Street between Victoria and Willis Street on Wellington City's Golden Mile. This 100 m section of Manners Street in the northbound lane is bus only and the southbound lane is bus only between 6am and 7pm on weekdays. The speed limit on Manners Street is 30 km/hour. The Manners Street monitoring site is located at bus stop 5006 on the northbound lane, approximately 1 m from the kerbside (Figure 3.2). The street segment is relatively narrow with tall buildings either side that form a 'street canyon' orientated northwest to southeast. Therefore, most of the black carbon measured at the bus stop will be generated by bus emissions rather than from vehicles on nearby streets.

Figure 3.2. Monitoring site at bus stop 5006 on Manners Street northbound lane (Lat -41.28967, Lon 174.7750).

Site description Wellington Central reference site

The Wellington Central air monitoring reference site is located on the corner of upper Willis Street and the southbound Urban Motorway (Figure 3.3). The site is designated as a traffic-impacts monitoring site as it is within 10m of a busy arterial road (southbound Urban Motorway) with annual average daily traffic count of about 20,000 vehicles.

This site is also close to apartments and a student hostel and therefore represents inner city residential exposure. Approximately 100 Metlink bus trips per weekday travel northbound along the one-way section of Willis Street past the Wellington central monitoring site (24 m to road centreline). Unlike Manners Street, these buses are predominantly lower emissions EURO VI

models, and the fleet composition has not changed significantly since mid-2018.

Figure 3.3. Wellington Central air monitoring site on the corner of the Urban Motorway (SH1) and Willis Street (Lat -41.29364 Lon 174.7719).

4. Vehicle count trends

4.1 Manners Street, Golden Mile bus counts

Total daily bus counts travelling past the Manners Street air monitoring site are shown in Figure 4.1. Daily counts varied due to service reductions during the COVID-19 affected period (August to September 2021), public holidays, cancellations due to driver shortages, and Saturday timetable schedule operating during January 2023.

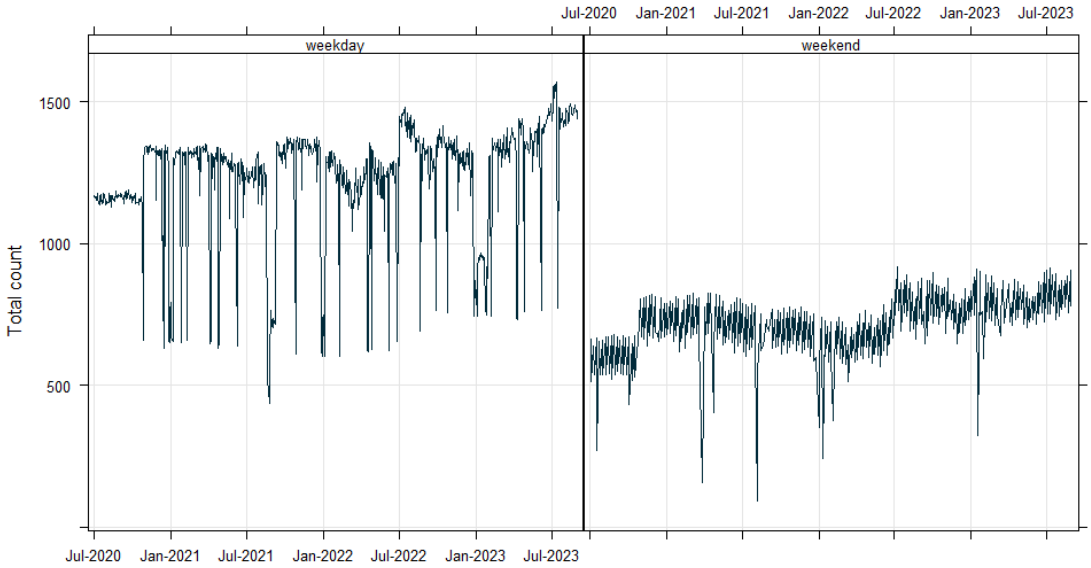

Figure 4.1. Daily bus counts on Manners Street section between Victoria Street and Willis Street split by weekday and weekend (1 July 2020 to 30 June 2023).

The engine-type profile of the bus fleet travelling through Manners Street changed between late August 2021 to mid-September 2021 with growth in the number of electric buses and corresponding decrease in EURO III and EURO V buses (Figures 4.2 and 4.3). In 2020/21 95% of trips were diesel powered and 5% electric and this proportion changed in 2022/23 to 48% diesel and 52% electric.

Electric services increased in 2021/22 due to electrification of Route 2 and increased interpeak timetable frequency. The electric Airport Express service was introduced on 1/7/2022 which further boosted the number of electric bus trips travelling through Manners Street.

The total number of bus trips along Manners Street split by engine type and financial year is shown in Figure 4.3.

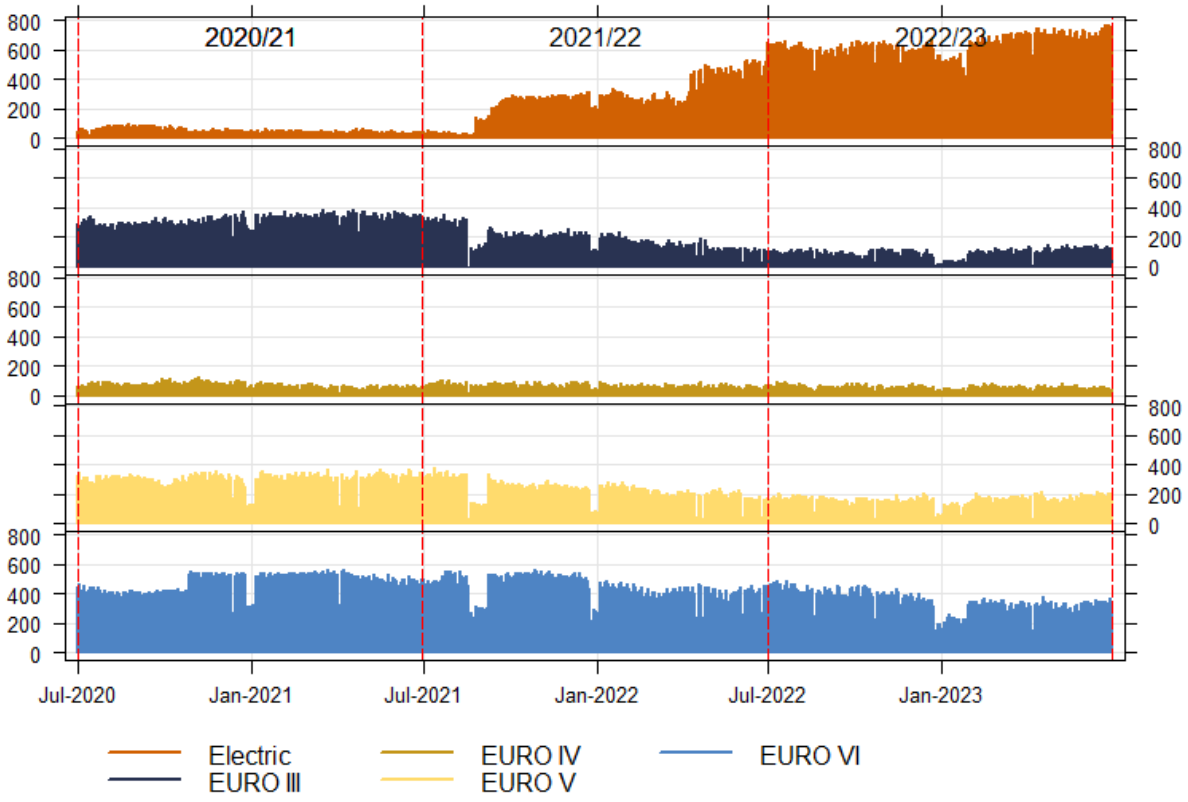

Figure 4.2. Daily bus counts on Manners Street section between Victoria Street and Willis Street by engine type with financial years shown by red dashed line (1 July 2020 to 30 June 2023).

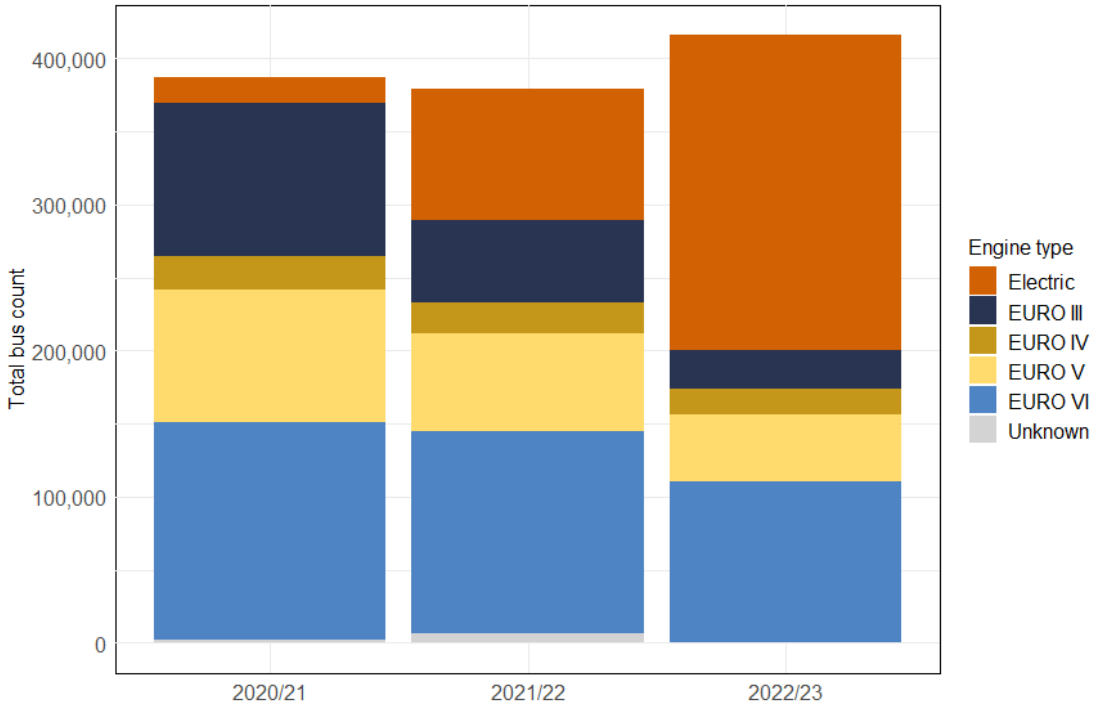

Figure 4.3. Total bus counts on Manners Street section between Victoria Street and Willis Street by financial year and by engine type (1 July 2020 to 30 June 2023).

4.2 Wellington Central (urban motorway)

Daily traffic counts recorded by NZ Transport Agency Waka Kotahi (southbound Terrace Tunnel) represent general trends in traffic intensity influencing the Wellington Central reference air monitoring site alongside the Urban Motorway. Figure 4.4 shows traffic counts were significantly lower during COVID-19 affected period (August to September 2021) and lower over the Christmas/New Year holiday periods.

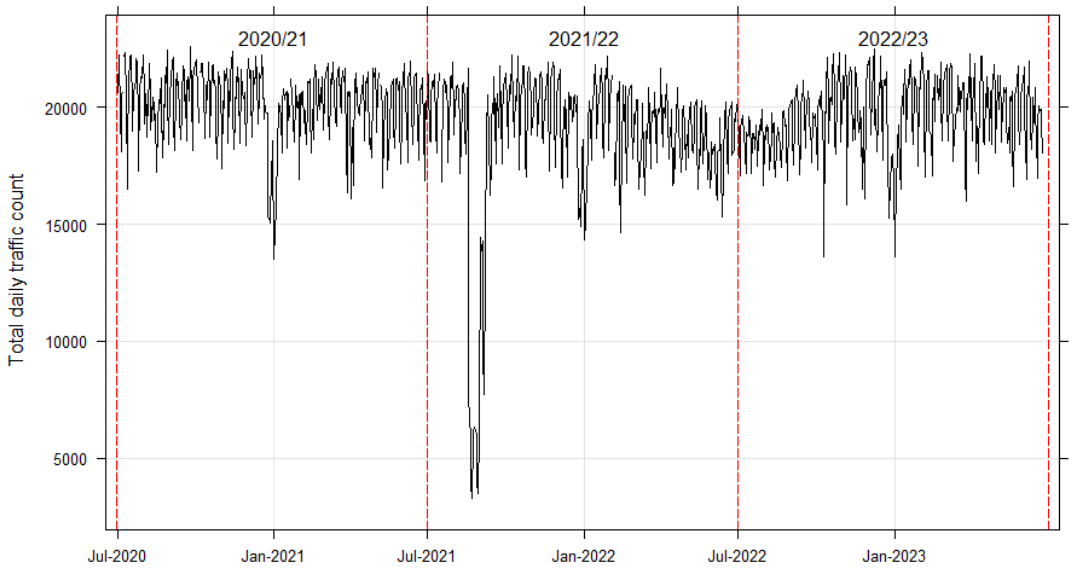

Figure 4.4. Daily time series of traffic counts terrace tunnel southbound with financial years shown by red dashed line (1 July 2020 to 30 June 2023).

4.3 Vehicle count summary by site and year

Table 4.1 summarises the percentage changes in bus and traffic counts in 2021/2022 and 2022/23 compared to the 2020/21 baseline. In 2022/23 total bus counts on Manners Street were 7.4% higher than in 2020/21, while traffic counts on the urban motorway reduced by 2.6%. NZ Transport Agency Waka Kotahi annual average daily traffic (AADT) summaries for 2018 to 2022 show that Wellington city SH1 traffic counts in 2022 had not yet returned to pre-COVID levels[4].

[4] Online interactive map at State highway traffic monitoring – annual average daily traffic (nzta.govt.nz)

Table 4.1. Bus and traffic count summary statistics by site and financial year (1 July to 30 June). Percentage change compared to baseline (2020/21) is shown in brackets.

Financial year	Urban Motorway	Manners Street			
	AADT	AADT buses	Total buses	% electric	% EURO III
2020/21	20,170	1,064	387,155	4.7%	27.0%
2021/22	18,736 (-7.1)	1,052 (-1.1%)	378,796 (-2.5%)	23.6%	15.0%
2022/23	19,652* (-2.6)	1,148 (8.0%)	415,664 (7.4%)	51.9%	6.4%

*Missing last 6 days of June 2023

5. Air quality trends

5.1 Black carbon (diesel particulate)

Figure 5.1 shows daily black carbon concentrations measured at both monitoring sites. The drop in black carbon concentrations on Manners Street coincides with lower bus and traffic counts during the COVID-19 affected period (August to September 2021).

Black carbon levels have remained low following the end of the COVID-19 restrictions as from this time the proportion of electric buses operating on Manners Street increased with a corresponding decrease in EURO III and EURO V diesel buses (Figure 4.2). A box plot summary of daily black carbon concentrations by financial year shows Manners Street concentrations reduced over the three monitoring periods, but comparatively little change at Wellington Central (Figure 5.2).

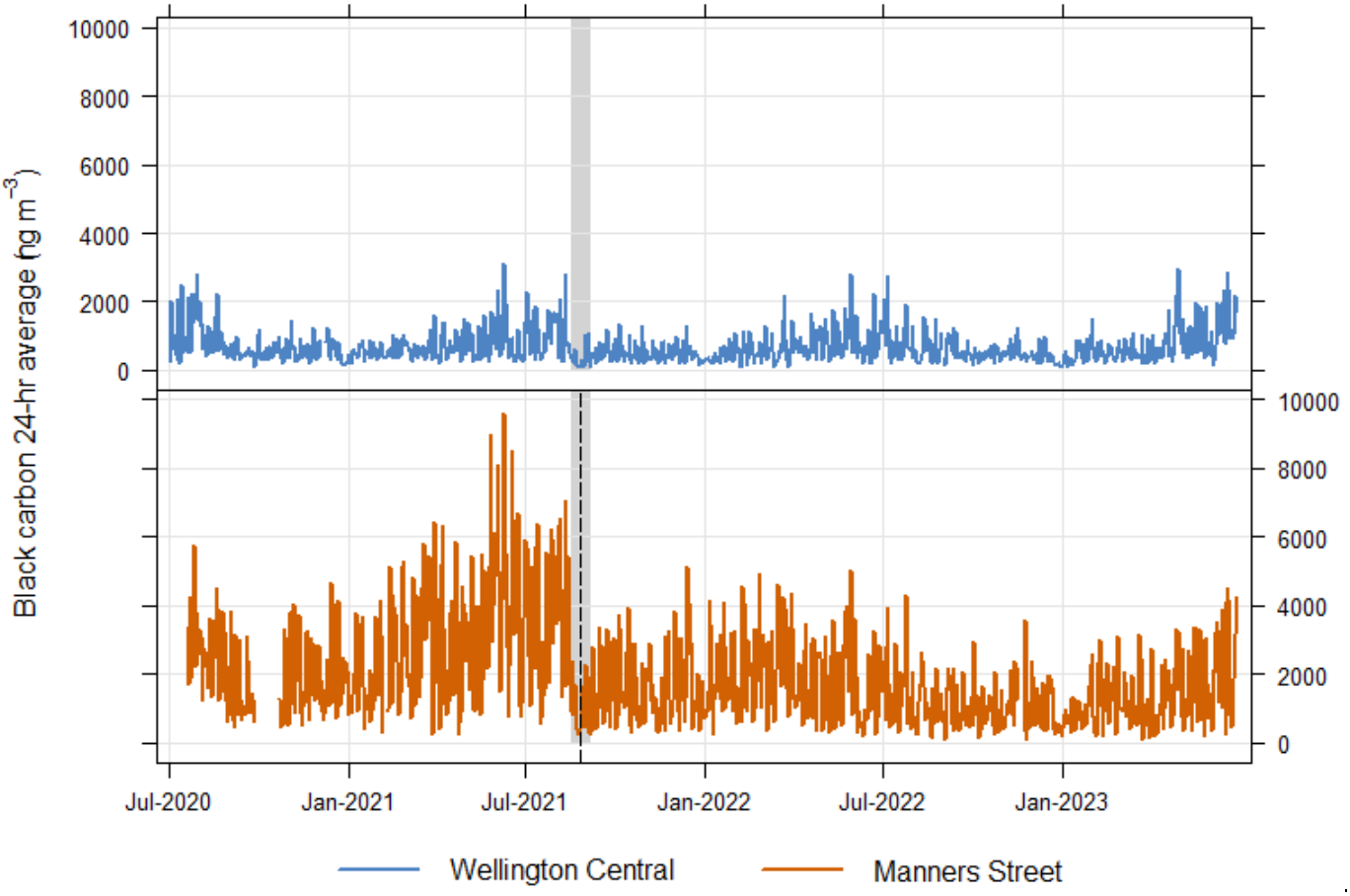

Figure 5.1. Daily black carbon concentrations measured at Manners Street and Wellington Central air monitoring sites from 1 July 2020 to 30 June 2023. The grey shaded area shows the COVID-19 affected period and date of increase in electric bus counts along Manners Street by dashed vertical line.

At both sites black carbon concentrations were higher in winter, most likely due to colder and more frequent calmer conditions which are less favourable for pollutant dispersion. At Wellington Central there was also a small black carbon

contribution from winter home wood burner emissions. There is also likely to be some contribution from non-exhaust emissions, such as tyre and road wear. Further investigation is needed to quantify the relative contribution of these sources to measured black carbon levels.

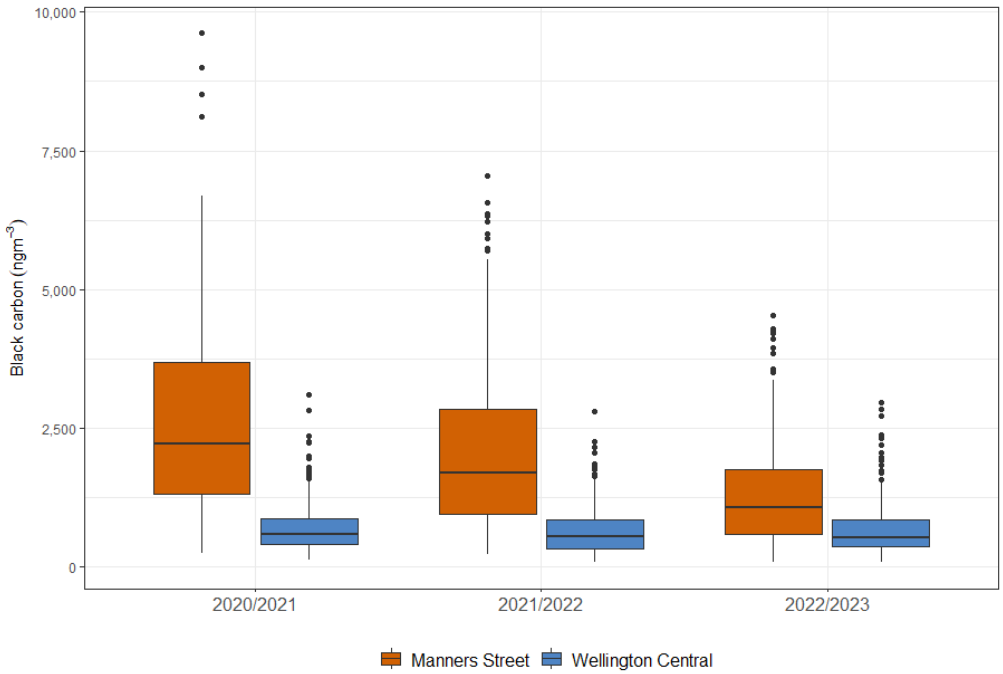

Figure 5.2. Box plots of daily black carbon concentrations measured by site and financial year. The horizontal box lines are the median values, the box is the interquartile range (distance between 25th and 75th percentile). The whiskers extend 1.5 times the interquartile range and the dots show outlying data points.

Table 5.1 compares average black carbon concentrations by financial year. In 2022/23 levels were almost 50% lower than baseline year 2020/21. Note the percentage change (23%) between 2020/21 and 2021/22 was slightly lower than the 28% reduction reported previously (Mitchell & Clark, 2022) which was based on a shorter period, ie, nine months (October to June).

Table 5.1. Annual average black carbon concentrations by financial year with percentage change from 2020/21 to 2022/23

	Manners Street		Wellington Central	
Financial year	**Black carbon (ng/m^3)**	**n days**	**Black carbon (ng/m^3)**	**n days**
2020/21	2579	313	717	356
2021/22	1991	364	667	360
2022/23	1296	344	676	359
Change %	-49.7%		-5.7%	

5.2 Nitrogen dioxide passive diffusion tube trends

5.2.1 Six-year trend from 2016/17 to 2022/23

Nitrogen dioxide concentrations showed strong seasonality, with maximum concentrations occurring in winter and minimums occurring in summer (Figure 5.3). This seasonal pattern is common to all regional and national NO_2 tube monitoring sites.

Seasonality in NO_2 concentrations is most likely due to a combination of factors such as:

- Seasonal differences in temperature, wind and height of boundary layer which can restrict or enhance atmospheric mixing and transport of air pollutants (NZ Transport Agency Waka Kotahi, 2023).
- Dependence of NOx exhaust emissions on temperature, with emissions increasing as temperature decreases during winter (Grange et al., 2019).
- The December/January public holiday period typically has lower traffic counts and bus frequency counts which is expected to lead to reduced NO_2 concentrations.

NO_2 levels measured at Manners Street and Wellington Central reference air monitoring site show a converging trend (Figure 5.3). From 2017/18 to 2020/21 NO_2 concentrations on Manners Street were approximately double the concentrations measured at Wellington Central (Table 5.2). However, in 2022/23 NO_2 concentrations at Manners Street had reduced to 1.4 times higher than Wellington Central.

Table 5.2. Annual average NO_2 concentrations by financial year with percentage change from 2020/21 to 2022/23.

Period	Nitrogen dioxide (µg/m³)				
	Manners-Cuba St (WEL082)	Manners St bus stop (GW001)	Wellington Central (WEL073)	Courtney Place (WEL083)	Lambton Quay (WEL081)
2016/17	40.4		21.3	36.5	37.4
2017/18	42.8		20.3	36.9	39.8
2018/19	37.2		18.5	32.9	32.5
2019/20	32.6		15.7	29.2	28.2
2020/21	32.3	34.0	16.7	28.4	29.7
2021/22	26.4	26.9	16.3	24.2	25.3
2022/23	22.9	23.9	16.3	22.9	24.1
%Change	-29.1%	-29.7%	-2.5%	-19.7%	-18.8%

Annual average NO_2 has decreased significantly on the Golden Mile since monitoring began in July 2016 (Table 5.2). Wellington Central also shows a decreasing trend over the same period. Interestingly, in 2022/23 all Golden Mile tube sites (Manners Street, Courtney Place and Lambton Quay) recorded

similar NO_2 concentrations, indicating the diminishing impact of bus emissions on air quality relative to other traffic, as the fleet transitions to all electric.

Despite this improvement, 2022 NO_2 annual averages measured on the Golden Mile and Wellington Central sites did not meet the World Health Organization guideline (2021) of 10 µg/m^3 (Figure 5.4). However, the WHO annual average guideline may be more relevant at locations where people are likely to be exposed to NO_2 on a long-term continuous basis, such as a residential dwelling (NZ Transport Agency Waka Kotahi, 2023) rather than at a roadside monitoring site.

About 15% of Wellington City residents are estimated to live in areas that don't meet the WHO guideline[5]. Where people they live and how they travel determines their daily exposure to traffic-related air pollution, which can be highest during commuting (Kachhara & Longley 2019, Cepeda et al., 2017).

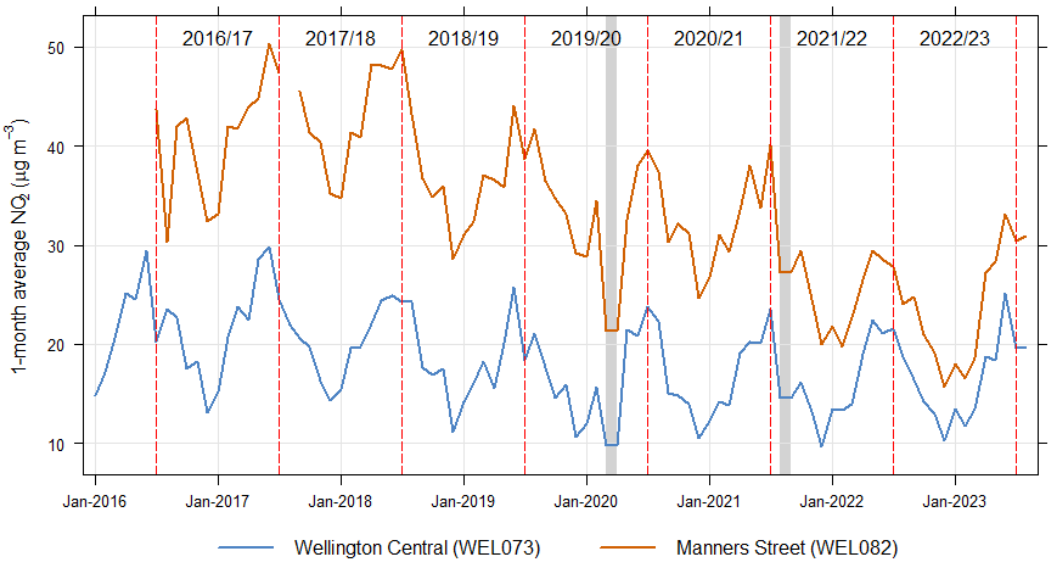

Figure 5.3. Monthly average NO_2 concentrations by passive diffusion tubes at Manners-Cuba Street (WEL082) and Wellington Central (WEL073). Financial years delineated by red dashed lines and the COVID-19 impacted periods shaded in grey.

[5] HAPINZ 3.0 (instantatlas.com)

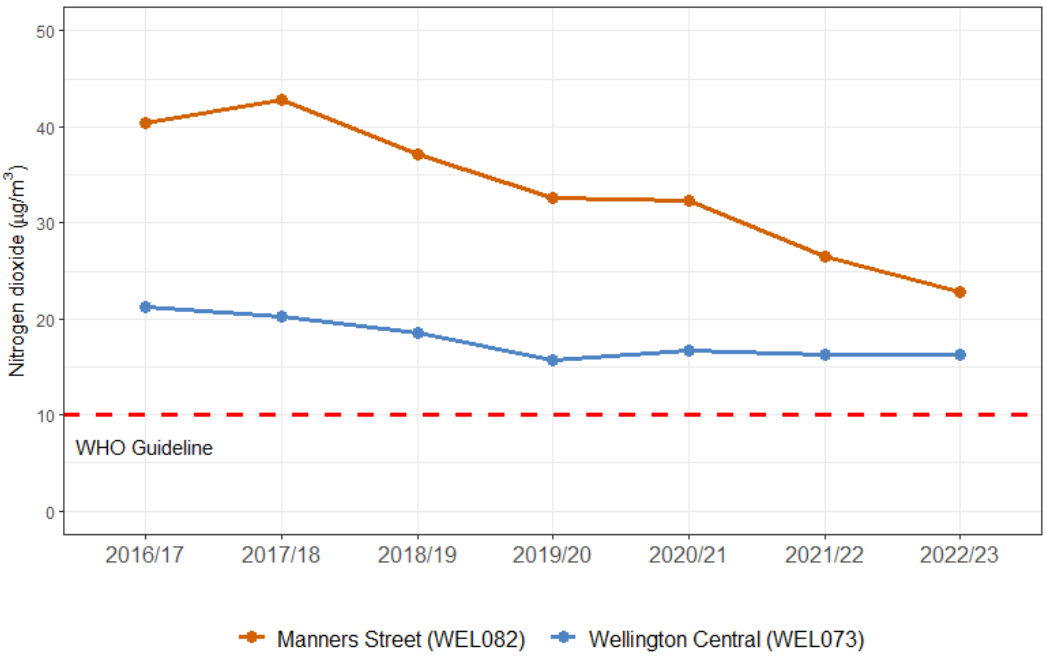

Figure 5.4. Nitrogen dioxide (NO_2) annual trends by financial year measured by passive diffusion tubes at the Manners-Cuba Street (WEL082) and Wellington Central (WEL073) monitoring sites from 2016/17 to 2022/23 compared to the 2021 World Health Organization annual guideline of 10 µg/m^3.

5.2.2 Three-year trend

Between 2020/21 and 2022/23 there was an almost 30% reduction in NO_2 measured at Manners Street sites (WEL082 and GW001) and 20% reduction at the Courtney Place (WEL083) and Lambton Quay (WEL081) sites. In contrast there was a relatively small percentage change (-2.5%) in NO_2 concentration at Wellington Central (WEL073) (Table 5.2).

As a cross check comparison, changes in NO_2 concentrations (µg/m^3) between 2020/21 and 2022/23 at other monitoring sites in Wellington City (with available data) were calculated. These sites also show reducing NO_2 over this period, but to a much lower level than observed on the Golden Mile sites (Figure 5.5).

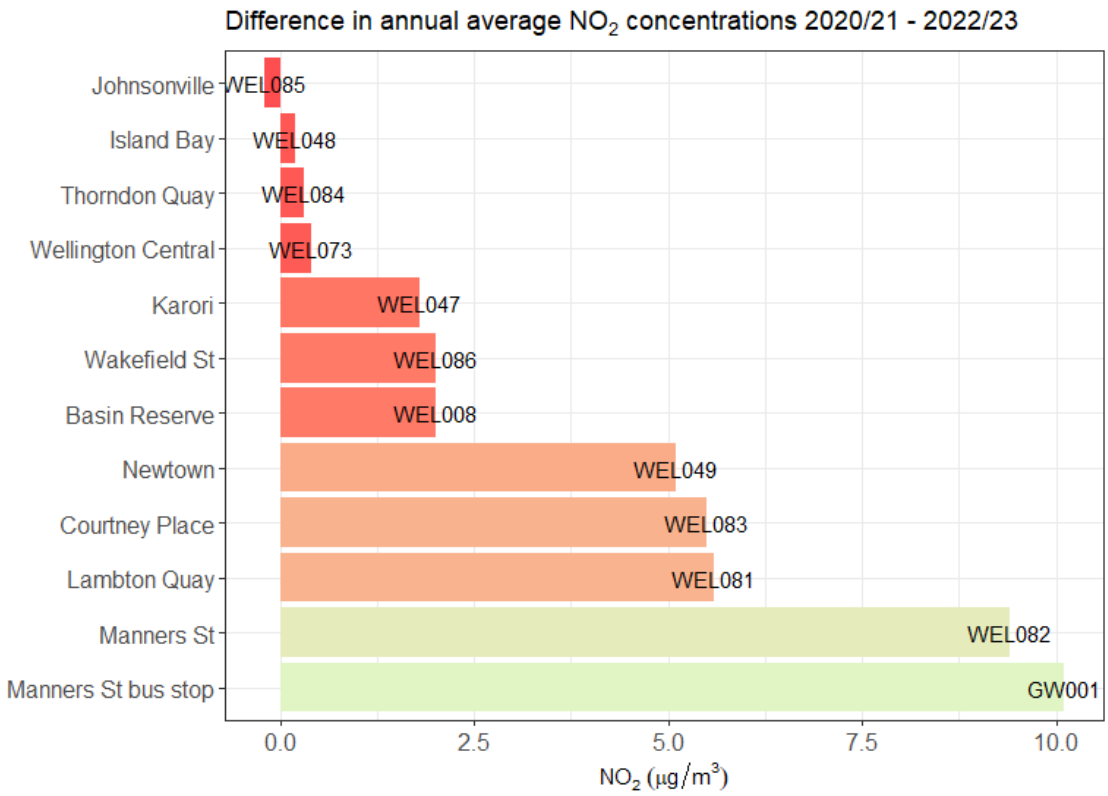

Figure 5.5. Difference in annual nitrogen dioxide (NO_2) concentration between 2020/21 and 2022/23 at Wellington City passive diffusion tube monitoring sites.

The percentage reduction in NO_2 on the Golden Mile and at Wellington Central was lower than the percentage reduction in black carbon. This most likely reflects the different pollutant emission and dispersion characteristics. Black carbon is a primary pollutant which is directly emitted as exhaust particulate. NO_2 is a secondary gas pollutant, and concentrations depend on atmospheric reactions with ozone and other precursors.

6. Conclusion

From July 2021 to June 2023, the proportion of diesel buses operating on Manners Street has reduced from 95% to 48% with a corresponding increase in the proportion of electric buses.

Air quality monitoring on a bus-only lane on the Golden Mile showed diesel particulate levels were almost halved, and there was an almost 30% reduction in NO_2 concentration associated with the change in bus fleet composition.

These results show there can be significant co-benefits for local air quality from bus-fleet decarbonisation along inner city corridors. Improved local air quality along inner city streets will reduce exposure for pedestrians, bus users, cyclists, and car occupants to traffic-related air pollution.

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Appendix A1: Air monitoring methods

Parameters measured and instrument methods used at each monitoring site are shown in Table A1.1.

Black carbon was monitored using aethalometers which analyse airborne particles by continuously drawing sampled air through a spot on a filter tape. Black carbon concentration is then calculated based on the intensity of light transmission at different wavelengths through the collected particulate sample compared to an unexposed portion of the filter tape.

A previous co-location of the two aethalometer methods (AE33 and MA350) found the methods were strongly correlated, but the MA350 underestimated concentrations by around 22% compared to the AE33 (Mitchell, 2021). This difference in measured concentration does not affect the validity of this study as we are most interested in the relative change over time at each monitoring site, not the absolute difference between sites.

Nitrogen dioxide was measured by passive diffusion tubes at monthly resolution following NZ Transport Agency Waka Kotahi protocols used for the national NO2 tube monitoring network (NZ Transport Agency Waka Kotahi, 2017). All NO_2 monitoring results were provided by Watercare Ltd following laboratory analysis by Staffordshire Highways Laboratory (United Kingdom). Triplicate tubes deployed at Wellington Central show good precision with the maximum annual average difference in any calendar year between any of the three tubes being less than 1 µg/m^3 for all years monitored from 2016 to 2022. At Wellington Central although annual average NO_2 by passive tubes is strongly correlated with the reference method (R^2=0.92), the reference measured concentrations were approximately 33% lower than the tube method.

Table A1.1. Measurement sites, instrumentation used, parameters measured and measurement resolution.

Site	Parameters	Instrument/Method	Resolution
Manners Street	Black carbon (880 nm)	MA350 5-channel aethalometer (Aethlabs). Inlet height 3m	5-min
	NO_2 (WEL082 & GW001)	Passive diffusion tube. Height 3.2m	1-month
Wellington Central	Black carbon (880 nm)	AE33 7-channel aethalometer (Magee Scientific). Inlet height 3m.	5-min (based on 1-min sample)
	NO_2 (WEL073)	Passive diffusion tube (triplicate). Height 3m	1-month
	NO_2	Reference chemiluminescence (T200, Teledyne API). Inlet height 3m.	5-min
	Wind speed & Direction (6m)	Vaisala WMT700	5-min
	Air temperature & relative humidity (3m)	Vaisala HMP155	5-min
	Barometric pressure (3m)	Vaisala PTB100A Bar Pressure	5-min

References

Mitchell TA. 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 https://www.gw.govt.nz/assets/Documents/2022/08/Pilot-study-black-carbon-monitoring-of-bus-emissions.pdf

NZ Transport Agency Waka Kotahi. 2017. Ambient air quality (nitrogen dioxide) monitoring network. Operating manual 2017-18. October 2017, Wellington. https://www.nzta.govt.nz/assets/resources/air-quality-monitoring/docs/ambient-air-quality-monitoring-programme-operating-manual-2017-2018.pdf

Appendix A2 Datasets and treatment

Air quality

Black carbon 1-hour averages from Manners Street and Wellington Central monitoring sites were averaged to 24-hour periods where there was at least 75% data capture at both sites. All statistical summaries were based on days where there was 75% capture at both sites. Black carbon data on 25 August 2023 was removed from the dataset as there was a house fire on Abel Smith Street resulting in elevated black carbon measurements at Wellington central un-related to traffic. An extreme outlier black carbon measurement on 25 November 2022 was removed from the Manners Street dataset (63,771 ng/m^3).

Nitrogen dioxide passive tube dataset of monthly averages was based on exposure times from the NZ Transport Agency Waka Kotahi exchange schedule being the first Wednesday of every month +/- two days. Due to COVID-19 movement restrictions tubes could not be changed resulting in two-month exposure period for August-September 2021 and March-April 2020. Watercare re-calculated concentrations based on the extended exposure period and assigned that value to each of the affected months, so the annual average was not biased upwards. There was also a two-month exposure for GW001 over May-June 2023 due to an incorrect tube replacement. All annual averages used in the analysis had greater than 75% data capture.

Traditionally air quality data in New Zealand are analysed by calendar year to capture the peak winter period. In this study data were analysed by financial year (1 July to 30 June) due to the start and end point of the available time series. Black carbon and NO_2 tube measurements on the Golden Mile started in July 2020 and July 2016 respectively. NO_2 tube measurements were available to August 2023 at the time of writing.

Bus counts by engine type on Manners Street

Hourly counts of buses by engine type (EURO III, EURO IV, EURO V, EURO VI and electric) that traversed the section of Manners Street where air monitoring was located were extracted from the Bus Emissions Tool described by Mitchell & Clark (2022). Bus counts were based on all bus vehicle IDs geolocated as passing Bus stop 5006 (Manners Street northbound) and at bus stop 5510 (Willis Street southbound). Vehicle IDs were matched to a fleet lookup table to determine engine classification. Bus IDs that could not be matched to an engine type were classified as ‘unknown’ but were counted in the total. Typically, less than 1% of total monthly bus counts were unknown apart from August 2021 (1.1%), March 2022 (8.5%), February 2022 (7.9%), and April 2022 (2.7%). Nine days with zero or unrealistically low counts were removed from the data set resulting in 1157 valid count days (data capture rate 99%). Note reliable bus counts for Manners Street were not available prior to July 2020.

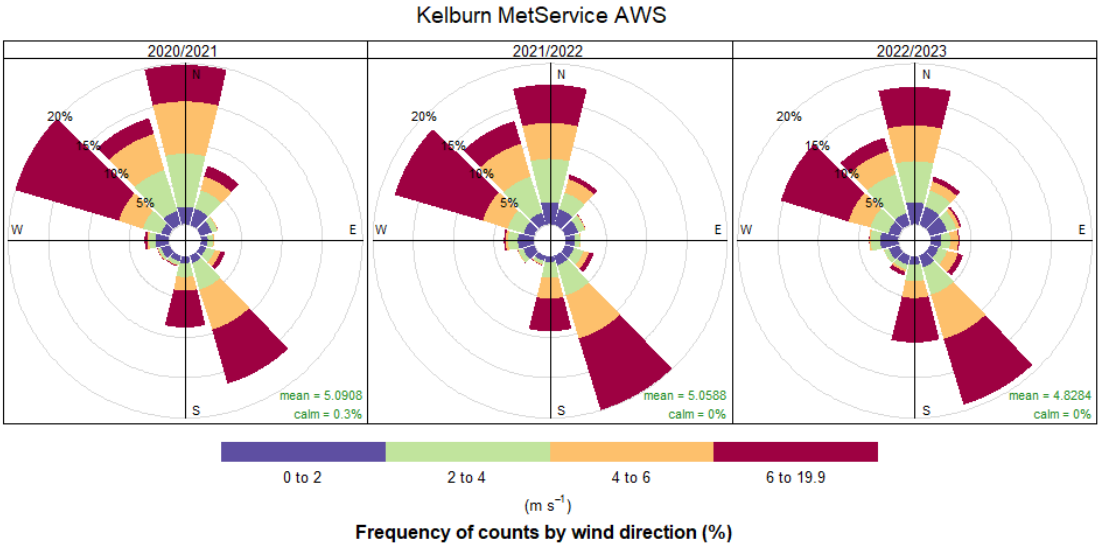
General traffic counts

There were no site-specific traffic counts available for the monitoring study. One-hour traffic counts representing the Wellington central (urban motorway) air monitoring site were downloaded from (NZ Transport Agency Waka Kotahi) State Highway Traffic Monitoring System for the SH1 continuous traffic counter located approximately 220m before the southbound Terrace Tunnel entrance (ID 01N11074). Non-bus traffic counts were not available for the Manners Street bus-only segment where the monitoring was conducted. It is expected that non-bus traffic will be minimal and mainly restricted to the southbound lane between 7pm and 6am.

Meteorological

Wind flows across Wellington city are almost always from either N-NNW or S-SE but how these winds are experienced locally varies due to funnelling of wind around buildings and sheltering effects depending on building orientation. Meteorological data was obtained from the Wellington Central monitoring site. The site does not meet reference siting criteria AS/NZS 3580.14:2014 for wind measurements due to mast height of less than 10 m and nearby multi-storey building which blocks wind flow from the northeast and northwest direction. Therefore, wind speeds and direction measured here will not necessarily represent wind fields in other parts of Wellington city. Meteorological data from the automatic weather station at Kelburn was purchased from MetService. Wind roses for both sites showing frequency of wind speed and wind direction counts over the monitoring period are presented in Figure A2.1.

A previous pilot study concluded that Manners Street was affected by street canyon re-circulation leading to higher black carbon concentrations during south-to-south westerly winds which are perpendicular to the orientation of the street (Mitchell, 2021).



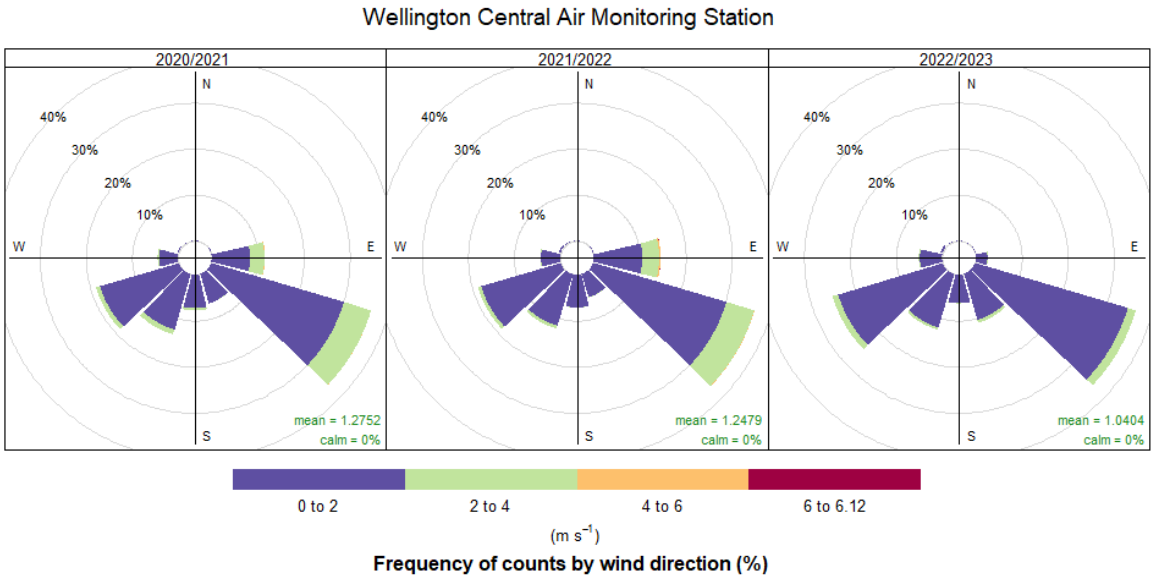


Figure A2.1. Wind roses at Wellington Central air monitoring site (Lat -41.29364 Lon 174.7719) and Kelburn Automatic Weather Station (MetService) (Lat -41.28333 Lon 174.76666)

Data analysis and visualisation

All datasets were analysed and visualised using R version 4.3.2 (R Core Team, 2023) using the following R packages: Openair (Carslaw & Ropkins, 2012); Tidyverse (Wickham et al., 2019); Leaflet (Cheng et al., 2023).

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