# The Impacts of Transport Emissions on Air Quality in Auckland's City Centre

Nick Talbot and Rita Lehn

December 2018 Technical Report 2018/028

RIMU Research and Evaluation Unit

Auckland Council
Te Kaunihera o Tāmaki Makaurau

# The Impacts of Transport Emissions on Air Quality in Auckland's City Centre

December 2018 Technical Report 2018/028

Nick Talbot and Rita Lehn

Auckland Council
Technical Report 2018/028

ISSN 2230-4525 (Print)
ISSN 2230-4533 (Online)

ISBN 978-1-98-856494-4 (Print)
ISBN 978-1-98-856495-1 (PDF)

| |
|---|
| This report has been peer reviewed by the Peer Review Panel. |
| Review completed on 10 December 2018<br>Reviewed by two reviewers |
| Approved for Auckland Council publication by:<br><br>Name: Eva McLaren<br><br>Position: Manager, Research and Evaluation (RIMU) |
| Name: Matt Hope<br><br>Position: Manager, Environmental Monitoring, Research and Evaluation |
| Date: 10 December 2018 |

Recommended citation

Talbot, N and Lehn, R (2018). The impacts of transport emissions on air quality in Auckland's city centre. Auckland Council technical report, TR2018/028

# Executive summary

The City Centre area is the rapidly expanding economic, social and cultural heartland of Auckland. Unfortunately, it is also where Auckland's highest air pollution levels are observed. Narrow roads flanked by high buildings create deep street canyons that restrict ventilation of air pollutants such as nitrogen dioxide ($NO_2$) and fine particulate matter 2.5 micrometres and smaller ($PM_{2.5}$) resulting in levels which sometimes exceed national and international regulatory standards for air quality. This is despite an otherwise favourable geographical location that encourages a reliable airflow and has little long-range transportation of pollutants from neighbours.

An awareness of the impacts of air pollution along with a recognition of Auckland's climate change commitments has helped focus attention on the impacts of policy implementation on air quality. Key stakeholders require evidence to help guide strategy development that is consistent with the local climate, urban design and environmental goals. Policy decisions that promote safer streets, climate action, active and public transportation modes as well as congestion mitigation strategies have multiple and interdependent benefits. These include increased economic activity, vibrant social spaces and a cleaner, more sustainable environment, including cleaner air.

All fossil fuelled vehicles degrade air quality to some extent. However, diesel vehicles tend to emit higher concentrations of air pollutants than petrol vehicles. Multiple studies have drawn attention to the relationship between the volume of bus traffic and elevated concentrations of $NO_2$ and black carbon. Black carbon is a component of fine and ultra-fine particulate matter produced during diesel fuel combustion. These very small airborne particulates have been connected to chronic and acute health impacts world-wide and are a concern in an area of Auckland that has over 10 million pedestrians a year.

Studies indicate that a key method of reducing air pollution in Auckland's City Centre is to reduce emissions from buses and other large heavy goods and construction vehicles. Evidence provided in this report demonstrates multiple benefits to proposed traffic calming, bus electrification and street pedestrianisation projects across downtown Auckland.

# Table of contents

# List of figures

## List of tables

# 1.0 Introduction

The Auckland City Centre has New Zealand's highest population density at 10,393 people per km² (Fredrickson, 2014), and receives over 2.6 million visitors a year (ATEED, 2017). This area supports in excess of 10 million pedestrians each year (Greater Auckland, 2016), houses over 50,000 permanent residents and contributes 20 per cent of Auckland's GDP (Rohani et al., 2017). It represents the centre of a healthy, vibrant and prosperous Auckland from economic, social and cultural perspectives.

Auckland's geography receives a reliable westerly wind from the Tasman Sea. This airflow acts to dilute and remove air pollutants from emission sources across the city. In fact, with no neighbouring countries upstream and nothing but open ocean surrounding it, Auckland should be able to offer its residents and visitors some of the best air quality of any major city world-wide. However, emission sources within the City Centre pollute the airshed to such an extent that air quality measurements have exceeded national and global regulatory air quality guidelines for nitrogen dioxide ($NO_2$) and particulate matter (PM). The degradation of air quality across Auckland results in upwards of 300 premature deaths (Kuschel et al., 2012) and has been shown to increase hospital admission cases for acute respiratory disorders (Dirks et al., 2017; Hales et al., 2012).

Concentrations of air pollutants are notably higher in the City Centre than measured elsewhere across Auckland. To determine why, there is a need to understand the physical impacts of dispersion within a complex urban topography. Narrow streets surrounded by tall buildings restrict ventilation reducing airflow out of the street 'canyon' (Figure 1). This process traps locally emitted pollutants close to the ground, raising concentrations and encouraging the formation of secondary air pollutants (Baik and Kim, 1999; Kwak et al., 2018; Martilli, 2002).

Queen Street is Auckland's busiest thoroughfare. It runs for three kilometres, orientated south-west, north-east through the heart of the city. As well as being surrounded by tall buildings, the street itself is in a valley with modest hills to the south, east and west, which limit dispersion and encourage pooling of pollutants from nearby streets. Moreover, prevailing winds from the south-west encourage the flow of pollutants from the busy motorway that surrounds the City Centre towards the waterfront, the most densely populated area of central Auckland.

On-road vehicle emissions are the major contributing source of air pollutants within the City Centre. Vehicles emit particles that are generally less than 0.1 µm (100 nm) in diameter. This is two orders of magnitude smaller than a $PM_{10}$ particulate. One

10 µm diameter particle has approximately the same mass as one million 100 nm-diameter particles, 10 µm particles are considered less hazardous because they are unlikely to enter the alveoli gas exchange area of the human airway. Also, larger particles tend to be biogenic in origin, and in Auckland, largely consist of less harmful sea salt (Davy and Trompetter, 2017). The number/mass relationship of particulate matter is important to consider as most measurements are currently reported in mass concentrations, not particle counts.

Some of the smallest particulates are emitted from diesel emissions. Diesel exhaust also disproportionately influences total concentrations of $NO_2$ and perhaps more importantly black carbon (BC) (Kholod and Evans, 2016). The importance of BC particulate, in terms of health and climate impacts is becoming better understood. Studies in Rio de Janerio and Sau Paulo (Andrade et al., 2012), Shanghai (Geng et al., 2013), multiple European sites (Genberg et al., 2013) and four Australian cities (Hawas et al., 2003) have all connected BC emissions to diesel fuel. Aside from on-road vehicles such as buses and trucks, the proximity of a major port on the waterfront also contributes to elevated exposure levels of key air pollutants such as $NO_2$, $PM_{2.5}$ and especially sulphur dioxide ($SO_2$) which is addressed in a report by Talbot et al., (2017).

To measure pollutant levels within the City Centre, Auckland Council runs a permanent air quality monitoring station located on Queen Street (Figure 2). This site has recorded occasional exceedances of the recommended level of 40 $\mu g/m^3$ (WHO, 2018). In complex urban terrain spread across five square kilometres of land, one single receptor site is not spatially representative of ambient concentrations. To resolve this knowledge gap, researchers have used various methodologies and techniques that provide a broader picture of air pollution distribution across the central area and found pollutions levels vary over very short distances, including across the width of the road (NIWA, 2016).

Ongoing land use and infrastructure changes within the City Centre can make long-term trend assessments of air quality dynamics difficult to quantify. Traffic data is also inconsistent due to changes in bus scheduling and policy implementations that have encouraged the use of public transport and active modes over time. As this report will show, these changes are slowly shifting transport modes away from private vehicle use when entering the City Centre (Auckland Transport, 2018). The increase in foot traffic offers great opportunities to reduce air pollution but also potentially increases health risks from increased exposure to peak air pollution concentrations (Raza et al., 2018).

Auckland is a member of the C40 Cities Climate Leadership Group and is a signatory to its Fossil Fuel Free Streets (FFFS) declaration which includes commitments to create a fossil fuel-free area within the City Centre by 2030, as well as electrification of the bus fleet. This report discusses how policy interventions to improve road safety, relieve congestion, and create more liveable spaces for people can deliver on the climate and health outcomes of the declaration as well as deliver broader social and economic benefits.

To assess how effective policy changes are in achieving environmental social and economic goals related to air quality over the long term, a consistent, accurate and spatially representative dataset is required. To obtain such data, a dense network of air quality monitors across the Auckland City Centre is proposed.

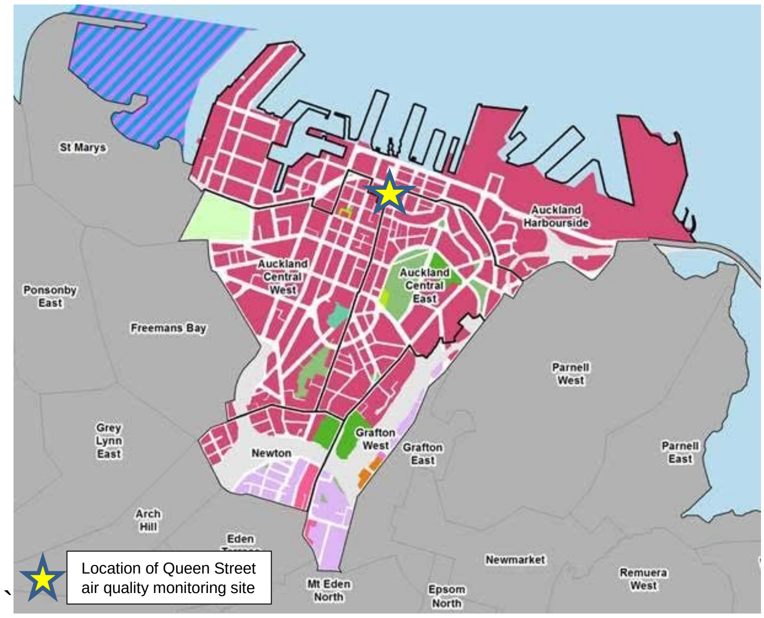
This report seeks to inform the development of an air quality network by reviewing published and unpublished research on air pollutants within Auckland's heartland, and planned policy implementation to identify pollution 'hot spots' and areas of significant change. Furthermore, this report draws attention to the complexity of inner city air quality and lesser known impacts, while also providing an evidence base to support policy development and implementation aligning to the C40 FFFS declaration.

**Figure 1** Graphical illustration of how city topography can help trap pollutants within the confines of the streets with commensurate increases in recorded concentrations (City of Helsinki Environment Centre, 2017).

# 2.0 Air Quality in Auckland's City Centre

## 2.1 Overview of Auckland's City Centre

Auckland City Centre is now home to over 57,000 permanent residents, workplace to 75,000 people, and hosts over 200,000 people every day (Auckland City Centre residence Group, 2018) (Figure 2). During 2017, almost 10 million pedestrians were counted on lower Queen Street adjacent to the Queen Street air quality monitoring site (Heart of the City, 2018). The waterfront area hosts the centrally located port, delivering valued tourism trade to the heart of the city and offering a first impression of Auckland and New Zealand to many of the 171,000 guests each cruise season (Stats NZ, 2016). Such densely populated areas can offer social and economic opportunities; however, they also expose far greater numbers of people to potentially harmful air pollutants.




| | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 |
|---|---|---|---|---|---|---|---|---|
| **Populations (5 CUA)** | | | | | | | | |
| 514101 Auckland Harbourside | 3,890 | 4,070 | 4,310 | 4,760 | 5,080 | 5,680 | 6,210 | 6,630 |
| 514102 Auckland Central West | 11,550 | 11,950 | 11,950 | 12,350 | 13,650 | 15,900 | 18,500 | 21,100 |
| 514103 Auckland Central East | 9,870 | 10,250 | 10,300 | 10,700 | 11,400 | 13,250 | 15,150 | 17,150 |
| 514200 Newton | 1,550 | 1,590 | 1,600 | 1,720 | 1,870 | 2,170 | 2,440 | 2,580 |
| 514301 Grafton West | 3,270 | 3,380 | 3,470 | 3,600 | 3,740 | 4,190 | 4,660 | 4,910 |
| Sum of these - 5-CAU City Centre | **30,130** | **31,240** | **31,630** | **33,130** | **35,740** | **41,190** | **46,960** | **52,370** |

**Figure 2** Map of Auckland City Centre separated into five census area units. Resident population data from 2010 until 2017 taken from ATAP (2018).

## 2.2 Sources of air pollutants in the City Centre

Transport is by far the highest contributor to $NO_x$ emissions, accounting for 79 per cent across the Auckland airshed (Figure 3) (Grange et al., 2015). Home heating is less prevalent in the city centre where there are fewer wood burners compared with residential suburbs (Stats NZ., 2012). Therefore, it is reasonable to assume $PM_{2.5}$ emissions from transport would be proportionally higher within the City Centre compared with the wider Auckland region.

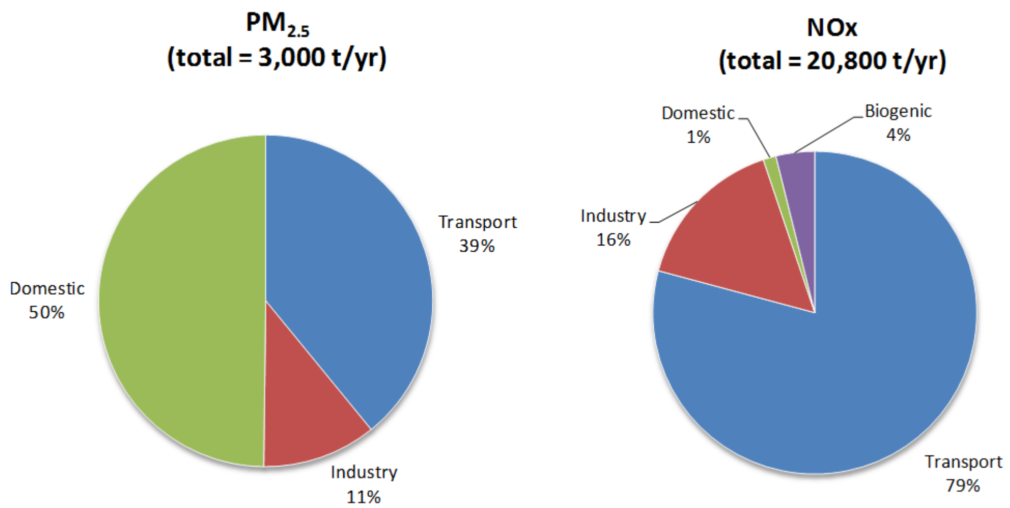



**Figure 3** Emission inventory percentage per emission source group for $PM_{2.5}$ (left) and $NO_x$ (right) given in units of tonne/year released across the whole Auckland region.

Transport emissions in the City Centre are dominated by on-road vehicles. Emissions profiles depend on the type of vehicle, traffic flow, age of vehicle, maintenance and fuel burnt (Davy et al., 2017; Platt et al., 2017). Petrol fuelled vehicles outnumber diesel vehicles on Auckland's roads (Sridhar and Metcalfe, 2018); however, diesel powered vehicles generally emit greater concentrations of particulate and $NO_2$ than petrol ones (Bluett et al., 2016). Aside from on-road vehicles, construction and shipping emissions also impact air quality. Shipping emission impacts on particulates and $SO_2$ are observed to a lesser degree at the Queen Street monitoring site, but increase with proximity to the port and shipping lanes (Talbot et al., 2017). Exceedances of the 1-hour standard for $SO_2$ on Auckland's waterfront have been reported in the past.

The City Centre is the heart of Auckland's public transport network, with most of all public transport trips having a destination in the City Centre. During 2015, there were 59.8 million passenger trips on the Auckland bus network, with 507.1 million passenger-kilometres travelled. Bus patronage has increased by 40 per cent between 2005 and 2015 (Auckland Transport, 2018). Despite the good availability of public transport, more people still travelled by car into the city centre than by any other mode of transport, (Table 1) (ATAP, 2018).

**Table 1** Transport counts for November 2017 as provided by Auckland Transport Alignment Plan (2018).

| Actual City Centre counts - AM inbound | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Year | Month | Pedestrians | Cyclists | People by Car | People by Bus | People by Train | People by Ferry | Total People Movements | by Car | by PT | Ped & Cycle |
| 2017 | Nov | 4709 | 1517 | 38072 | 21536 | 8474 | 4622 | 78931 | 48 % | 44 % | 8 % |

## 2.3 Results from air quality monitoring in Queen Street

Concentrations of key pollutants measured at Queen Street are significantly higher than those measured at all other permanent monitoring sites in Auckland. Annual average $NO_2$ concentrations are more than 20 µg/m$^3$ higher than other urban Auckland locations such as Takapuna, Henderson and Penrose, and 30 µg/m$^3$ higher than the urban background level at Glen Eden (Figure 4). Urban background concentrations represent residential locations away from significant transport sources and can be considered a baseline for urban Auckland. Therefore, comparison of concentrations from peak sites with the urban background provide an indication of the impacts from prominent local emission source(s).

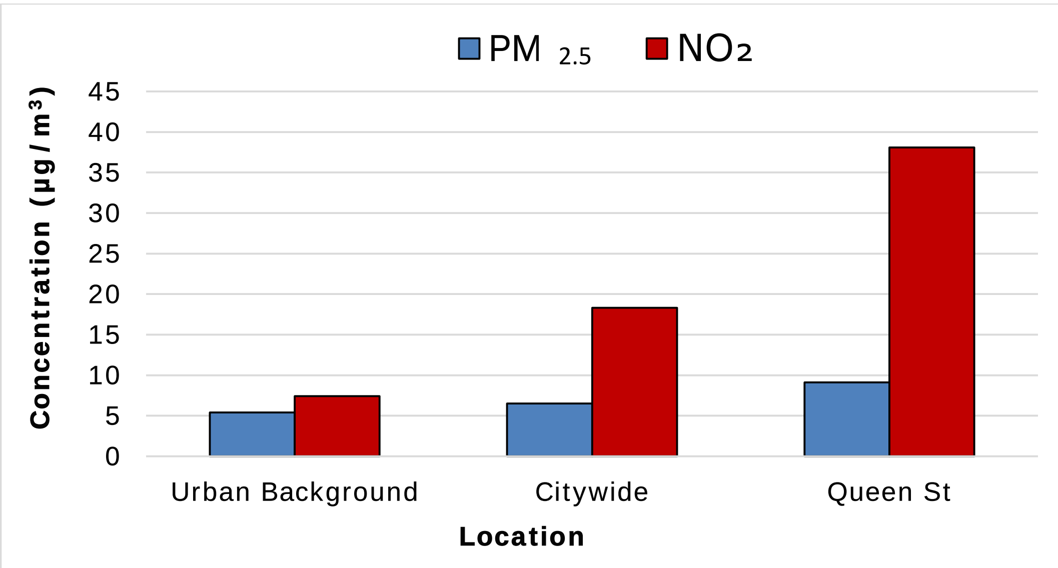



**Figure 4** 2006-2016 annual averaged data for $PM_{2.5}$ (blue) and $NO_2$ (red) at Auckland Council's urban background site (Glen Eden), Citywide (Penrose, Takapuna and Henderson) and Queen Street monitoring locations. Long-term averaged data has been used to smooth

short-term fluctuations in emissions caused by changes in emission sources such as traffic flow near monitoring sites.

Auckland Council's Queen Street air quality monitoring site is located towards the lower end of the road when tall buildings are concentrated (Figure 5). Within this complex urban terrain, ventilation rates from airflow are reduced, slowing the removal of air pollutants. The built up environment can cause eddies and vortices to form, which trap pollutants near the ground (Harrison et al., 2018), similar to the processes depicted in Figure 1. This results in higher concentrations of primary pollutants (derived directly from the tailpipe), and also promotes secondary processes that can cause physio-chemical changes in composition (Mayer, 1999).

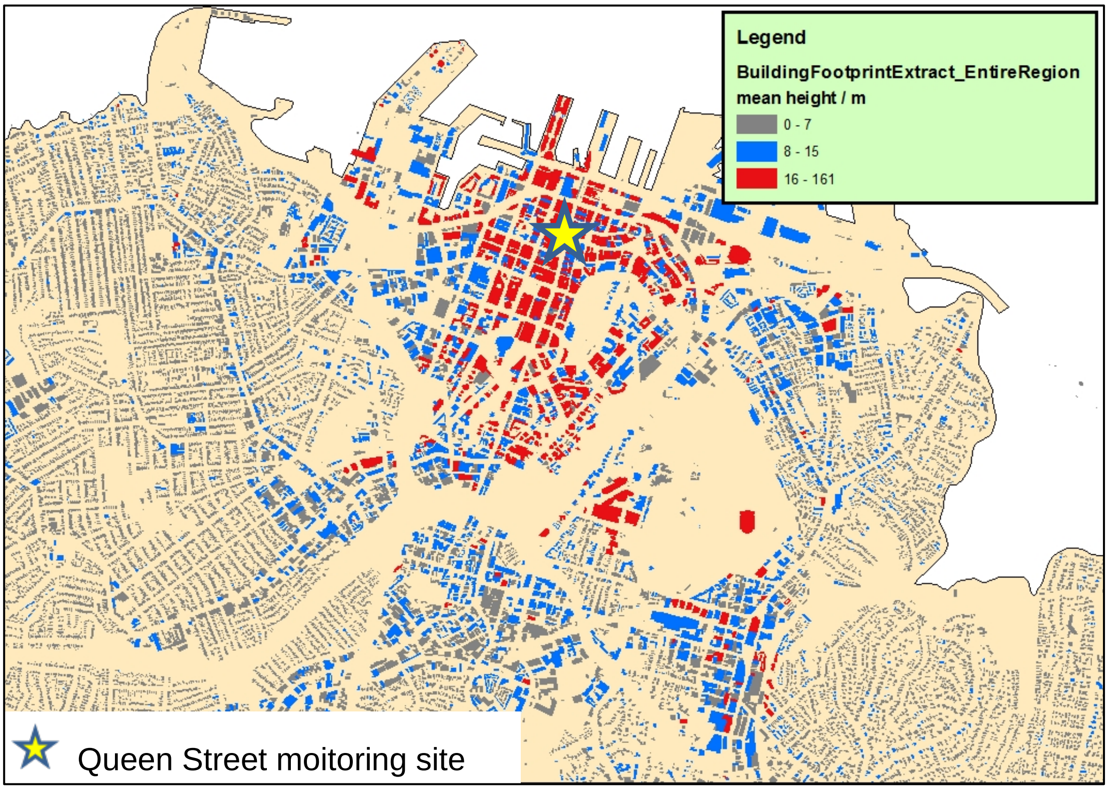



**Figure 5** GIS plots of building height within the City Centre showing the highest buildings are located centrally and towards the waterfront (Longley et al., 2017).

### 2.3.1 Nitrogen dioxide ($NO_2$) measurement

#### 2.3.1.1 Overview of nitrogen dioxide impacts

The main effect of breathing raised levels of $NO_2$ is the increased likelihood of respiratory problems (NZTA, 2017). $NO_2$ inflames the lining of the lungs and can reduce immunity to lung infections. This can cause or exacerbate existing respiratory disorders such as bronchitis (WHO, 2013). Increased levels of $NO_2$ can have significant impacts on people with asthma because it can cause more frequent and more intense attacks. Lung function may be decreased in children and susceptibility to certain forms of cancers is increased (Ministry for the Environment, 2018).

### 2.3.1.2 Nitrogen dioxide measurements from Queen Street

The seasonalised trend for ambient $NO_2$ concentrations on Queen Street has shown a statistically significantly reduction since 2006 (p-value <0.05) (Figure 6 *left*). The trend closely follows traffic flow and changes in vehicle and fuel standards over time (Davy and Trompetter, 2017; Xie et al., 2016). The greatest reduction in $NO_2$ was recorded before 2012. Since that time the trend has somewhat reversed, with a small, but non-significant (p = 0.43) increase in $NO_2$.

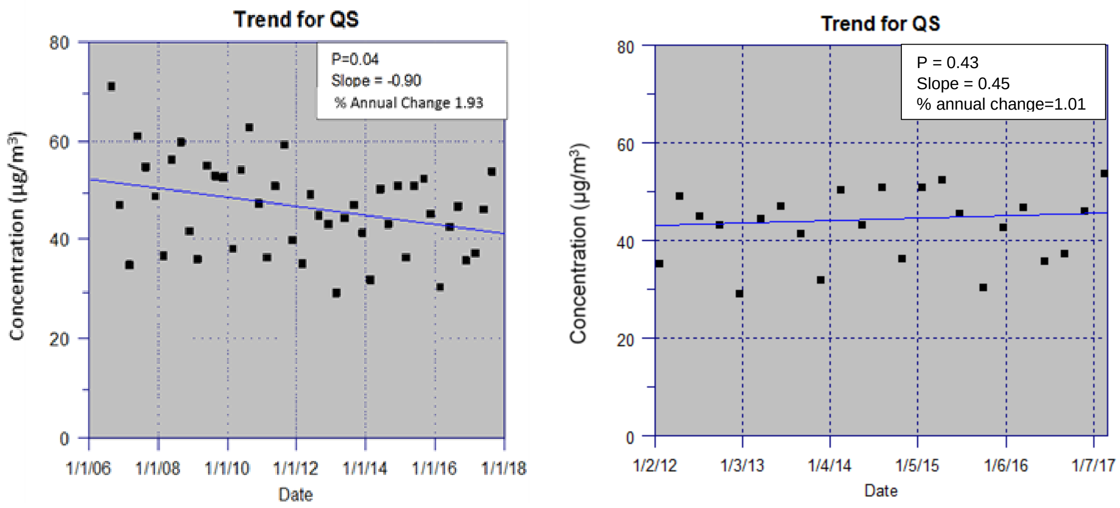



**Figure 6** Seasonalised trend analysis of $NO_2$ concentrations for Queen Street monitoring station taken from seasonalised Mann-Kendall non-parametric statistical analysis. Trends provided for 2006-2017 (left) and 2012-2017 (right). (Significance at p =< 0.05 at 95 per cent CI).

Compared to other Auckland and New Zealand-wide monitoring stations, Queen Street has notably higher hourly $NO_2$ concentrations (Figure 7). The 200 µg/m$^3$ hourly average standard, which is set as the minimum reasonable standard of air quality, has been breached on several occasions in Queen Street. This is set in context of one of the busiest pedestrian streets exposing large numbers of people to these short-term spikes in concentration.

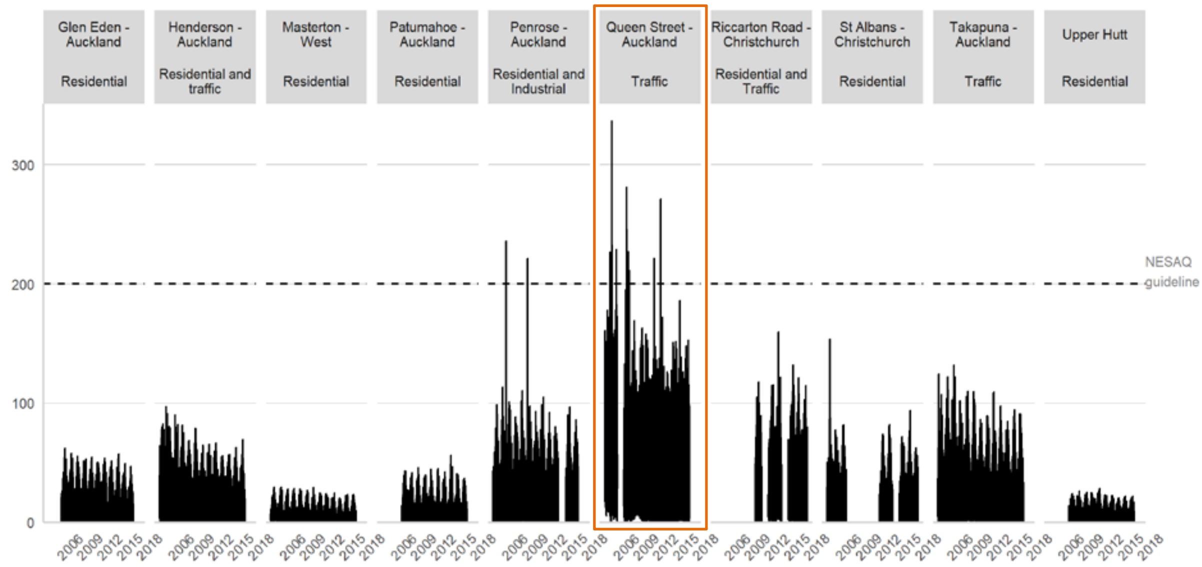



**Figure 7** Hourly average $NO_2$ concentrations at regional council monitoring sites from 2004-2017 (Ministry for the Environment, 2018).

### 2.3.2 Particulate data from Queen Street

#### 2.3.2.1 Overview of particulate impacts

Impacts of particulate pollution can range from a mild shortness of breath to cardiovascular and respiratory disease. An increasing body of evidence suggests that particulate pollution can cause some cancers and has even been linked to cognitive disorders such as Alzheimer's disease (WHO, 2013). The impacts of particulates on health depend on the size, concentration inhaled, exposure time and the chemical composition of the particulates (Ministry for the Environment, 2018). One of the key chemical components of particulates in New Zealand is black carbon, discussed in the following section.

#### 2.3.2.2 Measurements of particulate data from Queen Street

Until the end of 2015, particulate measurements at Queen Street were made daily using gravimetric techniques on filter substrate. This methodology is different to other measurement sites across Auckland, where real-time Beta Attenuation Monitors have been routinely used (Davy and Trompetter, 2017). Due to this methodology difference, caution should be used when comparing to other sites across the network. However, long-term trends at Queen Street can still be established from this dataset.

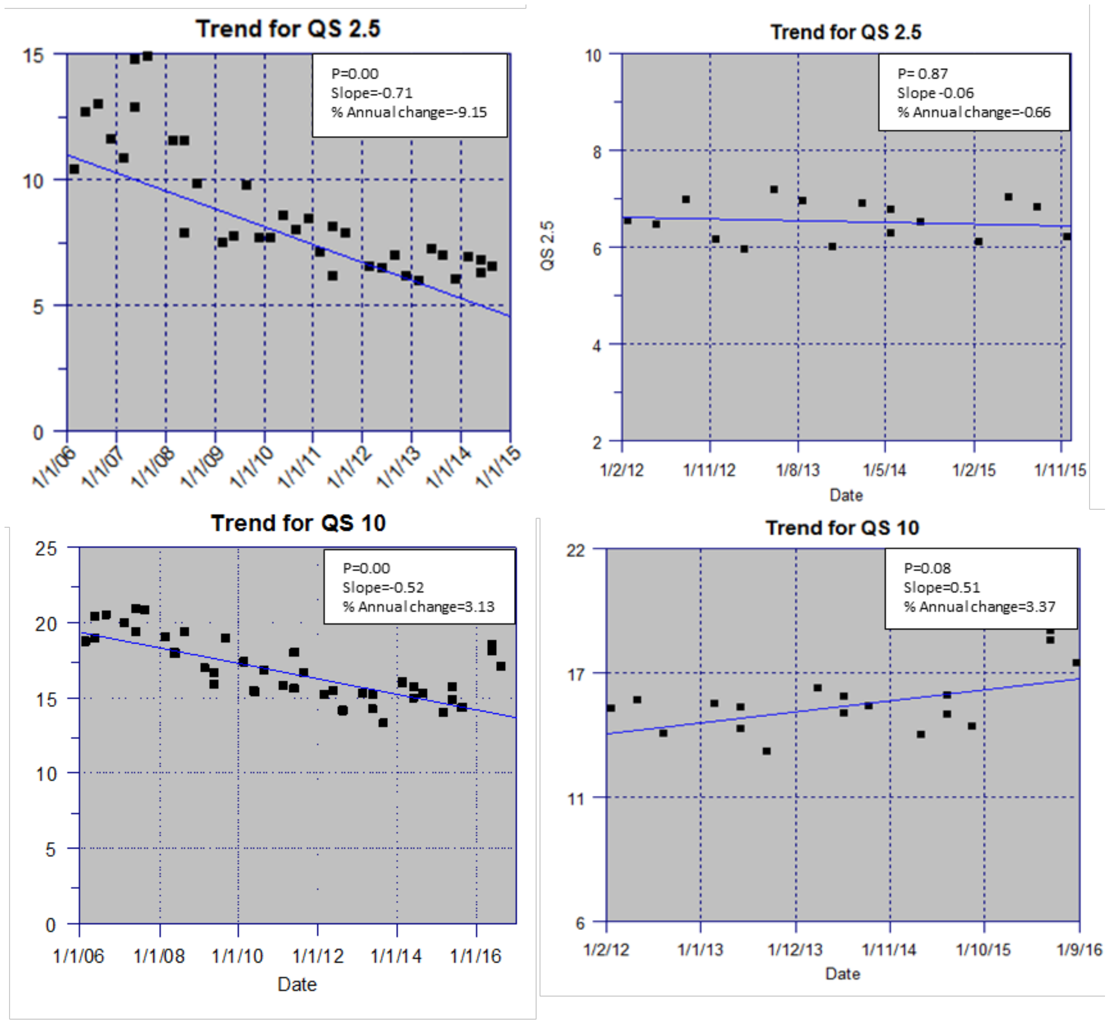



**Figure 8** Queen Street $PM_{2.5}$ data (top) and $PM_{10}$ data (bottom) seasonalised trend analysis concentrations using Mann-Kendall non-parametric statistical analysis. Trends provided for 2006-2016 (left), 2012-2016 (right). P = 0.05 at 95 per cent CI).

Statistically significant reductions in particulate concentrations have been observed at Queen Street for both $PM_{2.5}$ and $PM_{10}$ between 2006 and 2016 (Figure 8). The rate of decline is similar, if not slightly stronger, than those observed in the $NO_2$ time series. Concentrations of $PM_{2.5}$ have decreased more rapidly than concentrations of $PM_{10}$, which are likely associated with improvements in vehicle technology and fuel quality. Improvements in on-road vehicle performance, including the use of catalytic convertors has resulted in a reduction in particulate emissions from the tail pipe, while reductions in the sulphur content of fuel have reduced the formation of secondary sulphate particles (Maricq et al., 2002). This finding has been reported at all major traffic monitoring stations within Auckland (Davy et al., 2017).

The seasonalised $PM_{2.5}$ trend since 2012 shows a weak, non-significant, downward trend (Figure 8). However, $PM_{10}$ measurements have been increasing since 2012 (P = 0.08). Increasing $PM_{10}$ at Queen street is likely caused by road dust, construction activity, and naturally emitted particulate such as marine aerosols (Xie et al., 2016). It is unlikely that on-road tailpipe emissions are strongly represented in $PM_{10}$ due to the ultra-fine size of particulates (<$PM_1$) and therefore, low relative mass of BC and secondary formed particulates. Also, it is expected that an increasing vehicle emissions signal in $PM_{10}$ would correspond with an even greater increase in $PM_{2.5}$, which was not observed.

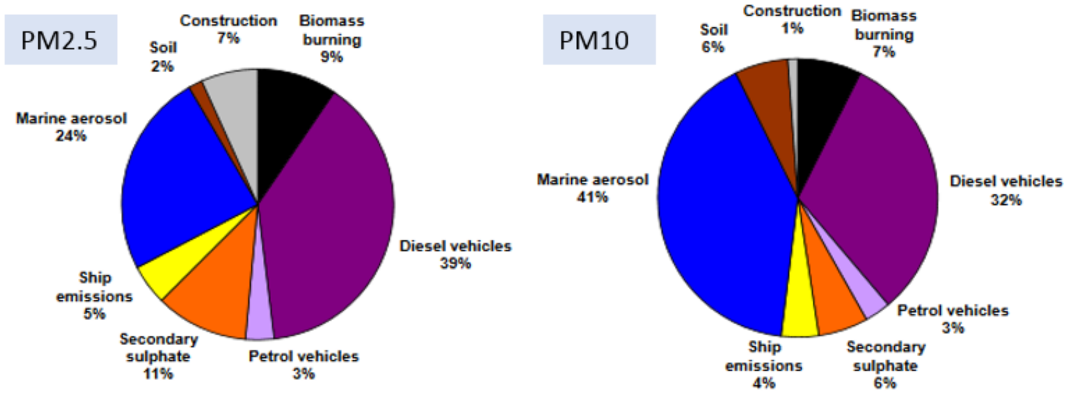



**Figure 9** Average source contributions to $PM_{2.5}$ (left) and $PM_{10}$ (right) from 2006-2013 at Queen Street (Davy et al., 2017).

### 2.3.3 Black Carbon measurements

#### 2.3.3.1 Overview of Black Carbon impacts

Black carbon (BC) is an important sub-micron particulate emitted in ambient air, associated with significant negative impacts on human health (Janssen et al., 2011), including increased hospital admissions and mortality due to cardiovascular diseases as well as infant mortality, cognition problems, and lung cancer (Grahame et al., 2014). BC also plays an important role on radiative forcing in climate science (Bond et al., 2013). The contribution of home heating to black carbon concentrations across the Auckland airshed is detailed by Crimmins (2017).

#### 2.3.3.2 Black Carbon measurements from Queen Street

Data obtained from the Queen Street air quality monitoring site provides robust information on the sources of pollutants released at that location. Figure 9 shows proportional source data for Queen Street averaged over an eight-year period.

Diesel vehicles were found to be the largest emission source of particulates on Queen Street (Figure 9). Note that biomass burning (including home heating) accounts for only nine per cent of $PM_{2.5}$ at the Queen Street site compared to over 30 per cent at Henderson and Takapuna. When looking specifically at BC measurements, 66 per cent comes from diesel vehicle emissions with the second largest contribution coming from shipping emissions at the waterfront (10 per cent; Figure 10). If we include 10 per cent from shipping emission and three per cent from petrol vehicles, then nearly 50 per cent of all $PM_{2.5}$ and 80 per cent of measured BC at Queen Street results from modes of transport.

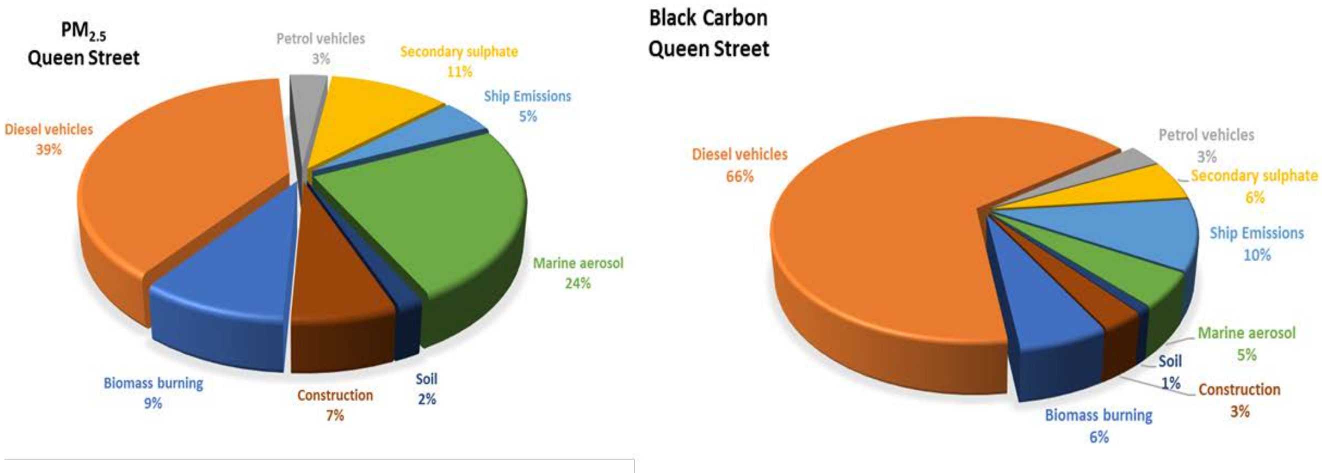



**Figure 10** Source apportionment data from filter measurements that identified $PM_{2.5}$ (top) and Black Carbon (bottom) (Davy and Trompetter, 2017).

Queen Street has the highest concentrations of diesel vehicle emitted black carbon when compared to all other sites (Figure 11). Note that Khyber Pass, which has a higher vehicle count than Queen Street has notably lower black carbon concentrations. Built-up urban topography within the City Centre and the larger number of diesel-emitting buses along Queen Street may help explain this finding.

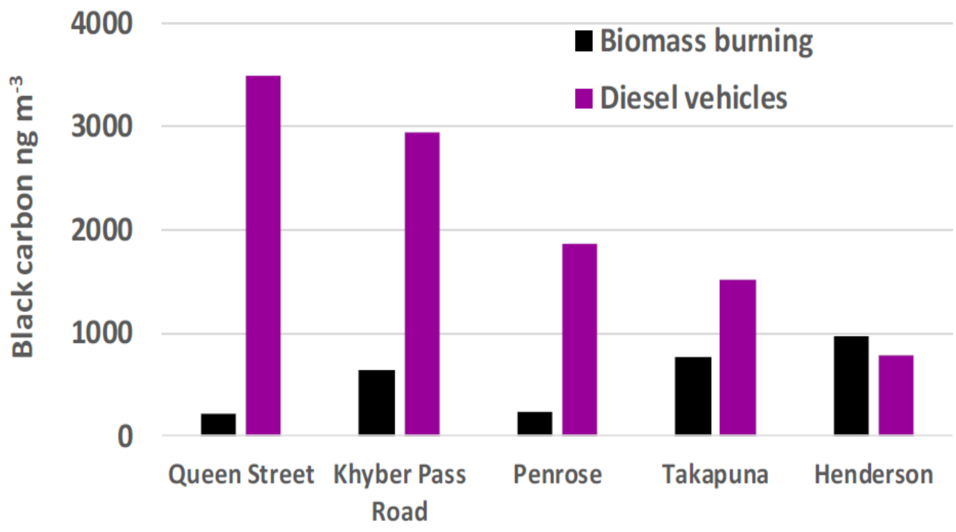



**Figure 11** Black carbon measurements averaged over 2006-2015 for each of the monitored sites across Auckland (Davy and Trompetter, 2017).

Traffic management and street realignment, which expanded paved areas and narrowed the road for vehicles, directly influenced air pollution levels recorded on Queen Street (Figure 12). Periods of construction are identified from source apportionment measurements that identify construction and cement elemental markers captured on filters along with black carbon measurements. The sudden drop in black carbon in 2007 coincides with the rerouting of buses away from the air quality testing site. This corresponds with an increase in construction activity. Once the Queen Street bus schedule was restored, black carbon increased, however, not to the same concentration as previously.

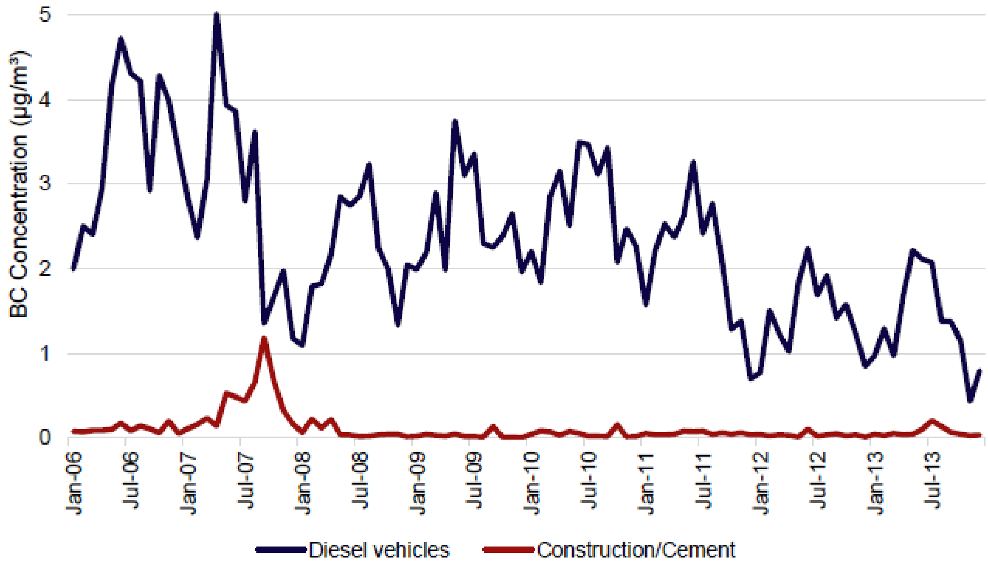



**Figure 12** Queen Street black carbon source apportionment results for diesel vehicles and construction showing the influence of major roadworks and construction in 2007 and traffic calming/ bus rerouting measures during 2011-12 (Crimmins, 2017).

#### 2.3.3.3 International Context of Queen Street Black Carbon Concentrations

Davy (2018) compared Queen Street BC measurements with those reported in cities world-wide. Concentrations within Auckland's City Centre are higher than in urban areas of any other OECD nation (Table 3).

**Table 2** Queen Street (highlighted in red) black carbon data compared to international locations (Davy and Trompetter, 2017).

| Region | Network | Year | Black Carbon µg/m³ | |
|---|---|---|---|---|
| | | | **Urban** | **Rural** |
| ***Queen Street: Auckland*** | ***Auckland Council*** | ***2006-2016*** | ***2.3 - 5.3*** | |
| **United States** | CSIN / IMPROVE /SLANS | 2005-2007 | 0.3 - 2.5 (~200 sites) | 0.1 – 0.6 (~150 sites) |
| **Canada** | NAPS | 2003-2009 | 0.9 – 1.8 (12 sites) | 0.4 – 0.8 (4 sites) |
| **Europe** | EMEP/ EUSAAR | 2002-2006 | 1.4 – 1.8 (4 sites) | 0.2 – 1.8 (12 sites) |
| **UK** | BC Network | 2009 | 1.0 – 2.9 (19 sites) | |
| **China** | CAWNET | 2006 | 9.3 – 14.2 (5 sites) | 0.3 – 5.3 (13 sites) |

Reported results in America and the UK show BC concentrations between 0.3 – 2.9 µg/$m^3$. Across Europe, recorded BC levels are between 1.4 - 1.8 µg/$m^3$. These comparisons reveal Queen Street to have higher concentrations than most developed cities where BC has been researched, with our minimum concentrations commensurate with peak values recorded at sites across many locations. The exception is China, where ambient concentrations were twice the concentration of Queen Street.

## 2.4 Diffusion tube $NO_2$ data across Auckland City Centre

There have been several deployments of passive $NO_2$ samplers across Auckland City Centre. Passive tubes have an advantage over reference methods in that they are cheap to deploy, easy to use, discreet and can be clipped onto lamp posts almost anywhere, allowing for dense networks that provide useful spatial data. The trade-off is the poor temporal resolution passive tubes offer, with tubes often deployed for a month at a time to allow suitable sample time (NZTA, 2017).

Major studies have utilised large-scale deployments of passive samplers across Auckland City Centre. The largest, PENAP (Personal Exposure to Noise and Air Pollution), was co-led by NIWA in late winter 2013. An overview of the study is provided in Longley et al. (2014). Briefly, the study focussed on 13 City Centre street blocks covering 62 sites. Street blocks were also chosen to cover a range of traffic profiles.

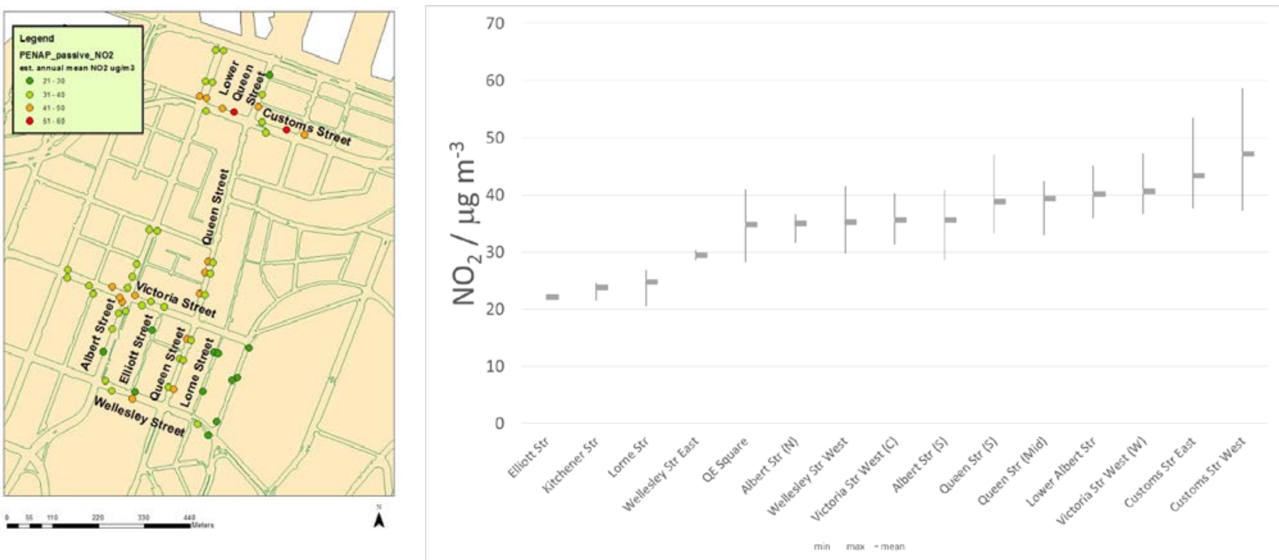



**Figure 13** The 'PENAP' $NO_2$ dataset depicting seasonally-adjusted mean concentrations for all sites (left) and distributions grouped by street block (right) (Longley et al., 2013).

The PENAP study revealed substantial variation in average $NO_2$ levels even within the inner Auckland City Centre (Figure 13). Although street traffic volume was considered the strongest influence on $NO_2$ concentrations, it was clear that other variables modified concentrations. PENAP identified that concentrations increased towards the waterfront area, but peaks in concentrations were also observed around many of the major junctions within the City Centre (Longely et al., 2014). When the diffusion tube data was extrapolated to estimate annual means, the values suggested that $NO_2$ concentrations may exceed the annual World Health Organization (WHO) guideline of 40 $\mu g/m^3$ towards the lower end of Queen Street and Customs Street.

The New Zealand Transport Agency (NZTA) set up its own $NO_2$ monitoring network as part of the state highway environmental plan to improve air quality. This has been in place since 2007 and is carried out using passive sampling tubes. The network is New Zealand-wide and consists of over 120 sites, with approximately 43 (± 2) of these in Auckland, but only one in the City Centre area on Canada Street (NZTA, 2017) near the central motorway in the Karangahape area (Figure 14). The Canada Street site has been recording the highest average $NO_2$ concentrations from the entire New Zealand network throughout the sampling years 2007-2016, resulting in annual averages exceeding WHO's recommended annual average guideline of 40 $\mu g/m^3$ (NZTA, 2017).


| Site ID | Site name | Annual average (µg/m³) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 2016 | 2015 | 2014 | 2013 | 2012 | 2011 | 2010 | 2009 | 2008 | 2007 |
| AUC009 | CMJ / Canada St | 47.9 | Insuff data (disrup) | 41.0 | 46.5 | 41.3 | 43.9 | 40.8 | 44.0 | 35.8 | 41.9 |

**Figure 14** Map of the location of the CMJ site on Canada Street marked with a (yellow star) and proposed new entrance to the central rail link (red triangle) (top) and annual average $NO_2$ concentrations in µg/m$^3$. The WHO guideline is 40 µg/m$^3$ (NZTA, 2017).

Traffic monitoring using the state highway network in this area shows the central motorway junction is impacted by very high traffic volumes, with more than 158,000 vehicles per week, of which five per cent were heavy vehicles. The impact from this heavy traffic flow is likely to be responsible for $NO_2$ concentrations that exceeded the WHO recommended annual maximum of 40 µg/m$^3$ on Mercury Lane (Figure 14) (WHO, 2013). It should also be noted that Mercury Lane has been put forward as the likely location for the new central rail junction, due to open in 2023 ("Karangahape train station," 2018).

# 3.0 Research on air quality in Auckland's City Centre

## 3.1 Summary of existing air quality research

There have been several air quality studies undertaken across Auckland that have been part of research programmes which have investigated specific air quality issues, and therefore have not been considered as part of a wider body of evidence. However, they provide insightful results that help determine the direction of future studies. Below, we summarise and evaluate these projects reported results to help fill knowledge gaps regarding air pollutants within Auckland's City Centre.

The effectiveness of modelling air pollution dispersion across the City Centre in relation to source and land use was investigated by (Miskell et al., 2015). They collected data within the central area to create a land-use regression (LUR) model, which showed that several areas could exceed the WHO health guidelines of 40 $\mu g/m^3$ for annual average concentrations of $NO_2$ (Figure 15). These results support previous findings that identify the harbour area to be problematic for $NO_2$ concentrations, as well as the major two-way, multiple-lane streets (Albert, Queen, Victoria, Wellesley and Custom Streets). Low concentrations were observed in smaller one-way or pedestrianised streets, such as Kitchener, Lorne and Elliot Street.


**Figure 15** The left-hand map shows locations where Miskell et al. (2013) deployed passive $NO_2$ samplers. The red dots indicate locations where the concentration exceeded the WHO annual guideline of 40 µg/$m^3$. The map to the right shows the top 10 highest $NO_2$ concentrations (red) and lowest (green) (Miskell et al., 2015).

Peak concentrations in $NO_2$ are shown in relation to bus stops (Figure 16). The clusters of red spots, indicative of those concentrations over 40 µg/$m^3$ are closely aligned to areas where there is the highest density of bus stops, including along Wellesley Street, Victoria Street, and the Queen Street section just before Wellesley Street. Wellesley Street and Victoria Street also have high concentrations in $NO_2$, in part due to the steep incline from Queen Street to Nelson Street. The Elliot Street shared space, a narrow street popular with pedestrians, runs between Wellesley and Victoria Street and a PENAP study observed raised particulate concentrations in this area as well (Longely et al., 2014).

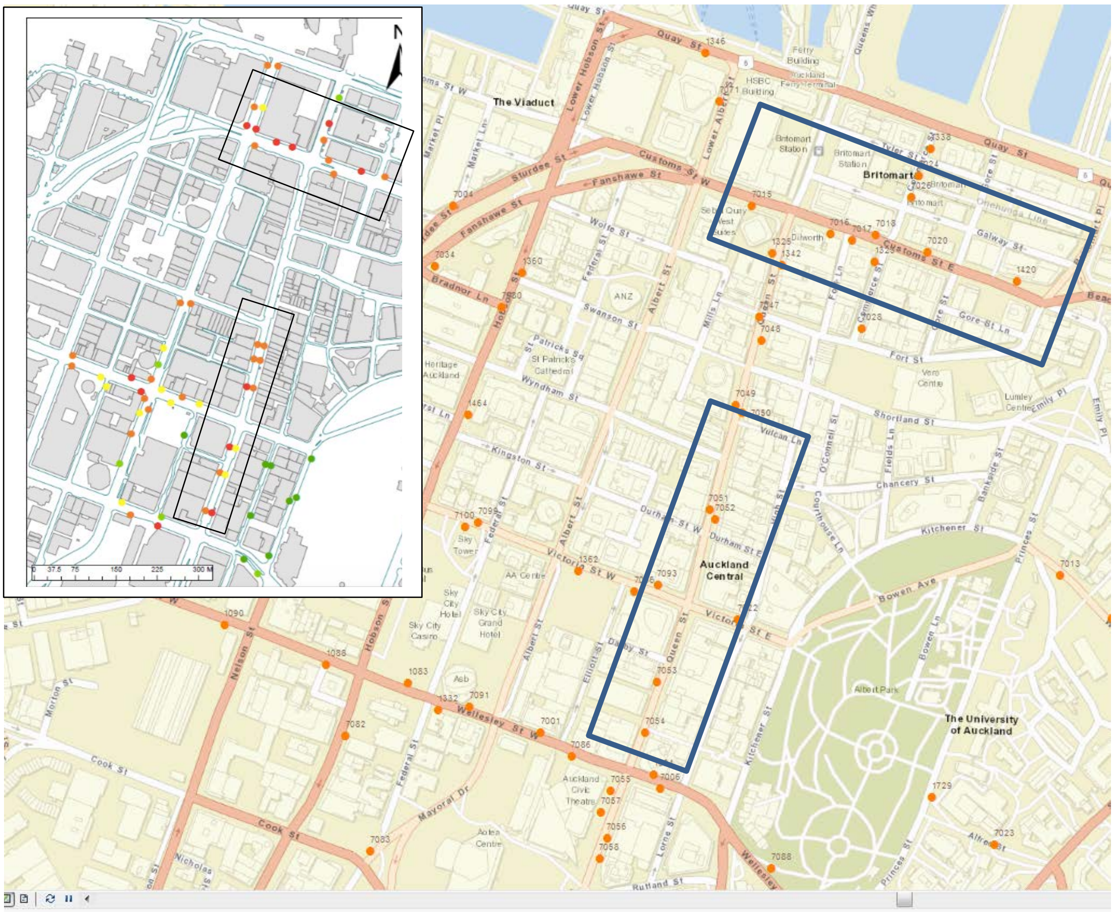



**Figure 16** Comparing the locations of bus stops across the City Centre against the peaks in $NO_2$. The boxed areas reveal Britomart area and Queen Street to be areas of high $NO_2$ concentrations. Wellesley Street and Victoria is a key route for west-bound buses.

The land use regression model calculated changes in $NO_2$ concentrations commensurate with the presence of various influencing factors identified by international studies. Results showed that increases in $NO_2$ concentrations were most closely associated with the number of bus stops, building footprint, and number of road lanes (Figure 17). Interestingly, model also found that roadside vegetation was effective in reducing $NO_2$ concentrations.

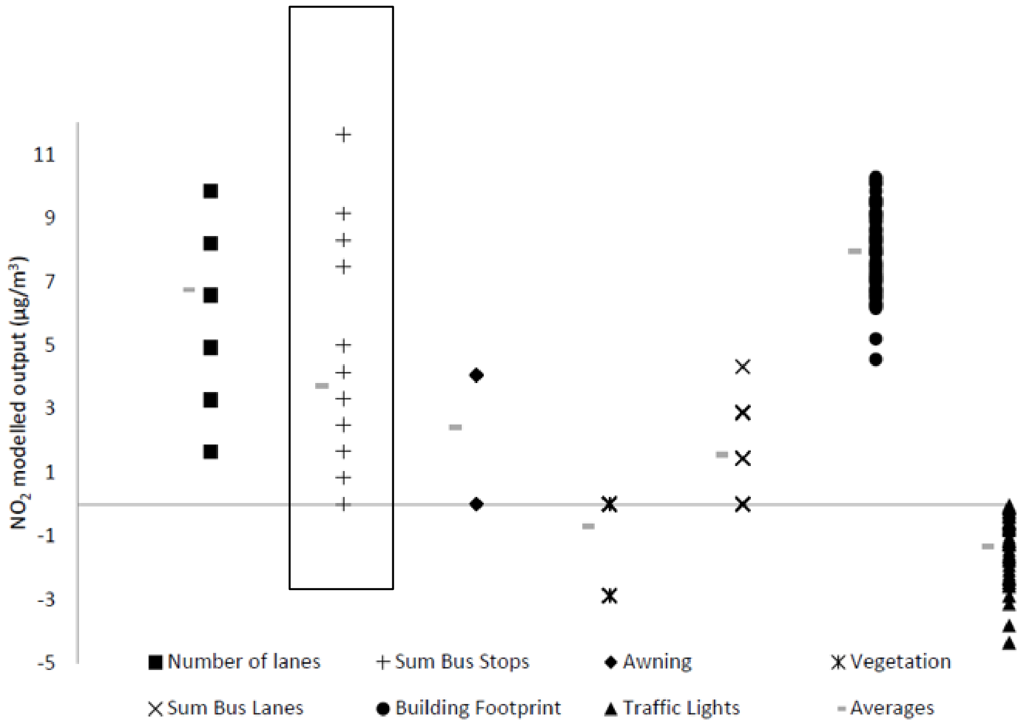



**Figure 17** $NO_2$ concentration output ranges for the variables considered in the land use regression model (Miskell, 2015).

The findings reported by Miskell et al. (2015) are similar to those from the PENAP (Personal exposure to noise and air pollution) report (Longley et al., 2014) which also identified traffic conditions, building height, street width and bus fleet to be the main drivers of peak $NO_2$ concentrations.

Research targeting other air pollutants has also been carried out in the City Centre, including particulate matter ($PM_{2.5}$ and ultra-fine particulate (UFP) (<1µm)), carbon monoxide (CO) and sulphur dioxide ($SO_2$). A pilot research project entitled, "Spatially Resolved Technique for Source Apportionment in New Zealand" (SpaRTANZ) focused on the waterfront area and measured multiple air pollutants. Although this was a pilot study and run over a short time period, results provided useful spatial and emission-source information. Results reported within the SpaRTANZ report found that $SO_2$ concentrations were up to four times higher near the waterfront compared to other areas in Auckland (Longley et al., 2016), suggesting shipping and, to a lesser extent, ports activity as main sources. Wind direction was also found to play an important role in influencing $SO_2$ concentrations, with concentrations peaking when northeast winds are present (Talbot, 2017; Barrowclough, 2014). The SparTANZ study found northeast winds to contain notable gas tracer pollutants emitted from shipping and port activity such as vanadium, nickel and sulphur. Winds from this direction were also found to reduce $NO_2$ concentrations at the waterfront area, with traffic emission plumes diluted by air from the Hauraki Gulf (Longley et al., 2016). When south-westerly winds prevailed, elevated levels of $PM_{2.5}$, black carbon and $NO_2$ were observed (Figure 18). Speciation sampling carried out during the same study identified a strong correlation between black carbon, $PM_{2.5}$ and diesel emissions across the area.

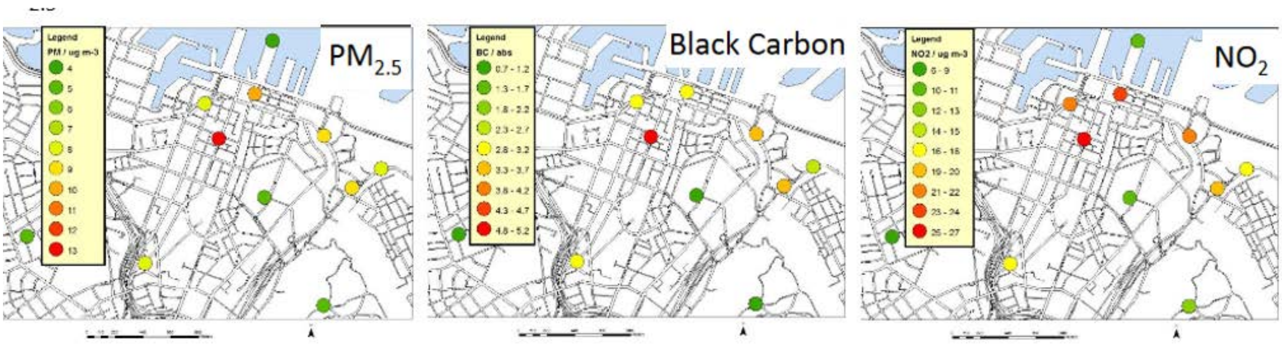



**Figure 18** Concentrations of $PM_{2.5}$ (left), black carbon (middle) and $NO_2$ (right). BC and $NO_2$ are commonly-used tracers for diesel emissions. Data taken from (Longley et al., 2016)

Investigations into UFP concentrations have also been undertaken using mobile monitoring devices. The findings of these studies also identified pollution hot spots. Narrow street canyons were found to limit the dispersion of pollutants, while traffic interrupting sites, such as intersections, bus stops or traffic signals all significantly increased concentrations. Open roads, green space and favourable wind conditions all contributed to the lowest UFP concentrations.

In one such study, Goodey (2011) used two particle counters mounted on a pram at 0.6 and 1.6 metres off the ground to determine concentrations along a route that covered Britomart, High Street, and Queen Street to Albert Park (Figure 19). The reported results show spikes in particle number concentrations that are caused by passing vehicles. The highest spikes show peak concentrations of particulates <1µm were recorded at 0.6 metres off the ground (child's height) with Britomart and Queen Street again showing highest pollution concentrations (Figure 19). There was a notable drop in particle number concentrations recorded at Albert Park. This supports a recent Auckland-based study describing the effectiveness of green spaces in reducing total particle concentrations (Salmond et al. 2018).

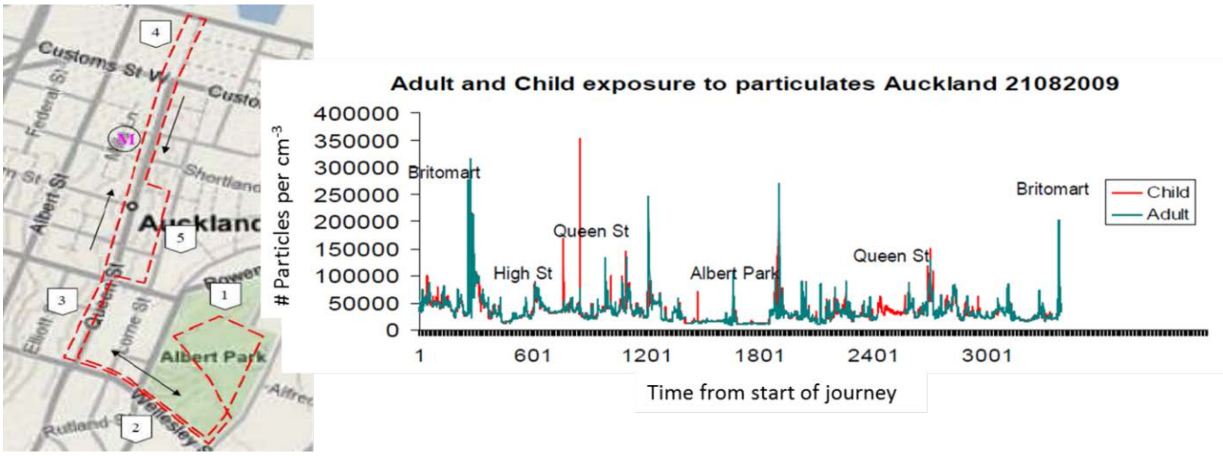



**Figure 19** Spikes in particulate concentrations recorded while Goodey (Goodey, 2011) travelled along the mapped route (left).

The results of Goodey (2011) and Miskell (2013) were corroborated by research carried out by Lim et al. (2015) that assessed UFP concentrations while commuting by bus. They found that spikes in UFP concentrations occurred more often when a bus was leaving a stop or travelling slowly between stops. Spikes in concentrations occurred most readily when passengers were boarding or alighting at bus stops (Figure 20).

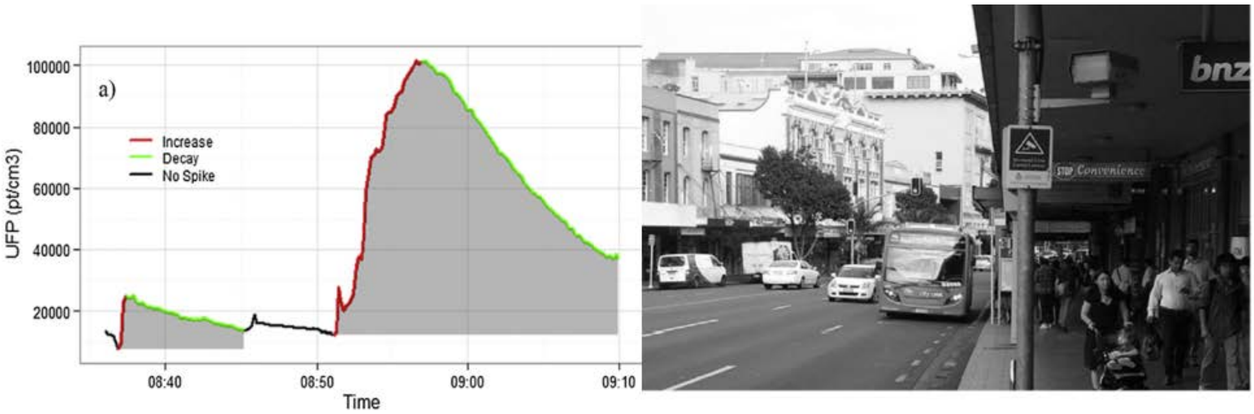



**Figure 20** An example of a spike in ultrafine particle data while the sampled bus travels along Queen Street. Note the awnings along the walkway (Lim et al., 2015).

Lim et al. (2015) also tested the hypothesis that the distance between a bus stop and traffic light was important for concentrations of UFP. They found a significant increase in the number of spikes found when bus stops were located within 50 m of traffic lights (P< 0.05 at 95 per cent CI). This suggests that placement of bus stops at distances greater than 50 m from traffic lights would improve air quality for bus commuters.

The use of lichens for air quality assessment in New Zealand has not been widely explored, despite their widespread application around the world (Käffer et al., 2011;

Llop et al., 2012). However, this technique was used in a 2013-2014 study by Boamponsem et al. (2017) who used lichens to carry out source apportionment on air pollutants across Auckland City Centre. Boamponsem et al. (2017) provide a detailed explanation of the methodology. Briefly, lichens were exposed to the environment for one month during 2013 and 2014. Three analytical techniques were used to identify five main pollutant sources, each identified by a fingerprint, represented by grouping trace elements typical of that source.

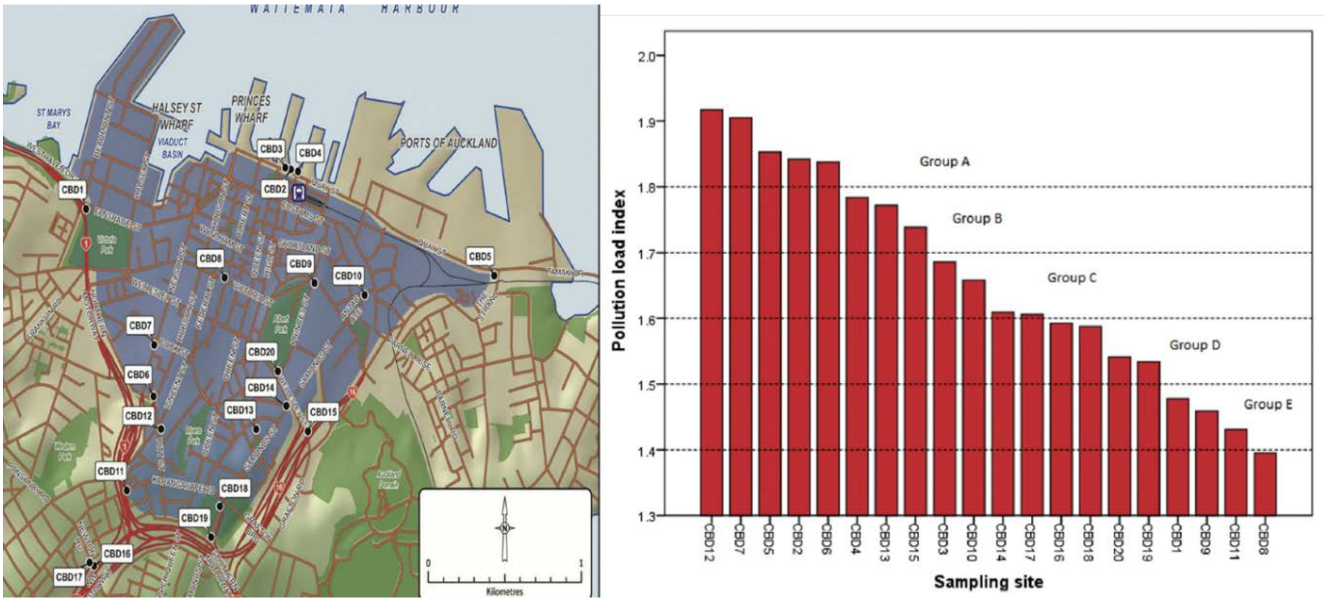



**Figure 21** The map of Auckland CBD to the left shows the location of the Lichen samples. The bar chart (right) shows the total pollution loading recovered from the lichen samples (Boamponsem et al., 2017).

The data showed the highest pollutant loadings were in the south-west segment of the City Centre near the motorway on-ramp at Nelson and Hobson Street. This is an area that has not been a focus of much air quality research to date (Figure 21) but is an area of considerable residential and commercial development. There was a clear traffic emission source trace to this sample set. The second highest cluster was found at the waterfront on Quay Street, with elemental analysis attributing 36 per cent of total pollution loading to shipping and ports activity (Boamponsem et al., 2017).

Their seasonal results were also interesting, showing that the highest concentrations for marine aerosols occurred in the spring when traffic emissions were lowest (Figure 22). This is explained by wind speeds which tend to strongest in Auckland around the spring equinox. Note that port activities (blue bars in Figure 22) remain consistent all year round, implying there is no detectable seasonal contribution from cruise ships.

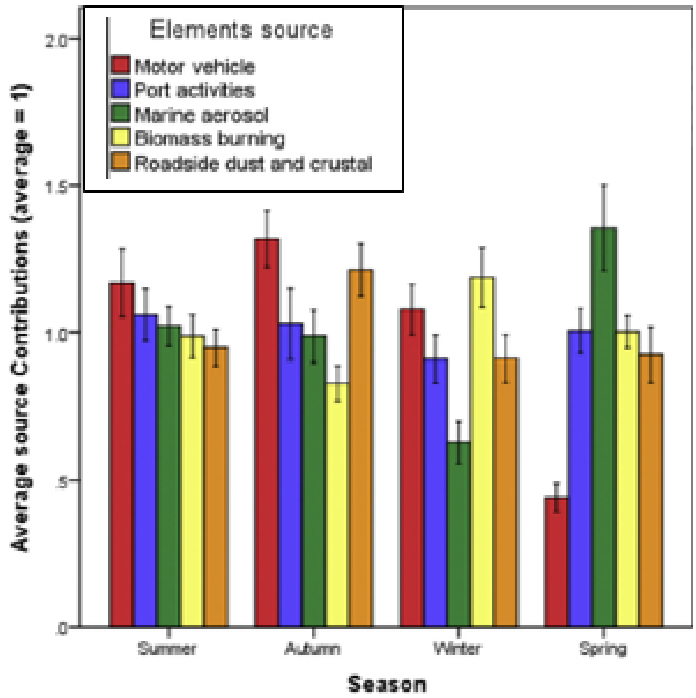



**Figure 22** Seasonal elemental speciation data from Boamponsem et al. (2017) is shown according to source.

## 3.2 Traffic data for Auckland City Centre

This report highlights that there is a strong relationship between transport emissions and key air pollution concentrations within Auckland City Centre (Figures 9 and 10). It is therefore valuable to understand the flow and composition of the vehicle fleet to help interpret air quality monitoring data and plan future monitoring programmes. Auckland Transport have long-term traffic data across the Auckland road network. Vehicle number and fleet composition entering and leaving the central area daily have been monitored periodically and show that there has been a considerable reduction in the number of all vehicles within the City Centre (Figure 23). This is interesting as it implies that most of the extra 10,000 jobs within the City Centre over the last two years have been covered by either people who are resident within the City Centre or those that use active-modes or public transport to travel. This result would support the added investment in public transport and active modes going forward. It should be noted that the only road to register an increase in traffic flow from 2006 – 2016 is Quay Street from 3443 (2006) to 3715 (2016), corresponding with increases in $NO_2$ concentrations.

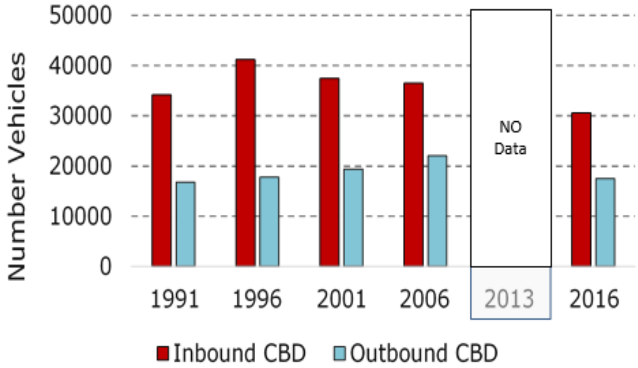



**Figure 23** Traffic data from Auckland Transport for city and outbound traffic**.** The data for 2013 was deemed invalid by Auckland Transport and therefore has not been provided here.

As reported above, diesel fuelled vehicles significantly influence $PM_{2.5}$ and $NO_2$ concentrations within the City Centre. Figure 24 draws together wind speed and direction data with $NO_2$ concentrations from the Queen Street monitoring station, showing a path of higher concentrations along Queen Street. The highest $NO_2$ concentrations, depicted by red colouration, occurred when winds of around 1.5 m/s were recorded from a southerly direction. This suggests that a significant concentration of recorded $NO_2$ at the Queen Street site is emitted near upper Queen Street.

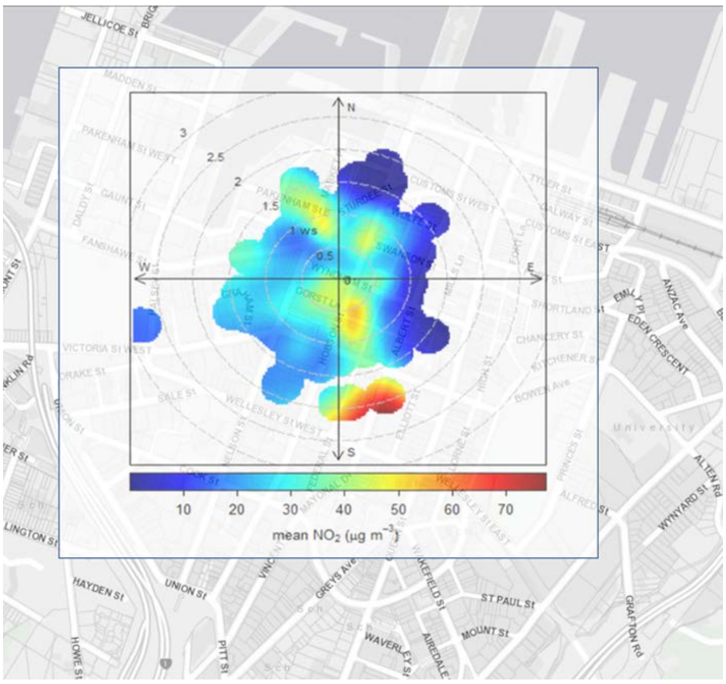



**Figure 24** Wind speed and direction set against $NO_2$ data for 1-hour data during 2017. The darker shaded areas show the highest concentrations of $NO_2$.

To determine the proportion of emissions coming from busses, we used automated HOP card payment data and GIS vehicle tracking to estimate the number of buses along Queen Street and Fanshawe Street for a Monday in September (Figure 25). Using the bus data alongside traffic count data for 2016 and 2017 along Queen Street (using Mondays data for the traffic signal), we found that citybound and outbound buses make up approximately 3.7 per cent of the vehicle fleet on lower Queen Street. If we assume similar traffic data for the Queen Street section between Wellesley St and Mayoral Drive, buses make up 11.3 per cent of the inbound (towards the waterfront) fleet and 7.2 per cent outbound (away from the waterfront). Link bus services contribute approximately 288 buses to the inbound Queen Street data. The wind rose in Figure 25 shows the prevailing south-westerly direction of winds, which pushes $NO_2$ emissions from upper Queen Street towards lower Queen Street, funnelled by surrounding high buildings and higher elevations to the east and west.

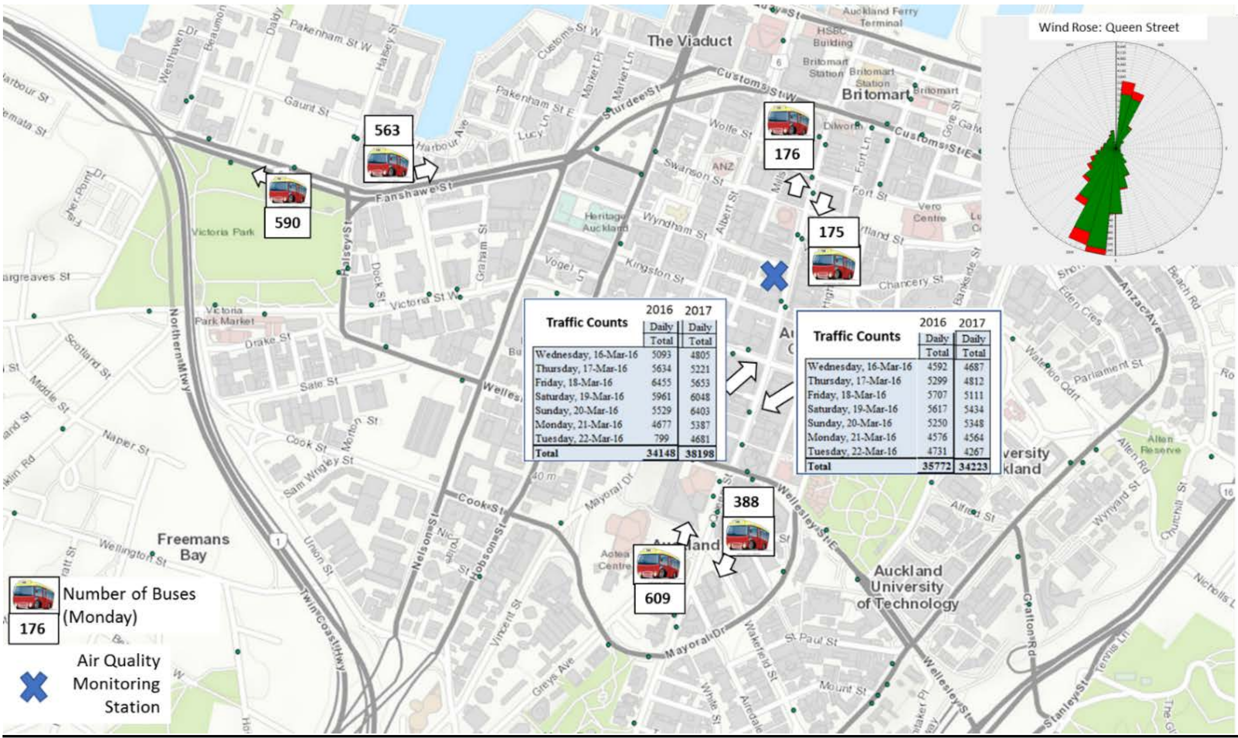



**Figure 25** Map of Auckland City Centre with bus data and traffic counts along with the location of the Auckland air quality monitoring site and a wind rose showing the direction of dominant winds generated from data at the site for the previous twelve months.

## 3.3 Developing a low-cost sensor network for Auckland's City Centre

To ascertain the effectiveness of policy decisions on air quality across Auckland City Centre an expanded sensor network is being considered. From the research results presented above and the traffic data available, eleven priority locations have been identified that should be considered for air quality sensor deployment.

Locations identified are those that will be subject to significant change, have a high volume of buses or overall traffic, are known to have high concentrations of air pollutants, or are areas where large numbers of people will be exposed to pollutants.

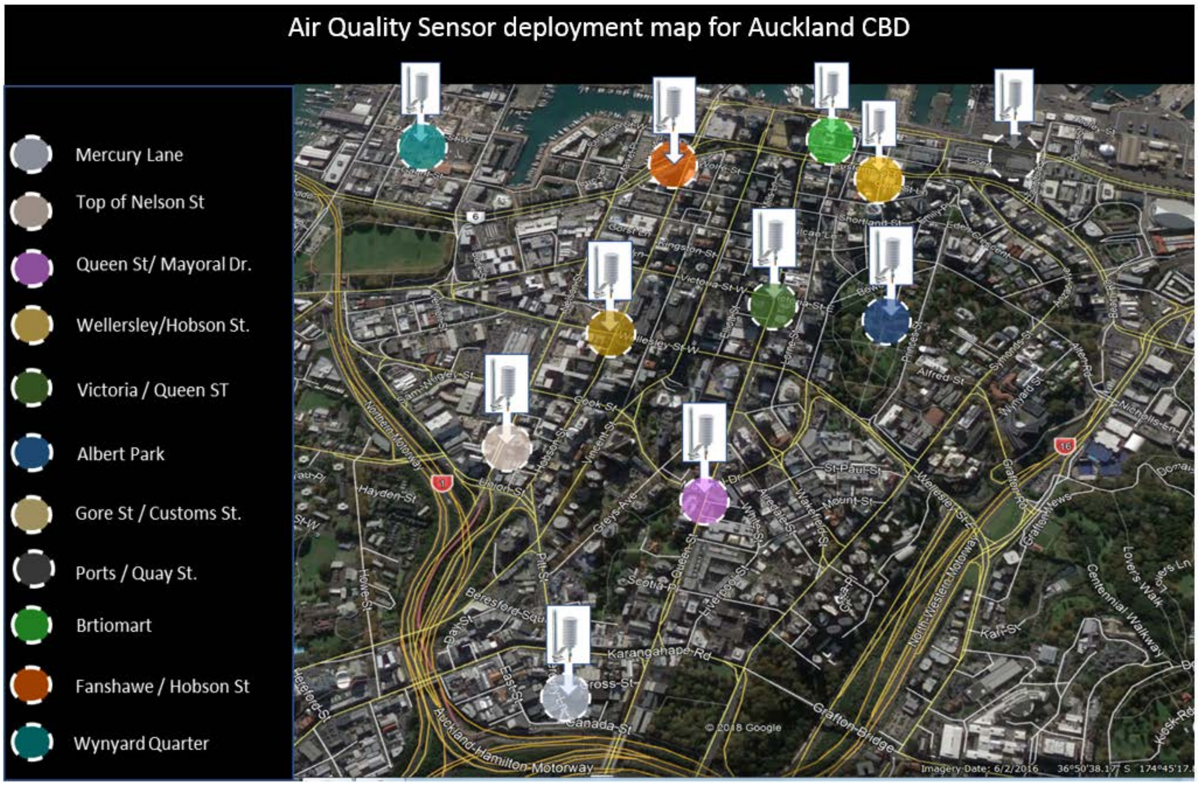



**Figure 26** A map showing the eleven priority locations that should be considered for air quality monitoring sensors across Auckland City Centre. The colour coded key identifies each site by road name.

Sites recording the highest concentrations are well represented at Mercury Lane, Britomart, Quay Street and Victoria/Queen Street. Source apportionment data has also revealed Upper Hobson Street to be a peak site for diesel emissions while traffic data shows Queen Street/Mayoral Drive to have a large proportion of buses. Wynyard Quarter is being considered for pedestrianisation, while Gore/Customs Street will undergo reconfiguration from five to two lanes of traffic. Monitoring at these sites will be useful to evaluate policy effectiveness. The Quay Street site is adjacent to the Ports and Albert Park has been shown to have very low concentrations so could be considered an urban background site. Installation of the network would occur in a minimum of two deployments; it is also proposed to deploy a multi-pollutant sensor, such as the Vaisala ATQ420 transmitter, at eleven different sites. Ideally, these sites would also incorporate noise and pedestrian counters, so a broad dataset can be collected. This project would the development data being collected by the Auckland Design Office.

# 4.0 Implications for future policy decisions for Auckland

## 4.1 Auckland transport policy

### 4.1.1 Healthy, Safer Streets

There has been a near-doubling in deaths and serious injuries on Auckland's transport network over the past five years (Figure 27), outweighing growth in population and vehicle kilometres travelled during the same period.

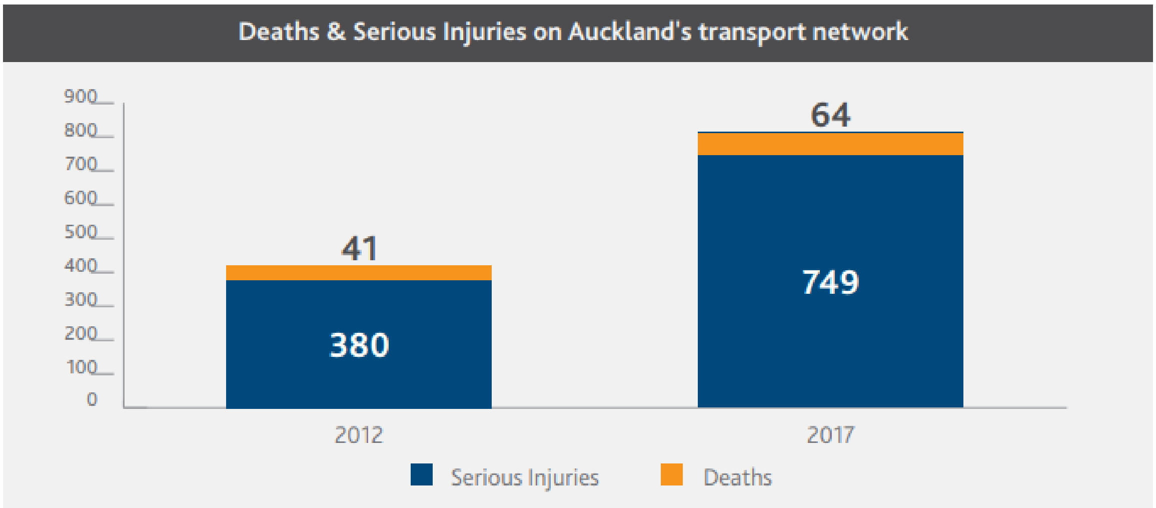



**Figure 27** Road safety data from 2012 compared to 2017. It should be noted that 2012 was the lowest road toll number for several decades (Howard, 2018).

With a large spike in road casualties, there is a corresponding decrease in the number of people on the streets, especially children as the perception of risks increase (Racioppi, 2004). This, in turn, disenfranchises people from utilising streets as public amenities for social and economic activities, limiting active communities and potentially increasing car use. This results in increased air pollutants, along with associated higher social and economic costs due to slower travel times and more congestion (Saunders, 2017).

A road safety discussion document, (Howard, 2018) describes a "safety neglected" transport network across Auckland. Howard (2018) noted that most accidents occur in 50 km/h zones, have a total cost over $1 billion NZD and that $30 fines were inadequate in preventing speeding in these zones. The pivotal message within the report suggests that the network should aim for "a safe, enjoyable and relaxing place with high amenity for people wishing to travel to and from and through its various 'place locations,' especially the City Centre and town centres, which make walking, cycling and use of public transport preferred options to private car use for many Aucklanders over time" (Howard, 2018). This recommendation would align road safety goals with benefits beyond air quality from removing traffic from streets within the City Centre.

### 4.1.2 Auckland Transport Alignment Project (ATAP)

Since 2015, local and national governance have developed an aligned strategic approach to improve transport networks across Auckland. The resulting project is a 10-year plan that targets the following goals for the transport network:

- Easily connects people, goods and services to where they need to go.
- Provides high quality and affordable travel choices for people of all ages and abilities.
- Seeks to eliminate harm to people and the environment.
- Supports and shapes Auckland's growth.
- Creates a prosperous, vibrant and inclusive city.

To achieve these goals, ATAP focuses on a package of committed projects, such as electrification of the train network and extension of the northern busway. Of most interest to the City Centre is the assignment of financial assets to new projects that include the development of a rapid transit network (Figure 28), walking and cycling priorities, and optimisation of the current network, which could include smart sensors for traffic signals to lessen waiting times for on-road vehicles and pedestrians.


**Figure 28** Rapid transit network proposed by ATAP would include light rail into central Auckland from areas to the north, west and south including a link to the airport, offering an alternative to the diesel emitting airport express bus link.

### 4.1.3 City centre development

Two main plans have been created that are expected to redevelop Auckland City Centre. These are The City Centre Masterplan and The Waterfront Plan. Key outcomes from these plans are already being implemented, including modernising industrial areas through downtown Auckland and along the waterfront. Revitalising streets and squares with shared spaces, new pedestrian lanes, new cycleways and better public transport have made movement easier, safer and more enjoyable. Auckland is poised for the next phase of regeneration, with projects from Karangahape Road to Quay Street.

#### 4.1.3.1 Downtown programme

Over the next 10 years, the Downtown Programme will be working to create a safer and more attractive environment in which to move, work, rest and meet. Quay Street is designated to become a revitalised waterfront boulevard with wider footpaths, easier navigation, more trees and street furniture, and more opportunity for business and events. Changes to Britomart east bus layouts and the ferry terminals are also proposed (Auckland Council, 2012).

As this report has shown, Quay Street has $NO_2$ concentrations close to or exceeding WHO annual recommended levels. The main project within this programme has a clear goal to increase foot traffic in the area. Amending the road layout of Quay Street from four to two lanes will likely reduce traffic flow in the area, with traffic encouraged to use Mayoral Drive to circumnavigate downtown Auckland. However, the impacts of the bus and ferry realignment projects on air quality need to be considered given their diesel emissions are one of the major contributions to air pollution downtown.

The data presented here suggest that reducing traffic flow but increasing bus and ferry volumes using a similar fleet composition as is in place today would likely increase air pollution levels to the detriment of the people using the area. The contribution of the ports emissions to air pollution in this area should also be considered. The City Centre Masterplan refresh currently under review hopes to create a coordinated approach between all key stakeholders to continue to improve emission reductions through vehicle removal, essential for the creation of a healthy and safe urban space for all to enjoy.

## 4.2 Congestion cordon around Auckland City Centre

In 2016, local and central government worked together on an aligned transport programme for Auckland. This identified a significant 30-year investment programme; but found that without congestion pricing traffic volume was unlikely to decrease. Demand management, along with significant investment plans for alternative modes, can contribute to a significant modal shift away from private vehicles.

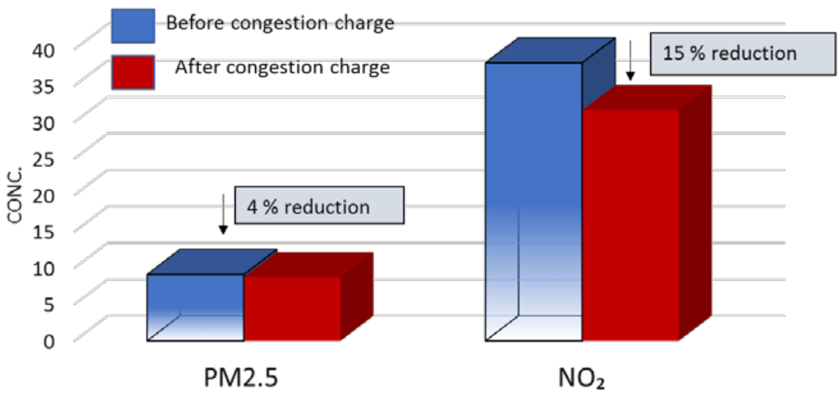



**Figure 29** Modelled changes in $PM_{2.5}$ and $NO_2$ if a $10 congestion cordon was implemented.

Using a model created by the C40 cities air quality and health project, reductions in $PM_{2.5}$ and $NO_2$ resulting from a proposed congestion charge were estimated, including a 15 per cent reduction in $NO_2$ (Figure 29). This is due to the assumed impacts of the cordon mainly removing private vehicles, largely petrol driven, and not the higher polluting diesel fleet. The social and economic value of reducing $NO_2$ across Auckland's City Centre area (Figure 30) were modelled using hospital admissions, dose response functions obtained through international peer review and Auckland fleet specifications. These estimations were purposely set to be conservative (Floater et al., 2016). Note the increase in expected life expectancy for every person in the CBD by 31 days due to the 15 per cent reduction in $NO_2$.

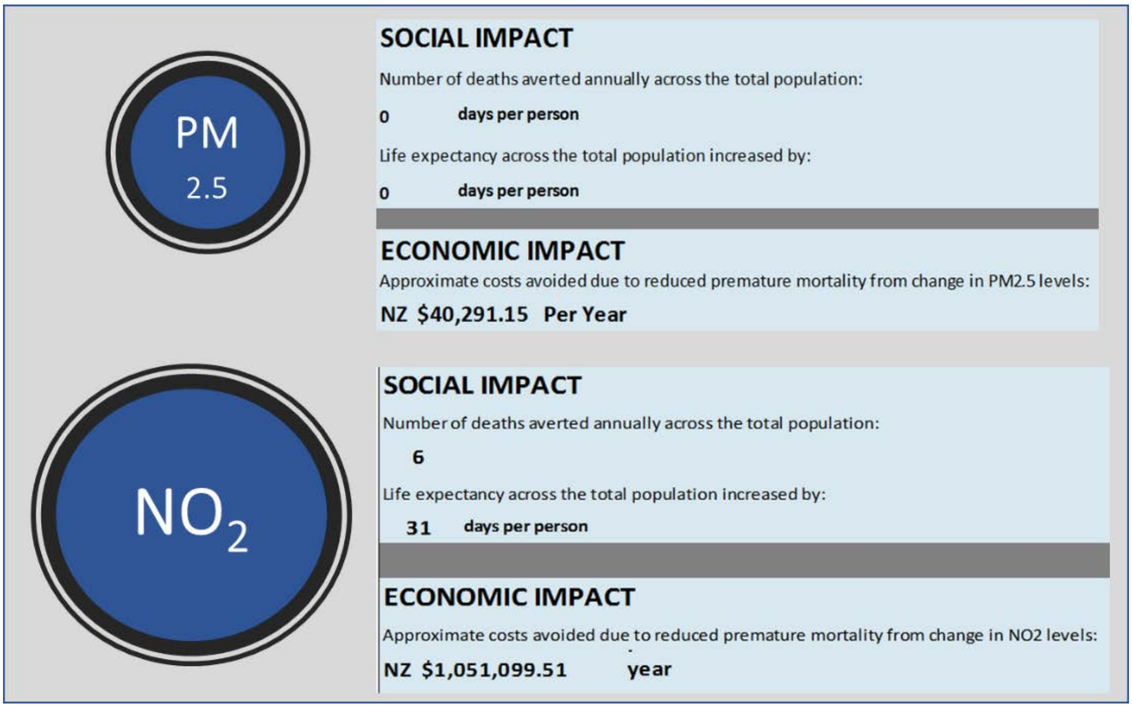



**Figure 30** Key social and economic consequences from implementing a $10 congestion charge cordon around Auckland City Centre.

#### 4.2.1 The Fossil Fuel Free Streets Declaration

In 2017, the Mayor of Auckland attended a city labs C40 meeting in Paris where he signed the Fossil Fuel Free Streets (FFFS) declaration alongside mayors from Paris, London, Los Angeles, Copenhagen, Barcelona, Milan, Quito, Vancouver, Cape Town, Seattle, Mexico City and Milan.

After signing the commitment, Mayor Phil Goff announced; “Zero-emissions targets for our bus network and our city centre create a framework and impetus for Auckland to contribute to the Paris Agreement our nation signed up to in 2015.” The mayor went on to say; "I am committed to making Auckland greener, healthier and safer for our people” (Our Auckland, 2017). The greener, healthier and safer principles closely align with the policy directions currently under consideration by the Auckland Council family of organisations.

To support this commitment, the following approaches are recommended by C40:

- Transform our cities through people-friendly planning policies.
- Increase the rates of walking, cycling and the use of public and shared transport that is accessible to all citizens.
- Reduce the number of polluting vehicles on our streets and transition away from vehicles powered by fossil fuels.

- Lead by example by procuring zero emission vehicles for our city fleets as quickly as possible.
- Collaborate with suppliers, fleet operators and businesses to accelerate the shift to zero emissions vehicles and reduce vehicle miles in our cities.
- Publicly report every two years on the progress the cities are making towards these goals

There are two main components of the FFFS agreement: (1) electric buses should be procured by bus companies by 2025; and (2) an area of Auckland should be fossil fuel-free by 2030. Although these are difficult and expensive pledges to uphold, these obligations are closely aligned with the wider benefits of reducing air pollutants within the City Centre and have synergies with other planning and policy directions.

## 4.3 Wider benefits reported from reducing traffic from urban centres

As well as environmental benefits, reviews of cities across the world which have implemented traffic calming or pedestrianised areas have reported wider “secondary” benefits, including:

- **Large reduction in traffic casualties:** Streets were found to be 10 times safer in cities where bus systems are implemented (Soehodho, 2017).
- **Large reduction in crime where car use has been reduced.** In Kansas City crime rate has reduced by 100 per cent during the weekend and 74 per cent overall since the pedestrianisation around the central park (Sallis et al., 2014).
- **Foot-fall numbers increase dramatically where pedestrianisation occurs**. This increases the economic expenditure in shops within that area and the value of property in the surrounding areas. For example, in London there was a 42 per cent increase in weekly consumer expenditure when switching from bus/car to walking (Bus £63, Car £64, Train/tube £46, On foot £91 (Lawlor, 2017).
- **Increased commercial activities.** Walking facilities in Union Square North (New York City) reduced commercial vacancies by 49 per cent. Similarly, bus and bike lanes on 1st and 2nd Avenue (NYC) reduced commercial vacancy rates by 47 per cent.
- **Increased health benefits.** Research has found that walking one km (the 3$^{rd}$ of the length of Queen Street) can reduce obesity by five per cent and depression by 47 per cent. (Simon, 2018).

- **Cooler Streets.** A recent report by (Pearce, 2018) has reported expected temperature increases across Auckland. This is likely to have greater impact upon more vulnerable communities. (Haddad and Aouachria, 2015) show that removing vehicles allow for cooler streets by increasing planting space for trees and shrubs.
- **Quieter Streets.** The removal of the combustion engine produces quieter streets which are also healthier. (Harding et al., 2013) show that noise over 85 decibels has been linked with high blood pressure, strokes, dementia and heart disease, with a total cost in the UK of 1.09 billion Euros.

# 5.0 Conclusions

Long-term air quality monitoring data from Queen Street in the Auckland City Centre have been considered together with source apportionment data from elemental analysis, emission inventory, $NO_2$ passive sampling and roadside research measurements. All these data sources contributed towards a big-picture analysis of major emission sources and spatial variability of air pollutants within the City Centre.

Long-term trends of $NO_2$ concentrations showed significant reductions (P-<0.05) until 2011-2012. At that point, the trend levelled off and has been found to be increasing slightly in recent years. This was also the trend for fine particulate ($PM_{2.5}$) measurements. Air pollutants within the City Centre are a concern due to high numbers of residents and visitors walking in the area. Pedestrian counts reveal that there are over 300,000 pedestrians travelling through the City Centre per day. Such numbers increase the potential of personal exposure, and therefore harmful impacts of air pollutants, along with the economic and social implications those impacts can cause.

Emission inventory data for the whole Auckland airshed shows that $NO_2$ is dominated by transport emissions, while $PM_{2.5}$ is a mix of transport, home heating and to a lesser extent, industrial source emissions. Source apportionment from Queen Street found diesel vehicle emissions contribute 40 per cent of $PM_{2.5}$, while accounting for more than two thirds of black carbon. Comparing black carbon concentrations for Auckland against other international cities revealed that concentrations within Auckland City Centre were up to three times higher than those measured in Canadian cities and twice those of cities in Europe, North America and the UK.

A source apportionment study using lichens offered a novel approach that complemented the spatial availability of data and agreed with findings that used more established methodology. They found the highest elemental pollution levels at key road junctions, and the waterfront area ports activity was identified as contributing year-round to overall levels of air pollutants.

Measurements carried out by research and academic institutions, including the University of Auckland, NIWA and GNS show peak $NO_2$ occurs at busy road intersections, bus stops and towards the waterfront area. Land use regression modelling identified bus stops, the number of traffic lanes, and building height to be the key contributing factors. Moreover, particulate data from handheld particle counters measured peak concentrations close to bus stops and road interchanges. The closer the proximity of the bus stop to the road junction the higher the reported concentrations, likely due to the stop-start process of large diesel vehicles.

Traffic and bus counts show that over 11 per cent of the on-road fleet on a typical work day at the upper end of Queen Street (near Auckland's Civic Centre) are buses. This percentage is reduced to near four per cent towards lower Queen Street. Air pollutants from the top half of Queen Street are assessed to be likely influencing concentrations towards the waterfront area due to prevailing south-easterly winds, with the high number of diesel powered buses the likely key emission source. Diesel emissions have contributed significantly to high pollution levels within the City Centre. This evidence is supported by research projects exploring pollutant spatial distribution that identified peak locations and is an important consideration when attempting to reduce harmful air pollutants in the most densely populated downtown area. Diesel emissions are also linked to the high recorded levels of black carbon.

Proposed changes to the City Centre infrastructure are discussed through policy mandates. Such changes should be considered in terms of their benefits to air quality within Auckland City Centre. However, such benefits should not be considered in isolation. Policy decisions supporting safer streets, climate action, transport infrastructure and congestion mitigation strategies, as well as economic connectivity through the City Centre have all been shown to have multiple and interdependent benefits.

For example, to achieve climate action targets fossil fuel emissions must decrease. Fossil fuel-free areas encourage uptake of zero emission vehicles or new light rail or electric rail transport options. Electrification of the bus fleet effectively removes the largest emitter of harmful diesel emissions within the City Centre. Pedestrianisation and active modes are encouraged, further reducing private vehicle numbers with a commensurate co-benefit of a reduction in the risks of road traffic accidents.

Safer streets should not be considered just in terms of the number of traffic accidents. Safer streets could also be thought of in terms of the health impacts of breathing cleaner air, lower crime rates through smart design, and improved urban areas for social interaction, rest and lower noise levels across the City Centre.

A key example is the internationally acclaimed Healthy Streets approach developed by Lucy Saunders (Saunders, 2017) through her research into the health impacts of transport, public realm and urban planning. Key urban elements are required to help improve the healthiness of public spaces are corresponding to those needed to make urban places socially and economically vibrant and environmentally sustainable.

This approach has received widespread acclaim and has been adopted as part of urban planning strategy in many major cities worldwide. It is notable that the indicators identified by Saunders (Saunders, 2017) are aligned to the desired outcomes from other key policy decisions currently under consideration that will affect Auckland City Centre.

Changes to central Auckland's design and infrastructure should be measured to assess impacts on factors such as air quality, traffic flow, pedestrian numbers, accident reductions, amongst many other factors. A preliminary design for a low-cost sensor network, based on the research evidence described in this report, is proposed to provide a valid spatial and temporal dataset for the monitoring of air quality impacts and policy effectiveness.

# 6.0 References

2013 Census Map – QuickStats about a Place. Accessed September 13, 2018.

Andrade, Maria de Fatima, Regina Maura de Miranda, Adalgiza Fornaro, Americo Kerr, Beatriz Oyama, Paulo Afonso de Andre, and Paulo Saldiva. 2012. "Vehicle Emissions and $PM_{2.5}$ Mass Concentrations in Six Brazilian Cities." *Air Quality, Atmosphere, & Health* 5 (1): 79-88.

ATAP. 2018. "Auckland Transport Alignment Project." Auckland.

ATEED. 2017. "Annual Report-2017." Annual Report. Auckland: ATEED.

Auckland City Centre residence Group. 2018. "City Centre Facts." CCRG. 2018.

Auckland Council. 2012. "The City Centree Masterplan." Technical Report. Auckland Council.

Auckland Transport. 2018. "Statement of Intent 2017/18-2019/20." Auckland.

Baik, Jong-Jin, and Jae-Jin Kim. 1999. "A Numerical Study of Flow and Pollutant Dispersion Characteristics in Urban Street Canyons." *Journal of Applied Meteorology* 38 (11): 1576-89.

Bluett, Jeff, Maria de Aguiar, and Robin Smit. 2016. "Understanding Trends in Roadside Air Quality." Research Report NZ Transport Agency. Golder Associates.

Boamponsem, Louis K., C. R. de Freitas, and David Williams. 2017. "Source Apportionment of Air Pollutants in the Greater Auckland Region of New Zealand Using Receptor Models and Elemental Levels in the Lichen, Parmotrema Reticulatum." *Atmospheric Pollution Research* 8 (1): 101-13.

Bond, T. C., S. J. Doherty, D. W. Fahey, P. M. Forster, T. Berntsen, B. J. DeAngelo, M. G. Flanner, et al. 2013. "Bounding the Role of Black Carbon in the Climate System: A Scientific Assessment." *Journal of Geophysical Research: Atmospheres* 118 (11): 5380-5552.

City of Helsinki Environment Centre. 2017. "Clean Air for Helsinki." 2017. https://www.hel.fi/static/ymk/esitteet/ilmansuojeluesite-en.pdf.

Crimmins, Paul. 2017. "Quantifying black carbon emissions from residential wood buring by a combination of bottom up and top down approaches." MSc Thesis, University of Auckland.

Davy, P, and B Trompetter. 2017. "Elemental Analysis Results for Air Particulate Matter Collected in Auckland 2006-2017." Technical Report. GNS Science.

Davy, P, W Trompetter, T Ancelet, and A Markwitz. 2017. "Source Apportionment and Trend Analysis of Air Particulate Matter in the Auckland Region." Technical Report 2017/001.

Dirks, K. 2012. "Personal Exposure to Air Pollution for Various Modes of Transport in Auckland, New Zealand." *The Open Atmospheric Science Journal* 6 (1): 84-92.

Dirks, K, J Scarfe, N Talbot, R Marshall, and J Salmond. 2017. "A Statistical Analysis of the Relationship between Brown Haze and Surface Air Pollution Levels on Respiratory Hospital Admissions in Auckland, New Zealand." *Climate* 5 (4).

Floater, G, C Heeckt, M Ulterino, L Mackie, P Rode, A Bhardwaj, M Carvalho, D Gill, T Bailey, and R Huxley. 2016. "Co-benefits of urban climate action: A framework for cities." Working Paper. London School of Economics Working Paper. C40.
Fredrickson, Craig. 2014. "Measuring Auckland's Population Density." Technical Report 1.2. Auckland Council.

Genberg, J., Denier van der Gon, H. A. C, D. Simpson, E. Swietlicki, H. Areskoug, D. Beddows, et al. 2013. "Light-Absorbing Carbon in Europe – Measurement and Modelling, with a Focus on Residential Wood Combustion Emissions." *Atmospheric Chemistry and Physics* 13 (17): 8719-38.
Geng, Fuhai, Jing Hua, Zhe Mu, Li Peng, Xiaohui Xu, Renjie Chen, and Haidong Kan. 2013. "Differentiating the Associations of Black Carbon and Fine Particle with Daily Mortality in a Chinese City." *Environmental Research* 120 (January): 27-32..
Goodey, H. 2011. "Ultrafine Particle Exposure of Adult and Child Pedestrians in Urban Environments." Masters Thesis, Auckland: University of Auckland.
Grahame, Thomas J., Rebecca Klemm, and Richard B. Schlesinger. 2014. "Public Health and Components of Particulate Matter: The Changing Assessment of Black Carbon." *Journal of the Air & Waste Management Association* 64 (6): 620-60.
Grange, Stuart, Shanju Xie, Auckland (N.Z.), and Council. 2015. *Auckland Industrial Air Emission Inventory 2011*.

Haddad, L, and Z Aouachria. 2015. "Impact of the Transport on the Urban Heat Island" 9 (8): 6.
Hales, Simon, Tony Blakely, and Alistair Woodward. 2012. "Air Pollution and Mortality in New Zealand: Cohort Study." *Journal of Epidemiology and Community Health* 66 (5): 468-73.
Harding, Anne-Helen, Gillian A. Frost, Emma Tan, Aki Tsuchiya, and Howard M. Mason. 2013. "The Cost of Hypertension-Related Ill-Health Attributable to Environmental Noise." *Noise and Health* 15 (67): 437.
Harrison, Roy M., David C. S. Beddows, Mohammed S. Alam, Ajit Singh, James Brean, Ruixin Xu, Simone Kotthaus, and Sue Grimmond. 2018. "Interpretation of Particle Number Size Distributions Measured across an Urban Area during the FASTER Campaign." *Atmospheric Chemistry and Physics Discussions*, September, 1-45.
Hawas, Olga, Eduard Stelcer, David Cohen, David Button, Lyn Denison, Andrew Chan, Rod Simpson, et al. 2003. "Elemental composition of fine particulate in four major Australian Cities"
Heart of the City. 2018. "Pedestrian Counts." 2018. https://www.hotcity.co.nz/city-centre/city-today/results-and-statistics/pedestrian-counts.
Howard, Eric. 2018. "Auckland Transport: Road Safety Business Improvement Review." Technical Review. Whiting Moyne. https://www.greaterauckland.org.nz/wp-content/uploads/2018/05/Road-Safety-Business-Improvement-Review-Executive-Summary-FINAL.docx.pdf.

Janssen, Nicole A.H., Gerard Hoek, Milena Simic-Lawson, Paul Fischer, Leendert van Bree, Harry ten Brink, Menno Keuken, et al. 2011. "Black Carbon as an Additional Indicator of the Adverse Health Effects of Airborne Particles Compared with $PM_{10}$ and $PM_{2.5}$." *Environmental Health Perspectives* 119 (12): 1691-99.

Käffer, Márcia Isabel, Suzana Maria de Azevedo Martins, Camila Alves, Viviane Camejo Pereira, Jandyra Fachel, and Vera Maria Ferrão Vargas. 2011. "Corticolous Lichens as Environmental Indicators in Urban Areas in Southern Brazil." *Ecological Indicators* 11 (5): 1319-32. https://doi.org/10.1016/j.ecolind.2011.02.006.

"Karangahape Train Station." 2016. City Rail Link. Accessed September 7, 2018. https://www.cityraillink.co.nz/stations-karangahape-rd/.

Kholod, Nazar, and Meredydd Evans. 2016. "Reducing Black Carbon Emissions from Diesel Vehicles in Russia: An Assessment and Policy Recommendations." *Environmental Science & Policy* 56 (February): 1-8.

Kuschel, Gerda, Jayne Metcalfe, Emily Wilton, Jajadish Guria, Simon Hales, Kevin Rolfe, and Alistair Woodward. 2012. "Updated Health and Air Pollution in New Zealand Study." Health Study. Prepared for Health Research Council of New Zealand, Ministry of Transport, Ministry for the Environment and New Zealand Transport Agency.

Kwak, Kyung-Hwan, Sung Woo, Kyung Kim, Seung-Bok Lee, Gwi-Nam Bae, Young-Il Ma, Young Sunwoo, et al. 2018. "On-Road Air Quality Associated with Traffic Composition and Street-Canyon Ventilation: Mobile Monitoring and CFD Modeling." *Atmosphere* 9 (3): 92.

Lawlor, Ellis. 2017. "The Pedestrian Pound The Business Case for Better Streets and Places." Living Streets. https://www.livingstreets.org.uk/media/1391/pedestrianpound_fullreport_web.pdf.

Lim, S, K Dirks, J Salmond, and S Xie. 2015. "Determinants of Spikes in Ultrafine Particle Concentration while Commuting by Bus." *Atmospheric Environment*, no. 112: 1-8.

Llop, Esteve, Pedro Pinho, Paula Matos, Maria João Pereira, and Cristina Branquinho. 2012. "The Use of Lichen Functional Groups as Indicators of Air Quality in a Mediterranean Urban Environment." *Ecological Indicators* 13 (1): 215-21. https://doi.org/10.1016/j.ecolind.2011.06.005.

Longely, Ian, Jennifer Salmond, Kim Dirks, David Welch, Daniel Shepherd, Stuart Grange, Gustavo Olivares, Georgia Miskell, Auckland (N.Z.), and Council. 2014. *Personal Exposure to Noise and Air Pollution (PENAP) in the Queen Street Valley, Auckland*.

Longley, I, J Clougherty, and B Tunno. 2016. "Spatially Resolved Technique for Source Apportionment in New Zealand." 2016157AK. NIWA.

Longley, I, S. Kingham, K. Dirks, E Sommervell, W Pattinson, and E Elangasinghe. 2013. "Detailed Observations and Validated Modelling of the Impact of Traffic on the Air Quality of Roadside Communities." NZ Transpor t Agency research report.

Longley, I, E Sommervell, and A Kacchara. 2017. "Air Quality Responses to Intensive Urban Scenarios (AQUARIUS)." ARC15103. NIWA.

Maricq, M. Matti, Richard E. Chase, Ning Xu, and Paul M. Laing. 2002. "The Effects of the Catalytic Converter and Fuel Sulfur Level on Motor Vehicle Particulate Matter Emissions: Light Duty Diesel Vehicles." *Environmental Science & Technology* 36 (2): 283-89.

Martilli, Alberto. 2002. "Numerical Study of Urban Impact on Boundary Layer Structure: Sensitivity to Wind Speed, Urban Morphology, and Rural Soil Moisture." *Journal of Applied Meteorology* 41 (12): 1247-66.

Mayer, Helmut. 1999. "Air Pollution in Cities." *Atmospheric Environment* 33 (24): 4029–37. https://doi.org/10.1016/S1352-2310(99)00144-2.

Ministry for the Environment, Stats NZ. 2018. "New Zealand's Environmental Reporting Series: Our Air 2018." NZ Environmental Reporting Series. Retrieved from www.mfe.govt.nz and www.stats.govt.nz.

Miskell, G. 2013. "Identifying Urban Design Details Affecting the Spatial Variability of Micro-Scale Ambient Nitrogen Dioxide for the Auckland CBD Area." Masters Thesis, University of Auckland.

Miskell, G, J Salmond, I Longley, and K Dirks. 2015. "A Novel Approach in Quantifying the Effect of Urban Design Features on Local-Scale Air Pollution in Central Urban Areas." *Environmental Science & Technology (ACS Publications)* 49 (15), (15): 9004-9011.

NIWA. 2016. "SpaRTANZ Auckland Pilot Study." Technical Report 2016157AK. Auckland: National Institute of Water and Atmospheric Sciences.

NZTA. 2017. "National Air Quality ($NO_2$) Monitoring Network." https://www.nzta.govt.nz/resources/air-quality-monitoring/.

Our Auckland, Auckland Council. 2017. "Mayor Commits to a Greener Auckland." 2017.

Pearce, Petra. 2018. "Auckland Region Climate Change Projections and Impacts." Auckland Council.

Platt, S. M., I. El Haddad, S. M. Pieber, A. A. Zardini, R. Suarez-Bertoa, M. Clairotte, K. R. Daellenbach, et al. 2017. "Gasoline Cars Produce More Carbonaceous Particulate Matter than Modern Filter-Equipped Diesel Cars." *Scientific Reports* 7 (1): 4926.

"Queen St: More Pedestrians, Fewer Vehicles." 2016. Greater Auckland. April 4, 2016. https://www.greaterauckland.org.nz/2016/04/04/queen-st-lots-of-people-few-vehicles/.

Racioppi, Francesca. 2004. *Preventing Road Traffic Injury: A Public Health Perspective for Europe*. Copenhagen: World health organization.

Raza, Wasif, Bertil Forsberg, Christer Johansson, and Johan Nilsson Sommar. 2018. "Air Pollution as a Risk Factor in Health Impact Assessments of a Travel Mode Shift towards Cycling." *Global Health Action* 11 (1).

Rohani, Mehrnaz, Grant Lawrence, Auckland (N.Z.), and Council. 2017. *The Relationship between Pedestrian Connectivity and Economic Productivity in Auckland's City Centre*. http://www.knowledgeauckland.org.nz/assets/publications/TR2017-007-Pedestrian-connectivity-economic-productivity-Auckland-city-centre.pdf.

Sallis, James F., Carmen L. Cutter, Deborah Lou, Chad Spoon, Amanda L. Wilson, Ding Ding, Prabhu Ponkshe, et al. 2014. "Making the Case for Designing Active Cities." *American Journal of Preventive Medicine* 46 (2): 195-207.

Salmond, Jennifer, Clive E. Sabel, and Sotiris Vardoulakis. 2018. "Towards the Integrated Study of Urban Climate, Air Pollution, and Public Health." *Climate* 6 (1): 14.

Saunders, Lucy. 2017. "An Introduction to Healthy Streets." January 6, 2017.

Simon, Heidi. 2018. "AW Health Benefits." Scribd. 2018. https://www.scribd.com/document/251051721/AW-Health-Benefits.

Soehodho, Sutanto. 2017. "Public Transportation Development and Traffic Accident Prevention in Indonesia." *IATSS Research*, Special issue: The first global interactive forum on traffic and safety (2015) symposium on "diverse, regionally-rooted transport cultures," 40 (2): 76-80.

Sridhar, Surekha, and Jayne Metcalfe. n.d. "Auckland Air Emissions Inventory 2016 Transport," 91.

Stats NZ.2018. "Cruise Ship Traveller and Expenditure Statistics: Year Ended June 2018 | Stats NZ." Accessed September 10, 2018. https://www.stats.govt.nz/information-releases/cruise-ship-traveller-and-expenditure-statistics-year-ended-june-2018.

Talbot, Nick, Nick Reid, Auckland (N.Z.), and Council. 2017. *A Review of Research into the Effects of Shipping on Air Quality in Auckland: 2006-2016*.

WHO. 2013. "WHO/Europe | Air Quality - Review of Evidence on Health Aspects of Air Pollution – REVIHAAP Project: Final Technical Report." 2013. http://www.euro.who.int/en/health-topics/environment-and-health/air-quality/publications/2013/review-of-evidence-on-health-aspects-of-air-pollution-revihaap-project-final-technical-report.

Xie, S, P Davy, S Sridhar, and J Metcalfe. 2016. "Quantifying Trends of Particulate Matter Emissions from Motor Vehicles in Auckland (New Zealand Collection) - Informit." *Air Quality and Climate Change* 50 (2).

**Find out more:** phone 09 301 0101, email rimu@aucklandcouncil.govt.nz or visit aucklandcouncil.govt.nz and knowledgeauckland.org.nz

Auckland Council
Te Kaunihera o Tāmaki Makaurau