Air Quality Benefits of COVID-19 Restrictions: Auckland Case Study 2020-2021

February 2023

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PREPARED FOR: **Ministry of Health**

CLIENT REPORT No: **FW22040**

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ACKNOWLEDGEMENTS

The author would like to acknowledge the input and guidance of Paul Baynham (Mote Ltd) with ambient air quality data review and Jayne Metcalfe (Emission Impossible Ltd) with health benefits modelling.

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EXECUTIVE SUMMARY

In 2020, the New Zealand Government introduced a four-tiered Alert Level system to help combat the spread of SARS-CoV-2, the virus that causes COVID-19. This system was widely supported by the New Zealand public and was highly successful in both reducing mortality and morbidity from COVID-19 infection and providing valuable time for the development and implementation of widespread vaccinations.

In March 2020 and August 2021, the entire country moved to Alert Level 4 with stay-at-home restrictions in place. While restrictions eased in most regions of New Zealand after infection rates dropped, the city of Auckland had these restrictions extended for work and travel, spending a total of 188 days at Alert Level 3 and 4.

An unforeseen outcome of the extended restrictions in Auckland was that significant reductions in both daily and annual concentrations of two key pollutants, nitrogen dioxide (NO_2) and particulate matter less than 2.5 micrometres in diameter ($PM_{2.5}$), were observed.

Table E-1 shows the average pollutant levels measured during different COVID-19 Alert Levels as compared with previous years (2017-19). Figure E-1 presents the NO_2 data as a box-whisker plot.

Table E-1: Average pollutant levels measured in Takapuna during different COVID-19 Alert Levels in 2020-21 as compared with pre COVID-19 levels (2017-2019)

COVID-19 Alert Level	Key Restrictions	Mean NO_2 Concentration (µg/m³)	Mean PM_{10} Concentration (µg/m³)
Alert Level 4 68 days	• Only essential workplaces open (e.g., supermarkets, health care, petrol stations) • Travel severely restricted, including police checkpoints	8	5.3[a]
Alert Level 3 120 days	• Construction permitted • Inter-regional travel severely restricted	12	7.2[b]
Alert Level 2 105 days	• People encouraged to work from home • No restrictions on personal movement	14	6.2
Alert Level 1 357 days	• No restrictions on travel	14	6.3
Pre COVID-19 1,095 days	• N/A	16	6.6

[a] 70% valid data (less than required 75% to be representative) [b] 60% valid data (less than required 75% to be representative)

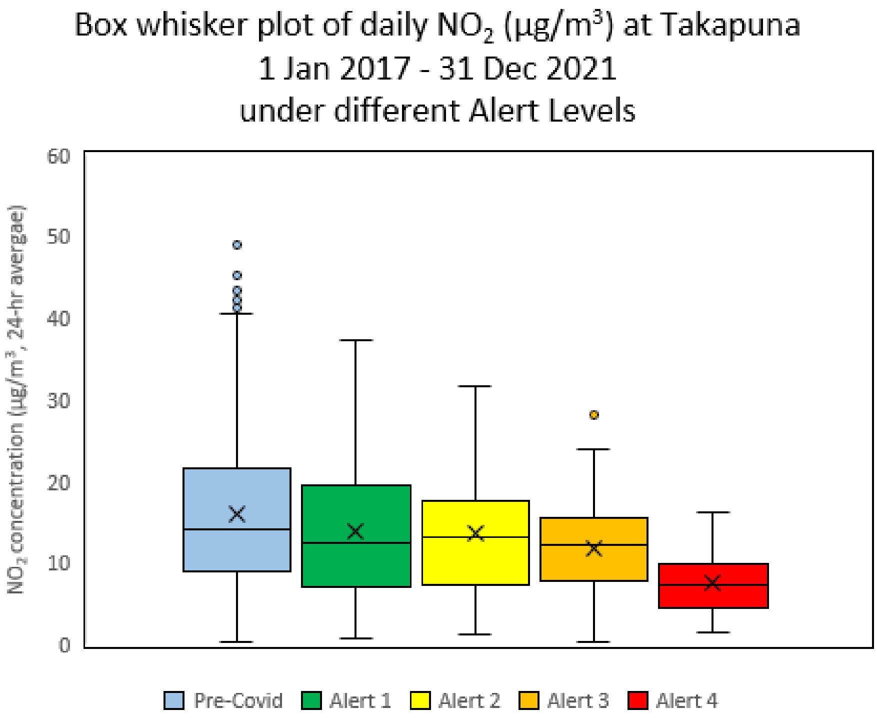

Figure E-1: Box Whisker Plot of Auckland daily NO_2 at Takapuna 2017 - 2021 [Source: Auckland Council]

This study reviewed levels of NO_2 and $PM_{2.5}$ prior to and during the social restrictions that were in place in 2020-21. From this review, it was possible to ascertain NO_2 and $PM_{2.5}$ reductions attributable solely to the restrictions and exclude reductions that were likely to occur anyway (specifically, a long-term decline in ambient NO_2 due to vehicle emissions regulations). In addition to the review any potential health benefits and avoided social costs were estimated.

From modelling estimates, we report that the COVID-19 restrictions reduced air pollution in Auckland in 2020 and 2021 for an estimated prevention of 236 cases of premature mortality (95% confidence interval -231, -242) with $1,070 million in averted social costs ($2019, low/high -$958M, -$1,239M). In addition, we estimate that around 350 cardiovascular and 800 respiratory hospitalisations were averted. The reduced levels of annual $PM_{2.5}$ averted just over 100,000 less restricted activity days and the reduction in annual NO_2 was associated with asthma prevalence being lessened by around 1,600 cases in under 18-year-olds.

Sensitivity testing using exposure response functions recommended by the World Health Organization reduced the estimated avoided premature mortality for 2020 and 2021 to 85 cases (95% confidence interval -54, -130), for an avoided social cost of around $385 million ($2019, low/high -$344M, -$446M).

There is a moderate degree of confidence in the modelling estimates.

These estimates are confined to health benefits due to reduced public exposure to air pollution and do not reflect other benefits likely to accrue from the COVID-19 social restrictions (e.g., avoided hospitalisations and mortality from reduced incidence of influenza and other communicable diseases).

1. INTRODUCTION

Early in the COVID-19 pandemic, it was hypothesized that people exposed to poor air quality long-term were at greater risk of becoming infected with COVID-19. In 2020, Zhu and colleagues demonstrated this, showing a statistically significant relationship between short-term exposure to concentrations of particulate matter (PM), carbon monoxide (CO), nitrogen dioxide (NO_2), ozone (O_3) and the number of COVID-19 cases in 120 cities in China (Zhu et al., 2020). Similar findings from 71 Italian provinces were reported by Fattorini and Regoli, (2022). They found significant correlations between chronic exposure to atmospheric contamination and a higher incidence of COVID-19 cases. Therein followed a wealth of studies finding associations between exposure to poor air quality and COVID-19 incidence or mortality around the world (Pansini & Fornacca, 2020; Ogen, 2020; Pozzer et al., 2020; van der Valk, J., 2021; Wang et al., 2021, Marquès et al., 2022).

In response to the COVID-19 pandemic, governments around the world implemented a range of public health measures and social restrictions on work and travel, including closed national borders. One unforeseen advantage of these restrictions was a sudden and marked improvement in ambient air quality, albeit with notable differences between pollutants, countries and cities.

A 2021 European workshop reported (Anderson et al., 2021):

> *"The largest decreases in monthly averages of up to 70% in NO_2, compared with expected concentrations in the absence of lockdown measures were observed at traffic monitoring stations in Spain and Italy, while reductions in background NO_2 concentrations for selected countries ranged from an average 61% in Spain to 20% in Czech Republic. In some cities, NO_2 levels remained relatively low even after lockdown measures were lifted (Milan, Italy), while in others (Athens, Greece) they rapidly returned to 'normal'.*
>
> *For $PM_{2.5}$, decreases in background concentrations ranged from 30% in Spain to 9% in the Czech Republic compared to expected levels. Reductions in $PM_{2.5}$ levels were smaller and less consistent than those for NO_2 due to the generally more varied sources of $PM_{2.5}$ especially in urban areas, including the combustion of fossil fuel for heating, industrial activities, long-range transportation of particles, road traffic and secondary particle formation.* ***Importantly, these reductions were largely short term, with levels rebounding as economic activity increased again****."*

Research in this area has gone on to demonstrate the health benefits that may accrue from reductions in air pollution due to a reduction in vehicle movement, because of COVID-19 restrictions (Chen K., *et al*. 2020, Chen L., *et al*. 2020, Wang *et al*. 2022).

The epidemiology is clear that more people are adversely affected, more seriously, through chronic exposure to PM than through short-term exposure (WHO, 2021). This is best illustrated through the difference in the quantified exposure response functions determined through epidemiology to inform the guidelines. Chen & Hoek, (2020) reported an exposure response function of 1.08 (95% confidence interval 1.06 – 1.09) with a certainty of evidence rated as high for all-cause mortality and *annual* $PM_{2.5}$. The World Health Organisation (WHO) determined all PM-outcome associations were deemed causal, or likely to be causal (WHO, 2021). This means that every 10 $\mu g/m^3$ increase in annual $PM_{2.5}$ results in an 8% increase in all-cause mortality (i.e., people die that would otherwise not have – this is also referred to as premature mortality). By comparison, Orellano *et al*., (2020) reported an exposure response function of 1.0065 (95% confidence interval 1.0044 – 1.0086) with a certainty of evidence rated as high for all-cause mortality and *daily* $PM_{2.5}$. This means that every 10 µg/m^3 increase in daily $PM_{2.5}$ results in a 0.7% increase in all-cause mortality. Thus, the annual guideline is more health protective than the daily guideline.

This in turn, means that any reduction in annual exposure attributable to stay-at-home restrictions for COVID-19 will be more significant than reductions in daily concentrations.

1.1 TIMELINE OF THE COVID-19 PANDEMIC

Since February 2020, the New Zealand Government has implemented ongoing and intermittent public health and social measures to reduce transmission of SARS-CoV-2. The measures have varied from personal controls (e.g., mandatory mask use in specified settings) to national restrictions (e.g., closed borders). The measures and controls have also changed over time with new or improved scientific knowledge but broadly speaking, a four-level alert system was in place throughout most of 2020 and 2021 (MoH, 2022).

The Alert Levels specified increasing restrictions, with Alert Level 1 having the least and Alert Level 4 the most restrictions. The restrictions are cumulative, for example at Alert Level 4, all restrictions from Alert Levels 1, 2 and 3 apply. Initially the Alert Levels applied nationally, but over time this changed with different parts of the country moving up and down the Alert Levels. Auckland, New Zealand's largest city and home to around one third of New Zealand's population, was subject to the longest period of restrictions of any part of New Zealand.

In March 2020 and August 2021, the entire country moved to level 4 with stay-at-home restrictions in place. New Zealand's borders closed in late March 2020 and did not open until mid-2022. While restrictions eased in most regions of New Zealand after infection rates dropped, the city of Auckland was subject to an extension of restrictions on work and travel, spending a total of 188 days at Alert Level 3 and 4. Home to 1.7 million people[1], Auckland is also the largest number of people of any urban conurbation in New Zealand. Auckland is, therefore, an ideal location for a case study into the potential health benefits that may accrue from reduced air pollution during COVID-19 stay-at-home restrictions.

Table 1 summarises the Alert Level restrictions and the number of days spent at each Alert Level in Auckland. A full timeline of COVID-19 related events and application of Alert Levels in New Zealand is provided in **Appendix A**.

[1] For the year 2019 [Source: NZStats usually resident population]

Table 1: Summary social restrictions and days at each Alert Level in Auckland in 2020-21

COVID-19 Alert Level	Key Restrictions	2020 (days)	2021 (days)	Total (days)
Alert Level 4	• People instructed to stay home in their bubble • Only essential workplaces open (e.g., supermarkets, health care, petrol stations) • Education facilities closed, gatherings cancelled. • Travel severely restricted, including police checkpoints	33	35	68
Alert Level 3	• People instructed to stay home in their bubble other than for essential personal movement, including going to work, school if they must, or for local recreation. • Construction permitted • Events of no more than 10 people allowed for specific purposes • Inter-regional travel severely restricted	38	82	120
Alert Level 2	• Businesses permitted to operate with risk-based assessment (social distancing, masks) but people encouraged to work from home • Gatherings up to 100 people permitted • No restrictions on personal movement	66	39	105
Alert Level 1	• No restrictions on personal movement • No restrictions on gatherings or business • No restrictions on travel	148	209	357

1.2 AIMS OF THE STUDY

The purpose of this assessment was to estimate the health benefits that would have accrued from improved air quality during extended periods of COVID-19 restrictions in the city of Auckland, New Zealand during 2020 and 2021. The approach taken in this assessment was to consider the changes in long-term exposure arising from COVID-19 restrictions.

The aims of the study were to:

- Review Auckland air quality data (NO_2 and $PM_{2.5}$) during periods of COVID-19 restrictions for comparison with periods without such restrictions.
- Calculate reductions, if any, to annual concentrations of NO_2 and $PM_{2.5}$ that were associated with pandemic restrictions in Auckland.
- Undertake modelling with New Zealand generated exposure response functions (Hales *et al.*, 2021) to assess potential changes in health impacts. Before doing so update HAPINZ 3.0 model base case year 2016 to 2019 with more recent air quality, population and health incidence data.
- Undertake sensitivity testing using WHO generated exposure response functions (Chen & Hoek, 2020; Huangfu & Atkinson, 2020) for comparison with modelled estimates.
- Make an estimate of uncertainty and the level of confidence in modelling.

2. METHOD

2.1 AUCKLAND AIR QUALITY DATA

Auckland Council undertakes comprehensive ambient air quality monitoring at a number of different types of monitoring locations across Auckland (refer **Appendix B**). These include traffic, industrial and residential monitoring locations. NO_2 (and $PM_{2.5}$ indicated by *) monitoring data were downloaded from Auckland Council's publicly available data portal for the following sites with sufficient valid data: [2]

- Queen Street (traffic)
- Takapuna (traffic/residential)*
- Penrose (traffic/industrial)*
- Henderson (residential/traffic)
- Glen Eden (residential)
- Patumahoe (rural)*

Data were reviewed to consider:

- Daily levels and how they varied with Alert Levels
- Sample size and whether there were sufficient valid data for robust comparisons between Alert Levels
- Monitoring locations and population exposure
- Interannual variability (i.e., how much does it vary each year anyway)
- Long-term trends – what reductions, if any, would have occurred anyway
- Two-year annual average (2018-2019) as a base year for comparison with 2020-21

Daily data were next reviewed to ascertain differences between periods with COVID-19 restrictions and previous years. This was used to establish context (only annual data were used to estimate health impacts) with data for Takapuna presented for illustrative purposes. The Takapuna site was selected because it is a residential monitoring site with the longest data record in Auckland.

Annual data were reviewed for long-term trends and to remove any increases or decreases in annual means that would have occurred anyway. The two years prior to the start of the pandemic (2018 and 2019) were used as a baseline for comparison with the stay-at-home restrictions in 2020 and 2021 for the assessment itself.

2.2 UPDATING HAPINZ 3.0 EXPOSURE MODEL

The national Health and Air Pollution in New Zealand Study (**HAPINZ 3.0**) (Kuschel et al., 2022) recently estimated the health impacts of long-term exposure to key pollutants $PM_{2.5}$ and NO_2 in New Zealand. In addition to reporting on national estimates, the HAPINZ 3.0 study published an exposure model (Sridhar et al., 2022) detailing annual exposure and health

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[2] https://environmentauckland.org.nz/Data/Dashboard/61

incidence statistics disaggregated by regional council boundaries, territorial authority (city and district councils), gazetted airsheds and (2013) census area units. The national exposure model permits scalar assessment of changes to long-term air quality concentrations, as well as sensitivity testing using alternative exposure response functions. These can be used to assess the health benefits that may accrue from improvements in air quality during pandemic restrictions.

The HAPINZ 3.0 model (Sridhar et al., 2022) primarily utilises New Zealand-specific exposure response functions reported in Hales et al., 2021. These are as follows (all Hales *et al.*, 2021 except where noted):

$PM_{2.5}$

- Premature mortality risk (per 10 µg/m^3) for all adults (30+years) associated with annual $PM_{2.5}$ exposure 1.105 (95% CI 1.065 – 1.145)
- Cardiovascular hospitalisation risk (per 10 µg/m^3) for all ages associated with annual $PM_{2.5}$ exposure 1.115 (95% CI 1.084 – 1.146)
- Respiratory hospitalisation risk (per 10 µg/m^3) for all ages associated with annual $PM_{2.5}$ exposure 1.070 (95% CI 1.021 – 1.122)
- Restricted activity days risk (per 10 µg/m^3) for all ages associated with annual $PM_{2.5}$ exposure 0.9 (lower/upper bounds 0.5 – 1.7, Ostro, 1987)

NO_2

- Premature mortality risk (per 10 µg/m^3) for all adults (30+years) associated with annual NO_2 exposure 1.097 (95% CI 1.074 – 1.120)
- Cardiovascular hospitalisation risk (per 10 µg/m^3) for all ages associated with annual NO_2 exposure 1.047 (95% CI 1.031 – 1.064)
- Respiratory hospitalisation risk (per 10 µg/m^3) for all ages associated with annual NO_2 exposure 1.130 (95% CI 1.102 – 1.159)
- Asthma prevalence risk (per 4 µg/m^3) for 0 – 18-year-olds associated with annual NO_2 exposure 1.05 (95% CI 1.02 – 1.07, Khreis *et al*., 2017)[3]

The HAPINZ 3.0 exposure model was established for a base year of 2016. This was updated for a base year of 2019 as outlined below.

Updated model estimates are provided in **Appendix C** for comparison with the base year of 2016.

2.2.1 Population

The HAPINZ 3.0 exposure model has an estimated resident population in Auckland of 1,608,140 for a base year of 2016. This was updated with the estimated resident population for Auckland as a two-year mean for 2018-19 (Metcalfe & Kuschel, pending) as detailed in **Appendix C**.

[3] Toi Te Ora requested an assessment of additional presentations for health care, which was not estimated by Hales et al., 2021. However, asthma prevalence in children (under 18-year-olds) associated with long-term NO_2 was assessed and is included here.

2.2.2 Mortality/Morbidity Statistics

The HAPINZ 3.0 exposure model has 3-year health statistics for mortality and morbidity for a base year of 2016. This was updated for a base year of 2019 (Metcalfe & Kuschel, pending). Kuschel et al., 2022 cautioned against using the HAPINZ 3.0 exposure model to make predictions of health impacts beyond 2019 as COVID-19 border closures and stay at home measures have severely limited the impact of seasonal influence and other diseases (such as the respiratory syncytial virus (**RSV**) which affects young children). In other words, there were additional health benefits that likely accrued from COVID-19 restrictions that were not due to reductions in long-term air pollution. These health benefits are not estimated in this study.

This assessment of the health benefits accruing from pandemic stay at home measures in 2020-21 is:

- *Hypothetical* - it assumes business as usual for incidence of mortality and morbidity (i.e., all other things remain equal whilst ambient levels of pollution reduce due to pandemic restrictions); and

- *Differential* – it only assesses health benefits that would accrue from the reduction in ambient air pollution as a difference from business as usual.

This simplistic approach means that other changes in mortality and morbidity arising from COVID-19 impacts in 2020-21 are excluded from consideration.

2.2.3 HAPINZ 3.0 Baseline Air Quality Data

Three-year mean pollutant levels were sourced from the Health and Air Pollution in New Zealand 3.0 health impacts exposure model (Sridhar et al., 2022). The HAPINZ 3.0 study assigns exposure as an average over each census area unit for the purpose of national assessment. The epidemiology in the HAPINZ model was based on this average exposure across the census area unit so it is robust for assessing health effects at the population level.

The HAPINZ 3.0 exposure model has ambient air quality data for a base year of 2016. This was updated for a base year of 2019 (Metcalfe & Kuschel, pending).

2.3 SENSITIVITY TESTING

A sensitivity analysis was carried out using the premature mortality exposure response functions published in support of the 2021 global air quality guidelines (WHO 2021):

- $PM_{2.5}$ exposure response function 1.08 (95% CI 1.06 – 1.09) per 10 µg/m^3 all-cause mortality (Chen & Hoek, 2020)

- NO_2 exposure response function 1.02 (95% CI 1.01 – 1.04) per 10 µg/m^3 all-cause mortality (Huangfu & Atkinson, 2020)

3. RESULTS

Table 2 presents pollutant levels averaged over each Alert Level with associated key COVID-19 restrictions.

TABLE 2: Average pollutant levels measured in Takapuna during different COVID-19 Alert Levels 2020-21 as compared with 2017-2019 [Source: MoH 2022, Auckland Council]

COVID-19 Alert Level	Key restrictions	Year (days) / Season	NO_2 ($\mu g/m^3$)	$PM_{2.5}$ ($\mu g/m^3$)
Alert Level 4 68 days	• People instructed to stay home in their bubble • Only essential workplaces open (e.g., supermarkets, health care, petrol stations) • Education facilities closed, gatherings cancelled. • Travel severely restricted, including police checkpoints	**2020** Autumn (33 days) **2021** Winter (35 days)	8	5.3[a]
Alert Level 3 120 days	• People instructed to stay home in their bubble other than for essential personal movement, including going to work, school if they must, or for local recreation. • Construction permitted • Events of no more than 10 people allowed for specific purposes • Inter-regional travel severely restricted	**2020** Winter (38 days) **2021** Spring (82 days)	12	7.2[b]
Alert Level 2 105 days	• Businesses permitted to operate with risk-based assessment (social distancing, masks) but people encouraged to work from home • Gatherings up to 100 people permitted • No restrictions on personal movement	**2020** Winter (66 days) **2021** Summer (39 days)	14	6.2
Alert Level 1 357 days	• No restrictions on personal movement • No restrictions on gatherings or business • No restrictions on travel	**2020** Summer, Winter, & Spring (148 days) **2021** Summer, Autumn (209 days)	14	6.3
Pre COVID-19 1,095 days	• N/A	**2017 – 2019** All seasons	16	6.6

[a] 69% valid data (less than required 75% to be representative) [b] 59% valid data (less than required 75% to be representative)

3.1 NITROGEN DIOXIDE

3.1.1 Daily NO_2

Table 3 presents key statistics for daily NO_2 concentrations measured in 2017-21 at the Takapuna monitoring site (a traffic and residential site) stratified by Alert Level. The average, maximum and 99th percentile daily NO_2 concentration reduced with each successive Alert Level. The reductions are significant, with the average daily concentration of NO_2 reducing by a mean of 53%.

TABLE 3: Key statistics for daily NO_2 measured at Takapuna 2017 – 2021 stratified by Alert Level [Source: Auckland Council]

Alert Level	Count (days)	NO_2 (µg/m^3)				Valid Data (%)
		Mean	Maximum	99th Percentile	Standard Deviation	
Pre-Covid	**1,145**	**16**	**49**	**39**	**9**	**97%**
Alert 1	351	14	37	33	8	98%
Alert 2	101	14	32	31	8	96%
Alert 3	118	12	28	24	6	98%
Alert 4	**68**	**8**	**16**	**15**	**3**	**100%**
Reduction: Pre-Covid → Alert 4		*-53%*	*-67%*	*-62%*		
Annual AQG = 10 µg/m^3 / Daily AQG = 25 µg/m^3 (WHO, 2021)						

Things to note from **Table 3**:

- The number of days at each Alert Level is an important statistic when considering how the air quality varies at each level. The more data there are, the more robust the dataset.
- The 99th percentile is the value below which 99% of the data sits. This is a more stable statistical representation of peak daily concentrations, as the maximum value each year can vary significantly due to interannual variability.
- The standard deviation indicates the variance. Typically, smaller air quality datasets vary less (i.e., have a lower standard deviation) because they cover a shorter time period with more consistent meteorology.
- The % valid data is how many days of data were successfully collected by the air quality monitor for each time period. Typically, 75% of a dataset is considered necessary for it to reasonably represent the period being monitored.

Figure 1 presents the same dataset for daily NO_2 in a box whisker plot.

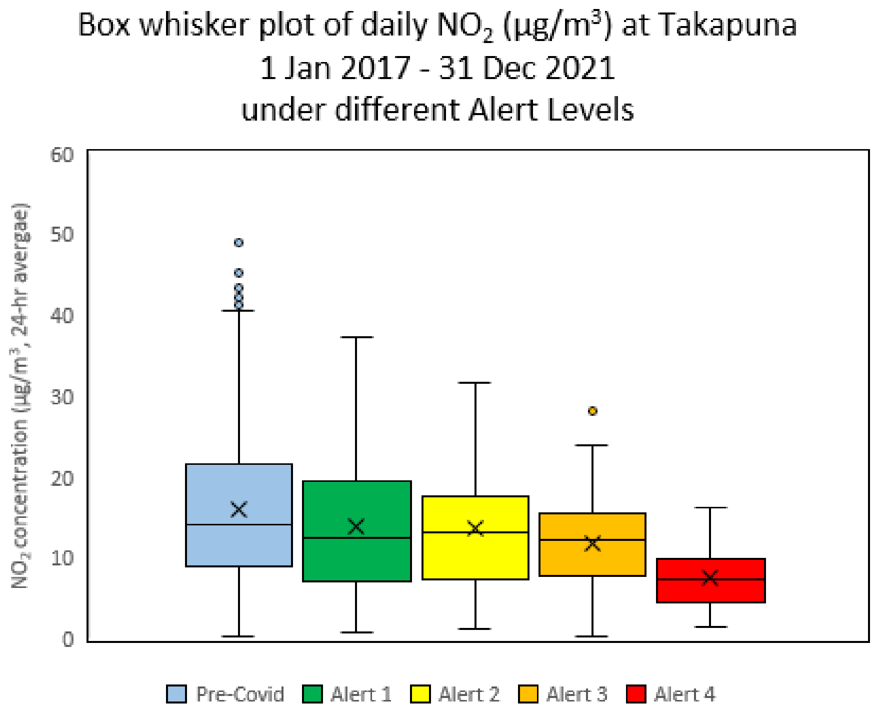

FIGURE 1: Box Whisker Plot[4] of Auckland daily NO_2 at Takapuna 2017 - 2021 [Source: Auckland Council]

The data in Table 3 and Figure 1 show successive reductions with increasing alert level. However, Alert levels occurred at different times of year during 2020 and 2021 and ambient levels of NO_2 can vary with seasonality.

Table 4 presents key statistics for daily NO_2 concentrations measured on the calendar days at Alert Level 4 (26 March – 27 April 2020 and 18 August – 21 September 2021) compared with NO_2 concentrations measured for the same calendar days pre-COVID (in 2017-2019) at the Takapuna monitoring site.[5] This comparison removes the effect of seasons (spring is the windiest time of year, with more dispersion of emissions and likely lower daily concentrations). Table 5 shows that when the same time of year is compared, the reduction in average daily NO_2 is slightly more pronounced, at a mean of 58%.

Figure 2 presents this same comparison for the calendar days of Alert Level 4 with pre-COVID days as a box whisker plot.

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[4] Things to note from a box whisker plot:

- Maximum daily concentration (top of I)
- Upper quartile (top of box)
- Median (line in box)
- Mean concentration (cross in box)
- Lower quartile (bottom of box)
- Interquartile range (side of box)
- Minimum daily concentration (bottom of I)

[5] NB: includes days at Alert Level 1 on 18 Aug – 21 Sep 2020 and Alert Level 2 on 26 Mar – 27 Apr 2021.

TABLE 4: Daily NO_2 measured at Takapuna during Alert Level 4 calendar days in 2017 – 2021 [Source: Auckland Council]

Alert Level	Count (days)	NO_2 (μg/m³)				Valid Data (%)
		Mean	Maximum	99th Percentile	Standard Deviation	
Pre-COVID-19	194*	18	35	33	7	95%
Alert 4	68	8	16	15	3	100%
Reduction: Pre-Covid → Alert 4		-58%	-54%	-54%		
Annual AQG = 10 μg/m³ / Daily AQG = 25 μg/m³ (WHO, 2021)						

*Only valid monitoring days included

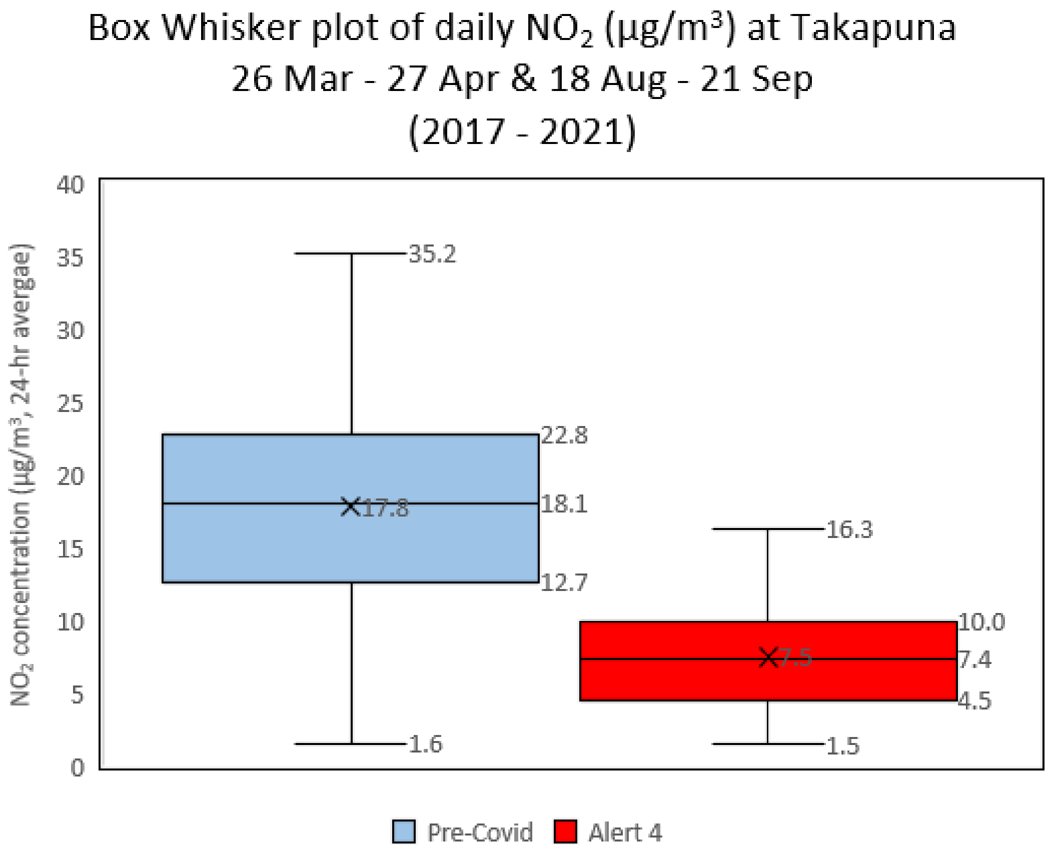

FIGURE 2: Box Whisker Plot of daily NO_2 at Takapuna on calendar days of Alert level 4 in 2017 - 2021 [Source: Auckland Council]

3.1.2 Annual NO_2

Health effects from chronic exposure to air pollution are more significant than effects from short-term exposure. This section reviews annual mean concentrations of NO_2 as follows:

Pre-COVID-19

- By census area unit for Auckland estimated for base year 2016 (Sridhar et al., 2022)
- Long-term trends at six monitoring locations in Auckland (Source: Auckland Council)

COVID-19 restrictions (2020-21)

- Two-year mean pre-COVID and during 2020-21 at six monitoring locations in Auckland (Source: Auckland Council)

Pre-COVID-19 NO_2

Figure 3 is a box whisker plot of 3-year mean NO_2 concentrations, estimated for the 417 census area units in the Auckland territorial authority for 2016.[6]

Figure 4 presents the same data by population exposed in each census area unit.

The estimated population weighted 3-year mean NO_2 concentration in Auckland is 10 μg/m³ (2016) (Sridhar et al., 2022).

Figure 5 presents the long-term data record of annual concentrations of NO_2 at six monitoring stations in Auckland:

- Queen Street (traffic)
- Takapuna (traffic/residential)
- Penrose (traffic/industrial)
- Henderson (residential/traffic)
- Glen Eden (residential)
- Patumahoe (rural)

Since the early 2000s, all NO_2 monitoring sites have shown an overall decline in annual NO_2 (albeit to a much lesser extent at the rural location Patumahoe). This decline needs to be taken into consideration when estimating any health benefits associated with COVID-19 restrictions in 2020-21 as it is likely there would have been some decline in annual NO_2 even in the absence of the COVID-19 pandemic.

FIGURE 3: Box Whisker Plot of Auckland 3-year mean NO_2 for base year 2016 [Source: Sridhar et al., 2022]

[6] Census area units as defined by StatsNZ for 2013.

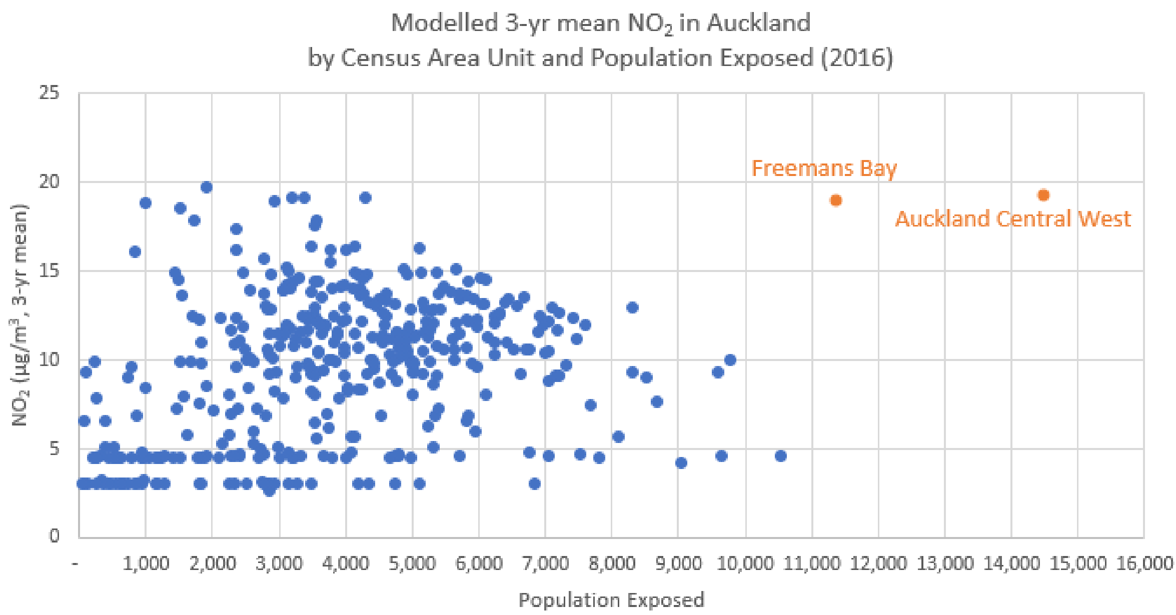

FIGURE 4: Auckland 3-year mean NO_2 for base year 2016 by population exposed [Source: Sridhar et al., 2022]

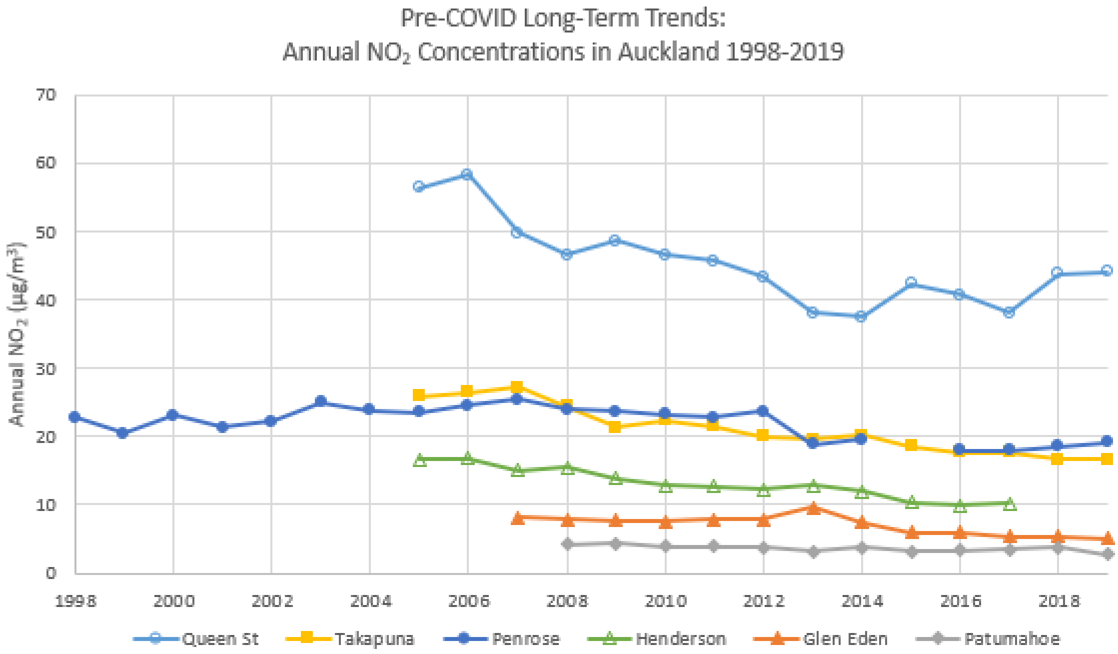

FIGURE 5: Long term trends: Annual NO_2 Concentrations in Auckland 1998 - 2021 [Source: Auckland Council]

NO_2 during COVID-19 restrictions (2020-2021)

Table 5 presents 2-year mean concentrations of NO_2 measured at six monitoring locations in Auckland between 2016 and 2021. These are compared with the WHO global air quality guideline (**AQG**) (WHO 2021) in the absence of any long-term New Zealand guideline or standard. **Figure 6** presents the same monitoring data as a box-whisker plot.

Table 5 also shows the difference between 2-year mean concentrations of NO_2 in 2020-21 compared with the 2-year mean in 2018-19 (pre COVID-19). There was a reduction in annual NO_2 in 2020-21 compared with pre COVID-19 levels. As would be expected, this reduction was larger at urban monitoring sites located close to traffic.

TABLE 5: Two-year mean NO_2 measured at six monitoring sites in Auckland 2016 – 2021 [Source: Auckland Council] [7]

Location	Site Type	2-year mean NO_2 (µg/m^3)			∆ 2020-21 cf 2018-19
		2016-17	2018-19	2020-21	
Queen St	Traffic	42	44	33	-23%
Penrose	Traffic/Industrial	18	18	14	-18%
Takapuna	Traffic/Residential	17	16	12	-23%
Henderson	Residential/Traffic	11	8	7	-6%
Glen Eden	Residential	6	5	4	-6%
Patumahoe	Rural	4	3	2	-9%
WHO AQG = 10 µg/m^3					

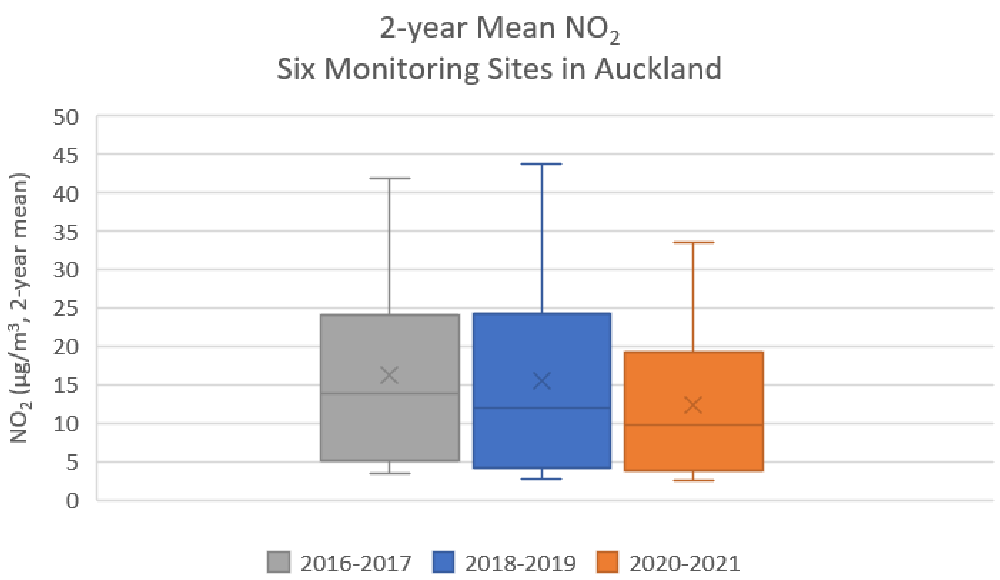

FIGURE 6: Box Whisker Plot of 2-year mean NO_2 at six Auckland monitoring sites (2016-2021) [Source: Auckland Council]

[7] All data meet good practice minimum data requirements

Reduction in annual NO_2 attributable to COVID-19 restrictions

Figure 7 shows the long-term trend in vehicle kilometres travelled in the Auckland Region (MoT 2022) as well as the Auckland region population and annual average concentrations of NO_2 at Takapuna (which is a residential monitoring site with the longest data record in Auckland). Figure 7 shows that since 2007 annual levels of NO_2 have declined despite increases in both population and vehicle kilometres travelled (VKT) (except for 2020 – when COVID-19 restrictions were in place).

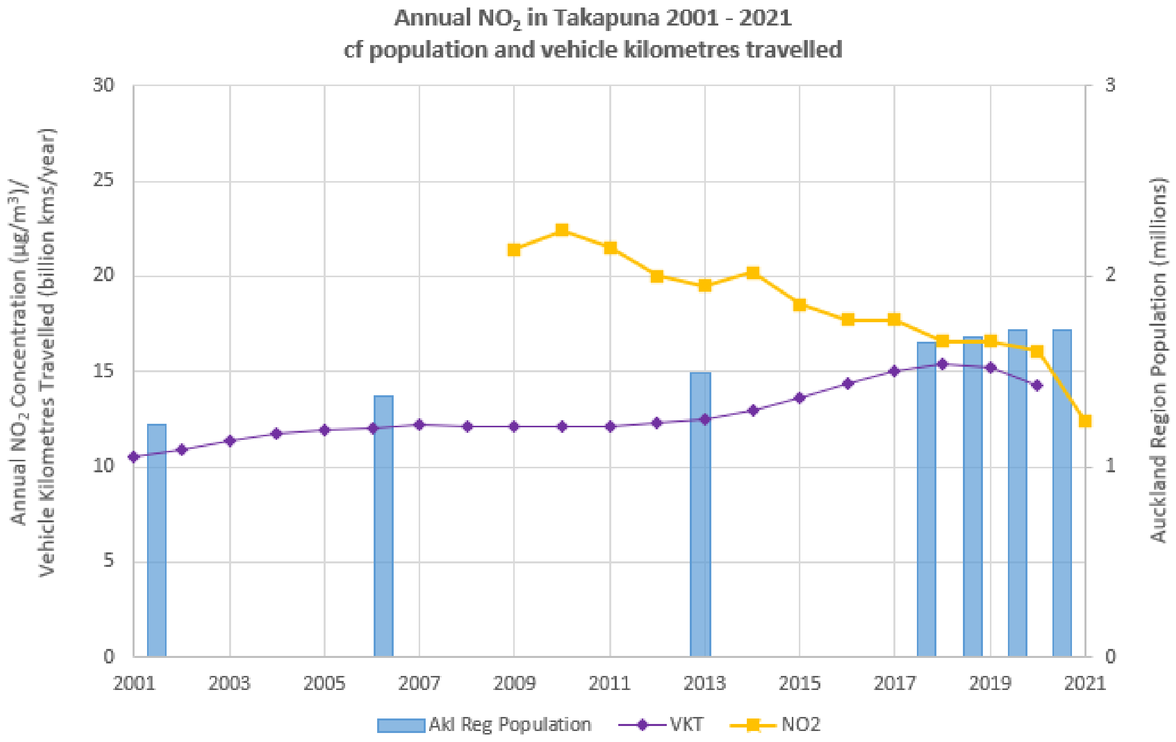

FIGURE 7: Long term trends: Annual NO_2 Concentrations in Takapuna 2005 – 2021 and Annual vehicle kilometres travelled in Auckland region [Source: Auckland Council, Ministry of Transport, Stats NZ]

The decoupling of ambient concentrations of NO_2 from VKT is associated with successive introduction of vehicle emissions standards (Waka Kotahi, 2020). This decline needs to be taken into consideration when estimating any health benefits associated with COVID-19 restrictions in 2020-21 as it is likely there would have been some decline in annual NO_2 in any case.

Table 6 presents the measured difference in annual average NO_2 at six monitoring sites in Auckland in 2020-21 compared with 2018-19 i.e., the difference between pandemic restrictions and pre-COVID as a 2-year mean. The use of a 2-year mean provides a more stable statistic as it lessens the influence of meteorology, which varies from year to year. It further facilitates inclusion of the full pandemic restriction period (i.e., 2020 and 2021).

Table 6 shows that there was a difference in the impact that COVID-19 restrictions had on 2-year mean concentrations at different monitoring stations around Auckland. For example, the 2-year mean reduced by 22% on average at monitoring sites close to traffic. However, at more residential locations, the reduction was less significant, 7% on average.

There are insufficient data to develop spatially disaggregated reduction estimates for NO_2. Accordingly, we calculated the average reduction in concentration measured at all monitoring sites to give an estimated reduction of 20%.

TABLE 6: Difference in 2-year mean NO_2 in 2020-21 compared with 2018-19 and estimated long term decline without COVID effects at six monitoring sites

Location	Site Type	Reduction	
		Comparison of 2-yr mean: 2020-21 and 2018-19	Long-Term NO_2 decline per annum (2010-19)
Queen St	Traffic	-23%	-0.7%
Penrose	Traffic/Industrial	-18%	-1.3%
Takapuna	Traffic/Residential	-23%	-2.4%
Henderson	Residential/Traffic	-6%	-3.6%
Glen Eden	Residential	-6%	-3.5%
Patumahoe	Rural	-9%	-3.8%
	Average	**-20%**	**-2.6%**

Figure 7 (and Figure 5) suggest that some of this reduction would likely have occurred in the absence of COVID-19 restrictions due to reductions in vehicle emissions. Table 6 shows the average annual reduction in NO_2 concentration measured at different monitoring stations around Auckland for the ten years prior to COVID-19 (2010-19). To estimate the reduction that would have occurred due to long-term decline in vehicle emissions, we averaged the reduction that occurred over all sites for 2010-19. This yielded an average reduction in annual NO_2 of -2.6% per year. This may be conservative as more recently, in the five years ending 2019, some monitoring locations show a flat (Takapuna) or potentially increasing trend (Penrose).

There are two years between 2019 (base case) and the end of Level 3 and 4 restrictions (2021). Therefore, we lessened the reduction due to COVID-19 by 2 x 2.6 = 5.2% to account for the known long-term decline in NO_2.

Our overall estimate of the reduction in long-term NO_2 attributable (only) to COVID-19 restrictions was 20% - 5.2% = 14.8%.

3.2 PARTICULATE MATTER LESS THAN 2.5 MICRONS ($PM_{2.5}$)

3.2.1 Daily $PM_{2.5}$

Table 7 presents key statistics for daily $PM_{2.5}$ concentrations measured in 2017-21 at the Takapuna monitoring site stratified by Alert Levels.

Table 7 shows the average, maximum and 99th percentile daily $PM_{2.5}$ concentration generally reduces with each successive Alert Level. The exception is Alert Level 3, during which average $PM_{2.5}$ concentrations rose slightly. However, there was only 59% valid data for $PM_{2.5}$ during Alert Level 3 and 69% valid data during Alert Level 4 which reduces certainty for these time periods.[8]

Figure 8 shows the same data as a box whisker plot.

[8] This appears to be due to an instrument fault coupled with limited site access during Alert Level 4 in late 2021, and a subsequent change in the monitoring service provider during Alert Level 3, also in late 2021.

TABLE 7: Key statistics for daily $PM_{2.5}$ measured at Takapuna 2017 – 2021 stratified by Alert Level

Alert Level	Count (days)	$PM_{2.5}$ (µg/m³)				Valid Data (%)
		Mean	Maximum	99th Percentile	Standard Deviation	
Pre-Covid	**1,088**	**6.6**	**21**	**16**	**3**	**93%**
Alert 1	341	6.3	22	16	2	95%
Alert 2	101	6.2	11	11	2	96%
Alert 3	71	7.2	17	16	3	59%*
Alert 4	**47**	**5.3**	**8**	**8**	**2**	**69%***
Reduction: Pre-Covid → Alert 4		-19%	-62%	-52%		
Annual AQG = 5 µg/m³ / Daily AQG = 15 µg/m³ (WHO, 2021)						

*Good practice is to have minimum 75% valid data (MfE, 2009).

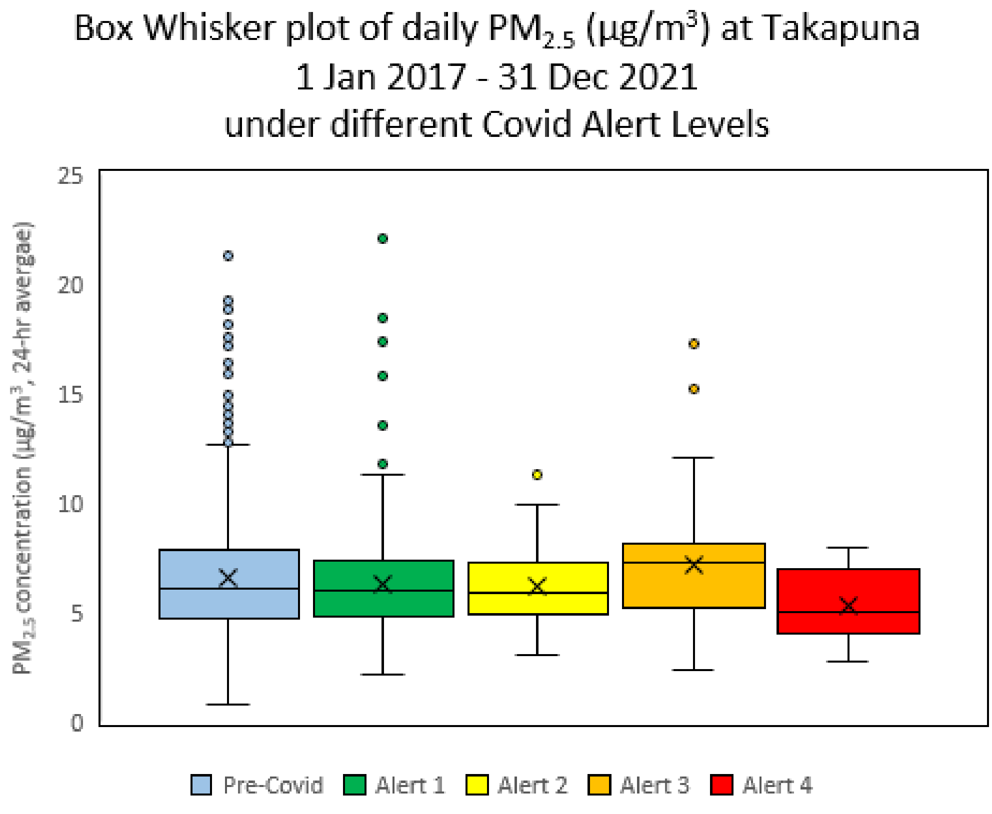

FIGURE 8: Box Whisker Plot of Auckland daily $PM_{2.5}$ at Takapuna 2017 - 2021 [Source: Auckland Council]

Unlike NO_2 which primarily (86%) arises from transport (Auckland Council, 2019), ambient $PM_{2.5}$ in Auckland have a significant (35%) natural component (Kuschel et al., 2022). This likely lessens the impact that social restrictions such as reduced transport may have had on ambient concentrations of $PM_{2.5}$. It is also conceivable that discharges of $PM_{2.5}$ from domestic solid fuel combustion (fireplaces) may have risen. The 2020 and 2021 restrictions occurred during autumn and winter and would have resulted in people spending more time at home than they otherwise would have with possibly increased domestic heating emissions.

Table 8 presents key statistics for daily $PM_{2.5}$ concentrations measured on the calendar days at Alert Level 4 (26 March – 27 April and 18 August – 21 September) in the years 2017-21 at the Takapuna monitoring site.[9] This comparison removes the effect of season (winter has the highest $PM_{2.5}$ emissions of all seasons and can also experience calm meteorological conditions that lead to high $PM_{2.5}$ concentrations).

Figure 9 presents this same comparison for the calendar days of Alert Level 4 in 2017-21 for daily $PM_{2.5}$ as a box whisker plot. Table 9 and Figure 9 show that when the same time of year is compared, the reduction in average daily $PM_{2.5}$ is more modest, at 13%.

TABLE 8: Daily $PM_{2.5}$ measured at Takapuna on Alert Level 4 calendar days in 2017-21 [Source: Auckland Council]

Alert Level	Count (days)	$PM_{2.5}$ (µg/m³)				Valid Data (%)
		Mean	Maximum	99th Percentile	Standard Deviation	
Pre-COVID	176*	6.2	13	12	2	86%
Alert 4	47	5.3	8	8	2	69%**
Reduction: Pre-Covid → Alert 4		-13%	-40%	-35%		
Annual AQG = 5 µg/m³ / Daily AQG = 15 µg/m³ (WHO, 2021)						

*Only valid monitoring days included. **Good practice is to have minimum 75% valid data (MfE, 2009).

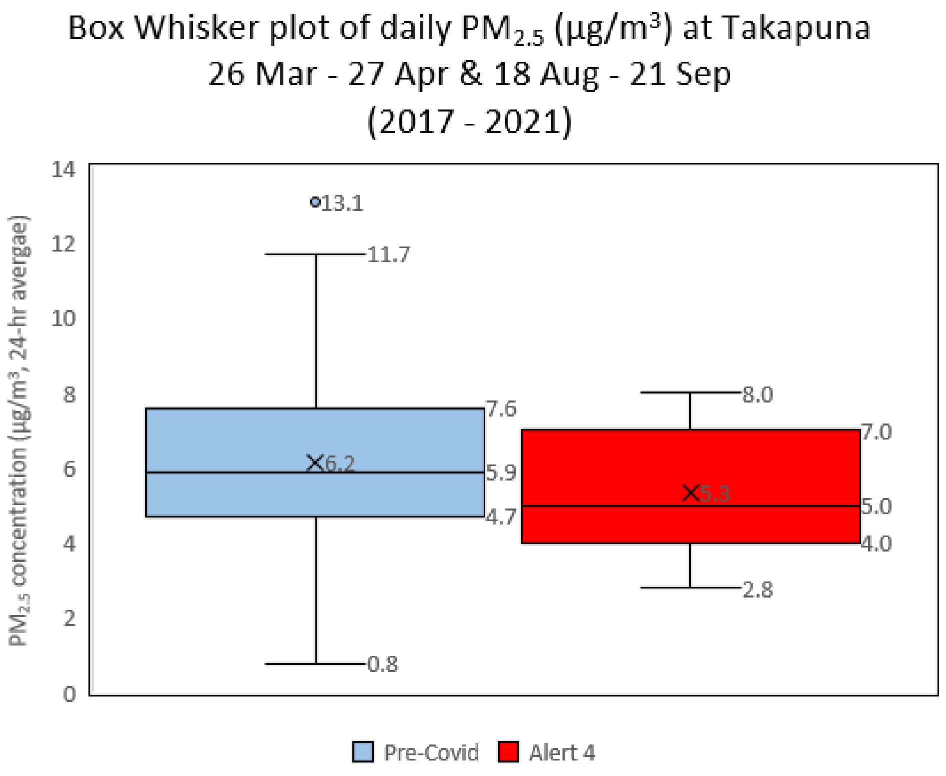

FIGURE 9: Box Whisker Plot of daily $PM_{2.5}$ at Takapuna on calendar days of Alert level 4 in 2017 – 2021 [Source: Auckland Council]

[9] NB: includes days at Alert Level 1 on 18 Aug – 21 Sep 2020 and Alert Level 2 on 26 Mar – 27 Apr 2021.

3.2.2 Annual $PM_{2.5}$

Health effects from chronic exposure to air pollution are more significant than effects from short-term exposure. This section reviews annual mean concentrations of $PM_{2.5}$ as follows:

Pre-COVID-19

- By census area unit for Auckland estimated for base year 2016 (Sridhar et al., 2022)
- Long-term trends at three monitoring locations in Auckland (Source: Auckland Council)

COVID-19 restrictions (2020-21)

- Two-year mean pre-COVID and during 2020-21 at three monitoring locations in Auckland (Source: Auckland Council)

$PM_{2.5}$ pre-pandemic

Long-term levels of $PM_{2.5}$ in Auckland are dominated by discharges to air from domestic solid fuel combustion. As a result, annual average concentrations of $PM_{2.5}$ are considered to be more uniform across the Auckland airshed than NO_2 (which aligns with traffic routes).

The HAPINZ 3.0 health impacts exposure model (Sridhar et al., 2022) utilises monitoring data for estimating annual average $PM_{2.5}$ concentrations in each census area unit.

The estimated population weighted 3-year mean $PM_{2.5}$ concentration in Auckland is 5.7 µg/m^3 (2016) (Sridhar et al., 2022).

Figure 10 presents the long-term data record of annual concentrations of $PM_{2.5}$ at three monitoring stations in Auckland:

- Takapuna (traffic/residential)
- Penrose (traffic/industrial)
- Patumahoe (rural)

Annual levels of $PM_{2.5}$ at the urban monitoring locations (Takapuna and Penrose) appear to show an overall long-term decline in annual $PM_{2.5}$ in Figure 9. This long-term trend is not assured, however, as the last five years (2015-19) suggest an *increase* in annual concentrations at all these urban monitoring sites.

There is a clear long-term, *increasing* trend in annual $PM_{2.5}$ concentrations at Patumahoe over the period 2010 – 2019. This may reflect the increasing population in this rural location.

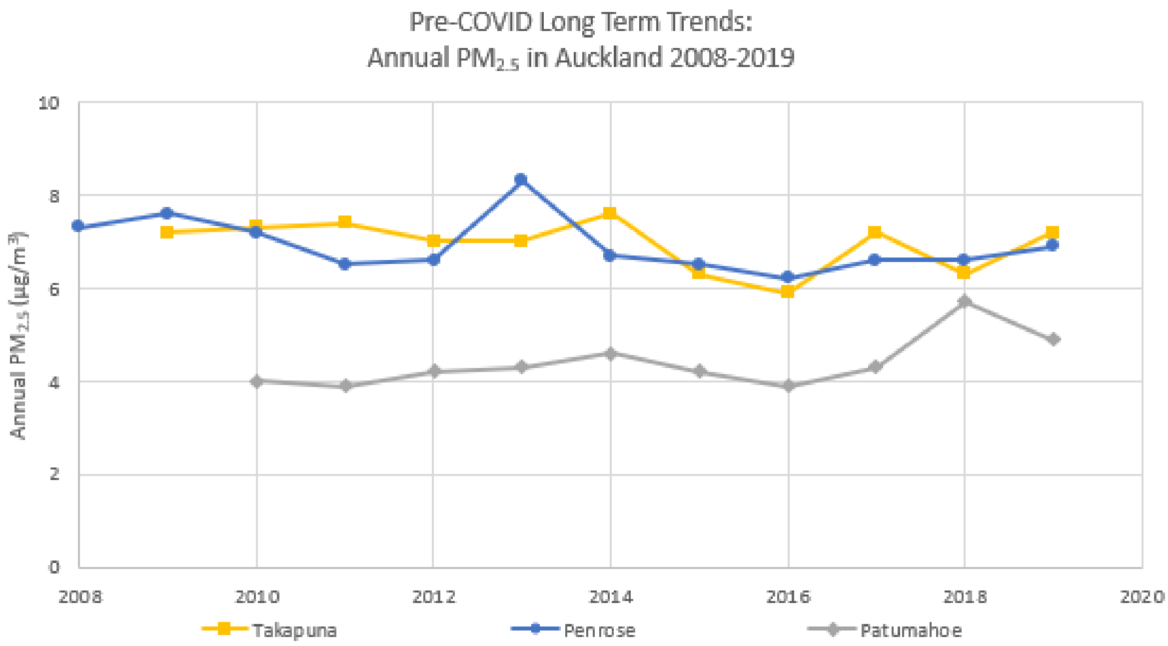

FIGURE 10: Long term trends: Annual $PM_{2.5}$ Concentrations in Auckland 2008 - 2019 [Source: Auckland Council]

$PM_{2.5}$ during Level 3 and 4 COVID-19 restrictions (2020-2021)

Table 9 presents 2-year mean concentrations of $PM_{2.5}$ measured at three monitoring locations in Auckland between 2016 and 2021. Table 9 also shows the difference between 2-year mean concentrations of $PM_{2.5}$ in 2020-21 compared with the 2-year mean in 2018-19 (pre-pandemic). The two-year mean $PM_{2.5}$ levels were little changed at two of three monitoring locations. The exception was Takapuna, which saw a 6% reduction in the 2-year mean $PM_{2.5}$ in 2020-21 compared with 2018-19. It is reasonable that this residential site better reflects changes in residential solid fuel combustion $PM_{2.5}$ emissions than the other monitoring locations.

There is an insufficient number of monitoring sites for the study period to support a box-whisker plot for annual $PM_{2.5}$ concentrations in Auckland.

TABLE 9: Two-year mean $PM_{2.5}$ measured at three monitoring sites in Auckland 2016 – 2021 [Source: Auckland Council]

Location	Site Type	2-year mean $PM_{2.5}$ (µg/m³)			∆ 2020-21 cf 2018-19
		2016-17	2018-19	2020-21	
Penrose	Traffic/Industrial	6.4	6.8	6.5	-3%
Takapuna	Traffic/Residential	5.9	7.0	6.2	-6%
Patumahoe	Rural	4.1	5.3	4.9	-1%
WHO AQG = 5 µg/m³					

Reduction in annual $PM_{2.5}$ attributable to COVID-19 restrictions

As shown in Figure 10, there is a clear, long-term *increase* in annual $PM_{2.5}$ concentrations at the only rural monitoring location in Auckland (Patumahoe). However, there does not appear to be any clear trend in annual $PM_{2.5}$ concentrations at the two urban monitoring locations in Auckland (Takapuna & Penrose). The last 20 years suggest a slow overall decline however, the last five years show an increase in annual $PM_{2.5}$. In the absence of a clear trend, we have assumed no change between 2016 (base case) and the mid-point of the initial 2-year mean (2018-19) for assessing COVID-19 restrictions.

Long-term concentrations of $PM_{2.5}$ in Auckland are predominantly influenced by residential solid fuel combustion. There is only one residential monitoring location in Auckland with long-term $PM_{2.5}$ data to estimate the difference between $PM_{2.5}$ concentrations during the period of COVID-19 restrictions and pre-pandemic $PM_{2.5}$ (Takapuna). Table 9 shows that this location measured a 6% reduction in the 2-year mean $PM_{2.5}$ in 2020-21 compared with 2018-19.

We attributed a 6% reduction in long-term $PM_{2.5}$ to COVID-19 restrictions.

This is somewhat conservative as the reduction would likely have been higher in the absence of restrictions (annual $PM_{2.5}$ increased in the last five years at Takapuna). This approach, however, ensures benefits are not overestimated.

3.3 MODELLED HEALTH BENEFITS

The modelling of accrued health benefits due to reduced air pollution during COVID-19 restrictions in 2020-21 assumed the following:

- A 20% reduction in NO_2 due to COVID-19 restrictions less a 5.2% reduction that would have occurred anyway.
- A 6% reduction for $PM_{2.5}$ due to COVID-19 restrictions.

The benefits were significant as shown in **Table 10**. The modelling estimates that over 2020 and 2021 as compared with the 2019 base case:

- 236 cases of premature mortality were averted with $1,070 million in averted social costs ($2019)
- 353 cardiovascular hospitalisations and 798 respiratory hospitalisations were averted
- 104,438 restricted activity days due to $PM_{2.5}$ were averted
- Asthma prevalence was lessened by 1,556 cases in under 18-year-olds

The modelling estimates that long-term exposure to $PM_{2.5}$ and NO_2 contributes around 12% to overall mortality in Auckland. The estimated 118 cases of premature mortality (per year) that were averted due to reductions in ambient air pollution from COVID-19 restrictions constitute a 1.5% reduction of this annual mortality.

TABLE 10: HAPINZ 3.0 exposure model differential estimates of health benefits associated with reductions in long-term NO_2 and $PM_{2.5}$ due to COVID-19 restrictions (-ve sign indicates cases/costs averted)

Difference from Base Year 2019 (Anthropogenic Only)			
Effect	**Cases/Year** (95% CI)	**Cases 2020-21** (95% CI)	**Social Cost 2020-21** $2019 million (low/high)*
Premature Mortality			
$PM_{2.5}$	-27	-53	-$241
NO_2	-92	-183	-$829
Total Prem. Mort.	**-118** (-115, -121)	**-236** (-231, -242)	**-$1,070** (-$958, -$1,239)
Cardiovascular Hospitalisations			
$PM_{2.5}$	-66	-132	-$5
NO_2	-110	-221	-$8
Respiratory Hospitalisations			
$PM_{2.5}$	-53	-106	-$3
NO_2	-346	-692	-$22
Total Hosp.	**-575**	**-1,151**	**-$38**
Restricted Activity Days			
$PM_{2.5}$	-52,219	-104,438	-$9
Asthma Prevalence 0–18-year-olds			
NO_2	-778	-1,556	-$0.2
Total Social Cost (Averted)		**-$1,118** (-$971, -$1,746)	

*Low/high-social cost estimates are for case estimates using exposure response function (not 95% confidence intervals)

3.4 SENSITIVITY TESTING, UNCERTAINTY & CONFIDENCE

The reduced exposure response functions (WHO, 2021) substantially lowered the health benefits estimated to accrue from COVID-19 restrictions as shown in **Table 11**.

An assessment of uncertainty and confidence was undertaken as detailed in **Appendix D**. Cumulatively, the overall uncertainty associated with the estimates is around +/-30%.

Overall, we have a moderate degree of confidence in the model estimates.

TABLE 11: Estimates of health benefits associated with reductions in long-term NO_2 and $PM_{2.5}$ due to COVID-19 restrictions based on WHO exposure response functions

Difference from 2018-2019 (Anthropogenic Only) [WHO exposure response functions]			
Effect	Cases/Year (95% CI)	Cases 2020-21 (95% CI)	Social Cost 2020-21 $2019 million (low/high)
Premature Mortality 2019			
$PM_{2.5}$	-21	-42	-$188
NO_2	-22	-44	-$197
Total Prem. Mort.	**-43** (-27, -65)	**-85** (-54, -130)	**-$385** (-$344, -$446)

*Low/high-social cost estimates are for case estimates using exposure response function (not 95% confidence intervals)

3.5 DISCUSSION

The reduction in daily levels of NO_2 is to be expected as the increasing restriction of movement associated with each Alert Level resulted in less vehicles on the road, with less emissions. However, Level 3 and 4 stay-at-home restrictions were only in place for 188 days over two years (26% of the time). Therefore, a 15% reduction in annual NO_2 levels, which excludes the long-term decline in ambient levels due to improved vehicle emissions regulation, is significant. The comparison of daily NO_2 levels during different Alert Levels (Figure 1) suggests most of this reduction may be attributable to reduced ambient NO_2 during Alert Level 4. We note construction and trade activities were permitted during Level 3, which may have lessened the significance of vehicle emissions reductions during Alert Level 3.

The increase in daily levels of $PM_{2.5}$ during Level 3 compared with Level 4 and pre COVID-19 periods was unexpected (Table 2). However, Level 3 had only 59% valid data, which is less than the required minimum of 75% to be representative. The higher levels recorded during this period mean that estimates of health effects avoided due to reduced concentrations may be underestimated.

The public health measure enacted to combat the COVID-19 pandemic in 2020 and 2021 including closed borders resulted in reduced hospitalisations for a wide variety of illnesses. For example:

- The number of respiratory disease hospitalisations per 1,000 people was nearly halved in 2020 compared with previous years (Kuschel et al., 2022).[10]
- New Zealand Health Survey data shows a significant drop in asthma prevalence for 2–14-year-olds in Auckland (EHINZ, 2022).

New Zealand was further notable in being one of a very few countries experiencing a **reduction** in excess mortality during 2020 and 2021 (Summers, Baker & Wilson, 2022). 'Excess mortality' is defined as the difference between the total number of deaths that have occurred and the number of deaths that would have been expected in the absence of the pandemic, i.e., a no-COVID-19 scenario.

Based on an excess mortality assessment published by the World Health Organization (WHO, 2022) Summer *et al.*, 2022 estimated that from the start of 2020 to the end of 2021 there were

[10] At page 142.

2,677 (95% confidence interval 2,206 to 3,178) fewer deaths in New Zealand than expected. Our estimate of 236 (95% confidence interval 231 to 242) premature deaths avoided (in Auckland) over this period due to annual reductions in air pollution comprises 9% of these fewer (national) deaths.

It is also worth noting that asthma prevalence is significant at around 36,000 cases in New Zealand, and a drop of just under 800 cases per year in Auckland (albeit only estimated for 0–18-year-olds) due to reduced exposure to long-term levels of NO_2 attributable to stay at home restrictions would be welcome.[11]

Numerous studies, both locally and globally, have reviewed the impacts of reductions in acute levels of pollutants due to COVID-19 restrictions (see for example, Chen K., et al., 2020, Lian et al., 2020, Venter et al., 2020, Talbot et al., 2021). As far as we are aware, this study is unique in assessing the impacts of COVID-19 restrictions on long-term concentrations and associated health effects.

It should also be noted that the Auckland area is somewhat unusual, from an international perspective, in enjoying an absence of elevated levels of ozone in its metropolitan area. This significantly simplifies consideration of the health impacts of COVID-19 restrictions (increases in ambient ozone have been noted in other metropolitan areas due to COVID-19 restrictions, see for example, Grange *et al*. 2021).

[11] Case numbers from EHINZ. [Online] Asthma prevalence (2-14 years). Total (unadjusted prevalence, %) (2017-2020). https://dashboards.instantatlas.com/viewer/report?appid=8eed490450534fa59bced69a44cd7c41

4. CONCLUSIONS

This study reviewed acute and chronic levels of NO_2 and $PM_{2.5}$ prior to and during the COVID-19 restrictions in 2020-21 in Auckland. From this review it was possible to ascertain reductions attributable solely to the COVID-19 restrictions and exclude reductions that were likely to occur anyway (specifically, a long-term decline in ambient NO_2 due to vehicle emissions regulations).

The modelling estimates that in Auckland over 2020 and 2021:

- 236 cases of premature mortality (95% confidence interval -231, -242) were averted with $1,070 million in averted social costs ($2019, low/high -$958M, -$1,239M).
- 353 cardiovascular hospitalisations and 798 respiratory hospitalisations were averted
- 104,438 restricted activity days due to $PM_{2.5}$ were averted
- Asthma prevalence was lessened by 1,556 cases in under 18-year-olds

Significant uncertainties are associated with the assumptions used to estimate pollution exposure and the simplification of the scenarios under consideration. Cumulatively, the overall uncertainty associated with the estimates is around +/-30%.

The HAPINZ 3.0 model utilises New Zealand specific exposure-response functions for NO_2 and $PM_{2.5}$. This means that the uncertainty in the exposure assessment is captured (to some extent) in the uncertainty of the exposure-response functions (and represented in the quoted 95% confidence intervals).

Sensitivity testing through modelling with exposure response functions recommended by WHO (2021) for 2020 and 2021 reduced the estimated avoided premature mortality to 85 cases (95% confidence interval -54, -130), for an avoided social cost of around $385 million ($2019, low/high -$344M, -$446M).

There is a moderate degree of confidence in the modelling estimates.

These estimates are confined to health benefits due to reduced public exposure to air pollution and do not reflect other benefits likely to directly accrue from the COVID-19 social restrictions (e.g., avoided hospitalisations and mortality from reduced incidence of influenza and other communicable diseases).

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APPENDIX A: TIMELINE OF COVID-19 PANDEMIC

2019	
1 Dec 2019	Earliest known onset of COVID-19 symptoms[12]
31 Dec 2019	China reports pneumonia of unknown origin to WHO
2020	
12 Jan 2020	WHO confirms novel coronavirus (SARS-CoV-2) from China
15 Jan 2020	First case confirmed in Japan
28 Jan 2020	NZ sets up National Health Coordination Centre
30 Jan 2020	**WHO declares public health emergency of international concern**
31 Jan 2020	First case confirmed in Italy
3 Feb 2020	NZ closes border to foreigners from China (only)
27 Feb 2020	Japan closes all schools for 3 million students
28 Feb 2020	First case confirmed in New Zealand, travel ban extended to Iran
8 Mar 2020	Hospitals in Lombardy, Italy overrun, regional COVID-19 restrictions commence
11 Mar 2020	**WHO declares pandemic**
14 Mar 2020	Anyone entering New Zealand must self-isolate for 14 days (except arrivals from the Pacific)
16 Mar 2020	Cruise ships banned
19 Mar 2020	**NZ borders closed to non-residents & self-isolation required for returnees** **Indoor gatherings of more than 100 people are to be cancelled**
21 Mar 2020	National Alert Level 2 (2 days)
23 Mar 2020	National Alert Level 3 (3 days)
26 Mar 2020	National Alert Level 4 (33 days) State of National Emergency declared
29 Mar 2020	First COVID-19 related death in New Zealand
28 Apr 2020	National Alert Level 3 (16 days)
4 May 2020	No new cases reported in New Zealand
14 May 2020	National Alert Level 2 (26 days) State of National Emergency expires
8 Jun 2020	No active cases of COVID-19 in New Zealand
9 Jun 2020	National Alert Level 1
11 Aug 2020	Four new cases of COVID-19 reported in the community
12 Aug 2020	Auckland at Alert Level 3 (19 days) / Rest of NZ at Alert Level 2 (41 days)
31 Aug 2020	Auckland at Alert Level 2+ (24 days)

[12] Wu, Yi-Chi et al., 2020.

22 Sep 2020		Rest of NZ at Alert Level 1
24 Sep 2020	Auckland at Alert Level 2 (14 days)	
8 Oct 2020	Auckland joins rest of New Zealand at Alert Level 1	
2021		
14 Feb 2021	Three new cases of COVID-19 reported in the community	
15 Feb 2021	Auckland at Alert Level 3 (3 days)	Rest of NZ at Alert Level 2 (3 days)
18 Feb 2021	Auckland at Alert Level 2 (5 days)	Rest of NZ at Alert Level 1
23 Feb 2021	Auckland joins rest of New Zealand at Alert Level 1	
28 Feb 2021	Auckland at Alert Level 3 (7 days)	Rest of NZ at Alert Level 2 (7 days)
7 Mar 2021	Auckland at Alert Level 2 (5 days)	Rest of NZ at Alert Level 1
12 Mar 2021	Auckland joins rest of New Zealand at Alert Level 1	
24 Jun 2021	Wellington at Alert Level 2 (6 days)	Rest of NZ at Alert Level 1
30 Jun 2021	Wellington joins rest of New Zealand at Alert Level 1	
18 Aug 2021	National Alert Level 4 (14 days)	
1 Sep 2021	Auckland (35 days) & Northland (16 days) at Alert Level 4	Rest of NZ at Alert Level 3 (7 days)
3 Sep 2021	Auckland at Alert Level 4	Northland joins rest of NZ at Alert Level 3 (5 days)
8 Sep 2021		Rest of NZ at Alert Level 2 (86 days)
22 Sep 2021	Auckland & Upper Hauraki at Alert Level 3	
26 Sep 2021	Auckland (only) at Alert Level 3	
4 Oct 2021	Auckland, parts Waikato at Alert Level 3	
9 Oct 2021	Auckland, parts Waikato & Northland at Alert Level 3	
20 Oct 2021	Auckland, parts Waikato at Alert Level 3	Northland joins rest of NZ at Alert Level 2
2 Nov 2021	Auckland, parts Waikato & Upper Northland at Alert Level 3	Rest of NZ at Alert Level 2
11 Nov 2021	Auckland, parts Waikato at Alert Level 3	Northland joins rest of NZ at Alert Level 2
16 Nov 2021	Auckland (only) at Alert Level 3 (72 days)	Waikato joins rest of NZ at Alert Level 2
3 Dec 2021	NZ moves to COVID-19 Protection Framework (traffic lights)[13]	

[13] For this study the "orange" setting is assumed equivalent to Alert Level 2

APPENDIX B: AUCKLAND COUNCIL AIR QUALITY MONITORING SITES

Figure B-1: Auckland Council air quality monitoring sites in Auckland [Source: lawa.org.nz]

*Pakuranga site does not measure NO_2 or $PM_{2.5}$

APPENDIX C: UPDATED HAPINZ 3.0 MODEL

Table C-1 presents the updated estimates from the HAPINZ model for a base year of 2019. These are little changed from the 2016 base year.

Table C-1: HAPINZ 3.0 model estimates (anthropogenic only) for base years 2016 and 2019

HAPINZ 3.0 Estimates (Anthropogenic Only)				
Effect	**2016**		**2019**	
	Cases/year	**Social Cost $M/year ($2019)**	**Cases/year**	**Social Cost $M/year ($2019)**
Annual $PM_{2.5}$	6.6		6.4	
Annual NO_2	8.0		7.4	
Population	1,608,140		1,661,300	
Premature Mortality				
$PM_{2.5}$	255	$1,153	274	$1,241
NO_2	685	$3,101	672	$3,044
Total Mortality:	**939**	**$4,253**	**946**	**$4,284**
Cardiovascular Hospitalisations				
$PM_{2.5}$	607	$22	680	$25
NO_2	757	$28	778	$29
Respiratory Hospitalisations				
$PM_{2.5}$	521	$17	541	$17
NO_2	2,747	$87	2,617	$83
Total Hospitalisations:	**4,633**	**$154**	**4,615**	**$154**
Restricted Activity Days				
$PM_{2.5}$	483,132	$43	520,942	$46
Asthma prevalence 0-18 year olds				
NO_2	6,144	$0.8	5,839	$0.8
Total Social Cost:		**$4,451**		**$4,485**

APPENDIX D: UNCERTAINTY & CONFIDENCE ASSESSMENT

The key sources of uncertainty in an assessment of air pollution health impacts are described as follows.

Air pollutants exist as a complex mixture

There is a considerable body of evidence from epidemiological studies confirming the adverse health effects associated with exposure to air pollution. Notably, WHO determined all PM-outcome associations were deemed causal, or likely to be causal (WHO, 2021). However, the adverse effects attributed to nitrogen dioxide may actually be attributable to other pollutants in the mixture.

Baseline disease burden

Data on the number of deaths and cases of disease can be uncertain, particularly if data from a number of sources are combined or if projections of future cases are made. In this study, health incidence statistics in the HAPINZ 3.0 model for a base year 2016 were assumed to be stable for an increased population in a base year 2018-19.

Of note:

- Kuschel et al., estimates only a negligible error when projecting baseline *mortality* two years into the future (+/-0.02%).
- Kuschel at al., estimates baseline *morbidity* is subject to a small error (+/-3.7%) when projecting two years into the future.

Pollution exposure level

This is a potentially significant limitation of the modelling. The approach in this study was to average reductions in measured pollutant concentrations at different monitoring locations to estimate an overall Auckland-wide reduction. Specifically, we compared 2-year mean concentrations measured pre-COVID-19 and during COVID-19 restrictions (i.e., long-term concentrations of NO_2 and $PM_{2.5}$ in 2020-21 as compared with 2018-19). The use of a 2-year mean, a relatively stable parameter, increases the confidence that the reduction is real.

However, there were only three monitoring stations for $PM_{2.5}$ and six monitoring stations for NO_2; some of which had very different emissions profiles.

We estimate this may introduce an error of around +/-20% to the overall assessment.

The exposure-response function

Exposure response functions are derived from epidemiological studies, in which assumptions made in the analysis inevitably introduce some uncertainty into the results. The HAPINZ 3.0 model utilises New Zealand specific exposure-response functions for NO_2 and $PM_{2.5}$. This means that the uncertainty in the exposure assessment is captured (to some extent) in the uncertainty of the exposure-response functions (and represented in the quoted 95% confidence intervals).

The counterfactual level of air pollution

The counterfactual level of air pollution is the baseline or reference exposure against which the health impacts of air pollution are calculated (e.g., having no air pollution). This is not a source of uncertainty in itself.

The modelling was differential, i.e., only changes were assessed for the purpose of assessing the impact of COVID-19 restrictions. As such the modelling estimates are not sensitive to the counterfactual.

Deliberate simplification of the model

In this assessment only single scalars were able to be used to represent airshed wide reductions in population exposure to pollutants during COVID-19 restrictions in 2020-21. Reductions were averaged across data from all available monitoring sites. We estimate this may introduce an additional error of around +/-10 to the overall assessment.

Confidence Assessment

Hales et al., assessed the risk of bias in accordance with WHO, 2020 and concluded it was low for all factors except potential confounding due to the inability to control for BMI due to a lack of data in NZ health incidence statistics. This increased the overall risk of bias to low-to-moderate.

The HAPINZ 3.0 model has been internationally peer reviewed and warrants a high degree of confidence for the base case 2016 (Kuschel et al., 2022). Similarly, WHO has stated their recommended exposure response functions support a high degree of certainty of evidence (WHO 2021).

The HAPINZ 3.0 model has been updated with 2018-2019 air quality, population and health incidence data which increases its representativeness. The projection of two years (2020-21) will add only negligible uncertainty to baseline mortality statistics (<1%) and only minor uncertainty to baseline morbidity statistics (<5%). Significantly higher uncertainties are associated with the assumptions used to estimate pollution exposure and the simplification of the scenarios under consideration. Cumulatively, the overall uncertainty associated with the estimates is around +/-30%.

Overall, we have a moderate degree of confidence in the model estimates.

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