# Air Quality Monitoring in the Terrace & Mt Victoria Tunnels, Wellington

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# Executive Summary

This is the third report produced by NIWA for NZTA (previously Transit NZ) regarding air quality in State Highway tunnels. The first report *"Guidelines for the Management of Air Quality In and Around Road Tunnels in New Zealand"* reviewed and recommended air quality guidelines to apply to the **interior** of road tunnels, for which no prior guidelines exist in this country. A summary of these guidelines is presented below in Tables a and b.

The second report *"Scoping Assessment of Air Quality in and around State Highway Tunnels"* reviewed available historical data describing air quality in and around the Terrace, Mt Victoria, Lyttelton and Homer tunnels. It extrapolated the available data describing air quality inside the tunnels to the present day based upon the assumption of reductions in the average emissions per vehicle, as predicted by the NZ-specific emission model VEPM. It concluded that there was a risk of the recommended guidelines being exceeded but that the quality and quantity of data available led to relatively low confidence in the extrapolated predictions.

Subsequently, NZTA commissioned NIWA to conduct air quality monitoring campaigns **inside** the Terrace and Mt Victoria tunnels in Wellington. This report presents the findings of that monitoring. The purpose of the study is to characterise current air quality inside the tunnel bores where traffic passes. This study **does not** consider air quality external to the tunnels or the risks to health of tunnel users or workers, other than the risk of non-compliance with the recommended air quality guidelines.

Monitoring of concentrations of the two pollutants covered by the recommended guidelines - carbon monoxide (CO) and nitrogen dioxide ($NO_2$) – was conducted within the Terrace tunnel from 9th September 2008 to 11th October 2008 and within the Mt Victoria tunnel from 20th October 2008 to 18th December 2008.

During our monitoring period the **Terrace tunnel** met the NIWA-recommended guidelines for the public for both CO and $NO_2$ by a significant margin. The tunnel also met the more restrictive PIARC (2010) recommendation of 70 ppm of CO. The 8-hour occupational safety guideline was met, as was the more restrictive PIARC guideline of 20 ppm, albeit by a small margin.

The jet fans installed in the Terrace Tunnel were found to be generally effective in providing sufficient dilution of air pollutants. Evaluating the potential to optimise the ventilation system was beyond our scope – however the data captured could be further analysed to investigate this. Systematically worse air quality was observed in the Terrace tunnel during northerly winds. This was suggestive of the ventilation fans blowing in the wrong direction – however this did not lead to breach of the CO guidelines. Air quality was substantially improved since 2003. This was at least partly due to the increasing numbers of new technology reduced-emission vehicles penetrating the vehicle fleet. Considerable protection from the effects of air pollution in the tunnel is provided by the fact that typical exposure times for the public are far below 15 minutes.

During our monitoring period the **Mt Victoria tunnel** met both the recommended 15 minute CO guideline for public users, and PIARC 2010 guideline, except during the period of 7am – 8am local time during which the PIARC 2010 guideline of 70 ppm was exceeded twice over a 2-month period. Although the 30 ppm occupational safety guideline was not exceeded, this was by a small margin (maximum observed 8-hour concentration was 24.5 ppm). The more demanding 20 ppm limit recommended by PIARC was exceeded 2 % of the time for which data exist. The risk of non-compliance was limited to 8-hour shifts ending between 1 pm and 11 pm local time.

The Mt Victoria tunnel met the recommended $NO_2$ guidelines.

Air quality in the Mt Victoria tunnel was also substantially improved since 2003. This was again at least partly due to the increasing numbers of new technology reduced-emission vehicles penetrating the vehicle fleet. Whereas vehicle users are offered considerable protection due to journey times usually being far below 15 minutes, this protection is reduced for pedestrians, especially those for whom the journey time may approach 15 minutes. However, the risk presented is still acceptable as long as the tunnel meets the 15-minute CO guideline.

Concentrations of $NO_2$ in both tunnels were low compared to both the guidelines and worst-case predictions in the Scoping Assessment. This was because the dominant source of $NO_2$ was indirect production of $NO_2$ through chemical reactions rather than direct vehicle emission. This chemical pathway requires ozone, which must penetrate into the tunnel from outside, but which is also depleted in the formation of $NO_2$. Our data showed that very little ozone penetrated into the tunnel due to its chemical and/or physical depletion, thus strongly limiting $NO_2$ concentrations. We observed rare and short-lived "chemical events" in which $NO_2$ could be rapidly produced inside the tunnel. This may have been due to the occasional penetration of ozone deep into the

tunnel, which may be more probable in the shorter Terrace Tunnel, or could be due to the temporary introduction of reactive chemicals, such as VOCs. We have insufficient data to preferentially support either hypothesis.

**Table a: Summary of NIWA's recommended guidelines for Occupational Safety for the protection of healthy adults working in a tunnel:**

| Contaminant | Threshold concentration | Averaging time | notes |
|---|---|---|---|
| CO | 200 ppm | 15 minutes | equivalent to NZ Workplace Standard |
| CO | 30 ppm | 8 hours | widely adopted abroad, PIARC 1995 recommendation |
| $NO_2$ | 1 ppm | | equivalent to NIOSH Recommended Exposure Limit |

**Table b: Summary of NIWA's recommended guidelines for all non-occupational users:**

| Contaminant | Threshold concentration | Averaging time | notes |
|---|---|---|---|
| CO | 87 ppm | 15 minutes | equivalent to WHO ambient guideline[1], widely adopted in Australia |
| $NO_2$ | 1 ppm | | PIARC proposal |

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[1] WHO guideline is 100 mg m$^{-3}$. If converted at 25° C (as is the convention in at least the EU, the US, Japan) this is equivalent to 87 ppm. If converted at 0° C, which is the convention in New Zealand (as recommended by MfE) this is equivalent to 80 ppm.

**Table c: Summary of peak pollutant concentrations and guideline compliance in the tunnels:**

| guideline | Terrace | | Mt Victoria | |
|---|---|---|---|---|
| | Max observed | Guideline exceedence | Max observed | Guideline exceedence |
| Public users: | | | | |
| CO, 87 ppm, 15 minutes | 30.1 ppm | nil | 75 ppm | nil |
| NO$_2$, 1 ppm | 0.45 ppm | nil | 0.16 ppm | nil |
| Occupational safety: | | | | |
| CO, 200 ppm, 15 minutes | 30.1 ppm | nil | 75 ppm | nil |
| CO, 30 ppm, 8 hours | 17.9 ppm | nil | 24.46 ppm | nil |

# Abbreviations

| | |
|---|---|
| AADT | annual average daily traffic |
| ANZS | Australia/New Zealand Standards |
| CO | carbon monoxide |
| HCV | heavy commercial vehicle |
| HGV | heavy goods vehicles |
| LCV | light commercial vehicle |
| NIOSH | National Institute for Occupational Safety and Health |
| NO | nitric oxide |
| $NO_2$ | nitrogen dioxide |
| $NO_x$ | oxides of nitrogen ($NO + NO_2$) |
| NZTER | New Zealand Traffic Emission Rates |
| $O_3$ | ozone |
| OH | hydroxyl radicals |
| PIARC | Permanent International Association of Road Congresses |
| ppb | parts per billion |
| ppm | parts per million |
| VEPM | Vehicle Emissions Prediction Model |
| VOCs | volatile organic compounds |
| WHO | World Health Organisation |

# 1. Introduction and scope

## 1.1 Background

In 2007 Transit New Zealand commissioned NIWA to develop guidelines for the management of air quality within State Highway road tunnels. This resulted in two reports, which were delivered to Transit in draft form in June 2008:

1. Guidelines for the Management of Air Quality in and around Road Tunnels in New Zealand (NIWA report AKL-2008-058)

2. Scoping Assessment of Air Quality in and around State Highway Tunnels (NIWA report AKL-2008-059)

The Scoping Assessment indicated a large degree of uncertainty surrounding the current air quality in both the Mt Victoria and Terrace tunnels, and whether their respective ventilation systems could deliver air quality meeting the guidelines recommended in the first report. Detailed assessment involving experimental monitoring campaigns for both tunnels was recommended. Transit NZ (now NZTA) accepted the recommendations and commissioned NIWA to conduct the suggested monitoring campaigns. This report summarises the findings of the campaigns and provides an extended detailed assessment.

## 1.2 Objectives

The objectives of the monitoring described in this report, and the analysis of the resulting data are:

1. To characterise current air quality (with respect to carbon monoxide, CO, and nitrogen dioxide, $NO_2$) inside the Terrace and Mt Victoria tunnels with respect to the road tunnel guidelines recommended by NIWA.

2. To interpret the determinants of the current air quality, such that the representativeness of the observation period and likely air quality at other times and in the near future could be assessed.

3. To provide current data to compare with that gathered in 2003 and before (as presented in the Scoping Assessment) and evaluate whether changes since then are consistent with the emission reductions predicted as a result of

developments in engine and emission control technology and the penetration of such technology into the vehicle fleet.

An additional objective which will be addressed if it is practical to do so is:

4. To determine the processes forming $NO_2$ in the tunnel and whether or not it is likely that each tunnel is subject to internal $NO_2$ production.

## 1.3    Scope

The scope of this study includes:

- Air quality with respect to the NIWA-recommended tunnel guidelines for the protection of members of the public using the tunnels regardless of mode,

- Air quality with respect to occupational safety guidelines for the protection of authorised persons working within the tunnels.

The scope of this study does not include:

- Air quality external to the tunnels,

- Health impacts or risks for tunnel users or workers,

- Predicted changes to air quality arising from any proposed or hypothetical changes to the design or operation of the tunnels or their ventilation.

## 1.4    Report format

The observational campaign described in this report is more than just a conventional air quality monitoring project. The analysis and interpretation required are more detailed than is often the case for air quality monitoring, and the guidelines against which observed air quality is being compared are not the conventional ambient guidelines, but tunnel-specific and still yet to be formally adopted in this country. Furthermore, we appreciate that this report may have a wider readership than is often the case for technical air quality reports.

As a consequence, this report has a different structure from that usually found in monitoring reports. The chapters are set out so that chapter 2 presents the key findings

for NZTA in terms of observed air quality in the tunnels with respect to guidelines established in a previous report to NZTA (see above). It effectively presents an extended executive summary.

Chapters 3 and 4 present further detail of an increasingly technical nature which aims to extract general conclusions about the present and future air quality in the tunnels.

Chapters 5 and 6 consist of an exploratory analysis of the longer term implications of meeting air quality guidelines in light of expected changes to vehicle emissions (arising from technological and traffic changes).

Chapter 7 presents overall conclusions.

The Technical Annex presents details of the instruments and methods used to measure, capture and quality control the observational data.

## 1.5 The Terrace tunnel

The Terrace tunnel was opened in 1978 and forms part of the Wellington Inner City Bypass on SH1N in central Wellington. Its location is shown in Figure 1. According to NZTA data, annual average daily traffic (AADT) in 2006 was 41 031, and traffic volume has been stable at just over 40 000 since 1998. The proportion of heavy goods vehicles (HGVs) is unknown, but anecdotal evidence suggests it is low. The posted speed limit was originally 100 km h$^{-1}$ but has recently been reduced to 80 km h$^{-1}$.

The tunnel is 460 m long, has a 1:40 gradient and has two northbound lanes and one southbound lane as shown in figure 2. It is unusual in having longitudinal ventilation in a single bi-directional tube. The original design had two three-lane uni-directional tubes for which longitudinal ventilation is appropriate but only one tube was constructed. Consequently, the longitudinal ventilation can be operated in either direction, in an attempt to aid the prevailing airflow. The prevailing airflow is detected using an anemometer at the southern end of the tunnel. The ventilation control system originally included feedback from three CO sensors, but this system was replaced with one based on observations of traffic speed and wind speed as proxies for emissions and dispersion respectively.
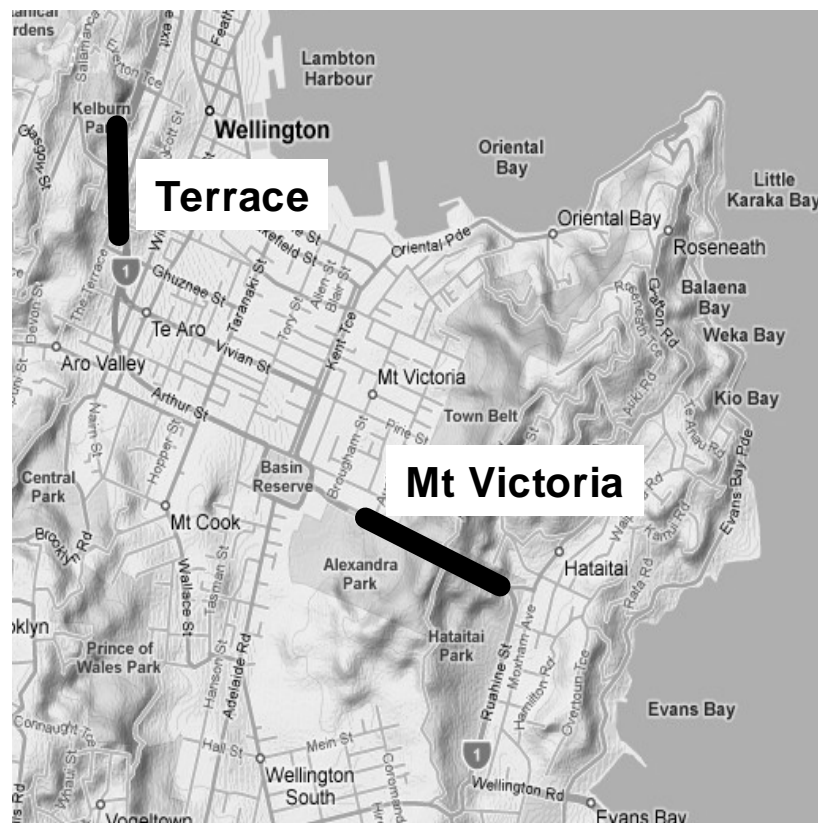
**Figure 1: Location of the Terrace and Mt Victoria tunnels.**



**Figure 2: Layout of the Terrace tunnel looking south.**

## 1.6 The Mt Victoria tunnel

The Mt Victoria Tunnel was opened in 1931. It is located on the eastern edge of central Wellington and carries SH1N through Mt Victoria providing access to Wellington Airport, as well as the suburbs of Kilbirnie, Miramar, Seatoun and Lyall Bay. AADT in 2006 was 38077, and traffic volume has been stable at 36 – 39 000 since monitoring began in 1997. The proportion of HGVs is approximately 2 %. The posted speed limit is 50 km h$^{-1}$, but congestion regularly reduces speeds well below this.

The tunnel is 623 m long, has a 1:100 gradient and consists of a single tube. Within this tube traffic is bi-directional with a single lane of traffic in each direction as shown in figure 3. The tunnel has mechanical transverse ventilation, with fresh air being drawn into a parallel duct via a fan house alongside both portals and released into the tunnel bore via slots along its length. Vitiated air is drawn through slots in the tunnel ceiling and extracted via vertical exhaust ducts. The fans have only a single operating speed and during the monitoring campaign were manually switched on at 6 am local time and off at 11 pm local time.



**Figure 3: Layout of the Mt Victoria tunnel looking west.**

# 2. Key Results

## 2.1 Purpose of this chapter

This chapter discusses the first and principal objective of the campaign – to assess current air quality in the tunnels with respect to the guidelines recommended by NIWA.

## 2.2 Recommended air quality guidelines inside road tunnels

NIWA recommended to Transit New Zealand (Longley *et al*., 2008b) that a guideline be adopted to ensure that any road tunnel is a safe environment and that a single traverse of any given tunnel does not give rise to adverse acute health effects. The recommended guideline was that concentrations of carbon monoxide do not exceed 87 ppm as a 15-minute moving average at any time. This is equivalent to the World Health Organisation's guideline for ambient exposure[2]. The World Road Congress (PIARC) has also recommended a guideline for CO of 70 ppm as a 15-minute average to be in force from 2010. NIWA's review was unable to find any health-based evidence upon which such a tightening of the CO guideline could be justified.

NIWA also recommended a guideline of 1 ppm of nitrogen dioxide. This is equivalent to a recommendation from PIARC. It was not possible to state an appropriate averaging time for this guideline due to gaps in the scientific understanding of the action of this pollutant on the body. The guideline is intended to protect asthmatics, which may become sensitized through inhalation of the gas, and as a precautionary measure against delayed or chronic effects on the health of tunnel users.

These guidelines for tunnel users are summarised in Table 1 below.

NIWA also recommended a guideline for **occupational** exposure of 30 ppm of CO, as an 8 hour average. The World Road Congress (PIARC) has also recommended a guideline for CO of 20 ppm as an 8-hour average to be in force from 2010. These are also listed in Table 2.

All guidelines are quoted in units of ppm (i.e. parts per million by volume), as this is the international convention for road tunnel management. This differs from ambient air quality standards and guidelines, which are expressed in mass-based units, e.g. $\mu$g

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[2] WHO guideline is 100 mg m$^{-3}$. If converted at 25° C this is equivalent to 87 ppm. If converted at 0° C (as recommended by MfE in New Zealand) this is equivalent to 80 ppm.

$m^{-3}$. Conversion between these units is pollutant-dependent and also dependent upon the standard temperature and pressure adopted[3]. However, as this report deals exclusively with in-tunnel and not ambient concentrations, and the fact that ambient standards and guidelines do not apply inside road tunnels, all concentrations in this report are expressed in volume-based units (i.e. ppm or ppb).

**Table 1: Summary of NIWA's recommended guidelines for all non-occupational users:**

| Contaminant | Threshold concentration | Averaging time | notes |
|---|---|---|---|
| CO | 87 ppm | 15 minutes | equivalent to WHO ambient guideline[4], widely adopted in Australia |
| $NO_2$ | 1 ppm | | PIARC proposal |

**Table 2: Summary of NIWA's recommended guidelines for Occupational Safety for the protection of healthy adults working in a tunnel:**

| Contaminant | Threshold concentration | Averaging time | notes |
|---|---|---|---|
| CO | 200 ppm | 15 minutes | equivalent to NZ Workplace Standard |
| CO | 30 ppm | 8 hours | widely adopted abroad, PIARC 1995 recommendation |
| $NO_2$ | 1 ppm | | equivalent to NIOSH Recommended Exposure Limit |

In our recommendations to Transit NZ, we also noted that more demanding $NO_2$ guidelines have been adopted or recommended elsewhere, as listed below in Table 3. A discussion as to why such a range of guidelines exist is contained in Longley *et al.* (2008).

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[3] In New Zealand a standard temperature and pressure of 0 °C and 1 atm are adopted for unit conversion. At these conditions 1 ppm CO = 1.25 mg $m^{-3}$, 1 ppb NO = 1.34 mg $m^{-3}$, 1 ppm $NO_2$ = 2.05 mg $m^{-3}$ and 1 ppb $O_3$ = 2.14 μg $m^{-3}$.
[4] WHO guideline for CO is 100 mg $m^{-3}$. If converted at 25° C this is equivalent to 87 ppm. If converted at 0° C (as recommended by MfE in New Zealand) this is equivalent to 80 ppm.

**Table 3: Other road tunnel air quality guidelines for nitrogen dioxide adopted elsewhere:**

| Threshold concentration | Averaging time | notes |
|---|---|---|
| 1 ppm | 5 mins | Hong Kong |
| 0.4 ppm | Unspecified | Norway |
| 0.2 ppm | 1 hour | Sweden, Belgium |
| 0.11 or 0.10 ppm[5] | 1 hour | WHO ambient guidelines |
| 0.5 ppm | 20 mins | Belgium |
| 0.4 ppm | 15 mins | France from 2010 |

### 2.3  Overview of observations made and omissions

The Technical Annex contains full details of instruments deployed, dates, locations and data processing. In brief, concentrations of carbon monoxide (CO) and nitrogen dioxide ($NO_2$) were measured continuously inside both tunnels. We also conducted measurements of basic meteorological parameters outside the Terrace Tunnel's southern portal and outside the Mt Victoria Tunnel's western exhaust stack. Additional measurements included wind speed and direction inside the Mt Victoria Tunnel only.

Special traffic observations were not conducted for this campaign. Hourly average traffic volume data was obtained from NZTA for both tunnels. These data are incomplete and do not cover the same periods as our monitoring campaign. However, as discussed in chapter 3, traffic volumes vary little from day to day, so we are confident that these data are representative of normal conditions in the tunnel during our campaign. Observations of vehicle fleet composition and reduced speeds (as a result of congestion) are important for interpreting emissions (see chapter 5). The existing NZTA counters do not provide this information. Traffic counting methods have a reduced reliability and accuracy in such driving conditions. We chose, therefore, not to install additional counting technology. Our original plan was to rely on manual and in-flow (car-based) observations. However, this is highly labour-intensive and proved not to be logistically feasible within the time scale and resources available.

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[5] The guideline is 200 μg m$^{-3}$, which is equivalent to 0.11 ppm when converted at 25° C, but is equivalent to 0.1 ppm at 0° C. MfE recommends the latter conversion factor.

Further parameters of importance include the operation of the tunnel's ventilation systems and tunnel closures for maintenance. Where available this information has been sourced from Fulton Hogan, the contractor operating the tunnels.

## 2.4 Terrace Tunnel

### 2.4.1 Monitoring arrangement

At the Terrace Tunnel air was sampled at a point at 1.8 m above road level on the eastern wall, 230 m into the tunnel from the southern portal and drawn through a duct to the instruments located in a trailer 60 m south of the southern portal giving a total sampling distance of 300 m. Further details are contained in the Technical Annex.

### 2.4.2 Overview of data

Descriptive statistics for the full monitoring period from 9th September 2008 are provided in Table 4, based on **15 minute moving averages**. Note that the $NO_x$ analyser's range (0 – 3 000 ppb) was exceeded for 15 minutes on 29th September 2008, resulting in missing data.

**Table 4: Descriptive statistics for monitored pollutants (15-minute moving averages) in the Terrace Tunnel.**

|  | CO / ppm | $NO_2$ / ppm | NO / ppm | $O_3$ / ppb |
|---|---|---|---|---|
| Max | 30.1 | 0.45 | 3.20[6] | 32.0 |
| Mean | 7.6 | 0.03 | 0.93 | 4.8 |
| Median | 6.9 | 0.03 | 0.83 | 4.7 |
| Min | 0.0 | 0.00 | 0.00 | -5.4 |
| Interquartile range | 3.3 – 11.1 | 0.02 – 0.04 | 0.35 – 1.42 | 3.2 – 6.2 |
| Guideline for users | 87 | 1[7] | None | None |
| Guideline for occupational safety | 30[8] | None | None | none |

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[6] Highest concentration recorded but it would have been higher when the analyser exceeded the set range

[7] Or 0.4 ppm in France and Norway.

[8] As an 8 hour moving average.

### 2.4.3 Carbon Monoxide

The 15-minute moving average CO concentrations are shown in Figure 4. The highest concentration observed was 30.1 ppm. On average the 15-minute CO concentration was 7.6 ppm. We conclude, that during our monitoring period the Terrace tunnel met the recommended 15 minute CO guideline with ease, with concentrations being below one tenth of the guideline on average and 35 % of the guideline in the worst case. The tunnel also meets the PIARC recommendation of 70 ppm of CO from 2010.

The maximum 8-hour moving average CO concentration observed was 17.9 ppm (see full time series in Figure 5). Thus, not only was the NIWA recommended guideline met during our observation period, but so was the more demanding 20 ppm limit recommended by PIARC (PIARC, 1995, see also Longley *et al*., 2008b for more detail), albeit by a minute margin.
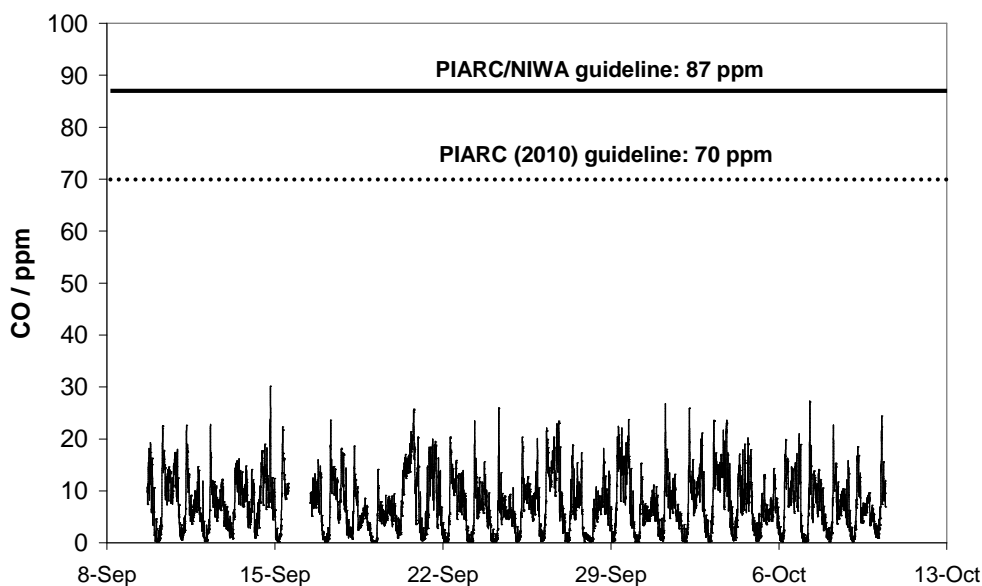


**Figure 4: Observed 15-minute moving average CO concentrations and non-occupational exposure guideline values.**
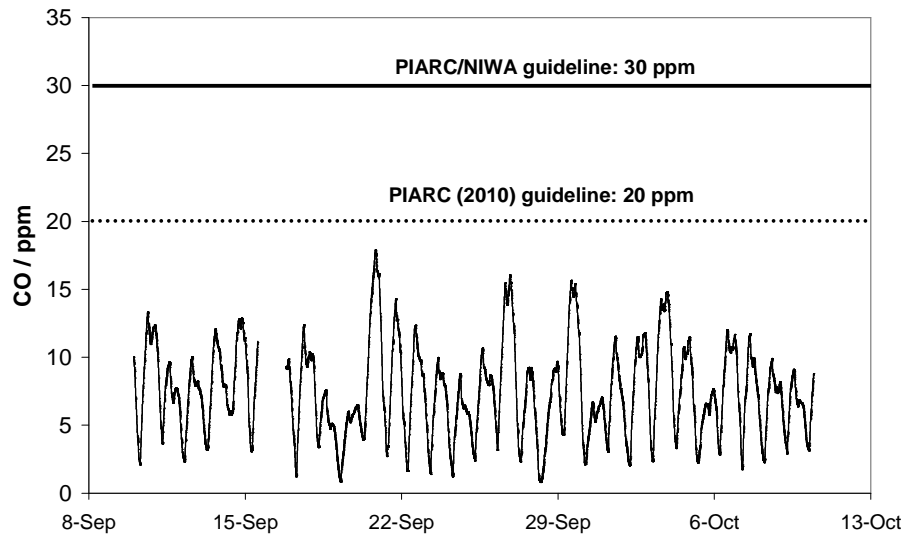
**Figure 5: Observed 8-hour moving average CO concentrations and *occupational* guideline values.**

Figure 6 displays the diurnal average range of CO concentrations, indicating a significant degree of day-to-day variability, which is discussed in more detail in chapter 3.
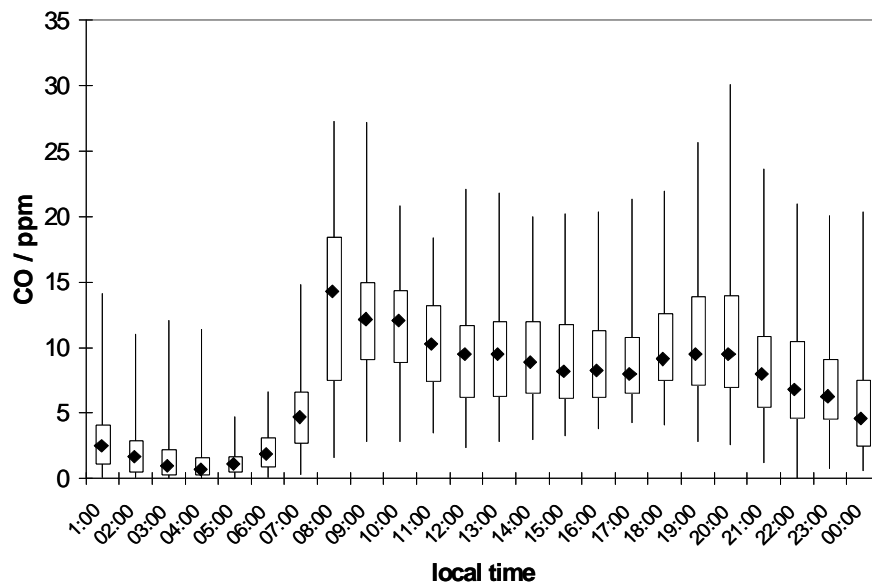


**Figure 6. Diurnal hourly average (of 15-minute moving average) CO concentrations for all data for the Terrace tunnel (white box shows interquartile range, whiskers show minimum and maximum, black diamond shows median).**

### 2.4.4 Nitrogen Dioxide

Interpretation of the NO$_2$ results is dominated by a single event on the 10$^{th}$ September 2008 in which 1-minute average concentration peaked at 0.53 ppm at 13:12 NZST. The event lasted approximately 40 minutes and its causes and probability of recurrence – are discussed in section 4.6. The distribution of NO$_2$ concentrations was highly skewed (the reasons for this are discussed in more detail in section 4), such that the second highest NO$_2$ concentrations were half of those observed during this event, and the 99$^{th}$ percentile concentration (0.10 ppm) was just under a quarter of the maximum.
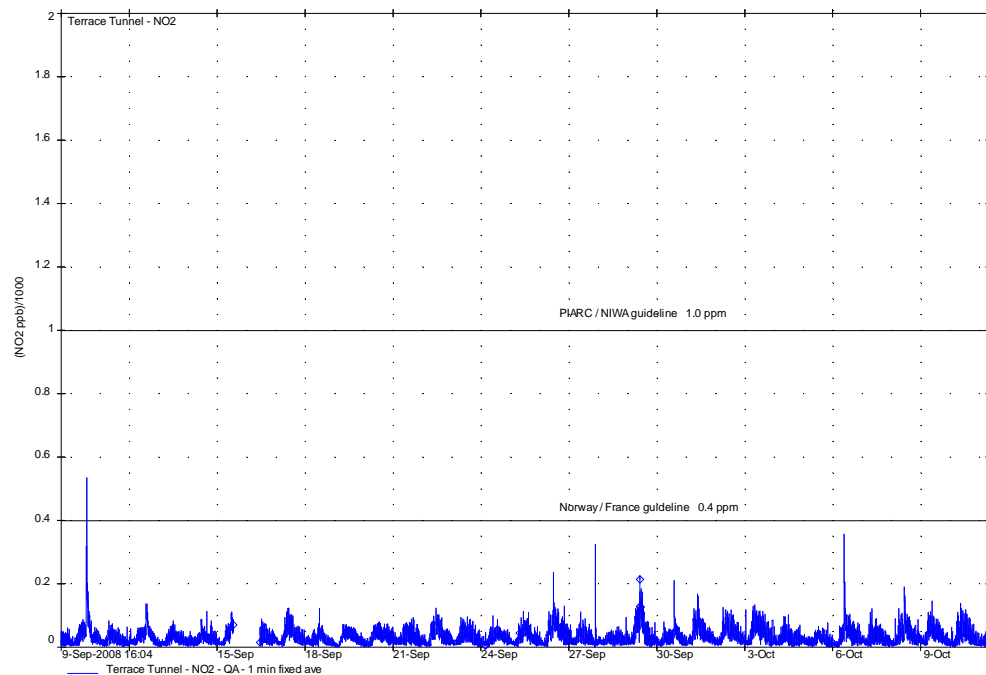


**Figure 7: Observed 1-minute fixed average NO$_2$ concentrations and non-occupational exposure guideline values in the Terrace Tunnel.**
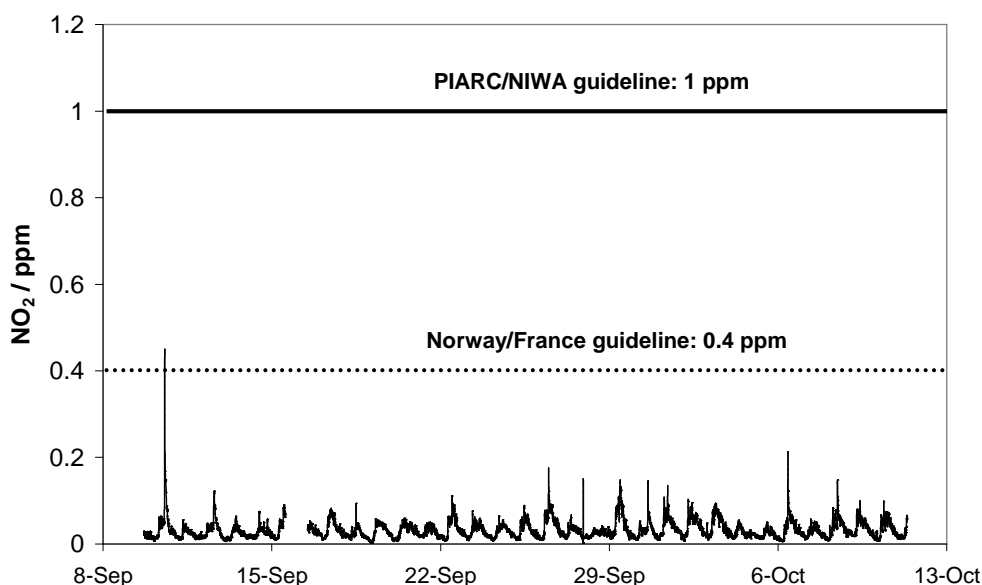
**Figure 8: Observed 15-minute moving average NO₂ concentrations and non-occupational exposure guideline values in the Terrace Tunnel.**

The maximum 1-minute average $NO_2$ concentration observed during this event, and the whole campaign, was just over half of the guideline value. Consequently, we can conclude that during the monitoring period, the Terrace tunnel met the recommended $NO_2$ guideline.

The French, Belgian and Swedish guidelines[9] (see Table 3 above) were exceeded during the 10th September 2008 event (peak 15-minute moving average $NO_2$ was 0.45 ppm), but at no other times. The WHO ambient guideline value was exceeded four times (Figure 9) with a peak 1-hour fixed average concentration of 0.26 ppm. However, it must be stressed that these values apply to *exposure* for a full 1-hour period, which does not apply to members of the public using the tunnel.

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[9] Note that the French, Belgian and Swedish guidelines apply to averaging periods of 15, 20 and 60 minutes respectively.
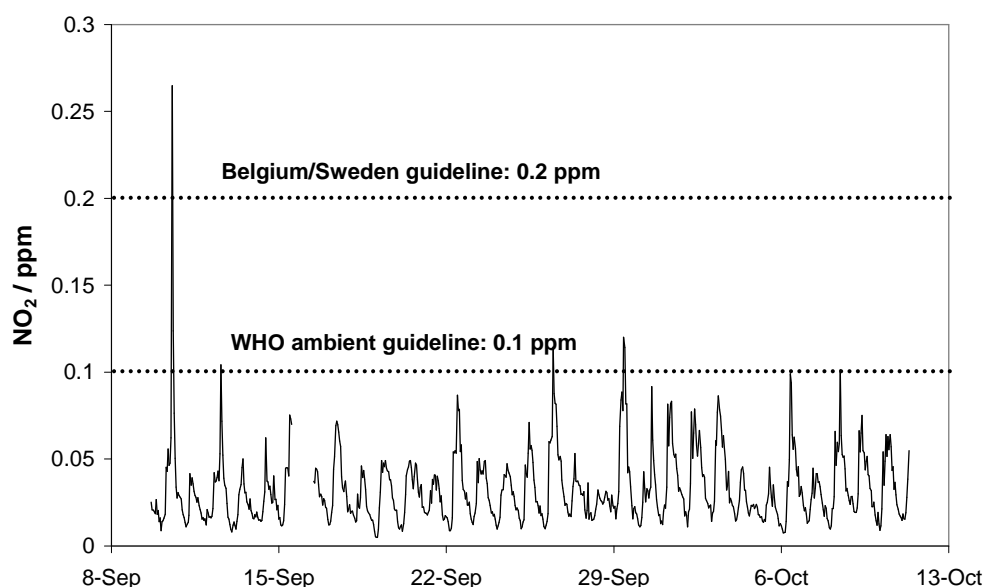
**Figure 9:** **Observed 1-hour average NO$_2$ concentrations in the Terrace Tunnel and non-occupational exposure guideline values.**

### 2.5  Mt Victoria Tunnel

#### 2.5.1 Monitoring arrangement

At the Mt Victoria Tunnel air was sampled from inside the western exhaust stack from a point 18 m from the top of the stack. The sampled air was drawn through a duct of total length 100 m to the instruments located in a trailer located outside the western exhaust stack building in the grounds of Wellington East Girls' College. Further details are contained in the Technical Annex.

#### 2.5.2 Overview of data

Descriptive statistics for the full monitoring period are provided in Table 5, based on 15 minute averages. Note that the CO analyser's range (0 – 50 ppm) was exceeded for 24 minutes on the morning of 30th October 2008, and 44 minutes on the morning of 31st October 2008, resulting in missing data. The NO$_x$ analyser's range (0 – 5 000 ppb) was also exceeded for 35 minutes on the morning of 30th October 2008, and 48 minutes on the morning of 31st October 2008, resulting in missing data.

**Table 5: Descriptive statistics for monitored pollutants (15-minute moving averages) in the Mt Victoria Tunnel.**

|  | CO / ppm | NO$_2$ / ppm | NO / ppm | O$_3$ / ppb |
|---|---|---|---|---|
| Max | 75[10] | 0.16 | 6.1[11] | 5.8 |
| Mean | 7.9 | 0.02 | 0.87 | 0.9 |
| Median | 4.8 | 0.02 | 0.56 | 0.9 |
| Interquartile range | 1.6 – 12.3 | 0.01 – 0.04 | 0.16 – 1.4 | 0.2 – 1.5 |
| Guideline for users | 87 | 1 (or 0.4) | None | none |

### 2.5.3 Carbon Monoxide

The time series of 15-minute moving average CO concentrations is shown in Figure 10. The highest 15-minute moving average CO concentration observed was 75 ppm. On average the 15-minute CO concentration was an order of magnitude lower. Figure 11 shows the range of observed concentrations for each hour of the day. It indicates that all concentrations above 50 ppm were observed during the period 7am – 8am **local time**.

We conclude, that during our monitoring period the Mt Victoria tunnel met both the recommended 15 minute CO guideline, and PIARC 2010 guideline, except during the hour of 7am - 8am **local time** during which the PIARC 2010 guideline of 70 ppm was exceeded twice.

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[10] Highest concentration recorded but it may have been higher when the analyser exceeded the set range

[11] Highest concentration recorded but it may have been higher when the analyser exceeded the set range
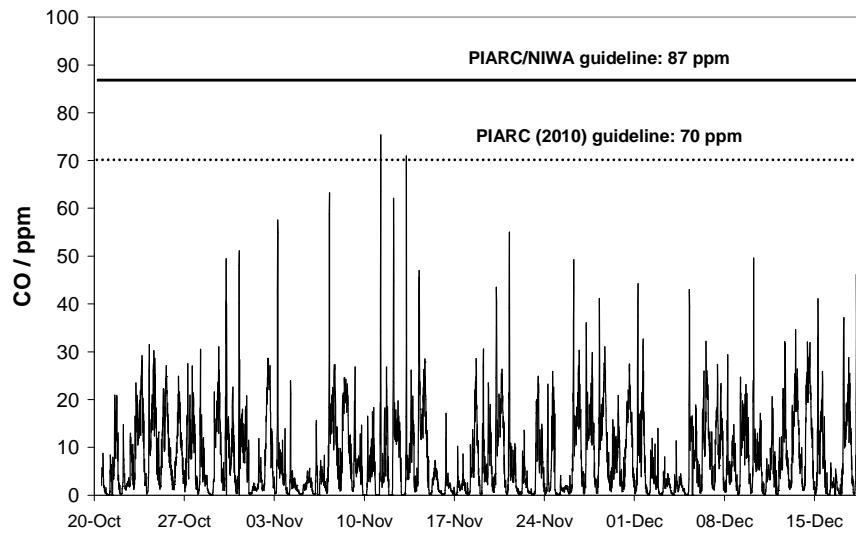
**Figure 10: Observed 15-minute moving average CO concentrations and non-occupational exposure guideline values in the Mt Victoria tunnel.**
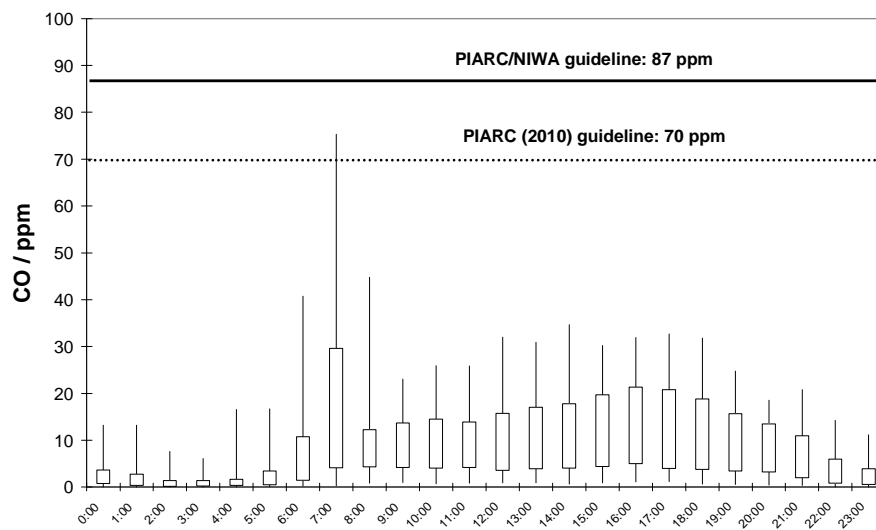


**Figure 11: Diurnal hourly average of 15-minute CO concentrations for each hour of the day *local time* (white box shows interquartile range and whiskers show minimum and maximum) and non-occupational exposure guideline values in the Mt Victoria tunnel.**

The maximum 8-hour CO concentration observed was 24.4 ppm. Thus, although the 30 ppm guideline was not exceeded, this was by a small margin. The more demanding 20 ppm limit recommended by PIARC (PIARC, 1995, see also Longley *et al*., 2008b for more detail), was exceeded 2 % of the time for which data exist.
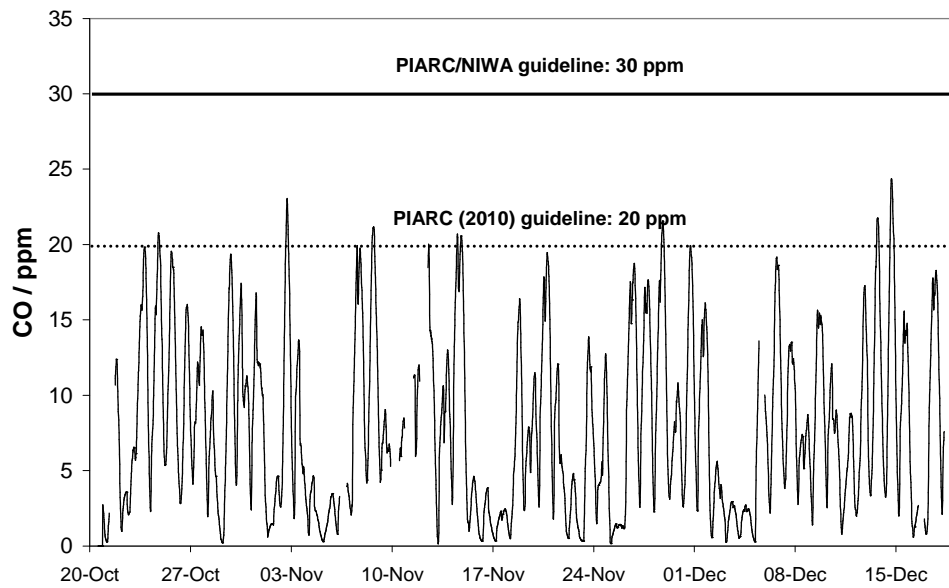
**Figure 12: Observed 8-hour average CO concentrations and *occupational* guideline values in the Mt Victoria tunnel.**

Figure 13 shows that exceedences of the 8-hour guideline occurred for 8-hour shifts **ending** between 1pm and 11 pm local time.
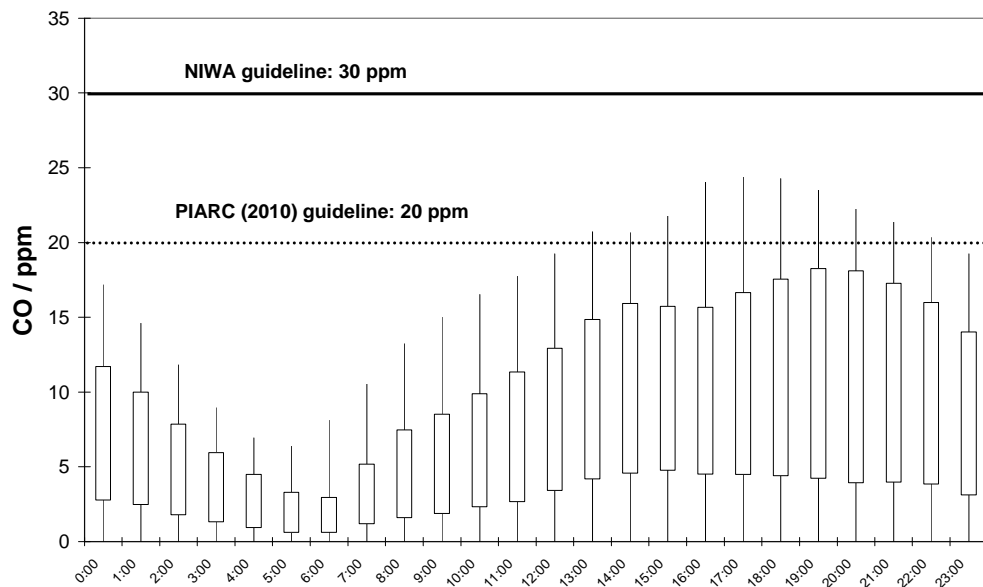


**Figure 13: Diurnal average of 8-hour CO concentrations for 8-hour periods ending at each hour of the day *local time* (white box shows interquartile range and whiskers show minimum and maximum) and *occupational* guideline values in the Mt Victoria tunnel.**

### 2.5.4 Nitrogen Dioxide

The following analysis is based on the API instrument located in the trailer outside the exhaust stack, sampling through a long inlet placed in the exhaust duct. It should be noted that the analyser was initially set to measure $NO_x$ over the range $0 - 5$ ppm. Due to over-ranging occurring (see Technical Annex for details) the range was reset to $0 - 8$ ppm on 31st October 2008.

The maximum $NO_2$ concentration observed was 0.01 ppm as a 1 hour fixed average, 0.16 ppm as a 15-minute moving average and 0.24 ppm as a 1 minute average. These values are all considerably lower than the 1 ppm guideline.
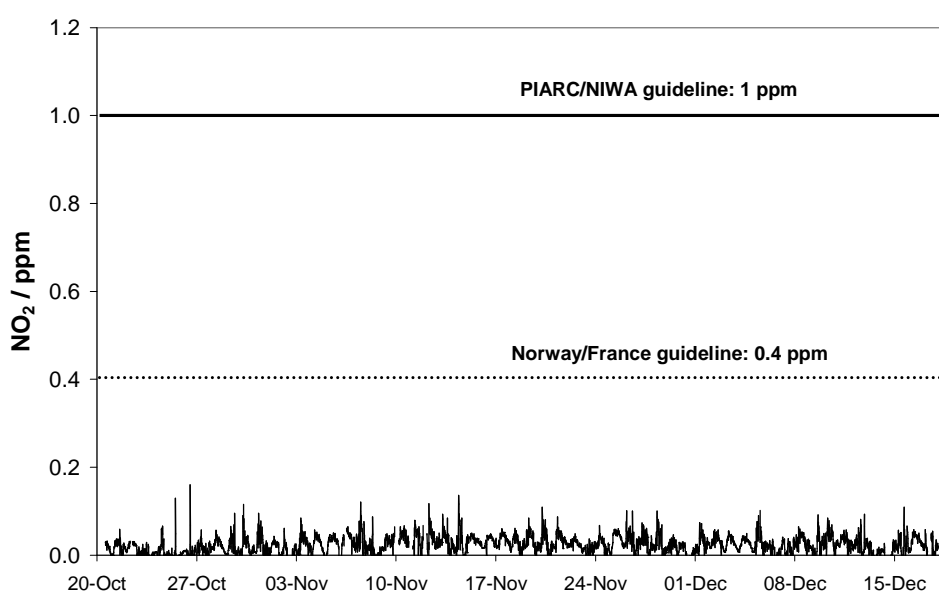


**Figure 14: Observed 15-minute moving average NO₂ concentrations in the Mt Victoria tunnel and non-occupational exposure guideline values. (Negative values have been removed from this chart for clarity. See section 4.3 for further discussion).**

In our recommendations to Transit, we also noted that more demanding $NO_2$ guidelines have been adopted or recommended elsewhere, as listed in Table 3.

None of these guidelines were exceeded during the campaign. The closest approach to an exceedence was a 1-hour average of 0.098 ppm at 13:00 on the 7th November 2008, which is marginally below the WHO ambient guideline value of 0.1 ppm[12] (Figure

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[12] The WHO guideline is 200 μg m$^{-3}$, which is equivalent to 0.1 ppm at 0°C and 1 atm. At 25°C it is equivalent to 0.11 ppm.

15). However, it must be stressed that these values apply to *exposure* for a full 1-hour period, which does not apply to members of the public using the tunnel.
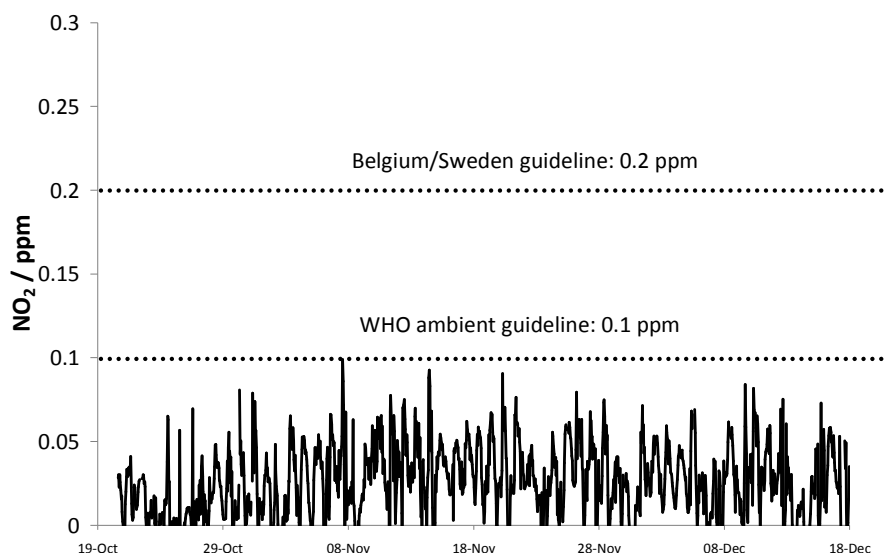


**Figure 15: Observed 1-hour fixed average NO₂ concentrations in the Mt Victoria tunnel and corresponding non-occupational exposure guideline values.**

### 2.6 Summary

During our monitoring period the Terrace tunnel met the recommended 15 minute CO guideline with ease. The tunnel also met the PIARC (2010) recommendation of 70 ppm of CO. The 8-hour occupational safety guideline was met, as was the more restrictive PIARC guideline of 20 ppm, albeit by a small margin. The maximum 1-minute average NO₂ concentration observed over the whole campaign, was just over half of the guideline value of 0.11 ppm. Consequently, we can conclude that during the monitoring period, the Terrace tunnel met the recommended NO₂ guideline.

During our monitoring period the Mt Victoria tunnel met both the recommended 15 minute CO guideline, and PIARC 2010 guideline, except during the hour of 7am - 8am local time during which the PIARC 2010 guideline of 70 ppm was exceeded twice. Although the 30 ppm guideline was not exceeded, this was by a small margin. The more demanding 20 ppm limit recommended by PIARC was exceeded 2 % of the time for which data exist. The Mt Victoria tunnel met the recommended NO₂ guidelines.

# 3. Key determinants of tunnel air quality

## 3.1 Purpose of this chapter

This chapter discusses the second objective of the campaign – to interpret the determinants of current air quality, as outlined in the previous chapter. We consider here the "physical" determinants – i.e. the interaction of variation in vehicle emissions, the tunnel ventilation system and external winds. This is primarily achieved by further analysis of carbon monoxide (CO) concentrations.

In the case of nitrogen dioxide ($NO_2$) concentrations are likely to be additionally determined by chemical reactions and dependent upon the concentrations of reactants. This is dealt with in the subsequent chapter.

## 3.2 Terrace tunnel

### 3.2.1 Influence of variation in traffic volume

Hourly average traffic data has been made available to us by NZTA for 8 whole, single weeks spread evenly over the period 19th Feb 2006 to 3rd Nov 2008 (Figure 16). Data are not available during our monitoring period. The closest available data in time is for the week 28th Oct – 3rd Nov 2008. Figure 17 shows the diurnal average weekday traffic volume for this week, and the range of data for all weekdays for which we have data. It indicates that there is low day-to-day variation. Traffic volume is seen to peak during the period 7 am – 9 am and 4 pm – 6 pm local time on weekdays with a less pronounced mid-day peak at weekends.
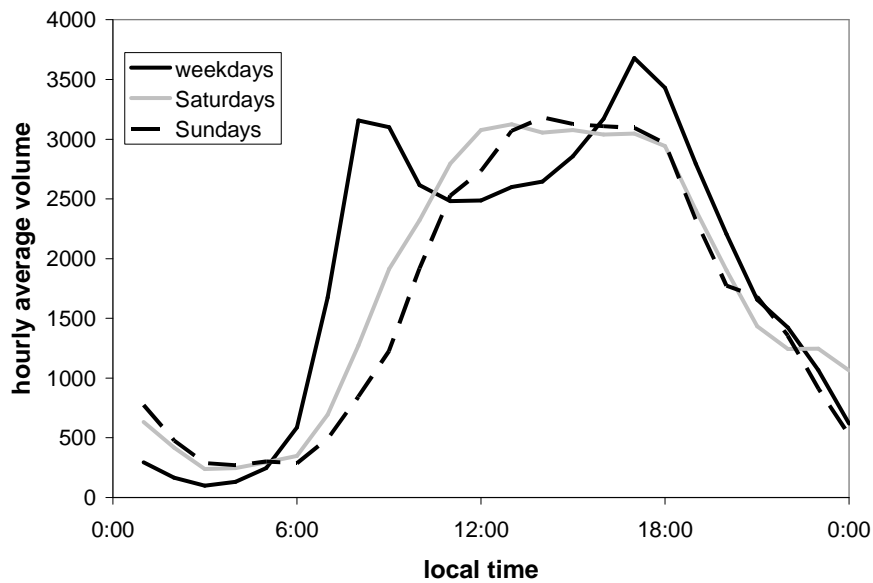
**Figure 16: Diurnal hourly average traffic volume in the Terrace Tunnel over 8 one-week periods covering 2006 – 2008 (see text above). Data provided by NZTA.**
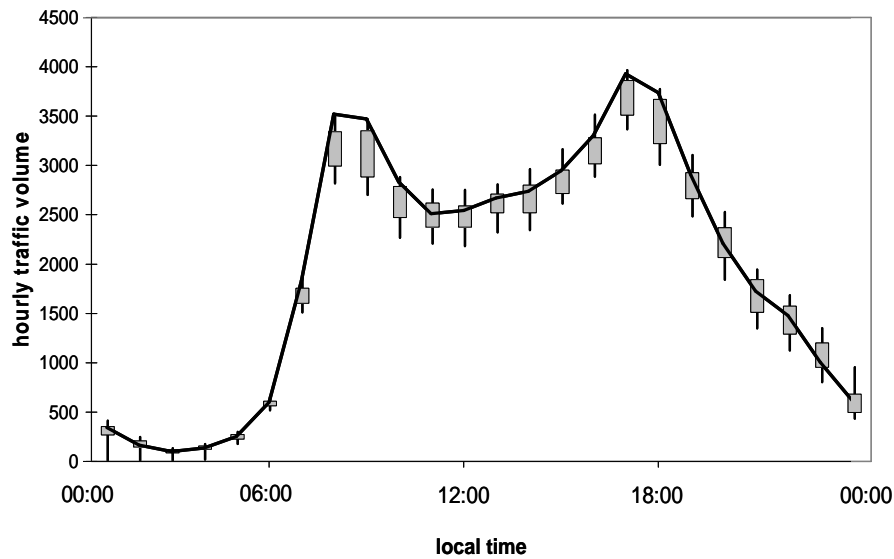


**Figure 17: Diurnal average weekday traffic volume for the week 28th Oct – 3rd Nov 2008 (black line) and "historic" (see text) weekday traffic volume in the Terrace Tunnel (box and whiskers – box indicates interquartile range, whiskers indicate 5th and 95th percentiles).**

The weekend peak volumes and the morning weekday peak volumes are very similar at ~ 3 000 hour$^{-1}$, as shown in Figure 16. The evening peak volume is larger. The

NZTA data reveals that this is due to the directional asymmetry in the flow with larger northbound flows in general and especially on weekday evenings (Figure 18). This can be directly related to there being two northbound lanes and only one southbound. This is potentially significant for air quality as northbound traffic is more likely to be accelerating and reaching higher speeds than southbound traffic, especially during peak times when southbound traffic may experience queuing from the Willis Street/Vivian Street intersection.
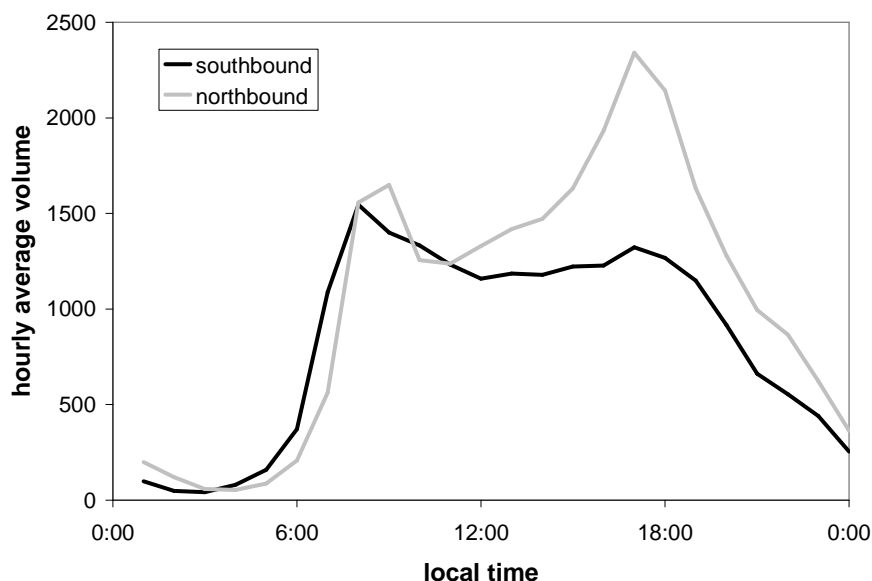


**Figure 18: Diurnal hourly average traffic volume in the Terrace Tunnel on weekdays for all data available, segregated by direction. Data provided by NZTA.**

Very broadly, concentrations of CO followed variations in traffic flow, as shown in Figure 19 for weekdays. Figure 6 (in section 2.4.3) shows the diurnal average CO concentration for all data including an indication of variability. It also shows the maximum 1-minute concentration observed throughout the whole campaign for each hour of the day. Together these figures show that the highest peak concentrations occurred during the morning peak traffic hours. However, the increased traffic volume in the evening peak did not lead to correspondingly high CO concentrations. This may be due to the higher traffic speeds and less congestion in the evening compared to the morning. We also note (below) that the jet fans were operating more frequently during the evening than the morning traffic peak. It may also be seen that some high concentrations were observed in the evening after the evening traffic peak, which may also be a result of either changes in traffic patterns (volume, fleet split and speeds) and/or jet fan operation (see below).
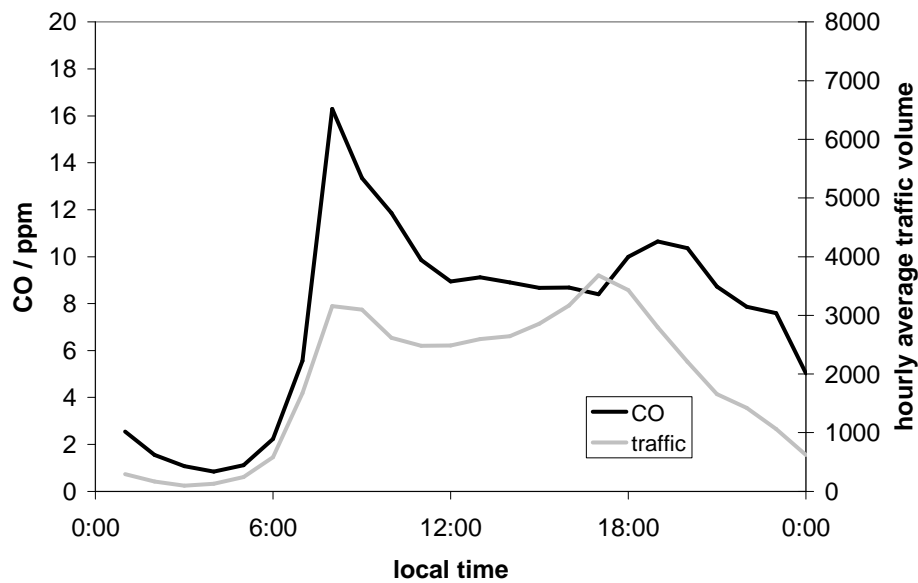
**Figure 19: Diurnal hourly average of 15-minute moving average CO concentrations and hourly average traffic volume in the Terrace Tunnel on weekdays only. Traffic data (from 28th Oct – 3rd Nov 2008 inclusive) provided by NZTA.**

### 3.2.2 Influence of jet fan operation

The operation of the Terrace Tunnel's jet fans can be observed in the CO concentration time series. The fans are automatically controlled by combined traffic speed monitoring (via infra-red detection above one of the northbound lanes and the southbound lane) and wind monitoring. Detection of low traffic speed in either direction – implying high traffic volumes – combined with low wind speeds will trigger the fans. The default fan direction (selected if no wind is detected in the tunnel) is set to operate in the southbound direction to take advantage of the prevailing northerly winds in Wellington. Figure 20 shows an example of the effect of the fans switching on and off during Sunday 14th September 2008. On this day the fans were mostly switched off, but when they were switched on the CO concentration typically halved in under 10 minutes.
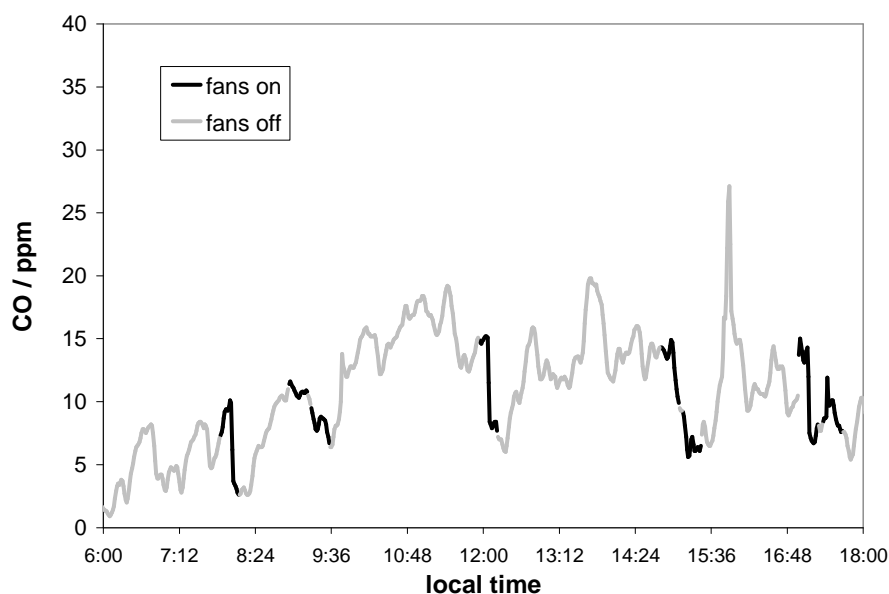
**Figure 20. An extract from the time series of 1-minute average CO concentrations (Sunday 14th September 2008) illustrating the effect of jet fan operation.**

The logs provided to us by Fulton Hogan indicate that during our monitoring campaign the jet fans were operational 25 % of the time. The two days with the lowest average wind speed (11th September and 13th September) were also the days with the highest duration of fan operation (37 % and 52 % respectively). However, other than this, patterns in the jet fan operation were difficult to discern in the absence of corroborating traffic speed data. On average, the fans were least likely to be operating during the hours of 5 am to 7 am local time and 9 pm to midnight local time, and most likely to be operating during the traffic peak hours (Figure 21). It may be noted that fans were more frequently operating during the evening traffic peak period than the morning traffic peak. This, plus the reduced fan operation between the evening traffic peak and midnight, may provide an explanation of the correspondingly reduced and increased CO concentrations, relative to traffic volumes, described in section 3.2.1 above.
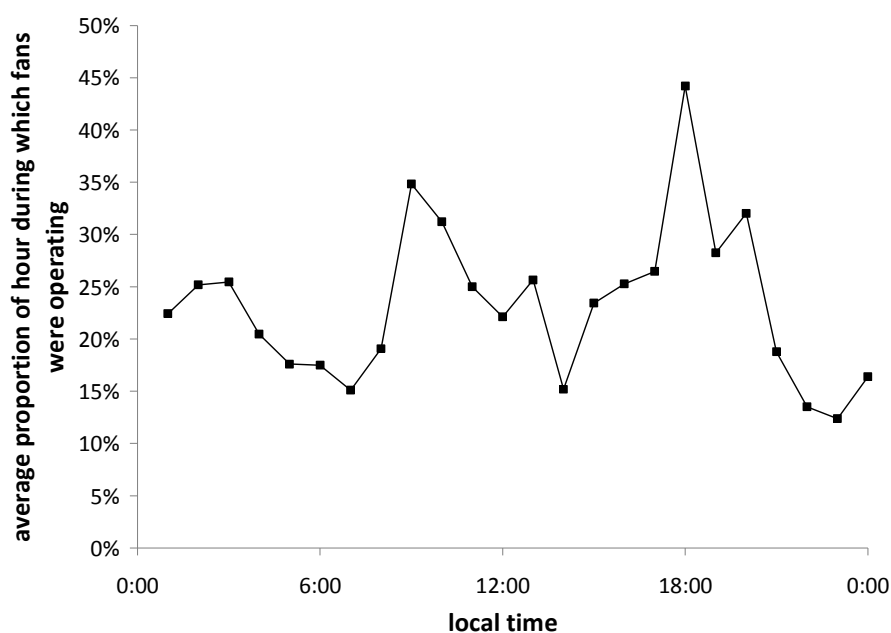
**Figure 21: Average proportion of each hour of the day during which jet fans in the Terrace Tunnel were operating.**

The relationships between fan operation, external wind speed and direction were insufficiently clear for us to draw further conclusions at this point. This prevents us from speculating as to whether the operation of the jet fans could be optimised. However, the dataset we have acquired may reveal further information on this matter if studied in further detail.

### 3.2.3 Influence of external winds

Closer analysis revealed that wind direction was a major determinant of CO concentrations, with northerly winds leading to concentrations almost twice as high as southerly winds (see Figure 22). It must be noted that wind direction here relates to wind direction observed at NIWA's monitoring station outside the southern portal, not inside the tunnel, and that the monitoring site was sheltered in most directions, but especially to the north.
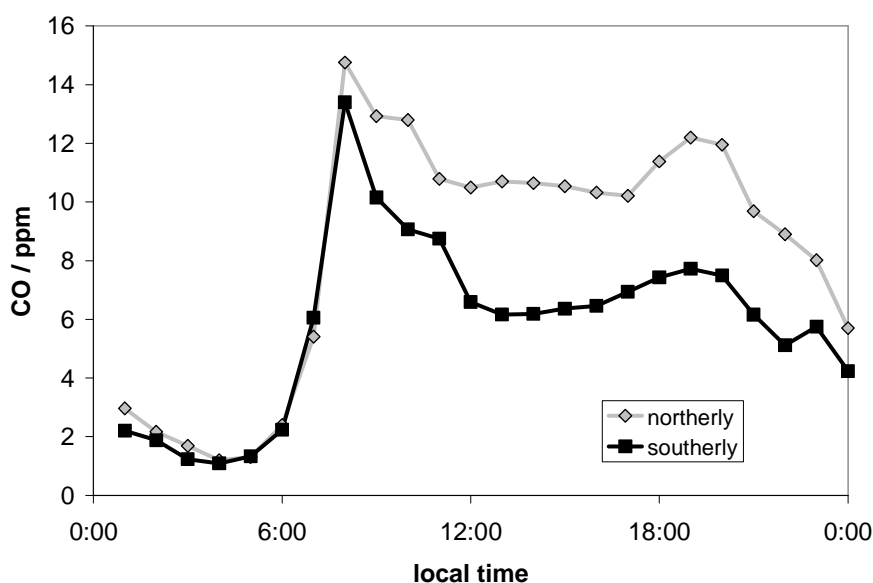
**Figure 22: Diurnal mean CO concentrations (hourly average of 1 minute averages) for all data in the Terrace tunnel, segregated as a function of wind direction (measured outside the southern portal).**

As we were unable to collect wind data from within the tunnel we cannot confidently assess whether this was due to a generally lower wind speed in northerly flow. It could, however, be due to the ventilation fans operating in the "wrong" direction, i.e. against the predominant natural wind direction rather than in the same direction. This has been a general fault previously identified with the Terrace tunnel (see Scoping Assessment for more details).

We further consider the effects of recent changes in traffic flow in the Terrace tunnel in chapter 5 below.

### 3.3 Mt Victoria tunnel

At first inspection CO concentrations displayed a diurnal cycle which bears some similarities to the diurnal cycle in traffic volume. Hourly average traffic data has been made available to us by NZTA for the week of 29th September – 5th October 2008 (i.e. up to 2 weeks before monitoring began on 20th October), and for the whole of 2007. These data reveal very little day-to-day variation, as shown by the analysis presented in Figure 23 for the 2007 data. Figure 24 shows the diurnally averaged total traffic volume for the week in September (to October) 2008 and the whole of 2007 for comparison. Traffic volume is seen to peak during the period 7 am – 9 am and 4 pm – 6 pm local time on weekdays with a less pronounced mid-day peak at weekends. The

peak volumes on weekdays (morning and evening) and on weekends (afternoon) are very similar. The 2007 data reveals no significant seasonal trend during the equivalent monitoring period of mid-October to mid-December.
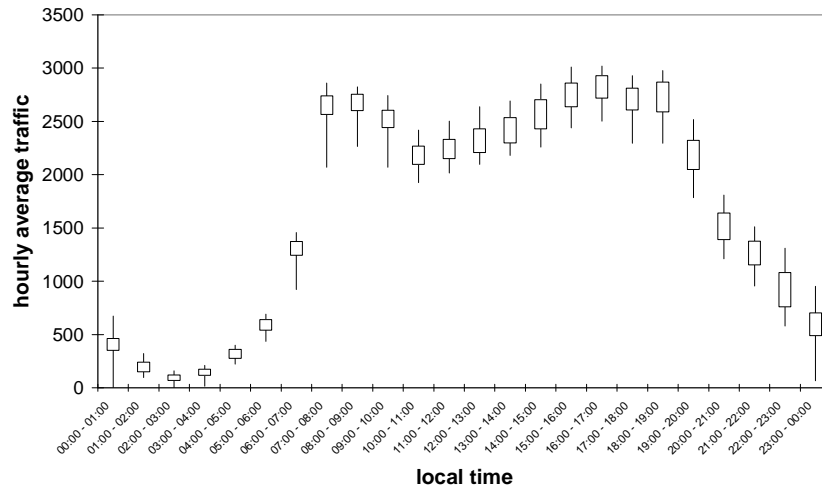


**Figure 23: Diurnal hourly average weekday traffic volume (2007) in the Mt Victoria Tunnel showing interquartile range (boxes) and 5th and 95th percentiles (whiskers). Public holidays excluded.**
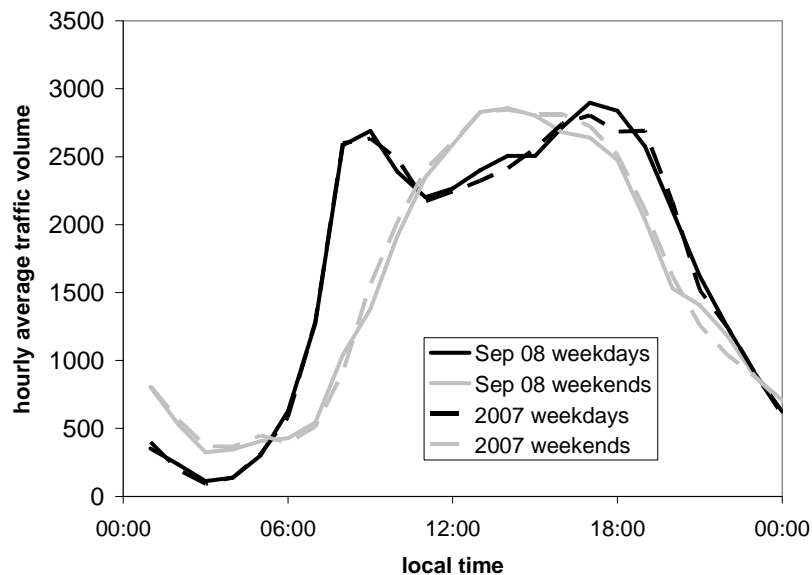


**Figure 24. Diurnal average traffic volume in the Mt Victoria Tunnel (data provided by NZTA) for the week 29th September – 5th October 2008, and the whole of 2007.**

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Figure 25 shows the diurnal average of 15 minute moving average CO concentrations and hourly average traffic volume for weekdays only. A strong correlation can be seen, except during the 7 am – 8 am (local time) peak. It may also be noted that this excessive CO peak is not seen during the evening traffic peak. Such behaviour could be indicative of an increase in congestion (leading to increased CO emissions) which is likely during the morning peak[13]. A small increase in the ratio of CO to traffic may also be seen in the evening traffic peak, although this peak (in terms of traffic volume) is somewhat more distributed over a longer duration and may be less prone to congestion and relatively increased CO emissions. Unfortunately, we were unable to capture traffic speed data to verify whether speeds were generally lower in the morning.
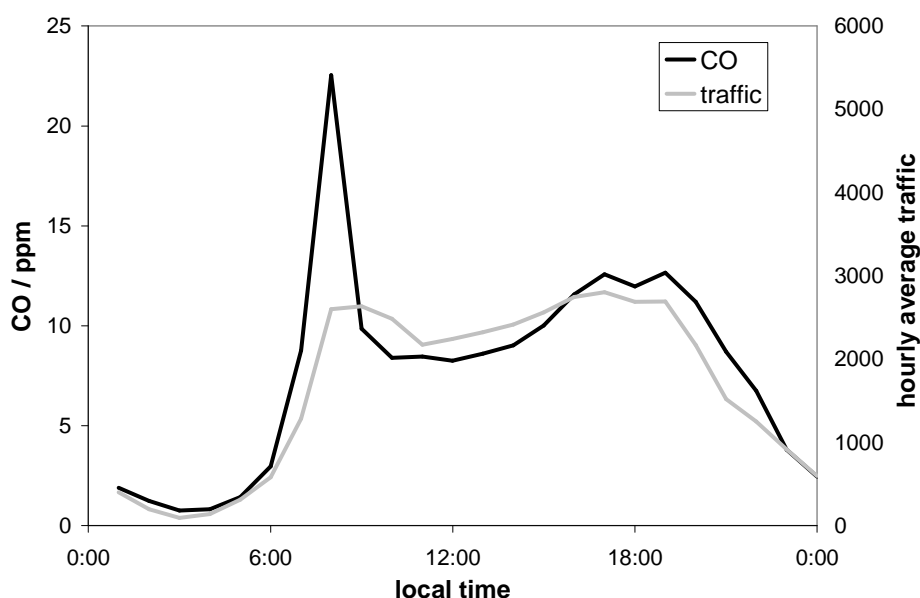


**Figure 25: Diurnal hourly average CO (from 15-minute moving averages) and traffic volume (from 1-hour averages) in the Mt Victoria Tunnel for weekdays only.**

Despite the extra length of the Mt Victoria tunnel, and the smaller cross-sectional area of its bore, we still found that external winds played a significant role in determining air quality in the centre of the tunnel. We have compared wind speed and direction measured in the tunnel mid-point with that measured concurrently at Wellington Airport (meteorological data recorded at the exhaust stack was strongly influenced by local topography and unlikely to be representative of winds in the area in general). During our observational campaign the wind direction at the Airport was either

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[13] Emissions of CO are known to be very sensitive to low speed driving for most vehicles. For a range of typical fleet compositions, the VEPM model predicts a doubling of average CO emissions if average speed is halved from 20 to 10 km h$^{-1}$.

northerly (71 % of the time) or southerly (24 % of the time). This split is broadly consistent with the long-term climatic norm with northerlies being approximately twice as common as southerlies at this location (see also Longley *et al*., 2008c). Southerly winds were observed on approximately half of all days at the Airport, whilst northerly winds were observed at some point on nearly every day. Southerly winds were more common during daylight hours and were generally associated with lower wind speeds.

Within the tunnel, we found wind speed was insensitive to external winds up to a threshold wind speed. When northerly winds were blowing at the Airport we found that this threshold wind speed was of the order 4 – 6 m s$^{-1}$. When southerly winds were blowing we found no clear threshold, i.e. internal wind speeds appeared to be unaffected by external winds (although external winds were generally lighter). The consequence of this was that internal wind speeds were generally held below 3 m s$^{-1.}$. The only exception to this, i.e. periods when winds above 3 m s$^{-1}$ were observed in the tunnel, was when northerly winds over ~5 m s$^{-1}$ were observed at the Airport, although such high external winds did not **always** lead to increased air flow in the tunnel.

Thus, in summary, wind speed inside the tunnel was generally low, as indicated in Table 6. CO concentrations were quite acutely dependent upon this internal wind speed, and the peak CO concentrations observed in the 7 – 8 am period local time (see above) all occurred at times when internal (and external) wind speed was particularly low. During the periods of favourable external wind for dispersion of pollutants (high northerlies) CO concentrations were significantly reduced. For example, extended periods of high northerly winds were observed over the period 15th – 17th November 2008 during which time 15-minute moving average CO peaked at 18 ppm and was mostly below 10 ppm (Figure 26 below).

**Table 6: Basic statistics for wind speed measured inside the Mt Victoria tunnel**

| | |
|---|---|
| Median wind speed | 1.2 m s$^{-1}$ |
| Mean wind speed | 1.6 m s$^{-1}$ |
| Interquartile range wind speed | 0.6 – 2.3 m s$^{-1}$ |
| 90th percentile wind speed | 3.6 m s$^{-1}$ |
| 99th percentile wind speed | 5.8 m s$^{-1}$ |

These observations are somewhat different from the predictions of a numerical modelling exercise undertaken by NIWA in 2008 (Revell & Popinet, 2008). This modelling (based on predicted pressure gradients across the tunnel due to external

winds) suggested external northerly winds should not induce flow in the tunnel (we observed induced westerly flow in high winds), but that external southerly winds could induce an easterly flow in the tunnel. Although our data confirmed the latter point, the flow was very light.
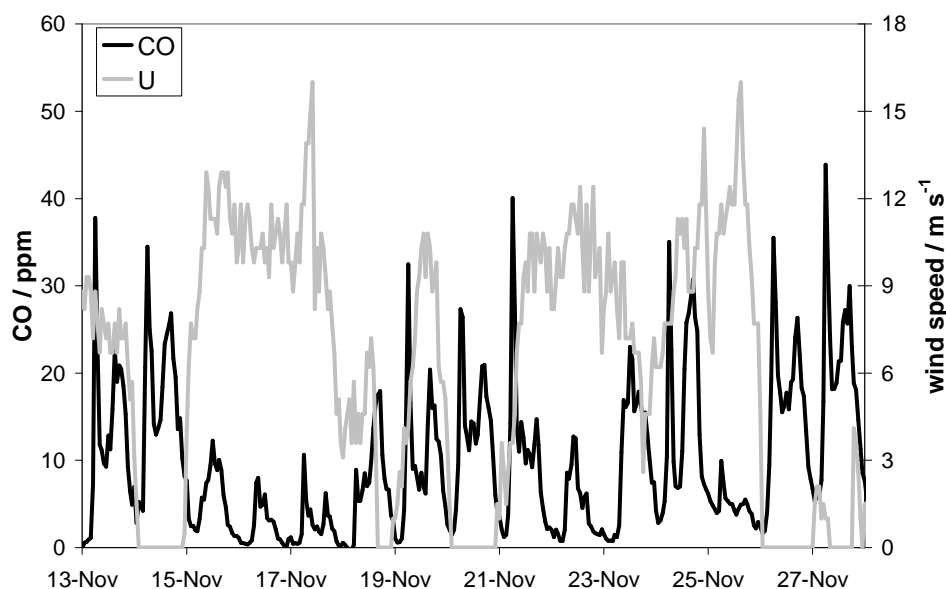


**Figure 26: Concentrations of CO in the Mt Victoria Tunnel and wind speed, *U* (for northerlies only), at Wellington Airport in November 2008 and early December 2008. Note how periods of high winds coincided with periods of reduced CO.**

Most of the time, however, the effect of external meteorology on air flow in the tunnel was minimal or could not be distinguished. The "piston effect" of moving vehicles cannot be ruled out, but is likely to be minor due to the bi-directional nature of the traffic flow. Wind speeds within road tunnels are generally kept below 10 m s$^{-1}$ for purposes of safety, although lower limits are often applied to bi-directional tunnels. In the Mt Victoria tunnel the transverse nature of the ventilation system means that low wind speeds do not necessarily imply poor ventilation as the principal means of ventilation is vertically, not along the tunnel bore. However, our results show that meteorologically-driven along-bore winds strongly assist ventilation of the tunnel in a limited set of conditions.

The Mt Victoria Tunnel's ventilation fans operate at one speed only, during the hours of 6 am to 11 pm local time. There was no discernible impact of the switching of the fans. At 6 am traffic volume was low and no consistent dip in concentrations was observed. At 11 pm, we also did not observe any consistent rise in concentrations as ventilation was reduced. We therefore conclude that the timing of the ventilation

switch was not responsible for the peak concentrations observed between 7 am and 8 am local time, nor their sudden reduction between 8 am and 9 am.

## 3.4 Summary

Variation in traffic volume was found to be a major determinant of air quality in the tunnels (as represented by CO concentrations). In the Terrace tunnel worse air quality in northerly winds is suggestive of inappropriate operation of the ventilation system – however this did not lead to breaches of the CO guidelines. The jet fans were found to significantly reduce concentrations when they were operational. In the Mt Victoria tunnel high northerly winds external to the tunnel aided the tunnel's ventilation system by inducing an additional wind along the tunnel bore. However, in most conditions external winds were ineffective for tunnel ventilation and some of the highest CO concentrations in the Mt Victoria Tunnel coincided with the lowest external wind speeds.

## 4. Physical and chemical determinants of concentrations of NO$_2$

### 4.1 Purpose of this chapter

In this chapter we review what can be deduced from observational data about the relative roles of physical determinants (such as ventilation) and chemical reactions on the levels of NO$_2$ in road tunnels in general, and the Wellington tunnels in particular. This section in necessarily incomplete at this stage as understanding these processes would require far more detailed observation than was practical for this campaign.

### 4.2 Sources of NO$_2$ in a road tunnel

Whereas carbon monoxide in a road tunnel arises solely from direct vehicle emissions, nitrogen dioxide is a reactive substance which, in a tunnel, is expected to arise from three main sources:

1. Background (mostly traffic) sources external to the tunnel,

2. Primary emissions from traffic, particularly diesel vehicles, in the tunnel.

3. Chemical oxidation of the nitric oxide (NO) and volatile organic compounds (VOCs) present in vehicle exhausts, requiring an oxidant (ozone, hydroxyl radicals and/or oxygen),

Primary emissions of oxides of nitrogen (NO$_x$) from vehicles are predominantly in the form of NO (nitric oxide) rather than NO$_2$. The proportion of NO$_x$ emitted directly in the form of NO$_2$ varies substantially between vehicles, but in a way that is poorly understood, especially for the New Zealand fleet. It is conventionally assumed to be of the order 2 – 5 % on average (based on studies such as those by Hilliard & Wheeler, 1979). However, studies principally from Europe indicate that certain types of vehicles under certain operating conditions can emit up to 50 % of NO$_x$ as NO$_2$ – particularly Euro III and Euro IV diesel vehicles (with the highest values for diesels with catalysed particulate filters). The average fraction of NO$_x$ emitted as NO$_2$ amongst the New Zealand fleet is currently unknown. It is likely to be less than 10 % but if European trends in diesel vehicle usage are followed here we may expect the fraction to be increasing (see Longley *et al.*, 2008a).

In the ambient roadside atmosphere $NO_2$ contributes a small percentage (typically 5 – 20 %) of $NO_x$. The principle source of $NO_2$ in the urban atmosphere is generally the oxidation of NO and/or VOCs. These processes are crucially dependent upon the presence of an oxidant, with ozone ($O_3$) being the most important. $O_3$ is usually ever-present in the troposphere (although varying on daily and seasonal scales), but is rapidly depleted by the oxidation of NO to $NO_2$ so that this reaction slows as $O_3$ becomes scarce. Thus it is normally observed that roadside levels of $O_3$ are reduced and $NO_2$ increased compared to non-roadside or non-urban sites. The tunnel portals are effectively roadside sites and the air entering the tunnels (whether through the main bore or separate inlet ducts) will contain the same levels of $O_3$ and $NO_2$ as outside the tunnel.

It is to be expected that high levels of NO in a road tunnel, which will be far in excess of the available ozone, will rapidly deplete available ozone from the portals inwards. Production of ozone (from oxygen) requires sunlight, and we may also assume that ozone is not generated and replaced within the darkness of a tunnel. As well as depletion in contact with NO, ozone also readily deposits to surfaces. Therefore key questions for $NO_2$ levels in road tunnels therefore are:

- how far into the tunnel does ozone from the outside penetrate before it is depleted?

- can transverse ventilation systems (in which fresh air is delivered at multiple points deep inside the tunnel via a separate air duct, thus minimising contact with NO) deliver ozone throughout the tunnel thus permitting $NO_2$ production along the full length?

The presence of volatile organic compounds (VOCs) provides an extra chemical pathway to $NO_2$ production but also requires a more powerful oxidant – hydroxyl radicals (OH). VOCs will be rapidly oxidised in an atmosphere containing OH and NO producing $NO_2$ in a process that is not dependent (at least directly) upon $O_3$.[14] VOCs and NO are abundant in vehicle exhaust. What is less certain is the availability of OH in any given road tunnel and the significance of this source of $NO_2$ relative to the other sources.

Hydroxyl radicals (OH) have a very short atmospheric lifetime. In a road tunnel there are potentially two major sources of OH: external and internal. We may expect that external OH will be depleted more rapidly than ozone and this will effectively limit

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[14]     In the open air, during daytime, the action of sunlight converts the $NO_2$ back into NO and $O_3$.

this $NO_2$ production mechanism to the portal area only. There are a few potential internal sources - the most significant is likely to be the reaction of ozone with unsaturated VOCs, such as alkenes and dienes. These are present in vehicle exhausts, but this mechanism is also dependent upon penetration of ozone into the tunnel. In summary, it is suspected that vehicles may produce the reagent to oxidise their own emissions if ozone is present to initiate the process. To our knowledge no measurements of OH have been performed in a road tunnel to evaluate the significance or otherwise of these postulated mechanisms.

The weakest oxidant is oxygen ($O_2$). NO can be directly oxidised by oxygen to produce $NO_2$. However, this reaction requires high concentrations of NO to be significant. Such concentrations are present in the vehicle tailpipe and perhaps immediately behind it. There have been reports that this reaction may be significant in road tunnels with persistently high NO concentrations and poor ventilation (Indrehus & Vassbotn, 2001, see also discussion in Longley *et al.,* 2008b).

A few other chemical pathways may be responsible for $NO_2$ production (and $NO_2$ removal) in a road tunnel but there are no known measurements to confirm them and remain speculative (e.g. those involving organic peroxy nitrates and the nitrate radical).

### 4.3   Detailed analysis of $NO_2$ in the Wellington tunnels

Data from both tunnels indicate two possible chemical regimes – one describing long-term average or "normal" levels of $NO_2$ and one describing short-term "chemical events" leading to peaks, and potential guideline exceedances. The conditions controlling these regimes are likely to be different and will be discussed separately.

Our analysis is based largely on data from the Terrace tunnel. $NO_2$ data as measured by the API instrument in the Mt Victoria tunnel included a large number of negative data points. This affects 16 % of the valid data. We have been unable to determine the cause of this phenomenon. Calibration errors can be discounted as the instrument was calibrated and checked on-site at the beginning and end of the campaign, and subsequently at NIWA. We have been unable to identify any "chemical" reason (such as cross-sensitivity or interference from other substances) for these anomalies.

### 4.4   "Normal" patterns of $NO_2$

The average diurnal cycle of $NO_2$ in both tunnels shows higher daytime concentrations compared to nightime, in common with CO (Figures 27 & 28). However, unlike CO,

concentrations of $NO_2$ tended to have a less distinct morning peak with elevated concentrations persisting into early afternoon on average. Inspection of the time-series also shows that $NO_2$ concentrations were not as closely linked to traffic patterns as CO. This is to be expected and represents additional indirect chemical sources of $NO_2$.
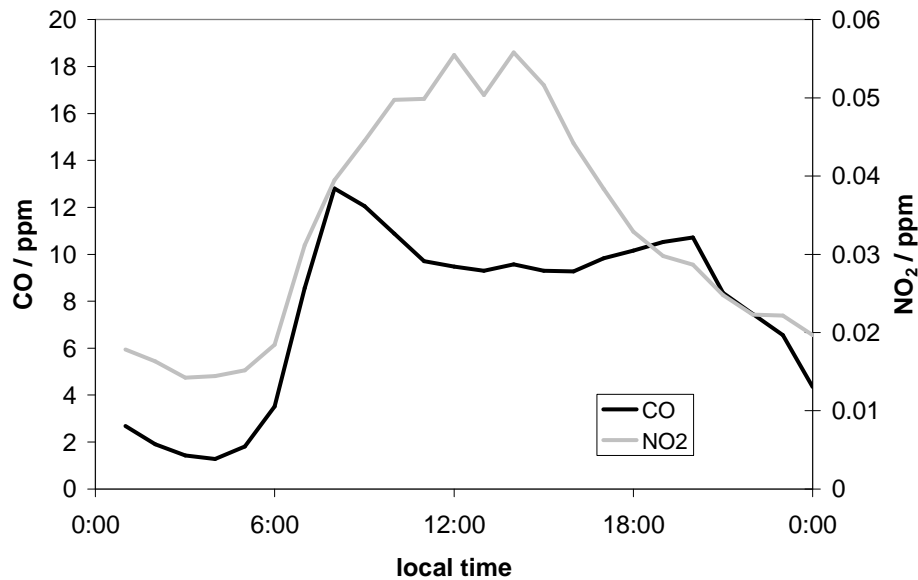


**Figure 27: Diurnal average (local time) CO and $NO_2$ in the Terrace tunnel.**
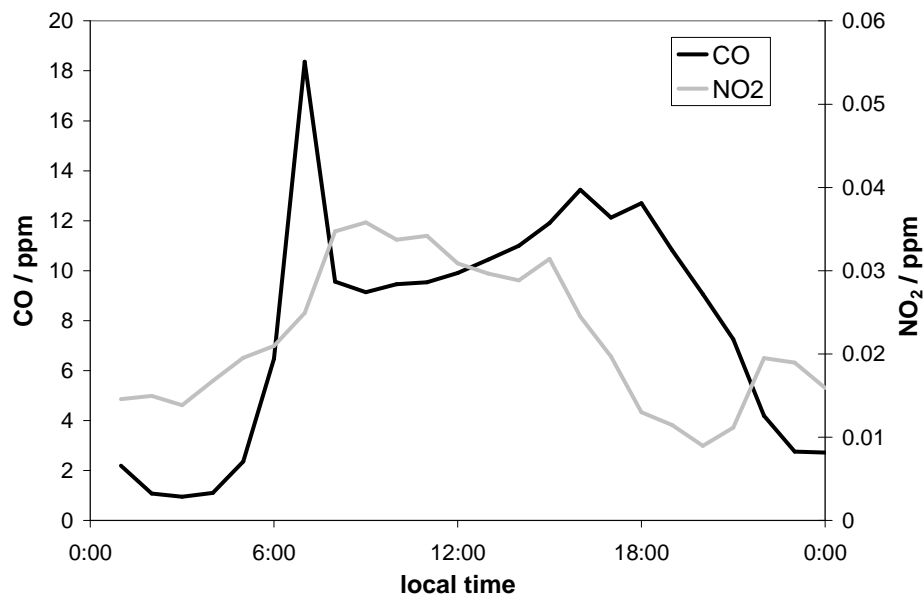


**Figure 28: Diurnal average (local time) CO and $NO_2$ in the Mt Victoria tunnel.**

**4.5    Processes controlling "normal" NO$_2$**

Concentrations of NO in both tunnels were strongly correlated with CO ($R^2 = 0.86$ in the Terrace tunnel, $R^2 = 0.96$ in the Mt Victoria tunnel), as might be expected due to the common in-tunnel traffic source, and concentrations of NO exhibited a similar diurnal pattern to CO.

In the Terrace tunnel, after the morning traffic peak, NO was much higher in northerly winds compared to southerly winds in the same way as was apparent for CO (Figure 22). However, a similar influence of wind direction was not apparent for NO$_2$. This lack of correlation between NO and NO$_2$ is suggestive of most of the NO$_x$ in the tunnel being held in the form of NO rather than being converted to NO$_2$, and a relative lack of in-tunnel NO$_2$ production.
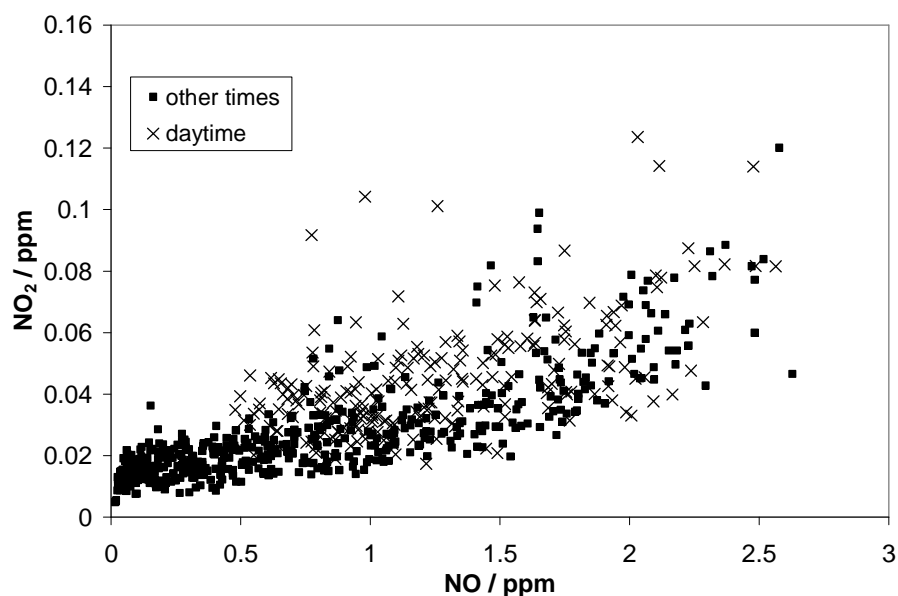


**Figure 29. Plot of hourly fixed average NO$_2$ versus NO concentrations in the Terrace tunnel, segregated by time of day ("daytime" = 10 am to 5 pm inclusive).**

A plot of NO$_2$ versus NO (Figure 29) reinforces this hypothesis. At very low concentrations of NO (as occurs at night with low emissions) NO$_2$ concentrations varied from approximately 0 to 0.02 ppm. At these times the tunnel air acted much like ambient air, as may be expected in the relative absence of vehicles and limited ozone depletion. When traffic volume increased in the daytime (and late evening)

increases in NO above around 0.1 ppm led to much smaller corresponding increases in $NO_2$, consistent with production being limited by depletion of available oxidant (ozone and probably OH) needed to convert NO to $NO_2$. The influence of ozone availability is hinted at by segregating the data by time of day. For any given level of NO there is a range of observed $NO_2$ concentrations, although that range is higher in the "daytime" period (10 am to 5 pm), during which time ozone concentrations were elevated (Figure 30).
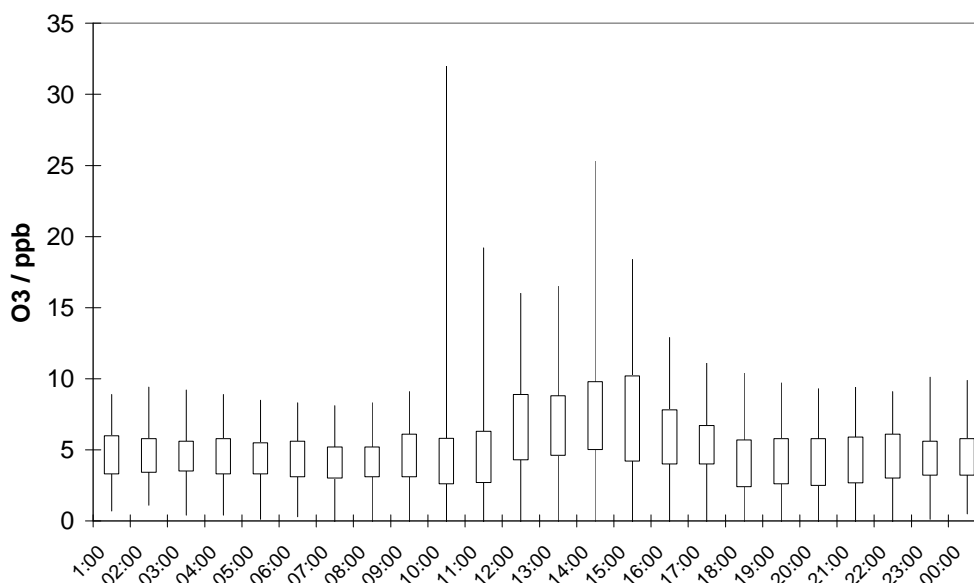


**Figure 30: Diurnal average ozone concentrations (hourly fixed averages of 15 minute moving average concentrations) in the Terrace tunnel (box shows interquartile range and whiskers show minimum and maximum).**

The influence of background concentrations (i.e. external to the tunnel), direct emission of $NO_2$ and other $NO_2$ production mechanisms can be inspected by comparing concentrations measured in the tunnel with the nearest available external ambient measurements. These measurements were made at the "Corner V" monitoring site and hourly concentrations of NO and $NO_2$ have been provided courtesy of Greater Wellington Regional Council.

The Corner V site is at the corner of Vivian Street and Victoria Street, 300 m SSE of the Terrace tunnel's southern portal, and alongside SH1. This dataset is not perfect as it is known to be affected by recirculation due to its street canyon location. It is also less representative of background concentrations at the tunnel in northerly winds (as it is downwind, not upwind of the tunnel). Nevertheless, it does allow us to identify some informative trends.

The simultaneous 1-hour average $NO_2$ concentrations at Corner V and in the Terrace Tunnel are shown in Figure 31.
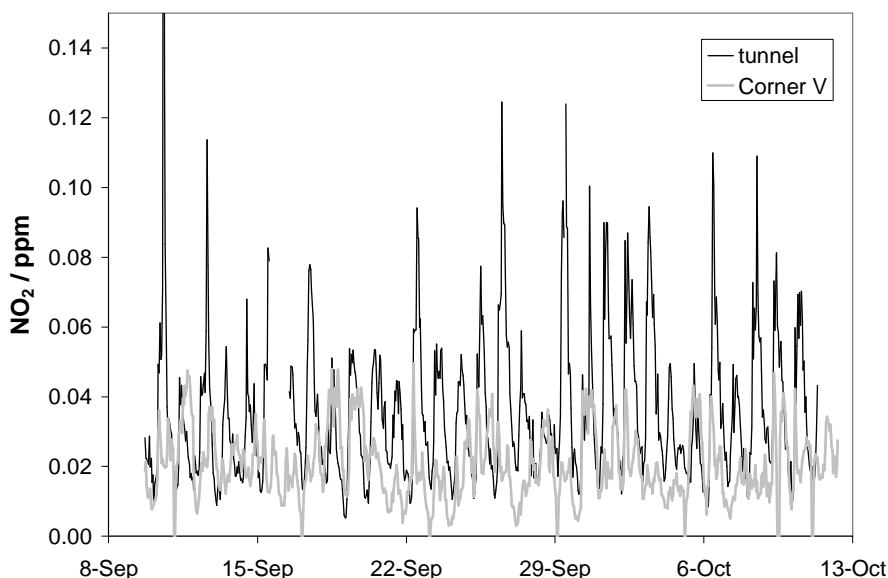


**Figure 31: Simultaneous 1-hour fixed average $NO_2$ concentrations at the Terrace Tunnel and at the Corner V monitoring station (data provided by GWRC).**

We have subtracted the hourly average Corner V concentrations from the simultaneous hourly average concentrations measured in the Terrace tunnel to estimate the concentrations arising solely from emissions within the tunnel. We have done this regardless of wind direction on the assumption that Corner V represents an upper band of likely ambient concentrations in central Wellington and is thus broadly representative of air entering through the northern portal as well as the southern portal. In doing this we assume that we have determined an estimate for the pollutant concentration arising from emissions in the tunnel only.

Figure 32 shows the relationship between $NO_2$ and NO arising from the tunnel only, with a polynomial best-fit curve. The relative flatness of this curve indicates that below approximately 1 ppm of NO, there is no significant production of $NO_2$ inside the tunnel in excess of what would happen alongside SH1 in the absence of the tunnel. However, above 1 ppm of NO, extra $NO_2$ does begin to appear. That this extra production appears to be related to the NO concentration, and the data fit a curve more than a straight line, are indicative that this extra production is related more to secondary chemical reactions rather than direct emission of $NO_2$ from diesel vehicles, although these data are not conclusive. Extra $NO_2$ production above 1 ppm of NO is consistent with an increasing role for the oxidation of volatile organic pollutants

within the tunnel due to the ozone-initiated in-tunnel production of oxidant as a by-product of VOC emissions. However, these results do not rule out a role for the oxidation of NO by oxygen.
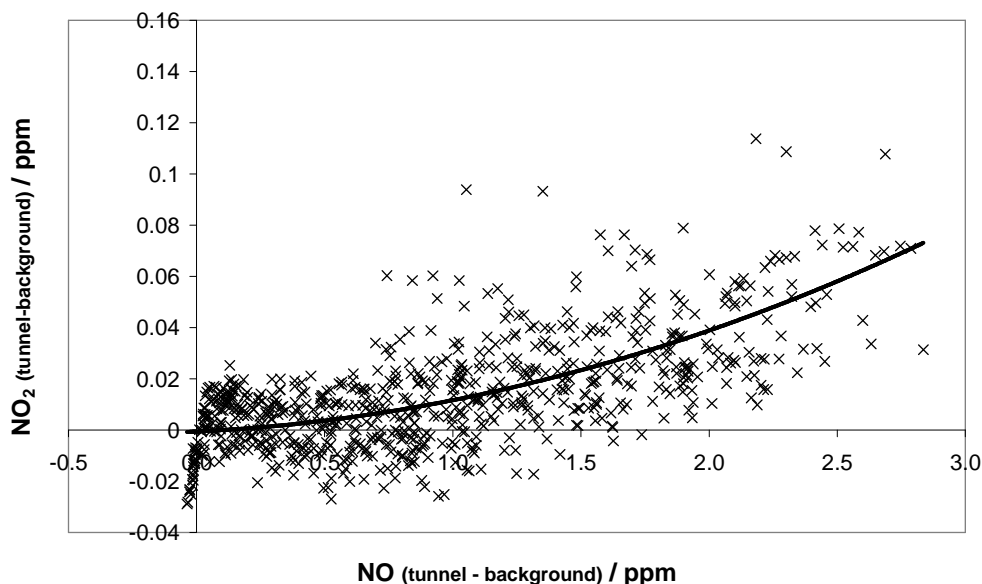


**Figure 32. Plot of estimated levels of hourly average NO$_2$ and NO related to emissions within the tunnel only (i.e. background concentrations subtracted), with best-fit polynomial curve.**

The generally lower level of NO$_2$ in the Mt Victoria tunnel compared to the Terrace tunnel (the opposite pattern to the directly-emitted CO and NO), along with the lower level of ozone observed in Mt Victoria suggests that ozone availability was the dominating factor determining NO$_2$ levels. The Mt Victoria tunnel's bore has a smaller cross-sectional area, generally has a higher vehicle density and is ~50 % longer. These factors all lead us to expect the faster depletion of ozone with length at Mt Victoria. That both O$_3$ and NO$_2$ levels at Mt Victoria were lower than at the Terrace (see tables 4 and 5) confirms these expectations, but also indicates that the transverse ventilation system at Mt Victoria is not effective in delivering sufficient fresh oxidant to the depths of the tunnel to stimulate NO$_2$ production.

In summary, during our monitoring campaign, the dominant process controlling NO$_2$ in the tunnel was the suppression of NO$_2$ production through "natural" ozone (and OH) depletion and adequate ventilation (reducing reactant concentrations and the time available for reactions to progress). Additional NO$_2$ sources – background, direct emissions from diesel vehicles and reactions involving OH and O$_2$ - were all found to

be of minor significance during our monitoring campaign. Much higher levels of diesel traffic or reduced ventilation could make these processes more significant.

### 4.6 Peaks in $NO_2$

The Terrace Tunnel was generally affected by brief peaks in $NO_2$ whereas the Mt Victoria Tunnel was not. Relative to CO, $NO_2$ had a much more skewed distribution in the Terrace Tunnel. For CO, peak 1-minute concentrations were, on average, approximately 2.8 times higher than the median, but for $NO_2$, the ratio was 5 times higher during hours of significant traffic levels. CO concentrations did not exceed 5 times the median at any stage. However, $NO_2$ concentrations exceeded 5 times the median 0.5% of the time (approx. 4 hours) and 10 times the median for approximately 30 minutes.

The skewed distribution of $NO_2$ peaks in the Terrace Tunnel is illustrated in Figure 8. Whereas $NO_2$ was below 0.1 ppm 98.4 % of the time, it reached 0.2 ppm three times and 0.5 ppm once (based on 1-minute average data). There are at least 7 more occasions when $NO_2$ briefly and rapidly rose then returned to "normal". We identified these "episodes" by calculating the change in 1-minute average $NO_2$ concentrations over 10-minute periods. The statistical distribution of this measure is highly skewed with a 10-minute increase of 0.1 ppm or more being highly atypical (affecting 0.1 % of all data) and associated with correspondingly atypical peaks in concentration (1-minute average concentrations above 0.15 ppm). As this episodic behaviour appears to manifest in rapid and potentially unpredictable increases in $NO_2$ we seek to analyse their nature in more detail.

The most dramatic event occurred around the middle of the day on the 10th September 2008 (see Figure 33). $NO_2$ concentrations jumped almost ten-fold from 0.05 ppm to 0.45 ppm in 23 minutes. Concentrations returned below 0.15 ppm 47 minutes after the peak. During this period there was no significant change in wind speed, wind direction, temperature or solar radiation; nor was there any significant change in CO or NO concentrations. However, there was a large, simultaneous and temporally correlated jump in ozone levels. This suggests that a brief and large increase in ozone availability occurred in the tunnel (due to atmospheric processes external to the tunnel) leading to a boost in NO to $NO_2$ conversion lasting as long as the excess oxidant lasted. Greater Wellington Regional Council do not operate a permanent ozone monitoring station, so it has not been possible to corroborate the existence of temporarily elevated levels of ozone outside the tunnels.

Reference to the Terrace Tunnel's jet fans operation logs reveals an "anomalous" entry for this day. The log automatically records the times when the fans start and stop. On the 10th September 2008, the log records the fans stopping at 5:45 am. The next entry reports an additional "stop" at 12:40, not associated with a preceeding "start" At this time the "event" is just about to start – $NO_2$ levels are still "normal" but a rise in ozone has already begun (see Figure 33). The sudden large rise in levels of both pollutants begins at 12:53. It is clearly pertinent to consider whether operations associated with the jet fans and the spike in $NO_2$ and $O_3$ are related.
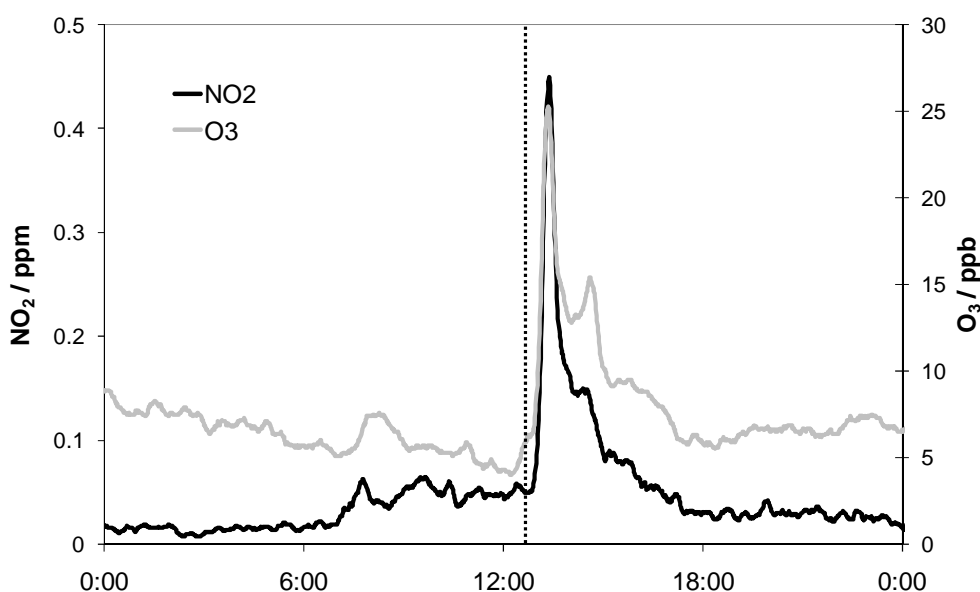


**Figure 33: Detail of the $NO_2$ production event on 10th September 2008 in the Terrace Tunnel. The dotted line marks the time of the anomalous "stop" record in the jet fan logs.**

We sought an explanation of the anomalous fan log entry from Fulton Hogan, who told us that the appearance of two consecutive "stop" records could be due to a hardware fault, a software error or a manual stop. A manual stop may occur for sprinkler testing, a smoke alarm, or other system testing. However, there were no such planned tests or activities on 10th September 2008. There were also no permits issued for access to the roadway or roof space on this date.

A possible alternative explanation of this event, other than excess ozone penetrating from outside the tunnel, is the presence of a high concentration of VOCs which became oxidised _in situ_ leading to the conversion of NO to $NO_2$ without the depletion of ozone. In such a scenario, ozone levels could rise towards ambient levels and Figure 33 seems to suggest that this may have happened. However, there are no data

to corroborate this hypothesis at this time, including no records of paint and/or solvents being used in the tunnel.

Another event occurred on the morning of $6^{th}$ October 2008. Again an approximately ten-fold increase in $NO_2$ occurred within 10 minutes, with the whole event lasting about half an hour. A similar and concurrent episodic rise in ozone also occurred. On $26^{th}$ September 2008, also, a smaller but equally rapid rise in $NO_2$ was accompanied by the same rise in $O_3$, followed by a slower decay over approximately half an hour. However, neither of these events was accompanied by any similarly "anomalous" fan log entry, or any change in jet fan operation.

In general every episode occurred within the period 9:30 am to 2:30 pm. There was no clear relationship with wind speed, and no significant change in solar radiation, but episodes did seem to occur in northerly winds (although with a small sample we cannot conclude whether this was indicative of a general process or cause, or was purely coincidental). That the peaks in $NO_2$ coincided with peaks in $O_3$, but neither NO nor CO, is indicative that the peaks were not caused by gross exhaust emission. The observed behaviour could conceivably be caused by a sudden tunnel closure following a busy period when the removal of traffic could permit ozone to penetrate the tunnel reacting with NO to produce excess $NO_2$. However, we have no record of any such closure during the periods we observed these peaks.

That such episodes were generally not observed in the Mt Victoria Tunnel is likely to reflect the reduced penetration of external oxidant into the depths of this longer tunnel. If the events in the Terrace Tunnel were due to the temporary release of VOCs, we can only speculate that the effects in the Mt Victoria Tunnel might be less pronounced due to the lower levels of ozone which are required to initiate the VOC oxidation reactions which lead to temporary peaks in $NO_2$.

## 4.7 Summary

Data from the Wellington tunnels strongly suggests that chemical production of $NO_2$ in the tunnels (from vehicle emissions of NO) was strongly suppressed due to the rapid depletion of ozone. Ozone levels were lower (close to zero) in the Mt Victoria Tunnel probably due to its greater length and higher density of traffic, despite its transverse ventilation which injects ambient air along the tunnel's length. In this way, both tunnels were mostly self-regulating in terms of $NO_2$. The Terrace Tunnel's shorter length may have made the occasional penetration of ozone more likely, leading to rare and short-lived "chemical events" in which $NO_2$ could be rapidly produced inside the tunnel. These events may alternatively have been caused by the temporary

release of highly concentrated VOCs into the tunnel, although we have found no data to corroborate this.

In the Wellington tunnels, direct emissions of $NO_2$ from vehicles did not appear to be a major source of $NO_2$ concentrations. This may be a reflection of the relatively low proportion of diesel vehicles, and especially Euro III and IV compliant (and equivalent) diesels using these two tunnels. Other chemical production mechanisms, including the self-catalysing oxidation of volatile organic compounds, or the oxidation of NO with oxygen, were also relatively minor determinants, suggesting that limitation of oxidant in the tunnel was the dominant process affecting $NO_2$ levels.

# 5. Long-term trends and forecasting

## 5.1 Purpose of this chapter

This chapter discusses the third objective of the campaign – to compare the observational data with that gathered in 2003 and before (as presented in the Scoping Assessment) and to evaluate whether changes since then are consistent with the emission reductions predicted as a result of developments in engine and emission control technology and the penetration of such technology into the vehicle fleet. Our purpose here is not to make predictions of future air quality in the tunnels, but to indicate whether such predictions *could* be made using the Vehicle Emissions Prediction Model (VEPM).

## 5.2 Context and limitations of this analysis

This analysis is inherently limited. Our goal is to investigate whether VEPM can adequately describe emissions from the vehicle fleet using the tunnels. We intend to achieve this by testing VEPM's ability to reproduce the patterns of variation in emissions arising from variations in traffic fleet composition and speed, validated against observations. It is therefore dependent upon there actually being significant variations in these factors and in having sufficiently detailed data describing those variations. Unfortunately we were unable to capture vehicle speed information and have only limited data regarding variations in the fleet mix. Additionally, we do not expect large variations in fleet composition either within each tunnel or between these two tunnels (as they form nearby sections of the same State Highway).

It is our intention to follow up this campaign with future campaigns in other road tunnels with significantly different traffic fleet compositions and speeds. This will greatly enhance the potential power of this analysis, and as such we present the following analysis as an exploratory introduction.

## 5.3 Correlation between observations and emission modelling

The Vehicle Emissions Prediction Model (VEPM) was released in 2008 and represents a substantial improvement over the preceding New Zealand emission model (NZTER). VEPM predicts fleet-average emission factors (equivalent to the average emissions per km driven over representative driving cycles) based upon a percentage breakdown of the fleet (e.g. petrol/diesel, car/LCV/HCV, etc) and average driving speed.

As noted in section 2.3 above, we did not collect continuous observations of traffic speed during the campaign. We have therefore investigated the results from using four different traffic fleet split scenarios on estimated emissions based on

1. brief manual observations of traffic in the tunnels (from which we also derived estimated average speeds),

2. observations of fleet split made at five locations in Greater Wellington for a previous NIWA research campaign (Bluett & Dey, 2006),

3. the default fleet splits provided as part of the VEPM package and derived from the Ministry of Transport fleet database and model,

4. a combination of 1 and 3 above.

Based on our observations, for calculations with VEPM we set the average speed to 70 km h$^{-1}$ (Terrace) and 45 km h$^{-1}$ (Mt Victoria).

The full list of input parameters and emission modelling results are shown in the Technical Annex (chapter 10). Table 7 summarises the predicted values for the $NO_x/CO$ emission ratio.

Research conducted by NIWA (within a programme funded by the Foundation for Research, Science & Technology, FRST, unpublished at time of writing) have indicated that these results have a low sensitivity to error for an average speed in the 60 – 80 km h$^{-1}$ range, but an increased sensitivity at lower speeds, such as those observed in the Mt Victoria tunnel. The same research indicates that errors in the fleet split may lead to significant errors in the $NO_x$ emission factor.

Although our observational data cannot be used to directly verify these emission factors, some indirect validation can be achieved by considering the ratio $NO_x/CO$. The ratio in these emission factors should correspond to the ratio in their concentrations within the tunnel when expressed in terms of mass (i.e. $\mu g\ m^{-3}$) if the concentrations are large compared to the non-tunnel contribution (which they are in our case). There is more than one approach to converting the observed NO and $NO_2$ concentrations (in ppb) to $NO_x$ in $\mu g\ m^{-3}$ and further details (and implications of the choice of method) are provided in chapter 10. The following analysis is based upon the conventional approach of expressing $NO_x$ as $NO_2$.

**Table 7: Mean vehicle emission factors predicted for the tunnels by VEPM (v3.0)**

| | Fleet scenario | NOx/CO emission ratio |
|---|---|---|
| Terrace | 1 | 0.16 |
| | 2 | 0.16 |
| | 3 | 0.19 |
| | 4 | 0.20 |
| Mt Victoria | 1 | 0.14 |
| | 2 | 0.12 |
| | 3 | 0.14 |
| | 4 | 0.18 |

As shown in Table 7 for the Terrace tunnel VEPM predicts inter-peak $NO_x$/CO ratios of 0.16 – 0.20. On average, the $NO_x$/CO mass concentration ratio observed in the tunnel was 0.21. However, this ratio varies diurnally, as would be expected if the fleet split or average speeds (or proportion of cold starts) in the tunnel also vary diurnally. Figure 34 shows this average variation and indicates that during the inter-peak period (10 am to 3 pm local time) the average ratio is 0.25. Ratios calculated using an alternative method (see chapter 10) more closely correspond to the values predicted by VEPM.

For the Mt Victoria tunnel VEPM predicts inter-peak $NO_x$/CO ratios of 0.12 – 0.18. On average, the $NO_x$/CO mass concentration ratio observed in the tunnel was 0.19, with inter-peak average of 0.21 (see Figure 35). This represents values 8 % lower on average than for the Terrace Tunnel (14 % in the inter-peak period). VEPM predicts ratios 9 – 26 % lower for the Mt Victoria Tunnel compared to the Terrace Tunnel. The lower ratios predicted by VEPM for the Mt Victoria Tunnel compared to the Terrace Tunnel arise due to higher CO emissions from a more petrol/car-biased fleet, plus both higher CO emissions and lower $NO_x$ emissions due to the lower average speed. Thus, the **comparative patterns** in our observations agree with those predicted by emission modelling.

This simple analysis should be treated with caution as it is based on a number of assumptions and incorporates several uncertainties. Firstly, our limited traffic observations may be inaccurate or unrepresentative. Secondly, VEPM, like many

emission models, is designed to predict the average emissions of the whole national fleet over a wide range of driving conditions. It is not explicitly designed to predict emissions of a limited fleet on a single stretch of road. Many micro-scale features are known to affect emissions quite strongly which are not captured by VEPM. In the case of the tunnels these include gradient, but especially smooth versus stop-start driving. Anecdotally we expect driving in the Terrace tunnel to be relatively smooth (generally smooth acceleration for northbound traffic and deceleration or coasting for southbound). In contrast we expect driving in the Mt Victoria tunnel to be more characterised by vehicle interactions indicative of congested or near-congested conditions. This kind of driving is known to be associated with higher CO emissions than smooth driving at the same speed.
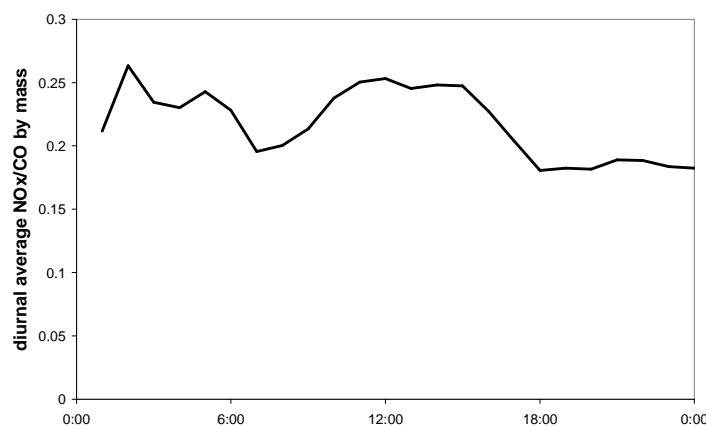


**Figure 34: Observed diurnal average $NO_x$/CO mass concentration ratio in the Terrace tunnel.**
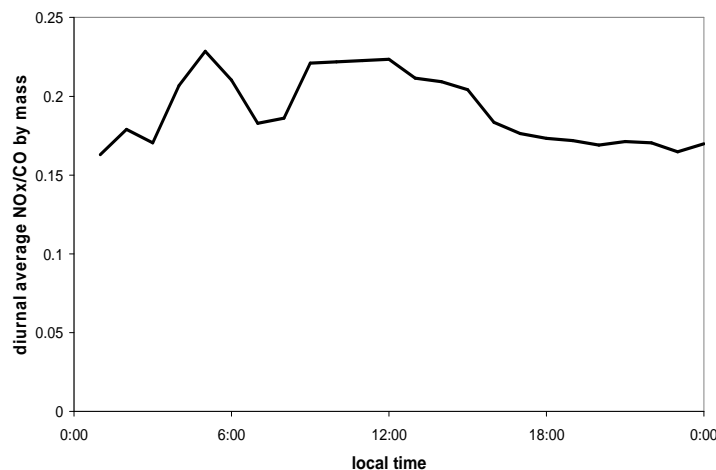


**Figure 35: Observed diurnal average $NO_x$/CO mass concentration ratio in the Mt Victoria tunnel.**

### 5.4 Comparison with Screening Assessment carried out in early 2008

This report follows a Scoping Assessment conducted by NIWA and delivered to Transit NZ in draft form in 2008. That report included a review of previous observations of CO, NO and $NO_2$ inside the Terrace and Mt Victoria tunnels. The most recent data for both tunnels were from 2003. We extrapolated the results to 2008 based on predicted improving trends in vehicle emissions due to adoption of cleaner vehicles into the NZ fleet, but also assuming no changes to fleet mix, speeds, traffic volume or congestion. In the Scoping Assessment this extrapolation was based on trends predicted by both the NZTER and VEPM emission models. We have now re-run the emission modelling using VEPM version 3.0 and based on the same traffic scenarios as discussed above. Full details are provided in chapter 10. In brief, we now conclude that VEPM predicts reductions in CO and $NO_x$ emissions of 28 % in the period 2003 – 2008. Tables 7 and 8 summarise the main indicative data from 2003 (from MWH, 2003a,b, also reported in Longley *et al*., 2008c), the extrapolated estimates for 2008 and the data from the 2008 monitoring campaign.

**Table 8: Indicative statistics for the Terrace tunnel from the 2003 observations, estimations for 2008 based on extrapolation of 2003 data (from Scoping Assessment) and observations from 2008 monitoring. Percentages in brackets are reduction since 2003.**

|  | 2003 | 2008 estimated | 2008 observed |
|---|---|---|---|
| Max observed CO / ppm | 135 | 97 | 30.1 (-78 %) |
| Typical morning peak CO / ppm | ~ 60 | 43 | 14.3 (-76 %) |
| Typical inter-peak[15] CO / ppm | ~ 30 | ~22 | 9 (-70 %) |
| Mean CO over 24 hrs / ppm | 26 | 19 | 7.6 (-71 %) |

**Table 9: Indicative statistics for the Mt Victoria Tunnel from the 2003 observations, estimations for 2008 based on extrapolation of 2003 data (from Scoping Assessment) and observations from 2008 monitoring. Percentages in brackets are reduction since 2003.**

|  | 2003 | 2008 estimated | 2008 observed |
|---|---|---|---|
| Max observed CO / ppm | 91 | 66 | 75 (-18 %) |
| Typical morning peak CO / ppm | ~ 50 | ~ 36 | 20 (-60 %) |
| Typical inter-peak[16] CO / ppm | ~ 20 | ~14 | 12 (-40 %) |
| Mean CO over 24 hrs / ppm | 14.8 | 10.7 | 7.9 (-47 %) |

In the Scoping Assessment we predicted a reduction in CO concentrations of the order of 28 % between 2003 and 2008 as a result of technological changes alone. This is less that what we generally observed in the Mt Victoria Tunnel (40 – 60 % for average measures), and reductions were even greater in the Terrace Tunnel (70 – 80 %).

There are a number of factors which need to be considered when interpreting these reductions:

- **Reliability of the 2003 data**: as noted in the Scoping Assessment, the 2003 data were relatively poorly described. It was also captured using an electrochemical technique which does not comply with NZ Standards and is known to be less accurate than the technique used in 2008.

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[15] Inter-peak is 10 am to 3 pm local time inclusive.
[16] Inter-peak is 10 am to 3 pm local time inclusive.

- **Changes in traffic volume**: Transit NZ traffic count data indicate no significant change in traffic volumes for either tunnel in either direction between 2003 and 2008.

- **Changes in traffic fleet**: we have no data on the fleet mix using the tunnels. We also have no anecdotal evidence of any notable change in the nature of the fleet. However, our sensitivity study using VEPM (see section 10.2) indicates that the predicted reductions have a low sensitivity to fleet split within the ranges of likely change.

- **Accuracy of the emission model extrapolation**: the predicted concentrations for 2008 were based on changes in average vehicle emissions only as a result of penetration of lower-emission vehicles into the fleet, as predicted by two emission models. There are uncertainties associated with accuracy of the emission models VEPM and NZTER.

- **Changes in congestion**: we have no data concerning congestion in the tunnels. Congestion is significant because congested, low speed driving can lead to elevated per-km emissions of CO. The Scoping Assessment cites historical anecdotal evidence of regular congestion occurring inside the Terrace tunnel at peak times. However, since the completion of the Inner Ring Road, we have collected further anecdotal evidence that this congestion has been substantially reduced in the tunnel itself. In the absence of more rigorous data we hypothesise that this could be a substantial contributing factor to the reduction in concentrations of CO within the Terrace tunnel. We have no similar evidence of a change in congestion in the Mt Victoria tunnel. This could potentially contribute to the greater reduction in CO concentrations in the Terrace Tunnel.

- **Operation of the ventilation system**: as noted in the Scoping Assessment, the Terrace tunnel has had historic problems with inappropriate operation of the ventilation system. The system is based upon longitudinal jet fans which are intended to assist the "natural" air flow in the tunnel. I.e. if there is a northerly wind blowing through the tunnel, the fans will blow in this direction. However, detection of the natural airflow is technically difficult, and it has been previously reported that the fans can sometimes be operating in the wrong direction, thereby reducing the ventilation efficacy. The system is also designed to operate over three settings. This is achieved by having 6, 3 or none of the 6 banks of fans operating. We have no data from the 2003 campaign which is able to verify whether the fans were operating in the

correct direction, nor which setting was being used at which times. However, for the 2008 campaign we were advised by the engineer responsible for the system that the intermediate setting (3 out of 6 fans) could not be operated due to a system fault. At the time when 3 fans should have been operating, the system was set to operate all 6 fans. Thus, the system was effectively operating at "maximum" more often than it was designed to. This may have reduced the in-tunnel pollutant concentrations relative to what may have been found had the intermediate setting been operational.

## 5.5  Summary

We found that the $NO_x$/CO ratio predicted by the emission model VEPM was similar to that observed in the Terrace tunnel, based on very limited vehicle fleet and speed data observed during daytime hours. VEPM broadly reproduced the same comparative patterns between the two tunnels. These observations give us limited confidence in our ability to make predictions about future trends using VEPM. This analysis will be greatly enhanced if data becomes available from other road tunnels with different speeds and/or fleet mixes.

Our observations broadly confirm reductions in CO concentrations over the last 5 years of at least the magnitude predicted by the emission model VEPM due to developments in engine and emission control technology and the penetration of such technology into the vehicle fleet (i.e. 28 %). However, we also observed an additional reduction totalling 40 – 60 % in the Mt Victoria Tunnel and 71 – 78 % in the Mt Victoria Tunnel over this period. Several reasons have been postulated, particularly changes in ventilation operation, changes in congested traffic flow and inaccurate historical data.

# 6. Implications

## 6.1 Emission trends and future air quality in the tunnels

We have noted how the apparent improvement in air quality in the Mt Victoria tunnel over recent years is consistent with the trends in vehicle emissions as described by the emission model VEPM. These trends are linked to increasing penetration of vehicles compliant with recent emission standards due to technological advances. These trends are continuing. In the absence of any change to the fleet split (i.e. diesel/petrol split or proportions of different vehicle class, e.g. cars, light-goods and heavy goods vehicles), VEPM predicts that CO emissions will fall by another two thirds on average over the next decade in the New Zealand vehicle fleet, compared to 2008. Beyond ten years, further reductions in emissions will be smaller. Reductions in $NO_x$ emissions are predicted to be smaller but still significant (50 – 60 % over the next ten years). Increases in congestion (and/or decreases in vehicle speed) are generally believed to lead to increases in CO emissions and possibly (smaller) reductions in $NO_x$ emissions (depending upon fleet mix).

These predictions must be interpreted with care. The VEPM emissions model is currently unvalidated in New Zealand and its predictions of the future are based on a wide range of assumptions about the rate of adoption, import and state of maintenance of new technology vehicles, and the rate of removal of older vehicles. Emission factors for newer technology vehicles are not as well quantified and subject to significant uncertainty. As such, the predictions of VEPM should be seen as plausible rather than reliable.

Lower CO emissions should lead directly to lower CO concentrations in the tunnels. The effect of reduced $NO_x$ emissions on $NO_2$ concentrations is less clear. Our analysis of the Wellington tunnels has indicated that ozone availability, rather than NO emissions, is the dominant control on $NO_2$ concentrations. We have found that direct emission of $NO_x$ in the form of $NO_2$ currently plays a minor role in $NO_2$ concentrations. However, VEPM does not predict direct $NO_2$ emissions. Evidence from abroad has indicated trends of increasing direct $NO_2$ emissions, associated with increasing use of diesels. If such trends occur in New Zealand, it is plausible that $NO_2$ concentrations could rise in road tunnels, independently of the ozone-limited secondary production mechanism.

These preliminary conclusions should be revisited if the ventilation system of either Wellington tunnel were to be changed.

## 6.2 Exposure of tunnel users

The recommended carbon monoxide guidelines are based upon exposure limits. This means that they specify the maximum allowable concentration that a person should be exposed to over a given period without any risk of adverse acute health effects. For members of the public, the given period is 15 minutes. A shorter exposure period implies a reduced risk.

The posted speed limit in the Mt Victoria tunnel is 50 km h$^{-1}$. Travelling at this speed a vehicle should remain inside the tunnel for 44 seconds. However, congestion in and around the tunnel has been reported since at least 1982 and actual speeds in the tunnel can be much lower, and hence exposure times can be longer. At an average 10 km h$^{-1}$ the journey time is 224 seconds (approx. 4 minutes), indicating that exposure durations are well below the 15-minute averaging period applied in the CO guideline recommended by NIWA for use in road tunnels.

Pedestrians and cyclists are permitted to use the Mt Victoria tunnel. Pedestrian journey times are typically less than 10 minutes, but could extend towards 15 minutes for some users. Cyclists are likely to have a higher breathing rate and breathe more deeply. However, our calculations indicate that this is more than compensated for by the reduced exposure time due to a faster transit through the tunnel (see Longley *et al*., 2008c for more details). Thus, "slow" pedestrians represent the group of users most at risk from the effects of carbon monoxide in the tunnel. However, they are adequately protected as long as their journey time remains below 15 minutes, and the 15-minute CO guideline is met within the tunnel.

The Terrace tunnel is only two thirds of the length of the Mt Victoria tunnel, and average speeds are higher. Consequently journey times in the Terrace tunnel are generally much shorter. Pedestrians and cyclists are not permitted in the tunnel. Therefore it is highly unlikely that any member of the public is exposed to pollutants within the tunnel for 15 minutes. This simple fact provides considerable protection to users from the hazard to health presented by the levels of air pollution observed.

# 7. Conclusions from the monitoring programme

During our monitoring period the **Terrace tunnel** met the recommended 15 minute CO guideline with ease. The tunnel also met the PIARC (2010) recommendation of 70 ppm of CO. The 8-hour occupational safety guideline was met, as was the more restrictive PIARC guideline of 20 ppm, albeit by a minute margin. The maximum 1-minute average $NO_2$ concentration observed during the whole campaign was just over half of the guideline value. Consequently, we can conclude that during the monitoring period, the Terrace tunnel met the recommended $NO_2$ guideline.

Variation in traffic volume was found to be a major determinant of air quality in the Terrace tunnel (as represented by CO concentrations). Worse air quality in northerly winds is suggestive of inappropriate operation of the ventilation system – however this did not lead to a breach of the CO guidelines. Air quality has substantially improved since 2003. This was at least partly due to the increasing numbers of new technology reduced-emission vehicles penetrating the vehicle fleet. Additional improvement may have been due to improvements in traffic flow, although the observed improvements may be an artefact of the fans being operated to full capacity more often or inaccurate historical data. Considerable protection from the effects of air pollution in the tunnel is provided by the fact that exposure times for the public are far below 15 minutes.

During our monitoring period the Mt Victoria Tunnel met both the recommended 15 minute CO guideline for public users. During the period of 7am - 8am local time the PIARC 2010 guideline of 70 ppm was exceeded twice over a 2-month period. Although the 30 ppm occupational safety guideline was not exceeded, this was by a small margin. The more demanding 20 ppm limit recommended by PIARC was exceeded 2 % of the time for which data exist. The risk of non-compliance was limited to 8-hour shifts ending between 1 pm and 11 pm local time.

In the Mt Victoria tunnel high northerly winds external to the tunnel aided the tunnel's ventilation system by inducing an additional wind along the tunnel bore. However, in most conditions external winds were ineffective for tunnel ventilation and some of the highest CO concentrations in the tunnel coincided with the lowest external wind speeds.

The Mt Victoria tunnel met the recommended $NO_2$ guidelines.

Air quality in the Mt Victoria tunnel has substantially improved since 2003. This was at least partly due to the increasing numbers of new technology reduced-emission vehicles penetrating the vehicle fleet. Whereas vehicle users are offered considerable

protection due to journey times usually being far below 15 minutes, this protection is reduced for pedestrians, especially those for whom the journey time may approach 15 minutes. However, the risk presented is still acceptable as long as the tunnel meets the 15-minute CO guideline.

Data from the Wellington tunnels strongly suggest that chemical production of $NO_2$ in the tunnels (from vehicle emissions of NO) was strongly suppressed due to the rapid depletion of ozone. Ozone levels were lower (close to zero) in the Mt Victoria tunnel probably due to its greater length and higher density of traffic, despite its transverse ventilation which injects ambient air along the tunnel's length. In this way, both tunnels were mostly self-regulating in terms of $NO_2$. The Terrace tunnel's shorter length may have made the occasional penetration of ozone more likely, leading to rare and short-lived "chemical events" in which $NO_2$ could be rapidly produced inside the tunnel.

In the Wellington tunnels, direct emissions of $NO_2$ from vehicles did not appear to be a major source of $NO_2$ concentrations. This may be a reflection of the relatively low proportion of diesel vehicles, and especially Euro III and IV compliant (and equivalent) diesels using these two tunnels. Other chemical production mechanisms, including the self-catalysing oxidation of volatile organic compounds, or the oxidation of NO with oxygen, were also relatively minor determinants, suggesting that limitation of oxidant in the tunnel was the dominant process affecting $NO_2$ levels.

# Technical Annex

## 8. Sampling Methods

The following sub-sections describe the methods and equipment used during the monitoring of pollutants and meteorology in the Terrace and Mt Victoria tunnels.

### 8.1 Instrument deployment

Our approach to this campaign was to deploy the most accurate instrumentation available. Thus, we chose instrumentation which could be compliant with appropriate Australia/New Zealand Standards. These standards require regular on-site calibration using gas cylinders. Such cylinders cannot be transported inside most State Highway tunnels. The analysers selected require operating in a controlled environment to maintain a constant temperature and humidity. In practical terms we achieve this using a purpose-built trailer. These requirements meant that monitoring directly inside the tunnels was not a practical option for these analysers.

Where possible we followed the appropriate Australia/New Zealand Standard. The main deviations were:

- sampling tube length and material,

- calibration frequency,

- detection range of the analyser.

Our solution was to deploy a long sampling tube into the tunnel to draw air to the trailer, which was located outside the tunnel.

At the Terrace tunnel, the trailer was located at the "Ghuznee stub" 60 m outside the southern portal as shown in the photo in Figure 36. The inlet point was located 230 m inside the tunnel (from the southern end) mounted at 1.8 m height on the eastern wall as shown in the photo. The total length of tubing was 300 m.

**Figure 36: The air quality trailer at the southern portal of the Terrace Tunnel.**
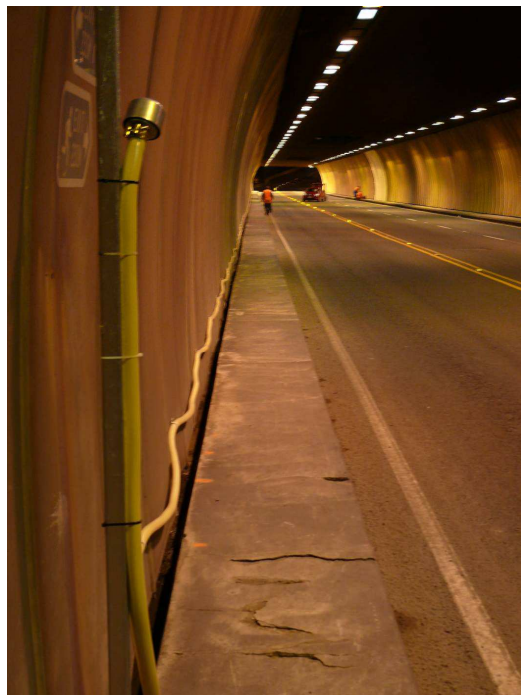


**Figure 37: The sampling point near the mid-point of the Terrace Tunnel.**

At the Mt Victoria tunnel the trailer was located outside the western exhaust stack in the grounds of Wellington East Girls College, whilst the sampling tube was lowered 18 m into the western exhaust duct, making a total sampling length of 100 m. The next photos show the tubing inside the fanhouse and the location of the trailer.



**Figure 38: The interior of the Mt Victoria Tunnel western exhaust stack building showing the top of the exhaust vent (below left) and the sampling duct passing from the duct along the wall to the trailer at the exterior of the building.**

In addition to this sampling, a sonic anemometer was attached to a bracket hanging over the roadway approximately 2 m down from the roof.

## 8.2 Carbon Monoxide (CO)

An API Model 300 CO analyser was used to monitor CO. This unit continuously measures the concentrations of CO in ambient air by collecting a sample of air and then passing a beam of infrared light through the sample. The amount of infrared energy absorbed by the gas sample is measured and the Beer-Lambert law used to calculate the CO concentration. The API Model 300 analyser can measure CO in the range of 0 to 1 000 ppm, although the range for approval by the Australian Standard is for 0 to 50 ppm only. The precision of the analyser is 0.5% of the reading.

In the Terrace Tunnel the range was set at 0 to 50 ppm, while at the Mt Victoria Tunnel the range was initially set at 0 to 50 ppm but it had to be changed to 0 to 100 ppm on 31$^{st}$ October 2008 as the 50 ppm range was exceeded. The accuracy of the data (taking into account the analyser and the calibration system) is ± 1ppm when the range is 0 to 50 ppm and ± 2 ppm when the range was 0 to 100 ppm.

## 8.3 Nitrogen Dioxide (NO$_2$)

An API Model 200 NO$_x$ analyser was used to calculate NO$_2$. This unit continuously measures the concentrations of NO and NO$_x$ and calculates the concentration of NO$_2$ by using the equation NO$_2$ = NO$_x$ - NO.  The measurements are taken by collecting a sample of ambient air, which is introduced into an ozone reaction chamber. The NO in that sample is reacted with ozone to produce NO$_2$. Light is released as a product of this reaction in a process known as chemiluminescence. The amount of light released is proportional to the number of NO molecules that have just been converted from NO to NO$_2$.

The sample is then passed through a molybdenum converter where all the NO$_2$ is converted to (or back to) NO. The sample is reintroduced into the ozone reaction chamber, where again the NO reacts with ozone to produce NO$_2$ and light. The difference in the amount of light released between the first and second pass through the reaction chamber is proportional to the amount of NO$_2$ in the original sample.  The API Model 200 analyser can measure NO$_x$ in the range of 0 to 20 000 ppb, although the range for approval to the Australian Standard is for 0 to 10 000 ppb only. The precision of the analyser is 0.5% of the reading.

In the Terrace Tunnel the range was set at 0 to 3 000 ppb, although this value was exceeded over 15 minutes on 29th September 2008. At the Mt Victoria Tunnel the range was initially set at 0 to 5 000 ppb but it had to be changed to 0 to 8 000 ppb (on 31st October 2008) as the 5 000 ppb range was exceeded three times (covering 83 minutes). The accuracy of the data (taking into account the analyser and the calibration system) is $\pm$ 110 ppb when the range is 0 to 3000 ppb, $\pm$ 180 ppb when the range is 0 to 5000 ppb and $\pm$ 300 ppb when the range was 0 to 8000ppb.

## 8.4 Ozone (O$_3$)

An API Model 400 ozone analyser was used to monitor ozone. Ambient air is continuously sampled using a pump unit. Ozone concentrations are calculated from the absorption of ultra-violet light at 254 nanometres wavelength. The absorption is measured using a UV detector. An ozone-removing scrubber is used to provide a zero reference intensity. The concentration is calculated using the Beer-Lambert equation. The API Model 400 analyser can measure ozone in the range of 0 to 10 000 ppb, although the range for approval to the Australian Standard is for 0 to 1 000 ppb only. The precision of the analyser is 0.5% of the reading.

In the Terrace Tunnel and Mt Victoria Tunnel the range was set at 0 to 500 ppb. The accuracy of the data (taking into account the analyser and the calibration system) is $\pm$ 15 ppb when the range is 0 to 500 ppb,

## 8.5 Meteorological Data

Weather, particularly wind speed and direction, has a very strong influence on contaminant dispersion and concentrations, and without meteorological data the air quality data is almost impossible to interpret. The meteorological parameters monitored from the trailer at both sites were wind speed and direction, air temperature, relative humidity and solar radiation. At both sites the sensors were at a height of 6m above the ground. The sensors used in the trailer were:

- wind speed - Vector A101M anemometer (m/s to 0.1)

- wind direction - Vector W200P wind vane (°T to $\pm$ 2°)

- air temperature – Vaisala 50Y air temp /RH sensor (ºC to ± 5%)

- relative humidity - Vaisala 50Y air temp /RH sensor, (%RH to ± 5%).

- Solar radiation - Licor LI200SZ pyranometer

## 8.6  Sampling from within the tunnel

The inlet was made up of 50 m long sections of food grade tubing to reduce the possibility of contaminants coming out of the tubing and affecting the sample.  A paper filter was attached to the tunnel end to remove any large particles as shown in the photo on the next page.  This type of filter is used on our zero air generators for this purpose. The tubing was attached to the wall in the Terrace tunnel and allowed to fall naturally in the Mt Vic Tunnel

Once inside the trailer the sample inlet went through a T junction with the main flow being sucked through with a large pump mounted on the bench and the secondary flow going to the analyser sampling manifold.   This system also had a bypass flow to eliminate the possibility of back flow.  To check this, a pressure gauge was installed into the glass sampling manifold and the positive pressure was checked to ensure it was sufficient for the purpose.



**Figure 40: the sampling manifold inside the air quality trailer.**

The air sample for the analysers was sucked by a second pump though a glass sampling manifold. This manifold is the same one used for normal ambient air sampling. The analysers can then take off their required flows from this manifold.
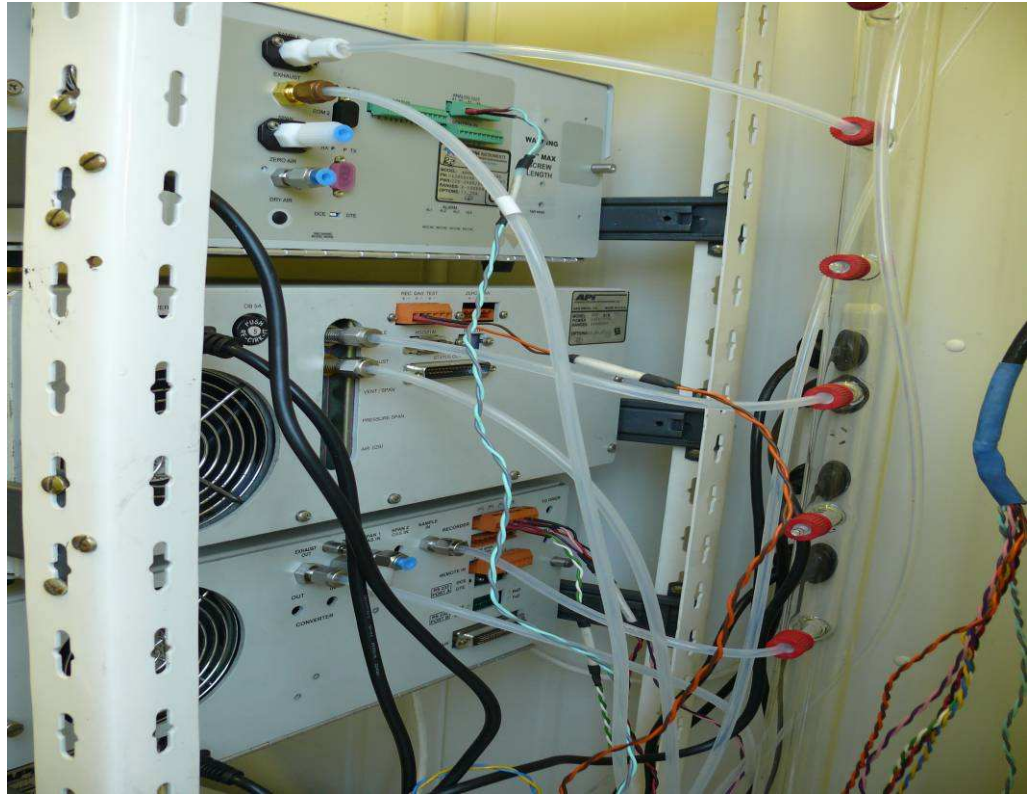


**Figure 41: The gas inlet connections to the analysers inside the air quality trailer.**

To check the validity of using such a long sampling inlet, checks were done on the flow rate and the concentration. The potential issue was that the concentration of the pollutant would drop as a result of the length of time in the tube.

To test the concentrations, checks were done using ambient air as the flow rate being used was too high for the use of a known gas bottle sample. On the day selected (February 25th), the wind was blowing from across an area of housing and thus was not being affected by a nearby road. Data had been logged from this location for a number of weeks. The background concentration as shown on the display of the analyser was around 6 ppb for ozone and -0.3 ppm for carbon monoxide.

We then connected up a short length of the tubing (~2 m) and allowed the analysers to sample the air until both the ozone and CO displays were stable. The concentrations

did not change significantly. This same procedure was repeated for 100 m of the tubing (as used at Mt Victoria) and 300 m of the tubing (as used at Terrace) and the concentrations did not change significantly at any length. The concentrations varied between 5 and 7 ppb for ozone and -0.2 and -0.3 ppm for carbon monoxide which was within the naturally occurring conditions on that day. Graphs of the stable data at each setup were recorded. This confirmed that the length of the tubing did not effect the concentration recorded on the analyser.

The flow rate in the tube at both the 100 m and 300 m lengths was checked and was stable throughout the five minute sampling period, and was well within the expected range.

# 9. Data Management

## 9.1 Data Logging and monitoring

The raw data from the CO, $NO_x$ and $O_3$ analysers, as well as from the meteorological sensors in the trailer were recorded on Campbell CR10 data loggers. The air quality raw data were logged as one minute and ten minute averages based on 3 second samples. The meteorological raw data were logged as one minute, ten minute and one hour averages also based on 3 second sampling.

The data were downloaded from the loggers via cell phone telemetry and checked on each working day to ensure the data was coming in and looked realistic.

Data from the sonic anemometer could only be downloaded manually during a site visit into the tunnel. These data were logged as an instantaneous sample recorded every two minutes which is the minimum resolution possible for this logger.

## 9.2 Nitrogen Dioxide ($NO_2$)

The analyser was calibrated at the start and end of each installation and intermediary checks were done when required.

Data for nitrogen dioxide were calculated from the one minute data. The data were graphed and checked for errors. Any invalid data were removed and a comment included in the metadata file to explain why they were taken out. Fifteen minute moving average and one hour fixed average data were calculated from the 1 minute data.

## 9.3 Carbon Monoxide (CO)

The analyser was calibrated at the start and end of each installation and intermediary checks were done when required.

Data for carbon monoxide were calculated from the one minute data. The data were graphed and checked for errors. Any invalid data were removed and a comment included in the metadata file to explain why they were taken out. Fifteen minute moving average and one hour fixed and 8-hour moving averages were calculated from the 1 minute data.

## 9.4 Ozone Data (O$_3$)

The analyser was calibrated at the start and end of each installation and intermediary checks were done when required.

Data for ozone were calculated from the one minute data. The data were graphed and checked for errors. Any invalid data were removed and a comment included in the metadata file to explain why they were taken out. Fifteen minute moving average and one hour fixed average data were calculated from the 1 minute data.

## 9.5 Meteorological Data

The sensors were calibrated before the programme started, and checked at the start of each installation with any offsets applied to the data logger programme. A final check was made at the end of the installation to be used as a check for any drift.

The data were graphed and checked for errors. Any invalid data were removed and a comment included in the metadata file to explain why they were taken out. Fifteen minute moving average data was calculated from the one minute data (vector averaging for wind direction). The one hour data is based on 3 sec sampling.

## 9.6 Removal of data points during tunnel maintenance closures

The Mt Victoria tunnel was closed to traffic on the nights of 9$^{th}$/10$^{th}$, 10$^{th}$/11$^{th}$ and 11$^{th}$/12$^{th}$ November 2008 between 10 pm and 4:30 am. During these periods very low concentrations were interrupted by very high "spikes" affecting CO, NO and NO$_2$. This is consistent with the maintenance schedule which shows painting (during which ventilation fans are operated to aid drying) and cleaning involving slow moving diesel vehicles operating in the tunnel. As neither the operation of the fans at night, nor the slow moving maintenance traffic represent typical conditions in the tunnel, all data during these periods have been removed from the dataset used to produce the analysis discussed in this report.

There were no closures of the Terrace Tunnel during the monitoring campaign.

## 9.7 Data coverage and quality

### 9.7.1 Terrace Tunnel

Air quality and meteorological data became available from 9th September 2008. From that point monitoring continued until 11th October 2008 (10th October 2008 for CO and $O_3$).

**Table 10: Data capture rates for the Terrace Tunnel**

| | |
|---|---|
| Carbon dioxide, CO | 97 % |
| Nitrogen dioxide, $NO_2$ | 97 % |
| Nitric oxide, NO | 98 % |
| Ozone, $O_3$ | 97 % |

The following tables show the data that has been removed

## Instrument & Site History Summary

**Site:** Terrace Tunnel
**Pollutant:** CO
**Instrument Description:** API Model 300
**Owner:** NIWA

| Start Date | Finish Date | Data affected ? (y/n) | Event |
|---|---|---|---|
| 19/08/2008 | | n | Analyser **API M300 serial no 421** installed. |
| 21/08/2008 | | n | Calibration check |
| 21/08/2008 14:42 | | y | **Data logging begins – not sampling tunnel air** |
| 25/08/2008 11:55 | | n | Site visit |
| 08/09/2008 11:45 | 08/09/2008 13:37 | y | Calibration and investigation of air sampling problems – found leak in the system |
| **09/09/2008 16:03** | | y | **VALID DATA BEGINS** |
| 15/09/2008 13:28 | 16/09/2008 11:09 | y | Site visit – fault with the sample intake tubing when lever was knocked. |
| 16/09/2008 11:17 | | n | Site visit |
| 24/09/2008 03:47 | 24/09/2008 03:47 | y | Missing data due to telemetry fault |
| 25/09/2008 07:50 | 25/09/2008 07:50 | y | Missing data due to telemetry fault |
| 03/10/2008 13:00 | | n | Site visit |
| **10/10/2008 10:38** | | y | **VALID DATA ENDS** |
| 10/10/2008 10:38 | | n | Final calibration begins |
| 12/10/2008 20:35 | | n | Analyser turned off |

# Instrument & Site History Summary

**Site:** Terrace Tunnel
**Pollutant:** Ozone
**Instrument Description:** API Model 400
**Owner:** NIWA

| Start Date | Finish Date | Data affected ? (y/n) | Event |
|---|---|---|---|
| 19/08/2008 | | n | Analyser **API M300 serial no 1440** installed. |
| 21/08/2008 | | n | Calibration check |
| 21/08/2008 16:04 | | y | **Data logging begins – not sampling tunnel air** |
| 25/08/2008 11:58 | | n | Site visit |
| 08/09/2008 11:45 | | y | Investigation of air sampling problems – found leak in the system |
| **09/09/2008 16:27** | | y | **VALID DATA BEGINS** |
| 15/09/2008 13:27 | 16/09/2008 17:00 | y | Site visit – fault with the sample intake tubing when lever was knocked. |
| 16/09/2008 11:25 | | n | Site visit |
| 24/09/2008 03:47 | 24/09/2008 03:47 | y | Missing data due to telemetry fault |
| 25/09/2008 07:50 | 25/09/2008 07:50 | y | Missing data due to telemetry fault |
| 03/10/2008 13:03 | | n | Site visit |
| **10/10/2008 07:14** | | y | **VALID DATA ENDS** |
| 10/10/2008 07:15 | | n | Final calibration begins |
| 12/10/2008 20:38 | | n | Analyser turned off |

## Instrument & Site History Summary

```
Site: Terrace Tunnel
Pollutant: Nitrogen oxides
Instrument Description: API Model 200
Owner: NIWA
```

| Start Date | Finish Date | Data affected ? (y/n) | Event |
|---|---|---|---|
| 19/08/2008 | | n | Analyser **API M200 serial no 756**installed. |
| 22/08/2008 | | n | Calibration check |
| 22/08/2008 14:38 | | y | **Data logging begins – not sampling tunnel air** |
| 25/08/2008 12:01 | | n | Site visit |
| 08/09/2008 11:45 | | y | Investigation of air sampling problems – found leak in the system |
| **09/09/2008 16:04** | | y | **VALID DATA BEGINS** |
| 15/09/2008 13:29 | 16/09/2008 11:09 | y | Site visit – fault with the sample intake tubing when lever was knocked. |
| 16/09/2008 11:27 | | n | Site visit |
| 24/09/2008 03:47 | 24/09/2008 03:47 | y | Missing data due to telemetry fault |
| 25/09/2008 07:50 | 25/09/2008 07:50 | y | Missing data due to telemetry fault |
| 29/09/2008 10:19 | 29/09/2008 10:21 | y | Over-ranged analyser (>3000 ppb) |
| 29/09/2008 10:47 | 29/09/2008 11:00 | y | Over-ranged analyser (>3000 ppb) |
| 03/10/2008 13:05 | | n | Site visit |
| **11/10/2008 08:23** | | y | **VALID DATA ENDS** |
| 11/10/2008 08:23 | | n | Final calibration begins |
| 12/10/2008 20:40 | | n | Analyser turned off |

# Instrument & Site History Summary

<table>
<tr><td><b>Site:</b> Terrace Tunnel<br><b>Pollutant:</b> Meteorological<br><b>Instrument Description:</b> various<br><b>Owner:</b> NIWA</td></tr>
</table>

| Start Date | Finish Date | Data affected ? (y/n) | Event |
|---|---|---|---|
| 20/08/2008 | | n | Sensors in use:<br>**Wind speed** - Vector A101M<br>**Wind Direction** - Vector W200P<br>**Air Temp / Relative Humidity** - Vaisala 50Y |
| 20/08/2008 14:00 | 20/08/2008 16:00 | y | Calibration |
| 20/08/2008 16:01 | | y | **VALID DATA BEGINS – for 10 min and 1 hr data** |
| 24/08/2008 11:17 | | y | New program loaded **- VALID DATA BEGINS – for 1 min data** |
| 12/10/2008 07:20 | | y | **VALID DATA ENDS.** Calibration of sensors then equipment removed. |

### 9.7.2 Mt Victoria Tunnel

Quality assured monitoring data are available from 20th October 2008 until 18th December 2008. The data capture rates are shown in Table 10.

**Table 10: Data capture rates for the Mt Victoria Tunnel**

| | |
|---|---|
| Carbon dioxide, CO | 99 % |
| Nitrogen dioxide, $NO_2$ | 97.5 % |
| Nitric oxide, NO | 98.7 % |
| Ozone, $O_3$ | 94 % |

The following tables show the data that has been removed

## Instrument & Site History Summary

**Site:** Mt Vic  Tunnel
**Pollutant:** CO
**Instrument Description:** API Model 300
**Owner:** NIWA

| Start Date | Finish Date | Data affected ? (y/n) | Event |
|---|---|---|---|
| 16/10/2008 | | n | Analyser s/n 421 installed. – logging ambient air |
| 20/10/2008 13:45 | | n | Sampling air from inside the tunnel begins |
| **20/10/2008 13:45** | | **y** | **VALID DATA BEGINS** |
| 21/10/2008 08:41 | 21/10/2008 10:32 | y | Calibration check |
| 30/10/2008 06:43 | 30/10/2008 07:07 | y | Over-ranged analyser (>50 ppm) |
| 31/10/2008 06:17 | 31/10/2008 06:35 | y | Over-ranged analyser  (>50 ppm) |
| 31/10/2008 06:39 | 31/10/2008 07:05 | y | Over-ranged analyser  (>50 ppm) |
| 31/10/2008 10:29 | 31/10/2008 10:43 | y | Range on analyser changed from 0 to 50ppm to 0 to 100 ppm |
| 06/11/2008 08:32 | 06/11/2008 12:48 | y | Calibration carried out before analyser 421 is replaced.   Analyser s/n 1483 installed and calibrated |
| 05/12/2008 11:49 | 05/12/2008 13:43 | y | Telemetry fault |
| 16/12/2008 13:44 | 16/12/2008 15:29 | y | Final calibration carried out |
| **18/12/2008 11:24** | | y | **VALID DATA ENDS** |

## Instrument & Site History Summary

**Site:** Mt Vic Tunnel
**Pollutant:** Ozone
**Instrument Description:** API Model 400
**Owner:** NIWA

| Start Date | Finish Date | Data affected ? (y/n) | Event |
|---|---|---|---|
| 16/10/2008 | | n | Analyser **API M300 serial no 1440** installed. |
| 20/10/2008 13:45 | | n | Data logging begins – sampling tunnel air |
| **20/10/2008 13:48** | | **y** | **VALID DATA BEGINS** |
| 21/10/2008 10:32 | 21/10/2008 12:39 | y | Calibration |
| 31/10/2008 10:29 | 03/11/2008 10:30 | y | New program loaded on 31st but there was an error in it which affected the ozone only. |
| 06/11/2008 08:31 | 06/11/2008 12:48 | y | Site visit for CO analyser replacement caused faulty data on ozone and NOx analysers. |
| 05/12/2008 11:49 | 05/12/2008 13:43 | y | Telemetry fault |
| **18/12/2008 08:40** | | y | **VALID DATA ENDS.** Final calibration and analyser turned off |

# Instrument & Site History Summary

**Site:** Mt Vic Tunnel
**Pollutant:** Nitrogen oxides
**Instrument Description:** API Model 200
**Owner:** NIWA

| Start Date | Finish Date | Data affected ? (y/n) | Event |
|---|---|---|---|
| 17/10/2008 | | n | Analyser s/n 756 installed. – logging ambient air |
| 20/10/2008 13:45 | | n | Sampling air from inside the tunnel begins |
| **20/10/2008 14:11** | | **y** | **VALID DATA BEGINS** |
| 22/10/2008 08:07 | 22/10/2008 12:11 | y | Calibration check |
| 30/10/2008 06:06 | 30/10/2008 06:12 | y | Over-ranged analyser (>5000 ppb) |
| 30/10/2008 06:36 | 30/10/2008 07:05 | y | Over-ranged analyser  (>5000 ppb) |
| 31/10/2008 06:16 | 31/10/2008 07:04 | y | Over-ranged analyser  (>5000 ppb) |
| 31/10/2008 10:29 | 31/10/2008 10:43 | y | Range on analyser changed from 0 to 5000 ppb to 0 to 8000 ppb. |
| 06/11/2008 08:32 | 06/11/2008 12:48 | y | Site visit to replace CO – data affected. |
| 09/11/2008 22:07 | 09/11/2008 22:10 | y | Over-ranged analyser  (>8000 ppb) |
| 05/12/2008 11:49 | 05/12/2008 13:43 | y | Telemetry fault |
| 17/12/2008 07:40 | 17/12/2008 13:43 | y | Final calibration carried out |
| **18/12/2008 11:21** | | **y** | **VALID DATA ENDS** |

# Instrument & Site History Summary

**Site:** Mt Vic Tunnel
**Pollutant:** Meteorological
**Instrument Description:** various
**Owner:** NIWA

| Start Date | Finish Date | Data affected ? (y/n) | Event |
|---|---|---|---|
| 17/10/2008 | | n | Sensors in use:<br>**Wind speed** - Vector A101M<br>**Wind Direction** - Vector W200P<br>**Air Temp / Relative Humidity** - Vaisala 50Y |
| 17/10/2008 09:00 | 17/10/2008 10:50 | y | Calibration |
| 17/10/2008 13:01 | | y | **VALID DATA BEGINS – for 1 min, 10 min and 1 hr data** |
| 18/12/2008 09:24 | | y | **VALID DATA ENDS.**  Calibration of sensors then equipment removed. |

## 9.8  Data Plots
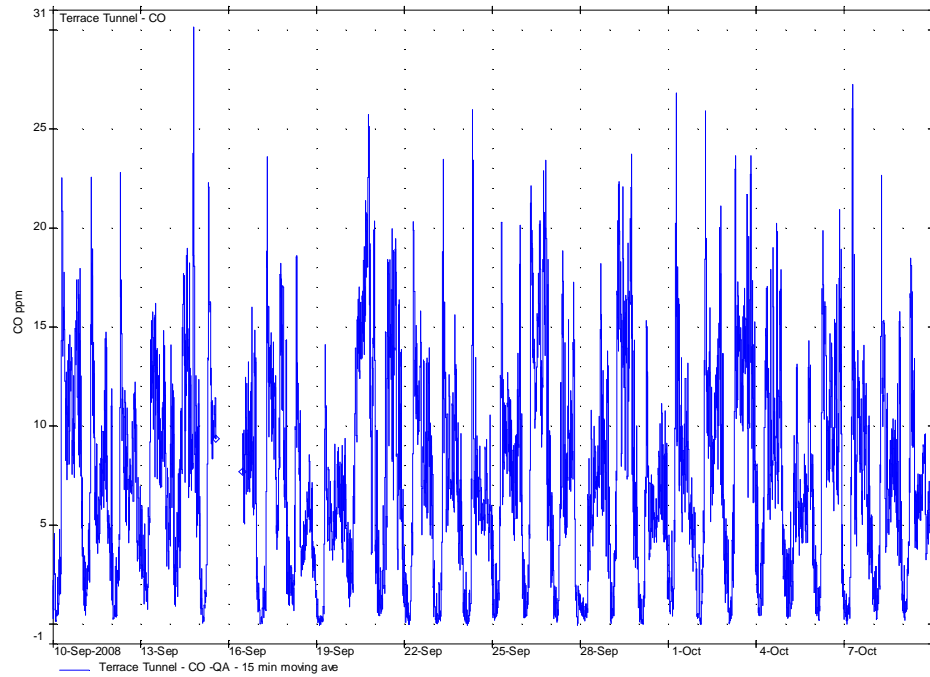
### 9.9.1    Terrace Tunnel



**Figure 42: 15-minute moving-average CO Concentrations in the Terrace Tunnel.**
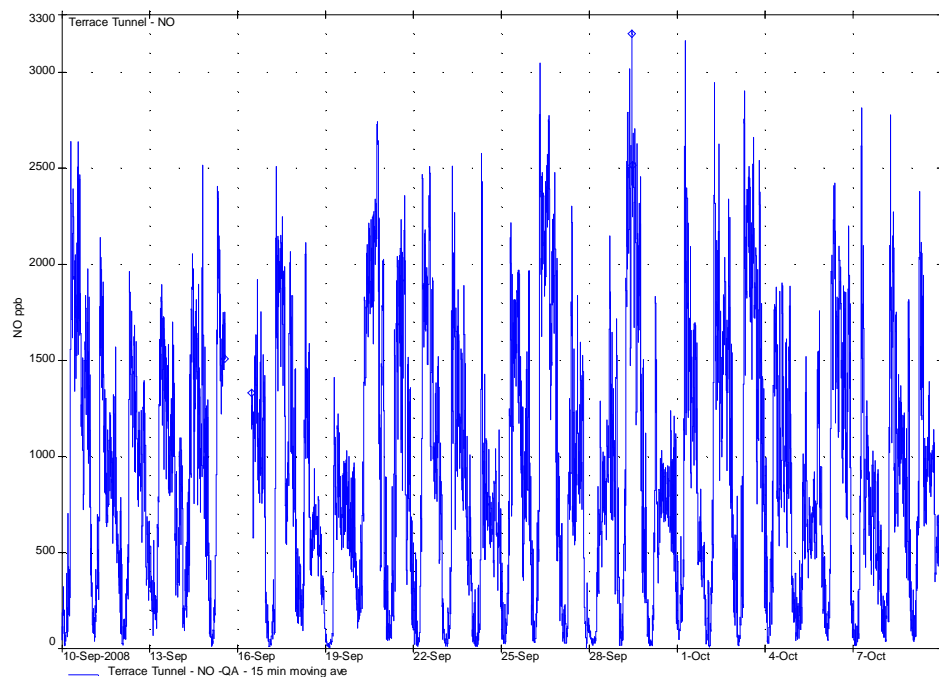


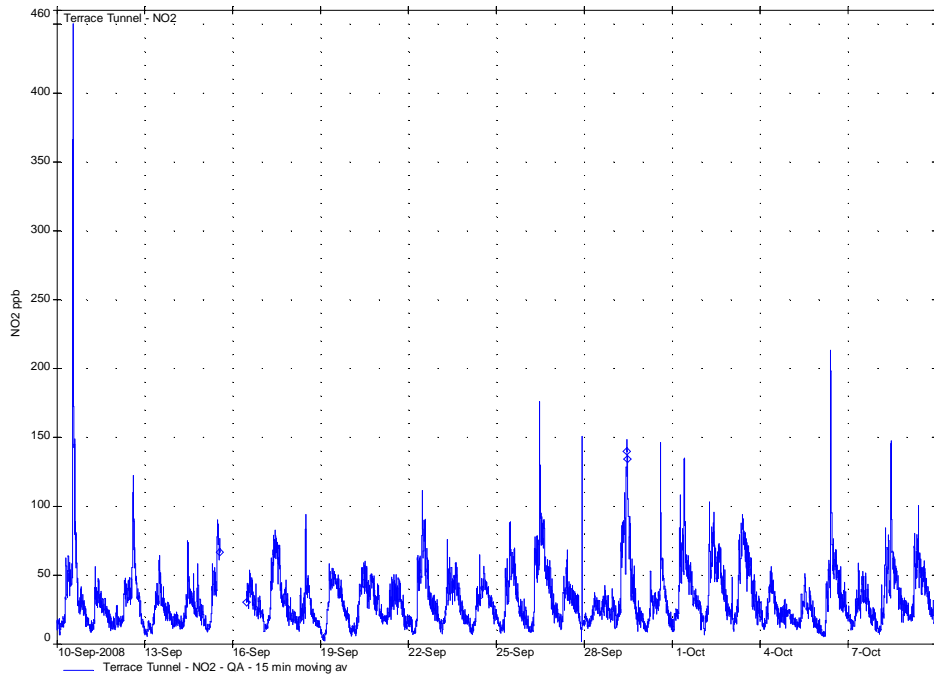**Figure 43: 15-minute moving-average NO Concentrations in the Terrace Tunnel.**

**Figure 44: 15-minute moving-average NO₂ Concentrations in the Terrace Tunnel.**
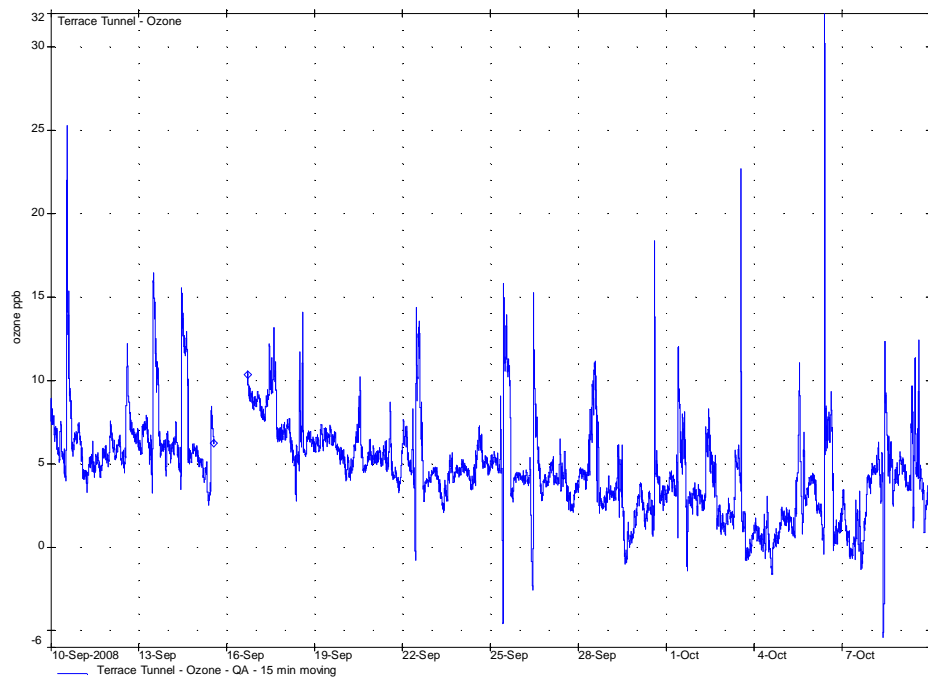


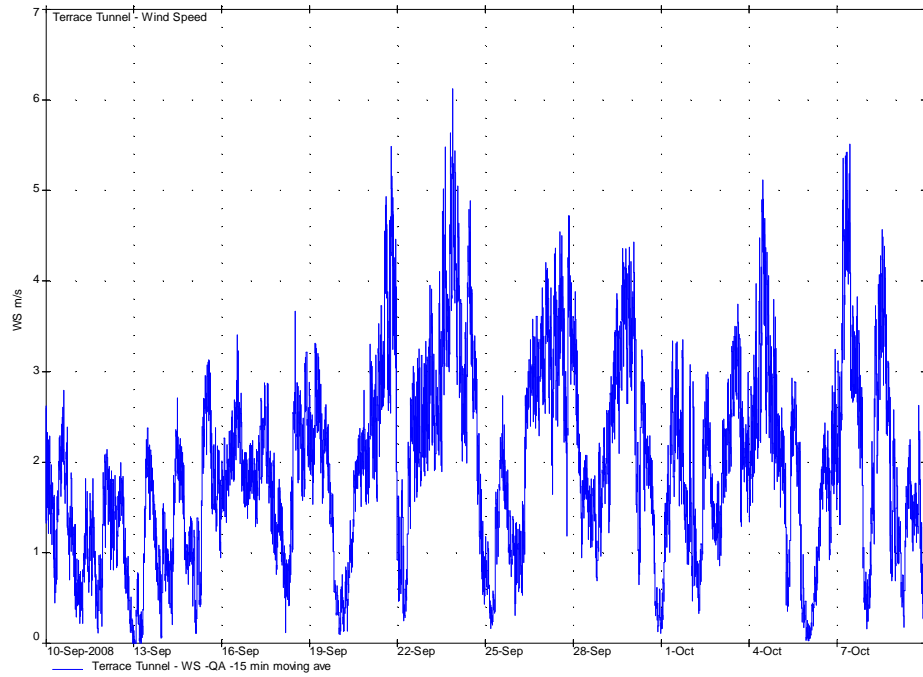**Figure 45: 15-minute moving-average O₃ Concentrations in the Terrace Tunnel.**

**Figure 46: 15-minute moving-average wind speed outside the Terrace Tunnel southern portal.**
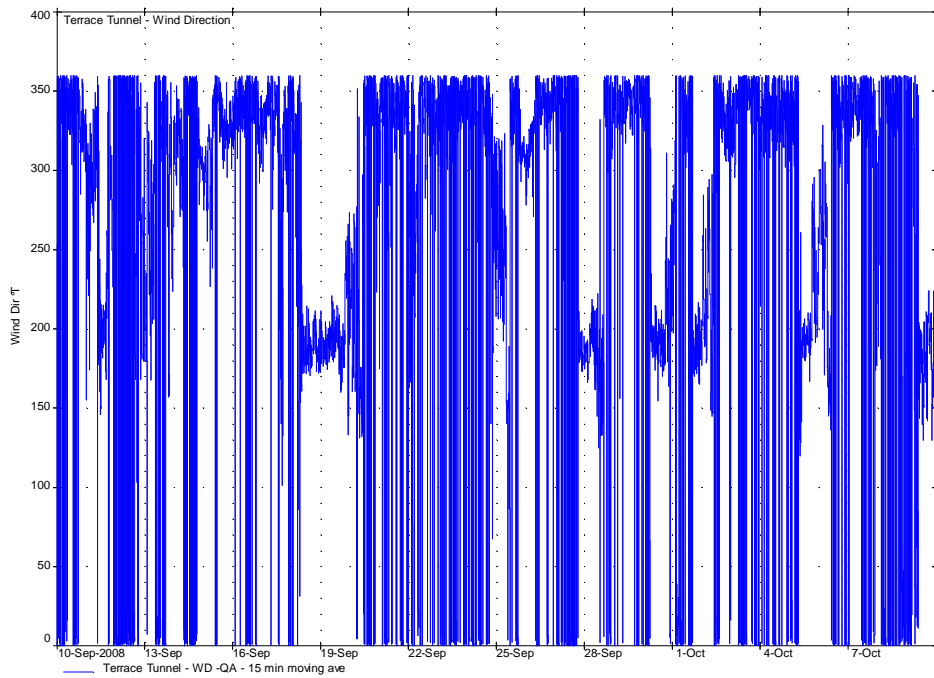


**Figure 47: 15-minute moving-average wind direction outside the Terrace Tunnel southern portal.**
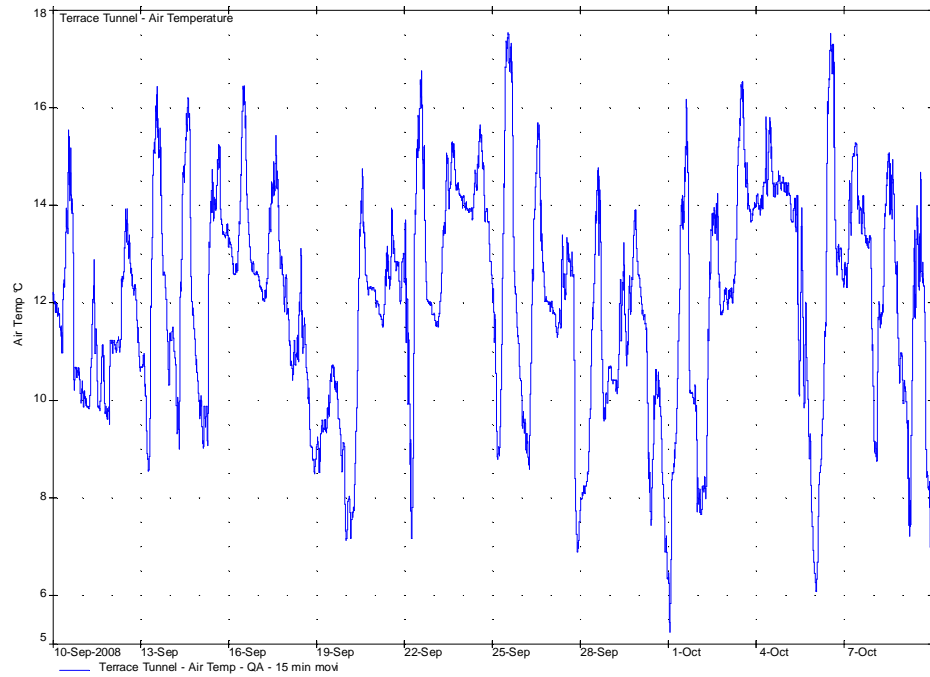
**Figure 48: 15-minute moving-average air temperature outside the Terrace Tunnel southern portal.**
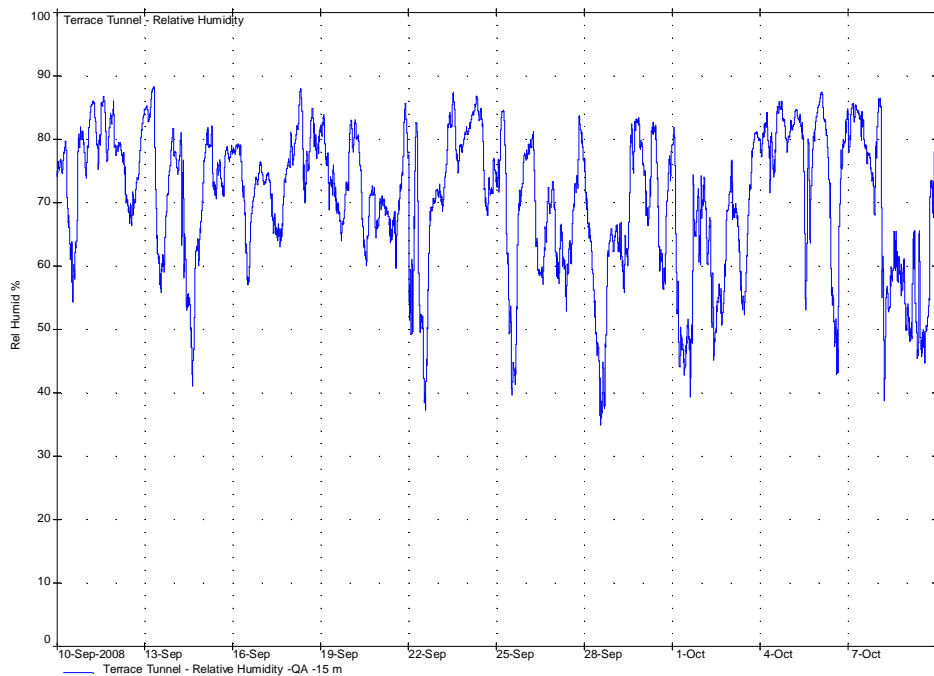


**Figure 49: 15-minute moving-average relative humidity outside the Terrace Tunnel southern portal.**
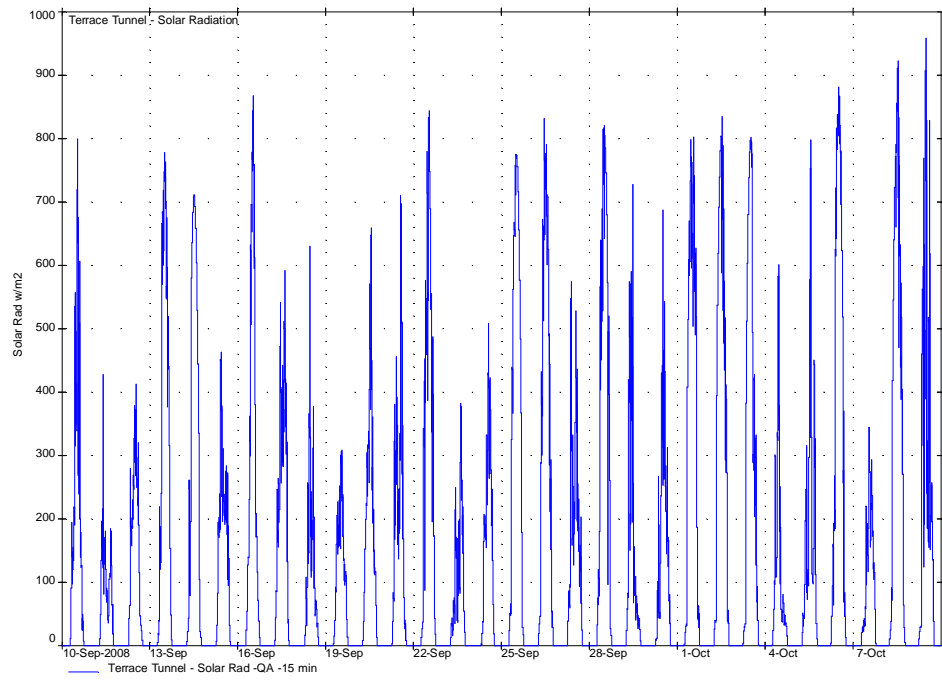
**Figure 50: 15-minute moving-average solar radiation outside the Terrace Tunnel southern portal.**

## 9.9.2    Mt Victoria Tunnel



**Figure 51: 15-minute moving-average CO concentrations in the Mt Victoria Tunnel.**
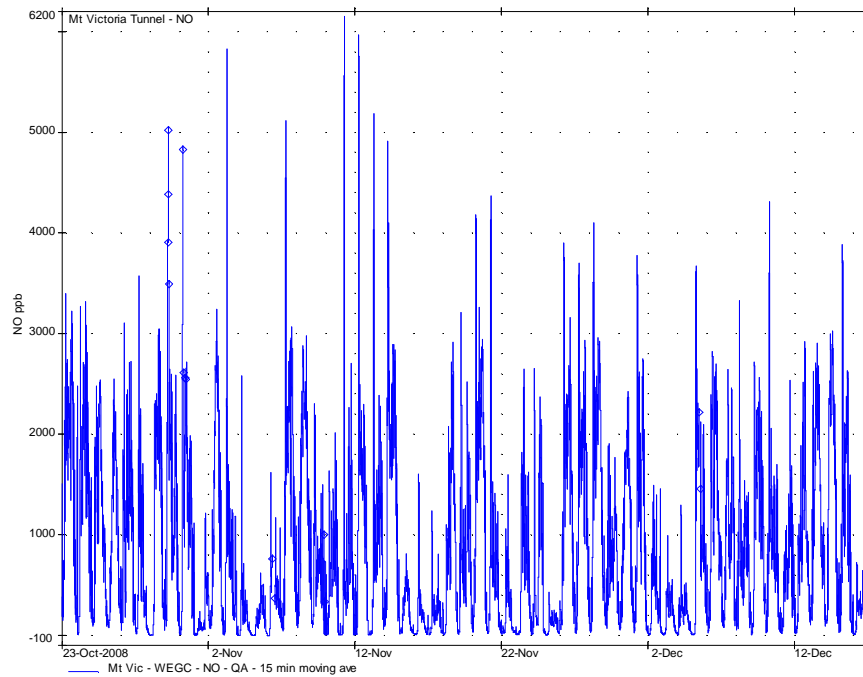


**Figure 52: 15-minute moving-average NO concentrations in the Mt Victoria Tunnel.**
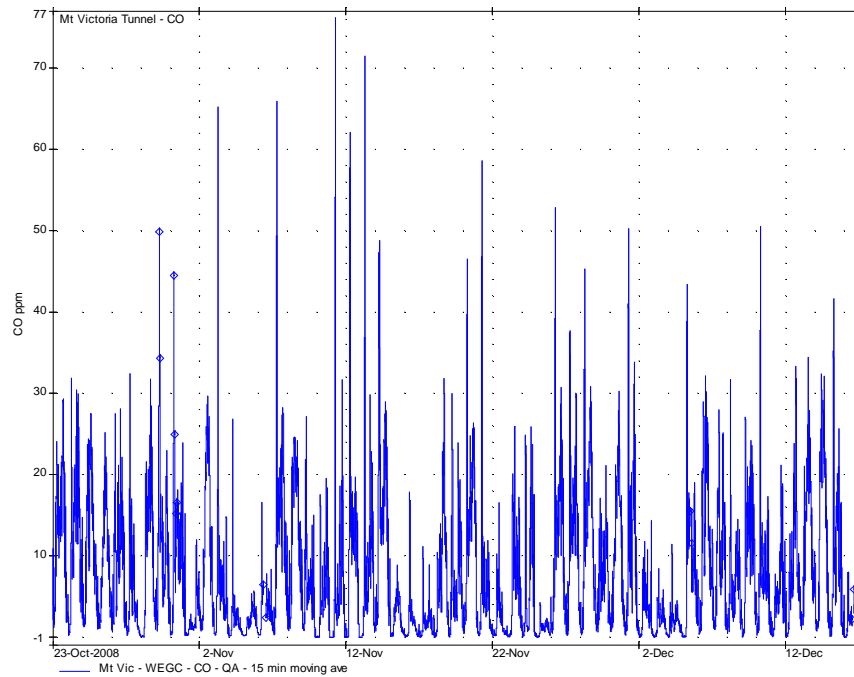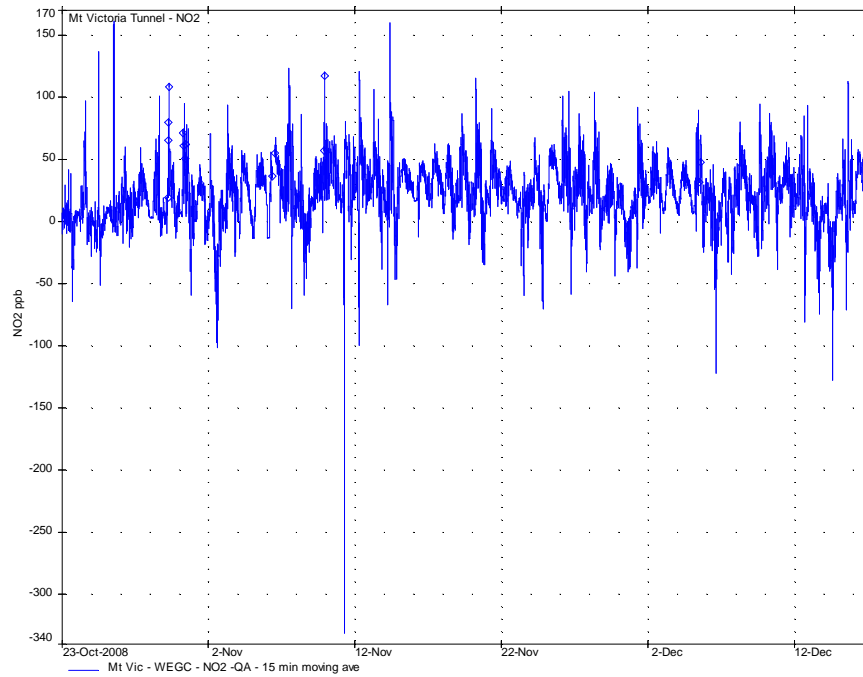
**Figure 53: 15-minute moving-average NO₂ concentrations in the Mt Victoria Tunnel.**
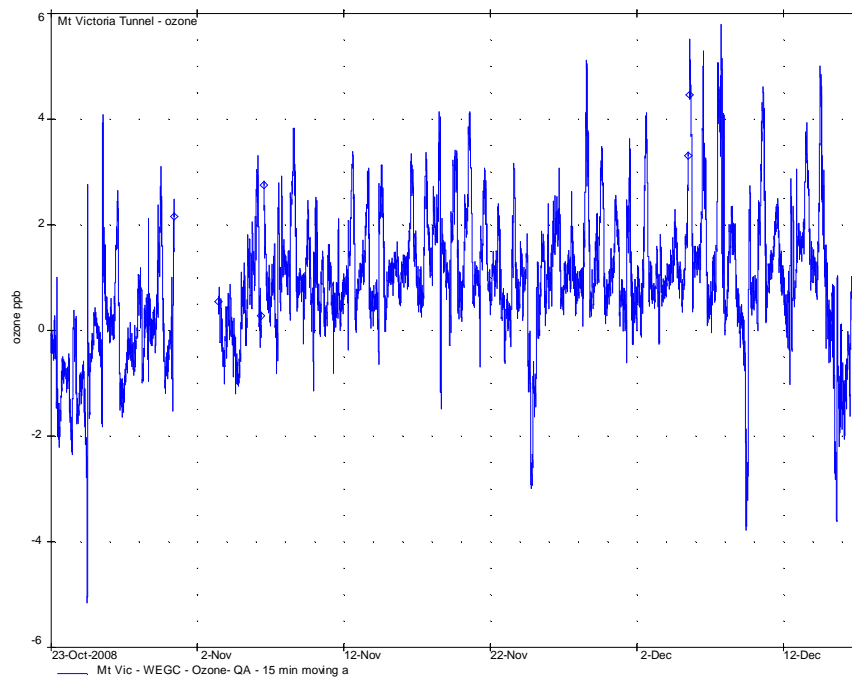


**Figure 54: 15-minute moving-average O₃ concentrations in the Mt Victoria Tunnel.**

**Figure 55: 15-minute moving-average wind speed at the Mt Victoria Tunnel western exhaust stack.**



**Figure 56: 15-minute moving-average wind direction at the Mt Victoria Tunnel western exhaust stack.**

**Figure 57: 15-minute moving-average air temperature at the Mt Victoria Tunnel western exhaust stack.**



**Figure 58: 15-minute moving-average relative humidity at the Mt Victoria Tunnel western exhaust stack.**

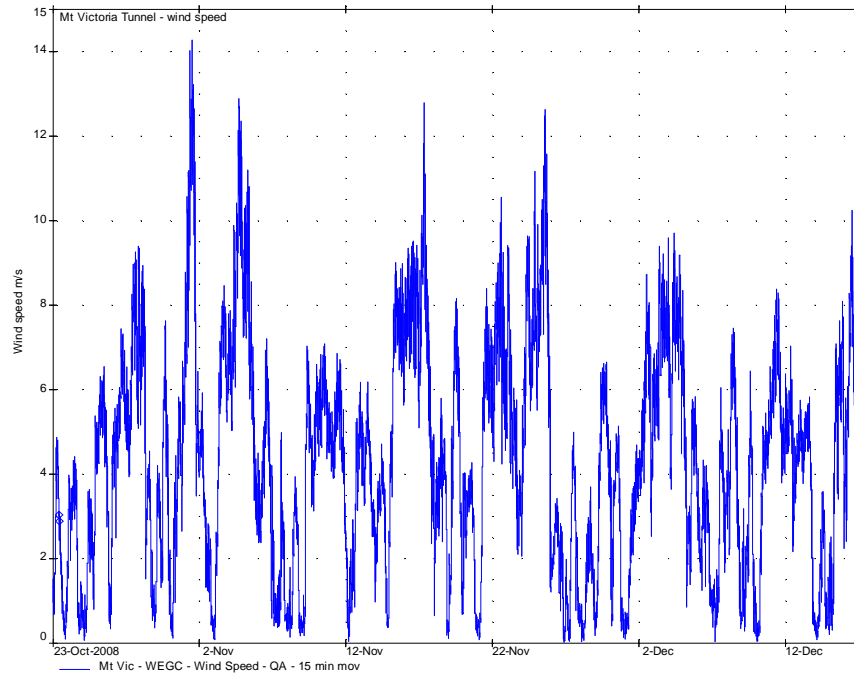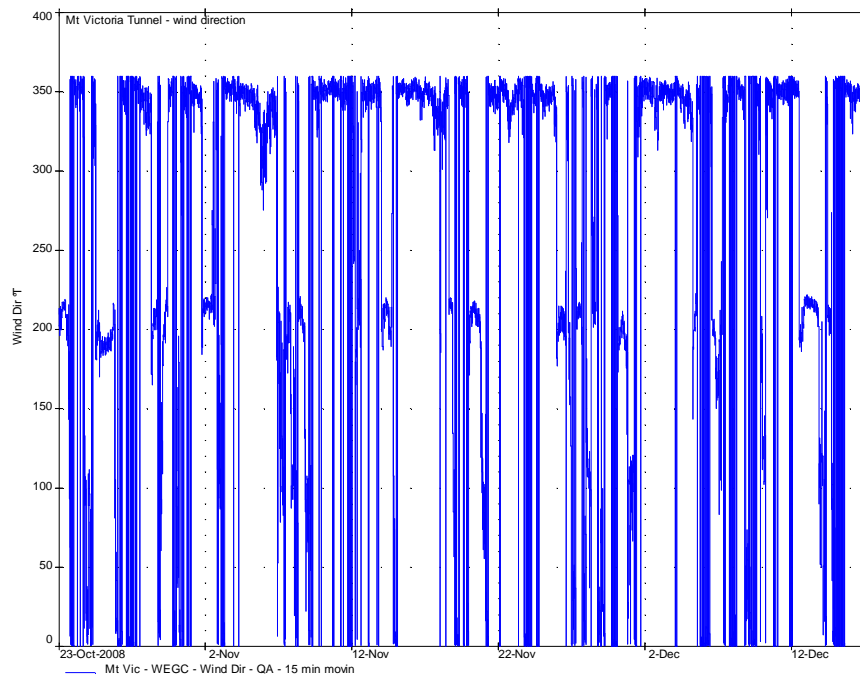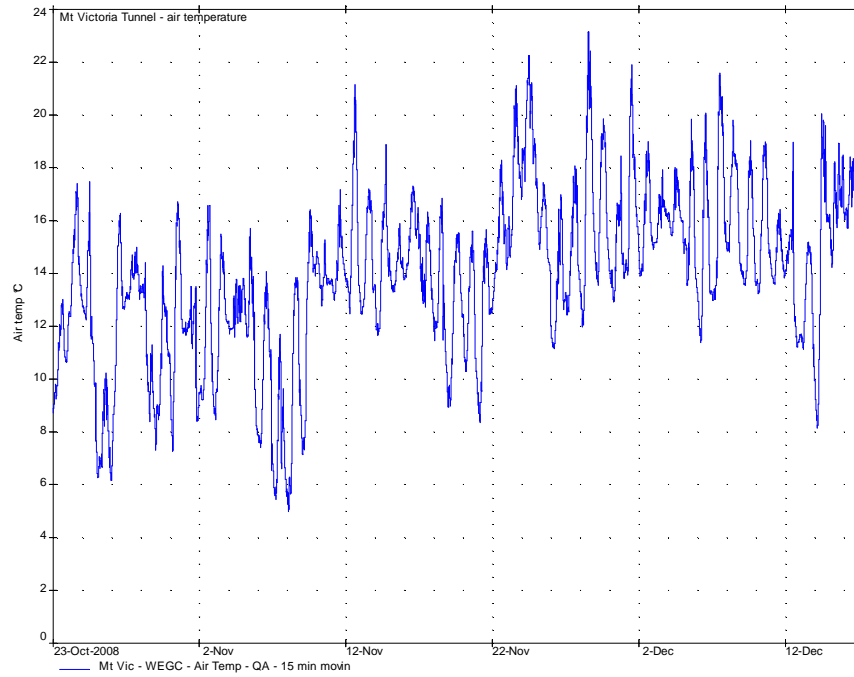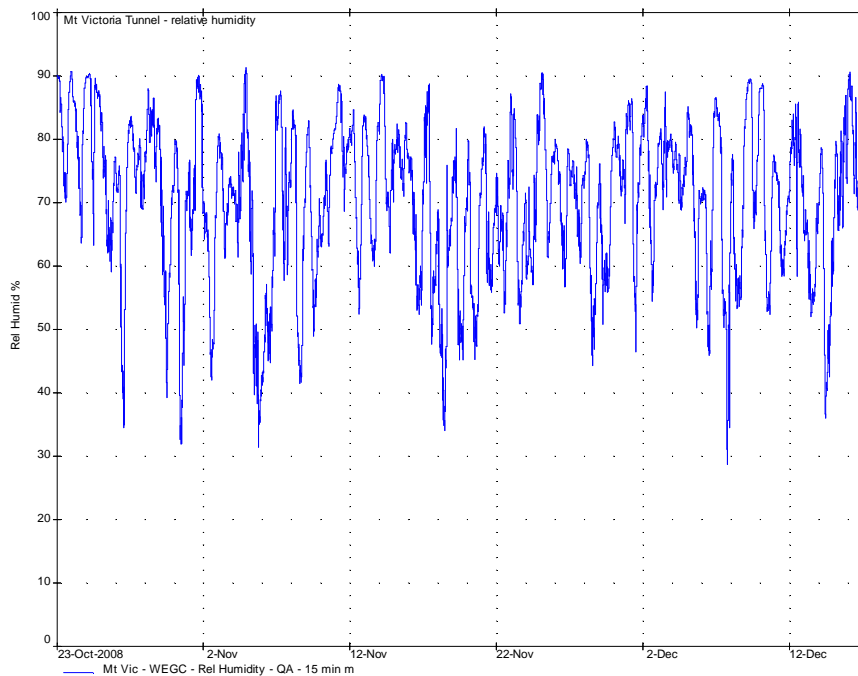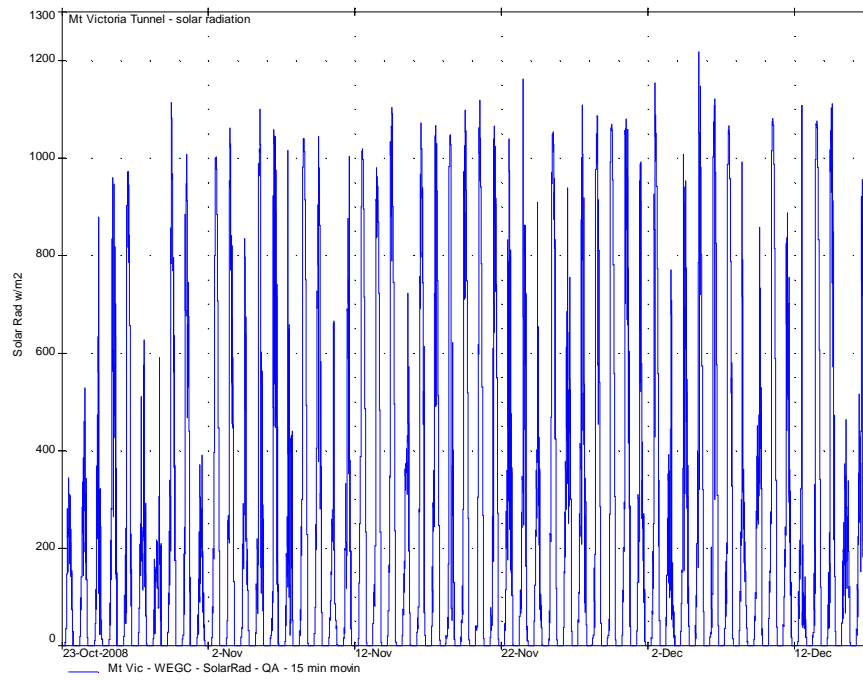**Figure 59: 15-minute moving-average solar radiation at the Mt Victoria Tunnel western exhaust stack.**

# 10. Emission Modelling Details

## 10.1 Traffic scenarios

VEPM version 3.0 was used to model emission factors for both tunnels based on 4 traffic scenarios. As noted in section 2.3 above, we did not collect continuous observations of traffic speed during the campaign. We have, however, undertaken brief observations of traffic speed and flow in the tunnels, the data are summarised in Table 11. Speeds were derived from drive-throughs between 10 am and 1pm on 20th September 2008. Fleet splits were derived from observations on the afternoon of 22nd June 2008 and the morning of 23rd June 2008.

**Table 11. Traffic characteristics of the tunnels based on brief observations during 2008.**

|  | Terrace | Mt Victoria |
|---|---|---|
| Common vehicle speeds[17] / km h$^{-1}$ | 55 - 80 | 35 - 55 |
| % cars | 81 | 93 |
| % LCVs | 14 | 6 |
| % HCVs | 5 | 1 |
| % buses | <1 | <1 |

Based on these observations, for calculations with VEPM we set the average speed to 70 km h$^{-1}$ (Terrace) and 45 km h$^{-1}$ (Mt Victoria). In the absence of more specific fleet split data (e.g. split between petrol and diesel vehicles and smaller and larger HCVs) we have tested four separate split scenarios:

1.  used the Wellington-wide fleet split observed during NIWA's remote sensing campaign[18].

2.  adopted the general split in table 11 but assumed all cars were petrol, and all other vehicles were diesel powered,

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[17]     During inter-peak periods, i.e. outside of morning and evening traffic peaks.

[18] Observations of 7283 vehicles across 5 sites in Greater Wellington conducted in 2006. Full details in Bluett & Dey, 2007.

3. adopted the general split in table 11, but further split into fuel type and HCV size using the VEPM default proportions for 2008,

4. used the VEPM default split for 2008 and ignored our observations,

A further parameter in VEPM is the ambient temperature. We have set this to the campaign mean **ambient** temperature of 12 °C for the Terrace Tunnel and 14 °C for the Mt Victoria Tunnel.[19]

The full list of input parameters and model results are given in tables 13 and 14.

## 10.2 Calculation of $NO_x$/CO ratios

Two methods for converting observed NO and $NO_2$ concentrations (in ppb) to $NO_x$ concentrations (in µg m$^{-3}$) were adopted.

1. The "conventional" approach of calculating "$NO_x$ as $NO_2$",
   i.e.
   $$NO_x \, as \, NO_2 [\mu g \, m^{-3}] = NO[ppb]\left(\frac{mw_{NO}}{M}\right)\left(\frac{mw_{NO_2}}{m_{NO}}\right) + NO_2[ppb]\left(\frac{mw_{NO_2}}{M}\right)$$
   where $mw$ = molecular weight, and $M$ = molar volume at 0 °C and 1 atm. This formula simplifies to
   $$NO_x \, as \, NO_2 [\mu g \, m^{-3}] = \left(NO[\mu g \, m^{-3}] \, x \, 1.533\right) + NO_2[\mu g \, m^{-3}]$$

2. An alternative approach in which we convert NO and $NO_2$ to µg m$^{-3}$ individually using their individual molecular weights, and sum the resulting values.

Method 1 is adopted in reporting ambient monitoring data. However, whereas the fraction of $NO_2$ in $NO_x$ may be 20 – 80 % in the ambient atmosphere, in the tunnels we observed average fractions of ~ 5 %, which we believe casts doubt on the suitability of a 100 % assumption.

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[19] Air temperature was not measured inside the Terrace Tunnel. The mean air temperature inside the Mt Victoria Tunnel was 19 °C.

The difference between these two methods was that method 1 produced values of the diurnal hourly average $NO_x/CO$ ratio that were 50 % higher than those produced by method 2 (see Table 12).

**Table 12: calculated mean $NO_x/CO$ ratios by mass from observations in both tunnels using methods 1 and 2 described in the text.**

|  |  | Terrace Tunnel | Mt Victoria Tunnel |
|---|---|---|---|
| Mean $NO_x/CO$ ratio | Method 1 | 0.21 | 0.19 |
|  | Method 2 | 0.14 | 0.13 |
| Inter-peak mean $NO_x/CO$ ratio | Method 1 | 0.25 | 0.21 |
|  | Method 2 | 0.17 | 0.14 |

In the case of both methods, the calculated ratios for the Terrace Tunnel are approximately 8 % higher than for the Mt Victoria Tunnel for the whole dataset, and 16 % higher during the inter-peak period.

**Table 13: Input and output data for modelling of emissions in the Terrace Tunnel using VEPM 3.0.**

| Scenario | year | Speed Car | speed LCV | Speed HCV | % car petrol | % car diesel diesel | % LCV petrol | %LCV diesel | % buses | % HCV 3.5-7.5 t | % HCV 7.5-16t | % HCV 16 30t | % HCV >30 t | CO g/km | CO2 g/km | VOC g/km | NOx g/km | PM₁₀ exhaust g/km | PM brake&tyre g/km | FC l/100km | NOx/CO ratio |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 2008 | 45 | 45 | 45 | 74.7% | 5.1% | 6.4% | 13.2% | 0.0% | 0.3% | 0.0% | 0.1% | 0.1% | 5.39 | 203.50 | 0.35 | 0.75 | 0.03 | 0.01 | 8.84 | 0.14 |
| 2 | 2008 | 45 | 45 | 45 | 93.0% | 0.0% | 0.0% | 6.0% | 0.0% | 1.0% | 0.0% | 0.0% | 0.0% | 5.99 | 194.60 | 0.38 | 0.73 | 0.01 | 0.01 | 8.64 | 0.12 |
| 3 | 2008 | 45 | 45 | 45 | 82.7% | 10.3% | 1.7% | 4.3% | 0.2% | 0.2% | 0.2% | 0.4% | 0.2% | 5.50 | 199.62 | 0.36 | 0.77 | 0.04 | 0.01 | 8.72 | 0.14 |
| 4 | 2008 | 45 | 45 | 45 | 69.9% | 8.7% | 3.9% | 10.1% | 0.6% | 1.6% | 1.1% | 3.0% | 1.1% | 4.99 | 234.07 | 0.38 | 0.91 | 0.06 | 0.01 | 9.89 | 0.18 |

*(Column groups: "All runs" = Scenario–Speed HCV; "fleet composition" → Light Duty Vehicles <3.5t = % car petrol–%LCV diesel, Diesel HCV >3.5t = % buses–% HCV >30 t; "fleet weighted emissions factors" = CO–FC)*

**Table 14: Input and output data for modelling of emissions in the Mt Victoria Tunnel using VEPM 3.0.**

| Scenario | year | Speed Car | speed LCV | Speed HCV | % car petrol | % car diesel diesel | % LCV petrol | %LCV diesel | % buses | % HCV 3.5-7.5 t | % HCV 7.5-16t | % HCV 16 30t | % HCV >30 t | CO g/km | CO2 g/km | VOC g/km | NOx g/km | PM₁₀ exhaust g/km | PM brake&tyre g/km | FC l/100km | NOx/CO ratio |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 2008 | 70 | 70 | 70 | 74.7% | 5.1% | 6.4% | 13.2% | 0.0% | 0.3% | 0.0% | 0.1% | 0.1% | 5.01 | 187.36 | 0.28 | 0.82 | 0.03 | 0.01 | 8.15 | 0.16 |
| 2 | 2008 | 70 | 70 | 70 | 81.0% | 0.0% | 0.0% | 14.0% | 0.0% | 5.0% | 0.0% | 0.0% | 0.0% | 5.04 | 190.06 | 0.30 | 0.82 | 0.03 | 0.01 | 8.23 | 0.16 |
| 3 | 2008 | 70 | 70 | 70 | 72.0% | 9.0% | 3.9% | 10.1% | 0.6% | 1.0% | 0.7% | 2.4% | 0.7% | 4.74 | 206.52 | 0.29 | 0.90 | 0.05 | 0.01 | 8.80 | 0.19 |
| 4 | 2008 | 70 | 70 | 70 | 69.9% | 8.7% | 3.9% | 10.1% | 0.6% | 1.6% | 1.1% | 3.0% | 1.1% | 4.63 | 214.35 | 0.29 | 0.93 | 0.05 | 0.01 | 9.07 | 0.20 |

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