Johnstone's Hill Tunnel air quality monitoring March to July 2010

Summary report
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NZ TRANSPORT AGENCY
WAKA KOTAHI

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Acknowledgements

This report summarises the results of a comprehensive monitoring programme that was undertaken with the assistance of the following agencies:

- Auckland Motorway Alliance (AMA)
- Institute of Geological and Nuclear Sciences (GNS)
- National Institute of Water and Atmospheric Research (NIWA)
- NZ Transport Agency
- Watercare (WSL)

Foreword

The NZ Transport Agency is a Crown entity responsible for managing the New Zealand state highway system, including six major road tunnels as follows:

- Mt Victoria Tunnel in Wellington (opened in 1931)
- Homer tunnel which provides access to Milford Sound (opened in 1953)
- Lyttelton Tunnel near Christchurch (opened in 1964)
- Terrace Tunnel in Wellington (opened in 1978)
- Johnstone's Hill Twin Tunnels northwest of Orewa (opened in 2009)
- Victoria Park Tunnel in central Auckland (opened in 2011).

The Transport Agency is reviewing the management of these existing tunnels to assist in the design of future upgrades and to develop standards and guidelines to cover new tunnels. As part of the review, the Transport Agency has already completed two projects to provide advice on the management of air quality both in and around road tunnels, as follows:

1. *Guidance for the management of air quality in road tunnels in New Zealand*[1] and
2. *Stocktake of the air quality in and around existing state highway tunnels*[2].

The first report proposed a set of guidelines for occupational and non-occupational exposure in tunnels. These have now been adopted as interim guidelines by the Transport Agency[3]. The second report reviewed the monitoring of air quality and other key parameters that have previously been undertaken for the existing tunnels and highlighted the key gaps that need to be addressed to improve future tunnel management.

Complementary to these two projects, the Transport Agency has embarked on a programme of detailed monitoring for each of the six tunnels. The programme is designed to fill in the knowledge gaps identified and develop a robust set of findings, upon which to base future tunnel management plans such as upgrades of existing tunnels and the design of new tunnels.

Tunnel monitoring campaigns are critical for ensuring that the Transport Agency '*maintains and operates all air quality management/air pollution mitigation measures, such as road tunnel ventilation systems, correctly to ensure they continue to provide the designed level of mitigation'* in order to meet objectives set in the Environmental Plan[4]. The first tunnel monitoring campaign was undertaken for the Mt Victoria and Terrace tunnels in Wellington between September and December 2008[5].

This report summarises the findings of the second tunnel monitoring campaign, undertaken for the Johnstone's Hill Twin Tunnels in March to July 2010.

[1] NIWA (2010a). *Guidance for the management of air quality in road tunnels in New Zealand*, NIWA Report AKL-2010-045 prepared for NZ Transport Agency, December 2010

[2] NIWA (2010b). *Stocktake of air quality in and around state highway tunnels*, NIWA Report AKL-2010-016 for NZ Transport Agency, April 2010

[3] NZ Transport Agency (2009). *NZTA standards for air quality in road tunnels*, Memo to Value Assurance Committee by Carl Reller, Rudolph Kotze, and Rob Hannaby, 24 September 2009

[4] Transit NZ (2008). *Environmental Plan, version 2*, Transit NZ (now NZ Transport Agency), June 2008

[5] NIWA (2009). *Air quality monitoring in the Terrace and Mt Victoria tunnels, Wellington*, NIWA Report AKL-2009-021 prepared for NZ Transport Agency, June 2009

Contents

Summary

The NZ Transport Agency currently manages six major road tunnels as follows:

- Mt Victoria tunnel in Wellington (opened in 1931)
- Homer tunnel which provides access to Milford Sound (opened in 1953)
- Lyttelton tunnel near Christchurch (opened in 1964)
- Terrace tunnel in Wellington (opened in 1978)
- Johnstone's Hill twin tunnels northwest of Orewa (opened in 2009)
- Victoria Park Tunnel in central Auckland (opened in 2011).

The Transport Agency has embarked on a programme of detailed monitoring for each of the six tunnels. Tunnel monitoring campaigns are critical for ensuring that the Transport Agency *'maintains and operates all air quality management/air pollution mitigation measures, such as road tunnel ventilation systems, correctly to ensure they continue to provide the designed level of mitigation'* in order to meet objectives set in the Environmental Plan[6]. The first tunnel monitoring campaign was undertaken for the Mt Victoria and Terrace tunnels in Wellington between September and December 2008[7].

This report summarises the findings of the second tunnel monitoring campaign, undertaken in the northbound tunnel of the Johnstone's Hill Twin Tunnels in 2010. The Johnstone's Hill Tunnels operate permanent in-tunnel sensors which measure carbon monoxide, air flow and jet fan operation. In addition to these, measurements were also taken of:

- in-tunnel carbon monoxide (CO) using a continuous analyser for comparison with the in-tunnel sensor
- in-tunnel nitrogen dioxide (NO_2) using a continuous analyser at one point and an array of passive samplers (to provide an indication of how concentrations vary along the tunnel length)
- external NO_2 using an array of passive samplers (to provide an indication of how concentrations vary before, inside and after the tunnel)
- in-tunnel particulate[8] (PM_{10}) using a continuous analyser, with a set of individual samples collected using a streaker sampler for subsequent source apportionment analysis
- external wind speed and wind direction for comparison with in-tunnel air flow and
- traffic data (counts, % heavy commercial vehicles and speed) using dual inductive loops installed in each lane.

Campaign monitoring was undertaken for three months from late March to early July 2010 to enable a comparison of weekday and weekend emissions, and to investigate the impact of long holiday weekends (Easter in April and Queen's Birthday in June were included in the campaign).

The key findings were:

- In-tunnel air quality in the northbound tunnel is well within the Transport Agency interim standards for CO and NO_2 set to protect workers and the general population travelling through the tunnel.

[6] Transit NZ (2008). *Environmental Plan, version 2*, Transit NZ (now NZ Transport Agency), June 2008

[7] NIWA (2009). *Air quality monitoring in the Terrace and Mt Victoria tunnels, Wellington*, NIWA Report AKL-2009-021 prepared for NZ Transport Agency, June 2009

[8] PM_{10} is particulate matter less than 10μm in diameter

- The key parameters affecting in-tunnel air quality are traffic volume and composition (specifically the proportion of heavy duty commercial vehicles). However, it is likely that external wind speed and in-tunnel ventilation are also important.
- The in-tunnel CO sensors perform well relative to a regulatory method air quality monitor but need to be calibrated at least once every 12 months to correct for instrument drift - particularly as their output is used as the trigger for activating the jet fans.
- External air quality near the northern exit of the tunnel appears to be close to the World Health Organisation's annual average guideline for NO_2 but this was based on three months (only) of monitoring. It should be noted that the nearest potentially sensitive receptors (ie residences) are located more than 300m away from either portal; therefore it is unlikely that any person is being exposed to 'high' NO_2 levels for a year.

The principal recommendations for future work include:

- All in-tunnel equipment should be connected to a data management system (rather than overwritten each day) which generates and records averages against the Transport Agency interim standards (ie 15-minute averages). This would enable the tunnel operation to be reviewed periodically to confirm all Transport Agency standards are being met and/or to investigate possible causes of non-compliance. It may further be used to signal emerging trends that may impact tunnel performance.
- All in-tunnel sensors should be checked frequently and calibrated at least annually. The northbound in-tunnel CO sensor is subject to upwards drift and on current trends may trigger the jet fans (erroneously) by May 2014. It is likely the southbound in-tunnel sensor is also drifting[9].
- Campaign monitoring should be undertaken periodically (ideally every five years) to validate the performance of the in-tunnel sensors and confirm (through the use of regulatory method equipment) that the Transport Agency in-tunnel standards are being met. This monitoring should be for key air pollutants (eg CO, NO_2 and PM_{10}), on-site meteorology and on-site traffic. There would be considerable value in undertaking passive sampling of NO_2 inside and outside tunnels on an extended basis.
- Internationally, tunnel monitoring campaigns are also employed to research other aspects of vehicle emissions management, which are highly relevant to New Zealand. These include verifying predicted vehicle emission factors/trends, developing new emission factors for sources such as road dust, assessing air pollution dispersion from tunnel portals and investigating the toxicity of emissions.

[9] Since the tunnel monitoring campaign ended, both in-tunnel CO sensors have been repaired and re-calibrated several times. Both sensors are now being serviced annually with more regular calibration checks being undertaken. T Sullivan (2013) of Auckland Motorway Alliance, *pers. comm.*, 4 February

A well-designed and well-coordinated future campaign could address most (if not all) of this report's recommendations and lead to improved design/management of tunnels in the state highway network as well as furthering a better understanding of general vehicle emissions management in New Zealand.

This report briefly reviews the monitoring that was undertaken and summarises the data that were collected. More detailed information relating to the specific phases of the tunnel monitoring campaign is available in the following technical reports:

- Continuous air quality monitoring[10]
- Passive NO_2 monitoring[11]
- Particulate matter concentration, composition and sources[12]

[10] WSL (2010a). *Johnstone's Hill tunnels – Continuous air quality monitoring report 30 March to 13 July 2010*, Report prepared by Watercare Services Ltd for NZ Transport Agency, August 2010

[11] WSL (2010b). *Johnstone's Hill tunnels – Passive nitrogen dioxide air quality monitoring report March to June 2010*, Report prepared by Watercare Services Ltd for NZ Transport Agency, August 2010

[12] GNS (2011). *Concentration, composition and sources of particulate matter in the Johnstone's Hill tunnel*, Auckland, GNS Science Report 2010/296 prepared for NZ Transport Agency, November 2011

1. Introduction

1.1 Background

Of the six tunnels that the Transport Agency manages in the state highway network, the Johnstone's Hill Twin Tunnels are relatively recent. The twin tunnels were opened in January 2009 to improve travel times on the Auckland Northern Motorway between the Orewa turnoff and Puhoi by between 10 and 30 minutes. As a toll road, they form part of State Highway 1 North (SH1N) and bypass the seaside townships of Orewa, Hatfield's Beach, Waiwera and the Wenderholm Regional Park.

The tunnels are two identical semi-circular uni-directional tubes, approximately 12m wide, 9m high and 380m long. They are built to carry two lanes each, plus a shoulder and an emergency pathway. Currently, the southbound tunnel has two lanes open but the northbound tunnel has only one lane open due to the merging of the traffic into a single lane immediately after the tunnel. The intention is to open the northbound tunnel to two lanes of traffic once the Puhoi to Wellsford double-laning project has been completed (scheduled for potential completion post 2015).

Based on the traffic volumes for 2010, the annual average daily traffic (AADT) for the Johnstone's Hill tunnel is approximately 14,000 vehicles per day, with the proportion of heavy duty commercial vehicles (HCVs) at 9.5%.

The route is an important link for inter-regional traffic, including freight, between Northland and Auckland as well as local traffic movements. The hourly weekday traffic counts suggest some influence of commuter travel with broad peaks in the morning and in the evening. However, the hourly counts are significantly higher for the weekend days when increased numbers of light duty vehicles travel to and from destinations in the northern part of the Auckland region and Northland. Although HCVs use the road daily, the number of these vehicles on weekend days is lower than on weekdays.

Due to safety considerations and the need to regularly access monitoring equipment for filter changes and calibrations, the campaign was focused on the single lane northbound tunnel. Opting for the northbound tunnel had advantages and disadvantages as follows:

- This tunnel had more free space available and installation of, and access to, monitoring equipment is not expected to require a full shutdown.
- This tunnel was likely to be more prone to congestion, and therefore experience higher contaminant concentrations, than the southbound tunnel. The northbound tunnel has already recorded the highest levels of carbon monoxide to date since the tunnels have been in operation. Using a tunnel with greater extremes in traffic flow conditions might make it easier to isolate the factors that have the greatest impact on the in-tunnel air quality.
- The southbound tunnel, with two lanes of traffic, has a different traffic profile. This will not be reflected in monitoring the northbound tunnel only.

1.2 Objectives

The objectives of the detailed monitoring undertaken at the Johnstone's Hill tunnels were to:

- measure current in-tunnel air quality and compare it against the Transport Agency interim standards
- determine the influence of key other parameters (eg traffic flow) on the in-tunnel air quality
- investigate various tunnel air quality monitoring methods and develop a standard approach for future tunnel monitoring programmes
- identify key parameters to be used for future on-going management of in-tunnel air quality.

1.3 Agencies involved

Due to the comprehensive requirements of the detailed monitoring programme, a number of agencies were involved in the collection of data as follows:

- Auckland Motorway Alliance (AMA)
- Institute of Geological and Nuclear Sciences (GNS)
- National Institute of Water and Atmospheric Research (NIWA)
- NZ Transport Agency
- Watercare (WSL)

The overall responsibility for coordinating the individual programme elements was undertaken by Emission Impossible Ltd (EIL).

1.4 Report layout

This report is structured as follows:

- Chapter 2 outlines the equipment, sites and analysis techniques used in the monitoring programme
- Chapter 3 presents the results
- Chapter 4 discusses the key findings
- Chapter 5 gives conclusions and recommendations

A full list of references and a glossary of terms are provided at the end of the report.

2. Methodology

This section summarises the methodological aspects of the report – including the monitoring method, monitoring sites and analysis of results.

2.1 Site description

2.1.1 Tunnel purpose and location

The Johnstone's Hill Twin Tunnels were opened in January 2009 to improve travel times on SH1 north of Auckland. The tunnels bypass the seaside townships of Orewa, Hatfield's Beach, Waiwera, and the Wenderholm Regional Park (see figure 1 and figure 2) and reduce travel times by between 10 and 30 minutes. The section of SH1N between the Orewa turnoff and Puhoi is a toll road but vehicles are able to travel free by using the old coastal route (SH17).

The Johnstone's Hill Tunnels are open to all vehicular traffic.

Figure 1: Location of the Johnstone's Hill Tunnels

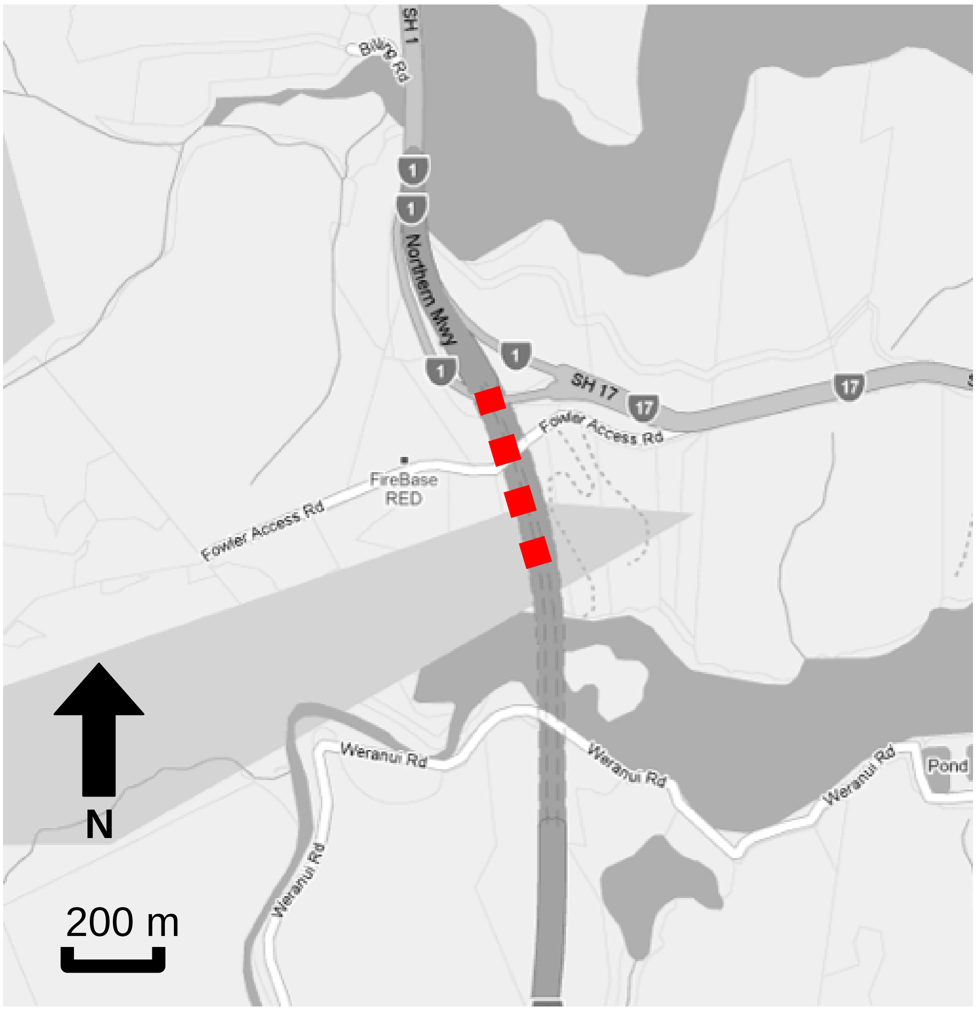

Figure 2: Road map of the Johnstone's Hill Tunnels

2.1.2 Geometry and ventilation

The tunnels are two identical semi-circular uni-directional tubes, approximately 12m wide, 9m high and 380m long, with a 1:100 gradient from each portal to the tunnel midpoint. The tunnels are 15m apart (see figure 3) and are both built to carry two lanes each, plus a shoulder and an emergency pathway. The northbound tunnel has only one lane open due to the merging of the traffic into a single lane after the tunnel. The southbound lane has two lanes open.

Each tunnel has longitudinal ventilation, with each tunnel running three banks of paired jet fans. The fans are triggered when carbon monoxide (CO) levels reach 30 parts per million (ppm).

Figure 3: View of the Johnstone's Hill Twin Tunnels from the northern end

2.1.3 Traffic flow and fleet composition

Based on 2010 traffic data (from the ALPURT Telemetry Site – ref01N00388), the annual average daily traffic (AADT) for the Johnstone's Hill Tunnels is approximately 14,000 vehicles per day, with the proportion of heavy duty vehicles (HCVs) at 9.5%.

The route is an important link for inter-regional traffic, including freight, between Northland and Auckland as well as local traffic movements. The hourly weekday traffic counts in figure 4 suggest some influence of commuter travel with broad peaks in the morning and in the evening. However, the hourly counts are significantly higher (up to 45% more)[13] for the weekend days when increased numbers of light duty vehicles travel to and from destinations in the northern part of the Auckland region and Northland. Although heavy commercial vehicles (HCVs) use the road daily, the proportion of these vehicles on weekend days is much lower (down to 40% below) than on weekdays.

The posted speed limit is 80km/h.

[13] Between 10am and 5pm on weekends (compared with week days).

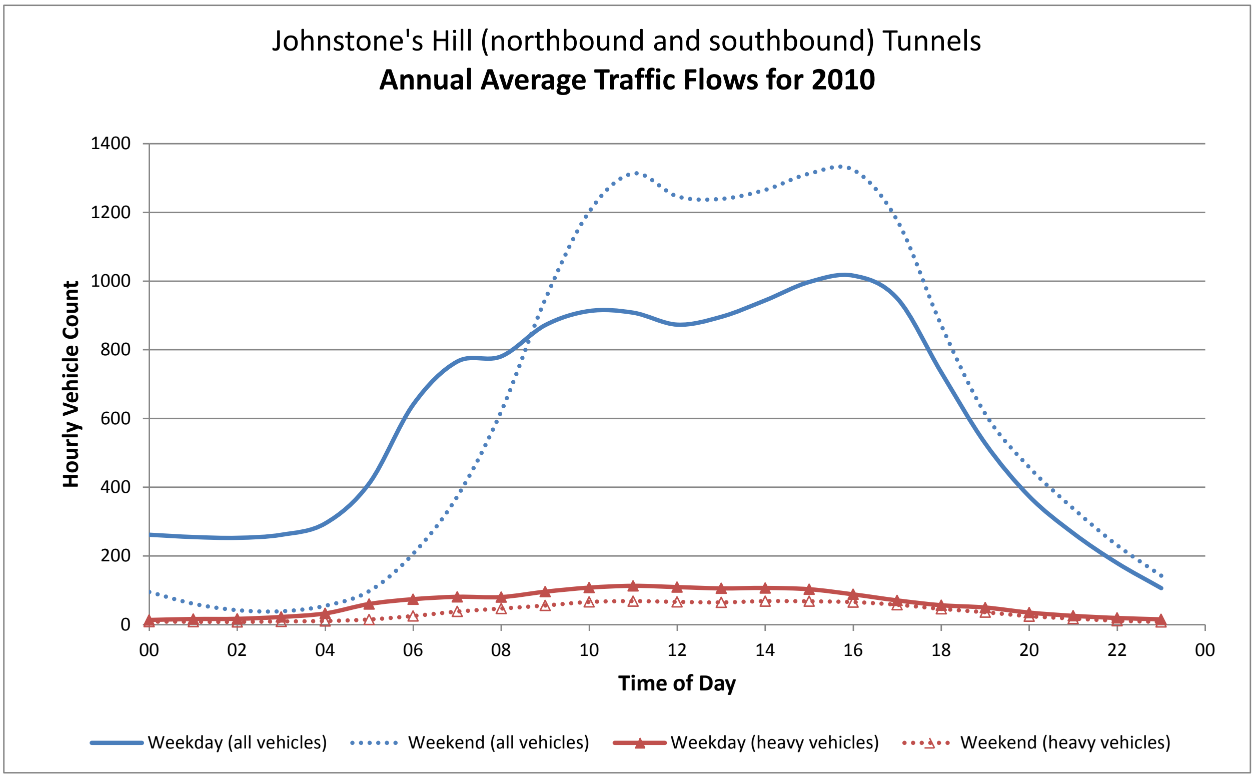

Figure 4: Annual average daily traffic (AADT) flow for the Johnstone's Hill Tunnels in 2010

2.1.4 Traffic monitoring

The nearest permanent traffic monitoring devices are four over height detectors which have traffic loops connected to the system. Southbound, the first monitor (OHD101) is located just after the toll machines turnaround (~1.2km before the tunnel entrance) and the second monitor (OHD102) is just after the Waiwera turnoff (~250m before the tunnel entrance) but before the road splits into two lanes as shown in figure 5. Northbound, the first monitor (OHD202) is on the SH1 motorway before the Grand Dr Exit (392) (~7.6km before the tunnel entrance) and the second monitor (OHD201) is at the start of the Waiwera Viaduct (~640m before the tunnel entrance) just before the traffic merges into one lane.

Unfortunately, none of these permanent sites is likely to be fully representative of the traffic flow behaviour in the tunnel. Going south as the road widens to two lanes, traffic will tend to accelerate on approach and through the tunnel so the OHD102 readings will be lower than the traffic speed through the tunnel. Conversely, northbound traffic will tend to slow down going across the Waiwera viaduct as it merges into one lane meaning the northbound tunnel speeds will be lower than recorded on OHD201.

Traffic flow behaviour, especially vehicle speed, impacts vehicle emissions. Even relatively small changes in speed result in appreciable changes in emissions and therefore in-tunnel air quality. For example, a typical vehicle travelling 5km/h faster than the posted 80km/h speed limit in the tunnel generates 2.8% more oxides of nitrogen NO_x and 4.2% more exhaust particulate per kilometre driven. On the other hand, travelling 5km/h more slowly results in a 1.5% decrease in NO_x and a 2.6% decrease in exhaust particulate.

Because the tunnels are toll roads, video surveillance is in place to record licence plates of vehicles using the tunnels. These images are captured and stored by the Transport Agency, and therefore could be interrogated to get more detailed fleet information.

Figure 5: General location of traffic monitoring devices in relation to Johnstone's Hill Tunnels

2.1.5 Receiving environment

The tunnels are in a rural setting with very few residents nearby. There is a property adjacent to SH1 ~300m north of the northern portal and scattered properties on Fowler Access Road which follows the ridge of Johnstone's Hill (see figure 2).

2.1.6 Meteorological conditions

The nearest permanent meteorological site is the Warkworth electronic weather station located at the satellite station approximately 11.5km north of the tunnels (36.43435°S, 174.66766°E). Data from this site is presented in figure 6.

The wind at the Warkworth electronic weather station site is measured at the top of a transmission tower 32m above ground level.

Given the relative distance and height of the Warkworth station, and the influence of local topography at the tunnels, the Warkworth station is unlikely to be representative of the winds experienced at the tunnels.

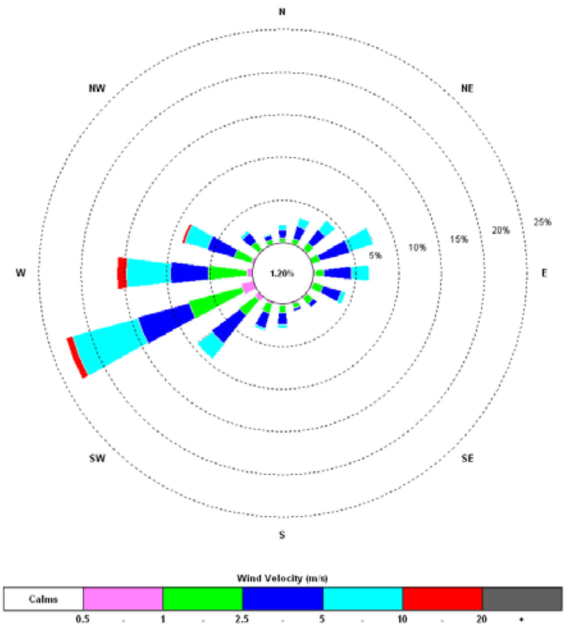

Figure 6: Wind rose based upon hourly data from Warkworth EWS (January 2003 to December 2009 inclusive).

2.1.7 Previous monitoring

Prior to this monitoring campaign, there have been no reported measurements of air quality or visibility in or near the Johnstone's Hill Tunnels.

2.2 Parameters measured

Monitoring was undertaken by a variety of providers at the Johnstone's Hill Tunnels in late March/early April 2010 for a period of approximately three months. The parameters measured are shown in table 1. Due to safety considerations and the need to regularly access monitoring equipment for filter changes and calibrations, the campaign was focused on the single lane northbound tunnel. However, some parameters were also able to be measured for the southbound tunnel (as highlighted in bold in table 1).

Table 1: Parameters measured at Johnstone's Hill Twin Tunnels for March to July 2010

Parameter	Location	Campaign instrument	Permanent instrument
Air flow*	In tunnel (at 25m in from exit)		Flowsic 200 air flow meter (AMA)
Carbon monoxide CO*	In tunnel (at 30m in from exit)	Continuous CO analyser (WSL)	Vicotec 412 CO sensor (AMA)
Fine particulate PM_{10}	In tunnel (at 30m in from exit)	Continuous beta attenuation monitor (GNS)	
Jet fan operation*	In tunnel (at 80m in from entrance and from exit)		In tunnel Sensor (AMA)
Nitrogen dioxide NO_2	In tunnel (at 30m in from exit)	Continuous NO_2 analyser (WSL)	
	7x In tunnel and 10x external (from 200m S of entrance to 200m N of exit)	Passive samplers (WSL)	
Traffic counts %HCVs and speed*	At both tunnel entrances		Golden River marksman 680 traffic counter connected to dual inductive loops (AMA)
Wind speed and direction	External (on top of the hill in Fowler Access Rd)	Anemometer on 6m mast (WSL)	

* Parameters measured for both the northbound and southbound tunnels

AMA – Auckland Motorway Alliance
WSL – Watercare Services Laboratory
GNS – Institute of Geological and Nuclear Sciences

2.2.1 Permanent monitoring

The Johnstone's Hill Tunnels have permanent in-tunnel sensors installed as part of the ventilation control system measuring CO, air flow and jet fan operation. These sensors provide online 'live' data to the tunnel operator at approximately 1-minute intervals but are not continuously logged. At any time a 3-month running record is available but this is updated and over-written each day.

During the campaign, data from the in-tunnel sensors were retrieved periodically by the Auckland Motorway Alliance (AMA) and stored separately to maintain a data record for the whole monitoring period. Due to a system problem, data were lost at the beginning of the campaign for the period of 26 March to 7 April 2010 inclusive (which unfortunately, incorporated the Easter period).

(i) Carbon monoxide

A Vicotec 412 CO sensor is located approximately 30m from the exit of each tunnel. The CO sensor measures concentrations (as ppm) in the tunnel using an infrared beam. When CO level reach 30ppm the jet fans are triggered.

(ii) Air flow

Permanent Flowsic 200 air flow sensors are located 25m from the exit of each tunnel. These sensors use ultrasonic technology to measure air velocity in m/s (which can be positive or negative depending on whether the flow is in or against the direction of the tunnel traffic).

(iii) Jet fan operation

Three sets of paired jet fans are located in each tunnel - at approximately 80m from the entrance, 80m before the exit, and at the midpoint. Each fan sends a signal indicating its state of operation as follows:

11	Stopped
130	Starting forward
131	Starting reverse
134	Run up forward
135	Run up reverse
129	Forward
5	Reversing
10	Spin down

2.2.2 Campaign monitoring

The Transport Agency commissioned several providers to undertake specific campaign monitoring during the monitoring period to supplement the permanent in-tunnel data and better understand the factors influencing the in-tunnel air quality. The campaign monitoring comprised:

- continuous monitoring of CO and NO_2 to compare against readings from the in-tunnel sensors and assess against in-tunnel air quality guidelines (by Watercare Services Ltd)
- passive sampling of NO_2 to indicate the spatial distribution of concentrations in and around the tunnel (by Watercare Services Ltd)
- continuous monitoring and source apportionment of particulate to establish the major sources/parameters contributing to in-tunnel air quality (by Institute of Geological and Nuclear Sciences)

- continuous monitoring of wind speed and wind direction to assess the effect of external meteorology on in-tunnel air flow and concentrations (by Watercare Services Ltd)
- specific traffic monitoring to provide actual counts, %HCVs and average speeds in the tunnel during the monitoring period (by Auckland Motorway Alliance).

The following subsections discuss the campaign monitoring in more detail.

The general location of the campaign monitoring sites for continuous measurement of gaseous pollutants (CO and NO_2) and meteorology (wind speed and wind direction) are shown in figure 7.

Figure 7: Location of the sites for continuous gaseous monitoring (CO, NO_2) and continuous meteorology monitoring (wind speed, wind direction)

(i) Continuous CO and NO_2 monitoring

Continuous monitoring of CO and NO_2 was carried out from 30 March to 13 July 2010 at a location 30m inside the northbound exit of the Johnstone's Hill Tunnels as shown in figure 8. The inlet was connected to monitoring equipment located in a mobile trailer parked just outside the north end of the tunnels as shown in figure 9.

Carbon monoxide was measured using *AS 3580.7.1 – 1992 Method 9.1: Determination of carbon monoxide – direct reading instrumental method* using an Ecotech model 9830. The instrument is an infrared absorption gas analyser which continuously measures carbon monoxide.

Nitrogen dioxide was measured using *AS 3580.5.1-1993 Method 5.1: Determination of oxides of nitrogen – chemiluminescence method*. The instrument was a Teledyne API model 200E which continuously measures oxides of nitrogen (NO_x), which include NO_2.

Figure 8: Location of the inlet for the continuous CO and NO_2 monitoring

Figure 9: Location of the trailer which housed the continuous CO and NO_2 monitoring equipment

(ii) Passive NO_2 sampling

Nitrogen dioxide was also measured at 50m intervals at five locations before the tunnel (travelling northbound), six locations inside the tunnel and five locations after the tunnel (travelling northbound) at monthly intervals using passive samplers. These monitoring locations are shown in figure 10.

Passive NO_2 samplers consist of an acrylic or PTFE tube 700mm long and 10mm internal diameter with the ends machined to take close fitting polythene caps. Each tube contains two stainless steel mesh discs, coated with triethanolamine. Nitrogen dioxide is determined spectrophotometrically by a variation of the Saltzman reaction.

Passive samplers were exposed for 1-month periods, from 29 March and 26 June 2010 (three separate monthly periods in total).

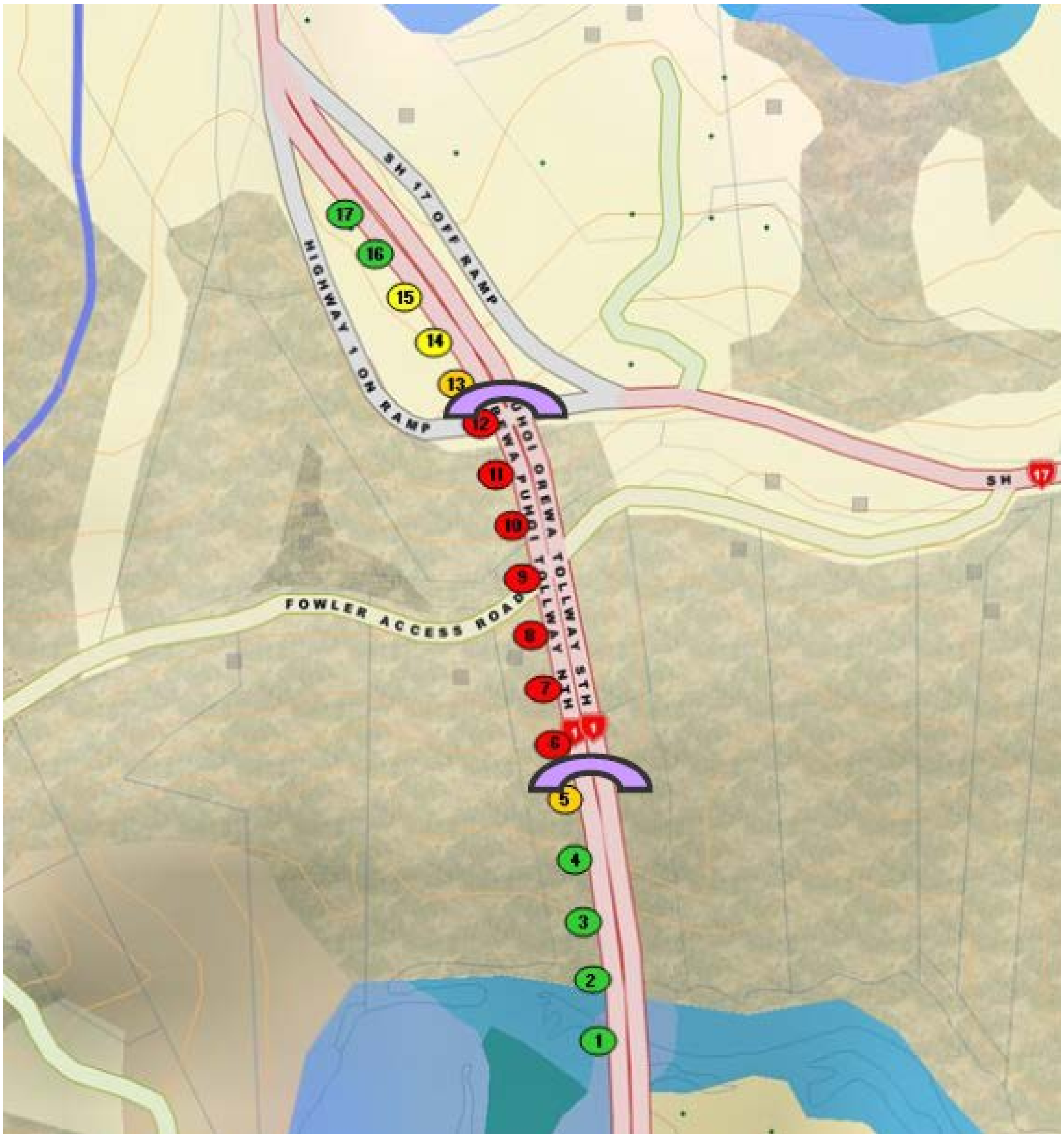

Figure 10: Location of passive NO_2 samplers

(iii) Particulate monitoring

Fine particulate (PM_{10}) was measured continuously between 29 April and 14 July 2010, using a beta attenuation monitor located approximately 25m from the exit of the northbound tunnel. The PM_{10} sampling equipment was contained in a pillar box bolted to the western wall of the tunnel as shown in figure 11.

Figure 11: Pillar box housing the particulate monitoring equipment inside the tunnel

Source apportionment was carried out at the same location using a Streaker sampling system as shown in figure 12. This collected discrete 3-hourly particulate samples in two size fractions ($PM_{2.5}$ and $PM_{2.5-10}$) through all of June 2010.

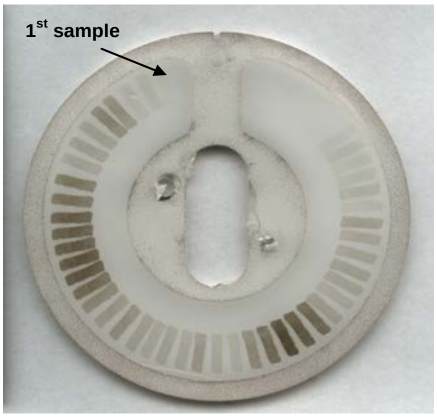

Figure 12: Streaker sampling system (shown left) with a typical sample filter showing hourly particle samples collected as discrete bands (shown right)

PM_{10} concentrations were derived from the beta attenuation monitor and elemental concentrations were provided by ion beam analysis.[14] Receptor modelling was then performed using two multivariate analysis approaches:

- Principal components analysis was used to characterise the *p* variables (elemental concentrations) in sample *X* in terms of a small number *m* of common factors *F* in order to examine relationships between the variables and provide an initial estimate of the number of factors (contributing particulate matter sources) present.
- Positive matrix factorisation (a linear least-squares approach) was applied to the multivariate data to provide source profiles (elemental composition of particulate matter from each of the sources) and apportion per-sample PM_{10} mass concentrations (to the various sources).

(iv) Meteorology monitoring

The meteorological monitoring station was located in a 50m wide clearing, 60m east of the tunnels on Fowler Access Road as shown in figure 13.

Measurements of wind speed and wind direction were measured at 6m above ground level in accordance with *AS 2923 – 1987 Ambient air – guide for measurement of horizontal wind for air quality applications*. The instruments continuously measured wind speed and wind direction from 30 March to 13 July 2010.

Figure 13: Meteorological monitoring station on Fowler Access Road

[14] A full description of ion beam analysis and receptor modelling is provided in GNS (2011)

(v) Traffic monitoring

Traffic monitoring was undertaken from 26 March to 1 July 2010 (inclusive) using Golden River Marksman 680 traffic counters connected to dual inductive loops, which were installed at both tunnel entrances to ensure capture of representative traffic flow measurements.

The traffic counters logged 15-minute counts broken down into four axle lengths:

- <5.5m, <11m, <17m and 17m

as well as 12 average speed bins:

- <20km/h, <30km/h, <40km/h, <45km/h, <50km/h, <55km/h, <60km/h, <70km/h, <80km/h, <90km/h, <100km/h and >100km/h

The axle length data were used to calculate the fraction of heavy duty commercial vehicles (%HCVs) in a 15-minute period – basically the number of vehicles with axle lengths greater than 5.5m over the total number of vehicles.

The counts in each of the average speed bins were pro-rated by the speed to provide an overall average speed for all vehicles passing through the tunnel in a 15-minute period.

All traffic monitoring was conducted in accordance with the NZTA's *SM052 Traffic monitoring for state highways*.

Note: these loops were left in place at the end of the campaign and would be able to be reconnected to a data logger for any future monitoring undertaken at Johnstone's Hill.

2.3 Assessment criteria

2.3.1 In-tunnel air quality

Table 2 presents the interim Transport Agency in tunnel air quality standards for CO and NO_2. These apply in tunnel and are designed to protect both workers and the general population (as specified in table 2). For vehicles travelling at the speed limit of 80 km/h through the Johnstone's Hill Tunnel, it would take approximately 14 seconds to traverse the 300m tunnel length.

Table 2: Interim Transport Agency in-tunnel air quality standards

Air pollutant	Limit	Averaging period	Protection	Application
CO	200ppm	15-minute	Workplace	Design and compliance monitoring standard
	30ppm	8-hour	Workplace	
	87ppm	15-minute	General population	
NO_2	1.0ppm	15-minute	Workplace and general population	Design standard only

2.3.2 External air quality

Table 3 presents ambient air quality guidelines and standards that apply to outdoor air (ie, outside the tunnel) in New Zealand. It should be noted that these standards and guidelines do **not** apply to the short-term exposure periods that vehicle occupants or workers may be exposed to in a tunnel.

The air quality criteria presented in table 3 are sourced from the national ambient air quality guidelines[15], the national environmental standards for air quality[16] and the World Health Organisation[17].

Table 3: Various ambient air quality standards and guidelines

Air pollutant	Limit	Averaging period	Protection	Standard
CO	30mg/m^3	1-hour	General population	AAQG
	10mg/m^3	8-hour	General population	AQNES
NO_2	200µg/m^3	1-hour	General population	AQNES
	100µg/m^3	24-hour	General population	AAQG
	40µg/m^3	annual	General population	WHO
PM_{10}	50µg/m^3	24-hour	General population	AQNES
	20µg/m^3	annual	General population	AAQG

2.4 Data processing/analysis

2.4.1 Permanent monitoring

The Vicotec 412 CO sensor (northbound tunnel) was last calibrated during commissioning (20-24 October 2008). The operation manual does not state how often maintenance or calibration is required.

The Flowsic 200 air flow meter (northbound tunnel) was last calibrated during commissioning (20-23 October 2008). The operation manual states that maintenance (cleaning) is required every six months to five years, depending on the individual installation and the model device installed. No information is provided on the need, or otherwise, of calibration.

Permanent monitoring data (collected continuously and recorded as 1-minute averages) was aggregated into base 15-minute fixed averages for further review.

[15] MfE (2002). *Ambient air quality guidelines, 2002 Update*, Air Quality Report No 32 prepared by the Ministry for the Environment and the Ministry of Health, May 2002

[16] *Resource Management (National Environmental Standards for Air Quality) Regulations 2004*

[17] WHO (2006). *Air quality guidelines global update 2005: Particulate matter, ozone, nitrogen dioxide, and sulphur dioxide*, World Health Organisation, October 2006

2.4.2 Gaseous (CO and NO_2) monitoring

Watercare Laboratory Services (instrumental campaign monitoring for CO and NO_2) is accredited by International Accreditation New Zealand for the standard methods employed (AS 3580.7.1:1992 and AS 3580.5.1:1993). The station was environmentally-controlled ensuring instrument requirements and relevant standard requirements were within specifications. Data return was excellent (greater than 95%) for all parameters monitored.

Passive samplers were analysed by Staffordshire County Council Scientific Services in the United Kingdom. A travel blank was transported and analysed with the samplers to flag potential contamination issues (none were found). All passive sampling was undertaken in accordance with the Transport Agency's operating manual[18].

All pollutant concentrations were calculated at New Zealand standard conditions of temperature (0°C) and pressure (1atm).

2.4.3 Particulate monitoring

The E-BAM (Met One Instruments Inc.) used to monitor PM_{10} was operated and calibrated in accordance with the Operation Manual (E-BAM 9800 RevK). During the Johnstone's Hill Tunnel campaign monitoring the E-BAM (Serial no. K10255) was calibrated and audited on start-up and monthly thereafter. Specific checks include leak tests, sample flow audits (using a Sensidyne Gillian 'Gilibrator 2' primary standard flow calibrator), self-test diagnostics and membrane tests for PM mass calibration. PM_{10} data collected by the E-BAM was vetted for anomalies and data collected during calibration was removed from the final dataset.

Diagnostic and statistical checks on the receptor modelling are reported in full in GNS (2011).

[18] NZTA (2012a). *Ambient air quality (nitrogen dioxide) monitoring programme – operating manual 2012/13*, prepared by Watercare Services Ltd and Emission Impossible Ltd for NZ Transport Agency, September 2012.

3. Results

The results in this section are presented by in-tunnel ventilation, in-tunnel traffic, in-tunnel air quality, meteorology and source apportionment.

3.1 In-tunnel ventilation

3.1.1 Air flow

Summary air flow data for both tunnels from the period of monitoring are given in figure 14 (northbound tunnel) and figure 15 (southbound tunnel) as 1-hour averages.

Negative air speed, which appears repeatedly throughout figures 14 and 15, appears to indicate that air is moving backwards and forwards in both tunnels. In other words, the northbound tunnel experiences both northbound and southbound air flow movement, as does the southbound tunnel.

Negative data occurred often, but not always, in the early hours of the morning. This may reflect the influence of external wind speeds and low vehicular traffic in the absence of any ventilation (the jet fans were off for the entire duration of campaign monitoring). Alternatively, the sensors may need recalibrating. It appears the sensors were last calibrated in October 2008.

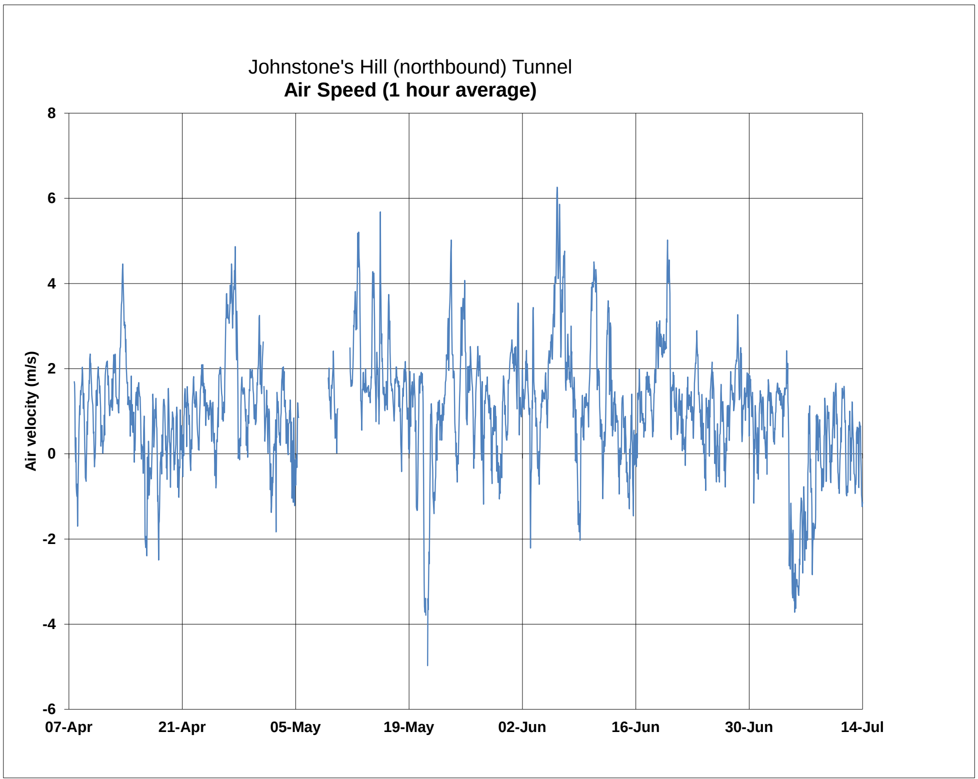

Figure 14: Air flow monitoring (northbound tunnel)

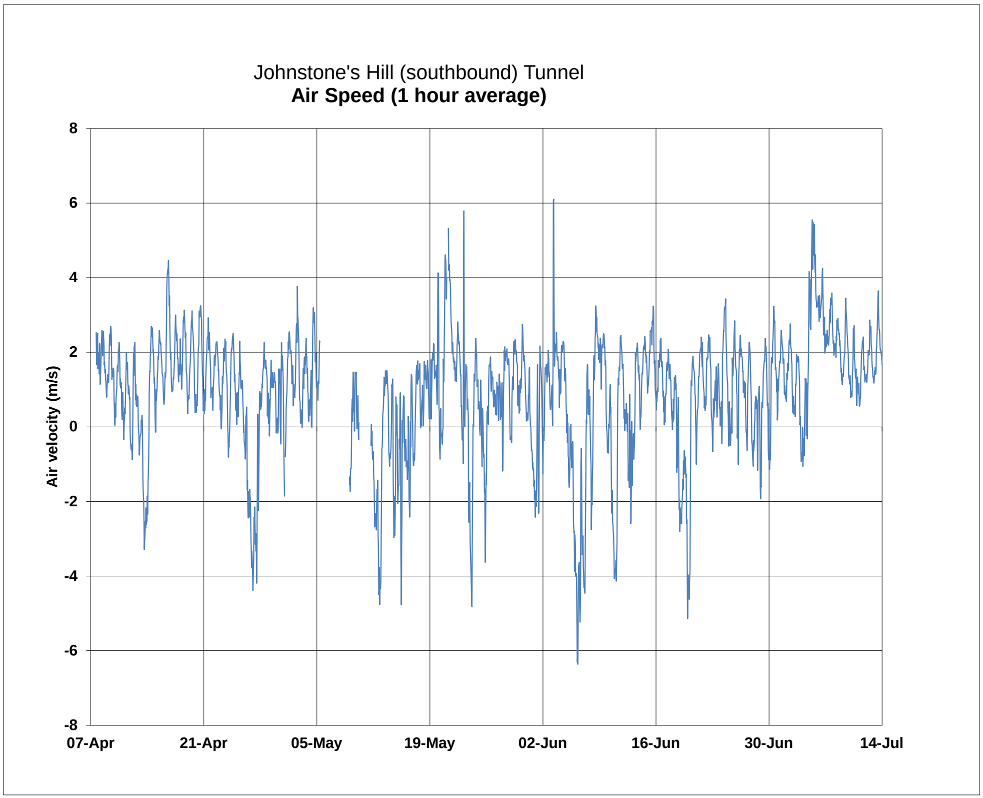

Figure 15: Air flow monitoring (southbound tunnel)

3.1.2 Jet fan operation

The jet fans were not triggered (so did not operate at all) during the period of monitoring between 30 March–13 July 2010.

3.2 In-tunnel traffic

In-tunnel traffic over the campaign monitoring period is presented in figure 16. The flow of heavy commercial vehicles is consistent on weekdays, dropping on weekends and public holidays. Conversely, the flow of passenger cars peaks consistently each Friday and on the Friday and Saturdays of public holiday weekends.

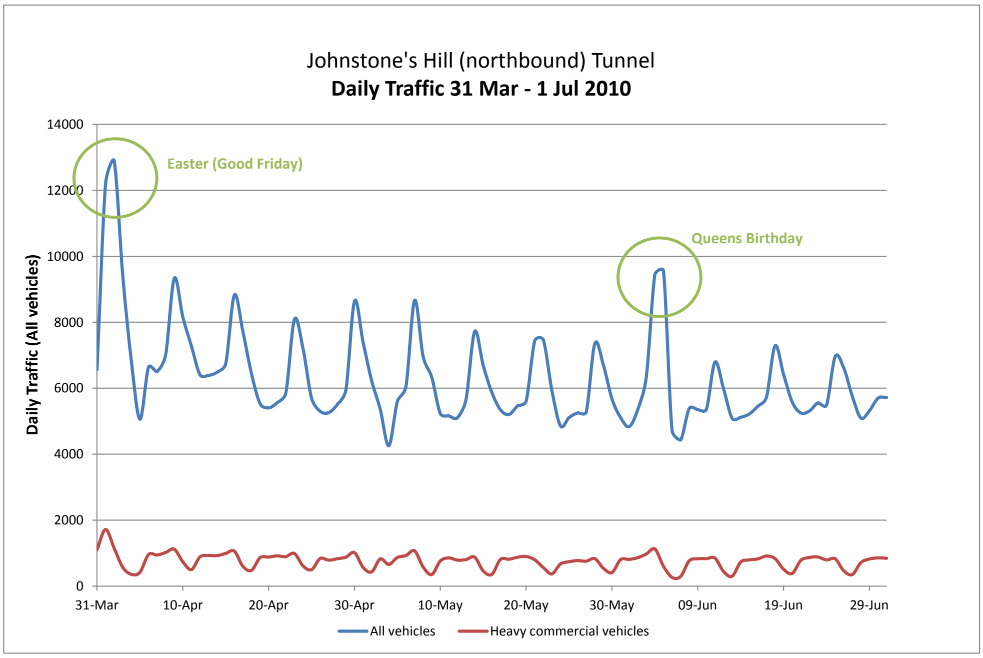

Figure 16: In-tunnel traffic during the period of campaign monitoring

3.3 In-tunnel air quality

3.3.1 Carbon monoxide

The results of in-tunnel monitoring for CO (both campaign and permanent) are presented in figure 17 (15-minute average) and figure 18 (8-hour average).

All recorded levels of CO were well below the relevant Transport Agency interim in tunnel air quality guidelines.

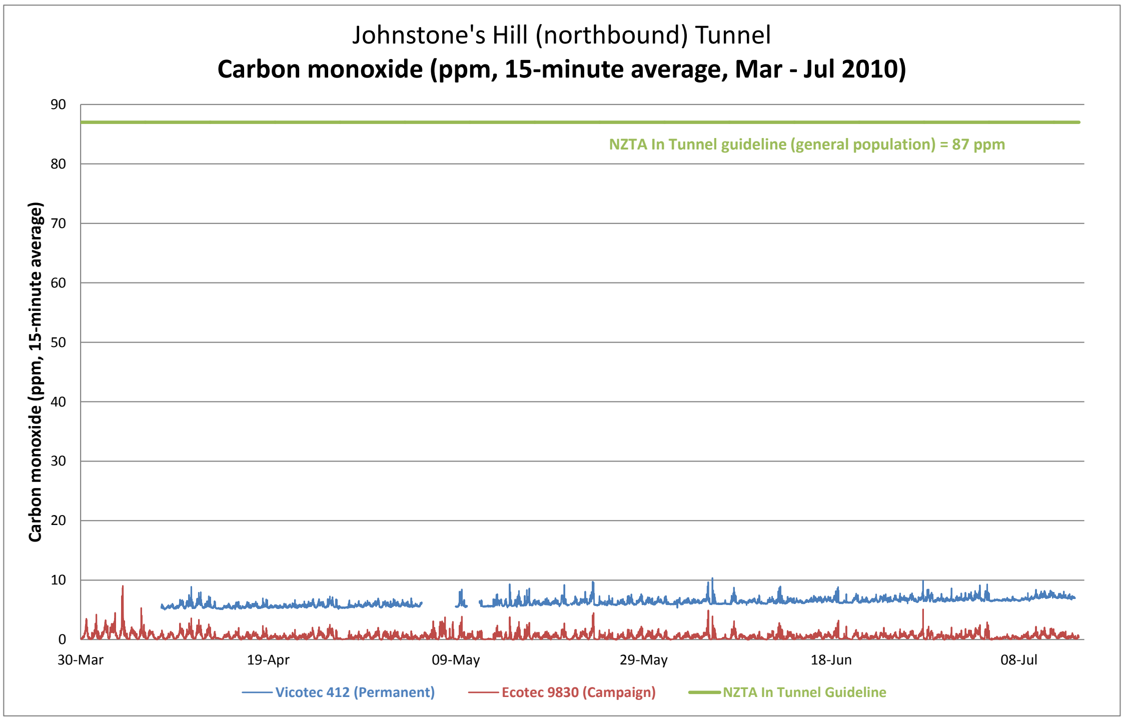

Figure 17: In-tunnel CO (15-minute average), March – July 2010

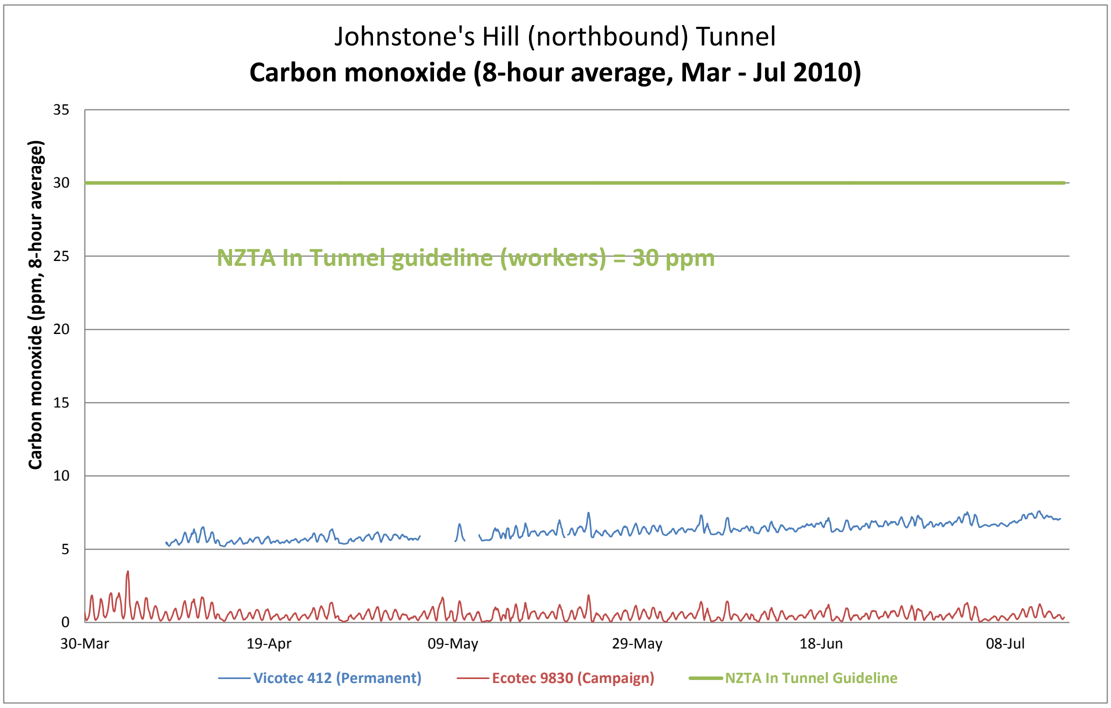

Figure 18: In-tunnel CO (8-hour rolling average), March–July 2010

3.3.2 Nitrogen dioxide

Nitrogen dioxide was measured both continuously (instrumental monitoring) and at monthly intervals (passive sampling). Continuous NO_2 monitoring is presented in figure 19 (15-minute average), with monthly sampling presented in figure 20.

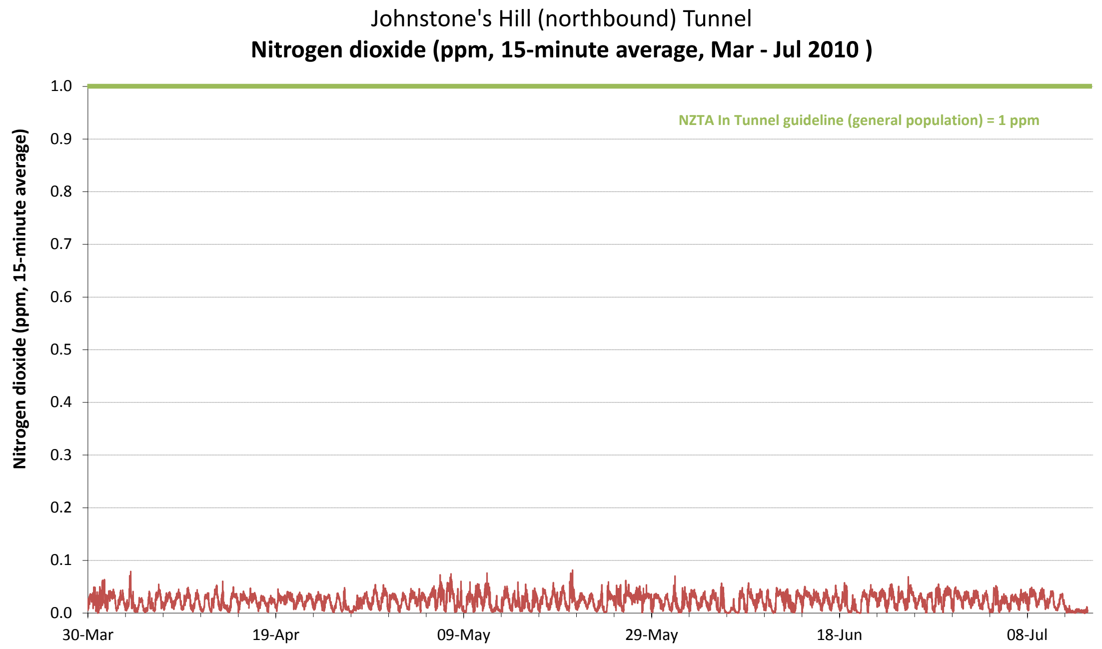

Figure 19: In-tunnel NO_2 (15-minute average), March – July 2010

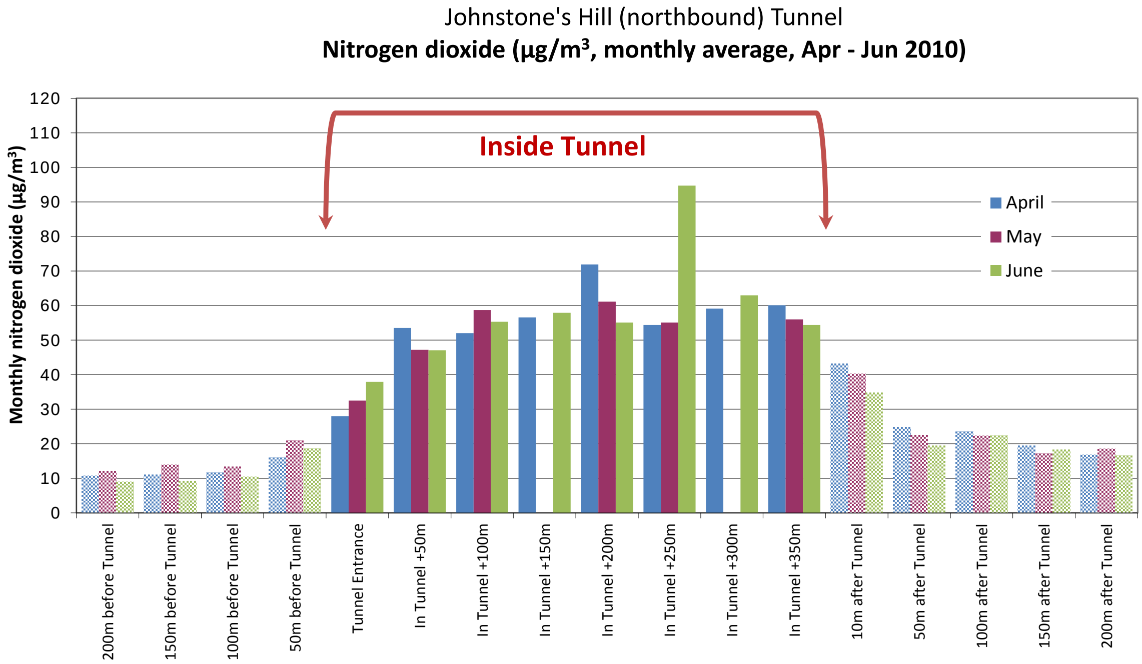

Figure 20: Monthly NO_2 inside and outside northbound tunnel, April – June 2010

A comparison of both methods is given in figure 21 and shows that the passive method measures slightly higher than the continuous method (on average, 16% higher). This finding is in keeping with the results of the Transport Agency's national passive monitoring programme which found that passive samplers over-read by 27% on average versus co-located continuous monitors[19].

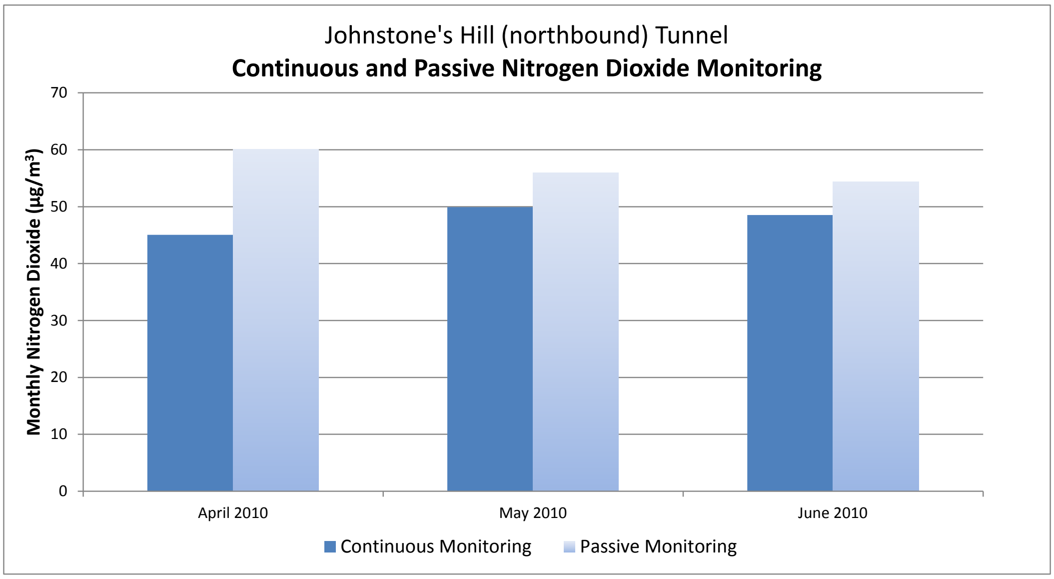

Figure 21: Passive and continuous in-tunnel NO_2, April – June 2010

All recorded levels of NO_2 inside the tunnel were well below the relevant NZTA interim in-tunnel air quality guidelines. However, elevated concentrations were recorded just outside the tunnel exit (site AUC165) with monthly averages of 43.2µg/m^3 in May, 40.2µg/m^3 in June and 34.8µg/m^3 in July. Although close to the World Health Organisation annual NO_2 guideline of 40µg/m^3, the AUC165 results for three months cannot be directly compared to a guideline which covers 12 months. NO_2 concentrations vary seasonally with winter (June, July and August) concentrations nearly twice those of summer (December, January and February) levels[20].

NIWA has previously undertaken work to seasonally de-trend monthly passive data and developed adjustment factors for estimating annual average concentrations based on monthly means[21]. In this work, the adjustment factors are 0.810 for April, 0.748 for May and 0.742 for June. Applying these factors to the AUC165 data yields an annual average estimate in the range of 25.8 to 35.0 µg/m^3. However, it is not possible to say definitively whether the WHO annual NO_2 guideline would have been exceeded had the monitoring continued for a full 12 months.

[19] NZTA (2012b). *Ambient air quality (nitrogen dioxide) monitoring network – Annual report 2007 to 2011*, NZ Transport Agency, September 2012.

[20] *Ibid.*

[21] NIWA (2010c). *A regression approach to assessing urban NO_2 from passive monitoring – Application to the Waterview Connection.* NIWA Report AKL-2010-023 prepared for NZ Transport Agency, June 2010.

3.3.3 Particulate matter

PM_{10} monitoring is presented in figure 22 (15-minute average) and figure 23 (24-hour average).

A peak in PM_{10} concentrations is evident in the 15-minute and 24-hour averages (around midday on 16 May 2010). This may have been due to dust generating activities (maintenance or roadworks) in the tunnel environs but was unable to be confirmed.

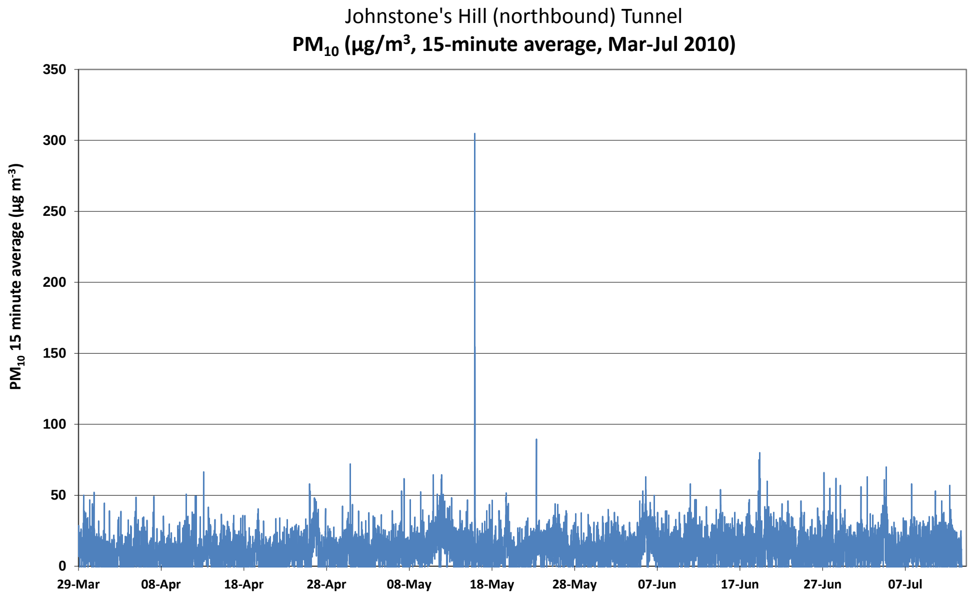

Figure 22: In-tunnel PM_{10} (15-minute average), March – July 2010

The Transport Agency has no **in-tunnel** guidelines for PM_{10}. However, ambient (outdoor) PM_{10} is regulated by a national environmental standard (NES) which sets an upper limit of 50µg/m^3 for a 24-hour average. In-tunnel concentrations were well within this NES during the monitoring period.

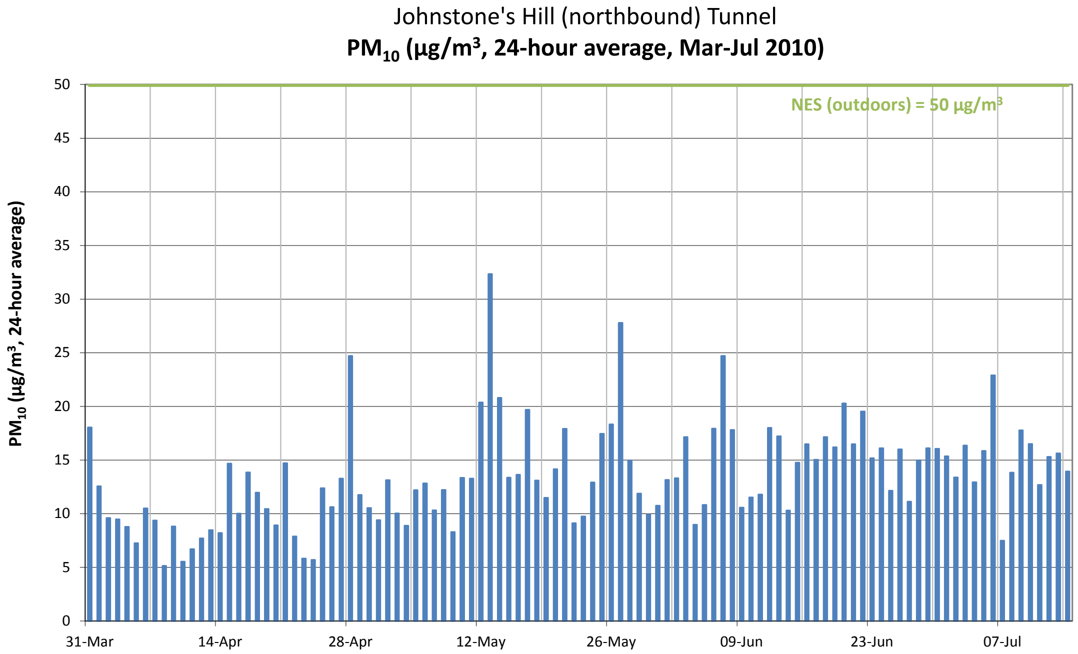

Figure 23: In-tunnel PM_{10} (24-hour average), March – July 2010

3.4 Meteorology

The predominant wind directions during the monitoring period in the Johnstone's Hill area were from the north north-west, and east south-east as shown by the wind rose in figure 24. This confirms the site meteorology is significantly different to that measured at the nearest permanent station at Warkworth where winds are predominantly from the west south-west and the west (refer figure 6).

The predominant north north-westerly measured in the Johnstone's Hill area also aligns with the tunnel direction.

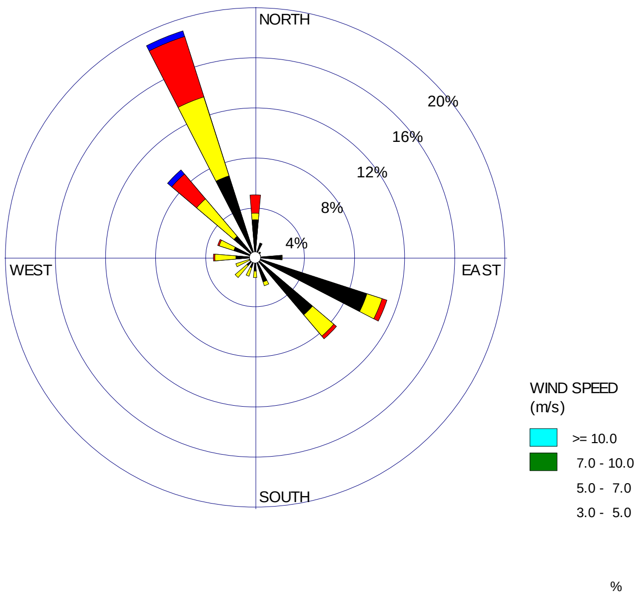

Figure 24: Wind rose for April-July 2010

3.5 Source apportionment

Six primary sources were found to contribute to in tunnel particulate matter concentrations:

- Light duty vehicles
- Heavy duty commercial vehicles
- Smoky vehicles
- Re-suspended road dust
- Biomass (wood) burning
- Marine aerosol (sea salt)

As would be expected, the predominant sources of PM_{10} in the tunnel were related to vehicles. Figure 25 presents the average source contributions to PM_{10}. Heavy duty commercial vehicles were responsible for 66% of the vehicle-related PM_{10} (excluding the road dust component) despite contributing only 10% of total traffic volume. Heavy duty vehicles are almost exclusively powered by diesel. Light duty vehicles (90% of traffic volume), mainly petrol-fuelled, contributed 17% of the vehicle related PM_{10}.

Figure 26 presents PM_{10} from motor vehicles aggregated over the monitoring period.

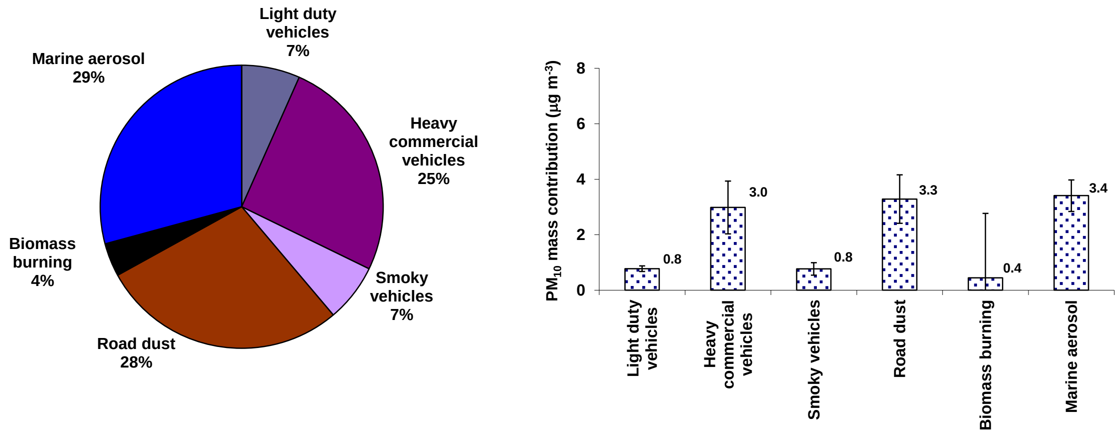

Figure 25: Average source contributions to in tunnel PM_{10} (June 2010)

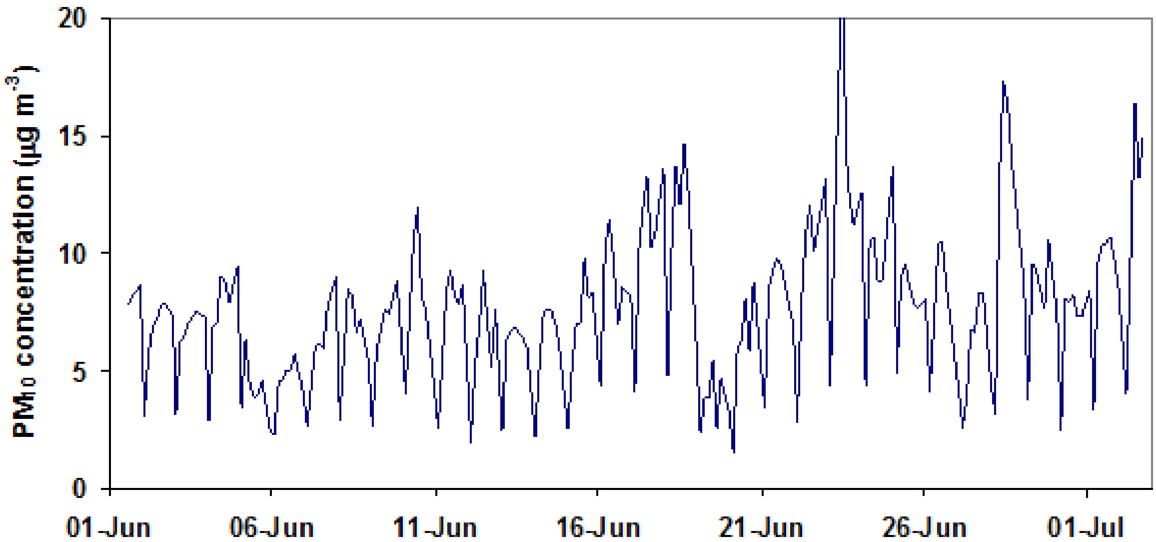

Figure 26: Aggregate time-series of vehicle source contributions to PM_{10} mass in Johnstone's Hill Tunnel (light duty vehicles, heavy duty commercial vehicles, smoky vehicles and road dust)

4. Key findings

4.1 Diurnal trend

The continuous CO and NO_2 results both peaked in the middle of the day as shown in figure 27. This figure presents results for 3 April 2010 (which recorded the maximum CO levels for the monitoring period) but the trends was typical of all days monitored.

This trend matches vehicle traffic as shown in figure 28 which plots CO and traffic counts for the same day. However, the same could **not** be said of PM_{10} which displayed no obvious temporal trend either daily or when comparing week days with weekends as shown in figure 29.

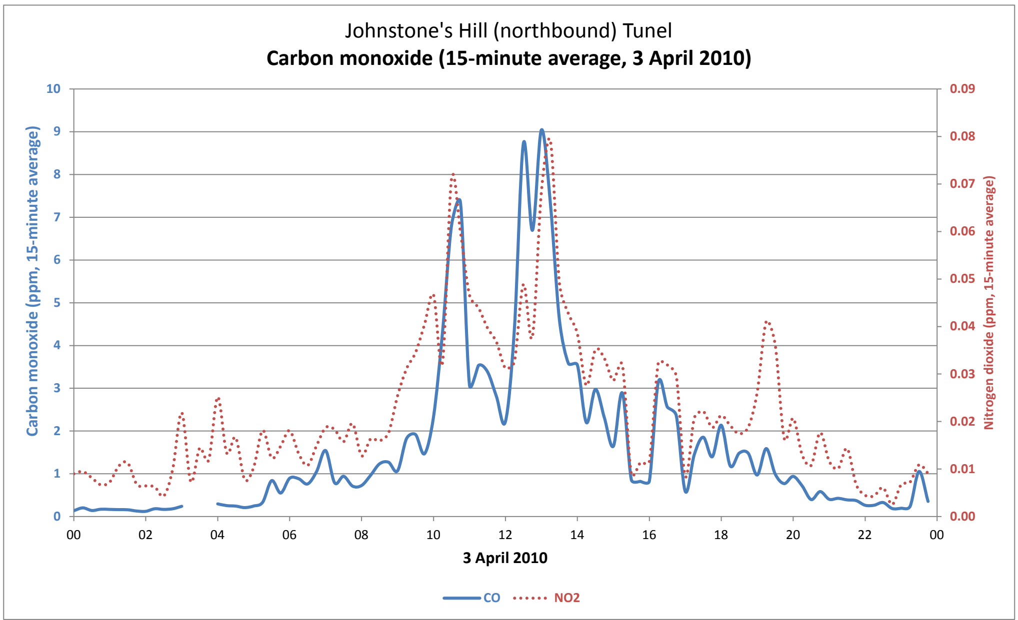

Figure 27: Daily trend in CO and NO_2 concentrations for 3 April 2010

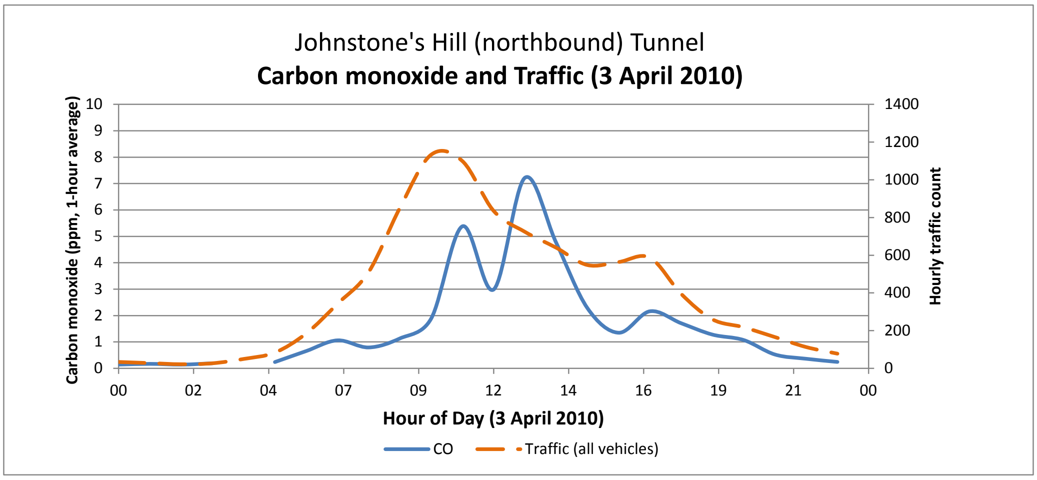

Figure 28: Comparison of CO with traffic count for 3 April 2010

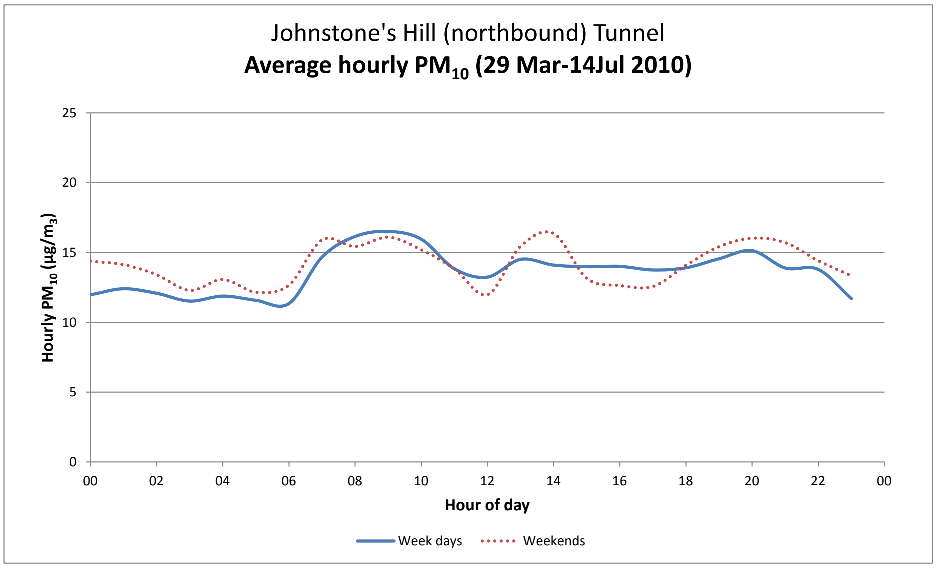

Figure 29: Average hourly PM_{10} on week days and weekends over monitoring period

4.2 Holiday traffic

The period of monitoring covered two holiday weekends, during which northbound traffic increased significantly as shown in figure 17. Because monitoring was carried out in the northbound tunnel, the analysis focuses on Good Friday when traffic heading north increased.

Surprisingly, the increased (northbound) holiday traffic during these periods was **not** reflected in increased levels of CO, NO_2 or PM_{10}. Figure 30 plots CO with hourly traffic over the Easter period and there is no clear correlation. This may be a result of increased air flow in the tunnel, however, the air flow data for this period were lost and this cannot be confirmed.

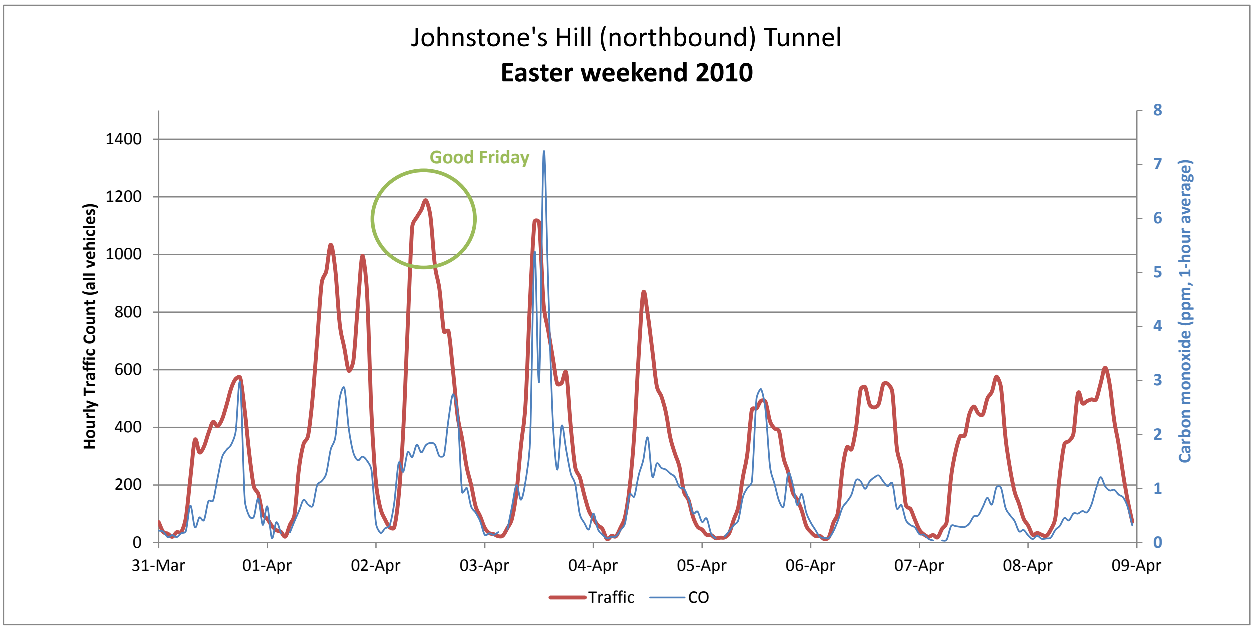

Figure 30: Carbon monoxide levels over Easter weekend, 2010

Similarly, pollutant levels (CO, NO_2 or PM_{10}) did not increase during the increased northbound traffic over Queens Birthday weekend. Available data suggest increased air flow through the tunnel at this time and this is likely to have offset elevated levels as shown in figure 31.

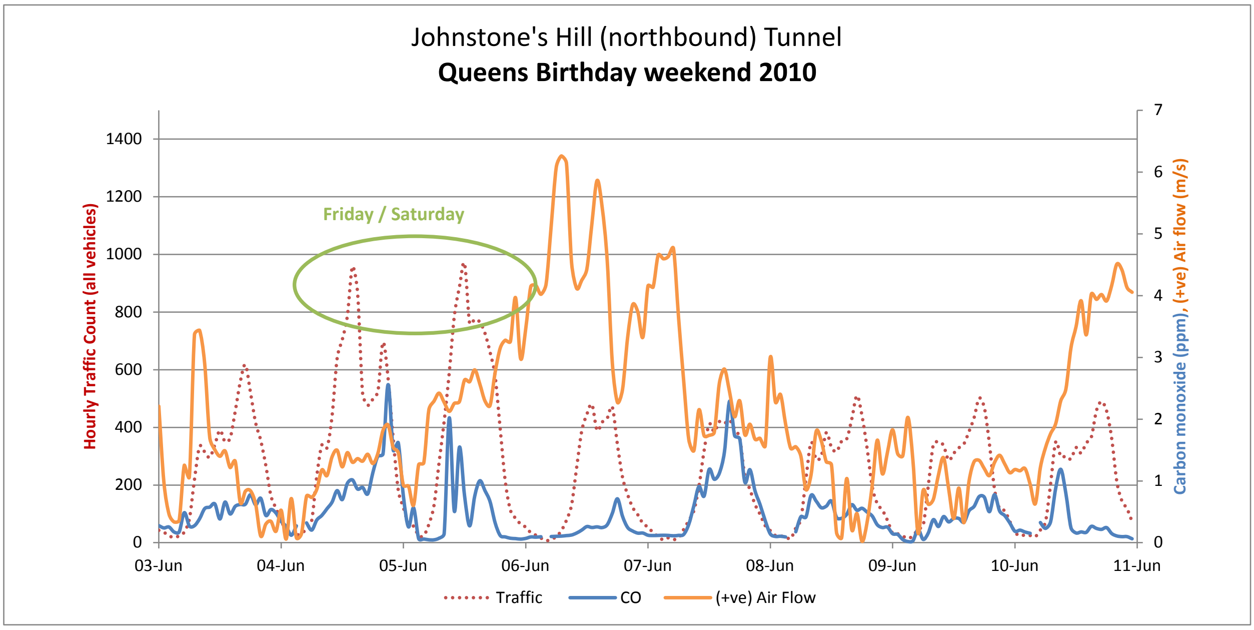

Figure 31: Carbon monoxide levels over Easter weekend, 2010, in relation to traffic and air flow

4.3 Operational monitoring of in-tunnel parameters

4.3.1 Tunnel ventilation

The tunnel air flow sensors appear to indicate prolonged periods of negative air speed. In other words, the northbound tunnel experiences both northbound and southbound air flow movement, as does the southbound tunnel. This may reflect the influence of external wind speeds and low vehicular traffic in the absence of any ventilation (the jet fans were off for the entire duration of campaign monitoring).

(Alternatively, the sensors may need recalibrating as discussed below).

4.3.2 Sensor performance

Data from existing operational monitoring of CO and air flow is limited and could be improved.

Whilst these sensors provide online 'live' data to the tunnel operator, they are not continuously logged. At any time a three-month running record is available but this is updated and over-written each day. This is why air flow data were not available to investigate any correlation between pollutant levels and traffic count during Easter.

The permanent, in tunnel CO sensor appears to be suffering from upwards drift and requires recalibration. The sensor consistently over-read by 5ppm relative to the continuous campaign monitor (which was calibrated daily) and appears to be increasing by around 0.5ppm per month. This is shown clearly in figure 32 (8-hour average). According to available records, the CO sensor was last calibrated during installation in October 2008. (This is likely to also be the case for the CO sensor in the southbound tunnel).

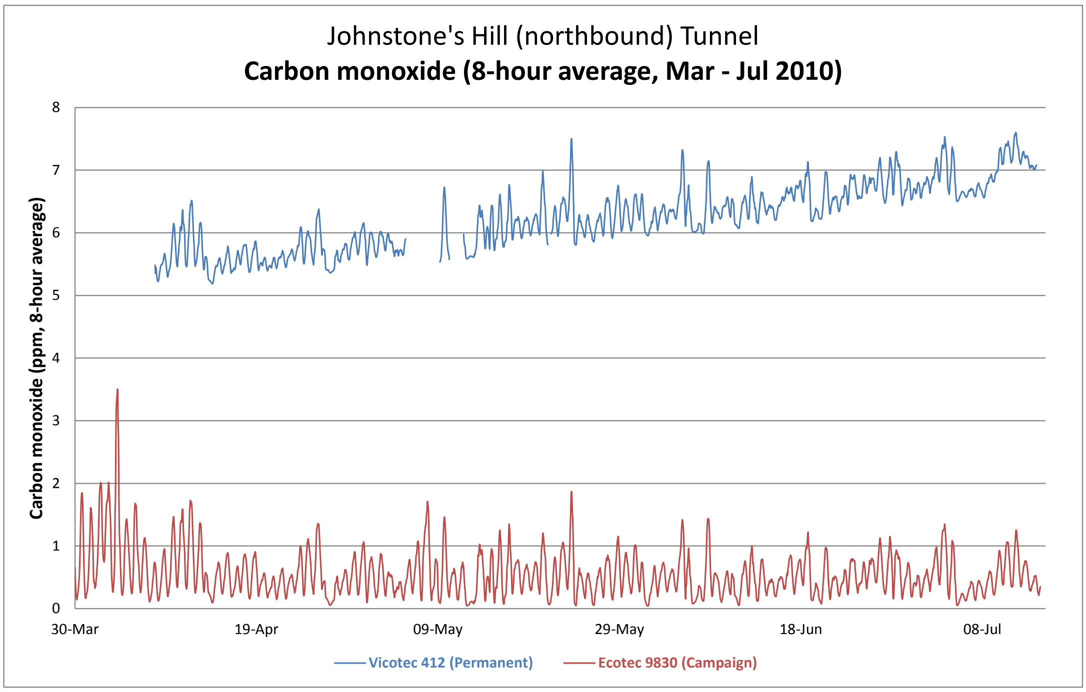

Figure 32: In-tunnel CO (8-hour rolling average), March – July 2010

Note: since the tunnel monitoring campaign ended, both the northbound and southbound in-tunnel CO sensors have been repaired and re-calibrated several times[22]. The southbound sensor was fixed and both sensors re-calibrated on 4 August 2011. The northbound sensor was fixed and both sensors re-calibrated on 14 August 2012. In both instances, the stepper motors had failed.

Both sensors are now being serviced annually with more regular calibration checks being undertaken.

4.4 In-tunnel dispersion

Local meteorological monitoring indicates that the predominant wind direction (at least for the period March to July 2010) is from the north north-west, which aligns with the direction of the tunnels. As a result, local winds have the potential to impact on in-tunnel air flow and subsequent dispersion of traffic emissions.

External wind speed does appear to impact in-tunnel air flow as shown in figure 33. The impact of external wind speed on in-tunnel dispersion is, however, less clear. Plots of PM_{10} and CO with external wind speed (figures 34 and 35 respectively) show little correlation.

In practice, it is likely that a combination of in-tunnel air flow, external wind speed, traffic volume and traffic composition all impact on in-tunnel pollutant levels.

[22] T Sullivan (2013) of Auckland Motorway Alliance, *pers. comm.*, 4 February

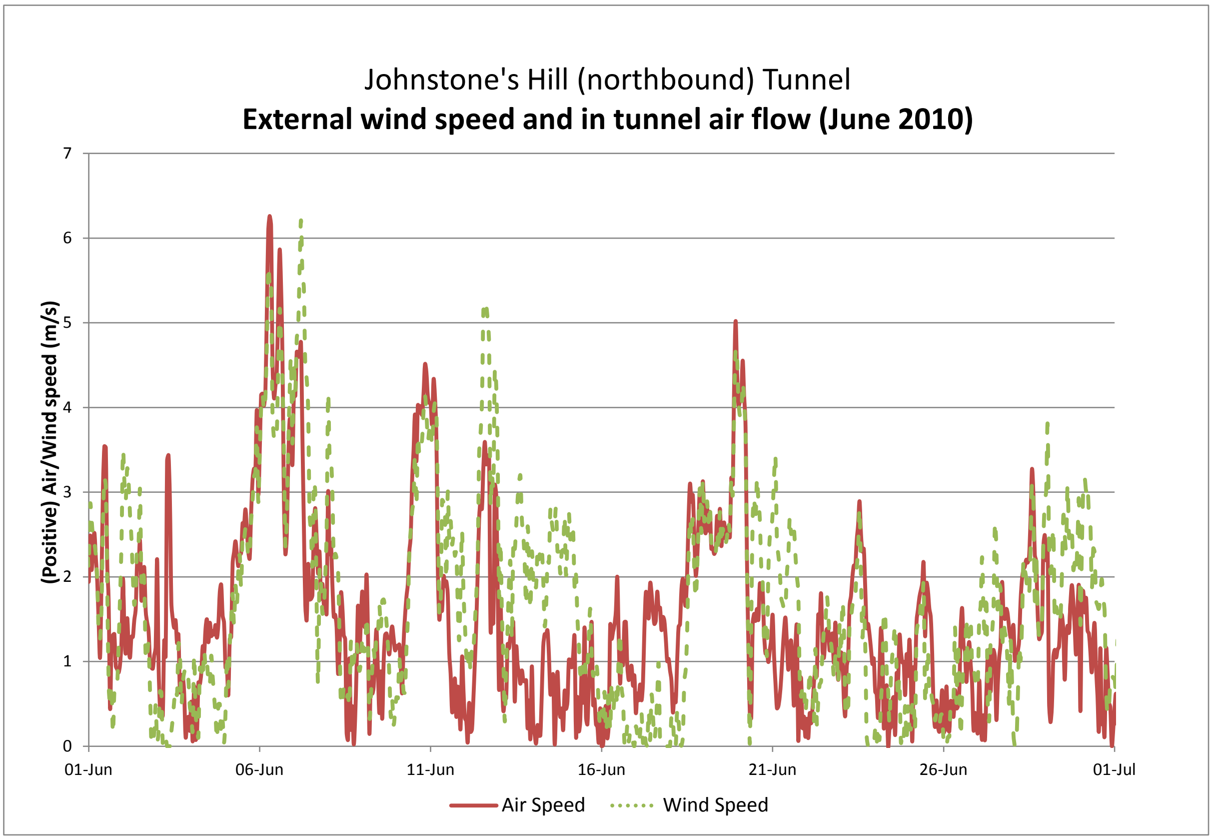

Figure 33: External wind speed and in-tunnel air flow (June, 2010)

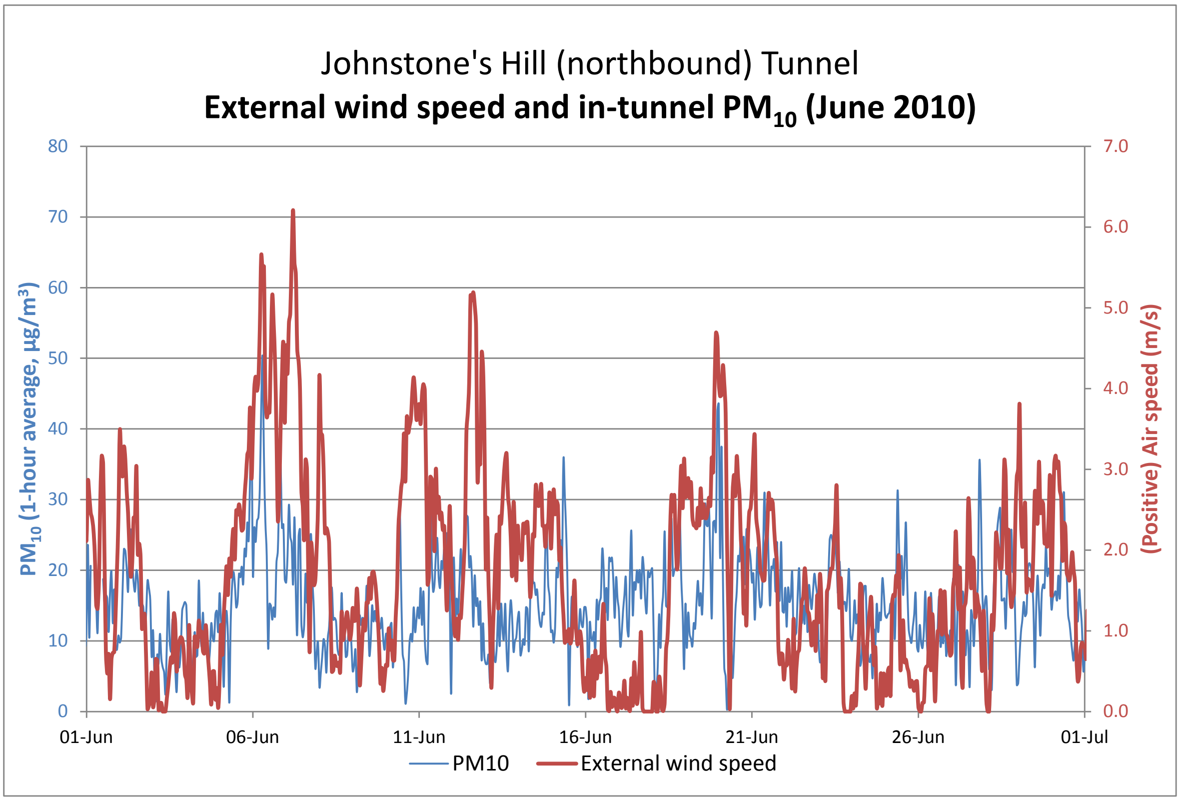

Figure 34: External wind speed and in-tunnel PM_{10} (June, 2010)

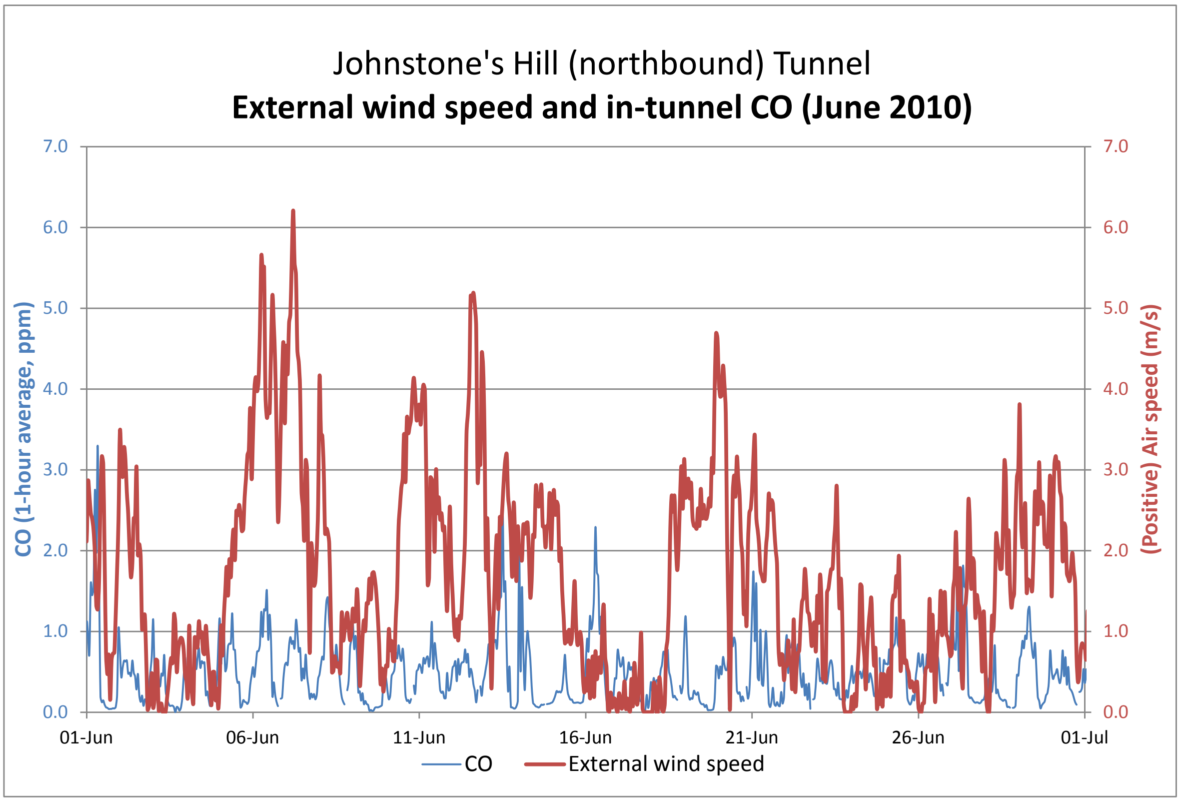

Figure 35: External wind speed and in-tunnel CO (June, 2010)

4.5 External air quality

Monthly sampling of NO_2 was undertaken at 50m intervals at five locations before the tunnel (travelling northbound), six locations inside the tunnel and five locations after the tunnel (travelling northbound) using passive samplers. The results indicate that levels of NO_2 increase along the length of tunnel and remain slightly elevated (compared with pre-tunnel levels) immediately beyond (ie, within 200m of) the tunnel exit.

There was, however, significant deviation in levels recorded in the tunnel centre, the entrance and the exit. These are likely to reflect the changing air flow in the tunnels (refer section 4.4).

4.6 Heavy duty vehicles

Whilst heavy duty vehicles average only 10% of weekday traffic through the tunnels (and less during weekends), they appear to disproportionately impact levels of some pollutants.

Typically light duty petrol vehicles emit higher quantities of CO per kilometre driven whereas heavy duty diesel vehicles emit higher quantities of PM_{10} and NO_2 per kilometre. Figures 36 and 37 show the relationships between the pollutant concentrations measured in the tunnel and vehicle counts for light duty and heavy duty vehicles, respectively. These figures confirm that CO concentrations are more strongly correlated with light duty vehicles (R^2=0.44 vs 0.11) whereas NO_2 concentrations are slightly more strongly correlated with heavy duty vehicles (R^2=0.40 vs 0.33).

Neither vehicle weight class has a strong influence on **total** PM_{10} concentrations (due to the presence of other PM_{10} sources) but the source apportionment shows that 66% of the **vehicle exhaust-related** PM_{10} is attributed to heavy duty vehicles alone.

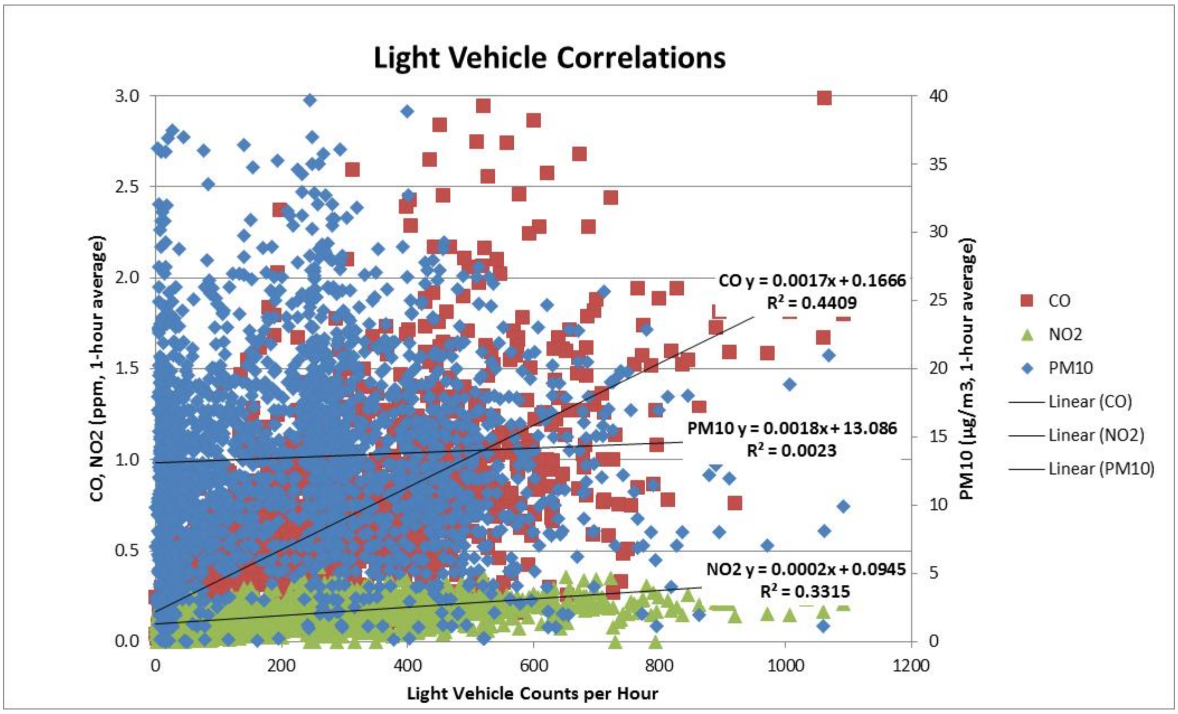

Figure 36: Correlation between pollutant concentrations measured in the tunnel and light duty vehicle counts (March - June, 2010)

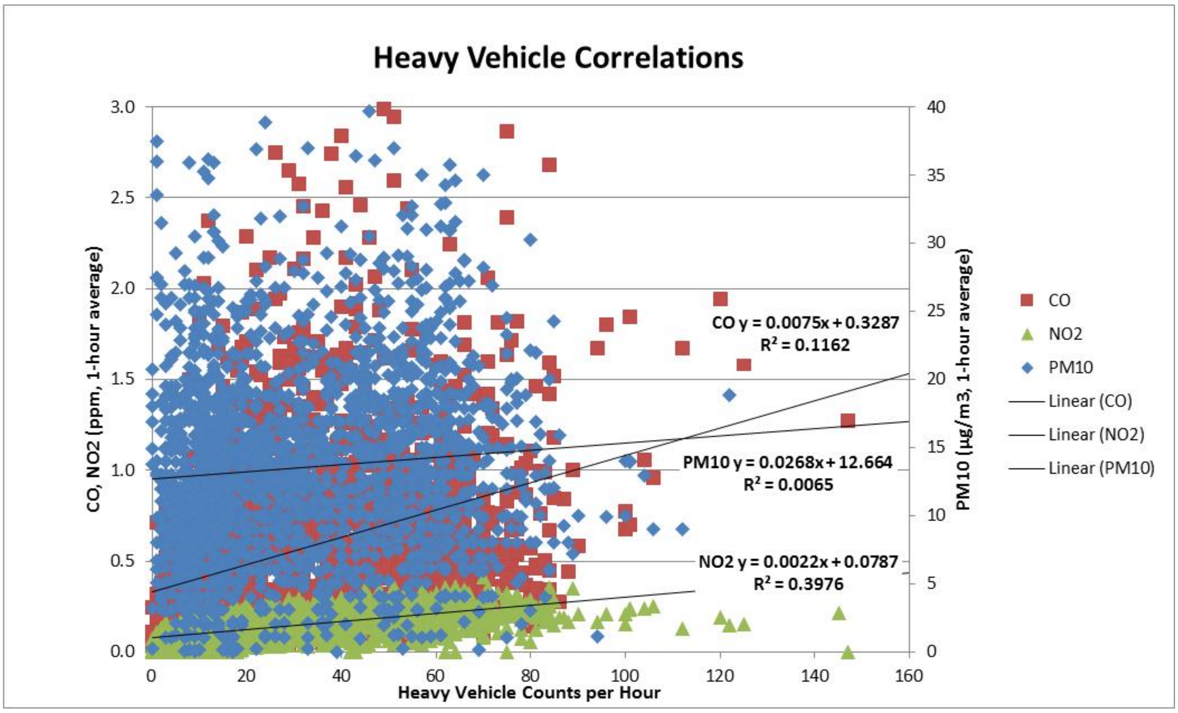

Figure 37: Correlation between pollutant concentrations measured in the tunnel and heavy duty vehicle counts (March - June, 2010)

As a further illustration, figure 38 presents in tunnel levels of NO_2 and PM_{10} with hourly counts of heavy duty vehicles. In general in-tunnel levels of NO_2 and PM_{10} track heavy duty vehicle counts reasonably well but there are also days when pollutant levels remain elevated and heavy duty vehicle traffic is low. This is most likely due to a combination of increased other (light duty) traffic and low air flow and/or in tunnel ventilation.

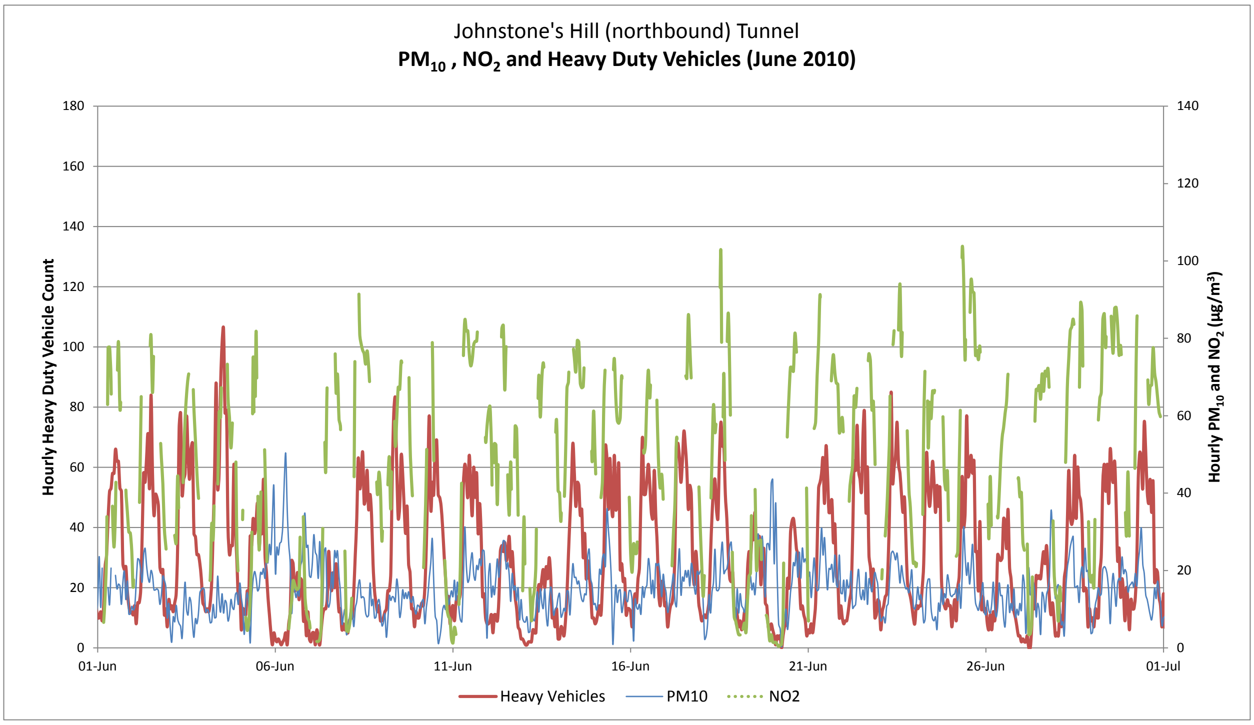

Figure 38: Comparison of in-tunnel NO_2 and PM_{10} with heavy duty vehicle counts (June, 2010)

5. Conclusions and recommendations

5.1 Conclusions

5.1.1 Compliance with standards and guidelines

In-tunnel air quality

All pollutants (CO, NO_2 and PM_{10}) measured inside the tunnel were well within the Transport Agency interim in tunnel air quality guidelines.

External air quality

Levels of NO_2 measured using (passive) diffusion tubes just outside the northern tunnel exit were close to the World Health Organisation annual average guideline for NO_2 (40 μg/m^3). However, monthly levels (43, 40 and 35 μg/m^3) for a period of only three months cannot be compared directly with the annual guideline which covers 12 months. Winter (June, July, August) NO_2 levels are typically twice those of summer (December, January, February) levels.

Applying adjustment factors developed for NIWA to seasonally de-trend monthly passive data yields an annual average estimate in the range of 25.8 to 35.0 μg/m^3. However, it is not possible to say definitively whether the WHO annual NO_2 guideline would have been exceeded just outside the tunnel exit had the monitoring continued for a full 12 months. It should be noted that the nearest potentially sensitive receptors (ie residences) are located more than 300m away from either portal; therefore it is unlikely that any person is being exposed to 'high' NO_2 levels for a year.

The meteorological monitoring confirmed that meteorology at the Johnstone's Hill tunnels is different to that of the nearest permanent station at Warkworth. The predominant wind direction (north north west) aligns with the direction of the tunnel.

5.1.2 Disproportionate impact of heavy duty vehicles

Whilst heavy duty vehicles average only 10% of weekday traffic through the tunnels (and less during weekends), they appear to disproportionately impact levels of some pollutants.

CO concentrations are more strongly correlated with light duty vehicles (which are predominantly petrol-fuelled) whereas NO_2 concentrations are slightly more strongly correlated with heavy duty vehicles (almost exclusively diesel-fuelled).

Neither vehicle weight class has a strong influence on **total** PM_{10} concentrations (due to the presence of other PM_{10} sources) but the source apportionment shows that 66% of the **vehicle exhaust-related** PM_{10} is attributed to heavy duty vehicles alone.

5.2 Recommendations

5.2.1 Key parameters for future management

Data logging

Currently sensor data (air flow, CO and jet fan operation) are over-written each day. It is recommended that this information be continuously logged instead and permanently stored or archived as 15-minute averages.

Sensor calibrations

The permanent, in tunnel CO sensors require recalibration. Currently, the northbound tunnel sensor is drifting upwards by about 0.5ppm per month (refer figure 32). If this drift continues, there is a risk that the sensor will erroneously measure levels in excess of the in-tunnel limit for CO (for workers) and hence trigger the jet fans. Based on current rate of drift, this may happen by May 2014. It is likely that the sensor in the southbound tunnel is also drifting upward and should also be checked as soon as possible.

The permanent, in tunnel air flow sensors may also need recalibrating. Negative air speed (refer figures 14 and 15) suggests the air is moving backwards and forwards in both tunnels. If so, this requires further investigation as it may impact on effective tunnel ventilation in the event of the jet fans being operated.

It appears that all sensors were last recalibrated during installation in October 2008.

Note: since the tunnel monitoring campaign ended, both the northbound and southbound in-tunnel CO sensors have been repaired and re-calibrated several times[23]. Both sensors are now being serviced annually with more regular calibration checks being undertaken.

5.2.2 Design suggestions for future tunnel monitoring campaigns

The Johnstone's Hill Tunnels are relatively short (~380m) and appear to be well-ventilated with low to moderate levels of traffic (around 14,000 vehicles per day) compared to other tunnels in the state highway network. For example, Lyttelton tunnel is 1,945m long and carries around 11,000 vehicles per day.

Whilst in-tunnel levels of CO correlate reasonably well with light duty vehicles and NO_2 with heavy duty vehicles, the correlations are not strong with and between all pollutants and all vehicle weight classes. Carbon monoxide did not correlate with either PM_{10} or NO_2. These findings indicate that future monitoring campaigns in other tunnels will need to monitor for all three pollutants simultaneously. This will be particularly true for longer tunnels with more traffic and/or less ventilation. Campaign monitoring is recommended on a five-yearly basis.

Similarly, the campaign showed the importance of on-site meteorological and on-site traffic monitoring. It is therefore recommended that future monitoring campaigns similarly include on-site measurements of both to maximise the understanding of all of the factors that influence in-tunnel and surrounding air quality.

Passive sampling was useful in ascertaining the spatial distribution of NO_2 levels before, inside and after the tunnel. Whilst measured levels were slightly over-estimated in comparison with continuously measured levels (at the same location), passive sampling appears to be a cost effective method for investigating

[23] T Sullivan (2013) of Auckland Motorway Alliance, *pers. comm.*, 4 February

spatial distribution. There would be value in running a 12 month passive sampling programme around the tunnel portals to better understand how levels compare with the WHO annual NO_2 guideline.

Internationally, tunnel monitoring campaigns are also employed to research other aspects of vehicle emissions management such as:

- verifying vehicle emission factors and predicted emissions from emission prediction models, such as the Vehicle Emission Prediction Model (VEPM[24])
- developing new emission factors for sources such as road dust, which is currently poorly understood in New Zealand
- assessing air pollution dispersion from tunnel portals using a combination of monitoring and modelling
- collecting concentrated samples for investigating the toxicity of vehicle emissions (especially those resulting from diesel vehicles[25])

A well-designed and well-coordinated future tunnel monitoring campaign could address most (if not all) of the recommendations in this section and lead to improved design/management of tunnels in the state highway network as well as furthering a better understanding of general vehicle emissions in New Zealand.

[24] See the NZ Transport Agency's transport and air quality website (air.nzta.govt.nz) for additional information on VEPM, including the model itself and the Users' Guide.

[25] The International Agency for Research on Cancer, which is part of the World Health Organisation, classified diesel engine exhaust as carcinogenic to humans on 13 June 2012.

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7. Glossary

Terms	Description
AADT	Annual average daily traffic
AAQG	MfE Ambient Air Quality Guidelines
AMA	The Auckland Motorway Alliance is a formal alliance led by the Transport Agency with Fulton Hogan, Opus, Beca, Resolve Group and Armitage Systems Ltd. The AMA is responsible for the maintenance and operation of the Auckland Motorway network and SH22, including renewals, and special projects but not large capital projects or planning issues.
AQNES	National Environmental Standards for Air Quality, which set standards for ambient air quality for key air pollutants to protect health. The AQNES apply to any location outdoors where people are likely to be exposed. The full title is *Resource Management (National Environmental Standards for Air Quality) Regulations 2004*.
CO	Carbon monoxide, an air pollutant produced from incomplete combustion of fuels, eg diesel and petrol used in transport. CO can cause health effects such as asphyxia.
EIL	Emission Impossible Limited
Exceedance	An occasion when the concentration of an air pollutant exceeds a standard or permissible measurement.
GNS	Institute of Geological and Nuclear Sciences
HCV	A heavy commercial vehicle is a motor vehicle (other than a motorcar that is not used, kept, or available for the carriage of passengers for hire or reward) having a gross laden weight exceeding 3500kg.
MfE	Ministry for the Environment
NIWA	National Institute of Water and Atmospheric Research
NO_2	Nitrogen dioxide, an air pollutant produced from the combustion of fossil fuels used in transport. NO_2 can cause health effects such as retarded lung development in children and increased susceptibility to lung infections.
NO_x	Nitrogen oxides, the collective term for air pollutants containing a mixture of nitrogen and oxygen
Passive monitoring	Air quality monitoring undertaken by collecting airborne gases through a diffusion barrier onto a sorbent medium without the use of a vacuum source, eg diffusion tubes.
PIARC	Permanent International Association of Road Congresses
$PM_{2.5}$	Fine particulate matter less than 2.5μm in diameter, an air pollutant produced from the combustion of transport fuels, primarily diesel
PM_{10}	Particulate matter less than 10μm in diameter, an air pollutant produced from the combustion of transport fuels, primarily diesel. PM_{10} can cause serious health effects such as increased cardio-respiratory illness and premature death. Although $PM_{2.5}$ is of increasing concern, because its emissions relate more directly to observed health effects, PM_{10} is commonly used in air quality assessments as it covered by an AQNES and more comprehensive monitoring

	records exist.
ppm	Parts per million, a measure of concentration
SH	State highway, eg SH1N is State Highway 1 North
Source apportionment	All air pollution has a unique combination of chemical elements depending on the source. Source apportionment establishes these ‘fingerprints’ or ‘signatures’ and uses them to quantify the contributing sources to air particulates ($PM_{2.5}$ or PM_{10}).
µg	Microgram, a millionth of a gram
µm	Micrometre, a millionth of a metre
WHO	World Health Organisation
WSL	Watercare Services Limited