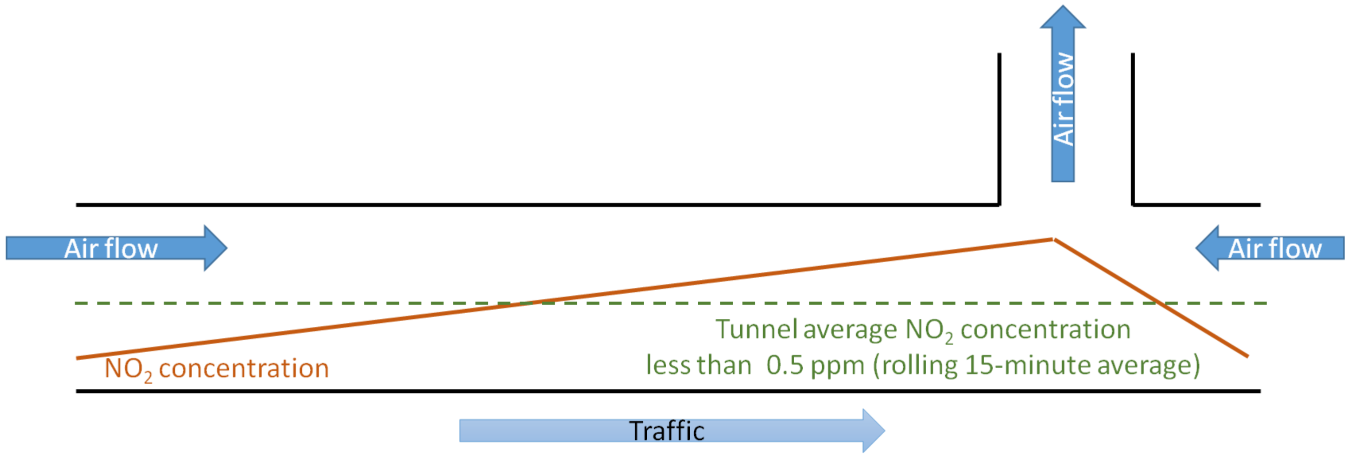
Advisory Committee on Tunnel Air Quality

IN-TUNNEL AIR QUALITY (NITROGEN DIOXIDE) POLICY

FEBRUARY 2016

POLICY REQUIREMENTS

All new road tunnels over 1 kilometre in length shall be designed and operated so that the tunnel average nitrogen dioxide (NO_2) concentration is less than 0.5 ppm as a rolling 15 minute average.



Sufficient monitoring equipment shall be installed to enable an accurate calculation of the tunnel average NO_2 concentration. As a minimum, monitors shall be installed at the entry and exit portals, any ramp junctions, at the base of any supply and exhaust ventilation shafts. Monitoring results should be made publicly available in a timely manner.

EXECUTIVE SUMMARY

- Historically, in-tunnel criteria for carbon monoxide (CO) were used to provide protection from all motor vehicle pollutants.
- NO_2 is a respiratory irritant with identified health effects at levels that may be encountered in road tunnels.
- Due to reductions in emissions of CO, there is relatively more NO_2 in tunnel air than in the past. Emissions of NO_2 from the Sydney motor vehicle fleet are likely to have peaked, and will reduce into the future as newer vehicles with tighter emission standards continue to replace older vehicles.
- Jurisdictions around the world are examining in-tunnel NO_2 criteria.
- An extensive review of the scientific literature commissioned by NSW Health found some evidence of health effects from short term exposure to NO_2 concentrations between 0.2 and 0.5 ppm. This review did not identify health effects from short term (20 – 30 minutes) exposure to NO_2 at levels below 0.2 ppm.
- A tunnel average criteria of 0.5 ppm as a rolling 15-minute average compares favourably to the international in-tunnel NO_2 guidelines which range between 0.4 ppm and 1.0 ppm.
- Modern cars with air vents set to recirculate can result in significantly lower in-cabin NO_2 levels than in-tunnel levels. A study conducted in Sydney motorway tunnels found that switching vehicle ventilation systems to recirculate results in in-cabin levels at least 70 per cent less than in-tunnel levels. Levels in newer vehicles were typically 90 per cent less than in-tunnel levels.
- The evidence indicates that application of a tunnel average criterion of 0.5 ppm as a rolling 15-minute average would result in an exposure of less than 0.2 ppm in passenger vehicles with the windows up and air vents set to recirculate ie below the level where health effects have been identified.

TABLE OF CONTENTS

Three technical papers were prepared to inform development of this policy, and are available at http://www.chiefscientist.nsw.gov.au/reports.

Technical Paper 1 – A Review and analysis of primary nitrogen dioxide emissions from road vehicles in Sydney

Technical Paper 2 - Review of experimental studies of exposures to nitrogen dioxide

Technical Paper 3 - Road tunnels: Reductions in nitrogen dioxide concentrations in-cabin using vehicle ventilation systems

GLOSSARY

Term	Description
ABS	Australian Bureau of Statistics
ADR	Australian Design Rule
Anthropogenic	Caused or produced by humans
BTS	(NSW) Bureau of Transport Statistics
DPF	diesel particulate filter
Emission factor	A quantity which expresses the mass of a pollutant emitted per unit of activity. For road transport the unit of activity is usually either distance (ie. g/km) or fuel consumed (ie. g/litre).
Emission rate	A quantity which expresses the mass of a pollutant emitted per unit of time (eg g/second)
EU	European Union
GMR	(NSW) Greater Metropolitan Region
HDV	heavy-duty vehicle
HGV	heavy goods vehicle
LCV	light commercial vehicle
LDV	light-duty vehicle
NO	nitric oxide
NO_2	nitrogen dioxide
NO_X	oxides of nitrogen
NPI	National Pollutant Inventory
NSW EPA	New South Wales Environment Protection Authority
O_3	ozone
OEH	(NSW) Office of Environment and Heritage
PM	particulate matter
ppb	parts per billion
ppm	parts per million
RMS	(NSW) Roads and Maritime Services
SCR	selective catalytic reduction
VKT	vehicle-kilometres travelled
$\mu g/m^3$	micrograms per cubic metre

1. INTRODUCTION

Road tunnels collect motor vehicle emissions that would otherwise disperse within a few hundred metres from a surface road.

To protect the safety and health of tunnel users, in-tunnel air quality criteria are established in jurisdictions around the world. The main air quality criteria considered in tunnel ventilation design are carbon monoxide (CO), nitrogen dioxide (NO_2) and visibility.

In the past, the CO criterion has been used to provide protection against all other motor vehicle pollutants. However, emissions of NO_2 have increased in relative importance due to:

- Emission standards for CO from new petrol cars reducing much more than emission standards for NO_x (until the introduction of Euro 3 in 2006).
- The increasing penetration of diesel cars. Diesel cars emit significantly more NO_2 and less CO than petrol cars.

Consequently, there is relatively more NO_2 compared with CO in tunnel air than was previously the case. This is recognised around the world, and has led many bodies to consider or implement in-tunnel NO_2 criteria in addition to the current CO criterion.

While fire safety is often the dominating factor influencing ventilation design in highway and non-urban tunnels, in tunnels with a high traffic load and frequent congested traffic, the fresh air requirement for normal operation can be dominant (PIARC, 2012). The in-tunnel air quality criterion for NO_2 could be a major factor in determining the size and performance requirements of tunnel ventilation systems.

This paper presents:

- An overview of NO_2 emissions from vehicles, explaining why NO_2 has emerged as an issue in tunnel ventilation design.
- An overview of NO_2 concentrations in tunnels.
- An overview of NO_2 concentrations in the ambient air to contextualise tunnel exposures.
- A discussion of in-tunnel exposure times and exposure pathways.
- A summary of a literature review of the health effects of in-tunnel NO_2 exposures.
- An overview of relevant national and international standards for NO_2.
- The basis for the policy requirements including international benchmarks, health effects, available measures to reduce exposure and risk evaluation.

2. NITROGEN DIOXIDE – TRENDS IN VEHICLE EMISSIONS

2.1. Key Points

- Emissions of NO_2 have increased in importance relative to CO due to the following two factors:
    - Emission standards for CO from new petrol cars reducing much more than emission standards for nitrogen oxides (NO_x) until the introduction of Euro 3 in 2006.
    - The increasing penetration of diesel cars. Diesel cars emit significantly more NO_2 and less CO than petrol cars.

- The proportion of new passenger car registrations that are diesel in NSW increased from 0.1 per cent in 2000 to 7.5 per cent in 2014. This is significantly less than the proportion of diesel passenger cars in Europe, where the proportion of new passenger car registrations that are diesel increased from 32.8 per cent in 2000 to 53.6 per cent in 2014.

- Emissions of NO_2 from the Sydney motor vehicle fleet is likely to have peaked, and will reduce into the future as newer vehicles with tighter emission standards continue to replace older vehicles.

2.2. Emissions of nitrogen oxides from vehicles

Nitric oxide (NO) and nitrogen dioxide (NO_2), together referred to nitrogen oxides (NO_x), are pollutants resulting from the combustion of fossil fuels. Motor vehicles such as on-road cars, trucks and buses contribute around 62 per cent of anthropogenic emissions of nitrogen oxides in Sydney (EPA, 2012). Over 80 per cent of NO_x emissions from motor vehicles in Sydney are NO. NO by itself is not considered a harmful pollutant at commonly encountered levels. However there have been associations found between human exposure to NO_2 and health effects, therefore particular focus is made on the NO_2 component of NO_x including in the development of standards and measurement techniques.

a. Vehicle emission limits

Improvements in vehicle technology over the last two decades have led to major reductions in air emissions per vehicle. Australia has had road vehicle emission standards for new vehicles in place since the early 1970s, and these have been progressively tightened. Australia's vehicle emission standards are set nationally in the Australian Design Rules (ADRs). More information on Australia's vehicle emissions standards can be found on the Department of Infrastructure and Regional Development website http://www.infrastructure.gov.au/roads/environment/emission/.

The current standards reflect Australia's commitment to harmonise the ADRs with the international standards. For heavy-duty vehicles there is some uncertainty concerning the adoption of Euro VI in Australia. A review at the Commonwealth level is still underway to determine whether and when Euro VI will be adopted in this country. Figures 1, 2 and 3 below present the emission standards for new petrol and diesel cars, and heavy duty vehicles.

Figure 1
Petrol Passenger Vehicle Emission Limits

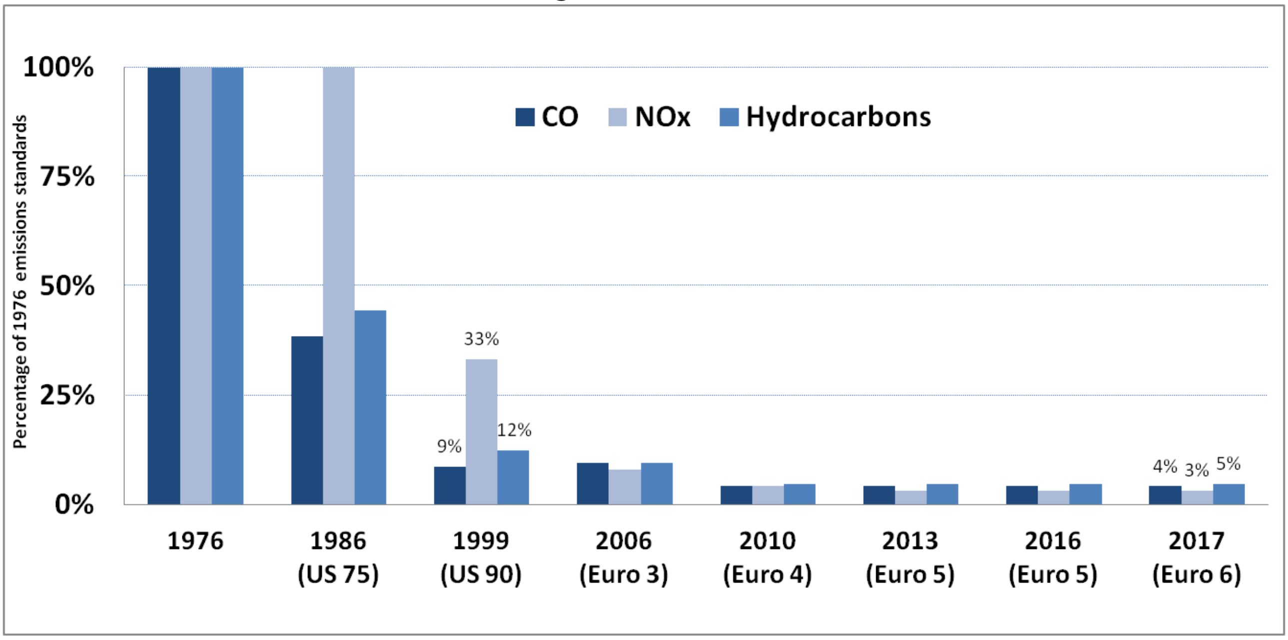


Figure 2
Diesel Car Emission Limits

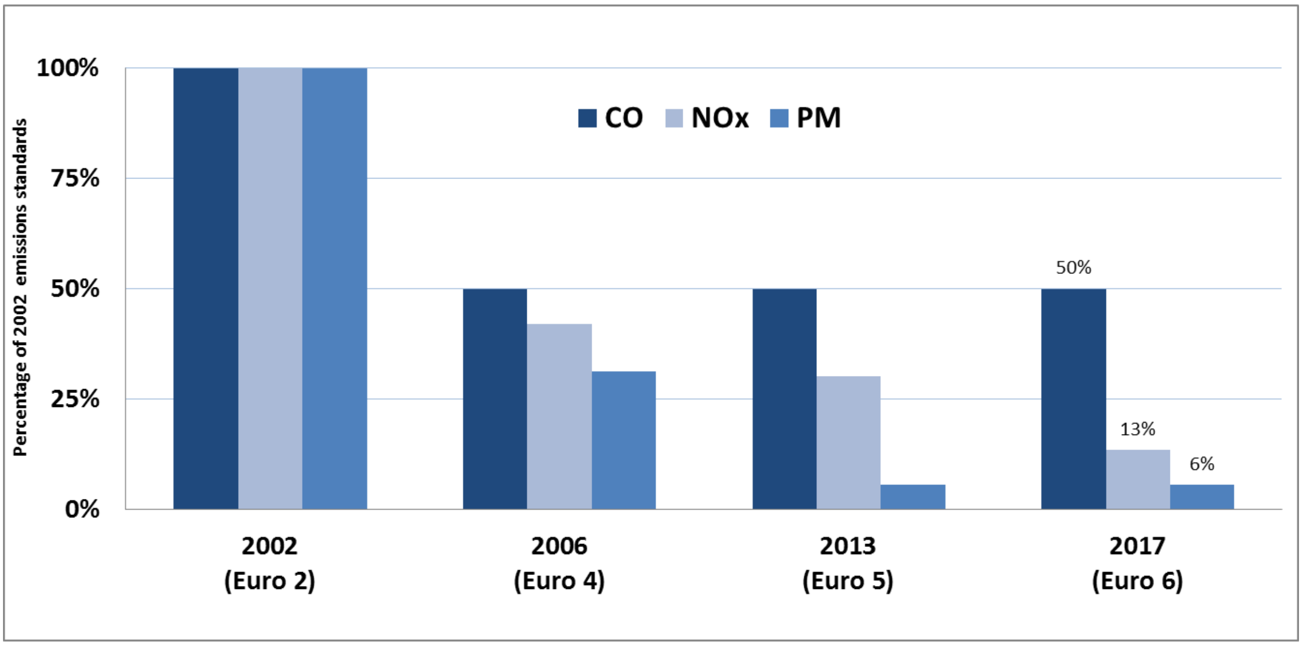
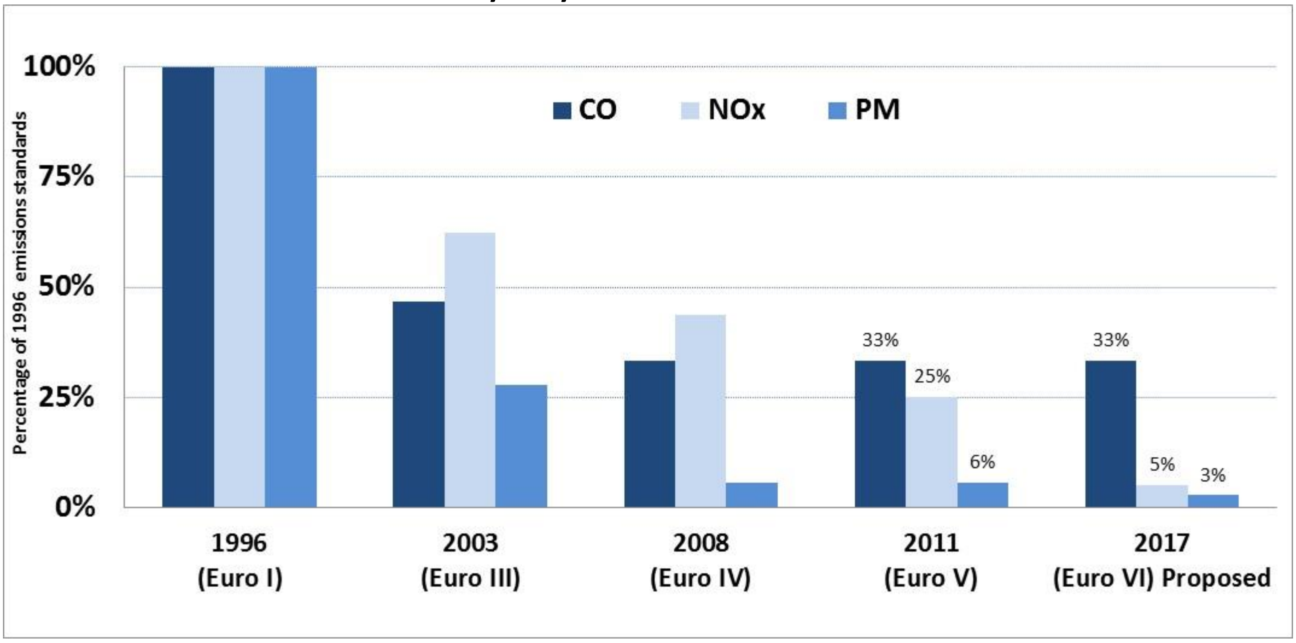


Figure 3
Heavy Duty Diesel Emission Limits



For petrol passenger vehicles and light duty diesel vehicles, the Euro 6 standards will commence for new models from 1 July 2017.

It has been acknowledged for over 10 years that real world emissions are significantly higher than certification test results. Work is already in progress to revise these procedures for light vehicles. The European Commission is scheduled to implement real-driving emissions test in two phases from September 2017. These improvements in testing requirements will address the issues recently highlighted regarding VW cars using 1.6 and 2 litre diesel engines.

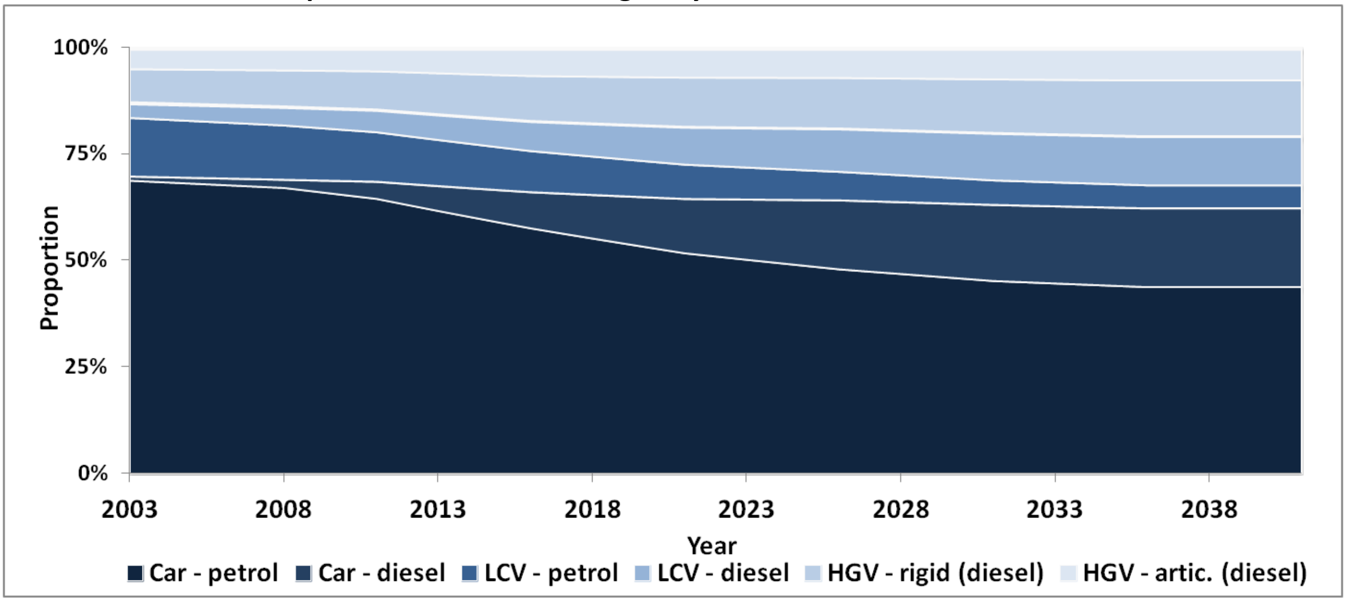
b. Sydney vehicle fleet

In road transport emission models it is important to distinguish between different types of vehicle, between vehicles using different types of fuel, and between vehicles conforming to different emission regulations.

Information on the composition of the Sydney vehicle fleets has been taken from the NSW Greater Metropolitan Region (GMR) emissions inventory. The information is based on vehicle-kilometres travelled (VKT) data from the Bureau of Transport Statistics' Household Travel Survey, the Strategic Travel Model and the Freight Movement Model (NSW EPA, 2012) and analysis of NSW registration data.

The composition of the traffic varies by road type. Figure 4 shows the VKT-weighted composition of the traffic on highways and freeways between 2003 and 2041. There are projected increases in the proportions of diesel cars and light commercial vehicles (LCVs) in the future.

Figure 4
Composition of Traffic on Highways between 2003 and 2041



The petrol/diesel splits used for cars and LCVs is shown in Figures 5 and 6. Historically, diesel vehicles have formed only a small proportion of the car fleet and VKT. In recent years the refinement of light-duty diesel engines and their superior fuel economy has led to increased sales and a larger market share. The proportion of new passenger car registrations that are diesel in NSW increased from 0.1 per cent in 2000 to 7.5 per cent in 2014. This is significantly less than the proportion of diesel passenger cars in Europe, where the proportion of new passenger car registrations that are diesel increased from 32.8 per cent in 2000 to 53.6 per cent in 2014.

Diesel LCVs have historically made up 15-30 per cent of total LCV sales, but as with cars the sales have risen rapidly in recent years (NSW EPA, 2012).

Figure 5
VKT Weighted Fuel Splits for Cars between 2003 and 2041

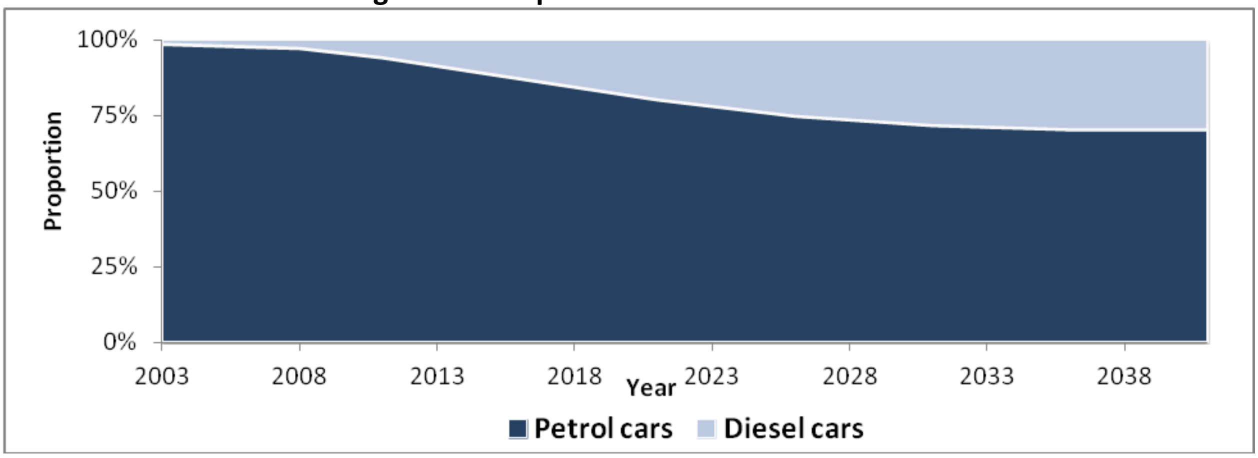
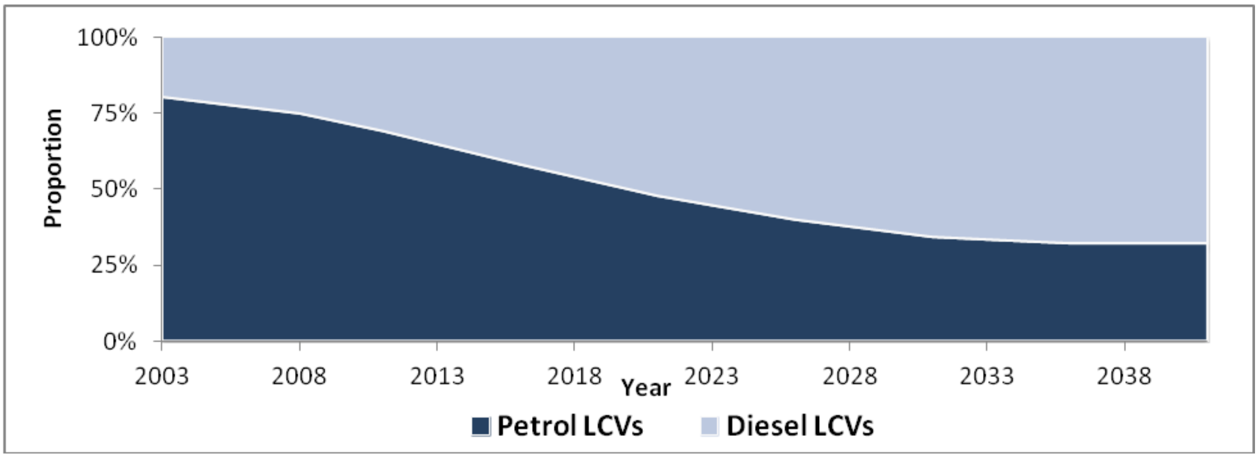
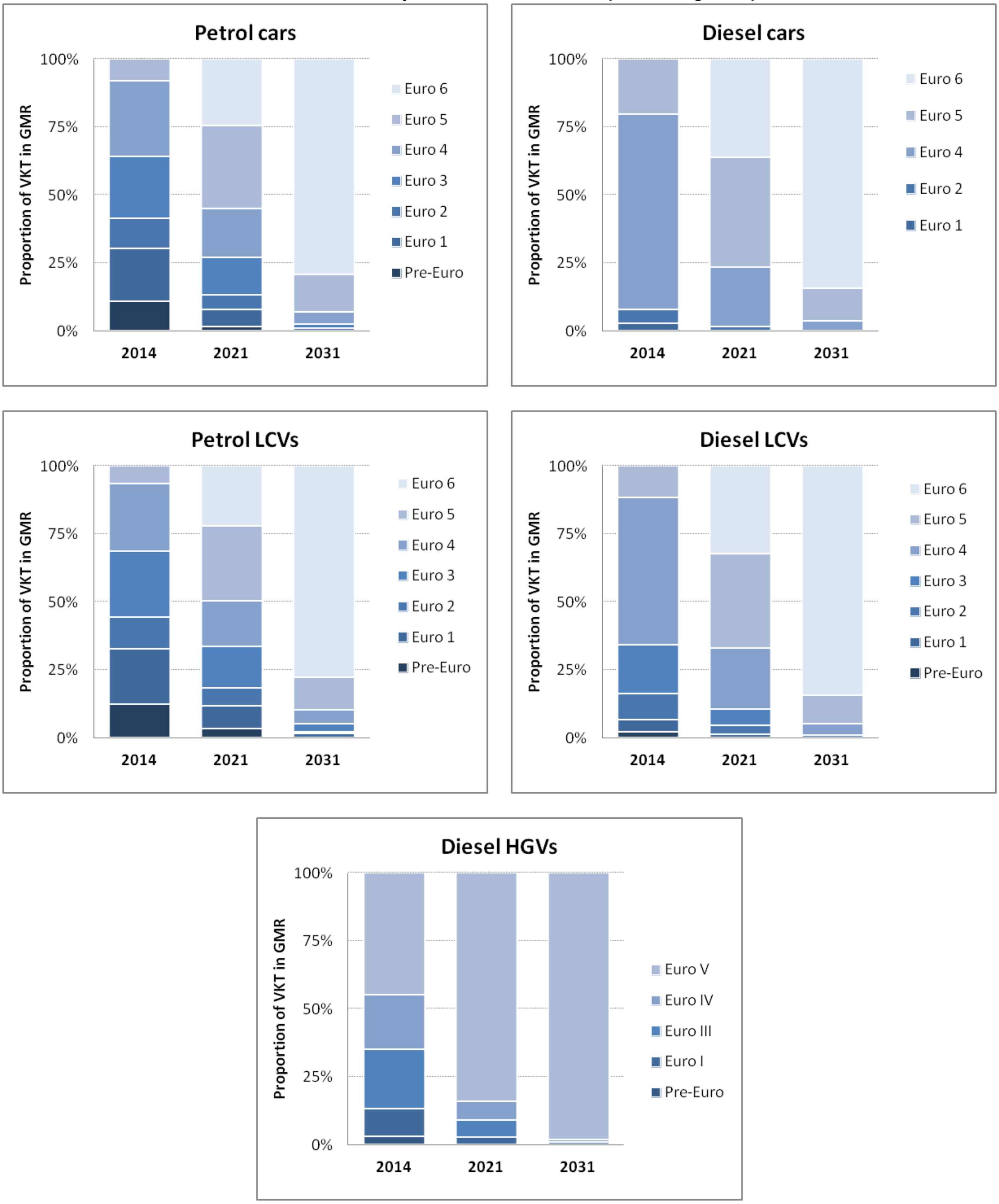


Figure 6
VKT Weighted Fuel Splits for LCVs between 2003 and 2041



The age distribution of the fleet for each vehicle type is a major determinant of the emissions from that vehicle type in a given year. This is because new vehicles are required to comply with more stringent emission regulations than older vehicles. The allocation of vehicle model years to specific emission standards has been taken into account in the emission projections. Some specific examples are shown in Figure 7.

Figure 7
Fleet Breakdown by Emission Standard (VKT weighted)

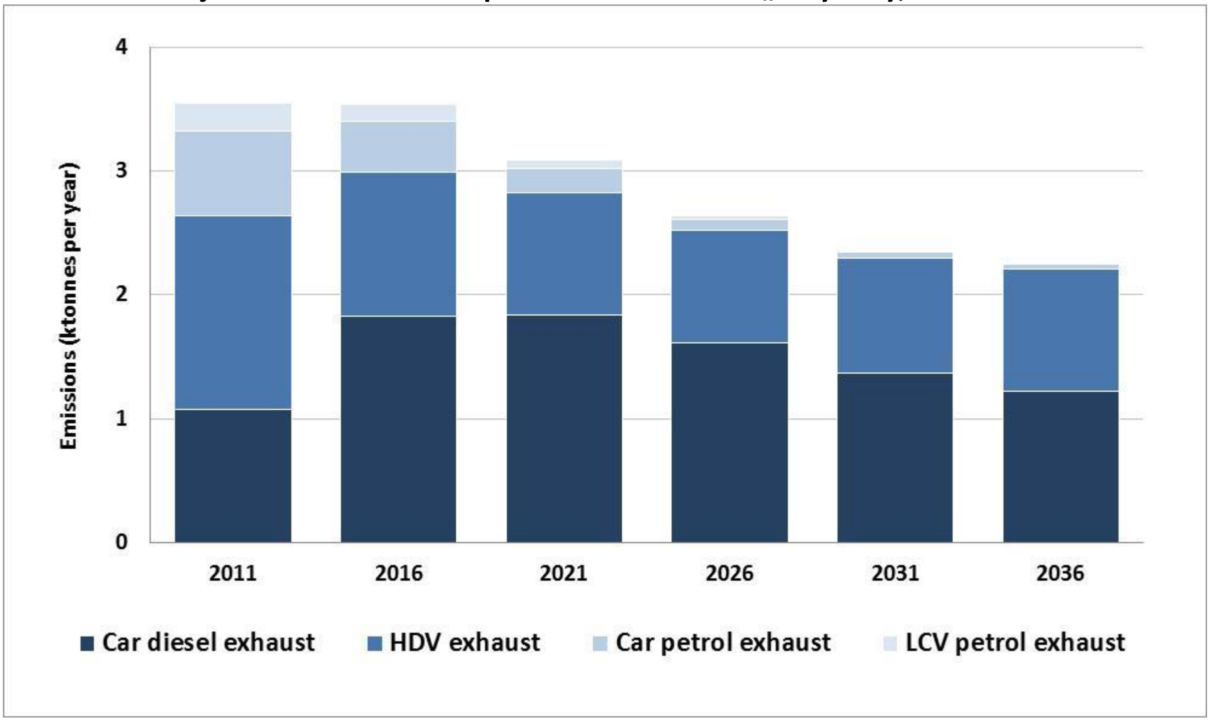


Euro VI emission standards for heavy vehicles have not been assumed in the emission projections as they have not yet been adopted in Australia. The implications of this are explored further in section 2.3

c. Emissions of nitrogen oxides from road transport in Sydney

The most detailed and comprehensive source of information on emissions in the Sydney area is the emissions inventory that is compiled periodically by NSW EPA (EPA, 2012). The EPA emission inventory is based on real world emission data, and is not significantly affected by issues related to compliance emission testing of diesel vehicles that came to light in 2015. NSW EPA projections of total road transport NO_X emissions in Sydney are presented by vehicle type in Figure 8.

Figure 8
Projections of road transport emissions of NO_x – Sydney, 2011-2036



Despite a continued increase in vehicle use, projections indicate there will continue to be substantial reductions in total emissions of NO_X from the vehicle fleet due to the effects of engine and emission-control technology.

2.3. Emissions of nitrogen dioxide from vehicles

In the ambient air, NO_x plays an important role in photochemical smog formation, and much of the NO emitted from vehicles is oxidised to NO_2 in the right circumstances. However, inside a road tunnel most of the NO_2 in the air is primary; that is, emitted directly from vehicle exhaust pipes rather than being formed in the tunnel atmosphere. Whilst it is possible that chemical reactions could form NO_2 in longer tunnels, the per cent NO_2 in fleet average vehicle exhaust provides a reliable indication of the per cent NO_2 in tunnel air (Boulter *et al.*, 2007).

Technical Paper 1 is a study conducted by Pacific Environment (Pacific Environment, 2015a) looking at trends in emissions of NO_2 from vehicles in Sydney. Key findings from the study are summarised in the following sections.

a. Per cent nitrogen dioxide in vehicle exhaust

Pacific Environment used work done for the European Air Pollutant Emission Inventory Guidebook (Pastramas *et al.*, 2014) to extend the EPA emission inventory. The per cent NO_2 values in vehicle exhaust for the various vehicles classes and emission standards in Table 1 have been applied to the EPA total NO_x values to arrive at emissions of NO_2.

Table 1
Per cent NO_2 in Vehicle Exhaust from Pastramas *et al.* (2014)

Light-duty vehicles			Heavy-duty vehicles	
Emission standard/ technology	NO_2 % Petrol cars and LCVs	NO_2 % Diesel cars and LCVs	Emission standard/ technology	NO_2 % Diesel HGVs and buses
Pre-Euro	7	15	Pre-Euro	11
Euro 1	6	13	Euro I	11
Euro 2	5	13	Euro II	11
Euro 3	4	27	Euro III	14
Euro 3 + DPF*	-	51	Euro III + CRT	36
Euro 4	5	46	Euro IV	10
Euro 4 + DPF*	-	42	-	-
Euro 5	3	33	Euro V	17
Euro 6	3	30	Euro VI	8

* DPF is a diesel particulate filter. The Euro 5 emissions standards for new diesel cars effectively require a DPF.

For petrol cars and LDVs, the proportion of NO_2 is quite low and does not vary greatly by emission standard. The efficiency of the three-way catalyst has led to a reduction in NO_x emissions over the consecutive Euro level vehicles, and at the same time has kept the proportion of NO_2 low (Pastramas *et al*., 2014). For diesel cars and LDVs the range of values is larger, and varies with emission standard and configuration of the emission-control technology (refer Table 1).

b. Nitrogen dioxide, nitric oxide emission factors and per cent nitrogen dioxide

The time series (2003-2041) of the NO_X and NO_2 emission factors for the main vehicle types and the associated per cent NO_2 values are shown for the 'highway/freeway' road category in Figure 9. These emission factors were calculated for a speed of 80 km/h, and for each vehicle type they take into account the age distribution of the fleet. The emission factors and projections do not assume adoption of Euro VI for HDVs.

Two features illustrated in Figure 9 are of particular relevance:

1. **The fraction of NO_2 in a tunnel is particularly sensitive to the proportion of diesel cars using the tunnel.**

   Diesel cars emit a much higher proportion of NO_x as NO_2 than petrol cars. This proportion increases significantly between 2003 and 2016 due to the uptake of Euro 4 vehicles. Oxidation catalysts were used to comply with the Euro 4 emission standards, and these can significantly increase the fraction of NO_2 in the exhaust by oxidising NO to NO_2. Uptake of Euro 5 and Euro 6 standards for diesel cars will see a small reduction in the fraction of NO_2 in the exhaust.

2. **The total amount of NO_2 emitted in a tunnel is particularly sensitive to the number of heavy goods vehicles using the tunnel.**

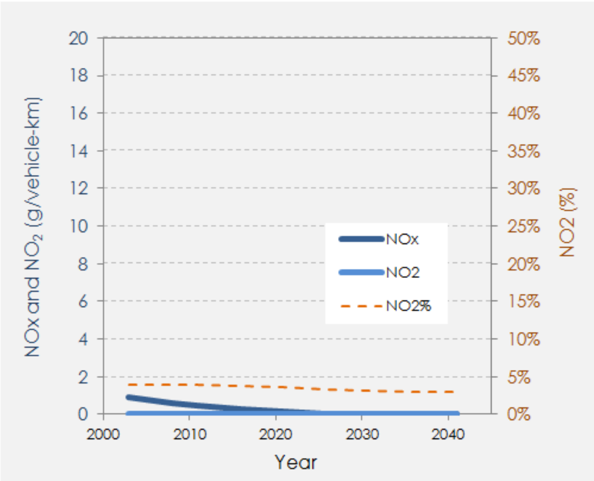
   Articulated heavy goods vehicles emit significantly more total NO_x and NO_2 per vehicle-km than any other vehicle type.

Figure 9

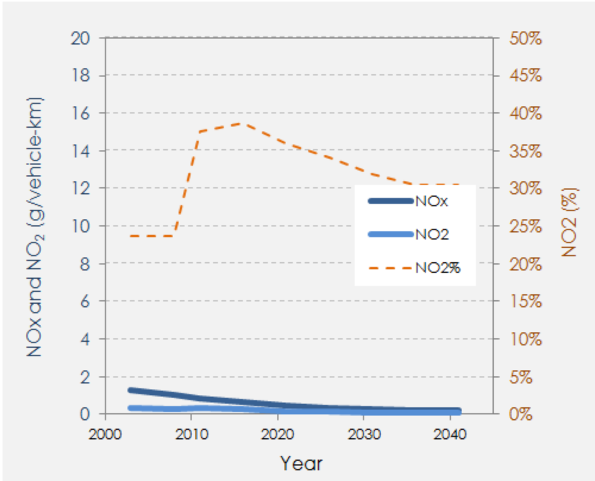
Emission factors for NO_x, NO_2 and per cent NO_2 from the GMR emissions inventory model.

The information relates to the driving conditions and fleet for highways/freeways.

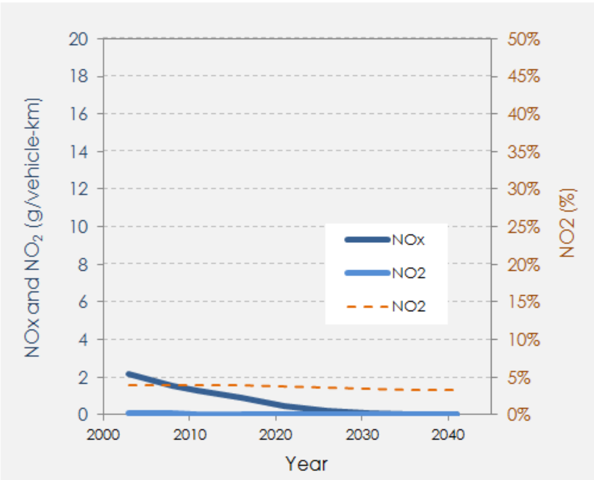
(a) Petrol car



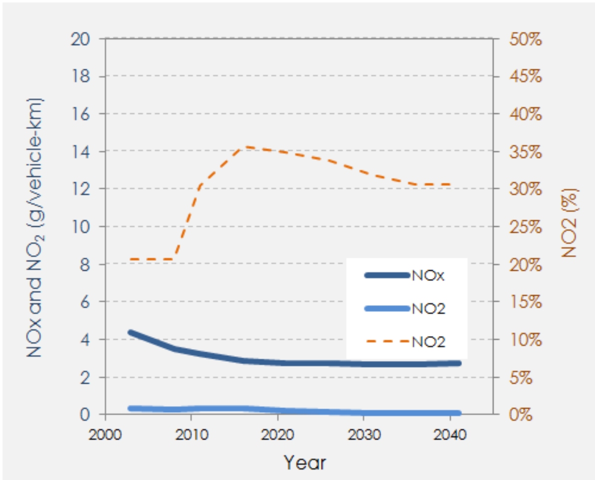
(b) Diesel car



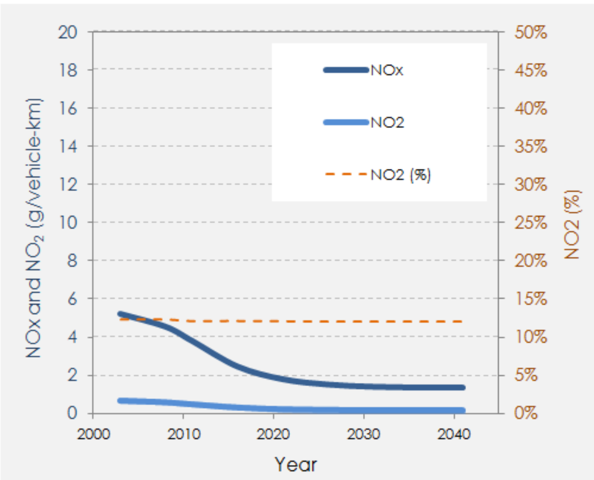
(c) Petrol LCV



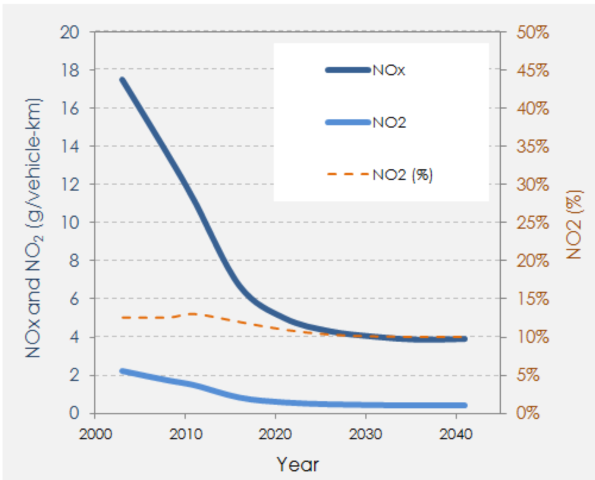
(d) Diesel LCV



(e) Rigid HGV (diesel)



(f) Articulated HGV (diesel)



The time series of the fleet average NO_X and NO_2 emission factors for the main vehicle types in Sydney, and the associated per cent NO_2, are shown for the 'highway/freeway' road category in Figure 10.

Figure 10
Fleet average emission factors for NO_x, NO_2 and per cent NO_2 from the GMR emissions inventory model.
The information relates to the driving conditions and fleet for highways/freeways.

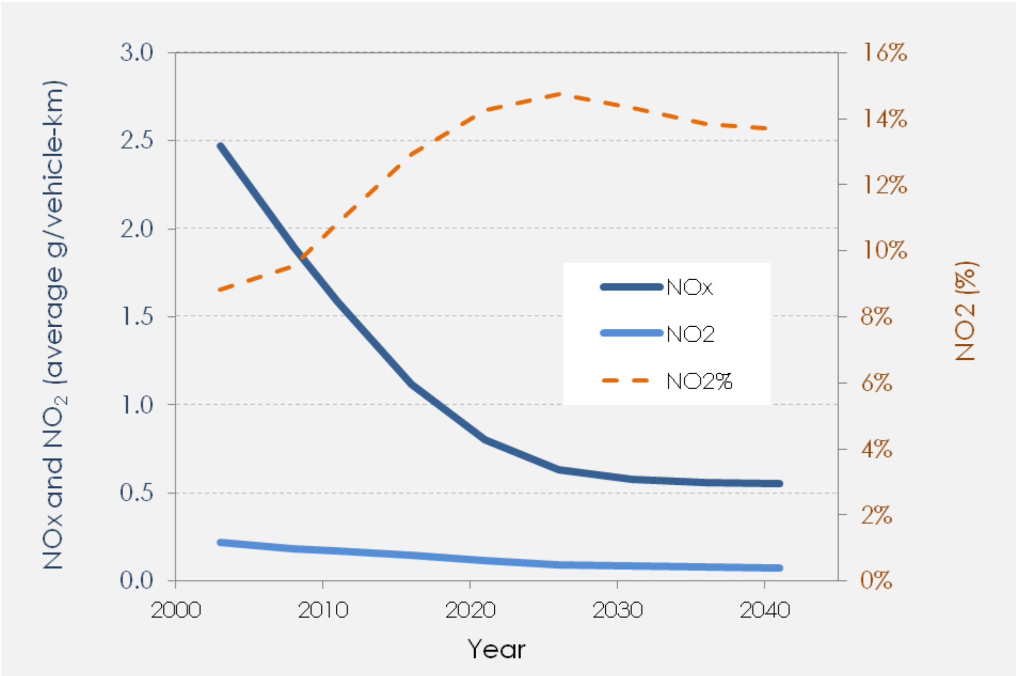


Figure 10 shows the effect of the increased per cent NO_2 in diesel car and diesel LCV emissions after 2008. The sensitivity of diesel car uptake on NO_2 emissions is examined in the next section.

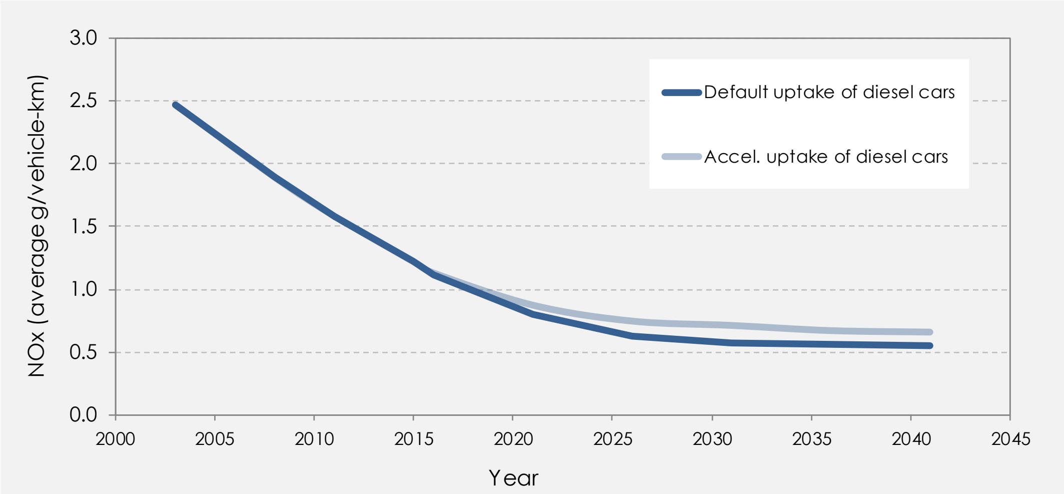
c. Effect of diesel car uptake on nitrogen dioxide emissions

The sensitivity to uptake of diesel cars has been examined by considering a hypothetical scenario where all passenger cars are diesel by 2030. Figure 11 compares emissions of NO_x, NO_2 and per cent NO_2 for the default uptake of diesel cars to the hypothetical scenario of all cars using diesel by 2030.

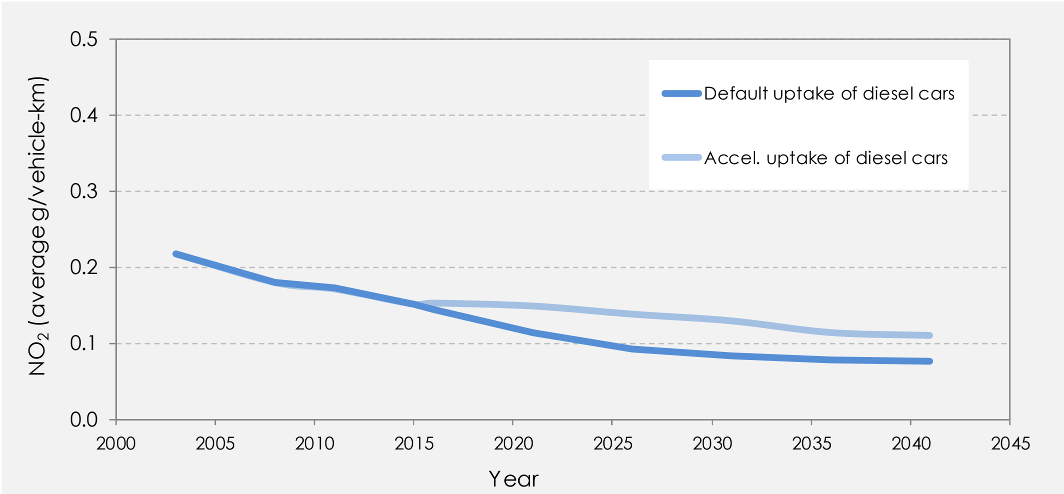
Figure 11
Sensitivity to diesel car uptake – all passenger cars diesel by 2030
Fleet average emission factors for NOx, NO_2 and per cent NO_2 from the GMR emissions inventory model.

The information relates to the driving conditions and fleet for highways/freeways.

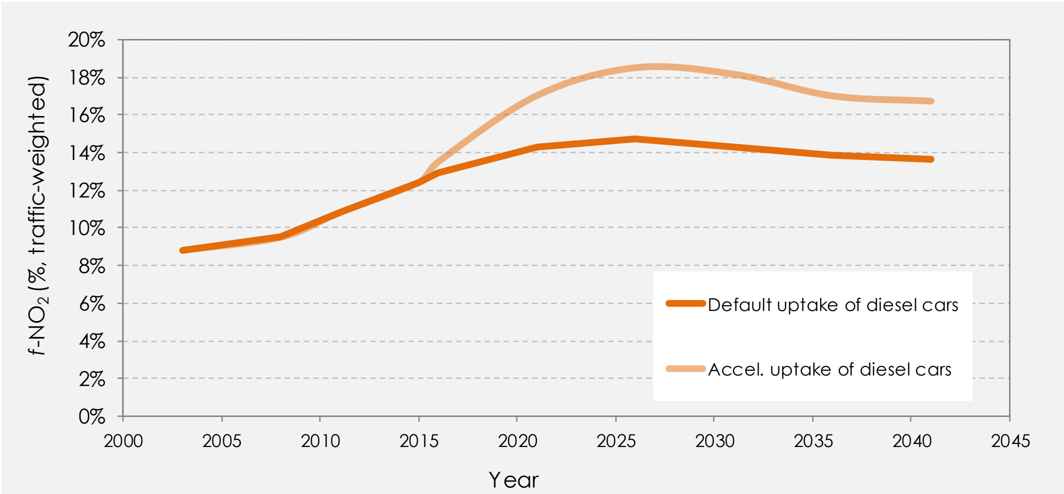
(a) NOx



(b) NO_2



(c) NO2%

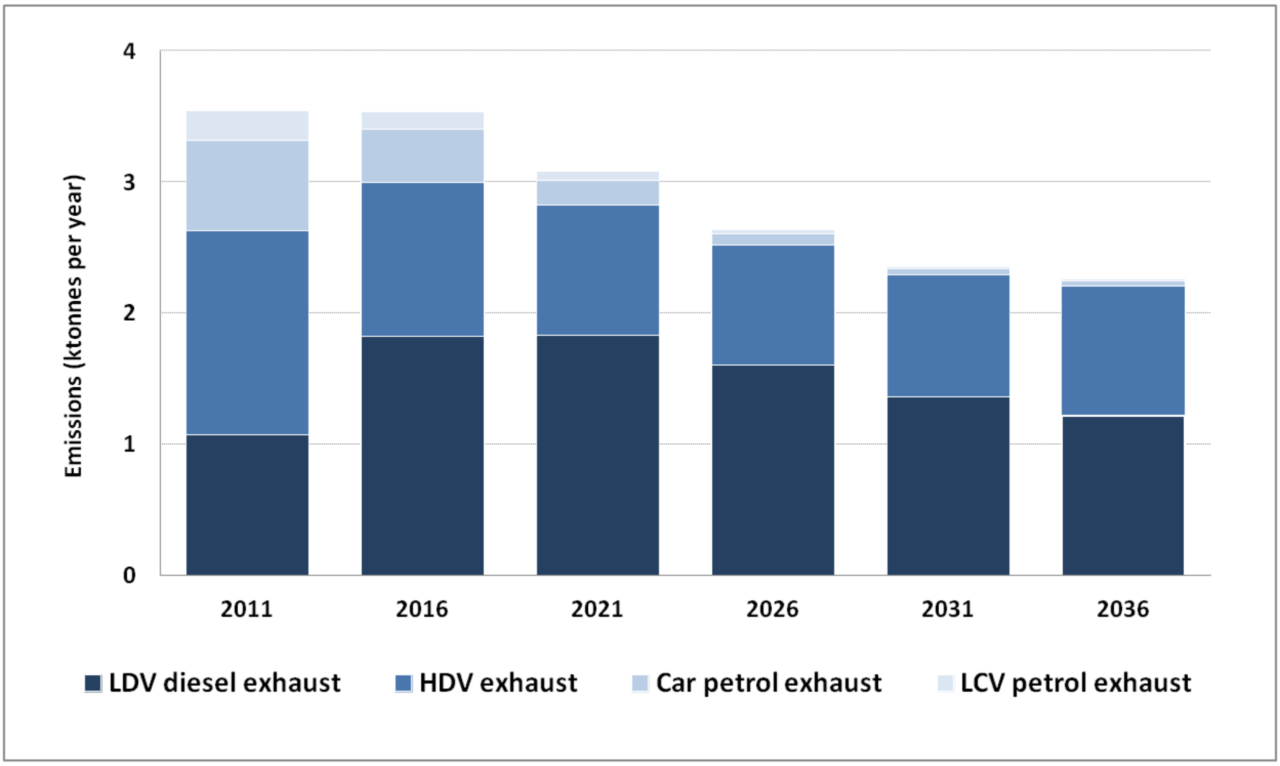


It can be seen that while emissions of total NO_x do not change significantly, an increased uptake of diesel passenger vehicles would slow the overall reduction in NO_2 emissions, and increase the maximum per cent NO_2 from around 14 per cent to 18 per cent.

d. Emissions of nitrogen dioxide from road transport in Sydney

Projections of total road transport NO_2 emissions in Sydney are presented by vehicle type in Figure 12.

Figure 12
Projections of road transport NO_2 emissions– Sydney, 2011-2036



Despite a continued increase in vehicle use, there is projected to be a continued reduction in NO_2 emissions from vehicles. However, the increasing proportion of passenger cars and light commercial vehicles using diesel is slowing the rate of reduction.

3. NITROGEN DIOXIDE HEALTH EFFECTS

3.1. Key Points

- NO_2 exposure has been associated with adverse health effects, with the strongest evidence for respiratory effects with exposure times of one hour or more.
- Evidence is limited, but chamber studies consistently find no adverse health effects for exposures less than 0.2 ppm over 20 to 30 minutes but some health effects in people with mild asthma at levels between 0.2 ppm and 0.5 ppm over 20 to 30 minutes.

3.2. Summary of literature review of in-tunnel nitrogen dioxide exposure

Technical Paper 2 is a literature review conducted by Professor Bin Jalaludin (Jalaludin, 2015) looking at the evidence of health effects from in-tunnel and short-term exposure to NO_2. Key findings from the study are summarised below.

NO_2 has been associated with adverse health effects, with the strongest evidence being for respiratory effects. It has not always been clear whether these effects are caused by NO_2 itself or by a pollutant with which it is correlated in ambient air. In recent years the evidence from epidemiological and experimental studies has found short term outcomes, particularly respiratory outcomes, which persist after adjustment for other air pollutants. This has led the World Health Organisation to conclude that NO_2 has direct effects on health (Jalaludin, 2015).

With regard to short-term exposures potentially applicable to road-tunnel transits in NSW, a review of the literature (Jalaludin, 2015) found:

- Four studies were identified that investigated health effects after exposure to ambient air in road tunnels.

  These studies found health effects using NO_2 as a marker at levels below 0.5 ppm for durations from 30 minutes to two hours. Current evidence suggests sensitive populations may experience health effects if exposed to tunnel air with an NO_2 concentration of 0.5ppm over 20 to 30 minutes.

- Eighteen chamber studies were identified that investigated the health effects of NO_2 exposures of less than 30 minutes.

  At concentrations between 0.2 ppm and 0.5 ppm for 20 to 30 minutes there were some health effects in susceptible groups. For concentrations above 0.5 ppm for the same time periods health effects were seen in susceptible groups and for healthy participants.

  For short-term (≤30 minutes) exposures to low levels of NO_2 (≤0.5ppm), the strongest evidence is for effects on airway responsiveness. These effects are generally seen in asthmatics, and the effects are small and transient.

  At concentrations lower than 0.2 ppm no health effects were observed in chamber studies.

Owing to ethical considerations the studies that demonstrate health effects have generally been on participants with mild asthma. There are gaps in the literature regarding the potential health effects on more sensitive populations, such as people with more severe asthma. Therefore it is prudent to take a precautionary approach in evaluating the literature.

4. IN-TUNNEL NITROGEN DIOXIDE CONCENTRATIONS AND EXPOSURES

4.1. Key Points

- Average in-tunnel NO_2 concentrations in 2015 were found to range from 0.15 ppm for the Eastern Distributor to 0.37 ppm for the M5 East. Tunnel average NO_2 concentrations for the M5 East were found to reach 0.5 ppm.

- Modern cars with air vents set to recirculate can result in significantly lower in-cabin NO_2 levels than in-tunnel levels.

- A study conducted in Sydney motorway tunnels found that switching vehicle ventilation systems to recirculate results in
    - average in-cabin NO_2 concentrations of less than 0.04 ppm for all tunnels
    - in-cabin levels at least 70 per cent less than in-tunnel levels. Levels in newer vehicles were typically 90 per cent less than in-tunnel levels.

- For a given traffic volume and mix, in-tunnel NO_2 concentrations are likely to decrease into the future as fleet average NO_2 emissions decrease. This decrease is predicted to occur, albeit at a reduced rate, even if all petrol passenger vehicles were replaced by diesel.

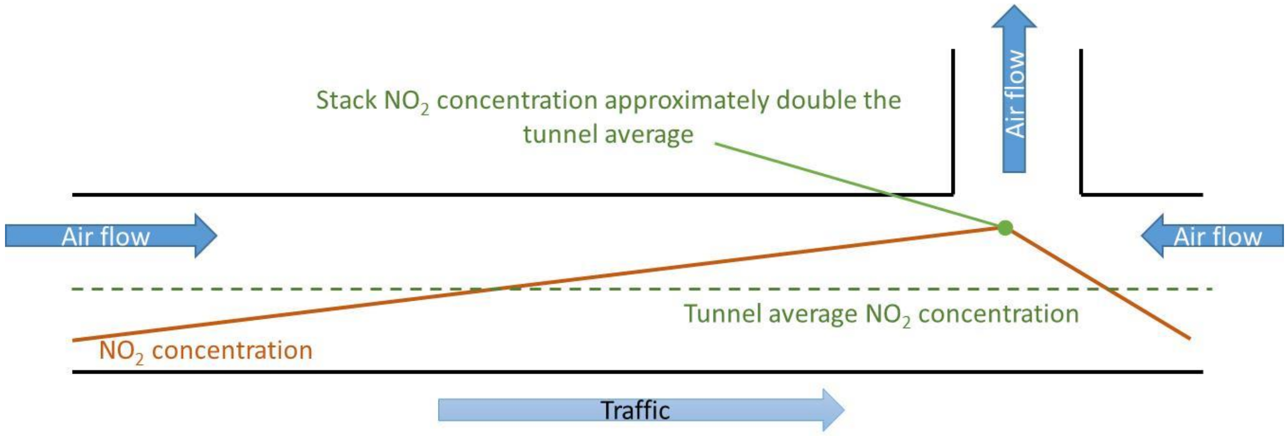
4.2. In-tunnel nitrogen dioxide concentrations in New South Wales

a. Current in-tunnel NO_2 concentrations

Pollutant concentrations are routinely monitored in Sydney road tunnels to manage ventilation systems. Monitoring methods for CO and visibility are well established. Monitoring in-tunnel NO_2 levels is a more complex task than monitoring CO or visibility, and techniques for reliably monitoring in-tunnel NO_2 levels are still being developed worldwide.

The best available data set to characterise tunnel average NO_2 levels is from the Lane Cove tunnel stack. NO_2 concentrations are measured continuously at the stacks, and due to the simple tunnel geometry and ventilation design, stack NO_2 concentrations are approximately double the tunnel average concentration (Figure 13).

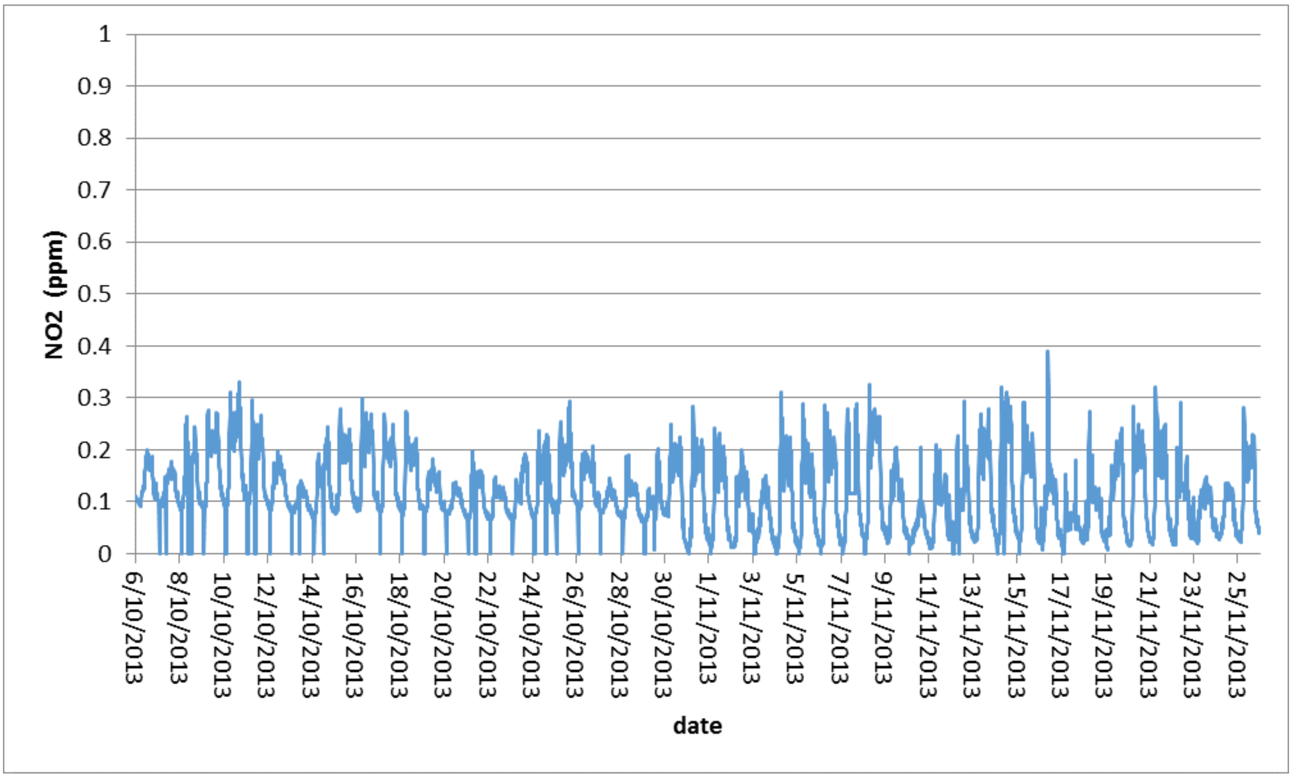
Figure 13
Schematic representation of relationship between tunnel average and stack concentration in the Lane Cove tunnel



Lane Cove Tunnel eastbound concentrations are significantly higher than the westbound concentrations. This is due to the eastbound direction being uphill, with vehicles travelling westbound under significantly lower load, with correspondingly reduced emissions.

Lane Cove Tunnel eastbound 15-minute NO_2 concentrations for October and November 2013 are shown in Figure 14. It can be seen that the maximum 15-minute average concentration was typically around 0.3 ppm, and was always below 0.4 ppm. This translates to a maximum tunnel average NO_2 concentration of typically 0.15 ppm, and always less than 0.2 ppm.

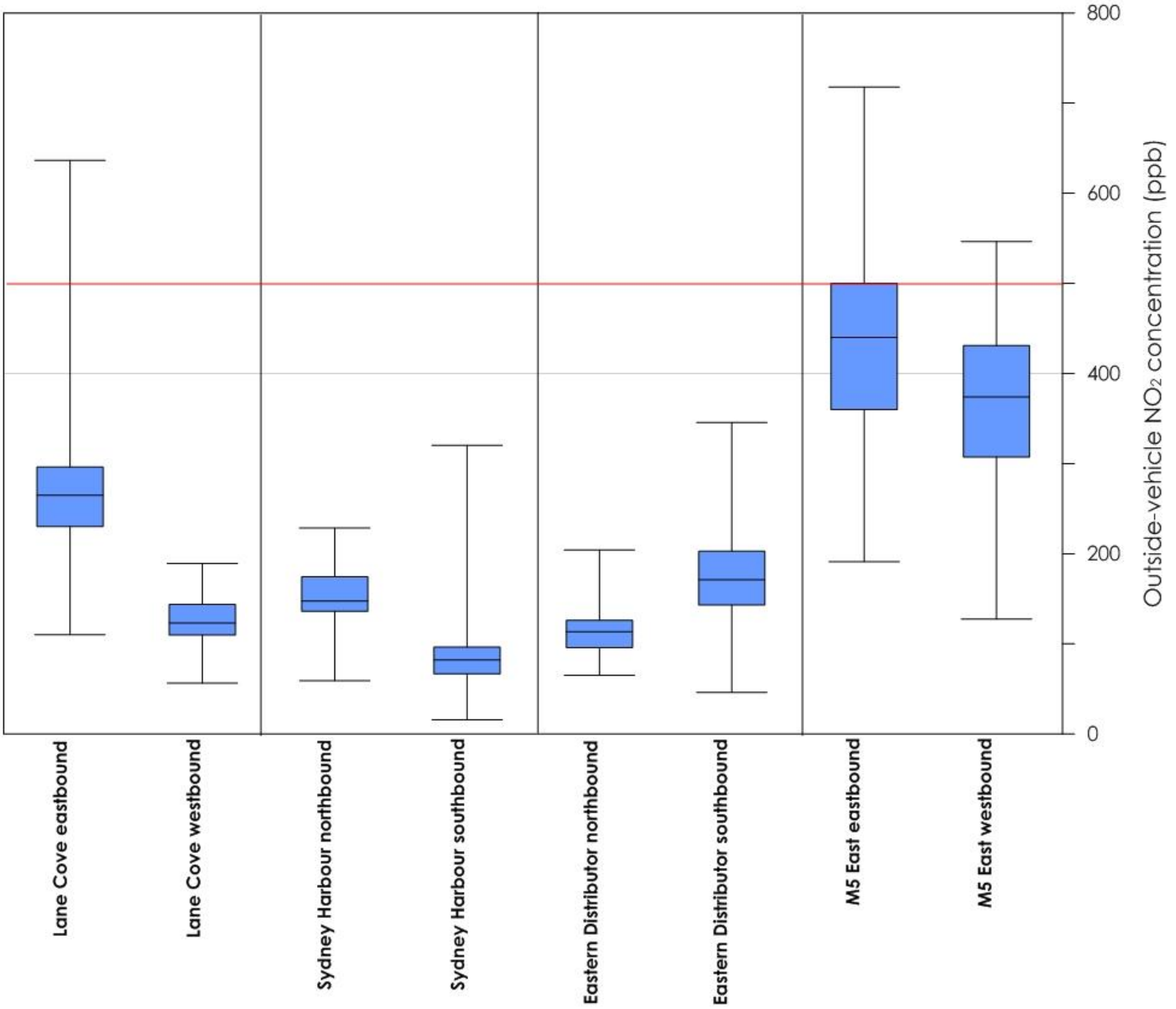
Figure 14
Lane Cove Tunnel Eastbound 15-minute Average NO_2 Concentrations



Technical Paper 3 is a study entitled *Road tunnels: Reductions in nitrogen dioxide (NO_2) concentrations in-cabin using vehicle ventilation systems* conducted by Pacific Environment (Pacific Environment, 2015b). The study involved an extensive monitoring campaign aimed at obtaining detailed measurements of NO_2 concentrations both inside and outside of cars being driven through road tunnels in Sydney.

Average in-tunnel NO_2 concentrations measured during tunnel transits were 0.2, 0.16, 0.15 and 0.37 ppm for the Lane Cove, Sydney Harbour, Eastern Distributor and M5 East tunnels respectively. Figure 15 is a box and whisker plot presenting measured trip average in-tunnel NO_2 concentrations during the study. Brief guidance on understanding and interpreting box and whisker plots is provided in Appendix A.

Figure 15
Comparison of trip average NO_2 concentrations measured within four major tunnels

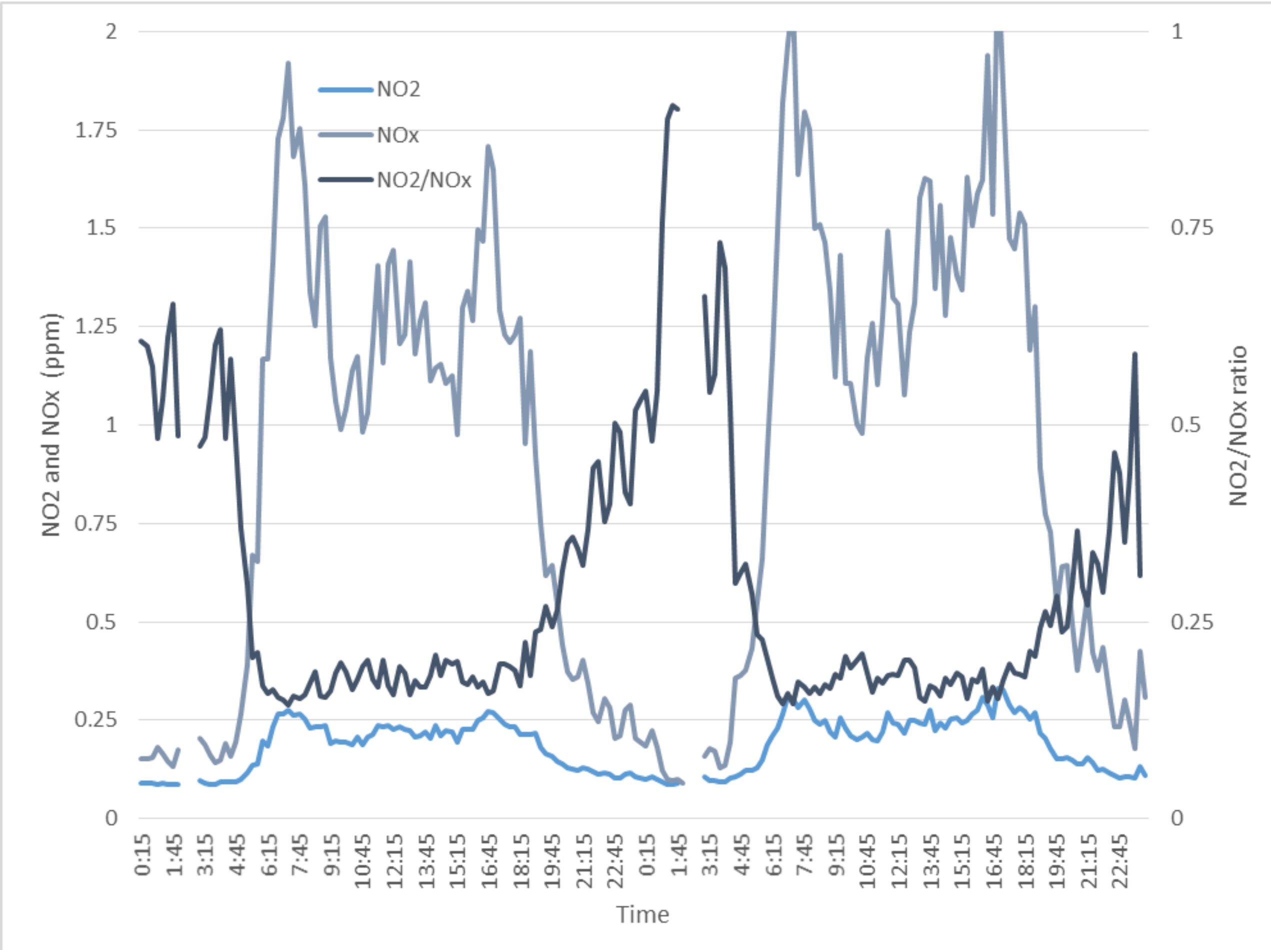


b. Current in-tunnel NO_2/ NO_x ratios

In-tunnel NO_2/NO_x ratios exhibit a strong daily pattern as shown below in Figure 16. This figure presents 15-minute average NO_2 and NO_x concentrations and NO_2/NO_x ratios for 2 days on the 9 and 10 October 2013 for the Lane Cove Tunnel eastbound. Key features of the figure are low NO_X and NO_2 concentrations at night (7 pm to 6 am), with higher NO_2 concentrations and significantly higher NO_x concentrations during the day. The NO_2/NO_x ratios are higher at night when the NO_x concentrations are low. This is because at night-time, NO_x concentrations and NO_2/NO_x in the tunnel are predominately influenced by the external ventilation supply, not the relatively low vehicle emissions. Observed NO_2/NO_x ratios in Sydney are high when the NO_x concentration is low.

During the day, the NO_2/NO_x ratios are significantly lower, and relatively constant between the hours of 7 am and 5 pm.

Figure 16
Lane Cove Tunnel Eastbound 15-minute average NO_2 and NO_x concentrations and NO_2/NO_x Ratios
9th and 10th October 2013



The NO_2/NO_x ratios of most significance are those during the day when NO_x (and NO_2) concentrations are highest. Figure 17 presents 15-minute average NO_2 and NO_x concentrations and NO_2/NO_x ratios from 7 am to 5 pm in October and November 2013 for the Lane Cove Tunnel eastbound.

Figure 17
Lane Cove Tunnel Eastbound 15-minute average NO_2 and NO_x concentrations and NO_2/NO_x Ratios 7 am to 5 pm October and November 2013

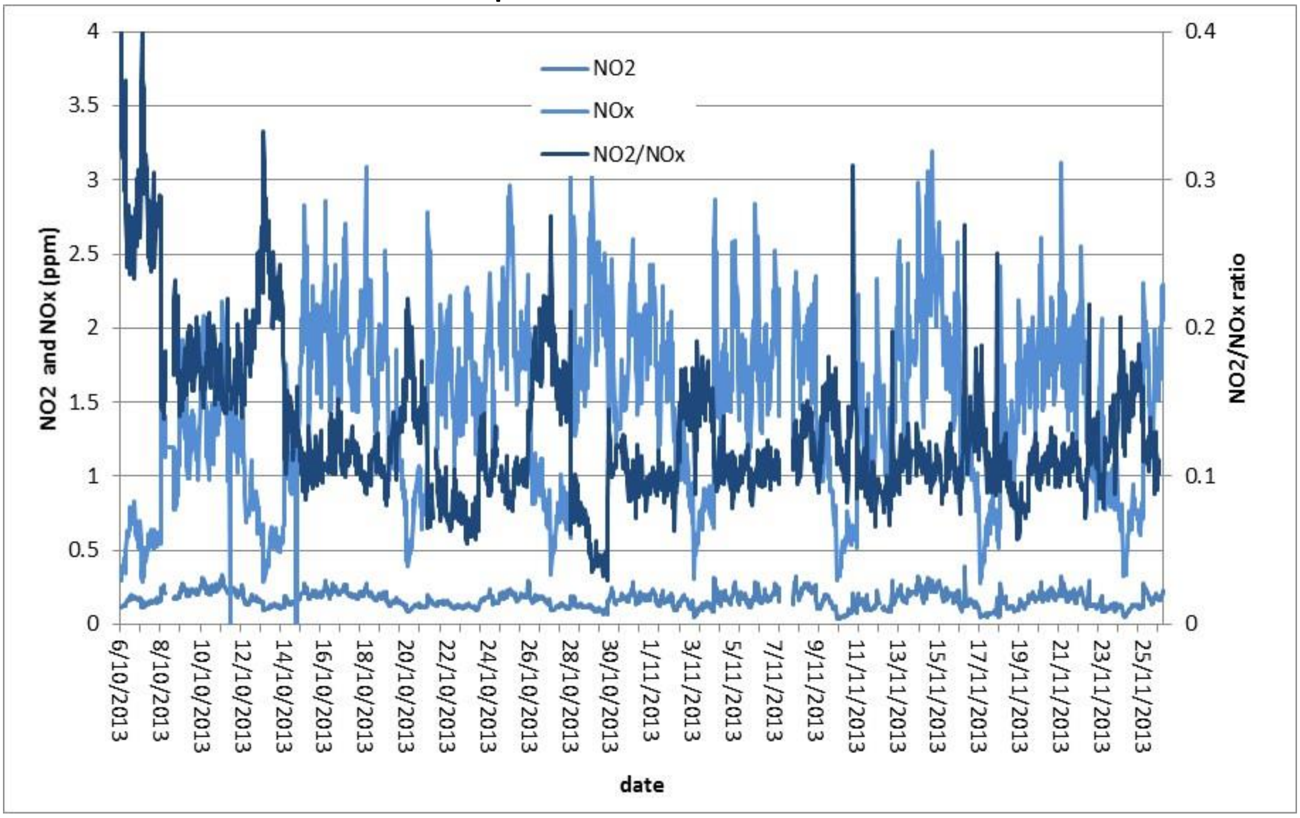


Figure 16 shows that even during the day, although range is reduced, there is still substantial variability in the observed NO_2/NO_x ratio. The calculated fleet average NO_2/NO_x ratio of 14 per cent sits within the observed variation in the Lane Cove Tunnel eastbound. It should be noted that the fleet average emission factors do not take into account grade, and use the fleet average vehicle mix. It is to be expected that there will be a difference when comparing fleet average emissions to the specific situation of the Lane Cove Tunnel Eastbound – due to it being up-hill and having a different traffic mix than the fleet average.

c. Future in-tunnel NO_2 Concentrations

During the day in-tunnel NO_2/NO_x ratios and NO_2 concentrations reflect tailpipe conditions. Figure 11 showed that for the fleet average:

- NO_x emissions are predicted to decrease
- NO_2/NO_x ratio is predicted to increase to a maximum of around 14% for the expected uptake of diesel passenger cars, with a maximum of around 18% assuming a worst case 100 per cent uptake of diesel passenger cars.
- Total NO_2 emissions are predicted to decrease even assuming a worst case 100 per cent uptake of diesel passenger cars.

This indicates that for a given traffic volume, in-tunnel NO_2 concentrations are expected to decrease into the future.

4.3. Length of tunnels and time spent in tunnels in Sydney

Any fully enclosed length of roadway may be called a road tunnel but there is general agreement that a structure less than 80 m long is not a tunnel.

Table 2 presents the lengths of existing and approved tunnels in Sydney, as well as the time spent in the tunnel for travel speeds of 80 km/hr, 60 km/hr and 40 km/hr.

Table 2
Sydney Road Tunnels

Road Tunnel	Length (km)	Travel time (min) 80 km/hr	60 km/hr	40 km/hr
NorthConnex	9.0	6.8	9.0	13.5
M5 East	4.0	3.0	4.0	6.0
Lane Cove	3.6	2.7	3.6	5.4
Sydney Harbour	2.2	1.7	2.2	3.3
Cross City	2.1	1.6	2.1	3.2
Eastern Distributor	1.7	1.3	1.7	2.6
Dacey Todman (ED)	0.6	0.5	0.6	0.9
Cooks River Crossing (M5 East)	0.6	0.4	0.6	0.8
Mascot (Airport)	0.6	0.4	0.6	0.8
King's Cross	0.5	0.4	0.5	0.8
Norfolk (M2)	0.5	0.3	0.5	0.7
Domain (Cahill Expressway)	0.4	0.3	0.4	0.6

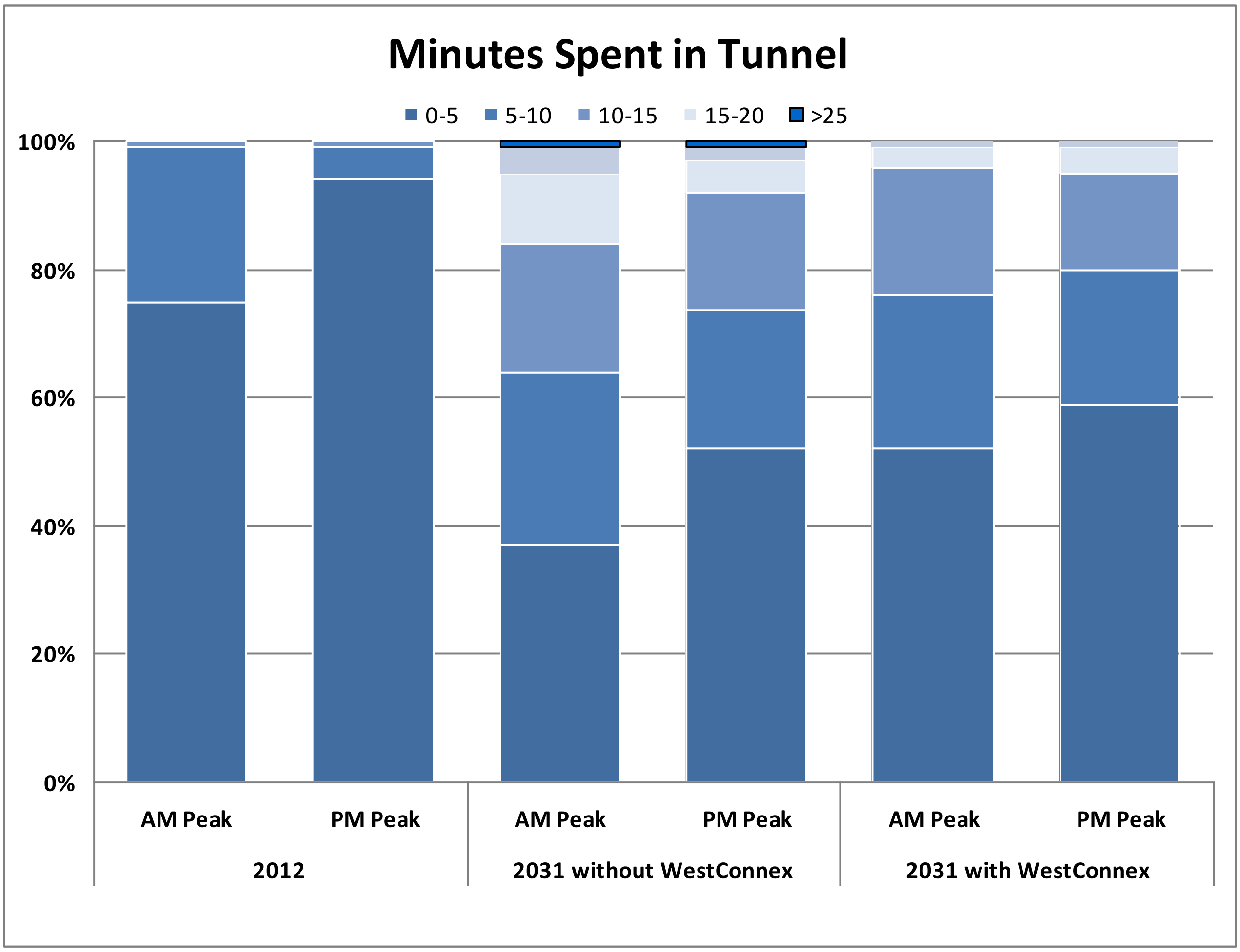
Traffic modelling presented in the 2015 WestConnex Strategic Environmental Review assessed potential changes to the length of time motorists would be expected to spend in a tunnel. Table 3 and Figure 18 below present the outcomes of this preliminary assessment for conditions in 2012, and with and without WestConnex in 2031.

Table 3
Time Spent in Road Tunnels in the Sydney Road Network

Minutes spent in tunnel	2012		2031 without WestConnex		2031 with WestConnex	
	AM Peak	PM Peak	AM Peak	PM Peak	AM Peak	PM Peak
	Per Cent of Time					
0-5	75	94	37	53	52	59
5-10	24	5	27	22	24	21
10-15	1	1	20	19	20	15
15-20	0	0	11	5	3	4
20-25	0	0	4	2	1	1
>25	0	0	1	1	0	0

Notes: Table is based on single trips where use of a tunnel is involved. A zero percentage excludes incidents in the tunnel. Modelling was undertaken for only the AM and PM peak periods and only calculates an average value for motorists travelling through multiple tunnels in a single journey.

Figure 18
Time Spent in Road Tunnels in the Sydney Road Network



The modelling predicts that by 2031 without WestConnex:

- Motorists are expected to significantly increase their time spent in a tunnel environment – with the proportion of vehicles spending 10 or more minutes in any one trip increasing from 1 per cent to around 36 per cent in the AM peak and 24 per cent in the PM peak.
- Between 8 and 10 per cent of motorists in tunnels would spend more than 15 minutes in a tunnel environment in any one trip.

The modelling predicts that by 2031 with WestConnex:

- The proportion spending more than 10 minutes would decline from 36 per cent to 24 per cent in the AM peak and from 27 per cent to 20 percent in the PM peak compared to the 'without WestConnex' scenario.

This is because with WestConnex would reduce congestion leading to better traffic flow through tunnels across the Sydney Network and therefore motorists would spend less time in tunnels.

4.4. In-cabin NO_2 concentrations

Technical Paper 3 is a study entitled *Road tunnels: Reductions in nitrogen dioxide (NO_2) concentrations in-cabin using vehicle ventilation systems* conducted by Pacific Environment (Pacific Environment, 2015b). The study involved an extensive monitoring campaign aimed at obtaining detailed measurements of NO_2 concentrations both inside and outside of cars being driven through road tunnels in Sydney.

Nine different vehicles were driven on multiple transits through the Lane Cove, Sydney Harbour, Eastern Distributor and M5 East tunnels. Both external (in-tunnel) and internal (in-cabin) NO_2 concentrations were measured during the transits.

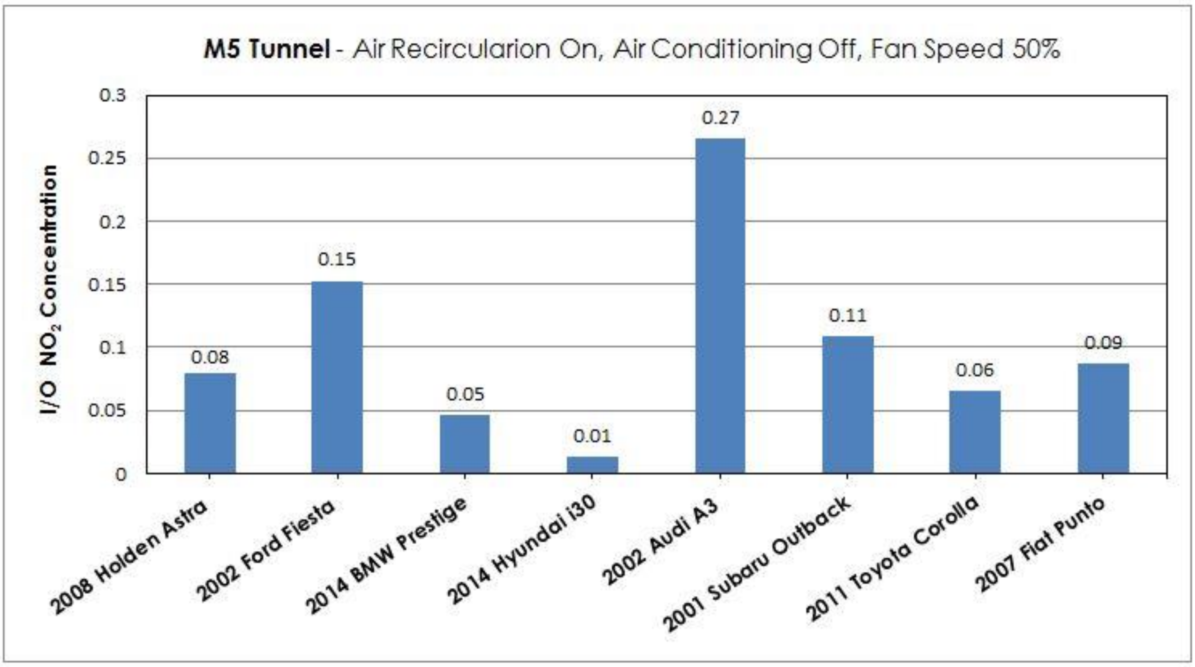
The results show that when recirculation settings are utilised, a significantly lower NO_2 concentration is experienced within the vehicle compared to external NO_2 concentrations.

Average in-tunnel NO_2 concentrations measured during tunnel transits were 0.2, 0.16, 0.15 and 0.37 ppm for the Lane Cove, Sydney Harbour, Eastern Distributor and M5 East tunnels respectively.

By winding the windows up and setting the vehicle ventilation system to recirculate, average in-vehicle NO_2 concentrations were reduced to less than 0.04 ppm for all tunnels.

Figure 19 presents the reduction achieved in cabin compared to the in-tunnel concentration in the M5 East by setting the ventilation settings to re-circulate.

Figure 19
Comparison of I/O ratio for each vehicle in the M5 East tunnel (both directions)



The reductions achieved by switching the ventilation settings to re-circulate ranged from 73 per cent in the 2002 Audi A3 (which had visibly degraded door seals), to 99 per cent for the 2014 Hyundai i30.

5. AMBIENT AND ROADSIDE NITROGEN DIOXIDE CONCENTRATIONS

5.1. Key Points

- Ambient NO_2 concentrations at both OEH sites and peak roadside sites are well below national and international standards.

5.2. Exposure times and averaging periods

The health effects of an individual air pollutant are a function of both the concentration and the time exposed. If you decrease the exposure time, a higher concentration is generally required to elicit the same health effect. This is commonly reflected in air quality standards, with standards for shorter averaging times (such as 1-hour average) being higher than for standards with longer averaging times (such as annual average).

When comparing air quality standards and monitoring data, it is important to keep in mind averaging times. Standards and monitoring data with similar averaging times are not identical. For an identical concentration, a shorter averaging time is more stringent than a longer averaging time. For example, a standard with a 60 minute average time is not as stringent as a 15-minute average standard with the same concentration. The smaller the difference between the averaging periods the less significant the difference.

5.3. Ambient nitrogen dioxide concentrations in New South Wales

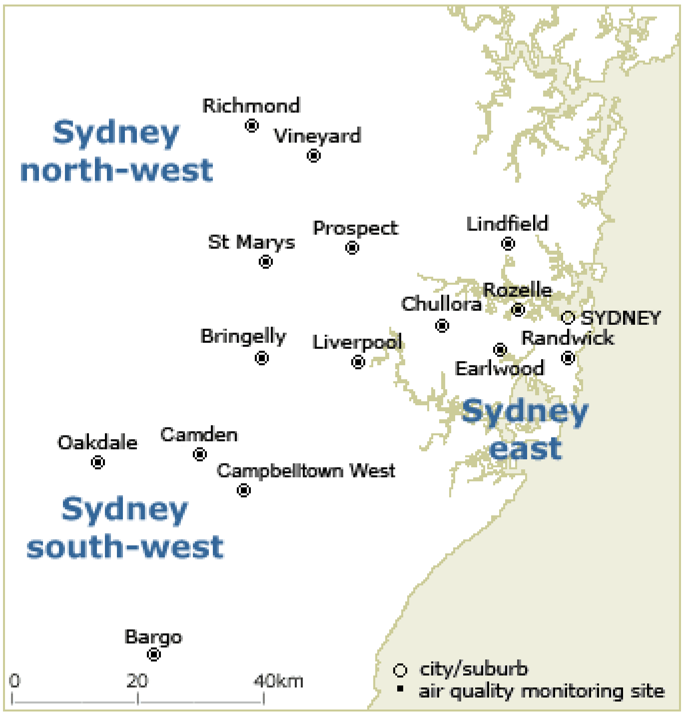
The National Environment Protection (Ambient Air Quality) Measure ('AAQ NEPM') establishes national standards for air pollutants (NEPC, 2003). The AAQ NEPM standards were set based on scientific studies of air quality and human health, with Australian conditions taken into account in estimating likely exposures. The AAQ NEPM standard for NO_2 was set in 1998. Standards for NO_2 around the world are becoming more stringent. Work has commenced on a review of the AAQ NEPM NO_2 goal. Table 4 below compares the AAQ NEPM standards, the World Health Organisation goal, European Union Standards, and the United States standards. Standards from different jurisdictions are not directly comparable due to differences in implementation and monitoring requirements. Comparisons are indicative only.

Table 4
Ambient Air Quality Goals for Nitrogen Dioxide

Jurisdiction	Averaging period	Goal/standard (ppm)	Date set
Australia	1-hour	0.12	1998
	Annual	0.03	
WHO	1-hour	0.1	2005
	Annual	0.02	
European Union	1-hour	0.1	2010
	Annual	0.02	
US	1-hour	0.1	2010
	Annual	0.053	1996

The Office of Environment and Heritage (OEH) operates 15 air quality monitoring stations in the Sydney Region shown in Figure 20.

Figure 20
OEH Air Quality Monitoring Network



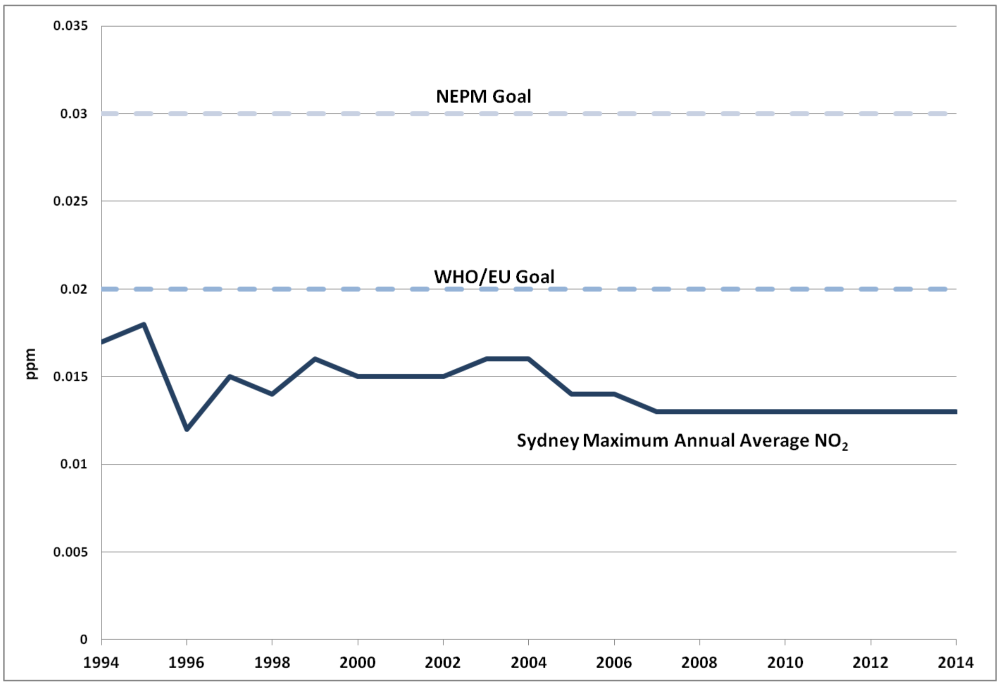
Ambient NO_2 concentrations measured at OEH sites in Sydney have been low for the last 10 years, with maximum recorded 1-hour average concentrations in Sydney typically around half the national standard of 0.12 ppm, and maximum annual concentrations typically slightly less than half the national standard of 0.03 ppm.

Figure 21 shows the maximum 1-hour NO_2 level recorded at any OEH site in a calendar year from 1994-2014 and compares this to both the national standard (NEPM) and the European Union/World Health Organisation goals (EU/WHO).

Figure 21
Sydney Maximum 1-hr average NO_2

Figure 22 shows the maximum annual NO_2 level recorded at any OEH site in a calendar year from 1994-2014 and compares this to both the national standard (NEPM) and the European union/World Health organisation goals (EU/WHO).

Figure 22
Sydney Maximum annual average NO_2

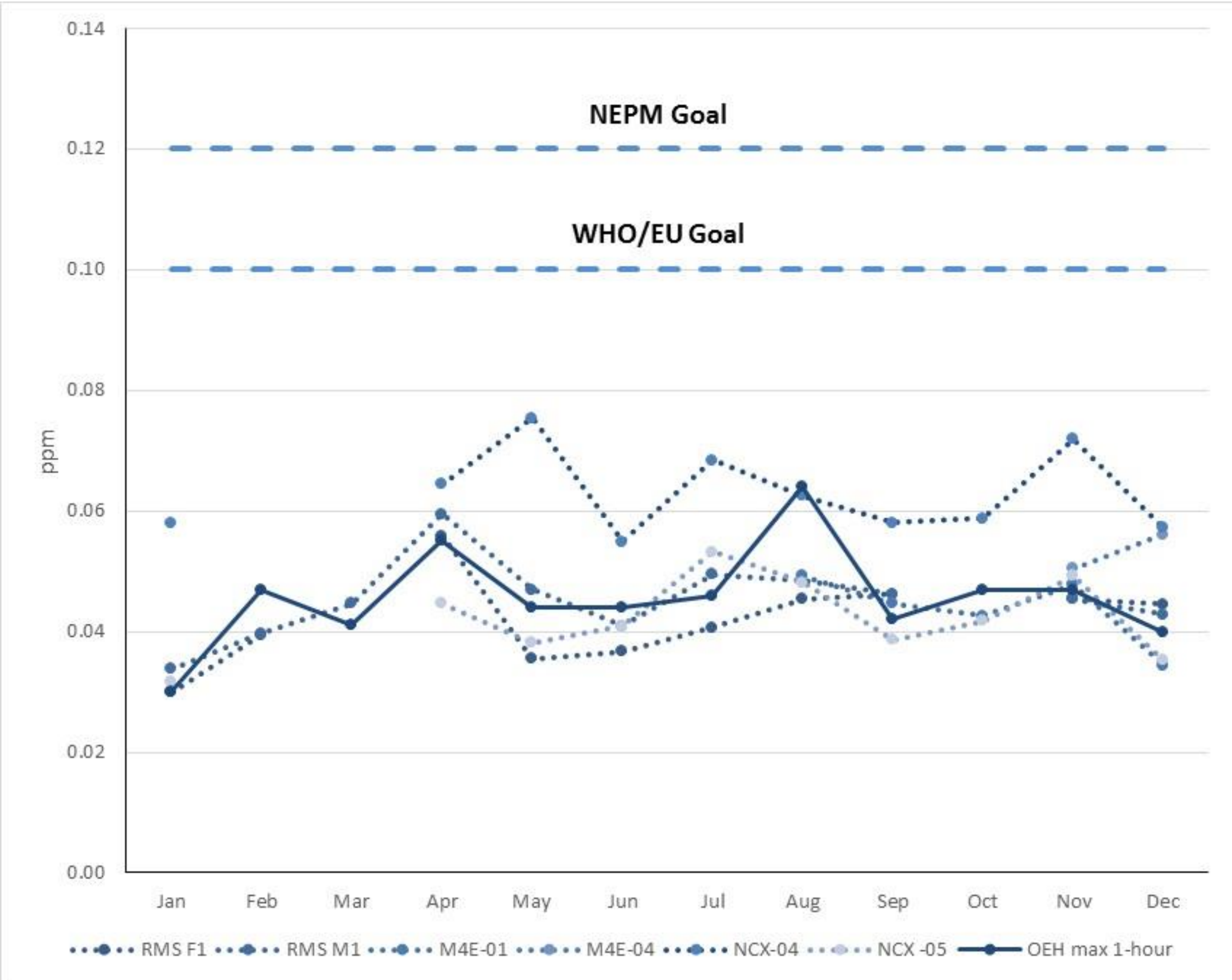


5.4. Roadside nitrogen dioxide concentrations in New South Wales

Ambient NO_2 concentrations have recently been measured at six roadside sites in Sydney. The locations of the roadside sites are presented in Appendix B. Figure 23 presents the maximum 1-hour NO_2 level recorded in each month at the five roadside sites as well as the maximum 1-hour NO_2 level recorded in each month at any OEH site in 2014, and compares these to both the national standard (NEPM) and the European union/World Health organisation goals (EU/WHO).

It can be seen that all results are well below both the EU/WHO and NEPM goals, and that most roadside sites record maximum monthly values similar to the maximum recorded in Sydney at the OEH sites. The only site that consistently recorded higher values was NCX-04 which was located in Observatory Park on the corner of Beecroft and Pennant Hills roads.

Figure 23
Maximum Monthly 1-hr average NO_2
Roadside and OEH Sydney Maximums 2014



6. POLICY CONTEXT

6.1. Key Points

- A tunnel average criteria of 0.5 ppm as a rolling 15-minute average compares favourably to the international in-tunnel NO_2 guidelines which range between 0.4 ppm and 1.0 ppm.

6.2. Ambient air quality standards

International ambient air quality standards for NO_2 are for 1-hour average and annual average exposures, and were developed based on health information for exposure times of 1-hour or greater. Exposure times in tunnels are short – typically less than 30 minutes. Hence, ambient air quality standards – and the health information used in their development – are not directly applicable to the in-tunnel environment.

The exception is CO where the health effects of short-term 15-minute exposures are well understood, and the WHO set a 15-minute and 30-minute ambient air quality goal for carbon monoxide (CO), which have been widely adopted as an in-tunnel criteria.

6.3. Workplace Health and Safety Standards

Workplace health and safety standards are based on the airborne concentrations of individual substances which, according to current knowledge, should not cause adverse health effects nor cause undue discomfort to nearly all workers. They do not account for particularly sensitive sub-groups such as the young, the elderly or those with pre-existing conditions. Nevertheless they can provide an upper bound when there are limited standards for the general population. Of particular relevance for in-tunnel exposures is that workplace health and safety standards set Short Term Exposure Limits (STELS) for NO_2. STELs are the time weighted average concentration of a substance that is permitted over a 15 minute period (Safe Work Australia, 2012), which is a time period comparable to typical in-tunnel exposures.

a. Scientific Committee for Occupational Exposure Limits to Chemical Agents

A recent review of NO_2 workplace health and safety limit values was conducted by the Scientific Committee for Occupational Exposure Limits to Chemical Agents (SCOEL). The SCOEL consists of 21 independent scientific experts and makes recommendations to the European Commission. The SCOEL assesses the most recent scientific data available for the identification of critical health effects and produces a recommendation document for consultation. In June 2014, the European Commission published the *Recommendation from the Scientific Committee on Occupational Exposure Limits for Nitrogen Dioxide*.

The SCOEL recommended an 8-hour time weighted average limit for NO_2 of 0.5 ppm as providing protection for healthy working adults. This recommendation was derived primarily from human data. The SCOEL noted there was no information available on effects of low concentrations of NO_2 at workplaces in asthmatics. The SCOEL recommended a 15 minute average short term exposure limit of 1 ppm.

b. International Workplace Health and Safety Short Term Exposure Limit Values

An overview of international 15 minute average short term exposure limit values (STELs) is available at http://limitvalue.ifa.dguv.de, and they range from 0.5 ppm to 6 ppm as a 15-minute time weighted average.

6.4. International in-tunnel nitrogen dioxide criteria

Globally, the most widely adopted in-tunnel exposure limits are for CO. This choice is supported by CO being the only traffic-dominated air pollutant for which WHO Guidelines exist for exposure durations relevant to passage through a road tunnel (typically a few minutes). NSW has adopted the WHO CO Guidelines as compliance criteria since the Eastern Distributor tunnel in 1999.

In the past a CO guideline has been used because of the serious short-term health effects (including dizziness, loss of consciousness and death) and it was assumed this guideline also provided adequate protection for the full range of constituents of road traffic air emissions. However, emissions of NO_2 have increased in relative importance due to:

- Emission standards for CO from new petrol cars reducing much more than emission standards for NO_x (until the introduction of Euro 3 in 2006 which significantly reduce NO_x emissions).
- The increasing penetration of diesel cars. Diesel cars emit significantly more NO_2 and less CO than petrol cars.

Consequently, there is relatively more NO_2 compared with CO in tunnel air than was previously the case, therefore the CO guideline may no longer be sufficient to manage for health effects of NO_2.

However, although the effects of short-term exposure to CO are well understood, there is limited available health information on which to develop an in-tunnel NO_2 standard. Different authorities have applied different levels and different exposure times, reflecting scientific uncertainties and different precautionary stances.

Table 5
In-tunnel NO_2 Criteria

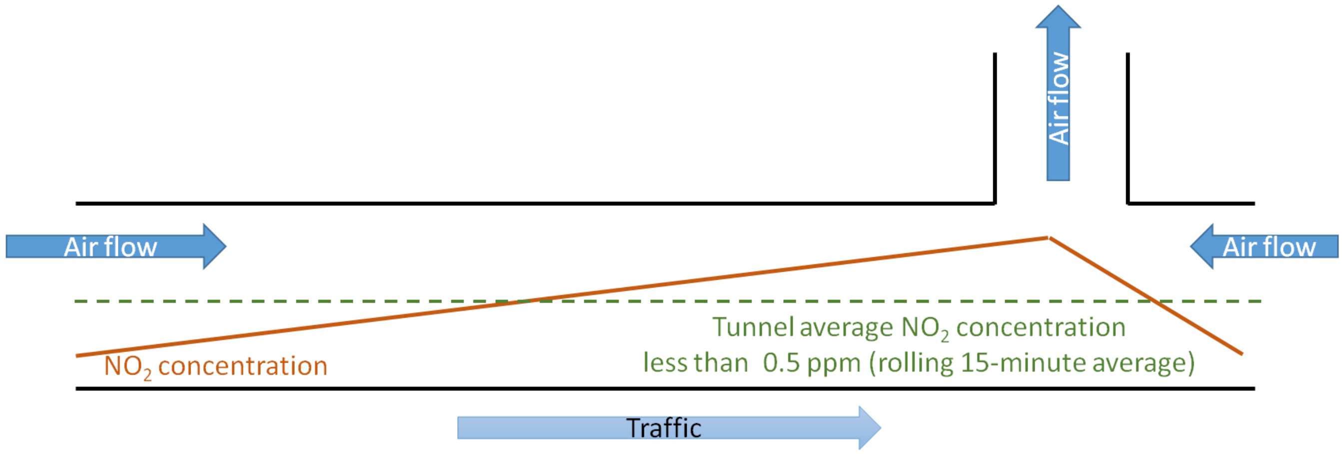
Jurisdiction/Project	In-tunnel NO_2 criteria	Design or Compliance	Averaging Period
NSW/NorthConnex[1]	0.5 ppm tunnel average	Design and Compliance	15 minute
Brisbane City Council/Clem 7 (2007)/ LegacyWay (2010) tunnels[2]	1 ppm average	Design and Compliance	None given
PIARC[3]	1 ppm tunnel average	Design only	None given
New Zealand[4]	1 ppm	Design only	15- minute
Hong Kong[5]	1 ppm	Design only	5 -minute
Norway[6]	0.75 ppm tunnel midpoint (equivalent to tunnel average)	Design and compliance	15-minute
France[7]	0.4 ppm	Design	15-minute

[1] https://majorprojects.affinitylive.com/public/163aa1c9b211c5d126fef2468a30e597/Instrument%20of%20Approval.pdf
[2] http://www.dlg.qld.gov.au/assessments-and-approvals/clem-jones-tunnel-formerly-north-south-bypass-tunnel.html
[3] http://www.piarc.org/en/order-library/16636-en-Road%20tunnels:%20vehicle%20emissions%20and%20air%20demand%20for%20ventilation.htm
[4] http://www.nzta.govt.nz/resources/guide-to-road-tunnels/
[5] http://www.epd.gov.hk/epd/english/envir_standards/files/asgn1e.pdf
[6] http://www.vegvesen.no/_attachment/61416/binary/14123?fast_title=Manual+021E++Road+Tunnels.pdf
[7] http://www.cetu.developpement-durable.gouv.fr/IMG/pdf/CETU_DocInfo_Air_treatment_EN_2011.pdf

7. DERIVATION OF POLICY REQUIREMENTS

7.1. Policy requirements

All new road tunnels over 1 kilometre in length shall be designed and operated so that the tunnel average NO_2 concentration is less than 0.5 ppm as a rolling 15 minute average.



Sufficient monitoring equipment shall be installed to enable an accurate calculation of the tunnel average NO_2 concentration. As a minimum, monitors shall be installed at the entry and exit portals, any ramp junctions, at the base of any supply and exhaust ventilation shafts. Monitoring results should be made publicly available in a timely manner.

7.2. Basis of policy requirements

a. Only applies to new tunnels

This policy sets out the compliance criteria for new road tunnels only. In-tunnel air quality is largely driven by the design of the ventilation system, and this policy will ensure that all new road tunnels over 1 km in length in NSW will comply with the most stringent in-tunnel compliance in Australia.

It appears likely that all existing motorway tunnels in Sydney would have a tunnel average NO_2 concentration less than 0.5 ppm as a rolling 15 minute average, with the exception of the M5 East. It should be noted that motorists using the M5 East can implement measures to reduce their exposure to below levels which have identified health effects in the literature by closing their windows and putting the ventilation system on re-circulate.

b. Length of tunnel

At speeds of 60 km and higher, transit times for tunnels less than 1 km are less than 1 minute. There is no health evidence to support the development of a standard for such short exposure times. The evidence indicates that with the windows up and ventilation on recirculate, transit times of less than 1 minute would not result in an appreciable increase in in-cabin NO_2 levels, or individual exposure.

c. Tunnel average concentration

A tunnel average concentration provides a surrogate for exposure that can be easily demonstrated and confirmed for compliance purposes.

d. 15-minute average concentration

Averaging times for health-based air quality standards are typically consistent with the elicitation time for the effect of concern, with the starting point for setting standard averaging times be the experimental data. (NHMRC, 2006). The shortest time period for which there is health evidence on which to base a standard is 15 to 20 minutes. Hence, an averaging time of 15 minutes for an in-tunnel standard is appropriate and evidence based.

e. International comparison

A tunnel average criteria of 0.5 ppm as a rolling 15-minute average compares favourably to the international in-tunnel NO_2 guidelines which range between 0.4 ppm and 1.0 ppm.

f. Health Protection

An extensive review of the scientific literature commissioned by NSW Health found some evidence of health effects from short term exposure to nitrogen dioxide concentrations between 0.2 and 0.5 ppm. This review did not identify health effects from short term (20 – 30 minutes) exposure to nitrogen dioxide at levels below 0.2 ppm.

Modern cars with air vents set to recirculate can result in significantly lower in-cabin NO_2 levels than in-tunnel levels. A study conducted in Sydney motorway tunnels found that vehicle ventilation systems can reduce in-tunnel levels by greater than 70 per cent, with reductions of greater than 90 per cent typical for newer vehicles.

The evidence indicates that application of a tunnel average criterion of 0.5 ppm as a rolling 15-minute average would result in an exposure of less than 0.2 ppm in passenger vehicles with the windows up and air vents set to recirculate ie. below the level where health effects have been identified.

8. REFERENCES

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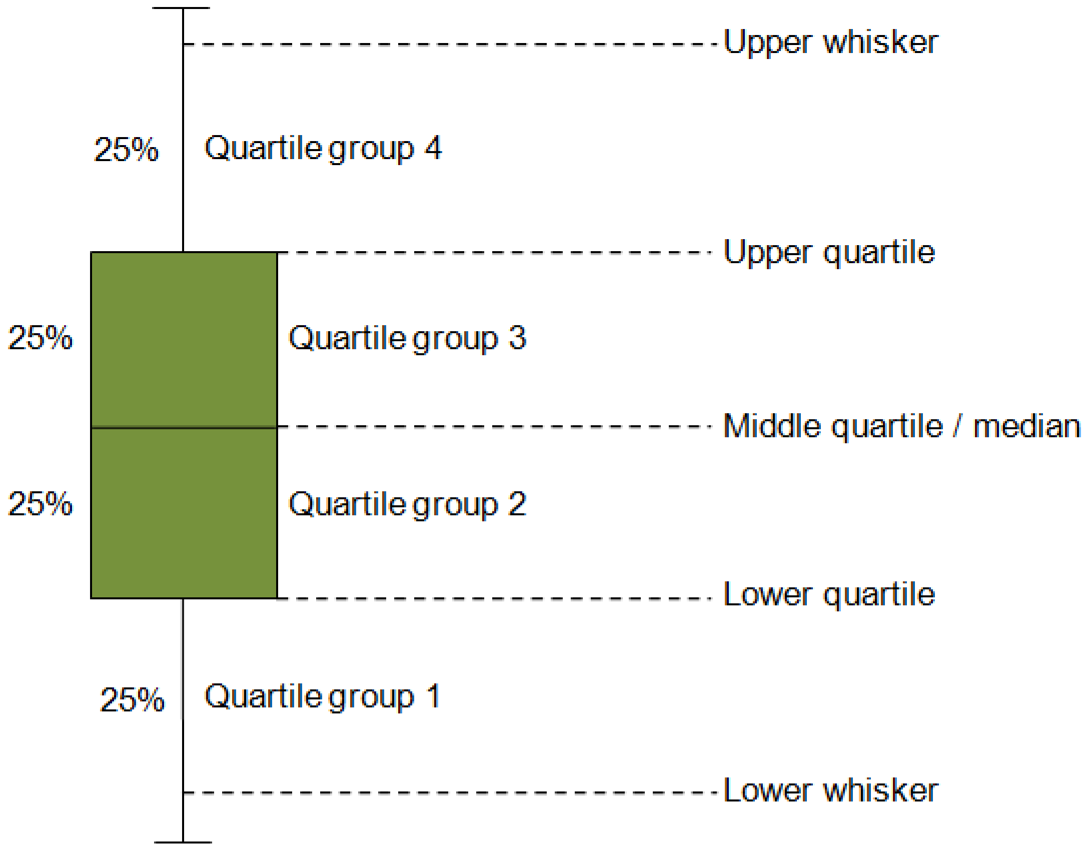
APPENDIX A – UNDERSTANDING AND INTERPRETING BOX AND WHISKER PLOTS

To create a box plot, the data is sorted in order. Then four equal sized groups are made from the ordered scores. That is, 25% of all scores are placed in each group. The groups are referred to as quartile groups, and are labelled 1 to 4 starting from the lowest to the highest.

A boxplot graphically presents quartile groups. The body of the boxplot consists of a "box" (hence, the name), which goes from the first quartile to the third quartile.

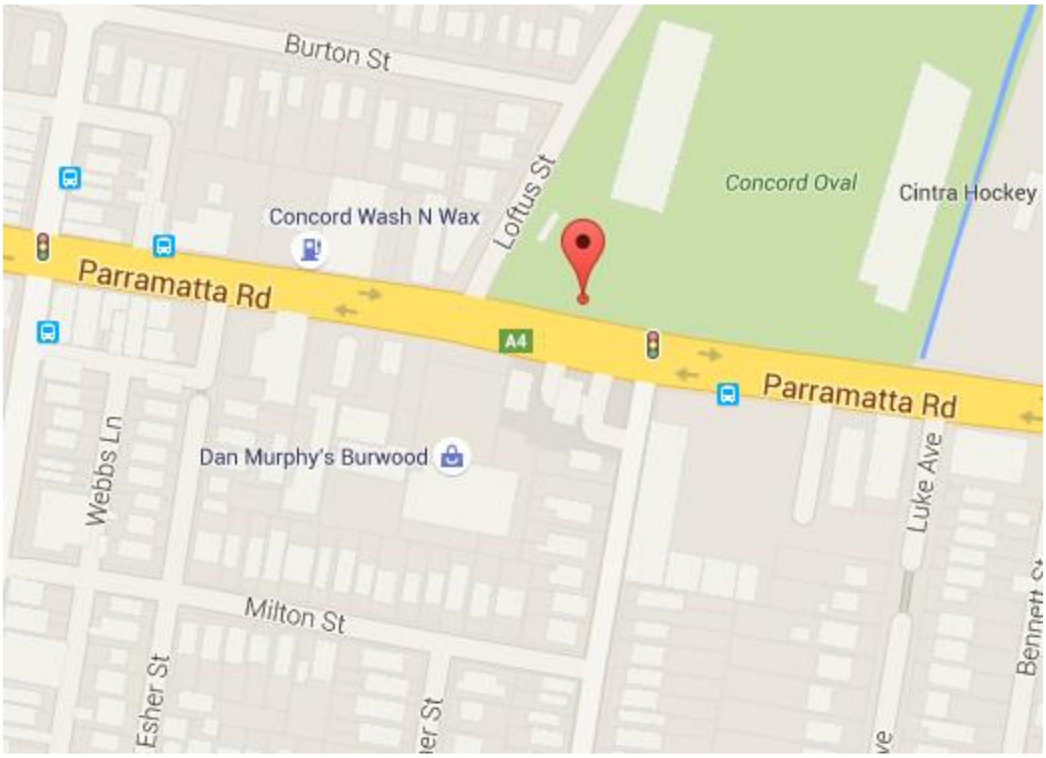
Within the box, a horizontal line is drawn at the second quartile, the median of the data set. Two horizontal lines, called whiskers, extend from the top and bottom of the box. The front whisker goes from the first quartile to the smallest value in the data set, and the top whisker goes from the third quartile to the largest value in the data set.



APPENDIX B – LOCATIONS OF ROADSIDE MONITORING SITES

WDA M4E-04

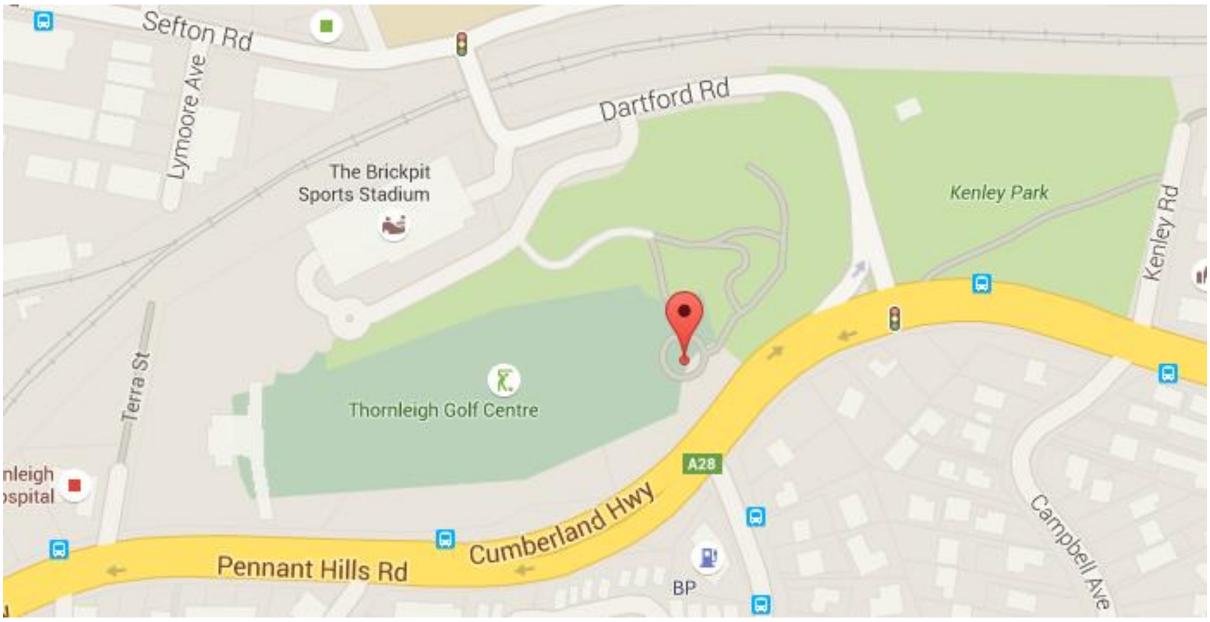
WDA M4E-05



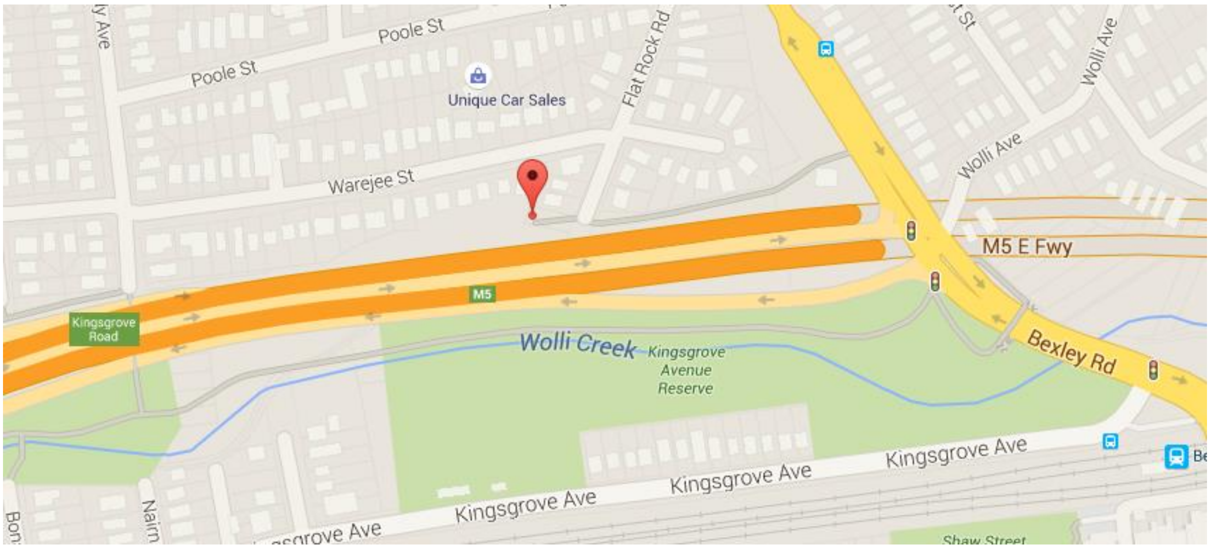
NCX-04


Wilson Rd
Pennant Hills Rd
Cumberland Hwy
Observatory
Park
Beecroft Rd
Beecroft Rd
Lilla Rd

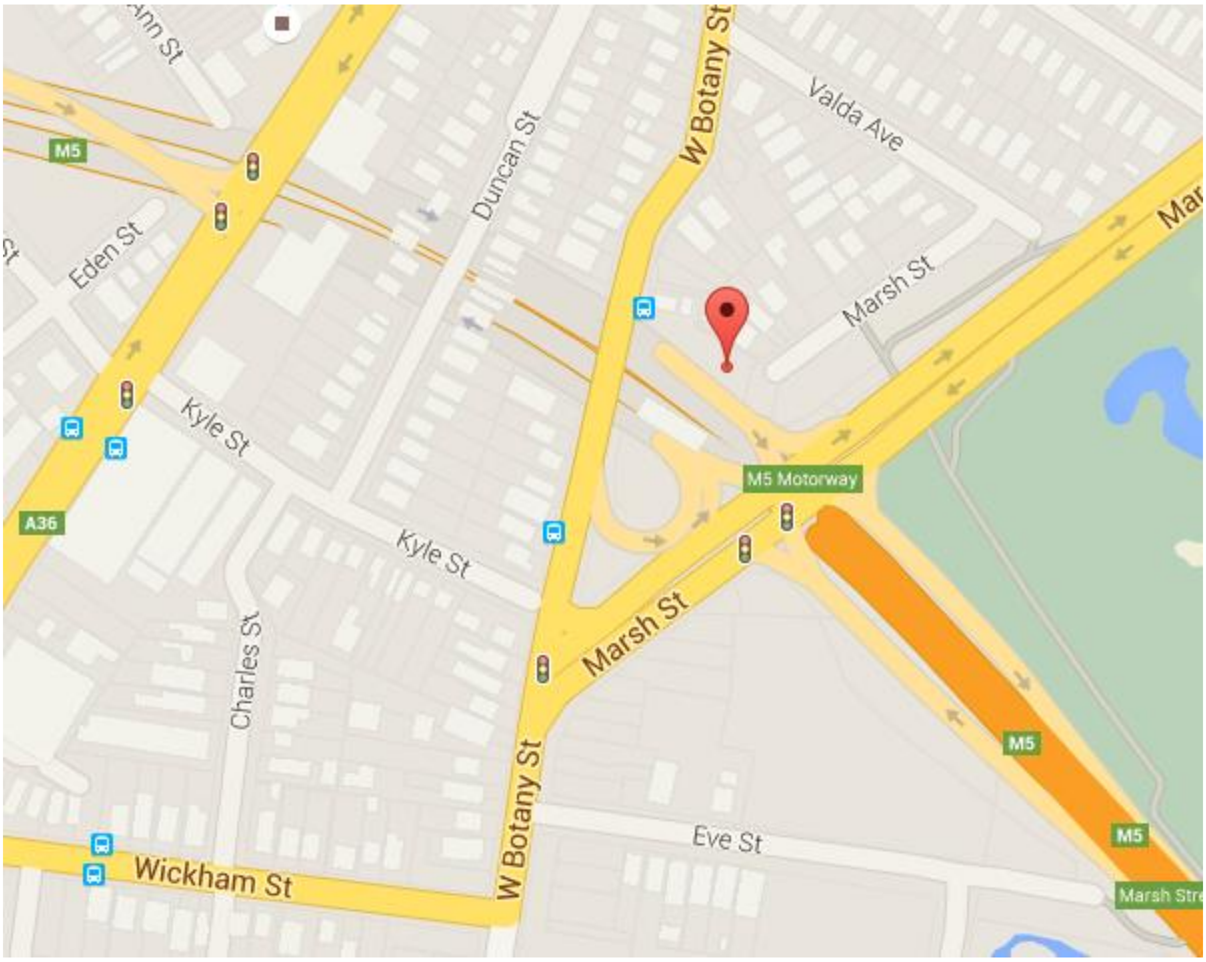
NCX-05


Sefton Rd
Lymoore Ave
Dartford Rd
The Brickpit
Sports Stadium
Kenley Park
Kenley Rd
Terra St
Thornleigh Golf Centre
A28
Cumberland Hwy
Pennant Hills Rd
BP
Campbell Ave

RMS-F1


Poole St
Poole St
Unique Car Sales
Flat Rock Rd
Warejee St
Wolli Ave
Wolli Ave
M5 E Fwy
M5
Kingsgrove Road
Wolli Creek
Kingsgrove Avenue Reserve
Bexley Rd
Kingsgrove Ave
Kingsgrove Ave
Kingsgrove Ave
Shaw Street

RMS-M1


W Botany St
Valda Ave
M5
Duncan St
Eden St
Marsh St
Kyle St
M5 Motorway
A36
Kyle St
Marsh St
Charles St
M5
W Botany St
M5
Eve St
Wickham St