NSW
GOVERNMENT

Advisory Committee on Tunnel Air Quality

Initial report on
Tunnel Air Quality

JULY 2014

Executive Summary

NSW Government agencies have more than two decades' experience in assessing and operating long motorway tunnels.

Sydney has five lengthy motorway tunnels with significant ventilation systems incorporating stacks to manage vehicle emissions. These tunnels, and the years in which they opened, are:

- Sydney Harbour Tunnel – 1992
- Eastern Distributor – 1999
- M5 East – 2001
- Cross City Tunnel – 2005
- Lane Cove Tunnel – 2007

Community groups have raised concerns about major tunnel developments over the years partly because of the potential impacts on air quality. In response, successive NSW Governments have subjected Sydney's road tunnels to detailed environmental assessment prior to approval. The M5 East, Cross City and Lane Cove tunnels are required to undertake extensive monitoring of in-tunnel air quality during operation.

The effectiveness of the stacks in dispersing tunnel emissions from the M5 East, Cross City and Lane Cove tunnels has also been measured as part of separate air quality monitoring programs, which have demonstrated that nearby residents experienced little, if any, increase in exposure to vehicle emissions.

Community confidence in the management of air quality within tunnels, as well as preserving local ambient air quality, is critical to the acceptance of road tunnels as an effective traffic and transport solution. This will be particularly important for Sydney's NorthConnex and WestConnex motorway projects, as the associated road tunnels are likely to be the longest in Australia.

The NSW Government, therefore, established an Advisory Committee on Tunnel Air Quality – chaired by NSW Chief Scientist & Engineer, Professor Mary O'Kane – to provide a 'whole-of-government' understanding of the scientific and engineering issues informing road tunnel ventilation design and operation based on NSW, national and international experience.

In this, its Initial Report, the Committee presents information on the design, assessment and operation of road tunnels; describes how the application of current knowledge can be used to make informed decisions regarding the design and operation of road tunnels; and identifies additional work that is recommended to improve decisions regarding the design and operation of road tunnels.

Up until now, approval conditions and requirements placed on one tunnel project have formed the starting point for the next, with the added inclusion of any precautionary controls to address emerging issues. However, a fresh approach is required for Sydney's newest road tunnel projects to address:

- Community concern as to whether air quality criteria properly address vehicle emissions
- Changes to vehicle technologies that, while reducing the magnitude of vehicle emissions, have also altered the composition of those emissions
- Experience from the Lane Cove and Cross City tunnels that has shown that the ventilation systems are over-designed and that the approval conditions have resulted in inefficient operating regimes.

While motor vehicles remain a significant source of air pollution in Sydney, stricter emission standards and improved fuel quality have resulted in substantial reductions in pollution in the past two decades and, by national and international standards, the city's overall air quality is generally good.

Executive Summary

The Committee called for a review of the up-to-date science literature, which concluded emissions from well-designed road tunnels cause a negligible change to surrounding air quality, and as such, there is little to no health benefit for surrounding communities in installing filtration and air treatment systems in such tunnels.

Outside Australia almost all road tunnels use portal emissions. Reductions in emissions has reduced the need for ventilation stacks, and it has become possible to meet both in-tunnel and outdoor air quality requirements using portal emissions alone for some or all of the time. However, in urban areas portal emissions are often supplemented by the use of stacks, which are seen as a precautionary measure – providing flexibility and resilience in the ventilation system design.

Despite it being common practice internationally to allow portal emissions, operating conditions have been set for the M5 East, Cross City and Lane Cove Tunnels requiring all emissions be expelled through stacks, which requires significant energy use and, during periods of low traffic, may deliver little appreciable environmental benefit.

The Committee therefore recommends that further work be undertaken in three areas to improve decisions regarding the design and operation of road tunnels:

1. **Provide information and make recommendations on the assessment and management of portal emissions to improve ventilation system efficiency, reduce overall environmental impacts and provide appropriate protection of the air quality for tunnel users and the community in the vicinity of the tunnel portals.**

This should include exploring the potential for:

a. optimising portal design on new tunnel projects to maximise dispersion and minimise impacts through the use of physical or computer models (eg wind tunnels or computational fluid dynamics)

b. an investigation of the potential for partial portal emissions at an operating Sydney tunnel without increasing nearby residents' exposure to vehicle emissions.

2. Research, develop and make recommendations on in-tunnel NO_2 limits.

At the present time protection from exposure to road vehicle pollutants in-tunnel is provided through a combination of the existing CO and visibility limits. However, as the composition of vehicle emissions continues to change a duly considered NO_2 limit would provide additional protection in the future.

3. Investigate and recommend fit-for-purpose standard methods for monitoring in-tunnel air NO_2 levels to improve consistency across projects.

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. There are a number of techniques for monitoring in-tunnel NO_2 levels. Although standard methods are specified for stack and ambient NO_2 monitoring, they do not take into account the specific circumstances of the in-tunnel environment.

Contents

Eleven technical papers have been produced by the advisory committee on tunnel air quality to provide additional background on key aspects contained in this interim report http://www.chiefscientist.nsw.gov.au/reports.

Technical papers

Technical paper 1
Trends in motor vehicles and their emissions

Technical paper 2
Air quality trends in Sydney

Technical paper 3
Health effects of traffic related air pollution

Technical paper 4
Road tunnel ventilation systems

Technical paper 5
Road tunnel stack emissions

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Road tunnel portal emissions

Technical paper 7
Options for reducing in-service vehicle emissions

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Criteria for in-tunnel and ambient air quality

Glossary

Term	Description
ADR	The Australian Design Rules (ADRs) are national standards for vehicle safety, anti-theft and emissions
Airshed	Part of the atmosphere that shares a common flow of air and that is exposed to similar influences.
Ambient	Ambient pollutant concentrations refer to the concentrations of pollutants in the air, which are generated by all local pollutant sources, ie the term refers to the general pollutant loads in the air.
CO	Carbon monoxide
DP&E	Department of Planning and Environment
EPA	Environment Protection Authority
EU	European Union
HDV	Heavy Duty Vehicle; a truck, semi-trailer or bus
IARC	International Agency for Research on Cancer
kg	kilogram
km	kilometre
LCV	Light commercial vehicle – any rigid vehicle seating 12 or less with a cab chassis construction, greater than 1.5 but less than 4.5 tonne gross vehicle mass (GVM), and two axles.
LDV	Light Duty Vehicle; a car, van or small bus seating 12 or less.
LEZ	Low Emission Zone. LEZs are areas in which vehicles are required to meet a minimum emissions standard.
mg/m^3	milligram per cubic metre. A concentration of 1 mg/m^3 means that one cubic metre of air contains one milligram (0.001 grams) of pollutant.
MW and MWh	A megawatt (MW) is a unit for measuring power that is equivalent to one million watts. One megawatt is equivalent to the power of 10 automobile engines. A megawatt hour (MWh) is 1,000 kilowatts of electricity being used continuously for one hour. It is about equivalent to the amount of electricity used by about 330 homes during one hour.
NO$_2$	Nitrogen dioxide
NO$_x$	Oxides of nitrogen, including nitric oxide (NO) and NO$_2$
O$_3$	Ozone
OEH	Office of Environment and Heritage
Particulate matter	Very small solid particles or liquid droplets, which may become suspended in air.
Piston effect	The forcing of air through a road tunnel as a result of moving vehicles.
Plume	A parcel of air in which substances (air pollutants) are present at concentrations higher than the surrounding airshed.
PM	Particulate matter
PM$_{10}$	Particulate matter with an equivalent aerodynamic diameter of 10 micrometres or less.
PM$_{2.5}$	Particulate matter with an equivalent aerodynamic diameter of 2.5 micrometres or less.
ppb	Parts per billion describes the concentration of a pollutant in air in terms of volume ratio. A concentration of 1 ppb means that for every billion (10^9) units of air, there is one unit of pollutant present.
ppm	Parts per million describes the concentration of a pollutant in air in terms of volume ratio. A concentration of 1 ppm means that for every million (10^6) units of air, there is one unit of pollutant present.
pphm	Parts per hundred million describes the concentration of a pollutant in air in terms of volume ratio. A concentration of 1 pphm means that for every hundred million (10^8) units of air, there is one unit of pollutant present.
TSP	Total suspended particulate matter.
UFP	Ultrafine particles (UFPs) are particulate matter with an equivalent aerodynamic diameter of 0.1 micrometres or less.
µg/m^3	microgram per cubic metre. A concentration of 1 µg/m^3 means that one cubic metre of air contains one microgram (0.000001 grams) of pollutant.
VKT	Vehicle kilometres travelled (VKT) is the total distance travelled by the specified group of vehicles. For example, total annual VKT in Sydney is the number of kilometres travelled by all vehicles in Sydney during one year.
VOCs	Volatile organic compounds. Organic compounds that vaporise (become a gas) at room temperature.
WHO	World Health Organization

1. Introduction

NSW Government agencies have in excess of 20 years' experience in assessing and operating long motorway tunnels. Sydney has five lengthy motorway tunnels with substantial ventilation systems incorporating stacks. These tunnels, and the years in which they opened, are:

- Sydney Harbour Tunnel – 1992
- Eastern Distributor – 1999
- M5 East – 2001
- Cross City Tunnel – 2005
- Lane Cove Tunnel – 2007

Some community groups have expressed concern about major tunnel projects over the years partly because of the potential impacts on air quality. Successive NSW Governments have responded by subjecting these tunnels to detailed environmental assessment prior to approval, and extensive monitoring of in-tunnel air quality during operation.

The effectiveness of ventilation stacks in dispersing emissions from the M5 East, Cross City and Lane Cove tunnels have been measured as part of project approval conditions which required extensive ambient air quality monitoring to ensure that residents in surrounding areas experience little, if any, increase in exposure to vehicle emissions.

Community confidence in the management of air quality within tunnels, as well as the preservation of air quality in surrounding areas, is vital to the acceptance of road tunnels as an effective traffic and transport solution. This will be particularly important for Sydney's NorthConnex and WestConnex motorway projects, as the associated road tunnels are likely to be the longest in Australia.

Previously, approval conditions and requirements for one tunnel project have formed the starting point for the next project, with the inclusion of any additional precautionary controls deemed necessary to address emerging issues.

However, a fresh approach is required for Sydney's newest road tunnel projects to address:

- Community concern as to whether air quality criteria properly address vehicle emissions.
- Changes to vehicle technologies that, while reducing the magnitude of vehicle emissions, have also altered the composition of those emissions.
- Experience from the Lane Cove and Cross City tunnels that has shown that the ventilation systems are over-designed and that the approval conditions have resulted in inefficient operating regimes.

The NSW Government, therefore, has established an Advisory Committee on Tunnel Air Quality – chaired by the NSW Chief Scientist and Engineer, Professor Mary O'Kane – to provide it with a 'whole-of-government' understanding of the scientific and engineering issues informing tunnel ventilation design and operation based on NSW, national and international experience.

The Advisory Committee on Tunnel Air Quality has commissioned the following Technical Papers:

- Trends in motor vehicles and their emissions (Technical Paper 1)
- Air quality trends in Sydney (Technical Paper 2)
- Health effects of traffic related air pollution (Technical Paper 3)
- Road tunnel ventilation systems (Technical Paper 4)
- Road tunnel stack emissions (Technical Paper 5)
- Road tunnel portal emissions (Technical Paper 6)
- Options for reducing in-service vehicle emissions (Technical Paper 7)
- Options for treating road tunnel emissions (Technical Paper 8)
- Evolution of tunnels in Sydney (Technical Paper 9)
- Role of regulators for tunnel projects (Technical Paper 10)
- Criteria for in-tunnel and ambient air quality (Technical Paper 11)

This initial report presents a synthesis of these Technical Papers, and:

- Provides information on the design, assessment and operation of measures to manage air quality associated with road tunnels.
- Describes how the application of current knowledge can be used to make informed decisions regarding the design and operation of measures to manage air quality associated with road tunnels.
- Identifies additional work that is recommended to improve decisions regarding the design and operation of road tunnels.

2. Context

Information about air quality in and around road tunnels needs to be understood in the context of air quality more generally. This section of the report addresses these background issues and includes a discussion of ambient air quality in Sydney, the sources of air pollution (including motor vehicles) and a discussion of the possible health effects of air pollution.

2.1. Air quality trends in Sydney

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. Each standard includes the maximum acceptable concentration (in ppm or µg/m^3) and the time period over which that concentration is averaged (in hours, days or years) (DEH, 2005). A summary of the maximum observed concentrations of air pollutants in Sydney during 2012, and how these perform against the standards in the AAQ NEPM, is provided in Table 2.1. Annual trends in air pollutant concentrations are shown in Figure 2.1. The different particle size fractions are explained in Section 2.1.2.

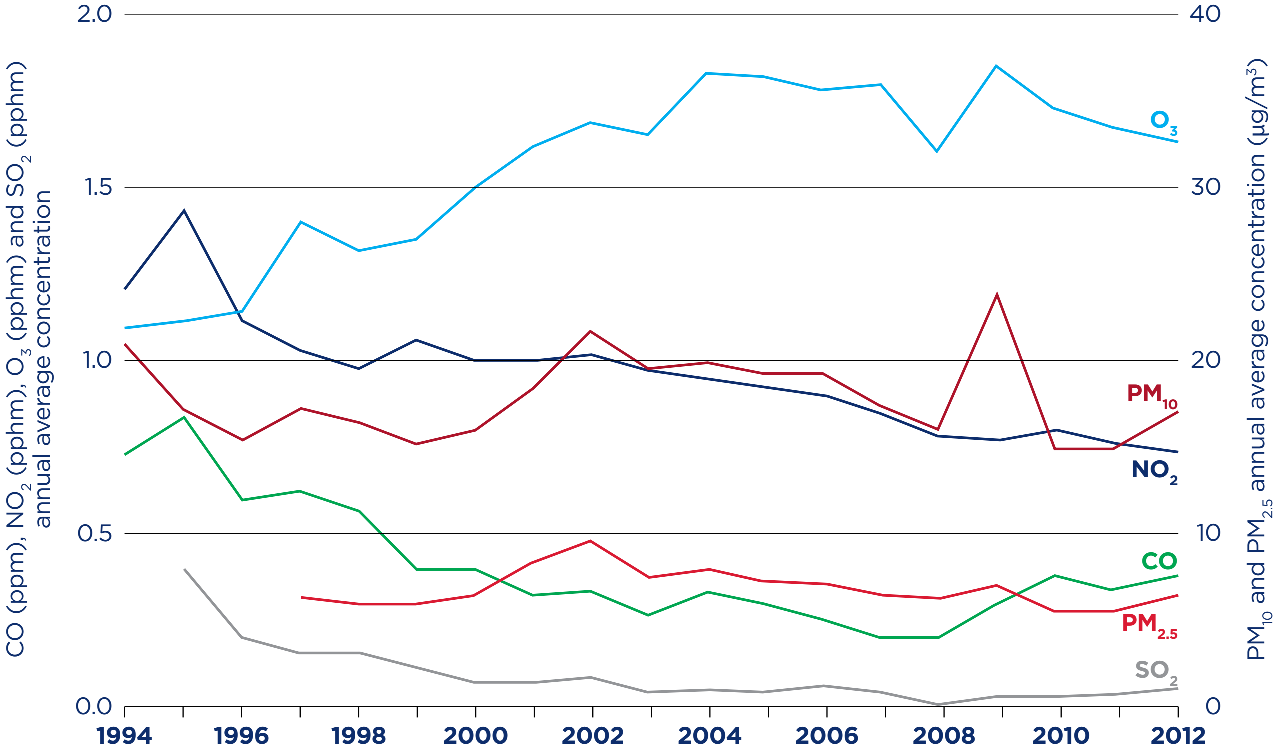
In the Sydney region, carbon monoxide (CO), nitrogen dioxide (NO_2) and sulphur dioxide (SO_2) concentrations are consistently well below the national standards. Ozone (O_3) and particulate matter (PM) levels occasionally exceed the national standards in the Sydney region, with no apparent downward trend in the concentrations of these pollutants.

Table 2.1: National air quality standards and maximum concentrations observed in Sydney 2012 (OEH data)

Pollutant	Averaging period	Standard	Maximum concentration in 2012	% of the Standard
Carbon monoxide (CO)	8 hours	9.0 ppm	2.2 ppm	24
Nitrogen dioxide (NO_2)	1 hour	0.12 ppm	0.062 ppm	52
	1 year	0.03 ppm	0.013 ppm	43
Sulphur dioxide (SO_2)	1 hour	0.20 ppm	0.025 ppm	13
	1 day	0.08 ppm	0.005 ppm	6
	1 year	0.02 ppm	0.001 ppm	5
Photochemical oxidants (as ozone O_3)	1 hour	0.10 ppm	0.095 ppm	95
	4 hour	0.08 ppm	0.084 ppm	**105**
Particles as PM_{10}	1 day	50 µg/m^3	99.2 µg/m^3	**199**
Particles as $PM_{2.5}$	1 day	25 µg/m^3(a)	116.7 µg/m^3	**467**
	Annual	8 µg/m^3(a)	8.5 µg/m^3	**107**

(a) AAQ NEPM Advisory Reporting Standard – the NEPM goal is to collect sufficient $PM_{2.5}$ data to develop national standards.

Figure 2.1: Maximum annual average pollutant concentrations recorded for Sydney, 1994 – 2012 (OEH data)



2.1.1. Ozone

Ozone is a major component of photochemical smog. It is formed in the lower atmosphere when a number of 'precursor' compounds – mainly oxides of nitrogen (NO_x) and volatile organic compounds (VOCs) – react in warm, sunny conditions. Peak ozone levels in Sydney are therefore typically observed between November and March.

Road transport is the main source of NO_x emissions in Sydney, and is the second largest source of VOCs. NSW Office of Environment & Heritage modelling shows that motor vehicle emissions are a major contributor to peak ozone concentrations in Sydney. Other significant sources of precursor emissions include domestic/commercial activities and natural processes (EPA, 2012). Factors affecting ozone concentrations in Sydney include changes to precursor emissions, meteorological conditions, and changes in background ozone concentrations. Figure 2.2 presents maximum ozone concentrations and number of days exceeding the AAQ NEPM standards from 1994 to 2011.

2. Context

Figure 2.2: Maximum 1-hour and 4-hour average ozone concentrations in Sydney and number of days exceeding national standards during November (previous year) to March (following year)

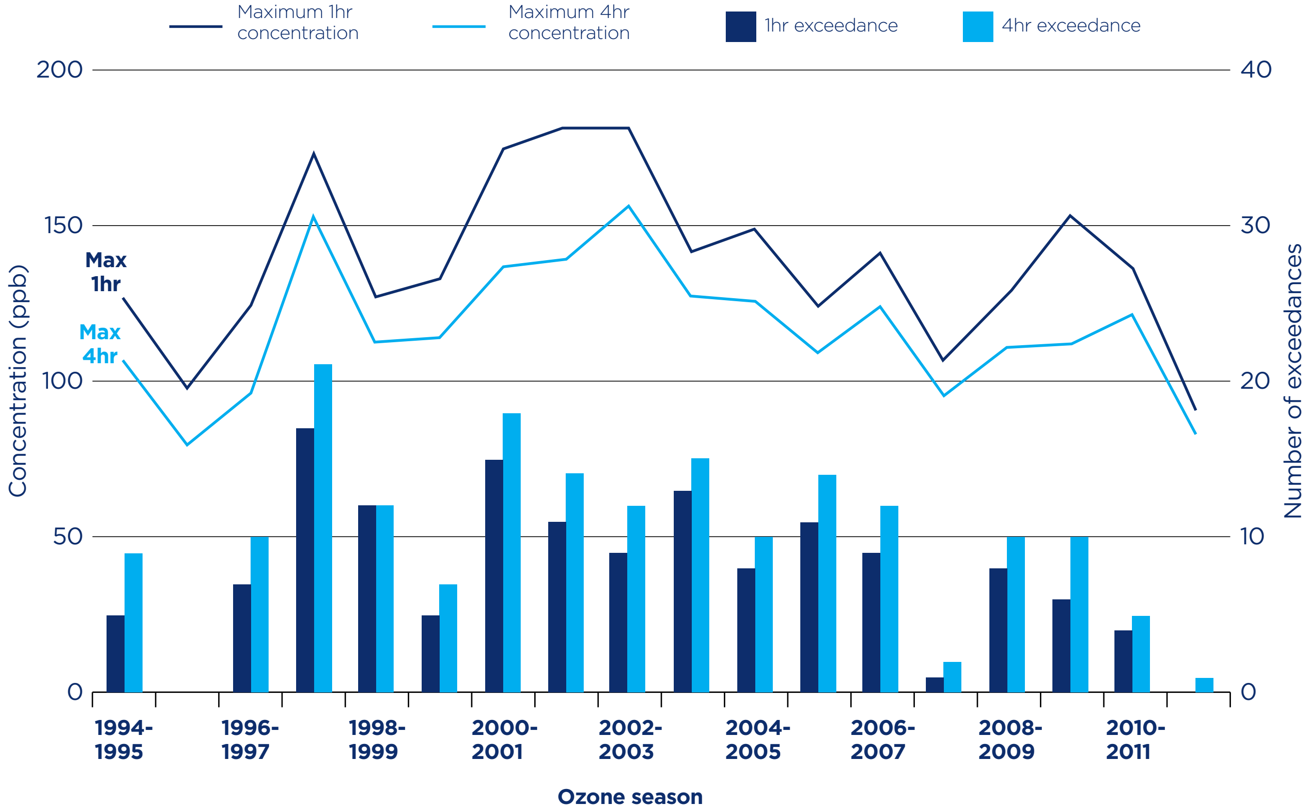


Figure 2.2 suggests that there has been a decrease in the number of high ozone days since 2003. However, as ozone concentrations are strongly influenced by the occurrence of hot, sunny conditions, there is variability associated with climatic fluctuations. A comprehensive statistical analysis over the period 1994–2010 concluded that there has been no significant upward or downward trend in ozone concentrations in Sydney when climatic variation is removed (Johnson and Quigley, 2013).

2.1.2. Particulate matter

Particulate matter (PM) in the air can come directly from natural sources such as bushfires and dust storms, and also from human activities such as wood burning, quarrying and mining, motor vehicle use and industrial processes. Particulate matter is also produced or altered by chemical reactions between gases, or between gases and other particles in the air. Particle pollution is evident as the brown haze sometimes seen in the cooler months of the year.

While particles larger than 10 micrometres in diameter readily deposit on the ground over short distances from their source, smaller particles may be carried long distances. Airborne particles cover a wide range of sizes, and they are commonly defined by the following size-based terms:

Ultrafine particles (UFPs) are particles of 0.1 micrometres (µm) in aerodynamic diameter or less. UFPs are formed during combustion processes or by chemical reactions in the atmosphere. They are transformed rapidly due to coagulation, adsorption and secondary particle formation (WHO Regional Office for Europe, 2013). UFP lifetimes in the atmosphere can be very short; under typical urban conditions the half-life is around one hour for particles with a diameter of 0.02 µm (WHO Regional Office for Europe, 2006).

$PM_{2.5}$ (fine particles) are particles of 2.5 µm in aerodynamic diameter or less and include ultrafine particles. $PM_{2.5}$ may be emitted directly into the atmosphere, and also created by reactions between gas-phase pollutants. Sources of direct $PM_{2.5}$ emissions include wood heaters, diesel vehicles, ships and industrial processes. Sources of the precursor pollutants that chemically react to form $PM_{2.5}$ include motor vehicles, shipping, agriculture, off-road industrial vehicles and evaporative emissions from paints and solvents.

PM_{10} are particles of 10 µm in aerodynamic diameter or less and include both UFPs and $PM_{2.5}$. The majority of particles in the size range $PM_{2.5}$ to PM_{10} (referred to as the coarse fraction) are typically generated by mechanical action such as vehicles on dirt roads and wind-blown dust from landfills and quarries.

The sizes of airborne particles are placed into context in Figure 2.3, in which they are compared with a human hair and beach sand.

Figure 2.3: Illustration showing the different particulate matter size fractions

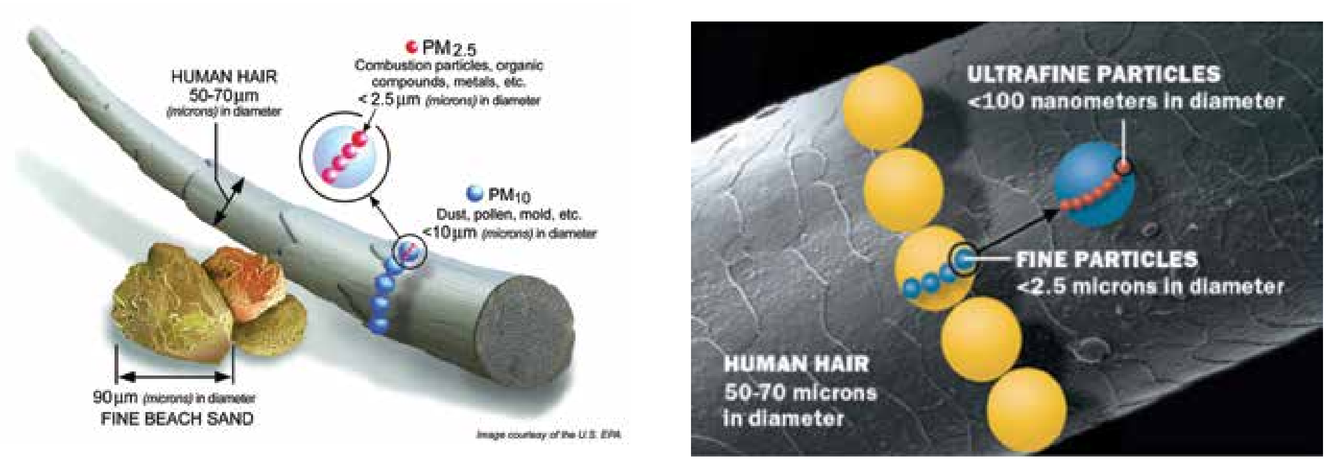
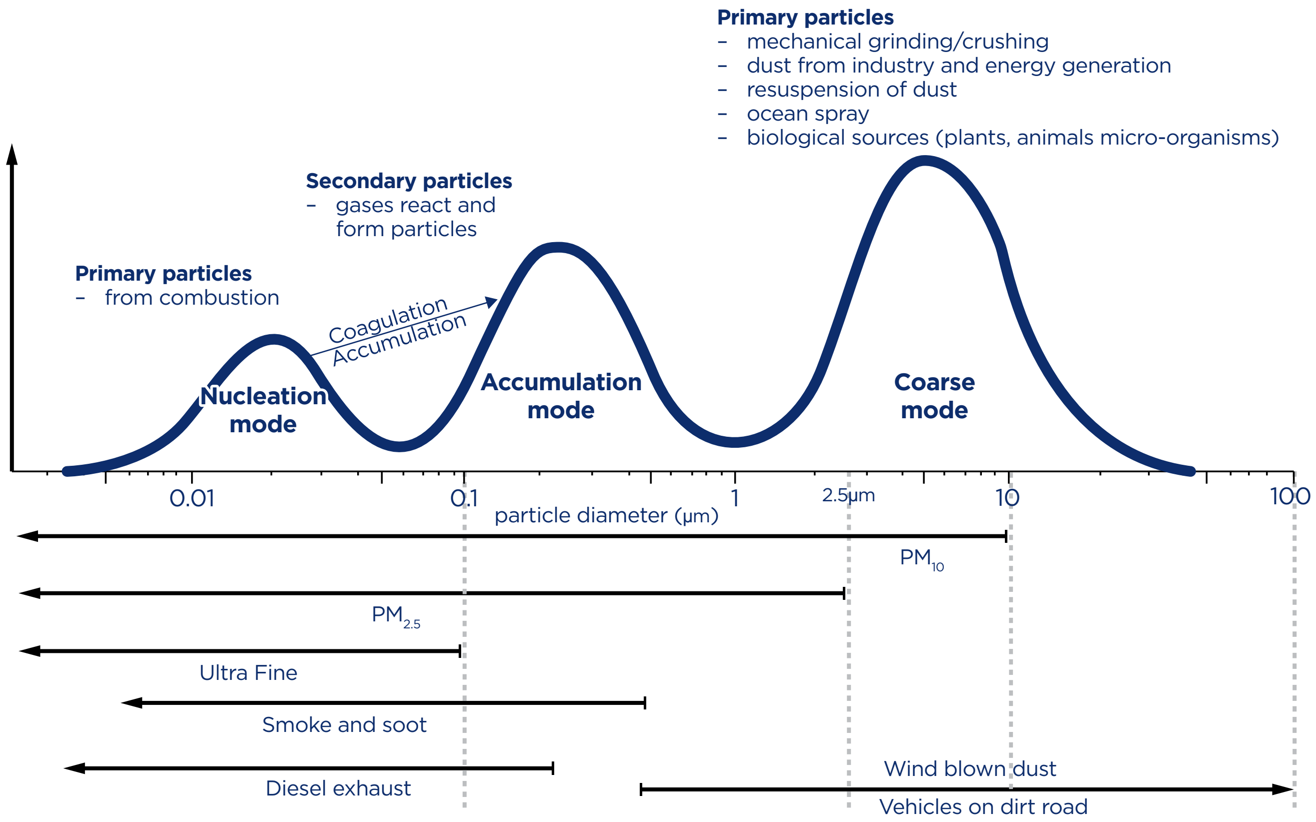


Figure 2.4 shows some of the most important sources of airborne particles in different size ranges, as well as the processes (mechanical and chemical) by which they are formed.

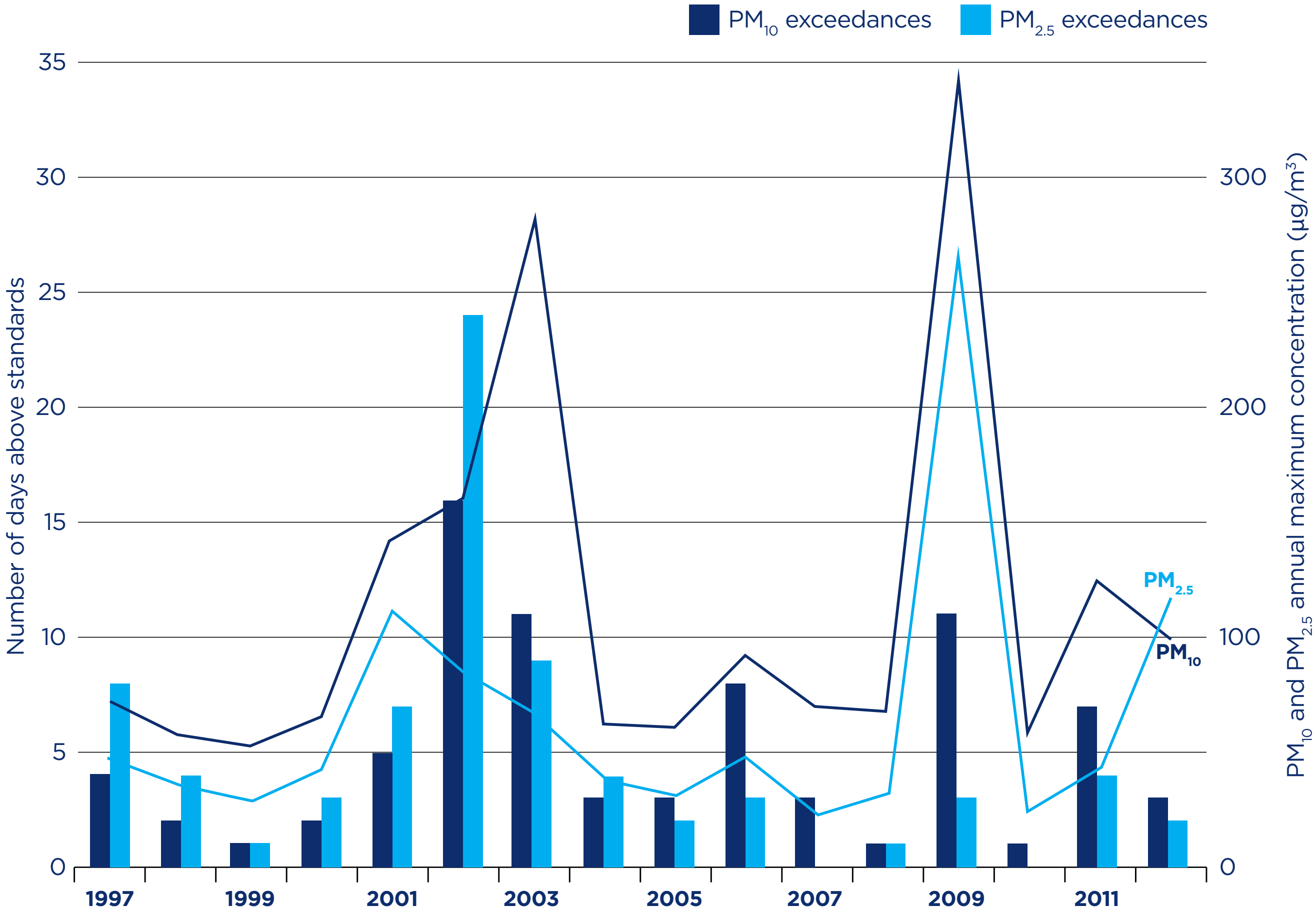
Figure 2.4: Particulate matter size fractions, sources, formation mechanisms and composition



The particle size fractions that are monitored in Sydney (and across NSW) are PM_{10} and $PM_{2.5}$. With recent advances in instrumentation and measurement technology, it is now possible to measure atmospheric UFPs. UFPs are most appropriately measured in terms of their number concentration. This is because their numbers are large, whereas their mass is small compared with the mass of larger particles. However, UFP measurement is still primarily a research activity, and air quality standards relating to UFPs have not yet been adopted by any major jurisdiction internationally. UFP measurement techniques are actively being developed to address issues such as the high cost and lack of robustness required for field operation (Kumar et al., 2011).

PM pollution varies significantly from year to year (Figure 2.5). High peak and average PM_{10} and $PM_{2.5}$ levels are typically recorded during years that are affected by large bushfires (eg 2001–2003) or by major dust storm events (eg September 2009).

Figure 2.5: PM_{10}[(a)] and $PM_{2.5}$[(b)] maximum 24-hour average concentrations and numbers of days exceeding national 24-hour standards in Sydney



(a) The AAQ NEPM permits maximum allowable exceedences of the PM_{10} standard of 5 days per year.

(b) AAQ NEPM Advisory Reporting Standard – the NEPM goal is to collect sufficient $PM_{2.5}$ data to develop national standards.

2. Context

2.2. Air quality – how Sydney compares

Air quality in Sydney is good by national and international standards. Care must be taken when comparing air quality in different urban areas. Differences in monitoring equipment, in the rationale behind placement of stations, and in the number of stations can influence the comparability of pollutant concentrations. Nevertheless, the data from various sources confirm that Sydney has good air quality by international standards. Figures 2.6 to 2.12 compare Sydney's air quality with that of other Australian and international cities/regions.

Figure 2.6: Annual average PM_{10} concentrations in 1,600 urban areas*, 2008–2013

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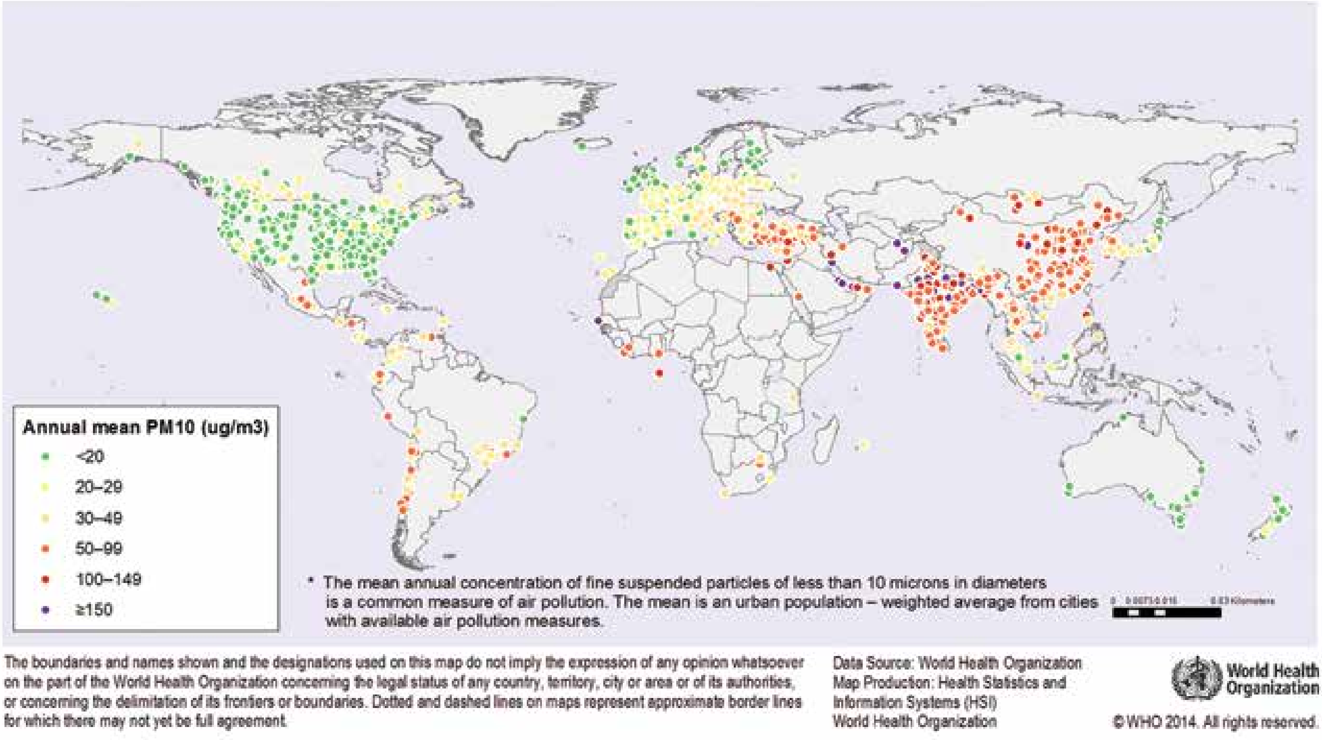


Figure 2.7: Global annual average $PM_{2.5}$ 2001–2006 (Donkelaar, 2010)
Reproduced with permission from Environmental Health Perspectives

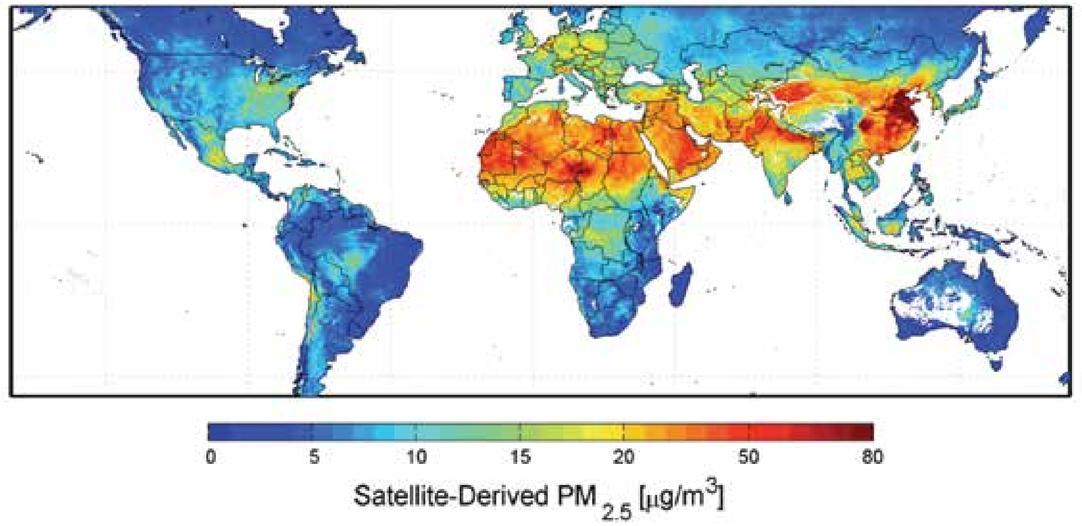
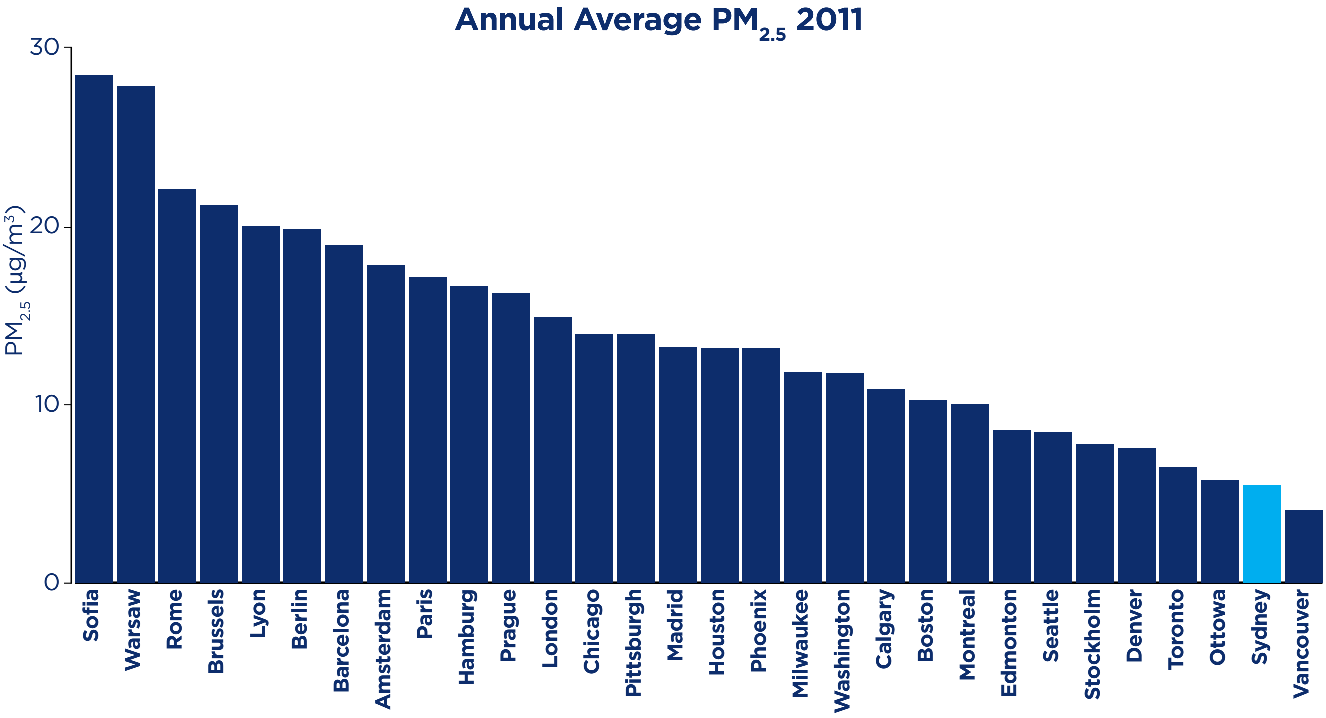
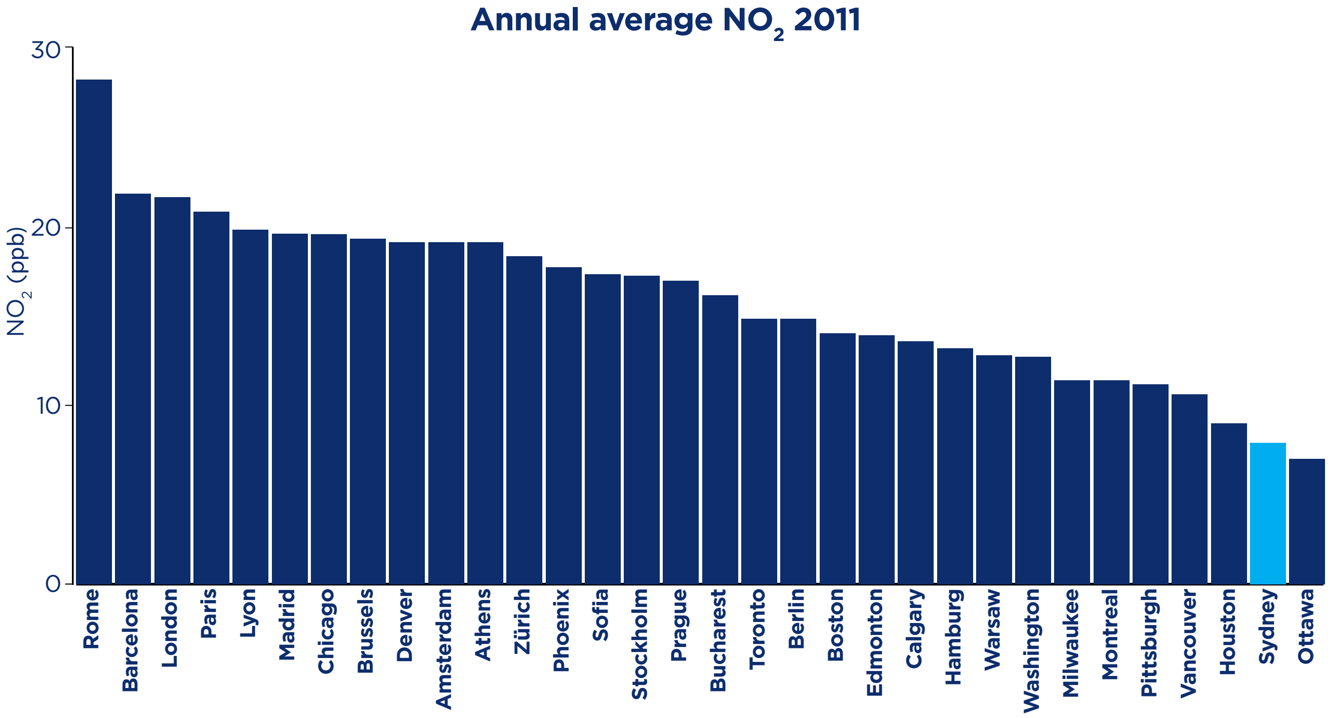


Figure 2.8: International $PM_{2.5}$ comparisons



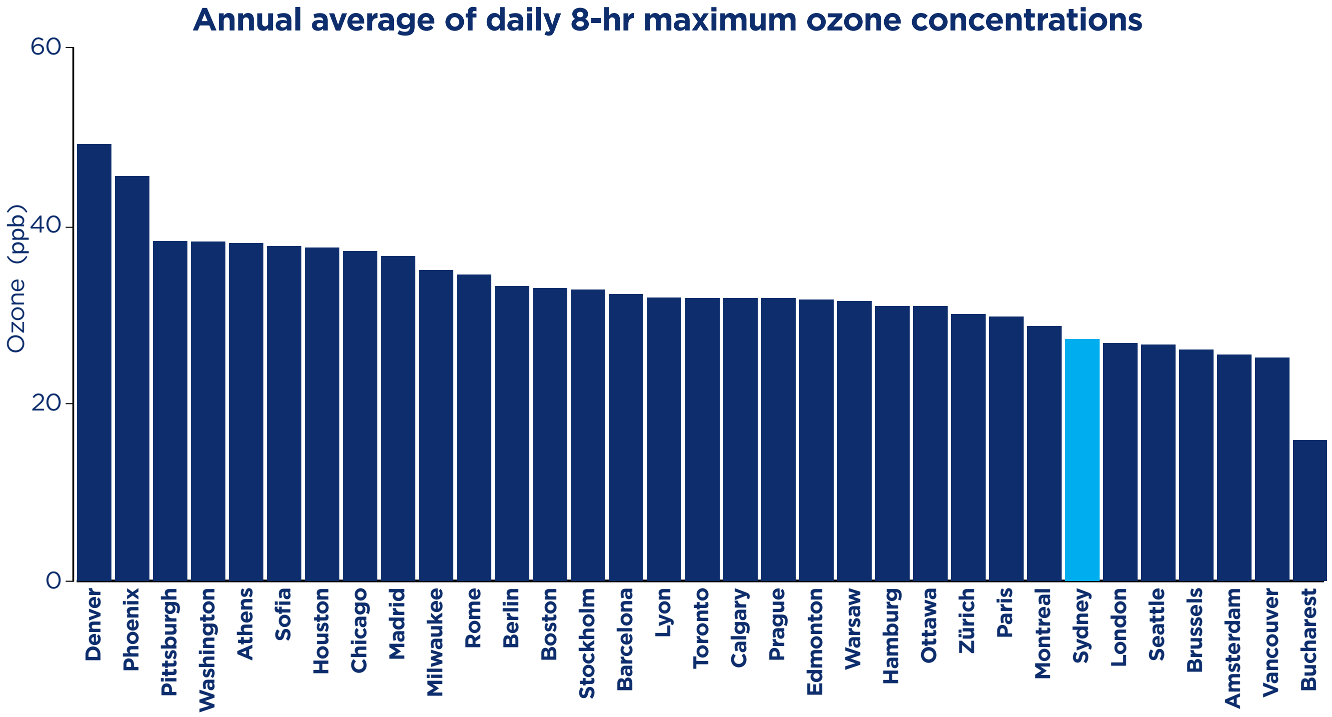
Source – Environment Canada http://ec.gc.ca/indicateurs-indicators/default.asp?lang=en&n=1B7C2AC9-1

Figure 2.9: International NO_2 comparisons



Source – Environment Canada http://ec.gc.ca/indicateurs-indicators/default.asp?lang=en&n=1B7C2AC9-1

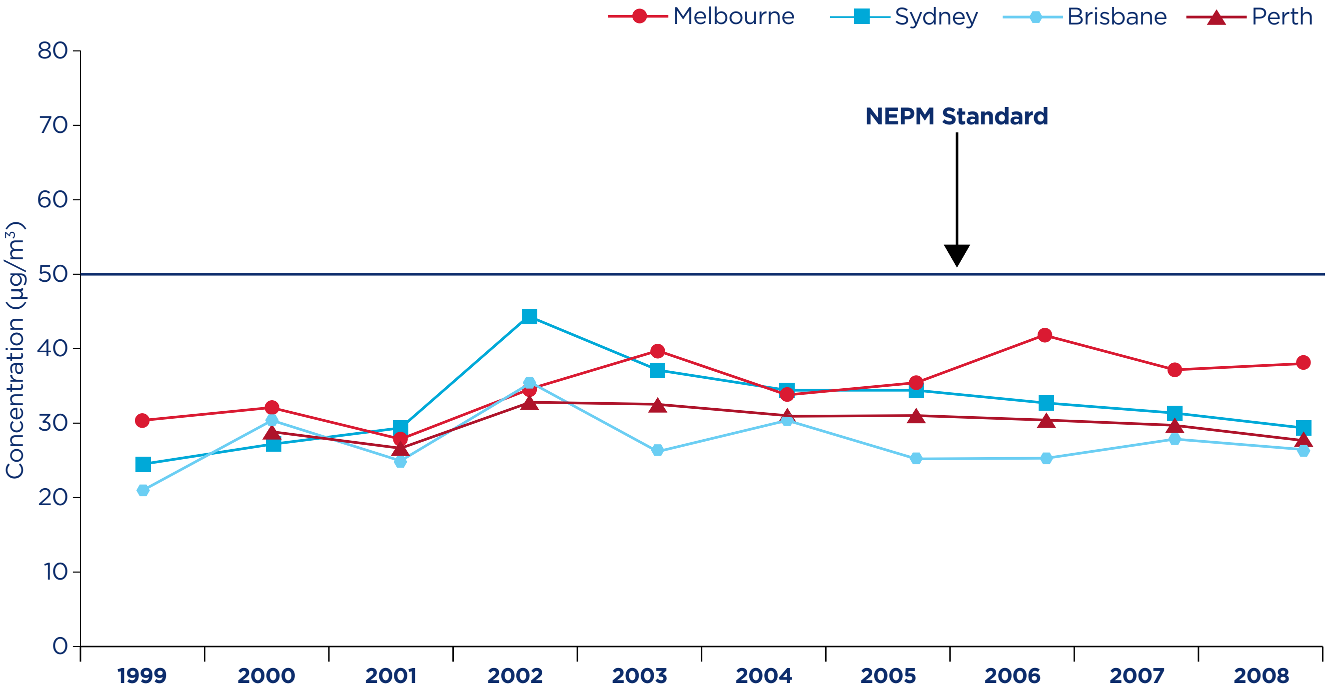
Figure 2.10: International ozone comparisons



Sources – Environment Canada http://ec.gc.ca/indicateurs-indicators/default.asp?lang=en&n=1B7C2AC9-1, Office of Environment and Heritage, New South Wales (2014) http://www.environment.nsw.gov.au/AQMS/search.htm

Note: The above ozone indicators are based on the annual average of the 8-hour daily maximum concentrations for a given city for the calendar year 2011. However the value for Sydney represents the annual average of the 4-hour daily maximum concentrations for the same year. This thus overstates the Sydney ozone indicator compared with other locations.

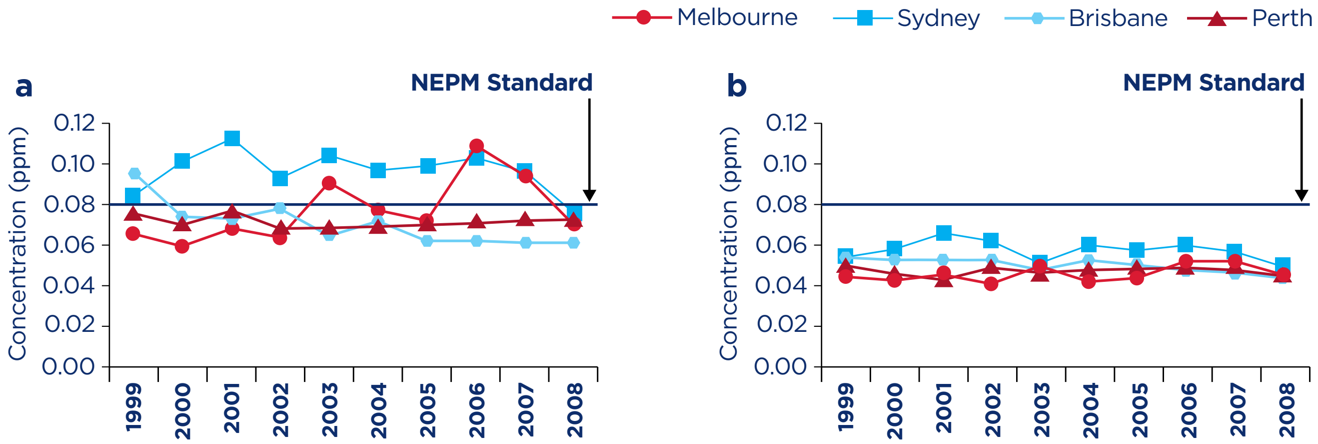
Figure 2.11: PM_{10} trends in Melbourne, Sydney, Brisbane and Perth



http://www.environment.gov.au/science/soe/2011-report/3-atmosphere/3-ambient-air-quality/3-1-state-and-trends#ss3-1-2

Note: The above PM_{10} indicators are based on the 95th percentile 24-hour average PM_{10} concentrations averaged across all city monitoring sites in Melbourne, Sydney, Brisbane and Perth, 1999–2008.

Figure 2.12: Ozone trends in Melbourne, Sydney, Brisbane and Perth



http://www.environment.gov.au/science/soe/2011-report/3-atmosphere/3-ambient-air-quality/3-1-state-and-trends#ss3-1-2

Note: Graph (a) shows the maximum four-hour ozone concentrations averaged across all city monitoring sites and Graph (b) shows the 95th percentile four-hour average ozone concentrations averaged across all city monitoring sites.

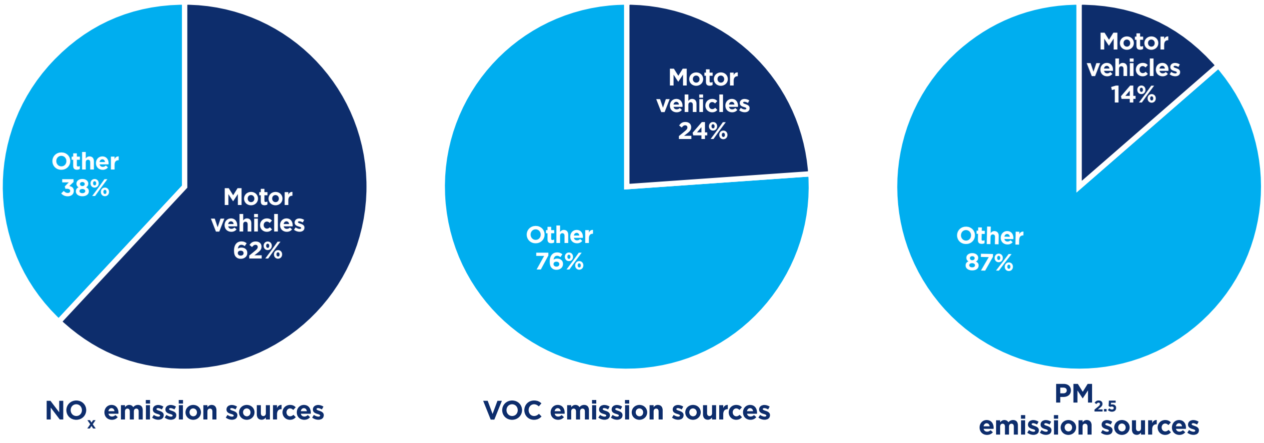
Additional detail on air quality trends in Sydney is provided in Technical Paper 2.

2.3. Motor vehicle emissions – sources and trends

Motor vehicles are a major source of human generated air pollution in Sydney, contributing 62 per cent of oxides of nitrogen (NO_x) emissions, 24 per cent of volatile organic compound (VOC) emissions, and 13 per cent of $PM_{2.5}$ emissions during 2008. While motor vehicles are contributors to particle pollution, there are many other sources of particles from both natural processes (eg bush fires) and human activities (eg wood burning, quarrying and mining).

Figure 2.13 below shows the emissions from motor vehicles compared with other human generated emissions sources (such as industry and wood heaters) (EPA, 2012).

Figure 2.13: Contribution of motor vehicle emissions to anthropogenic emissions in Sydney 2008



Based on data from the 2008 Calender Year Air Emissions Inventory for the Greater Metropolitan Region in NSW, (EPA, 2012)

2.3.1. National vehicle emission standards

New on-road motor vehicle emission limits are set by the Commonwealth Government via the Australian Design Rules (ADRs). The first ADR governing vehicle emissions (from petrol cars) was set in 1972, with ADR26 setting a limit for the exhaust concentration of CO at engine idle. The emission standards for light-duty vehicles (LDVs) and heavy-duty vehicles (HDVs) have been progressively tightened over time based on United States and – more recently – European Union (EU) standards.

Australia has adopted the 'Euro 5' and 'Euro 6' emission standards for petrol and diesel LDVs, and the 'Euro V' standards for HDVs. The adoption of 'Euro VI' for HDVs is currently under investigation. Meeting these standards will require the widespread adoption of diesel particulate filters on new vehicles. Diesel particulate filters are very effective at reducing both the mass of PM and the number of UFPs emitted. Implementation of the new standards led to a decrease in UFP levels in European environments (Jones et al., 2012; Wåhlin, 2009).

The current LDV emission standards are approximately 95 per cent lower than the original 1976 standards (Figure 2.14). The current HDV diesel standards are 75 per cent lower for NO_x and nearly 95 per cent lower for PM than those first introduced in 1996 (Figure 2.15).

Figure 2.14: Emission standard requirements for new heavy-duty diesel engines with time

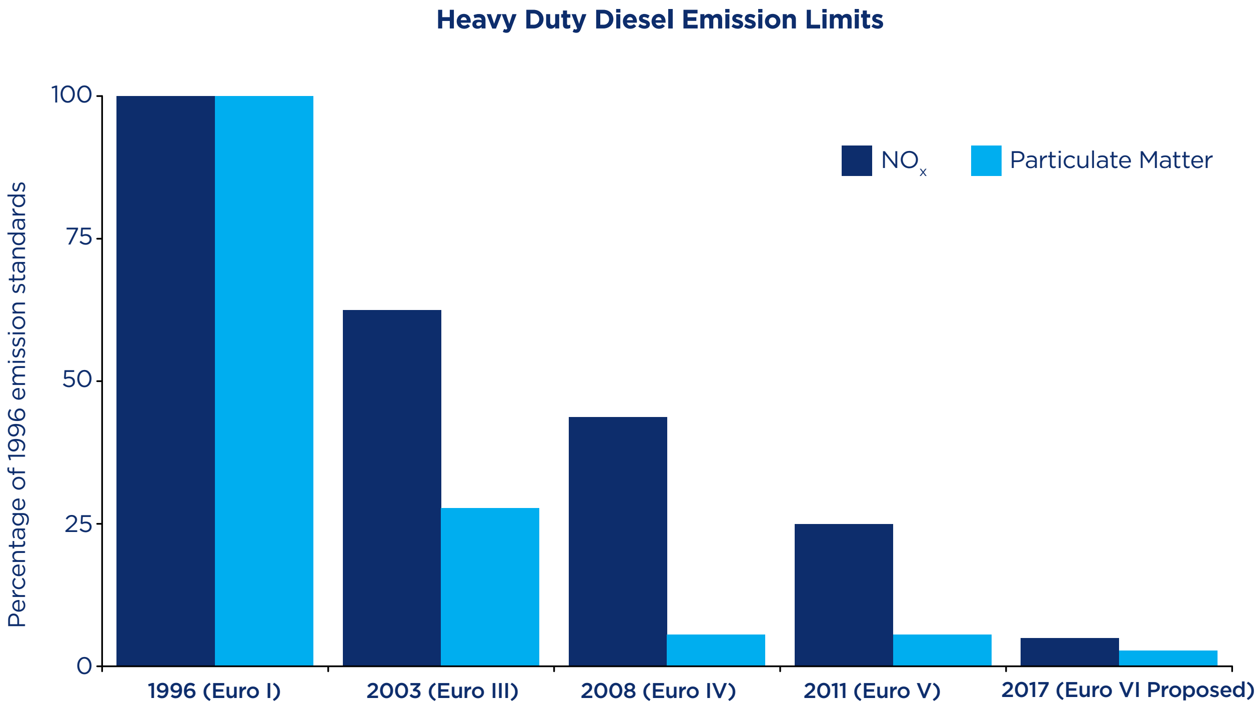
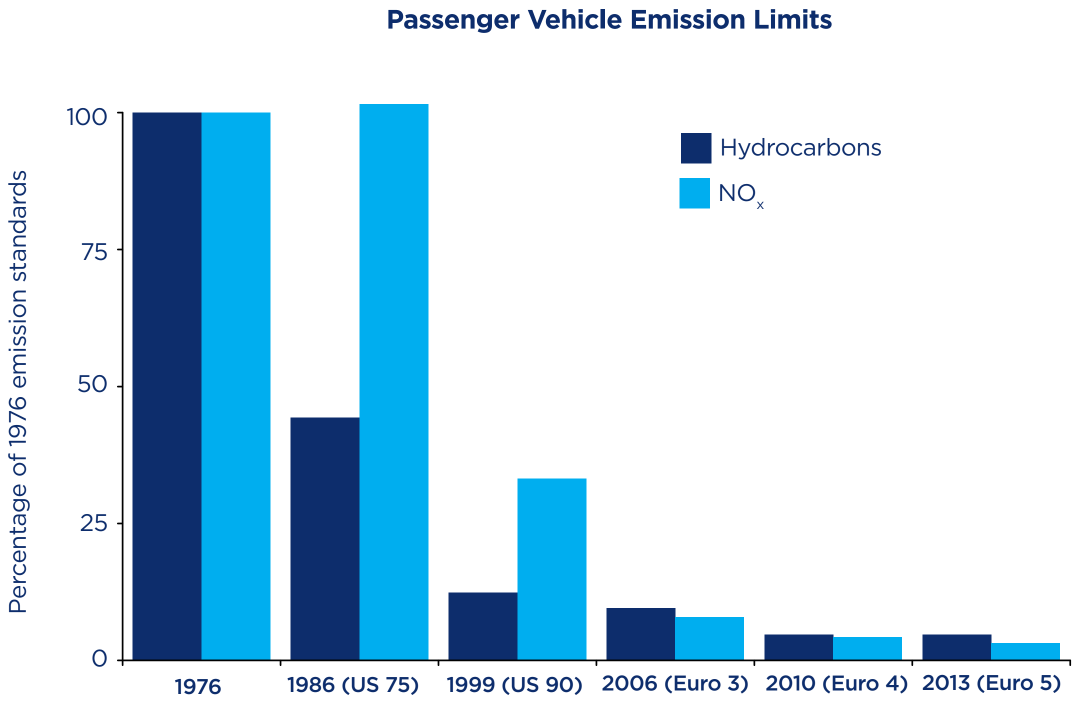


Figure 2.15: Emission standard requirements for new petrol passenger vehicles with time



As a result of these increasingly stringent emission standards, and also improvements in fuel quality, total exhaust emissions from motor vehicles have decreased over the past two decades. Emissions from road transport are also expected to continue to fall (Figure 2.16), despite a projected increase in the number of vehicles and the number of kilometres driven (Figure 2.17).

Figure 2.16: Projected emission trends for motor vehicles in the NSW Greater Metropolitan Region shown as a percentage of baseline year 2003

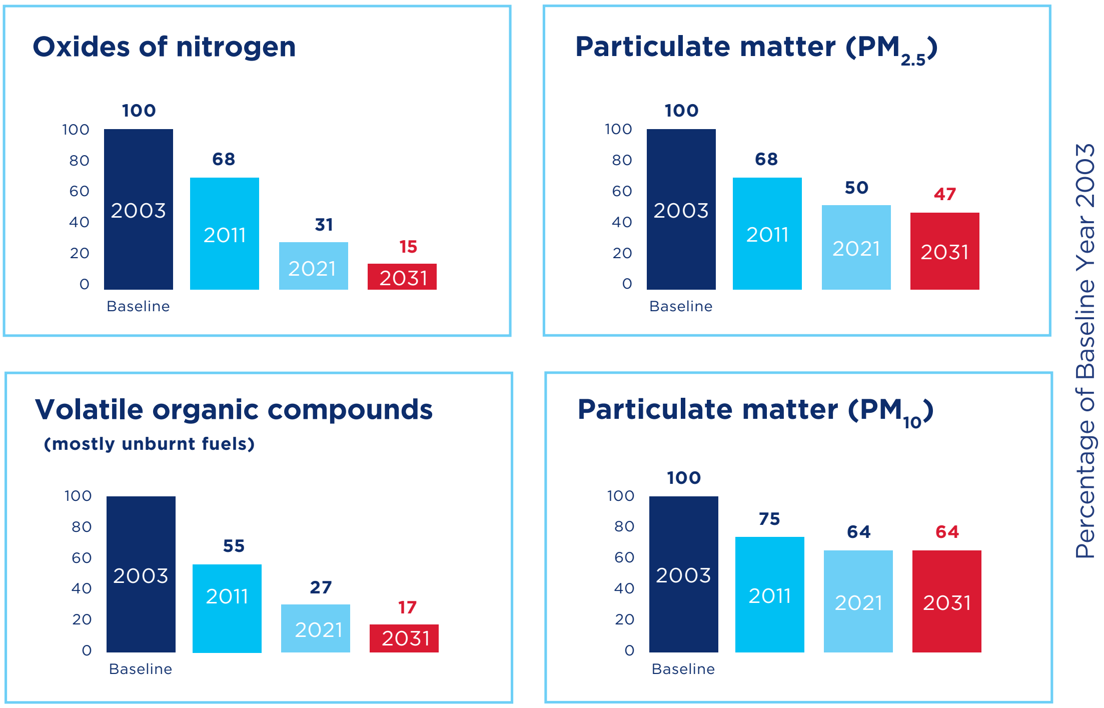


Figure 2.17: Historical and projected average weekday vehicle kilometres travelled (VKT) in NSW Greater Metropolitan Region

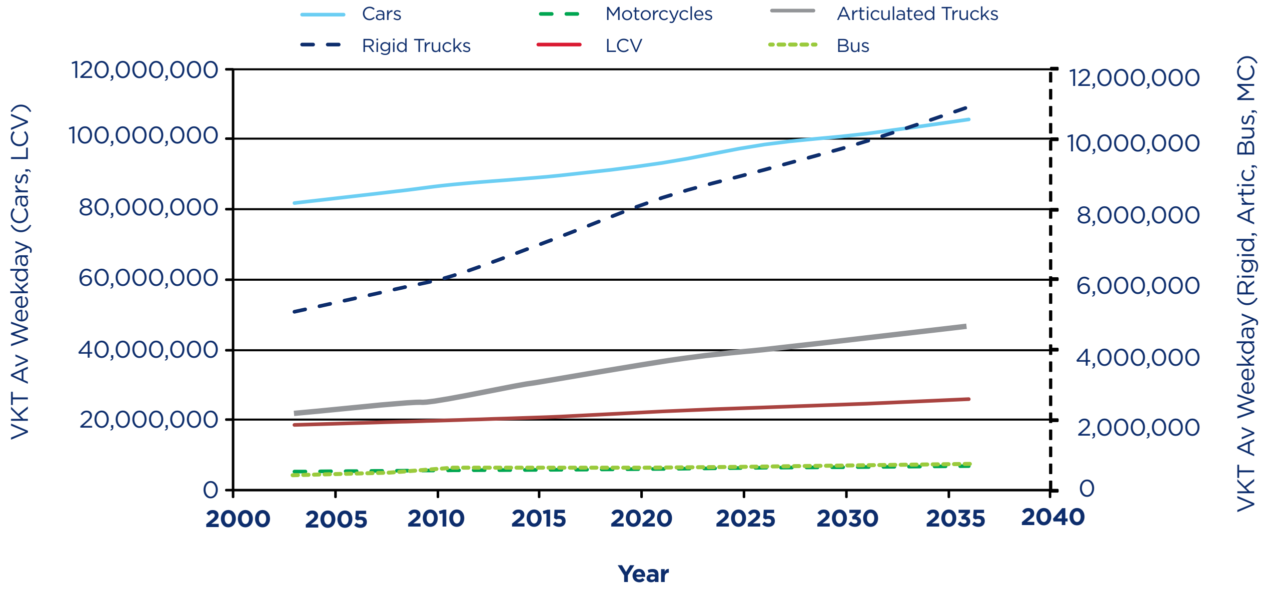


Figure note: The vehicle classes represented by the dashed lines refer to the right hand axis.

Additional detail on trends in motor vehicles and their emissions is provided in Technical Paper 1.

2.4. Health effects of traffic-related air pollution

Exposure to motor vehicle pollution is linked to several adverse health outcomes – ranging from irritation of the airways to early mortality. Reducing this exposure will provide various public health benefits, including improved cardiovascular and respiratory health and reduced rates of cancer.

One way of looking at the effects of motor vehicle pollution on health is to estimate the contribution of air pollution to the total burden of disease. Exposure to motor vehicle pollution is estimated to contribute less than 1 per cent of the health burden in Australia, as the Australian Institute of Health and Welfare calculated that urban air pollution was responsible for 1 per cent of the total burden of disease and injury in Australia in 2003 (Begg, 2007).

In-tunnel exposure to motor vehicle pollution is typically a small component of total exposure.

2.4.1. Health effects of proximity to traffic

Adverse health effects have been observed in association with proximity to roads. These effects persist after adjustment for traffic noise and socioeconomic status, and are only partly explained by exposure to $PM_{2.5}$. Therefore, it is likely that they result from exposure to other traffic-related pollutants, either individually or in combination (WHO Regional Office for Europe, 2013).

The Health Effects Institute synthesised the research on traffic-related air pollution exposure and health outcomes in 2010 (HEI, 2010), and concluded that exposure to traffic-related air pollution causes exacerbation of asthma. The evidence linking exposure to traffic-related air pollution to several other health outcomes was weaker, but was suggestive of a causal relationship. These outcomes were the onset of childhood asthma, non-asthma respiratory symptoms, impaired lung function, total and cardiovascular mortality, and cardiovascular morbidity. The HEI report identified that the area in the first 300 to 500m from a major road was the most highly affected by traffic emissions (HEI, 2010).

Non-combustion processes (brake wear, engine abrasion, tyre wear) also generate airborne PM. Toxicological studies have demonstrated that these non-exhaust emissions contribute to the health impact from exposure to traffic-related pollution (WHO Regional Office for Europe, 2013). Non-exhaust emissions are a significant source of on-road particle emissions in Sydney (NSW EPA, 2012). As exhaust emissions are further regulated and reduced, understanding non-exhaust emissions will increasingly become the focus to address health risks from future traffic pollution (HEI, 2010; WHO Regional Office for Europe, 2013).

2.4.2. Health effects from ozone exposure

Short-term exposure to ozone (hours) can result in reduced lung function, exacerbation of asthma and chronic respiratory diseases, and irritation and inflammation of the eyes, nose, throat and lower airways. There is a growing body of evidence to support the hypothesis that long-term exposure to ozone (years) may affect respiratory and cardiovascular mortality, and respiratory morbidity (WHO Regional Office for Europe, 2013).

The evidence is inconclusive for a threshold below which exposure to ozone is not associated with adverse health effects. However, from available evidence, if there is a threshold it would be below 0.045 ppm (1 hour average) (WHO Regional Office for Europe, 2013).

2.4.3. Health effects from fine particle exposure

A discussion of the commonly used PM measurement metrics was provided in Section 2.1.2. The health effects associated with these metrics are summarised below.

PM_{10}

Exposure to PM_{10} is associated with cardiovascular disease, respiratory disease and mortality. However, because PM_{10} includes $PM_{2.5}$ there is some uncertainty about how much of the observed effect is due to $PM_{2.5}$ and how much is due to the coarse PM size fraction ($PM_{10\text{-}2.5}$).

$PM_{2.5}$

There is very good evidence that exposure to $PM_{2.5}$ causes cardiovascular disease, respiratory disease and mortality. Associations have also been observed between $PM_{2.5}$ exposure and reproductive and development effects such as low birth weight.

UFPs

Motor vehicle exhaust is an important source of UFPs in urban settings (HEI, 2013). Ultrafine particles are thought to play a role in the adverse health impacts seen in association with exposure to PM pollution, although the epidemiological evidence of their effects is limited (HEI, 2013; WHO Regional Office for Europe, 2013). The World Health Organization (WHO Regional Office for Europe, 2013) recommends that current efforts to reduce the numbers of UFPs in vehicle emissions should continue and, until there is clearer evidence of the concentration-effect relationship for UFPs, management of PM should continue to focus on PM_{10} and $PM_{2.5}$.

A key feature of PM is that no threshold has been identified below which exposure is not associated with adverse health effects, therefore, reductions in ambient concentrations of PM would provide public health benefits.

2.4.4. Health effects from exposure to nitrogen dioxide

Nitrogen dioxide is a good marker of traffic-related pollution. Toxicological studies have found effects of NO_2 at levels far exceeding those normally observed in ambient air (WHO Regional Office for Europe, 2006). Nitrogen dioxide is highly correlated with other pollutants from combustion sources, which has made it very difficult to separate the effects of NO_2 from the effects of other traffic-related pollutants, especially PM. However, there is increasing evidence that indicates there are independent effects of NO_2 separate from PM (WHO Regional Office for Europe, 2013).

2.4.5. Carcinogenicity of air pollution and its constituents

The International Agency for Research on Cancer (IARC) has classified outdoor air pollution as carcinogenic to humans (IARC Group 1) (Loomis et al., 2013). The IARC has also concluded that diesel engine exhaust is carcinogenic to humans (Group 1). In coming to this conclusion, IARC found that diesel exhaust is a cause of lung cancer (ie there is sufficient evidence of this) and noted a positive association (ie there is limited evidence of this) with an increased risk of bladder cancer (Benbrahim-Tallaa et al., 2012). Benzene and formaldehyde (VOCs linked to vehicle exhaust) have also been classified by IARC as Group 1 carcinogens (IARC, 2009).

Further information on the health effects of traffic related air pollution is provided in Technical Paper 3.

2.5 Summary

Having provided an overview of the characteristics and issues related to ambient air quality and air quality related to vehicular traffic, the sections that follow deal more specifically with road tunnels and associated air quality.

3. Control of tunnel pollution by ventilation

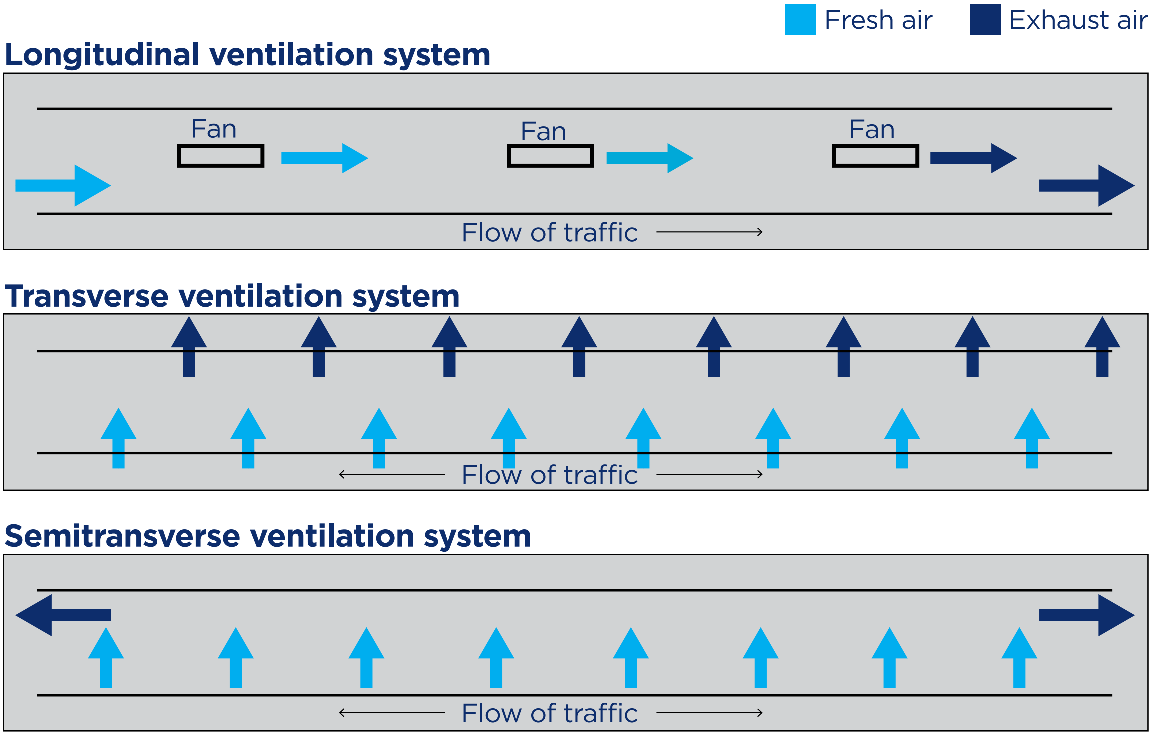
Good practice for tunnel ventilation must achieve the following requirements:

- Air quality inside the tunnel meets the relevant criteria for health and visibility.
- Discharges of vehicle emissions to the external atmosphere comply with the relevant ambient air quality standards, guidelines and targets.
- During fire events heat and smoke is managed and extracted from the tunnel, safe exit of vehicle occupants is enabled, and access for emergency services to deal with the fire is provided.

3.1. Tunnel ventilation system design

Figure 3.1 illustrates the three basic design options for tunnel ventilation, and these are described in the following paragraphs.

Figure 3.1: Illustration of the airflow in longitudinal, transverse and semi-transverse ventilation systems



3. Control of tunnel pollution by ventilation

Passive ventilation

Vehicles moving through a tunnel induce their own airflow in the same direction. This is known as the 'piston effect', and it is the basis of passive ventilation. Passive ventilation requires no additional ventilation infrastructure, and is generally only used over shorter distances. It is most effective if all the traffic is proceeding in the same direction. In situations where traffic flows in opposite directions within the same tunnel tube, there is reduced or no piston effect as the vehicle (and resulting air) flowing in opposite directions may cancel each other out. This is one of the reasons why many road tunnels have two separated tubes, one for each direction of travel.

Mechanical longitudinal ventilation

Mechanical longitudinal ventilation refers to installations in which the piston effect is boosted by fans to increase the ventilation rate. The significant reduction in vehicle emissions since the 1970s has enabled longitudinal ventilation systems to be used in longer tunnels while maintaining acceptable in-tunnel air quality during operation. According to the French Centre for Tunnel Studies, mechanical longitudinal systems can be used for any tunnel length provided there is an emergency smoke extraction system (CETU, 2003). Mechanical longitudinal systems have been routinely used since the 1990s in long, busy urban tunnels. Examples include the M5 East tunnel (Sydney), the Cross City tunnel (Sydney), Tate's Cairn tunnel (Hong Kong) and the Shing Mun tunnel (Hong Kong), all of which are over 2 km long. All road tunnels built in Australia in the last 20 years have been designed with longitudinal ventilation systems.

Transverse and semi-transverse ventilation

Transverse ventilation is a system that delivers fresh air and removes exhaust air at points along the full length of the tunnel. Normally, fresh air enters via the roof and exhaust air leaves through the floor. However, tunnels with a fully-transverse system are uncommon, and semi-transverse ventilation systems are more prevalent. These systems are based on either the provision of fresh air (the more common option) or the removal of exhaust air at points along the full length of the tunnel.

Longitudinal, transverse and semi-transverse systems can all be designed to use exhaust stacks, so that some or all of the air is discharged at height from stacks where improved dispersion of tunnel air is required to protect local air quality around a portal.

Additional information on road tunnel ventilation systems is provided in Technical Paper 4.

3.2. Stack operation and performance

Even when apparently still, the atmosphere is very dynamic and the air is constantly moving. Stacks work by exploiting this turbulent mixing to efficiently disperse pollutants. This point has been recognised by air quality scientists and air pollution engineers for decades, and has led to the widespread adoption of the stack as a means of reducing the impact of atmospheric releases.

The predictive air quality modelling of tunnel stacks is well tested and conservative in nature. Due to the very long history of stacks being used to disperse industrial air pollution, there are numerous validated and extensively used atmospheric dispersion models to predict stack impacts. These models are used by regulatory agencies and research communities; these communities continue to improve these models over time.

Discharging vehicle emissions via well-designed stacks ensures that they are dispersed and diluted so that there is minimal or no effect on local ambient air quality (NZ Transport Agency, 2013). Modelling and monitoring studies generally conclude that the impacts of emissions from road tunnel stacks on their surrounding communities are mostly indistinguishable from the impacts from all other sources (principally surface traffic emissions, domestic and industrial emissions, and background contributions, including natural sources) (NHMRC, 2008).

As an example, modelling by CSIRO using actual emission data from the M5 East tunnel predicted the maximum contribution of the stack to annual average concentrations is less than 1 per cent of background for PM_{10}, and less than 3.6 per cent of background for NO_x (Hibberd, 2003) at any location around the stack[1]. These predicted levels would not be measurable by ambient monitoring equipment because they are significantly smaller than normal day-to-day variation in background levels.

Extensive ambient monitoring around motorway tunnels such as the M5 East, Lane Cove and Cross City tunnels demonstrates that tunnel stack emissions for those tunnels does not have a measurable impact on local or regional air quality (Holmes Air Sciences, 2001 and 2008; PAE Holmes 2009).

3.2.1. Predicting and assessing the impact of stacks

The use of stacks for dispersing air pollution has a long history – dating back to the industrial revolution. Consequently, numerous validated atmospheric dispersion models are available (and used) for predicting the impacts of stacks. These models perform well in predicting the dispersion of air pollutants, especially in locations with flat or simple terrain.

In areas where the terrain is more complicated (eg significant valleys and ridges) model predictions can be more uncertain. In these situations, the model uncertainty is generally compensated for by modelling conservative scenarios (eg worst case and/or applying safety factors). Uncertainty in dispersion modelling may arise if tall or large buildings are close to the stack. This uncertainty is generally managed by carefully selecting a model that best handles the local challenges, using conservative assumptions or safety factors in the modelling, or avoiding such locations if possible.

In general, there is a ‘diminishing returns’ relationship between stack height and ground impact, with increases in stack height leading to progressively smaller reductions in ground level concentrations. The accuracy of dispersion modelling for road tunnel stacks hinges on accurate estimates of traffic flow, traffic composition, traffic speed, vehicle emission factors, ventilation system operating parameters, and the stack exhaust temperature (which influences how buoyant the emissions are). Uncertainty relating to these parameters is generally addressed by making appropriately conservative assumptions for the model inputs.

It is common practice to assess stack impacts against air quality standards and guidelines, such as those specified by the NSW EPA in the *Approved Methods for the Modelling and Assessment of Air Pollutants in New South Wales*.

Further information on road tunnel stack emissions is provided in Technical Paper 5.

3.3. Portal emissions

A key operating restriction for the M5 East, Cross City and Lane Cove tunnels is the planning approval requirement for zero portal emissions. This restriction was initially applied to the M5 East tunnel as a precaution to protect residents around the tunnel portals, and was retained for the Cross City tunnel and Lane Cove tunnel.

To achieve zero portal emissions all tunnel air must be expelled from a stack, with air being drawn in from all portals (Figure 3.2). This requires drawing air against its natural direction of flow due to the piston effect at the exit portal. This increases the quantity of ventilation air required to be discharged through the stack, and increases the girth of the stack.

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[1] The greater contribution of NO_x reflects that motor vehicles contribute a much greater proportion of NO_x than PM emissions.

3. Control of tunnel pollution by ventilation

The implications of operating the ventilation system in this way can vary significantly with time of day, and may not be warranted at all times. For example, during periods of low traffic volume at night the air quality inside the tunnel may be essentially identical to the air quality outside the tunnel. Requiring the tunnel to meet a zero portal emissions condition during off-peak periods may have little appreciable environmental benefit, and could require significant energy use with related environmental and cost impacts.

Outside Australia almost all road tunnels have portal emissions. In most cases the impact of portal emissions on outdoor air quality is mitigated through design of the portal and/or its location. In urban areas it has historically been the norm for long road tunnels to supplement portal emissions through the use of ventilation stacks. For example, in two new major road tunnel projects currently planned for Hong Kong, 60 – 90 per cent of emissions are anticipated to be dispersed from stacks to reduce emission levels at the portals (AECOM, 2013; Arup-Mott MacDonald Joint Venture, 2013).

Reductions in vehicle emissions over the last few decades have meant that the need for ventilation stacks has diminished. In many cases overseas it has become possible to meet both in-tunnel and outdoor air quality requirements using portal emissions alone for some or all of the time. Furthermore, avoiding excessive ventilation is desirable from the point of view of energy efficiency. For instance, the semi-rural Hafnerburg tunnel on Zurich's busy by-pass had stacks removed from its design, and nearby on the same motorway the stacks for the new third tube of the 3.3 km-long Gubrist tunnel are expected to be used for fire emergency use only.

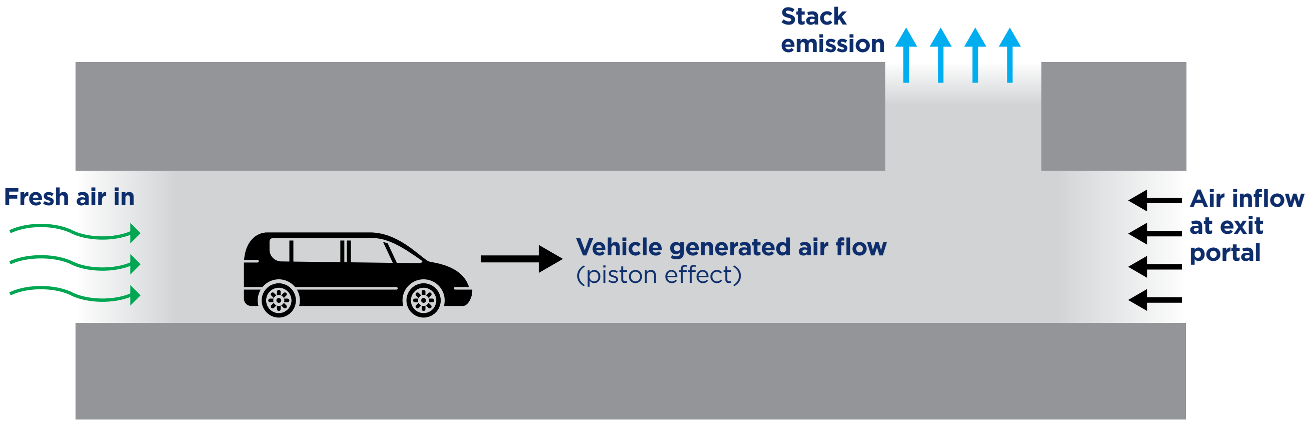
Both the 2.5 km-long Roer tunnel in the Netherlands and Hong Kong's busy 1.2 km-long Nam Wan tunnel both opened in 2009 without stacks. Stacks have generally been retained for urban tunnels in areas of particularly poor ambient air quality, or where there is a risk that the impact of portal emissions may not be adequately mitigated. Stacks can be seen as a precautionary measure that provides flexibility and resilience in the ventilation system design.

3.3.1. Predicting and assessing the impact of portal emissions

An important consideration in managing portal emissions is the potential for these emissions to adversely impact air quality of people near the portals.

The key characteristic of portal emissions is rapid and effective dispersion, reducing concentrations to background levels over relatively short distances. Our understanding of the impact of portal emissions on air quality comes from four types of evidence: computer modelling, wind-

Figure 3.2: Illustration showing tunnel air flow direction to avoid portal emissions



tunnel modelling, tracer-release experiments and air quality monitoring. Results from each of these approaches are broadly consistent. More specific key findings are:

1. Air exits the portal as a relatively fast-moving plume, but rapidly mixes with the ambient air.
2. In the immediate vicinity (about 10m) of the portal, air quality can be substantially worsened with the potential to exceed ambient air quality guidelines. However, the affected zone is normally limited to the roadway (McCrae et al.,2009, COB, 2009, Kuschel & Wickham, 2013).
3. Away from the immediate vicinity of the portal, concentrations of pollutants decrease rapidly, especially moving away from the roadway. The impact of portal emissions on roadside concentrations typically only extends up to about 100–200m from the portal (McCrae et al., 2009, Kuschel & Wickham, 2013). Beyond this distance, it is difficult to distinguish the impact of the portal from the surface road section (Brousse et al., 2005).
4. If the roadway is in a trench or cutting as it enters the portal, or is otherwise separated from the surroundings, the elevated concentrations can persist in the trench to larger distances from the portal, but locations to either side of the road will be afforded extra protection as lateral dispersion of pollutants is constrained (Brousse et al., 2005, COB, 2009).
5. There is generally little or no impact of portal emissions on the land above where the tunnel goes underground (Brousse et al., 2005).

While allowing portal emissions is common practice internationally, there is limited experience in NSW or Australia among proponents, operators and regulators in assessing and managing road tunnel portal emissions. This has been identified as an area for further investigation, and there would be benefit in developing a framework for the assessment and approval of portal emissions in a way that optimises energy use and operating costs while protecting the air quality of people living near the portals.

These investigations should give specific consideration to NO_2 levels surrounding portals due to the potential for extra NO_2 to be rapidly formed from in tunnel NO reacting with ozone (O_3) in the external air.

More information on road tunnel portal emissions is provided in Technical Paper 6.

3.4. Energy use

Table 3.1 shows the energy (electricity) consumption, tunnel length and daily traffic volume for four Australian road tunnels (three in Sydney and one in Melbourne). The energy consumption per km per year has also been calculated for each tunnel to allow a more direct comparison.

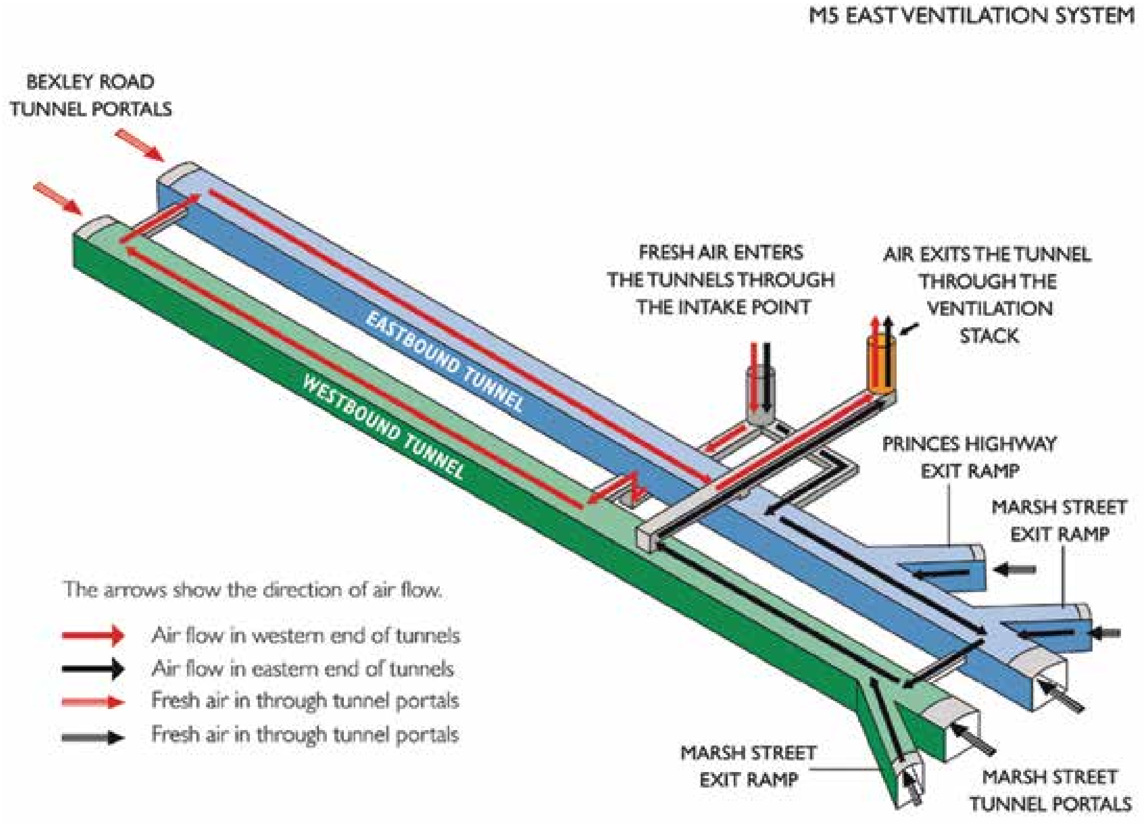
Table 3.1: Electricity consumption for four Australian road tunnels

Project	Electricity consumption (MWh/annum)	Total (2 way) tunnel length (km)	Traffic (vehicles per day)	MWh/km per annum
Eastern Distributor tunnel	4,400	3.2	110,000	1,375
Lane Cove Tunnel	15,400	7.2	70,000	2,139
CityLink tunnel (Melbourne)	21,500	5	100,000	4,300
M5 East tunnel	54,000	8	100,000	6,750

3. Control of tunnel pollution by ventilation

The M5 East ventilation system energy use is equivalent to that of nearly 7,400 households[2]. In addition to tunnel length and volume of traffic, a key driver of ventilation energy consumption is system complexity, and the M5 East has the most complex system of any Australian road tunnel (Figure 3.3). Air follows a circuit that is driven by fans and assisted by the piston effect of the traffic. During normal operation, fresh air is drawn into both tubes at intakes at Duff Street, Arncliffe, and at all portals. Near the end of each tube, air is directed from one tube to the other in cross-over tubes. This cross-over flow is controlled by fans with variable speeds that also control the flow of air at the portals. The exhaust air is removed into a ventilation tunnel approximately at the mid-point of the tunnel, and is expelled through a stack located approximately 900 m from the tunnel.

Figure 3.3: M5 East tunnel ventilation system



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[2] Average household energy consumption is 7,300 kWh/annum.

4. Options for reducing emissions from road tunnels

There are a number of options for reducing emissions from road tunnels. In evaluating these options it is important to bear in mind that tunnels do not create air pollution; rather, it is the motor vehicles moving through them. However, tunnels channel the motor vehicles and the associated air pollution. To reduce emissions from road tunnels it is therefore possible to either target the motor vehicles using the tunnel, or to treat the air pollution in the tunnel before it is released into the outside environment.

Tunnels form only a small proportion of the road network, and hence have negligible effect on regional air quality. More important considerations for tunnel design are optimising in-tunnel and local ambient air quality. For tunnels that are ventilated through well-designed stacks the effects on local air quality of reducing emissions will be very small; they have only negligible effect on local air quality. In-tunnel treatment systems have mostly been used where visibility levels are poor and increasing ventilation capacity is not practical, eg long tunnels under mountains.

Some potential options for reducing emissions from road tunnels, either at the (vehicle) source or after the point of emission, are discussed below.

4.1. Reducing overall vehicle fleet emissions

In 2008, the NHMRC found that the most effective long-term measure for improving air quality in and around tunnels – and throughout the road network – is to continue to implement measures to reduce emissions from vehicles. The NHMRC recommended that heavy duty vehicles should be a priority as emissions from heavy duty vehicles, particularly those that are poorly maintained, disproportionally contribute to emissions. Emission reductions from the whole fleet will deliver by far the greatest environmental benefits as they will improve air quality for everyone in the airshed. A continuing reduction in motor vehicle pollution is required for the future improvement of Sydney's air quality.

4.2. Smoky Vehicle Enforcement Program

Under NSW environmental legislation it is an offence for a vehicle to emit visible pollution for more than 10 seconds. The M5 East Smoky Vehicle Enforcement Project started on 1 March 2013 and uses a camera system to identify polluting vehicles in the M5 East tunnel. Operators of HDVs detected emitting excessive smoke inside the tunnel face fines of $2,000 for the first two offences. A third offence attracts a fine, as well as an automatic three-month suspension of vehicle registration. Offenders are invited to participate in a 'Diesel Retrofit and Repair Initiative'.

A Smoky Vehicle Enforcement Program for other tunnels:

- Could provide an in-tunnel benefit by reducing or eliminating gross-polluting vehicles from the tunnel, leading to improved visibility in the tunnel
- Could provide a regional air quality benefit if it results in an overall reduction in smoky vehicles
- Can be implemented using existing legislation and be based on the existing M5 East model

Further information on Smoky Vehicle Enforcement Programs is provided in Technical Paper 7.

4.3. Low-Emission Zones

Low-Emission Zones (LEZs) are areas in which vehicles are required to meet a minimum emission standard. Operators that do not meet these standards are subject to large fines if their vehicle(s) enter a LEZ. Although LEZs could apply to all types of vehicles, they have generally been applied to trucks due to their relatively large contribution to air pollution when compared with their representation in the vehicle fleet (Ellison et al., 2013). LEZs operate in many European cities, including London, as well as the ports of Long Beach and Los Angeles in the United States.

LEZs tend to be focussed on city and town centres, where land use is dense, traffic is heavy, and population exposure is high. Due to the high population exposure it is these locations that provide the largest potential health benefits of improved air quality (DEFRA, 2009).

Low Emissions Zones:

- Could provide an in-tunnel benefit by reducing or eliminating gross polluting vehicles from the tunnel, leading to improved visibility in the tunnel. Newer vehicles are less likely to be smoky vehicles
- Could provide a regional air quality benefit if it results in an overall reduction in fleet emissions
- Would require new legislation to implement

Further information LEZs is provided in Technical Paper 7.

4.4. Filtration and air treatment

Pollution control technologies have been used to clean the air in tunnels in a number of countries, including Norway, Austria, Germany and Japan. These technologies have included electrostatic precipitators to remove particles and catalytic, biological processes and adsorption technologies to remove nitrogen oxides. Evidence to date suggests the benefits of such controls when applied to road tunnels are limited to specific situations – eg improving visibility in long tunnels in Japan with a very high proportion of diesel vehicles (up to 50%) and in Norway where vehicles use studded tyres. However, technologies are pollutant-specific, only address local and not regional road transport-related air pollution and have significant capital and operational costs (PIARC, 2008; CETU, 2010; NZ Transport Agency, 2013).

The French Government undertook an international assessment of the treatment of air in road tunnels (CETU, 2010), and concluded that filtration systems are:

> *still bulky and less cost-effective than conventional ventilation systems, both in terms of investment and operation. Generally-speaking, these systems are also energy-intensive given the surplus ventilation requirements.*

The French Government report indicated that very few air filtration systems are routinely operated.

An 18-month trial of filtration of tunnel air was conducted in the westbound tunnel of the M5 East from March 2010 to September 2011. The filtration plant removed 200 kg of PM per year at a cost of $760,000 (operating costs only) (AMOG, 2012).

Damage costs are a simple way to value changes in air pollution. They are estimates of the costs to society of the likely impacts of changes in emissions. Damage costs assume an average impact on an average population affected by changes in air quality. Damage costs consider the impacts of exposure to air pollution on health – both chronic mortality effects (which consider the loss of life years due to air pollution) and morbidity effects (which consider changes in the number of hospital admissions for respiratory or cardiovascular illness).

Based on the damage cost for Sydney provided by PAEHolmes (2013), the estimated annual health benefit of removing 200kg PM is $56,000 at 2011 prices. This comparison suggests that the operating cost of removing PM in the M5 East was around 13 times the health benefits.

Table 3.2 compares the costs and PM_{10} reductions for the M5 East filtration trial and a range of other PM abatement measures. The then NSW Department of Environment Climate Change and Water (DECCW) engaged Sinclair Knight Merz to undertake a study to identify and analyse a range of emission abatement initiatives (SKM, 2010). In the Sydney Region, SKM identified 12 emission-reduction measures, with costs ranging from $1,000 per tonne to $274,000 per tonne of PM_{10} removed. A comparison with the damage cost for Sydney provided by PAEHolmes (2013) ($280,000 per tonne) indicates that all of the emission reduction measures considered in SKM (2010) would have health benefits that are greater than the costs.

This is consistent with the conclusions of the National Health and Medical Research Council that the most effective way to manage air quality both in and around tunnels is through vehicle fleet emission reductions (NHMRC 2008).

Table 3.2: Cost-effectiveness of PM_{10} reduction measures

PM_{10} reduction measure	Cost of PM_{10} reduction ($ per tonne)	Annual tonnes PM_{10} reduced
National emission standards for wood heaters (1 g/kg limit)	1,000	1,701
National emission standards for wood heaters (3 g/kg limit)	1,000	45
Emission limits for industry	5,000	359
Tier 4 emissions standards for off-road vehicles and equipment	12,000	31
Wood heaters – reduced moisture content of firewood	20,000	93
Small engines (2-stroke to 4-stroke) for recreational boating and lawnmowing	39,000	261
Truck and bus diesel retrofit program	151,000	1
Diesel locomotive replacement (USEPA Tier 0 to Tier 2)	156,000	53
Diesel locomotive replacement (USEPA Tier 0 to Tier 2 + Retrofit Tier 2 Locomotives with selective catalytic reduction)	191,000	72
Euro 5/6 emission standards for new passenger vehicles	209,000	131
Recommission and electrification of Enfield Port Botany freight line	244,000	3
Port Botany shore-side power	274,000	11
Approximate benefit of reducing PM (damage cost, PAEHolmes (2013)	280,000 per tonne	N/A
M5 East tunnel filtration (operating costs only)	**3,800,000**	**0.2**
M5 East tunnel filtration	**17,400,000**	**0.2**

Further detail on the options for treating road tunnel emissions is provided in Technical Paper 8.

5. Evolution of tunnels in Sydney

As summarised in Section 1, the NSW Government has more than 20 years of experience assessing and operating road tunnels, with five tunnels in operation in Sydney comprising extensive ventilations systems and stacks. There have been some important lessons learnt from the design and operation of the M5 East tunnel and other Sydney tunnels, and these include:

- The modelling and assessment processes for stack emissions are well established, robust and conservative.
- Extensive ambient monitoring around motorway tunnels such as the M5 East, Lane Cove and Cross City tunnels demonstrates that tunnel stack emissions do not have a measurable impact on local or regional air quality (Holmes Air Sciences, 2001 and 2008; PAE Holmes 2009).
- Emissions from well-designed stacks have negligible impact on surrounding communities and, as such, there is little health benefit in installing filtration and air treatment systems.
- It is important for community acceptance of road tunnels as an effective transport solution that tunnels are designed and operated to deliver a good user experience.

It is fair to say that, particularly in the first years after opening, the M5 East did not deliver a good user experience. As a result, the Lane Cove and Cross City tunnels were designed to ensure a good user experience. However, experience has shown that the Lane Cove and Cross City tunnel ventilation systems are over-designed, and that the approval conditions have resulted in inefficient operating regimes.

There are a number of lessons that can be learnt from the construction and operation of the M5 East, Lane Cove and Cross City tunnels that will enable future tunnel projects to have an efficient ventilation system that delivers a good user experience:

- **Minimising the gradient of the tunnel**

  The M5 East tunnel has a gradient of eight per cent at the exit of the westbound tunnel. This gradient resulted from a late design change to substantially reduce the number of truck movements on local roads during construction. The unintended consequence of this change is that vehicles exiting the westbound tunnel up this grade are under high load, significantly increasing emissions from HDVs. Consequently, the Cross City and Lane Cove tunnels were designed to minimise gradients. Similarly, a key design requirement for new road tunnel projects is to minimise road gradients.

- **Locating ventilation stacks close to entry and exit points**

  To address community concern regarding the location of the proposed three stacks for the M5 East tunnel, the ventilation system was redesigned to recirculate the tunnel air to a single stack 900 metres from the tunnel alignment. The design is inefficient, using significantly more energy than equivalent tunnels operating with ventilation stacks located near the portals. The most energy- and cost-effective location for stacks is at, or near to, the tunnel portals to avoid the use of additional energy to pull air though a service tunnel to a remote stack location.

- **Creating smooth traffic flows at the entry and exit points**

  Congestion within tunnels results in higher vehicle emissions and requires greater ventilation effort (ie energy use). Smoothing traffic flows at the entry and exit points to avoid congestion shortens the duration of the tunnel journey, thus reducing vehicle emissions within the tunnel. The Lane Cove tunnel was built with a two-lane entry and a three-lane exit to facilitate smooth traffic flow within the tunnel.

- **Regulation and elimination of smoky vehicles**

  The M5 East Smoky Vehicle Enforcement Project started on 1 March 2013, and uses a camera system that identifies polluting vehicles in the M5 East tunnel. Operators of HDVs detected emitting excessive smoke inside the tunnel face fines of $2,000 for the first two offences. A third offence attracts a fine as well as an automatic three-month suspension of vehicle registration. Offenders are invited to participate in a 'Diesel Retrofit and Repair Initiative'.

- **Increasing the clearance height and width of the tunnel**

  Sydney's tunnels have traditionally been built with a tight cross section to minimise construction costs and spoil generation. This limits the maximum volume of ventilation air that can flow through the tunnel, and may result in a more expensive ventilation system design. A lower clearance height compared with the adjacent network results in a greater frequency of over-height truck incidents, resulting in tunnel closures and network congestion.

More information on the evolution of tunnels in Sydney is given in Technical Paper 9.

6. Regulation of tunnels

6.1. Role of government agencies

The NSW Government manages the assessment, approval, construction, and operation of motorway tunnels and ventilation stacks as follows:

Department of Planning and Environment (DP&E) assesses proposals under the *Environmental Planning and Assessment Act 1979* (EP&A Act), and in consultation with State government agencies. The assessment process is public and transparent, with opportunities for agencies and the public to provide comment.

The Minister for Planning is the approval authority. If approved by the Minister an approval for a road tunnel will typically contain limits for both in-tunnel air quality and stack emissions, together with monitoring requirements.

The Minister for Planning and DP&E regulate the construction and operation of project in accordance with the project approval. These functions are generally delegated to the Secretary (or her nominee) under the approval.

The Environment Protection Authority licenses construction, and provides technical advice to DP&E on operational air quality impacts during the assessment and approval process.

NSW Health advises DP&E on air quality health impacts, including appropriate health assessment methodologies for in-tunnel and ambient air quality.

The role of regulators for tunnel projects is discussed further in Technical Paper 10.

6.2. Air quality criteria for tunnels

6.2.1. Ambient criteria

The assessment criteria for ambient air quality impacts from both tunnel and portal emissions are well established, and are provided in the *Approved Methods for the Modelling and Assessment of Air Pollutants in New South Wales* (NSW DEC, 2005).

6.2.2. Emission limits

Emissions limits for stack emissions – and potentially for portal emissions – can be determined in accordance with the procedures specified in the *Approved Methods for the Modelling and Assessment of Air Pollutants in New South Wales* (NSW DEC, 2005). Emission limits set using these procedures will protect the health and amenity of the surrounding community.

6.2.3. In-tunnel criteria

In the past, a CO limit has been used to provide protection against all other motor vehicle pollutants. However, reductions in CO emissions per vehicle have been more significant than reductions in PM and NO_x. Consequently, there is relatively more NO_2 (and PM) 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 limits in addition to the current CO limits. However, most of the health evidence regarding exposure to traffic emissions is based on ambient exposure lasting hours, days or longer, and the significance of exposure lasting minutes is an area of uncertainty. The international NO_2 limits are not consistent, reflecting scientific uncertainties and different precautionary stances. At the present time protection from exposure to road vehicle pollutants in-tunnel is provided through a combination of the existing CO and visibility limits. However, as the composition of vehicle emissions continues to change, the addition of a duly considered NO_2 limit would provide additional protection in the future. This has been identified as an area for further investigation.

Additional detail on the criteria for in-tunnel and ambient air quality is provided in Technical Paper 11.

6.3. Monitoring tunnel emissions and impacts

Monitoring of emissions and air quality can be conducted for several purposes, including:

a) Understanding the levels and sources of air pollutants, and associated trends
b) Establishing levels of exposure
c) Demonstrating compliance with conditions (eg air quality standards such as the NEPM, or consent conditions such as stack emission limits or in-tunnel limits)
d) Air quality management (eg pollution alerts, traffic management)
e) Developing and validating air quality model predictions
f) Tunnel ventilation control

Depending on the objectives, monitoring may be a limited-duration campaign, long-term or permanent. A variety of methods are available for monitoring pollutant concentrations in a range of environments, with a wide variation in durability, sensitivity and precision.

Monitoring methods should be selected considering the purpose and objectives of the monitoring program. The following are key factors to consider when selecting a monitoring method:

- **Purpose and objectives of monitoring:** ie screening, compliance monitoring or research. Different requirements apply to different types of monitors
- **Durability and robustness:** the monitoring method must be able to operate reliably in the environment it is deployed eg ambient air, in-tunnel or stack emission monitoring
- **Detection limit (sensitivity), precision and measurement range:** the method must be able to measure within the required range, based on the monitoring objective
- **Ease of use:** some instruments can be time consuming to maintain and operate, requiring frequent replacement of parts and regular manual calibration

6.3.1. Standard monitoring methods

Standard monitoring methods provide the requirements, specifications, and characteristics to ensure a monitoring method is fit-for-purpose. Standard monitoring methods are practical and achievable.

The NSW EPA specifies standard methods for monitoring stack emissions and ambient air quality in the *Approved Methods for the Sampling and Analysis of Air Pollutants in New South Wales* (NSW DEC, 2007).

Standard monitoring methods support consistent regulation and reporting of pollutant concentrations. Standard monitoring methods are often referred to in statutory documents such as planning approvals.

6.3.2. In-tunnel monitoring

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 there are a number of techniques for monitoring in tunnel NO_2 levels. Although standard methods are specified for stack and ambient NO_2 monitoring, they do not take into account the specific circumstances of the in-tunnel environment.

There is scope to investigate and recommend fit-for-purpose standard methods for monitoring in-tunnel air NO_2 levels to improve ensure consistency across projects.

6.3.3. Portal emission monitoring

There is relatively little information internationally regarding the monitoring of pollutant emissions from tunnel portals to inform ventilations system operation. Further investigation is warranted to develop fit-for-purpose monitoring of portal emissions. This would form part of the development of a framework for the assessment and approval of portal emissions such that energy use and operating costs can be optimised while protecting air quality of people living near portals.

7. Conclusions and recommendations

The application of current knowledge on the design, assessment and operation of road tunnels can be used to make decisions regarding the air quality impacts of road tunnels.

Tunnel ventilation systems, stack operation and performance are very well understood nationally and internationally. Experience gained from more than 20 years of operating road tunnels in NSW demonstrates that tunnel ventilation systems can be operated to achieve the desired in-tunnel air quality, and stacks can be designed and operated so that they have no discernable impact on ambient air quality.

There are three areas where further work could be undertaken to improve decisions regarding the design and operation of road tunnel proposals:

1. **Provide information and make recommendations on the assessment and management of portal emissions to improve ventilation system efficiency, reduce overall environmental impacts and provide appropriate protection of the air quality for tunnel users and the community in the vicinity of the tunnel portals.**

This should include exploring the potential for:

a. optimising portal design on new tunnel projects to maximise dispersion and minimise impacts through the use of physical or computer models (eg wind tunnels or computational fluid dynamics)

b. an investigation of the potential for partial portal emissions at an operating Sydney tunnel without increasing nearby residents' exposure to vehicle emissions.

2. **Research, develop and make recommendations on in-tunnel NO_2 limits.**

At the present time protection from exposure to all road vehicle pollutants in-tunnel is provided through a combination of the existing CO and visibility limits. However, as the composition of vehicle emissions continues to change, the addition of a duly considered NO_2 limit would provide additional protection in the future.

3. **Investigate and recommend fit-for-purpose standard methods for monitoring in-tunnel air NO_2 levels to improve ensure consistency across projects.**

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. There are a number of techniques for monitoring in-tunnel NO_2 levels. Although standard methods are specified for stack and ambient NO_2 monitoring, they do not take into account the specific circumstances of the in-tunnel environment.

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