# Technical Paper

## TP05: Road Tunnel Stack Emissions

Advisory Committee on Tunnel Air Quality

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# Key Points

- Road tunnel ventilation stacks work by exploiting the natural mixing of the atmosphere to efficiently disperse air pollutants. This point has been recognised by air quality scientists and pollution engineers for decades, and has led to the widespread adoption of the stack as a means of reducing the impacts of pollutant emissions from many sources.
- Due to the 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 collaborate continuously to improve and update these models.
- Experience from previous motorway tunnel projects, both in Sydney and in other areas of the world, has demonstrated that air dispersion modelling for tunnel stacks is robust and conservative, and that tunnel ventilation stack emissions result in nearby residents experiencing little, if any, increase in exposure to vehicle emissions.

# Contents

# 1. Introduction

Polluted air in tunnels can either be vented at the tunnel portals (ie where traffic also exits the tunnel) and/or from elevated ventilation outlets (eg stacks). This paper considers stack emissions, whereas portal emissions are covered in *Technical Paper 04 – International Practice for Tunnel Ventilation Design.*

# 2. When are stacks used?

Most road tunnels release exhaust air to the atmosphere at the exit portals. If the tunnel is short, or traffic volumes are low, there is insufficient build-up of emissions to cause a significant air quality problem. In longer, busier tunnels, however, pollutant levels can rise to levels that may cause concern.

Tunnel portals are often either in cuttings or adjacent to hillsides (Figure 1). This means that they are partly sheltered. Sheltering reduces the dispersion[1] of vehicle emissions and can cause a localised air quality problem typically extending a few tens of metres around the portal (see Technical Paper 4 for more details). In rural or remote locations where few, if any, people are exposed (except for the short period when driving through), this is not considered to present a risk. In urban locations, however, especially if there are nearby residences, more people could be exposed for much longer.

It is in these situations that stacks are used to provide an additional or alternative outlet for polluted tunnel air.

*Figure 1: Road tunnel portals are sheltered from wind either by being in a cutting (left) or in a hillside (right)*

Of the many thousands of tunnels in the world, only a small proportion (estimated as at less than one per cent) vent exhaust air vertically through either slots or stacks. Stacks are generally only used for tunnels longer than about 1 km to reduce, or eliminate, emissions from portals in urban areas.

In most cases, the stack provides an additional outlet, so that emissions from the portals of a longer or busier tunnel are reduced to levels comparable to a shorter or less busy tunnel. However, it is also possible to use stacks to reduce portal emissions to zero by using fans to redirect air (e.g. against the flow of traffic exiting the tunnel) and into a tunnel stack, albeit with an energy cost. This is used in special cases where portal emissions are not permitted.

This approach is used to eliminate portal emissions in the existing M5 East, Lane Cove and Cross City tunnels. At the time of writing, the planning approvals for the NorthConnex, the M4 East, New M5 and M4-M5 Link tunnels do not allow portal emissions. However, zero portal emissions are highly unusual internationally, where the ability to split emissions between the stack and portals is usually retained.

There are some longer tunnels without stacks that emit solely through portals located in non-residential semi-urban areas, such as the 1.37 km Hafnerberg tunnel (2005) on the outer edge of Zurich and the 1.2 km Nam Wan tunnel (2009) in an exposed port-industrial zone in Hong Kong. This has become possible because improved engine and fuel technology have significantly reduced noxious emissions from vehicles, and the levels of air pollution in tunnels (see T*echnical Paper 01 – Trends in motor vehicles and their emissions*).

1 Dispersion describes the mixing and dilution of pollution by turbulence in the atmosphere.

# 3. How do stacks work?

Stacks improve dispersion and lower ground level concentrations of vehicle emissions compared to releases at ground level by:

- moving the point of release further away from people at ground level, giving more time and distance for emissions to dilute
- moving the point of release higher in the atmosphere where dispersion is improved by more turbulence and stronger winds.

The atmosphere around us is constantly on the move. As the wind blows, even very lightly, several processes generate eddies and irregular random motion, a process called turbulence (Figure 2). This is especially true as the wind blows across the rooftops and treelines of the city, both of which create a drag effect that triggers and strengthens this turbulence. The effect is that small pockets of air are continually pushed up and down and sideways, and very effectively mixed together. The same happens horizontally, especially as air blows past the corners of buildings and around obstacles. If a pollutant is released into the air it instantly becomes part of this complex turbulent motion and is rapidly mixed with clean air, diluting it very effectively. At the same time, the wind carries it away from the point of emission and the turbulence continues the process of dilution. In Sydney, wind speeds are greater than 2 km/h for about 90 per cent of the time[2], and higher wind speeds further aid dispersion.

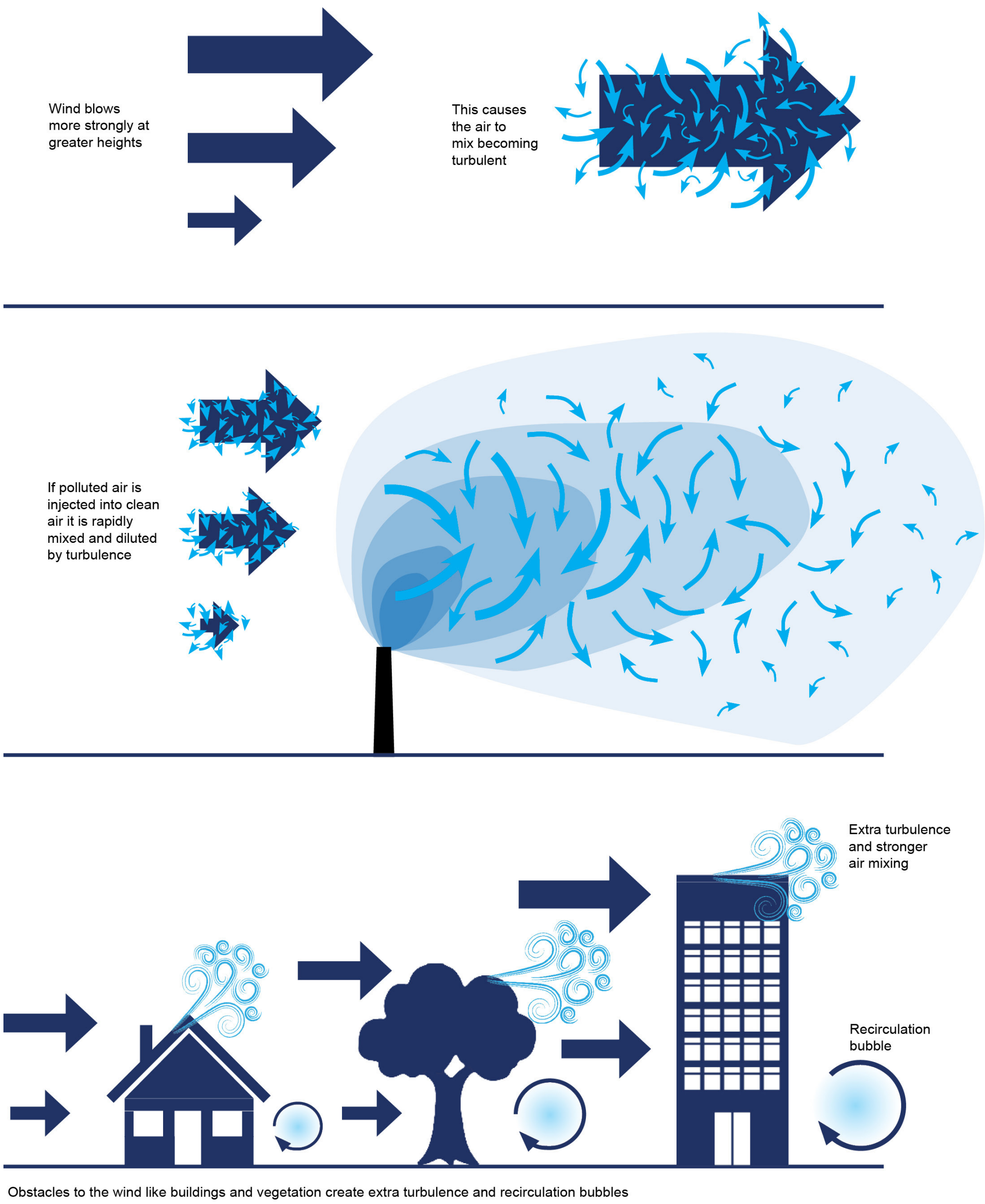


*Figure 2: Turbulence in the air, how it mixes and dilutes pollutants and how it is affected by buildings and vegetation*

2 Based on measurements at the OEH Randwick station which is considered the most representative station for Sydney due to minimal obstructions.

As height increases, winds become stronger (Figure 3). Most of the increase occurs in the first 10 m above the surface. In more open locations in Sydney it is estimated that average wind speeds increase by 36 per cent between 5 m and 20 m height above the ground. Above that, winds continue to increase but at a lesser rate, eg 13 per cent between 20 m and 35 m and eight per cent between 35 m and 50 m.

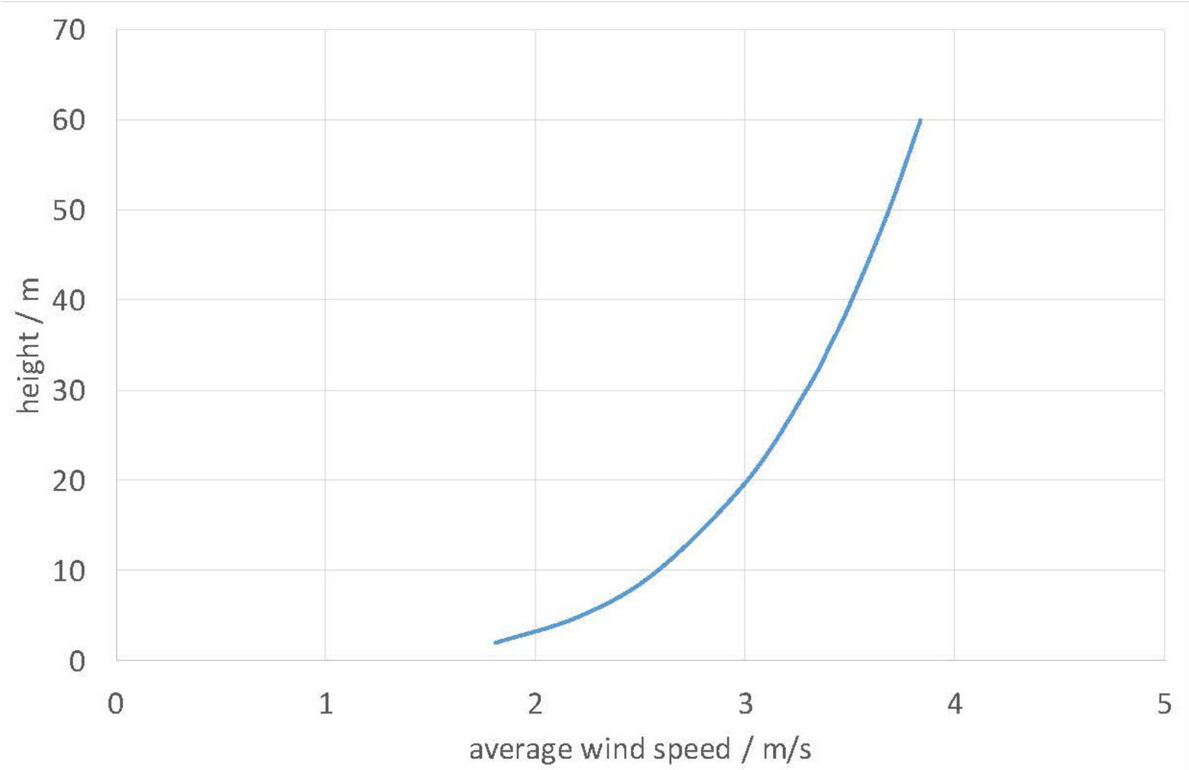


*Figure 3: Typical variation in average wind speed in Sydney with height based on standard modelling practice using typical conditions at Turella and for a 10 m wind speed of 2.5 m/s*

# 4. Why do stacks provide better dispersion than portals?

The difference in dispersion between portals and stacks can be explained by considering the fundamental principles of how air moves.

At ground level, obstacles can result in a sheltering effect causing localised 'recirculation bubbles' in which air can be temporarily trapped. This is especially true in the road cuttings typical of tunnel portals.

Stacks improve dispersion and lower ground level concentrations compared to emissions released at ground level by:

- moving the point of release further away from people at ground level, giving more time and distance for emissions to dilute
- moving the point of release higher in the atmosphere where dispersion is improved by more turbulence and stronger winds.

The combination of these effects is why stacks disperse tunnel emissions much more effectively than portals.

# 5. Where are stacks located?

Stacks are normally located as close as possible to the exit portals. This is especially important in those tunnels where the release of emissions through the tunnel portals is not permitted. This is to reduce the energy required for pumping air against the flow of traffic or through separate ducting from the portal to the stack.

However, in some cases the area near the portal may not be suitable for a stack due to unfavourable dispersion conditions (eg it is sheltered or overlooked by buildings or vegetation). The simplest and most common response to this limitation is to increase the stack height. However, that is not always possible (eg height limits for aircraft safety).

In principle, if there are practical constraints on the use of a stack adjacent to a portal (eg localised sheltering, height restrictions, etc), there is the option to duct the exhaust air to a less constrained location. In a small number of cases, this flexibility is used to relocate stacks not for reasons of improved dispersion, but in response to community concern about the impact of the stack. However, moving the location of the stack away from the portal results in additional capital, operational and maintenance costs that increase with distance without delivering any gains in air quality. In practice, displacements greater than around 100 m are rare. The displacement of the M5 East stack approximately 1 km away from the tunnel is an exceptional case. In 2017 the M5 East ventilation system consumed 49,245 MWh of electricity, equivalent to the electricity used to power 9,500 households.[3] Table 1 below compares the M5 East energy use to two other Australian road tunnels.

*Table 1: Electricity consumption for three Australian road tunnels*

| Project | Electricity consumption (MWh/annum) | Total (2 way) tunnel length (km) | Traffic (vehicles per day) | MWh/km per annum |
|---|---|---|---|---|
| Lane Cove Tunnel | 15,400 | 7.2 | 70,000 | 2,139 |
| CityLink tunnel (Melbourne) | 21,500 | 5 | 100,000 | 4,300 |
| M5 East tunnel | 49,245 | 8 | 100,000 | 6,156 |

3 Average household electricity use in 2017 was 5137 kWh (Report To Australian Energy Regulator, Energy Consumption Benchmarks Electricity And Gas For Residential Customers, Acil Allens Consulting, 13 October 2017)

# 6. How tall does a stack need to be?

To ensure low ground level concentrations, a road tunnel stack needs to have an 'effective' height that ejects tunnel air sufficiently clear of obstacles that could retain, trap or otherwise draw tunnel air down to the surface.

The 'effective' height of the stack is higher than the stack itself (Figure 4). Pollutants are discharged vertically to the atmosphere by a stack, propelled up with a momentum provided by the ventilation fans (Table 2), pushing the emissions higher into the atmosphere. For example, modelling for the M4-M5 Link predicts that, on average, effective stack heights are 67 – 89 m higher than the stacks themselves which range from 20 – 35 m high (Table 3). Even greater plume rise will occur in lighter winds. Plume rise is reduced in stronger winds (by about a third in the strongest winds) but the reduced effective stack height is compensated for by the increased dispersion due to the faster wind.

*Table 2: Average stack exit velocities (speed at which exhaust air leaves the stack) measured in three Sydney tunnels.*

| Tunnel stack | Plume vertical exit velocity | |
|---|---|---|
| | (m/s) | (km/h) |
| M5 East | 19 | 68 |
| Cross City | 8 | 28 |
| Lane Cove (westbound) | 5 | 19 |
| Lane Cove (eastbound) | 7 | 24 |

*Table 3: Average plume rise and effective stack heights, modelled for the three M4-M5 Link stacks*

| Stack | Stack height (m above ground level) | Mean plume rise (m) | Mean effective stack height (m above ground level) |
|---|---|---|---|
| Rozelle H | 35 | 67 | 96 |
| Rozelle I | 35 | 77 | 108 |
| Rozelle J | 35 | 81 | 109 |
| Iron Cove | 20 | 89 | 99 |
| St Peters | 22 | 87 | 101 |

Stacks are usually required to be taller than adjacent buildings and vegetation to be effective. Consequently, stacks in highly built-up areas tend to be taller. Where the stack is located in close proximity to a building taller than around one-third the height of the stack, modelling should be conducted that explicitly accounts for the interaction between the building and the plume to ensure that dispersion will be appropriate.

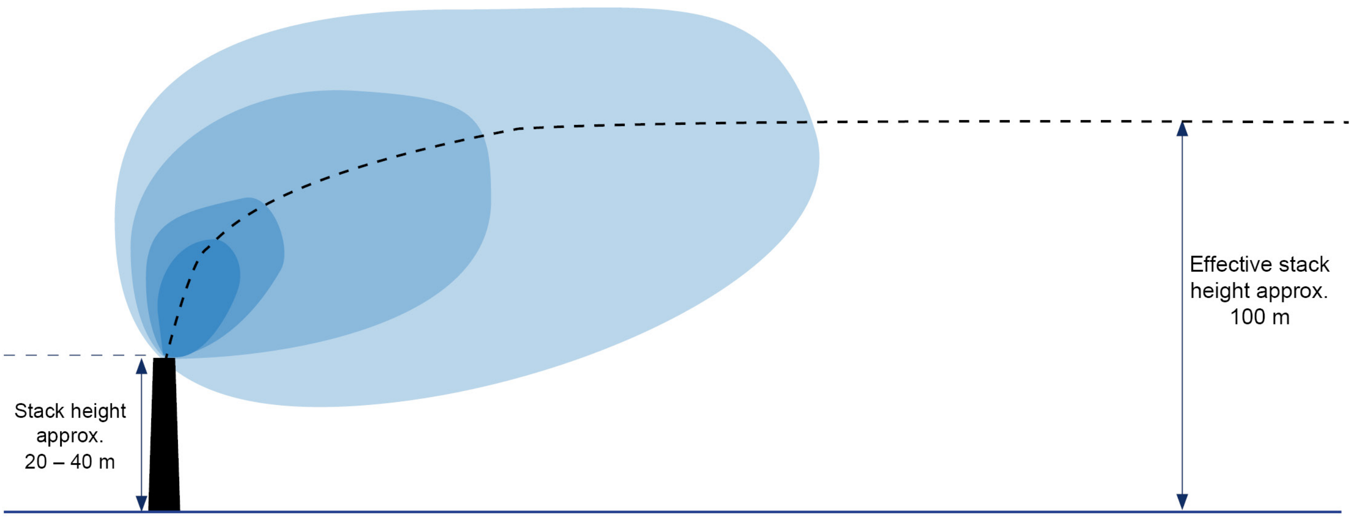


*Figure 4: The 'effective' height of the stack is higher than the stack itself.*

# 7. How do road tunnel stacks differ from industrial stacks?

Stacks have historically been used to disperse emissions from industrial facilities. These emissions are usually either combustion products from energy generation (burning of coal, oil, gas or other fuels) or waste products from industrial processes. Concentrations of combustion product emissions in modern day power plant stacks are far higher than concentrations of emissions found in urban road tunnels. Industrial process emissions may contain toxic emissions that are not present in road tunnels.

For these reasons, industrial stacks can be much taller than road tunnel stacks (eg several power plant stacks in NSW exceed 200 m in height). They are also more likely to require additional mitigation measures to meet licence criteria, such as a range of technologies to remove particles or certain substances from the exhaust air before it leaves the stack.

Oxides of nitrogen ($NO_x$) and particulate matter (PM) are two commonly used indicators of air pollution from fuel combustion, although PM may also include dusts, fumes and other particulate emissions from industrial processes or from mechanical abrasion (e.g. tyre and brake wear).

Table 5 compares measured concentrations in selected Sydney tunnels with the limits set in the planning approvals, and limits for industrial emissions. Care must be taken when comparing emission limits for air pollutants as differences in averaging periods and reference conditions influence the comparability of pollutant concentrations. This comparison demonstrates that:

- the emission limits for recent tunnel projects are well below the most stringent emissions limits in the NSW legislation
- the approval limit for PM of 1.1 mg/m$^3$ is approximately half the most stringent European Union (EU) limit for large combustion plant of 2 mg/m$^3$
- actual PM emissions from operating tunnels range from 0.05-0.30 mg/m$^3$, well below the most stringent NSW regulation limit of 20 mg/m$^3$ (for crushing, grinding, separating or materials handling activities) and the most stringent EU limit of 2 mg/m$^3$ (for large combustion plant)
- the approval limits for $NO_x$ of 20 mg/m$^3$ are comparable to the most stringent EU limits for large combustion plant which range from 10-25 mg/m$^3$
- actual $NO_x$ emissions from operating tunnels range from 1.3-9 mg/m$^3$, well below the most stringent NSW regulation limit of 70 mg/m$^3$ and below the most stringent EU limit of 10 mg/m$^3$.

*Table 5: Typical daytime concentrations of $NO_x$ and PM in tunnels, plus selected approval limits*

| Stack | $NO_x$ (mg/m$^3$) | PM (mg/m$^3$) |
|---|---|---|
| Lane Cove | 1.3 – 5.0 | $PM_{2.5}$: 0.06 – 0.15<br>$PM_{10}$: 0.08 – 0.17 |
| Cross City | 1.8 | $PM_{2.5}$: 0.05<br>$PM_{10}$: 0.07 |
| M5 East | 6.0 – 9.0 | $PM_{10}$: 0.30 |
| **Emissions Limit** | | |
| Approved limits for NorthConnex, M4 East and New M5 | 20 | 1.1 |
| NSW Regulation Limit for scheduled premises[1] | 70[3] | 20[4] |
| EU Best Available Techniques for Large Combustion Plants[2] | 10 – 2[5] | 2[5] |

1. https://www.legislation.nsw.gov.au/#/view/regulation/2010/428/sch4
2. Large Combustion Plant BREF, EU 2017 http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32017D1442&from=EN
3. Any turbine operating on gas, being a turbine used in connection with an electricity generating system with a capacity of 30 MW or more
4. Crushing, grinding, separating or materials handling activities
5. This is the most stringent annual average limit in the Large Combustion Plant BREF.

# 8. Where do pollutants go after leaving the stack?

After being discharged vertically to the atmosphere via a stack, the majority of stack emissions are transported many kilometres and become part of Sydney's background air quality. The emissions do not readily return to the ground, except in a highly diluted form. The pollutants found in road traffic exhaust, including particles, are not significantly heavier than air. The heaviest particles likely to be present in stack emissions will be of the order of 10 µm (one hundredth of a millimetre) in diameter (eg Gustafsson et al, 2016). Particles this small are light enough to remain suspended in the air for a day on average. Consequently, both particles and gases are generally transported away from the stack faster than turbulence can mix the bottom part of the plume down to the surface. It is important to understand however, what happens on the occasions when the bottom part of the plume is mixed down to ground level near the stack. This is to ensure that the stack is designed so that local air quality is protected.

Atmospheric dispersion models are computer programs that solve the mathematical equations that simulate how air pollutants disperse in the atmosphere. Dispersion modelling is the most flexible method to study the way a plume disperses after leaving a stack. We use dispersion models to describe the typical properties of a tunnel stack plume. Monitoring data can validate dispersion models and confirm that emissions dilute so they have little, if any, impact on local air quality. Monitoring studies however, cannot answer the following questions across the full geographical area of interest including:

- How many times do emissions dilute before being mixed down to ground level?
- What is the maximum contribution to local air pollution due to stack emissions?
- At what distance does the maximum contribution occur?

Due to the large number of road tunnel projects in Sydney, a database has been created of simulated tunnel stack dispersion encompassing hundreds of thousands of hours of simulated Sydney meteorology. In general, this modelling as represented in Figure 5 has shown:

- The pollutant will have diluted by over a thousand times after leaving the stack and over ten thousand times for taller stacks (Tables 6 and 7). This contrasts with portal emissions where dilution ratios are more like a hundred-fold at a distance of 50 – 100 m from a typical portal.
- For a typical tunnel stack, the maximum ground level impact is very low (<0.2 µg/m$^3$ of $PM_{2.5}$ annual average) compared with typical Sydney background levels of between 7 and 8 µg/m$^3$.
- The maximum ground level impact of the plume is typically 200 – 1,200 m downwind of the stack, with this distance increasing with stack height.
- Little, if any pollutant returns to ground level close to the stack's base.

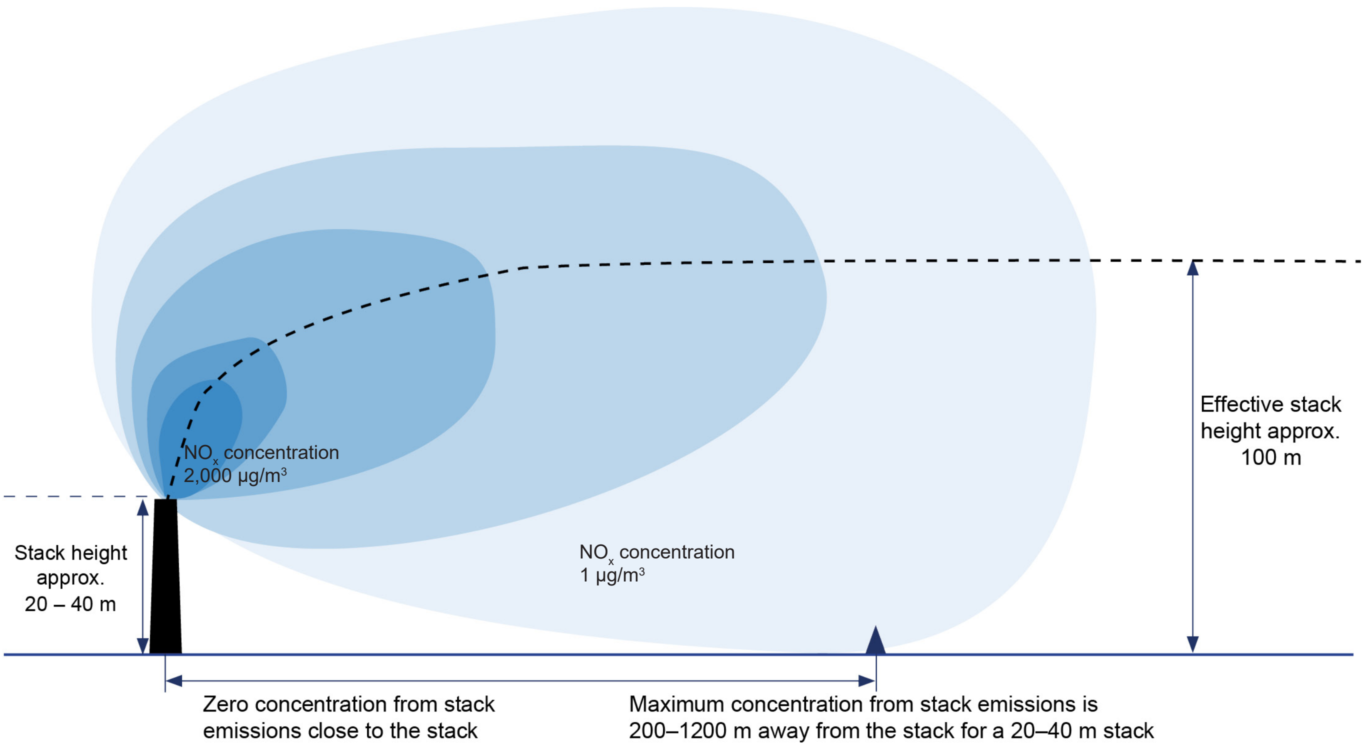


*Figure 5: Features of dispersion from a typical stack. The air pollution leaving the stack is rapidly diluted by wind and air movements. Note how only a small proportion of the plume is likely to reach the ground – most remains above the height of the top of the stack*

*Table 6: Typical concentrations and dilutions provided by selected Sydney tunnel stacks. Based on modelled concentrations of oxides of nitrogen*

| Tunnel stack | Stack height (meters) | Average stack concentration (μg/m³) | Peak ground-level impact (μg/m³) (annual average) | Approximate dilution ratio |
|---|---|---|---|---|
| M4-M5 Link St Peters Interchange | 22 | 2800 | 1.75 | 1600 |
| New M5 (westbound) | 30 | 2400 | 0.6 | 4000 |
| Lane Cove (westbound) | 24 | 518 | 0.1 | 5200 |
| Lane Cove (eastbound) | 60 | 1875 | 0.11 | 17000 |

*Table 7: Typical concentrations and dilutions provided by selected Sydney tunnel stacks. Based on modelled concentrations of* $PM_{2.5}$

| Tunnel stack | Stack height (meters) | Average stack concentration (μg/m³) | Peak ground-level impact (μg/m³) (annual average) | Approximate dilution ratio |
|---|---|---|---|---|
| M4-M5 Link St Peters Interchange | 22 | 310 | 0.193 | 1600 |
| New M5 (westbound) | 30 | 300 | 0.076 | 4000 |
| Lane Cove (westbound) | 24 | 28 | 0.0053 | 5200 |
| Lane Cove (eastbound) | 60 | 69 | 0.0042 | 17000 |

## 8.1 Effect of temperature inversions

In normal conditions, the air temperature gets colder with increasing height. This allows emissions that are normally warmer than the surrounding air to rise until they reach equilibrium with the atmosphere, where they mix and disperse effectively.

Sometimes the air temperature increases with height. The situation of having warm air on top of cooler air is referred to as a temperature inversion or inversion layer because the temperature profile of the atmosphere is 'inverted' from its usual state.

In Sydney, inversions are fairly uncommon, but can occur in winter on cool, clear nights when the earth's surface loses heat quickly. Since air is a very poor conductor of heat, the air just above the surface remains warm, resulting in a temperature inversion. During the daylight hours, inversions normally weaken and disappear as the sun warms the earth's surface.

A temperature inversion acts as a barrier to the vertical mixing of air. Releases of pollutants close to ground level can result in emissions becoming 'trapped' under a low level inversion. This situation can be seen in Sydney in winter when wood heater emissions become trapped close to ground level on cold winters mornings. As the ground heats up and vertical mixing begins to occur in the atmosphere, these emissions can be rapidly mixed down to ground level.

Elevated stacks have two advantages over lower level releases during inversion:

1. They can release emissions into the atmosphere above the inversion layer. In this situation, the inversion acts as a 'floor', preventing emissions from mixing down to ground level.
2. They move the point of release of emissions further away from people at ground level, giving more time and distance for emissions to dilute.

The effect of inversions and stack height is illustrated in Figure 6.

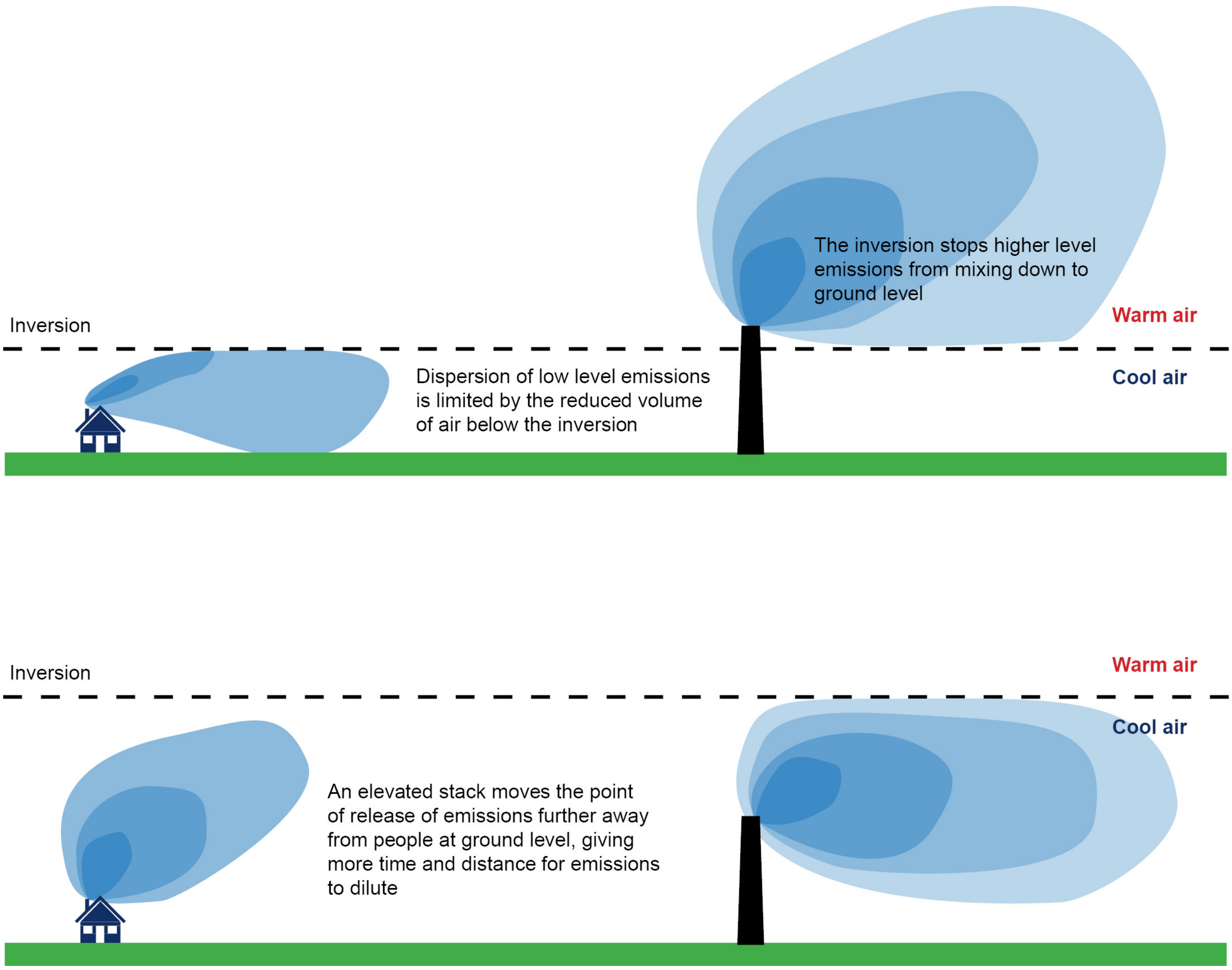


*Figure 6: Inversions and stack height*

The effect of temperature inversions have been recognised for decades, so commonly used dispersion models (including the GRAMM/GRAL system) incorporate the effects of inversions.

# 9. How do stack impacts compare with other exposures to traffic pollutants in Sydney?

Figures 7 and 8 show the dilution of road traffic exhaust pollution from the tailpipe to the urban background environment where most people live.

Figure 7 shows how most of that dilution occurs in the first second after pollutants exit the tailpipe. The values in Figure 7 represent typical concentrations of nitrogen dioxide measured in an extensive study in Sydney's road tunnels and the surface motorways that link them (PEL, 2016). Although all of these tunnels are mechanically ventilated, this does not need to be as effective as the natural ventilation of open roads by the wind (due to the short time spent in the tunnel). This means that in-tunnel concentrations are higher than on the surface road sections. It can also be seen that a vehicle cabin provides a limited amount of protection to the occupants (this degree of protection can be substantially increased if the vents are closed and air recirculated).

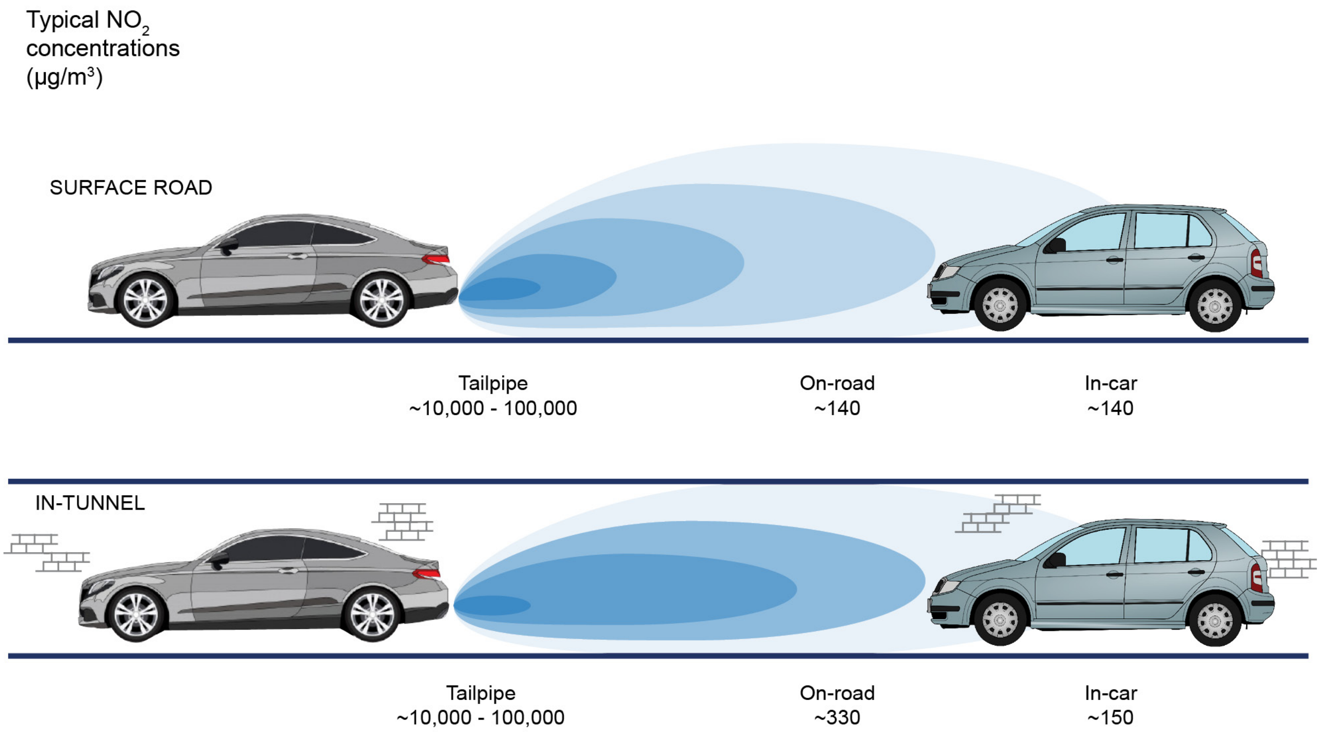


*Figure 7: The first few seconds – dilution of tailpipe emissions and impacts on vehicle occupants*

Figures 8 to 10 below summarise what happens as the polluted air leaves a surface road, a sunken tunnel portal (with portal emissions), and a tunnel stack respectively. Compared to Figure 7, in Figures 8 – 10 we switch from nitrogen dioxide ($NO_2$) to oxides of nitrogen ($NO_x$) due to better data availability. These values are all based on extensive monitoring data from multiple sites across inner Sydney and present approximate annual average concentrations.

Figure 8 shows how the combined action of the wind and turbulence rapidly dilutes pollutants over the first 10 m or so from a roadway, and then more gradually thereafter. Once the pollutants are around 200 m from the road they have fully mixed in with the surrounding air (and diluted emissions from other roads in the city) to reach an 'urban background' concentration.

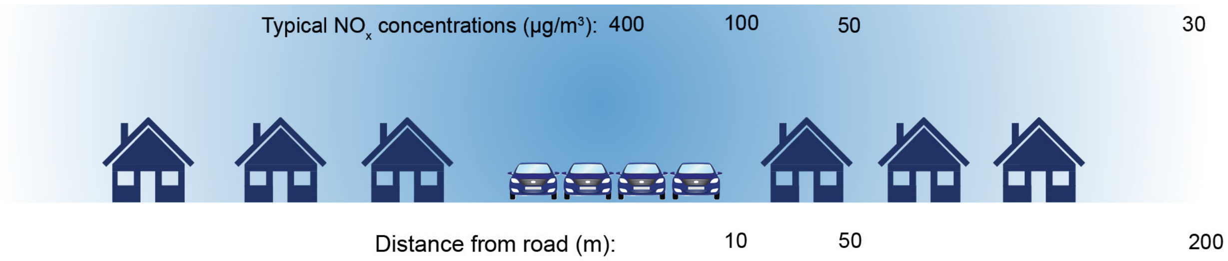


*Figure 8: The next few minutes – dilution of tailpipe emissions away from the roadway*

Figure 9 shows comparable data of the downwind impact of emissions from a road tunnel portal with portal emissions. Portal emissions are not permitted in most Sydney tunnels. The data here is taken from measurements around a portal on the Landy tunnel on the busy A1 motorway in Paris (200,000 vehicles/day, compared to 100,000 on weekdays in the M5 East tunnel) (Brousse et al, 2005). It can be seen that concentrations still fall to an urban background level over about 200 m. However, concentrations are progressively higher than for a surface road as you get closer to the portal. This figure is indicative - the specific details depend on the orientation of the road and detailed topography and layout (see *Technical Paper 04 – Road tunnel ventilation systems*), traffic volume, composition and road grade.

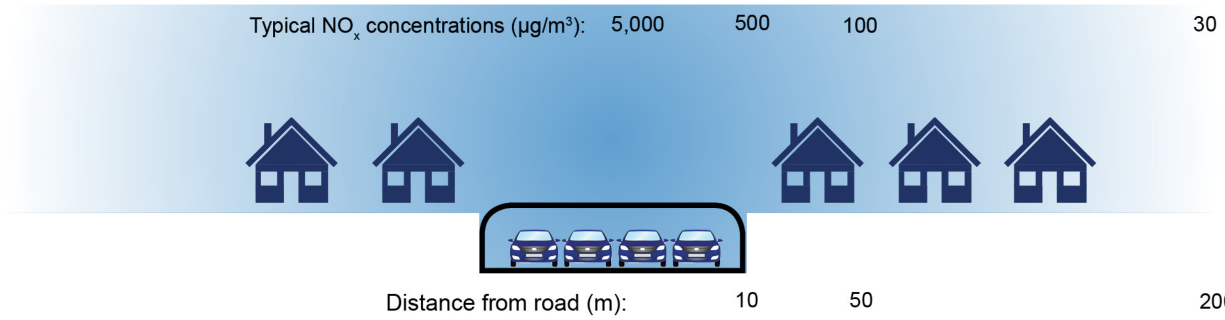


*Figure 9: Dispersion around a sunken tunnel portal (with portal emissions) – data based on measurements at the Landy tunnel in Paris*

The monitored values summarised in Figures 8 and 9 should be compared with the maximum modelled annual average contribution of tunnel stacks of up to 1 µg/m$^3$ of $NO_x$ (or 1.75 µg/m$^3$ in the case of the St Peters stack on the M4-M5 Link). The concentration of $NO_x$ 10 m from a busy road is 100 µg/m$^3$, 70 µg/m$^3$ higher than urban background levels. At 50 m from a busy road, the $NO_x$ concentration is still 50 µg/m$^3$, 20 µg/m$^3$ higher than urban background levels.

In comparison, the maximum increase due to stack emissions is 1 µg/m$^3$ (see Figure 10), 20 to 70 times less than the increase within 50 m of a busy road. This is because dispersion from a surface road is hindered by lower winds and obstructions compared to effective dispersion from a stack.

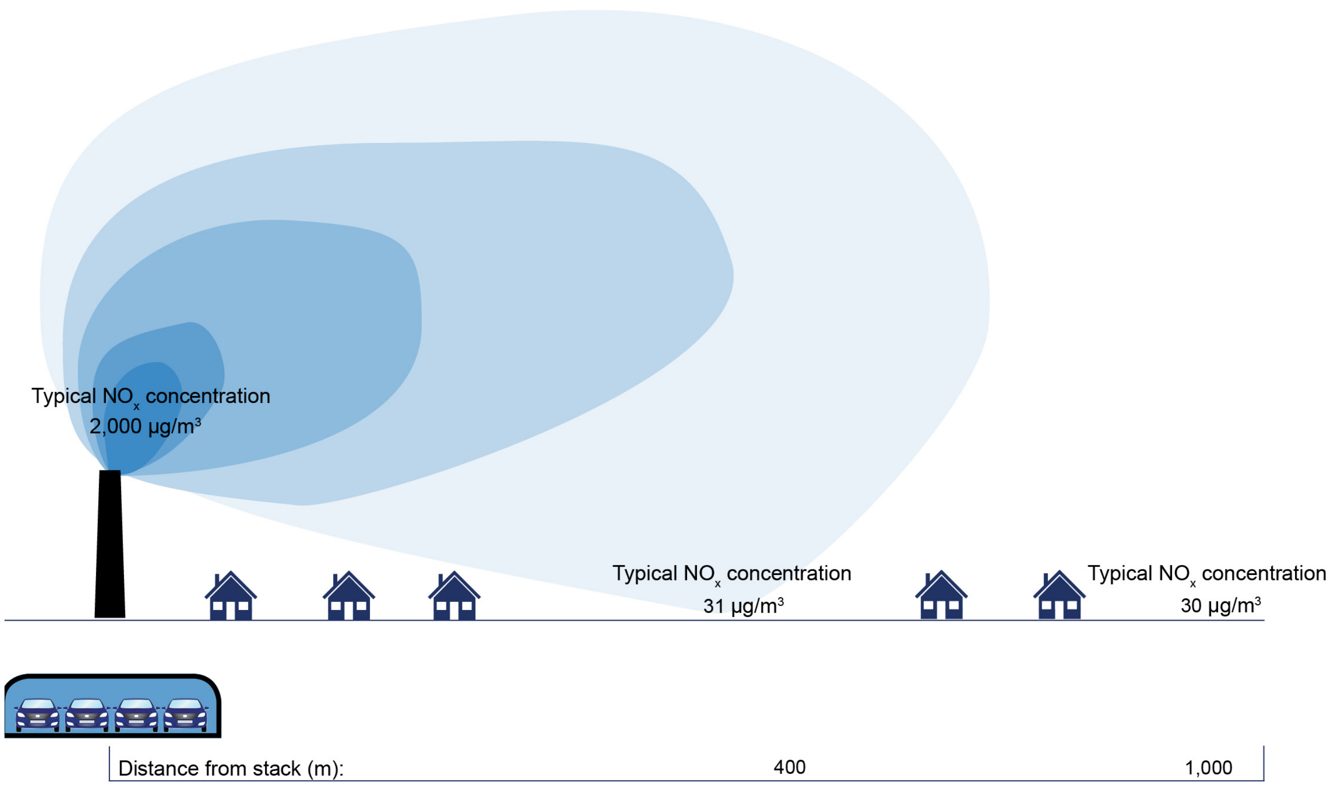


*Figure 10: Dispersion from a tunnel stack*

# 10. How good are the dispersion models?

The use of stacks for dispersing air pollution has a long history – dating back to the industrial revolution. The scientific theory of stack dispersion was initially developed from the 1930s to the 1960s (Sutton, 1932, 1947) and refined when compared to observational data (Pasquill, 1961, Gifford, 1961). However, these early observations were limited by the technology of the day – a common method being to release oily smoke at ground level or from a tower (Barad et al, 1954), and either relying on 'eyeball' estimates of spread and distance of smoke or by putting out sheets of filter material to be stained by the passing plume. Sometimes photos were taken for later analysis.

From the 1960s chemically inert and distinct 'tracers' began to be used that could be sampled at various points in the plume and accurately measured in the laboratory (Eggleton and Thompson, 1961; Vanderborght and Kretzschmar, 1967). Several major model validation experiments were conducted in the 1980s (Hanna, 2000). Particularly important are the Kincaid, Tracy and Indianapolis experiments. In each case the tracer sulfur hexafluoride (SF6) was released from the top of a power plant stack for over 100 hours and sampled hourly at up to 200 locations around the stack. Crucially, the data collected from these and many other experiments are freely available and have been widely used to validate and compare dispersion models (eg Hurley & Luhar, 2005).

Complex analytical methods to evaluate a model's ability to reproduce these measurements have been developed (and continue to be improved) by the international research and regulatory community, all of which is openly documented in detail in the scientific literature. Extensive literature, guidance and handbooks are available. For example, the USEPA hosts the Support Center for Regulatory Atmospheric Modeling – their website (https://www.epa.gov/scram) holds extensive model documentation, history, evaluation tools and reports, including archived observational data for model evaluation from at least 17 major experiments (including Kincaid, Tracy and Indianapolis). Statutory and non-statutory guidance is provided by various other bodies (eg NSWEPA, 2017, MfE, 2004). Regular international forums are also held to maintain transparency and advance understanding and consensus, such as the International Conference on the Harmonisation of Atmospheric Dispersion Models (http://www.harmo.org) held regularly for over 20 years.

This combination of improved data quality and open sharing of data has allowed the science of stack dispersion in open and flat terrain to mature so that it is now very well understood. Since the 1970s research has increasingly focussed on dispersion in more complex situations such as mountainous terrain, complex building clusters, low wind conditions, and buoyant or heavy gases. The understanding built up over the years has become incorporated into the range of atmospheric dispersion models that are commonly used to assess dispersion from stacks today.

The result is that atmospheric dispersion models perform well in predicting the dispersion of air pollutants, especially in locations with flat or simple terrain. Model predictions can be more uncertain in areas where the terrain is more complicated (e.g. valleys and ridges). In these situations, the model uncertainty is generally compensated for by modelling conservative scenarios (e.g. worst case and/or applying safety factors). Uncertainty in dispersion modelling may also 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, and using conservative assumptions or safety factors in the modelling.

The accuracy of dispersion modelling of 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). These are difficult to specify before a tunnel opens. However, this uncertainty is generally effectively managed through:

- Appropriately conservative modelling assumptions
- 'Regulatory worst case' modelling scenarios in which a stack is assumed to operate continuously at an upper limit of emissions, which in practice would rarely or never occur.

It is common practice to assess stack impacts with respect to a jurisdictions air quality impact assessment criteria which can be consistent with ambient air quality standards and guidelines, such as the National Environmental Protection Measure for Ambient Air Quality (AAQ NEPM), or international equivalents, and WHO Guidelines.

# 11. Monitoring stack impacts

Post-construction monitoring programs for road tunnel stack impacts are not common internationally. This is largely because the science of stack dispersion is mature and very well understood. The dispersion models used were extensively validated using specially collected observational data in carefully controlled trials, largely from the 1960s to 1990s. An exception would be dispersion in the lee of obstructions which typically requires more advanced modelling techniques and remains subject to some uncertainty.

Nevertheless, observational studies or monitoring programs have been established in the case of some road tunnel projects in NSW, as conditions of the planning approval issued by the Minister for Planning. The purpose of these programs is to validate modelling predictions and to provide the community with reassurance regarding a stack's effectiveness.

Where monitoring is undertaken, this can include the continuous measurement of key air pollutants over months or years. It can also include screening-style passive sampling campaigns, in which low-cost samplers provide an average concentration of a given pollutant over a week to a month.

Five continuous ambient air quality monitoring sites were installed around the M5 East Tunnel, four at the Cross City tunnels and six around the Lane Cove tunnel in Sydney, as well as two each (one for each stack) at the CityLink and EastLink tunnels in Melbourne. Analysis of monitoring data for the M5 East tunnel concluded that nearby residents experienced little, if any, increase in exposure to vehicle emissions, that air quality in the area had experienced no significant change and therefore the impact of the stack on the community was negligible (Barnett et al, 2003). Data from this monitoring confirmed the pre-construction modelling to be weakly conservative (Beyers et al, 2003).

For a given pollutant, the use of multiple ambient air quality monitors at different locations near a stack enables the impact of the stack to be distinguished from other influences. For instance, the use of five ambient air quality monitoring sites within the vicinity of the M5 East tunnel stack made it possible to determine that occasional high pollution values, especially those for $PM_{10}$, were related to background sources (predominantly bushfires) and were not associated with the M5 East tunnel itself (Barnett et al., 2003).

Monitoring near the Cross City Tunnel stack was continued for one year at two elevated sites and for three years at two ground-level sites. The monitoring data are available on the tunnel website (www.crosscity.com.au). Monitoring at four ground-level and two elevated sites around the Lane Cove Tunnel (two plus one near each stack respectively) was conducted between April 2005 and March 2010 (the elevated stations closed in April 2008). The monitoring data and periodic audit reports are available on the tunnel website (www.lanecovemotorways.com.au).

Monitoring of local air quality at Melbourne's CityLink tunnels has found that:

- levels of carbon monoxide and nitrogen dioxide showed a similar pattern to the EPA Victoria network
- levels of $PM_{2.5}$ and $PM_{10}$ showed a similar pattern to the EPA Victoria network, albeit at higher levels.

No impact of the emissions from the CityLink project on local air quality has been detected (Victoria EPA, 2002, 2003, 2004).

Screening-style passive sampling campaigns were conducted before and after tunnel opening as part of the Lane Cove Tunnel Air Quality and Respiratory Health Study (Woolcock, 2006). This study reported a reduction of between 0.3 and 7.0 parts per billion (ppb) in monitored nitrogen dioxide concentrations between the pre-tunnel and post-tunnel campaigns around the area of the stack. Analysis of the continuous monitoring data for the same study found that, after accounting for changes in regional air quality, the elevated sites near the ventilation stacks recorded significant decreases in PM, $NO_x$ and nitrogen dioxide in the year after the tunnel opened (Cowie et al, 2012).

In combination these Australian road tunnels, and particularly those in Sydney, represent probably the largest database of tunnel-related air quality monitoring in the world. Although the data is largely publicly available it has not previously been collated and summarised. At the time of writing this data is in the process of being made available to the public, whilst an analysis of the impact of road tunnels on ambient air quality is being conducted and will be published on the website of the Chief Scientist & Engineer.

# 12. Further information

For further information related to this topic please see:

- *Technical Paper 04 – International practice for tunnel ventilation design*
- *Technical Paper 06 – Options for treating road tunnel emissions*
- *Technical Paper 07 – Criteria for in-tunnel and ambient air quality*.

# 13. List of Figures

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