Technical Paper

TP07: Criteria for In-tunnel and Ambient Air Quality

Advisory Committee on Tunnel Air Quality

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Key Points

- Ambient air quality guidelines are intended to deal with general population exposure to pollution from various sources, rather than exposure at ‘hot spots’ or the control of individual point sources.
- In NSW, road tunnel stack and portal emissions are typically assessed with reference to both the NSW Environment Protection Authority’s (EPA) Approved Methods for the Modelling and Assessment of Air Pollutants in NSW and the National Environmental Protection (Ambient Air Quality) Measure (AAQ NEPM). However, the AAQ NEPM sets standards for the total ambient concentration of pollutants from all sources and does not provide a framework for assessing the contribution of individual sources such as a road tunnel stack.
- In-tunnel air quality criteria are established to protect the safety and health of tunnel users with respect to motor vehicle emissions.
- There is some degree of international consistency among in-tunnel and ambient criteria.
- Carbon monoxide (CO) has historically been a good marker for motor vehicle emissions and is the basis of in-tunnel criteria. However, reductions in CO emissions due to improved vehicle technology has advanced more quickly than nitrogen dioxide (NO_2) and particulate emission reductions. Consequently, a guideline based on CO alone can no longer be considered to automatically provide the same protection of health for tunnel users as in the past.
- An appropriate level of protection from the effects of all road vehicle pollutants inside tunnels has been provided through a combination of the existing in-tunnel CO and visibility limits. However, as the composition of vehicle emissions will continue to change as emissions decrease, the addition of an NO_2 limit will ensure an appropriate level of protection continues in the medium to long term.
- There are scientific knowledge gaps regarding the effects of very brief (a few minutes) exposures to high levels of air pollutants on health, and regularly repeated exposures, as occur in road tunnels. This requires an appropriately precautionary approach to standard setting that considers the potential health benefits of a standard and the costs of building infrastructure capable of achieving a standard under all possible conditions (e.g. energy use and capital investment that is not utilised).

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1. Introduction

There are significant capital, maintenance and running costs involved in providing forced tunnel ventilation, which also impacts the environment due to emissions associated with electricity generation. Ventilation systems should therefore be designed to provide only sufficient ventilation to maintain acceptable air quality in the tunnel, to optimise capital and operational costs while also including provision for worst case scenarios. The criteria for acceptable in-tunnel air quality has been driven by two factors: established evidence of adverse effects on human health associated with short-duration exposure to traffic-related air pollutants[1,2] and the reduction of visibility in the tunnel (PIARC, 1996).

An additional consideration in ventilation design and operation is ensuring that emissions from the tunnel stacks or portals results in an acceptably small increase in pollutant concentration outside the tunnel.

2. Origin, Purpose and Limitations of Ambient Air Quality Criteria

Ambient air quality criteria are the levels of various air pollutants in the outdoor air (measured over specified durations) which represent a means of judging acceptable air quality. In the case of road tunnels, ambient air quality criteria are required to judge the net impact of portal and stack emissions and, when combined with non-tunnel sources, on the air quality to which the local community is exposed.

The World Health Organization (WHO) has issued guidelines (WHO, 2006)[3] regarding the acceptable levels of key air pollutants based on a synthesis of research from around the globe regarding the known effects of these pollutants on human health. At the time of writing, a new update is being prepared by the WHO. The Guidelines cover a range of air pollutants including those that are the most relevant to motor vehicles: benzene, CO, NO_2 and particulate matter (PM). The WHO Guidelines have been widely used as a fundamental reference across the globe, and inform the AAQ NEPM. The WHO Guidelines are periodically reviewed and updated (as are the NEPM Standards) as new evidence on health and exposure trends becomes available.

The NEPM standard for PM is expressed in the form of PM_{10} and $PM_{2.5}$ (following the WHO Guidelines). These metrics refer to the mass of particles smaller than 10 or 2.5 microns[4] per unit volume of air. A PM_{10} NEPM has been adopted because of the relative practical ease of monitoring PM_{10} reliably, combined with a strong epidemiological basis which links episodes of high PM_{10} concentration to a short-term rise in mortality and morbidity across a city's population. NEPM Standards also exist for NO_2 and CO (Table 1). A NEPM Standard for $PM_{2.5}$ was also adopted in 2016.

Of significance in the case of road tunnels is that the ambient air quality standards in the NEPM are intended to deal with general population exposure rather than 'hot spots' (such as particularly busy sections of road) or the control of individual point sources (such as road tunnel portals). Individual jurisdictions are primarily responsible for the regulation of point sources.

The AAQ NEPM Standards are largely set on the basis of a statistically-expressed risk to a population, rather than the risk to small numbers of individuals close to pollution sources. The PM_{10} and $PM_{2.5}$ standards also do not represent a threshold for zero or negligible risk, but rather provide a set level of protection for the general population.

It may also be noted that both the PM_{10} and $PM_{2.5}$ metric assumes that particles of different compositions from different sources (such as diesel and petrol emissions, road dust, wood or bushfire smoke, desert dust and sea salt) are equally toxic and pose equal risk across the population.

1 PIARC, 1996. Road tunnels: emissions, environment, ventilation. Technical Committee 5 Road Tunnels.
2 WHO (World Health Organisation), 2000. Air quality guidelines for Europe – Second Edition.
3 WHO (World Health Organisation), 2006. Air quality guidelines. Global update 2005. Particulate matter, ozone, nitrogen dioxide and sulfur dioxide
4 1,000 microns (μm) = 1 millimetre

Motor vehicle exhaust is an important source of ultrafine pollution in urban settings.[5] Ultrafine particles (UFPs) are thought to play a role in the adverse health impacts seen in association with exposure to particulate pollution, although the epidemiological evidence of their effects is limited (HEI 2013).[6] Until there is clearer evidence of the concentration-effect relationship for UFPs, WHO recommends that management of PM should continue to focus on PM_{10} and $PM_{2.5}$.

Table 1: Relevant standards from the AAQ NEPM

	Maximum Concentrations			
	1 year	**24 hours**	**8 hours**	**1 hour**
NO_2	0.03 ppm			0.12 ppm
CO			9.0 ppm	
PM_{10}	25 µg m^{-3}	50 µg m^{-3}		
$PM_{2.5}$	8 µg m^{-3}	25 µg m^{-3}		

$PM_{2.5}$ = particles of less than 2.5 µm; PM_{10} = particles of less than 10 µm; ppm = parts per million

These standards apply to general population exposure rather than 'hot spots' or the control of individual point sources.

In NSW, the EPA prescribes ambient impact assessment criteria which are outlined in their 'Approved Methods for Modelling and Assessment of Air Pollutants in NSW' (NSW EPA, 2016).

The impact assessment criteria typically refer to the total pollutant load in the environment and impacts from new sources of these pollutants must be added to existing background levels for compliance assessment. These criteria would typically apply to the net impact of stack and/or portal emissions associated with a tunnel project, added to non-tunnel sources already present in the environment.

Table 2 summarises the ambient air quality goals that would typically be relevant to an assessment of a road tunnel project, sourced from the Approved Methods.

Table 2: Air quality criteria contained within the Approved Methods for pollutants relevant to road tunnel assessments

Pollutant	Standard	Averaging Period
NO_2	246 µg/m^3 (0.12 ppm)	1 hour
	62 µg/m^3 (0.03 ppm)	Annual
PM_{10}	50 µg/m^3	24 hour
	25 µg/m^3	Annual
$PM_{2.5}$	25 µg/m^3	24 hour
	8 µg/m^3	Annual
SO_2	712 µg/m^3	10-minutes
	570 µg/m^3	1 hour
	228 µg/m^3	Annual
CO	100 mg/m^3	15-minute
	30 mg/m^3	1 hour
Benzene	0.029 mg/m^3	1 hour
Xylene	0.19 mg/m^3	1 hour
Toluene	0.36 mg/m^3	1 hour
Ethyl benzene	8 mg/m^3	1 hour

Note: gas volumes are expressed at 25°C and at an absolute pressure of 1 atmosphere (101.325kPa).[7]

5 HEI Panel on Ultrafine Particles. (2013). Understanding the health effects of Ambient Ultrafine Particles. Health Effects Institute, Boston. www.healtheffects.org accessed 23 May 2018.

6 WHO Regional Office for Europe (2013). Review of evidence on health aspects of air pollution – REVIHAAP Project Technical Report. WHO Regional Office for Europe. http://www.euro.who.int/en/health-topics/environment-and-health/air-quality/publications/2013/review-of-evidence-on-health-aspects-of-air-pollution-revihaap-project-final-technical-report accessed 23 May 2018.

7 Concentrations of gases in air may be expressed in two ways: mass of gas per volume of air, or volume of gas per volume of air. The conversion between them depends on temperature and pressure.

3. Origin, Purpose and Limitations of In-tunnel Air Quality Criteria

In-tunnel air quality criteria are established to protect the safety and health of tunnel users with separate criteria used for occupational exposure of workers in tunnels. In-tunnel air quality criteria are a major factor in determining the size and performance requirements of the tunnel ventilation system. In many tunnels around the world, the air quality within the tunnel tubes is continuously monitored and the ventilation is actively adjusted to maintain pollutant concentrations below the criteria. In-tunnel air quality criteria typically allow exposures to higher pollutant concentrations than ambient air criteria due to the much shorter exposure times (usually no more than a few minutes).

3.1 Established criteria for carbon monoxide and visibility

Globally, the most widely adopted in-tunnel exposure limits are for CO. This choice is supported by CO being the only traffic-dominated air pollutant for which the WHO Guidelines exist for exposure durations relevant to passage through a road tunnel (typically a few minutes). Specifically, the WHO Guidelines state that concentrations of CO averaged over a 15-minute period should not exceed 100 mg m^{-3} (equivalent to 87 ppm at 25°C); the exposure at this level should not persist beyond 15 minutes, and should not be repeated within eight hours. This exposure level is based on maintaining a level of carboxyhaemoglobin (COHb) in the blood below 2.5 per cent. CO is also relatively resistant to physical or chemical change within a road tunnel (unlike NO_2), making it relatively simple to monitor.

The WHO Guidelines for CO have been adopted by the Permanent International Association of Road Congresses (PIARC) as a recommendation for road tunnels (Table 3), and national agencies around the world have either adopted or adapted this recommendation. The criterion is usually expressed as the maximum concentration of CO permitted within the tunnel averaged over 15 minutes. For example, 15-minute limits of 87 ppm are applied in Sydney tunnels, the limit is 100 ppm at the mid-point in Norway and 120 ppm in the United States (Table 4). This approach has a long history, has been proven to be relatively simple to implement and has been used as the basis of most tunnel ventilation designs. For CO, health evidence has confirmed that the concentration limit and averaging time can be traded off without altering the protection provided. As such, a higher level of CO may be allowed in a tunnel if a transit time below 15 minutes can be assured.

Table 3: PIARC recommended in-tunnel CO limits

Traffic situation	CO-concentration (ppm) Design year	
	1995	2010
Fluid peak traffic 50-100 km/h	100	70
Daily congested traffic, standstill on all lanes	100	70
Exceptional congested traffic, standstill on all lanes	150	100
Planned maintenance work in a tunnel under traffic	30	20
Closing of the tunnel	250	200

Table 4: In-tunnel carbon monoxide guidelines adopted around the world

CO threshold concentration	Averaging time	Notes
200 ppm	3 minutes	Cross City and Lane Cove tunnels, Sydney
120 ppm	15 minutes	United States
100 ppm	15 minutes	PIARC
87 ppm	15 minutes	M5 East, Cross City Tunnel, Lane Cove Tunnel, M4 East, New M5, M4-M5 Link
70 ppm	15 minutes	PIARC from 2010; Clem7 and Airport Link tunnels, Brisbane
100 ppm	5 minutes	Hong Kong
50 ppm	30 minutes	Cross City Tunnel, Lane Cove Tunnel, M4 East, New M5, M4-M5 Link
50 ppm	15 minutes	CityLink tunnels, Melbourne

A visibility limit (generally following advice from PIARC) is also applied in most tunnels for the purposes of safety (Table 5); however, it also provides some protection against the impacts of PM on the health of tunnel users. Loss of visibility is not related directly to effects on health, but has indirect effects, such as driver stress, as well as presenting a hazard to safe driving. The visibility in a tunnel is directly related to the presence of particles that scatter visible light and light absorption by larger dark particles, such as soot.

These particles are believed to have a direct effect on human health, but the impacts over such short durations are not known with sufficient confidence to support a health-based guideline. The WHO Guidelines for PM cover exposure durations of 24 hours and one year only, and are only strictly applicable to these exposure periods.

Table 5: PIARC recommended in-tunnel visibility limits

Traffic situation	Visibility	
	Extinction coefficient K m^{-1}	Transmission (beam length: 100 m) %
Fluid peak traffic 50-100 km/h	0.005	60
Daily congested traffic, standstill on all lanes	0.007	50
Exceptional congested traffic, standstill on all lanes	0.009	40
Planned maintenance work in a tunnel under traffic	0.003	75
Closing of the tunnel	0.012	30

3.2 Management of other in-tunnel pollutants

Most of the health evidence regarding exposure to traffic pollutants other than CO is based on ambient exposure lasting hours, days or longer. The significance of exposure of a few minutes or less remains a major gap in scientific knowledge. The uptake and effect of CO on the body is rapid and understood, but the way in which other key pollutants, particularly NO_2 or particles interact with the body is less well established.

Limited scientific evidence indicates the potential for subtle adverse effects among susceptible individuals. Researchers have observed respiratory effects in asthmatics in a study of exposures to road tunnel air, albeit with exposure durations of 30 minutes[8] and two hours.[9] This evidence and other studies of traffic pollution exposure in general suggest that the possible effects of high exposures to air pollution in road tunnels include aggravation of existing asthma, immediately or over subsequent hours, and slightly increased risks of a cardiovascular event in susceptible individuals within a few days. Accrued effects from repeated tunnel use might include small increases in the lifetime risk of cancer and the potential for increased bronchitic events or respiratory infection, although the same risk arises from spending long periods in general road traffic.

In the past, a CO guideline has been used on the assumption that it provides adequate protection for the full range of constituents of road traffic air emissions. However, improvements in vehicle technology over the last two decades have led to major reductions in emissions per vehicle of CO and other exhaust pollutants.[10] Reductions in PM and nitric oxide (NO) (from which most NO_2 is indirectly formed) emissions from vehicles have also occurred to a lesser degree; however, improvements lag behind reductions in CO by perhaps a decade. In Europe (where there generally is a higher proportion of light duty diesel vehicles within the fleet), there has been an observable increase in primary emissions and formation of NO_2 in response to the fraction of diesel-powered vehicles on the road.[11] Consequently, there is relatively more NO_2 (and PM) per amount of CO in tunnel air than was previously the case.

A guideline based on CO alone can no longer be considered to automatically provide the same protection of tunnel user health as it has in the past. This is recognised around the world and has led many bodies to consider or implement NO_2 exposure limits in addition to the current CO limits. Different authorities have applied different levels and different exposure times, reflecting scientific uncertainties and different precautionary stances (Table 6).

8 Svartengren, M, Strand, V, Bylin, G, et al., 2000. Short-term exposure to air pollution in a road tunnel enhances the asthmatic response to allergen.
9 Larsson B-M, Grunewald J, Sköld CM, Lundin A, Sandström T, Eklund A, et al., 2010. Limited airway effects in mild asthmatics after exposure to air pollution in a road tunnel.
10 Longley, I., Coulson, G., Olivares, G., 2010. Guidance for the Management of Air Quality in Road Tunnels in New Zealand.
11 Carslaw, D.C., 2005. Evidence of an increasing NO2/NOX emissions ratio from road traffic emissions.

Table 6: In-tunnel nitrogen dioxide guidelines adopted around the world

NO_2 threshold concentration	Averaging time	Notes
0.5 ppm	15 minutes	NSW In Tunnel Air Quality (Nitrogen Dioxide) Policy, NorthConnex, M4 East, New M5, M4-M5 Link (tunnel average)
1 ppm	15 minutes	New Zealand (design standard only)
1 ppm	5 minutes	Hong Kong
0.75 ppm	15 minutes	Norway (tunnel midpoint)
1.5 ppm (tunnel end)	15 minutes	Norway (tunnel end)
0.5 ppm	20 minutes	Belgium
0.4 ppm	15 minutes	France from 2010

The PIARC has recommended an NO_2 limit of 1 ppm not to be exceeded more than two per cent of the time.[12] More demanding NO_2 limits have been adopted in France and Hong Kong. These are based on a precautionary approach in view of evidence that asthmatics are more susceptible to NO_2. This evidence is based on exposures of 30 minutes or more and, unlike for CO, the significance for much shorter duration exposures to NO_2 is currently unknown. The Norwegian Public Roads Administration has a limit of 1.5 ppm at the tunnel end and 0.75 ppm at its mid-point.[13] The New Zealand Transport Agency has adopted a design standard of 1 ppm (15 minutes), but has not implemented a monitoring compliance standard, in part due to technical difficulties in monitoring in-tunnel NO_2 reliably. The NSW In-Tunnel Air Quality (Nitrogen Dioxide) Policy sets a limit of 0.5 ppm as a tunnel average. This limit is the most stringent in Australia and compares favourably to the international in-tunnel NO_2 design guidelines which range between 0.4 ppm and 1 ppm. Most standards for NO_2 levels around the world permit tunnel averages greater than 0.5 ppm, with the exception of France which has a standard of 0.4 ppm.

A somewhat different approach is currently being explored for the planned Stockholm Bypass, which will include 18 kilometres of tunnel. Here, an attempt is being made to explicitly consider the trade-offs between the impacts of in-tunnel and ambient air quality exposures.[14] In this instance, rather than focusing on trying to deliver effectively zero impact from a single tunnel trip by placing a limit on short-term exposures of tunnel users, the assessment accepts that any and every tunnel trip adds to the total long-term exposure and represents a small incremental increase in risk to the population. The reduction in that risk (i.e. benefit) achieved through more stringent in-tunnel limits can then be compared to the cost of achieving those limits. The increased long-term exposure for tunnel users can then be compared to any exposure reduction experienced by the general population due to the reduction in surface emissions arising from traffic being directed underground. It is anticipated that this analysis will inform adoption of an in-tunnel NO_2 or NO_x criterion in the future.

This method is made possible by using a common exposure measure for in-tunnel and ambient exposure to traffic emissions, supported by a credible dose-response relationship relating cumulative exposure to some health outcome risk. In the case of the Stockholm Bypass, this common measure is cumulative NO_x exposure and the health outcomes are excess mortality and asthma cases. This is due to the existence of a long-term Scandinavian study on NO_x exposures and their impacts. This method incorporates several challengeable assumptions and sources of uncertainty, in particular, the assumption that long-term exposures to NO_x are equivalent to cumulative short-term NO_x exposures, that ambient exposure (including exposure on surface roads) can be accurately assessed and that the dose-response relationship (derived from a study of adult men living in Oslo for above ground, ambient exposure – unrelated to road-tunnel exposures) is valid and can be appropriately adopted for this application.

12 PIARC, 2000. Pollution by nitrogen dioxide in road tunnels.
13 NPRA, 2004. Road tunnels. Norwegian Public Roads Administration.
14 Orru, H & Forsberg, B 2016, Assessment of long-term health impacts of air quality with different guideline values for NO_x in the planned by-pass tunnel Förbifart Stockholm

3.3. In-tunnel air quality criteria for occupational exposure

For most pollutants two types of occupational exposure limits generally exist – one as an eight hour average, intended to represent a typical workday exposure, and the other as a 15-minute average, intended to protect against peak short-term exposures.

For CO, the short-term exposure limit provided by the National Institute for Occupational Safety and Health (NIOSH) of 200 ppm seems to have been adopted universally. Occupational exposure limits have higher concentration values than the ambient air quality guidelines because of their shorter averaging periods, and because they are assumed to apply only to healthy adults (children and pregnant women, in particular, require extra protection from CO exposure). NIOSH also has a recommended eight hour exposure limit of 35 ppm.

PIARC recommends a limit of 30 ppm for road tunnels, reducing this to 20 ppm in 2010; however, this recommendation appears not to be supported by documentation providing a rationale.

Similarly to in-tunnel criteria for tunnel users, there is no internationally agreed short-term (15-minute average) occupational exposure limit for NO_2. Occupational NO_2 limits vary between countries and determining bodies, and have tended to change with time. In the US, the American Conference of Governmental Industrial Hygienists (ACGIH) and NIOSH have recommended a short-term exposure limit of 5 ppm (15-minute average). This value has subsequently been adopted in many other countries, including Japan, Australia and New Zealand; however, NIOSH also states a recommended exposure limit of 1 ppm (15-minute average). In the UK, a limit of 8 ppm was introduced in 2000 and reduced to 5 ppm in 2002. The limit was withdrawn in 2003 as it was felt that it did not provide adequate protection. There is no current UK occupational NO_2 limit.

Table 7: Road tunnel occupational safety air quality guidelines adopted

Pollutant	Threshold Concentration	Averaging Time	Notes
CO	20 ppm	8 hours	PIARC recommendation from 2010
	30 ppm	8 hours	PIARC recommendation from 1995
	35 ppm	8 hours	US (NIOSH) Recommended Exposure Limit
	200 ppm	15 minutes	US (NIOSH) Short-Term Exposure Limit; widely adopted internationally
NO_2	1 ppm	15 minutes	NIOSH Short-Term Exposure Limit
	5 ppm	8-hours	OSHA Recommended Exposure Limit

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