

Technical Paper

TP04: Road Tunnel Ventilation Systems

Advisory Committee on Tunnel Air Quality

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Key Points

- Road tunnels are an important part of transport infrastructure. Originally, they were built to improve traffic and transport conditions in mountainous regions; however, they are now often built in urban areas to reduce traffic congestion and improve local air quality. As road tunnels create an enclosed space around vehicles, ventilation is required to dilute vehicle emissions to provide a safe environment for tunnel users, and to support smoke dispersion/extraction in cases of incidents.
- Basic concepts of ventilation have not changed over the last few decades. Traditionally, due to fresh air supply requirements, longitudinal ventilation was limited to shorter tunnels with transverse ventilation used in long tunnels. Improved vehicle emission technology and the construction of twin tube tunnels operated with unidirectional traffic now safely enables the use of longitudinal ventilation systems also for long and heavily trafficked tunnels. All long road tunnels built in Australia over the last 25 years have been designed with longitudinal ventilation systems.
- In urban areas, complex tunnel systems with multiple slip roads to the surface and interconnections with other road tunnels are a popular means to improve the flow of inner-city traffic. These tunnels require individual project based approaches to ventilation as well as ventilation control, and different or combined ventilation systems might be employed within the same tunnel network.
- Tunnels in urban areas pose an increased risk of elevated pollution levels in the portal regions and may require management of tunnel air. Internationally, many longer tunnel systems in urban areas use stack dispersion only during peak traffic hours, while during the remaining time, tunnel air is released via the portals.



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1. Why is Tunnel Ventilation Required?

Vehicles on the open road create pollution which is diluted and dispersed through natural surface air flows. Road tunnels create an enclosed space around vehicles where emissions from the vehicles can build up to unacceptable levels without an engineered ventilation system to replace natural surface air flows.

The decision on whether a tunnel needs mechanical ventilation or not depends on various parameters such as tunnel length and the traffic situation. For tunnels up to around 500 m in length, the natural air flow through the tunnel driven by the movement of vehicles (the 'piston effect') is normally adequate to manage in-tunnel air quality, and forced ventilation is not required. For longer tunnels, forced ventilation in the form of fans may be required at times to ensure that air flow rates are sufficient to maintain in-tunnel air quality to required levels. At the international level, tunnels with a length exceeding 500 to 1,000 m require mechanical ventilation.

Mechanical ventilation in road tunnels serves two different purposes: normal and incident operations. Normal operation describes operation of a tunnel under regular traffic situations (free flowing or congested), while incident operation stands for operation of the ventilation system during incidents likely to produce smoke. Both aspects drive parameters for the selection of the appropriate ventilation strategy to be applied.

Road tunnels are enclosed roadways with vehicle access restricted to portals. The specific definition of how long a roadway needs to be enclosed to constitute a tunnel varies from source to source. In NSW, a tunnel is defined as an enclosed roadway for a length greater than 120 m. This length is used to determine when certain safety systems are required to be installed in the tunnel, such as fire safety systems.

Traffic in road tunnels can be unidirectional, meaning vehicles within the tunnel move only in one direction. Usually, two unidirectional tunnels will run side by side to allow for bidirectional traffic flow. Alternatively, road tunnels can be bidirectional, meaning traffic travels in both directions, sharing a common road space. When considering the need for tunnel ventilation, the requirements are determined by the vehicle emissions in the tunnel and the limits set for pollutant levels in the tunnel by a regulatory or approval authority.

1.1 Ventilation during normal operation

During normal operation of traffic, pollutants emitted from vehicles need to be diluted by fresh air to meet in-tunnel air quality criteria. The amount of pollutants produced depends on the emission rates of the individual vehicles. The parameters of vehicle type and age, driving situation and road gradient determine these emission rates. The newer the vehicle, the lower the vehicle-specific emission rate tends to be.

Attempts to decarbonise transport fuels has led to an increase of vehicles propelled by new energy carriers (electric, fuel cells, hybrid, hydrogen and synthetic fuels), and to alternative fossil fuels like compressed natural gas (CNG) or liquefied natural gas (LNG). However, the share of such vehicles is still quite small and this does not currently have any measurable impact on in-tunnel pollution levels.

1.2 Ventilation during incidents

In incident cases with smoke production, the aim of the ventilation system is to improve rescue conditions by managing smoke movement. During the beginning of a fire, the main goal is to keep escape ways free of smoke (self-rescue phase). In the second stage, when rescue services are already on site, the aim of the ventilation system is to support the rescue activities. Ventilation design criteria, as well as detailed description of operation strategies, are outside of the scope of this paper.

2. Tunnel Ventilation Systems

The basic principle of tunnel ventilation is the dilution of vehicle emissions by providing fresh air and then removing the exhaust air from the tunnel. The exhaust air can be removed via a portal (a location where the tunnel carriageway opens up to the surrounding environment), via a ventilation outlet (such as a stack), or via a combination of both.

Ventilation systems are traditionally characterised by the way the air flow in the tunnel is produced and in which direction the air is blown – in relation to the axis of the tunnel. Longitudinal ventilation, in its simplest form, comprises fresh air introduced within the entry portal and exhaust air expelled out of the exit portal. Transverse ventilation works on the same principle of dilution and removal as longitudinal ventilation; however, the supply of fresh air and the removal of exhaust air occurs across the tunnel (i.e. transversely).

The approach to tunnel ventilation has changed dramatically over time, mainly due to the significant reduction in vehicle emissions from emission control technology and better fuel quality. Improved vehicle emission technology and the construction of twin tube tunnels operated with unidirectional traffic now facilitates the use of longitudinal ventilation systems for long and heavily trafficked tunnels.

All road tunnels built in Australia over the last 25 years have been designed with longitudinal ventilation systems.

The decision on whether a tunnel needs mechanical ventilation or not depends on various parameters such as tunnel length and the traffic situation. At the international level, tunnels with a length exceeding 500 to 1,000 m require mechanical ventilation.

2.1 Traditional system classification

Ventilation systems are traditionally characterised by the way the air flow in the tunnel is produced and in which direction the air is blown – in relation to the axis of the tunnel (see also PIARC 2011). There is a clear distinction between longitudinal and transverse (semi-transverse or full transverse) ventilation systems; however, due to the complexity of some tunnels and networks of tunnels, combinations of various types of ventilation systems are often chosen as the most feasible solution¹.

The choice of ventilation is based on an iterative process whereby several factors such as operating conditions, safety/risk, environmental impact and, last but not least, costs (construction, operation, maintenance) have to be taken into account. Energy efficiency is a key objective due to operational costs, as well as the environmental footprint of the tunnel.

2.1.1 Longitudinal ventilation system

2.1.1.1 Standard longitudinal ventilation

Longitudinal ventilation, in its simplest form, comprises fresh air introduced within the entry portal and exhaust air expelled out of the exit portal as shown in Figure 1. As fresh air is entering one portal and the polluted (exhaust) air is exiting at the other, concentration values rise from ambient concentrations at the inlet to their highest value at the exit portal. The air moves along the axis of the tunnel and is driven in most cases by jet fans, supported by the air volume induced by the vehicles in tunnels with unidirectional traffic known as the 'piston effect'. In cases of tunnels with bidirectional traffic, the piston effect is strongly reduced and depends on the number and speed of vehicles driving in the various directions.



Figure 1: Longitudinal ventilation with jet fans

Source: PIARC 2011: Road tunnels: operational strategies for emergency ventilation

¹ PIARC 2016: Road tunnels: Complex underground road networks.

In case of a fire, smoke is transported from the fire location throughout the tunnel until it is expelled at the exit portal. The drawback of moving smoke throughout a longitudinally ventilated tunnel to the nearest portal or smoke extraction stack has to be compensated by measures to increase the safety of users, e.g. short distances between egress ways for passenger evacuation.

It is internationally recognised that the air speed in the tunnel during normal operation must not exceed 8 to 10 m/s to maintain a minimum level of safety in the event of a fire. This clearly restricts the application of simple longitudinal ventilation in long and/or heavily trafficked tunnels. In cases with 'excessive' air speeds, additional measures e.g. air exchange stations (see section 2.2.1) or transverse ventilation (see section 2.1.2) is required.

2.1.1.2 Longitudinal ventilation with portal air extraction

Venting tunnel air exhaust via portals is the standard procedure for the majority of all tunnels around the world. The measurable impact of portal air emissions on local air quality is generally confined to a distance of 100 to 200 m around the portal. In urban areas, the contribution of portal air may result in unacceptable air pollution. The release of portal air might be precluded under approval conditions as is the case for new long tunnels in NSW. To eliminate portal emissions, all of the tunnel air must be expelled via stacks.

In technical terms, such a ventilation system is called longitudinal ventilation with air extraction at the portal (portal air extraction). Depending on project specific requirements, either the full amount of tunnel air is extracted (zero portal emissions, see Figure 2) or only a partial air flow is extracted via the portal (reduced portal air emissions). Technical Paper 5 – Road tunnel stack emissions deals with the topic of venting the tunnel air exhaust via stacks. The overall conclusion of that paper is that, with properly designed stacks, it is possible to disperse pollution in such a way that there is little, if any change in local or regional air quality.

During periods with little traffic, the operation of stacks to avoid portal emissions is of little benefit with respect to local air quality; however, at the same time, it entails significant energy use and contributes to operating and environmental costs.

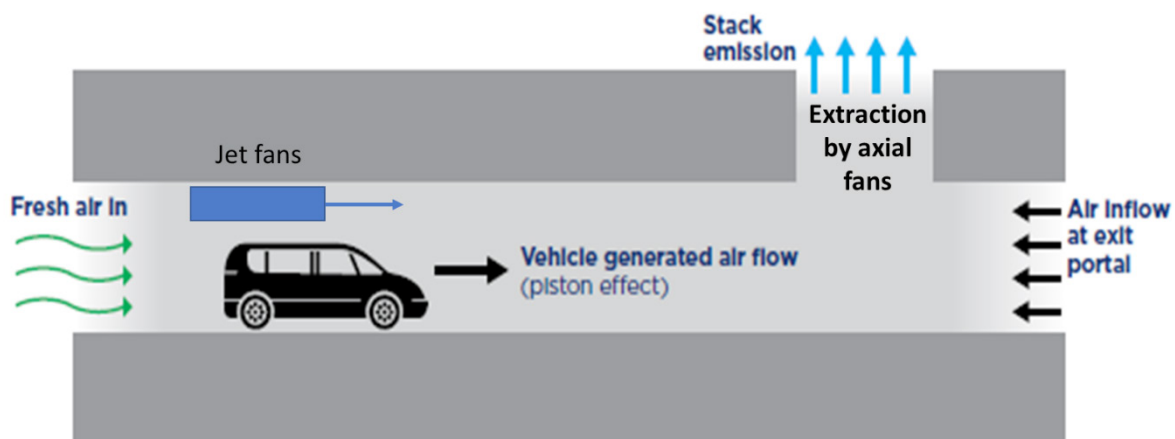


Figure 2: Longitudinal ventilation with portal air extraction and zero portal emissions

2.1.2 Transverse ventilation system

Another method for ventilation is the transverse ventilation system. Transverse ventilation systems are further classified into full transverse – with a full exchange of air in a certain section of the tunnel – and semi-transverse, where only a part of the air flow is exchanged. While in older long or heavily trafficked tunnels full transverse ventilation systems are employed, more recent applications are now using semi-transverse systems, mainly with air extraction. Advantages and disadvantages as well as operational strategies of such systems have been elaborated and described in detail in many publications, e.g. PIARC 2011.

2.1.2.1 Full transverse ventilation

In a full transverse ventilation system, air is blown into the tunnel at distinct locations and extracted within more or less the same tunnel section. This results in an air exchange perpendicular to the longitudinal axis of the tunnel (see Figure 3). In such a system, polluted air is constantly diluted which theoretically results in a uniformly distributed emission rate over the tunnel length at a constant concentration level.

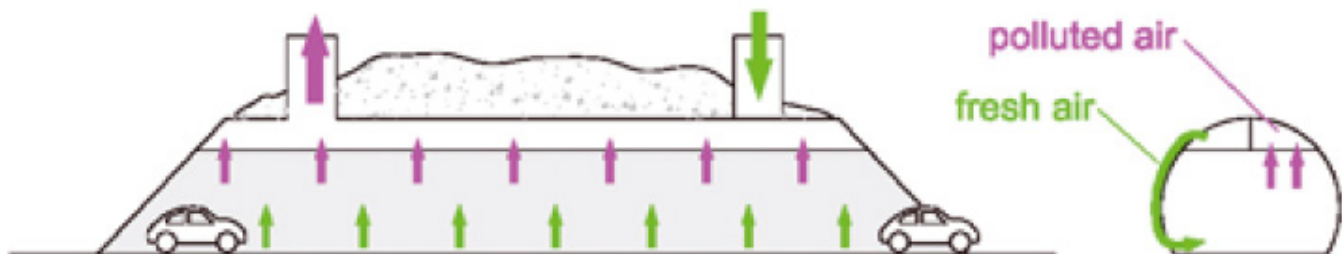


Figure 3: Full transverse ventilation with air injection and extraction via separated ducts
Source: PIARC (2011)

In case of a fire a transverse system enables smoke extraction in close proximity to the fire source. In such cases, smoke penetration of larger parts of a tunnel can be avoided (PIARC 2011).

2.1.2.2 Semi-transverse ventilation

Semi-transverse ventilation systems offer the possibility to either inject air uniformly over the ventilation section or to extract air from the tunnel, but cannot operate in both modes simultaneously. Operation of a semi-transverse ventilation system in injection mode offers the possibility to dilute pollution during normal operation. In the case of a fire, the fresh air support must be turned off and other means like jet fans employed to expel the smoke similar to longitudinal ventilated tunnels. Semi-transverse ventilation systems in extraction mode offer the same advantage as a full transverse ventilation system in an incident case; however, the system is not very effective in controlling in-tunnel air quality during high pollution periods in normal operation.

A reversible semi-transverse ventilation system would combine the benefits of a transverse ventilation system by running in injection mode during normal operation (dilution of pollution) and in extraction mode during incident operation (removal of smoke). However, due to the time required to reverse the fans and the air flow, some countries allow semi-transverse ventilation only in extraction mode.

2.2 Combined or complex tunnel ventilation systems

In an urban area, space restrictions, connections to surface roads, traffic, environmental constraints and proximity of populated areas requires unique solutions for ventilation. This results in complex systems, where tailored ventilation systems and operation strategies are required.

2.2.1 Tunnels with air exchange stations

Long and/or heavily trafficked road tunnels were traditionally equipped with transverse ventilation systems; however, in the last decade, many unidirectional tunnels and tunnel networks in urban areas have been equipped with longitudinal ventilation systems. This is primarily because less fresh air is required as a result of reduced vehicle emissions, unidirectional traffic and short distances between escape ways. To meet the requirements for in-tunnel air quality; however, it is necessary to exchange the tunnel air with fresh air from outside at select locations. This results in a virtual 'split' of a long tunnel into shorter sections with independent ventilation possibilities. Air exchange in these instances can be achieved via stacks (see Figure 4) or utilising on- and off-ramps to surface roads. Ventilation control is challenging for such systems due to the need to avoid an overflow of polluted air from one section into the other.

Such systems are currently used for many urban road tunnels and tunnel networks, especially in cases where the tunnels can be built in cut-and-cover and/or need to stay relatively close to the surface (small overburden, restrictions in depth due to various reasons).

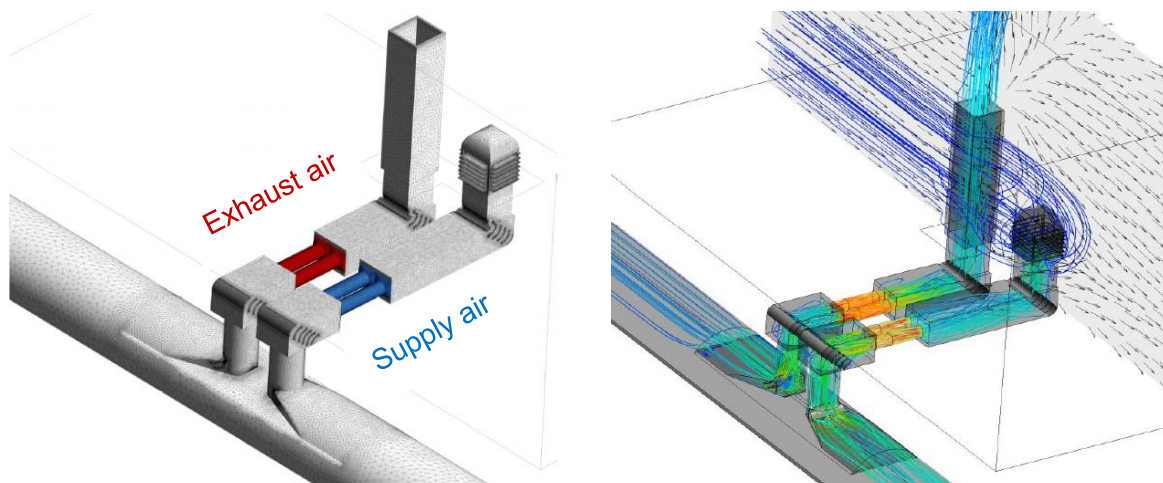


Figure 4: Sketch of an air-exchange stations, geometry (left) and streamlines of the air flow (right)

2.2.2 Double deck tunnels

Improvements in tunnel boring machine (TBM) technology allows for the excavation of tunnels with huge cross sections. This offers the possibility to build one tube with two decks for traffic. As the headroom of these decks is somewhat limited, the tunnels are normally only open for passenger car traffic. This is a cost-effective measure for improving road traffic where there is a small share of heavy duty vehicles in urban areas. Figure 5 provides an example of the cross section of the A86 duplex tunnel in Paris. Such tunnels are generally transversally ventilated, utilising the space above and below the two decks for the supply of fresh and to extract polluted air.

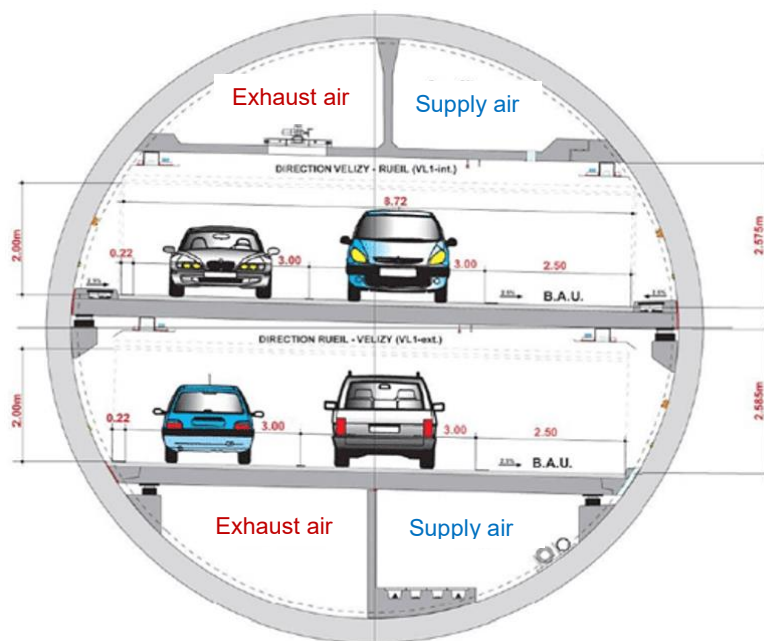


Figure 5: Example of a double deck tunnel for passenger cars, A86, Paris
Source: PIARC WG 5 (2017): 'Complex Underground Road Networks'

3. Design of Tunnel Ventilation Systems in Urban Areas

Road tunnels in urban areas provide for the possibility of subsurface traffic, improving traffic conditions by reducing congestion and removing traffic from the surface roads, reducing the contribution of surface road emissions to local air quality. Pollutants, however, accumulate in the tunnel between the entrance portal and any point of tunnel air extraction as well as the exit portal. As a consequence, pollution concentrations from the tunnel air at the point where the air is released is generally higher than that on the open road.

For long and/or heavily trafficked road tunnels in urban areas in NSW and some international jurisdictions, tunnel air is managed before it is released into the environment. Such management will involve an improvement in the dispersion conditions, e.g. by extracting air at the portal and releasing it via a stack, or by applying tunnel air cleaning technologies. Both procedures are well known and have been dealt with in specific NSW Advisory Committee on Tunnel Air Quality Technical Reports^{2, 3}, as well as in a PIARC publication⁴.

Internationally, health based air quality standards are the basis for legislative and policy requirements relating to tunnel emissions and consequently tunnel ventilation system design.

The main air quality criteria considered in tunnel ventilation design are carbon monoxide (CO), nitrogen dioxide (NO₂) and visibility. From a health perspective, exposure to particulate matter is particularly relevant; however, no jurisdiction has developed a health based particulate matter criteria for in tunnel ventilation design, primarily due to the short duration of exposure in tunnels compared with the longer exposure times (24 hours and one year) for which the health effects of ambient particles have been established.

In the current NSW context, approval conditions for new tunnel projects greater than 1 km in length:

- prohibit portal emissions and all tunnel air is released via stacks
- specify a tunnel average NO₂ concentration of less than 0.5 ppm as a rolling 15 minute average.

International case studies of tunnel ventilation systems are detailed in Appendix 1 of this paper.

When considering the need for tunnel ventilation, the requirements for ventilation operation are determined by the vehicle emissions in the tunnel and the limits set for pollutant levels in the tunnel by a regulatory or approval authority.

The key air quality performance requirements for tunnel ventilation systems are:

- In-tunnel air quality criteria
- External or ambient air quality criteria
- Other restrictions, such as limited or no portal emissions conditions
- Operation during incidents.

3.1 In-tunnel air quality

The main pollutants of concern are CO, particulate matter (PM) and in some countries, NO₂.

In previous years, CO values were used to trigger ventilation design and control. However, following the introduction of exhaust gas after-treatment systems (e.g. three-way catalytic converters for petrol cars), in an international context, the fresh air requirement due to visibility constraints became the decisive parameter (particle emissions standards for diesel vehicle exhaust were introduced in Australia in 1996). Due to the introduction of the NO₂ standard in NSW⁵, this pollutant gained in importance, mainly for tunnels where tunnel users are in the tunnel for long periods of time.

While in-tunnel air quality threshold values are commonly in use for CO and visibility (PM), the situation for NO₂ differs (PIARC 2012). In many countries, NO₂ is currently not controlled; however, The World Road Association (PIARC) recommends the application of 1 ppm⁶, based on the US National Institute for Occupational Safety and Health (NIOSH) short term exposure limit. NSW has adopted a more stringent criterion having 0.5 ppm as a path averaged concentration as limit value⁷.

2 Advisory Committee on Tunnel Air Quality Technical TP 05 – Road Tunnel Stack Emissions, NSW Government, 2018.

3 Advisory Committee on Tunnel Air Quality Technical TP 06 – Options for Treating Road Tunnel Emissions, NSW Government, 2018.

4 PIARC 2008: Road tunnels: a guide to optimizing the air quality impact upon the environment; 2008.

5 NSW Advisory Committee on Tunnel Air Quality, In-tunnel air quality (nitrogen dioxide) policy, NSW Government, Sydney, February 2016.

6 PIARC: Pollution by nitrogen dioxide in road tunnels. Technical Committee on Road Tunnel Operation, 2000.

7 NSW Advisory Committee on Tunnel Air Quality, In-tunnel air quality (nitrogen dioxide) policy, NSW Government, Sydney, February 2016.

3.2 Ambient air quality

Ambient air quality guidelines provide a reference point for evaluating pollution concentrations related to human health. The threshold values defined in the guidelines are related to certain exposure times, generally using a one-hour average as a minimum time period and a yearly average as a maximum. The focus of air quality standards is on the protection of humans and ecosystems.

Assessment of the contribution of tunnel air to local air quality with respect to air quality guidelines is required to inform decision making regarding choice of tunnel ventilation system. Information regarding ambient air quality criteria used for the assessment of road tunnel projects is found in Technical Paper 7 – Criteria for in-tunnel and ambient air quality.

3.3 Portal air management

Internationally, many tunnels are vented via portals; however, tunnels in urban areas pose an increased risk of elevated pollution levels in proximity to the portal and management of portal emissions may be required to meet environment and health based regulatory requirements. This might consist of releasing the tunnel air (either fully or partially) via a stack into the atmosphere.

Portal air management is mostly carried out in sensitive regions in urban areas. While in many applications stacks help facilitate dispersion (see also Technical Paper 5 – Road tunnel stack emissions), in rare cases – mainly where higher stacks are perceived as being unsightly or otherwise undesirable, the installation of a tunnel air filtering system upstream of the release point may be an alternative⁸.

It is challenging to measure the direct impact of portal emissions on air quality, as portals are always associated with the surface road leading from the portal and the local air quality is influenced by other surface roads and other sources. The rapid dilution of the portal plume presents a further challenge, which means that assessments based on one, or a few monitoring sites risk being located outside the zone of impact. To assess air quality around portals and ventilation shafts from a technical point of view, estimates of possible contributions from tunnel air on the environment have to be made. This is carried out during the Environmental Impact Assessment (EIA) phase of a project. The required steps for assessing this issue in the project approval process may differ in different countries; however, the general process comprises assessing the existing air quality, estimating potential contributions from the project (tunnel) and comparing the projected changes in air quality with air quality standards.

The decision on whether portal air management is necessary or not is based on the legal, regulatory and policy framework and air quality standards in place.

An example of restricted portal emissions is provided below, followed by a discussion of the additional ventilation system design and operation implications of the requirement for zero portal emissions.



⁸ Advisory Committee on Tunnel Air Quality TP06 – Options for Treating Road Tunnel Emissions, NSW Government, 2018.

3.3.1 Restricted portal emissions

The Linz, Austria tunnel project has a length of around 3 km, carries 60,000 vehicles per day (vpd), has two tubes with unidirectional traffic and includes six connection ramps to surface roads. During peak traffic, congestion cannot be avoided. The main pollutants to be considered were NO_2 and PM_{10} . For NO_2 , air quality standards exist for annual mean values and peak hourly mean values, while the PM_{10} standard concerns annual and daily mean values.

Figure 6 shows an image of the southern part of the tunnel network between the south portal, the ventilation building including the shaft and the slip roads towards the city centre.

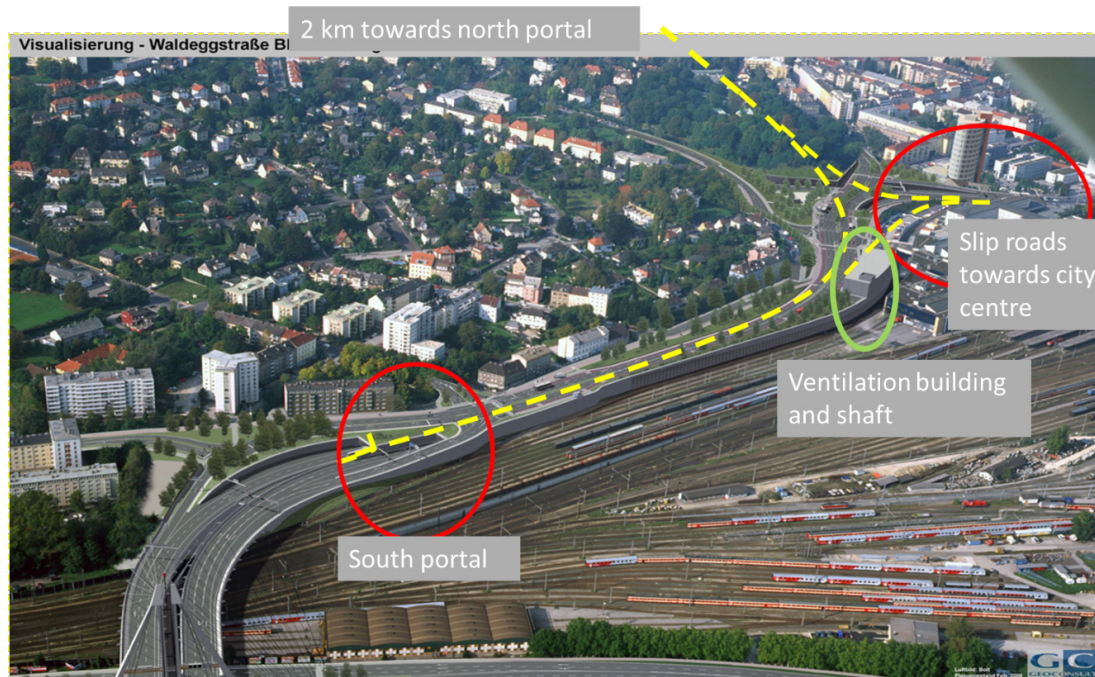


Figure 6: Southern part of the project

Source: ASFINAG: A26 Linzer Autobahn, Knoten Linz/Hummelhof (A7) - Ast Donau Nord, Einreichprojekt 2008

Figure 7 contains the results of the dispersion modelling for the southern part of the network. The difference between the 'with project' and the 'without project'⁹ scenarios for a certain base year is depicted. Within the portal regions, additional pollution is to be expected (reddish colours), while inner city regions (surface roads) experience a considerable reduction. The consideration of project-related pollution concentrations (difference and absolute value) led to the requirement that for certain times during the day (morning and evening peak hours), portal air emissions have to be restricted and the polluted air dispersed via a stack. The incorporation of the stack (see Figure 6) was part of the EIS. A monitoring program for air quality close to the nearest neighbouring houses will be installed to fine-tune the operation times of the portal air extraction system.

⁹ The 'with project' scenario is related to the erection of the tunnel including ventilation stack. The 'without project' scenario is related to the status quo, i.e. surface roads.

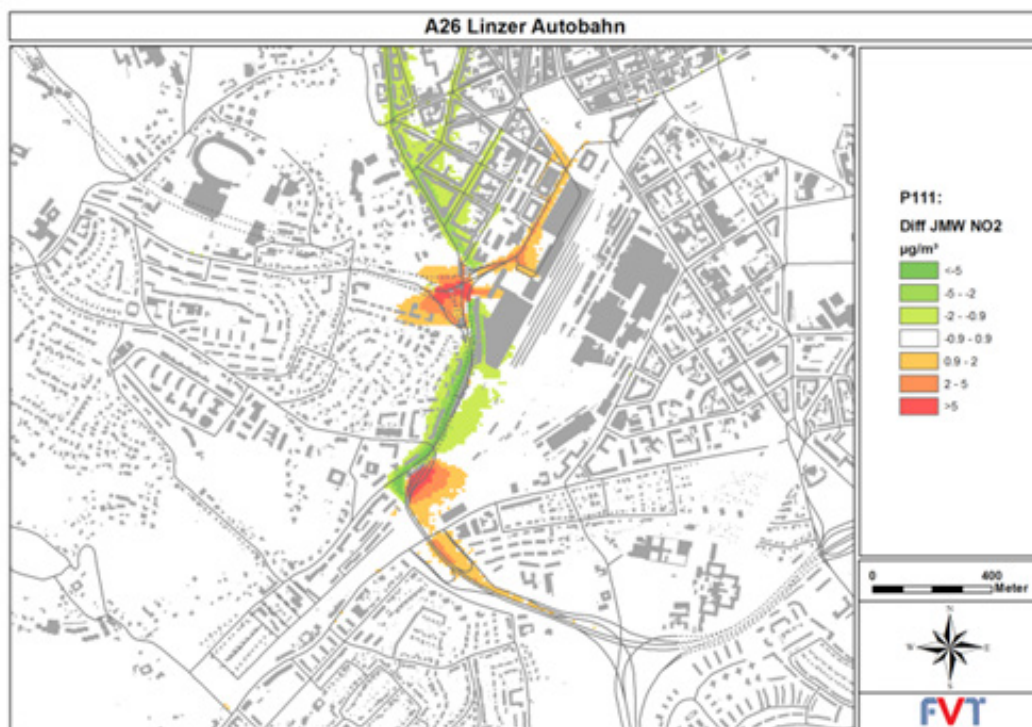


Figure 7: NO₂ annual mean value, difference between 'with project' and 'without project' scenarios; detail around south portal and ramps

Source: ASFINAG: A26 Linzer Autobahn, Knoten Linz/Hummelhof (A7) - Ast Donau Nord, Einreichprojekt 2008; allgemein verständliche Zusammenfassung

3.3.2 Zero portal emissions

A key operating restriction for some tunnels in NSW longer than 1 km is the requirement for zero portal emissions (i.e. no exhaust air is allowed to exit the tunnel at the portals). This is required by the Minister's Conditions of Approval for the M5 East, Cross City and Lane Cove tunnels. This was initially applied to the M5 East tunnel as a precaution to protect residents around the tunnel portals. The requirement for zero portal emissions was retained for the Cross City Tunnel and Lane Cove Tunnel, NorthConnex and WestConnex projects.

To meet the zero portal emissions condition, all air must be expelled from an elevated ventilation outlet (e.g. stack), with air drawn in from all portals. This requires, in the portal zones, ventilation against the natural direction of air flow due to vehicle movement (i.e. the piston effect).

The requirement for zero portal emissions leads to a number of design and operation implications:

- An alternative ventilation outlet is required, such as a stack.
- Drawing air in from the exit portal increases the quantity of ventilation air required to be discharged through the stack and can significantly increase the required size of the stack – leading to increased capital and operating costs and visual impacts.
- The ventilation system will need to be operated all the time, regardless of whether in-tunnel or ambient air quality warrants this operation.

4. Conclusion

Ventilation systems are traditionally categorised according to the main direction of the air flow through the tunnel. While in longitudinally ventilated tunnels, this air flow is along the longitudinal axis – and hence in or against the driving direction – in transversally ventilated tunnels, the air exchange occurs within the tunnel transverse to the driving direction. Both types have advantages and disadvantages. While longitudinally ventilated tunnels have in general smaller cross sections and consequently cheaper construction costs, transverse ventilated tunnels offer the possibility to permanently exchange polluted air with fresh air (full transverse ventilation system) and to avoid long smoke-filled tunnel sections in the case of fire by extracting smoke at locations quite close to the fire location.

In past years, the usage of longitudinal ventilation has been limited by the required amount of fresh air in normal operation and fire safety requirements. More recently, the significant reduction in vehicle emissions due to emission control technology and better fuel quality mean that limitations due to the fresh air requirement in normal operations are rare. This leads to new long tunnels and tunnel networks in urban areas being equipped with longitudinal ventilation systems – exchanging the air via slip roads and/or air exchange ventilation stations – and meeting safety requirements through the implementation of measures such as fixed firefighting systems and short distances to and between emergency exits.

Tunnels in urban areas are faced with additional constraints such as space limitations, the need for multiple connections to surface roads and restrictions on portal emissions in environmentally sensitive areas. Decisions about ventilation systems can only be made on a project by project basis.

In NSW and internationally, complex tunnels with multiple slip roads and access tunnels or networks of tunnels are being designed to meet air quality and fire safety performance requirements under expected operating scenarios.

5. Further Information

Advisory Committee on Tunnel Air Quality TP 03 – Health effects of traffic-related air pollution, NSW Government, 2014.

Advisory Committee on Tunnel Air Quality TP 05 – Road tunnel stack emissions, NSW Government, 2018.

Advisory Committee on Tunnel Air Quality TP 06 – Options for treating road tunnel emissions, NSW Government, 2018.

Advisory Committee on Tunnel Air Quality TP 07 – Criteria for in-tunnel and ambient air quality, NSW Government 2018.

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<http://siteresources.worldbank.org/INTECAREGTOPTRANSPORT/Resources/Session3Calle30.ppt>; access 12. January 2018

<http://www.landezine.com/index.php/2011/04/madrid-rio-by-west8-urban-design-landscape-architecture/>; access Nov. 24th 2017

<http://www.ktr.mlit.go.jp/gaikan/gaiyo/index.html>; web access Nov. 24th 2017

<http://www.ktr.mlit.go.jp/gaikan/gaiyo/hozentaishaku03.html>; web access Nov. 24th 2017

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8. Appendix 1: Examples of Urban Tunnels in an International Context

The following section describes existing tunnels operating in a complex urban context and using portal air management and/or tunnel air treatment systems to comply with national air quality standards in their respective countries.

The review is based primarily on publicly available information, which rarely includes comprehensive details about the operation, efficiency and maintenance of specific systems. The task of conducting individual on-site interviews to gain this detail was outside the scope of the present document.

Detailed information regarding tunnel stack systems and tunnel treatment systems can be found in the associated technical papers in this series: *Technical Paper 5 – Road tunnel stack systems* and *Technical Paper 6 – Options for treating road tunnel emissions*.

8.1 Tunnels with portal air management

8.1.1 Tunnel Milchbruck and Spier, Switzerland

Of the many urban tunnels in Europe, there are only a few with the capability of portal air emission management. Most of those with a portal emission control capability are equipped with additional axial fans to extract the polluted air. It has to be noted that some portal air emissions management installations in Switzerland ceased operation after measurements and/or expert statements indicated that their use did not provide a measurable benefit to local air quality. Figure 8 and Figure 9 show examples of two tunnels in Switzerland, one in Zurich (tunnel Milchbruck, 1.9 km, one tube, bidirectional traffic) and the other in Luzern (Spiertunnel, 1.6 km, two tubes unidirectional traffic). In both cases, provisions for portal air extraction are available but not in use.

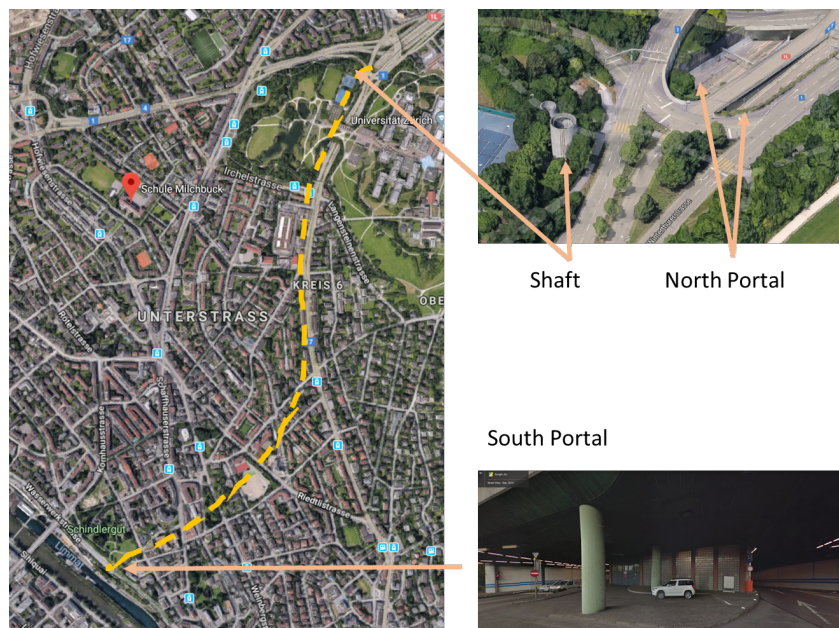


Figure 8: Tunnel Milchbruck, Zurich, Switzerland
Source: Google Maps



Figure 9: Spiertunnel, Luzern, Switzerland
Source: Google Maps

Portal air management is also performed for the Stockholm Södra Länken (southern-link tunnel) in Sweden. This tunnel opened in 2004 and has a length of ~4.5 km and a traffic volume of ~90,000 vpd. A longitudinal ventilation system with jet fans is employed in this tunnel. Portal air management with shafts is located at both portals. The decision on whether portal air is allowed through or diverted via the shaft is made with respect to the prevailing external air quality¹⁰.



Figure 10: Southern Link Tunnel, Stockholm, Sweden, east portal (left), ventilation building (right)

Source: http://www.stockholmbypixels.com/2007_05_01_archive.html

8.1.2 Stockholm ring road tunnels

Traffic around the city of Stockholm is managed by a ring road consisting of a network of tunnels. Some of these are already in operation and some are under construction or at the project phase. While the existing Södra Länken (southern-link) tunnel is equipped with a simple longitudinal ventilation system with portal air extraction (operation on demand), the other two projects (Förbifart and Norra Länken tunnel) consist of a network of tunnels, slip roads and access tunnels with a complex ventilation system, utilising longitudinal ventilation, air exchange systems and portal air management. Such tunnel networks are highly challenging in terms of ventilation control under normal and/or incident operation.

In the following section the Förbifart (Bypass) tunnel project is described in detail.

The Stockholm Förbifart (Bypass) project was initiated to manage traffic on the E4 in and around Stockholm. The project consists of a 17 km long mainline tunnel with 12 ramps connecting to the surface roads. Approximately 56 km of road is subsurface. Traffic frequency at full operation of the tunnel network is expected to be around 140,000 vpd and traffic congestion cannot be ruled out¹¹. Design values for ventilation sizing were the in-tunnel air quality threshold values for CO, NO_x (NO₂) and visibility. The NO₂ threshold value was set to 1 ppm as a maximum value inside the tunnel (time averaged). The decision for the 1 ppm criterion was based on information provided in Orru H., Forsberg B. (2016).

Figure 11 shows a map and the main parameters of the project. In general, the tunnel will be equipped with a longitudinal ventilation system; however, due to the length of the tunnel, six air exchange stations with capacity for a full exchange of polluted return-air by fresh supply-air will cut the tunnel virtually into shorter sections. Four portal stations will serve for extraction and release of the polluted air via a stack to minimise the environmental impact at these portals. Only the ramps at Lovö Island will allow permanent release of tunnel air via the portals. One additional shaft serves smoke extraction from both tubes in cases of an emergency. For normal operations, this ventilation station won't be in operation. The portal air extraction systems are designed for partial air extraction and will operate only during peak hours, i.e. most of the time portal air is allowed, and even during peak hours, a part of the polluted air will be vented via the exit portals.

10 Vägverket (2014): Södra Länken – en ny trafikled i Stockholm.

11 Brandt R., Elertson L. (2016): Commissioning of the Ventilation Control System of the E4 Stockholm Bypass; in: proceedings of the 8th intern. symposium 'Tunnel Safety and Ventilation'.



Figure 11: Map and main features of the Stockholm Bypass project

Source: Trafikverket 2016: E4 Förbifart Stockholm, FSK09, Installationer FSE903: Tunnelventilation, Forskningsprojekt tunnelluft

Figure 12 depicts the ventilation system with 250 jet fans providing the momentum required to vent the tunnel – mainly during congested periods. The air exchange stations as well as the portal air extraction fans and the smoke extraction fans will have a capacity of 200 m³/s each.

Ventilation in normal operation will be controlled via various subcontrollers, which are closed-loop controllers using the in-tunnel air quality sensors for input and the jet fans as actuators. Air exchange stations will be operated only on an as needed basis – defined by in-tunnel air quality.

The decision on whether the portal air extraction systems are to be used is based on ambient air quality recorded at stations close to the portals (Brandt R., Elertson L. (2016)).

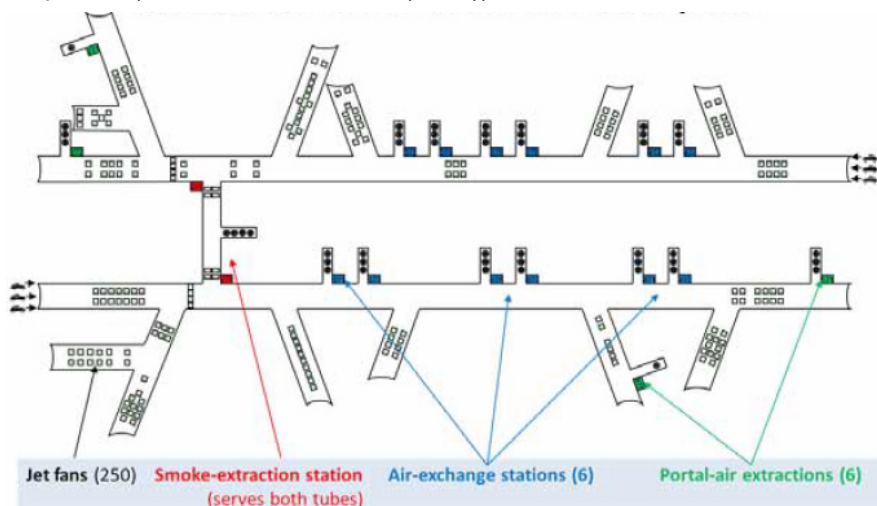


Figure 12: Sketch of the ventilation system of the Stockholm Bypass project

Source: Brandt R., Elertson L. (2016)

Definition of the shaft height was part of the EIS. Shaft height varies for the individual locations. Nevertheless, the proper shaft height, together with the adequate portal air management strategy, is sufficient to meet the regulatory air quality goals. Additional filtration of tunnel air is not required.

8.2 Portal air management combined with tunnel air treatment

In a limited number of cases, portal air management is combined with a treatment of the tunnel air. Filtration systems for managing PM and NO₂ are rare in the international context and are currently installed at locations where the erection of tall stacks was not favourable, and generally operate for only a few hours a day. The following projects are a combination of portal air management and tunnel air treatment systems. A detailed analysis of these systems can be found in *Technical Paper 6 – Technologies for treating road tunnel emissions*.

8.2.1 The Madrid 'Calle 30' tunnel projects

The multi-lane inner city circle of Madrid 'Calle 30' is a subsurface route network with three intersections, 22 entrances and 24 exits (Figure 13). Roughly 50 km of this ring road is constructed as tunnels¹², with two main tunnels:

- The Rio Tunnel (16.4 km including main branches), which runs along the River Manzanares, underneath the former exterior ring road. The old road has been replaced with a green area near the river.
- The Bypass Tunnel (5.6 km), which was constructed to reduce the distance between the eastern area and the western area of the city.

Traffic restrictions apply for Heavy Good Vehicles (HGV) >7.5 t and dangerous goods vehicles¹³.

High-rise stacks for pollution dispersion were precluded due to concerns about visual amenity. To comply with EU and Spanish national ambient air quality standards, exhaust air in the tunnel network required partial treatment. The air filtration system comprises 26 filtration plants consisting of electrostatic precipitators (ESP) for particle removal, and an additional four activated carbon filters for gas cleaning. The operation of air filtration plants is on a demand basis (Technical Paper 8).

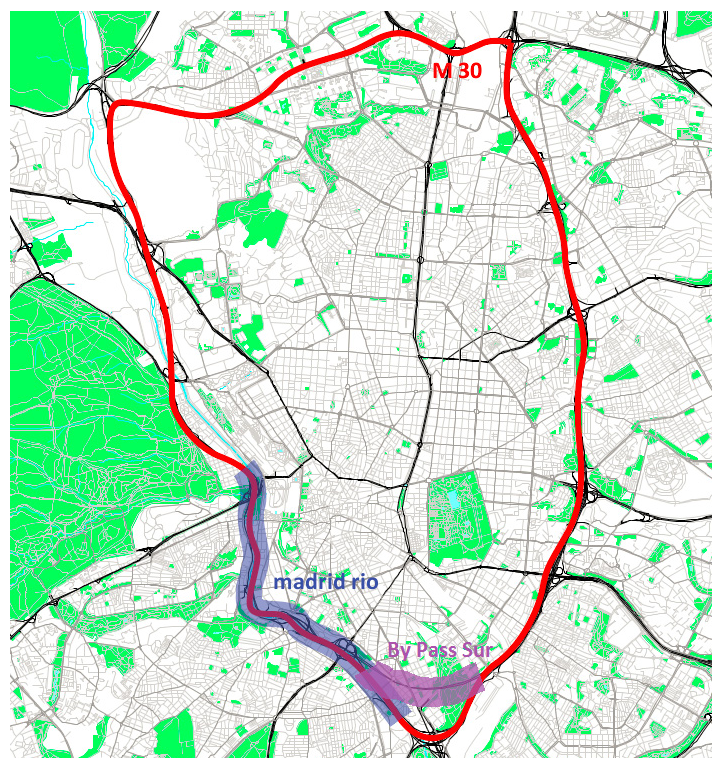


Figure 13: Map of the Madrid Calle 30 project, with DeNO_x installation in the 'Rio' and 'By-pass Sur' sections (marked)

Source: <http://siteresources.worldbank.org/INTECAREGTOPTTRANSPORT/Resources/Session3Calle30.ppt>

¹² Presa J.: Madrid Calle 30: An urban transformation project; Proceedings of the 4th international conference 'Tunnel Safety and Ventilation' 2008.

¹³ PIARC WG 5 (2017): 'Complex Underground Road Networks' – Part A 'Case Studies' – appendices, Appendix 2.16.

Figure 14 shows the redesigned landscape above the Rio tunnel close to the banks of the Manzanes River. The stacks for the air exchange as well as the smoke extraction stations are quite short.



Figure 14: Redesigned landscape above 'Rio tunnel'

Source: <http://www.landezine.com/index.php/2011/04/madrid-rio-by-west8-urban-design-landscape-architecture/>

8.2.2 The Hong Kong Central – Wan Chai Bypass and Island Eastern Corridor Link project

The Central – Wan Chai Bypass and Island Eastern Corridor Link (CWB) is a strategic road along the north shore of Hong Kong Island. It was designed to improve traffic conditions by taking traffic from the existing Gloucester Road – Harcourt Road – Connaught Road Central corridor. This road project consists of a 3.7 km tunnel from Central Rumsey Street Flyover, extending to the vicinity of City Garden at North Point, with slip roads for access to and from the Wan Chai area (see Figure 15). The peak traffic volume amounts to more than 10,000 vph.

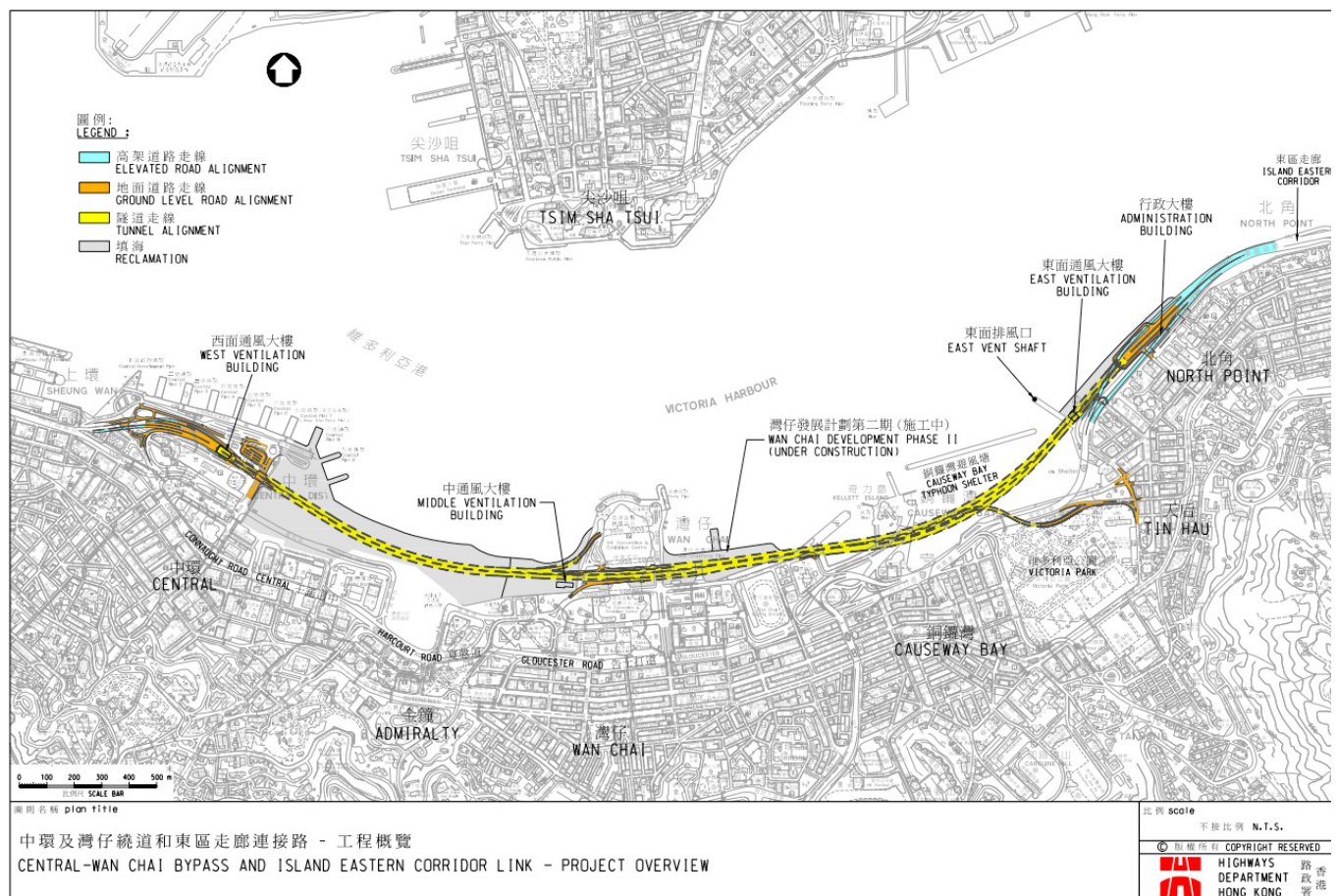


Figure 15: Map of the CWB link

Source: https://www.hyd.gov.hk/en/road_and_railway/road_projects/6579TH/HMW6579TH-SK0282.pdf

Image reproduced with the permission of the Highways Department of the Government of the Hong Kong Special Administrative Region. All rights reserved.

Three ventilation buildings serve as sites for ventilation and pollution release with the stack integrated into the ventilation building for the portals in west and the centre. For the station east, there is a dedicated ventilation shaft located 150 m in the breakwater of Victoria Harbour.

No information was found in the literature concerning portal air management or operation of the air treatment systems.

8.2.3 Japan

Urban tunnels in Japan generally tend to have longitudinal or transversal ventilation systems, according to traffic volume and congestion levels as well as tunnel complexity. Stacks are commonly used for air exchange and to improve dispersion and minimise impacts on local air quality. Owing to the height of the surrounding buildings, the stacks occasionally need to be quite tall with some of the ventilation stations in the stacks equipped with ESP.

The section between Nerima-ku and Setagaya-ku of the Tokyo Outer Ring Road is being constructed as a 16.2 km tunnel with multiple ramps for connection to the surface roads. Completion is expected in 2020. Traffic forecast for the tunnel is between 100,000 and 110,000 vpd in 2030. The tunnel location is shown as the dotted green line between Tomei and Oizumi in Figure 16 and Figure 17.

The ventilation system is based on a combination of longitudinal ventilation in the mainline tunnel, supported by air exchange at the ramps. The ventilation buildings provide for air exchange, portal air management and PM filtration (ESP in Figure 18).

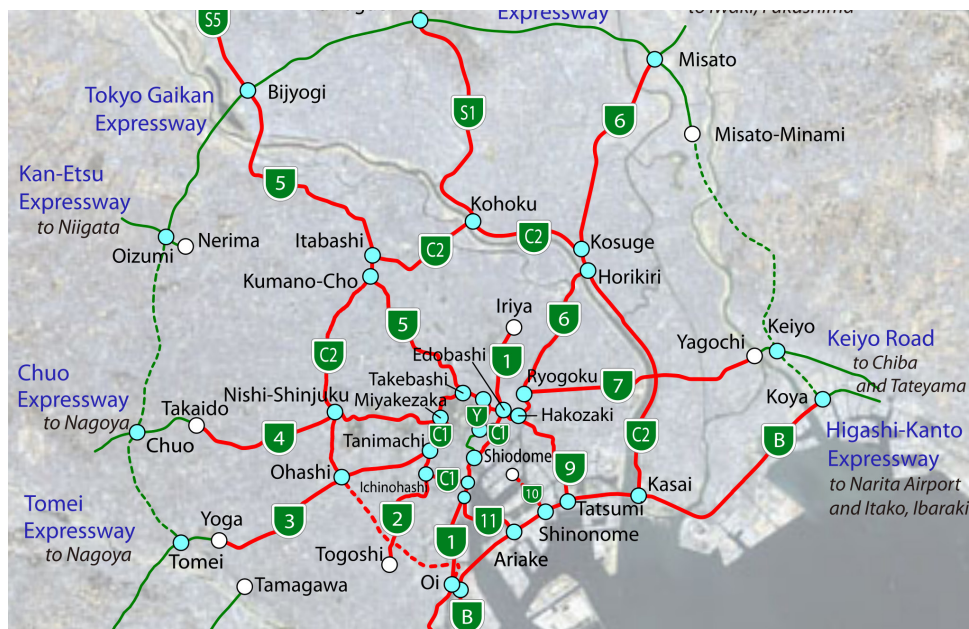


Figure 16: Map of the project area

Source: <http://www.ktr.mlit.go.jp/gaikan/gaiyo/index.html>

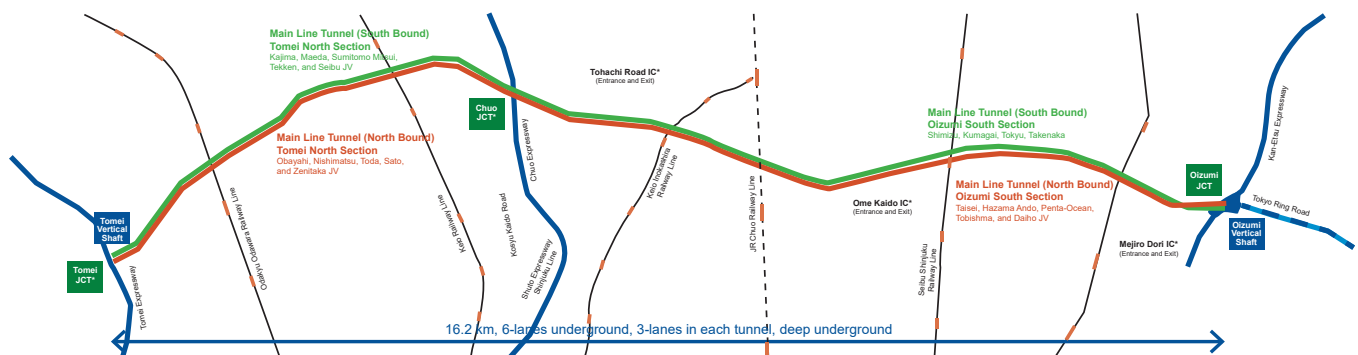


Figure 17: Map of the tunnel between Nerima-ku and Setagaya-ku

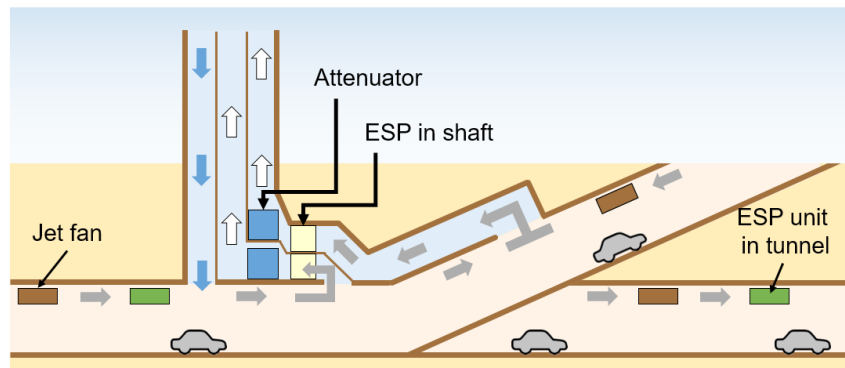


Figure 18: Sketch of the ventilation stations for air exchange and portal air management, picture modified from source
Source: <http://www.ktr.mlit.go.jp/gaikan/gaiyo/hozentaisaku03.html>

8.3 Portal air management by increased ventilation rates

An alternative approach to manage portal air emissions can be made by applying enhanced ventilation. Increasing the air flow through the tunnel portal decreases the concentration of the pollutants in the tunnel (but not the mass) and the dispersion conditions are improved. The operation of such systems is mostly based on kerbside air quality measurements at both ends of the tunnel. Ventilation is triggered by the pollution level at these locations: when a certain short-term threshold level is exceeded, the ventilation will be turned on. Ventilation control is based on the monitoring values at both portals, as well as in-tunnel air quality.

An example of this type of installation is Nordspange Tunnel Graz in Austria (Figure 19). Operation of the enhanced ventilation is based on onsite measurements of the air quality. At both portals, open-path air quality monitoring systems (OPSIS) for NO_2 were installed to monitor the concentrations in the vicinity of the neighbouring buildings.

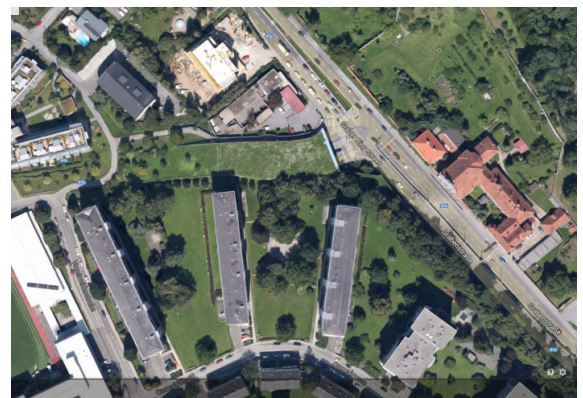


Figure 19: Nordspange Tunnel Graz, west portal (left), east portal (right) Austria
Source: Google Maps

Figure 20 shows the east portal and the two monitoring paths. If NO_2 – measured as a 15-minute average – exceeds a certain threshold value at one of the two paths, and traffic in the tunnel exceeds another threshold value, enhanced ventilation will result in an increase of air flow through the tunnel, reducing the concentration of the tunnel contribution to local air quality. Both threshold values triggering the enhanced ventilation were defined by use of dispersion models during the EIS phase, with the purpose of actively managing cumulative NO_2 exposure. Although the tunnel has now been in operation for more than 10 years, threshold values have not been exceeded and activation of the enhanced ventilation procedure has not been necessary.



Figure 20: East portal with air quality monitoring paths, Nordspange Tunnel Graz, Austria,
Source: Google Maps

