Technical Paper

TP06: Options for Treating Road Tunnel Emissions

Advisory Committee on Tunnel Air Quality

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Key Points

- The use of tunnel air filtration systems is not common worldwide and such systems present the challenge of capturing and treating high volumes of tunnel air with very low pollutant concentration levels (compared to industrial applications). This results in high infrastructure, operation and maintenance costs.
- To date, particulate filtration in tunnels is based solely on the use of electrostatic precipitators. The use of air treatment systems for nitrogen dioxide (NO_2) is a rarity and has currently only been implemented in full scale in the Calle 30 Madrid tunnel projects, as an alternative to stack dispersion.
- Any decision making process concerning tunnel air management (portal air management as well as air treatment systems) needs to prioritise health based air quality standards when considering engineering and economic practicabilities, and can only be made at the project level. While an air treatment system for particulates or NO_2 may be technically feasible, energy usage is high and it will not lower concentrations of other pollutants. Alternatives such as portal air extraction and stack dispersion may achieve the same outcomes at a reduced cost.

Contents

1. Introduction to the Treatment of Tunnel Air

The focus of this technical paper is tunnel air treatment – the application of tunnel air cleaning technologies to reduce pollutant concentrations before tunnel air is released into the environment.

An overview of tunnel ventilation systems including the management of portal emissions and information regarding the use of ventilation stacks to disperse tunnel emissions can be found in Technical Papers 4 and 5 of this series[1, 2].

In urban areas, road tunnels provide an alternative to surface traffic routes and serve to improve traffic conditions by reducing congestion at the surface. In addition, they allow for more valuable land uses at the surface, such as the provision of green space and active transport corridors.

However, the enclosed space of a tunnel means that pollutants from vehicle emissions accumulate between the entrance portal and any point of tunnel air extraction or the exit portal. As a consequence, tunnel air is generally more polluted than surface air. In addition, the pollutant concentration where tunnel air is released into the atmosphere may be higher than on an open surface road.

There are two key challenges – adequate ventilation to maintain in tunnel air quality at an appropriate standard (visibility, health) and management of emissions at the point of discharge to mitigate against changes in air quality in the vicinity of the portal/stack. As such, it may be necessary to manage tunnel air before it is released into the environment. There are two main approaches to this:

- Extracting air from the tunnel and releasing it via a stack in order to enhance dispersion conditions
- Applying tunnel air cleaning technologies to reduce pollutant concentrations before tunnel air is released into the environment.

This paper provides an update on current approaches to treating tunnel air and includes case studies from road tunnels in various countries.

1.1 Previous investigations into tunnel air treatment

1.1.1 PIARC 2008: Road tunnels: a guide to optimising the air quality impact upon the environment

In 2008, the World Road Association known as PIARC published a detailed report on road tunnel portal emissions and tunnel air treatment[3]. This included an outline of approaches to minimise the negative effects of air pollution from road tunnels, pollution dispersion strategies and a description of the technologies being used to treat particulates and NO_2 in tunnel air.

PIARC noted:

- Careful attention needs to be paid to the external air quality implications of operating road tunnels in urban areas due to the valid concerns about the effect of vehicle emissions on human health. However, the environmental consequences of the energy needed to achieve these external environmental air quality objectives must also be taken into account.
- The regulation of emissions from motor vehicles is the most critical factor in the management of tunnel emissions. Pollutant concentrations in the car exhaust are orders of magnitude more than the concentrations in tunnel exhaust air. More stringent emission standards will continue to reduce emissions from road vehicles – providing benefits across the entire road network – including the small proportion of the road network served by road tunnels.

1.1.2 Roads and Maritime 2014: Options for treating road tunnel emissions

In 2014, NSW Roads and Maritime Services (Roads and Maritime) published a report on emission treatment practices, focusing on a test installation in the M5 East tunnel in Sydney[4].

The 2014 report provided a general overview of tunnel air treatment options and, specifically, the findings of a test installation performed between March 2010 and September 2011 for particulate matter (PM) (electrostatic precipitator (ESP) technology) and nitrogen oxides (NO_x) (activated carbon adsorption technology) in the M5 East tunnel.

1 Dr Peter Sturm (2018). TP04 - International Practice for Tunnel Ventilation Design, NSW Government, Advisory Committee on Tunnel Air Quality.
2 Dr Ian Longley (2018). TP05 – Road Tunnel Stack Emissions, NSW Government, Advisory Committee on Tunnel Air Quality.
3 PIARC (2008) Road tunnels: a guide to optimizing the air quality impact upon the environment; 2008R04, www.piarc.org, ISBN: 22-84060-204-0, 2008.
4 Roads and Maritime Services (2014) TP08 - Options for treating road tunnel emissions; NSW Government, Advisory Committee on Tunnel Air Quality, July 2014.

The results of the test indicated a filtration efficiency of about 65 per cent of PM and 55 per cent of NO_2 from the extracted tunnel air. It was concluded that the denitrification ($DeNO_x$) system acted more as a catalyst, converting the NO_2 to nitrogen monoxide (NO), rather than collecting or absorbing the NO_2.

To continue adding to the body of knowledge, this paper mainly focuses on information published since the preparation of the two reports mentioned above.

2. Options for Tunnel Air Treatment: Pollutants and Technologies

The main pollutants of concern in tunnel air are PM and NO_2. While the impact of NO_2 is directly related to human health, the impact of PM is twofold. The presence of PM_{10} and moreover, $PM_{2.5}$ in the ambient environment has critical implications for human health. In the context of in-tunnel air quality, PM reduces visibility, which increases the risk of traffic incidents. As such, PM filtration in tunnels serves mainly for improving visibility while PM filtration at stack locations aims at reducing the environmental impact. Information regarding the health effects of PM and NO_2 is provided in Technical Paper 3 and in-tunnel air quality in Technical Paper 7 of this series[5,6].

To date, particulate filtration in tunnels is based solely on the use of electrostatic precipitators. Current research aims to optimise this technique rather than to develop new techniques[7].

The activated carbon adsorption technique is currently the only technology being used in a full size application to treat gaseous pollutants in tunnel air. Other techniques, such as the use of photocatalytic processes and biofilters are still at an experimental or test installation stage.

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

2.1 Particulate matter

2.1.1 Particle emissions

Particles in tunnel air have two sources: exhaust from internal combustion driven vehicles and so-called 'non-exhaust' particles generated from the wear of tyres, brakes and road surface, as well as re-suspended dust deposited on the road surface. While exhaust-related PM is usually smaller than 200 nm in diameter (see Figure 1), larger particles ($PM_{2.5}$ and higher) resulting mainly from the non-exhaust emission sources also occur. Light scattering, which is the dominant effect for reduction of visibility, is caused by very small particles with a size range around the wavelength of visible light (390 to 700 nm), while light absorption is caused by larger particles.

Figure 1 shows a typical size distribution of PM in tunnel air with the x axis showing particle size in nanometres (nm) and the y axis the number of particles per cubic centimetre of tunnel air. The number of particles is shown as a function of their size, covering the range of up to 700 nm in diameter. A further variable is the time of the day (7:00, 19:00 and 0:00) which represents different traffic conditions. The cut-off at 700 nm (0.7 microns) is due to the range of the measurement equipment used in the study. PM from the exhaust pipe is in the range < 700 nm (peak around 80 to 100 nm), while PM from tire and road wear (non-exhaust particle) is typically in the range > 2,500 nm (2.5 microns).

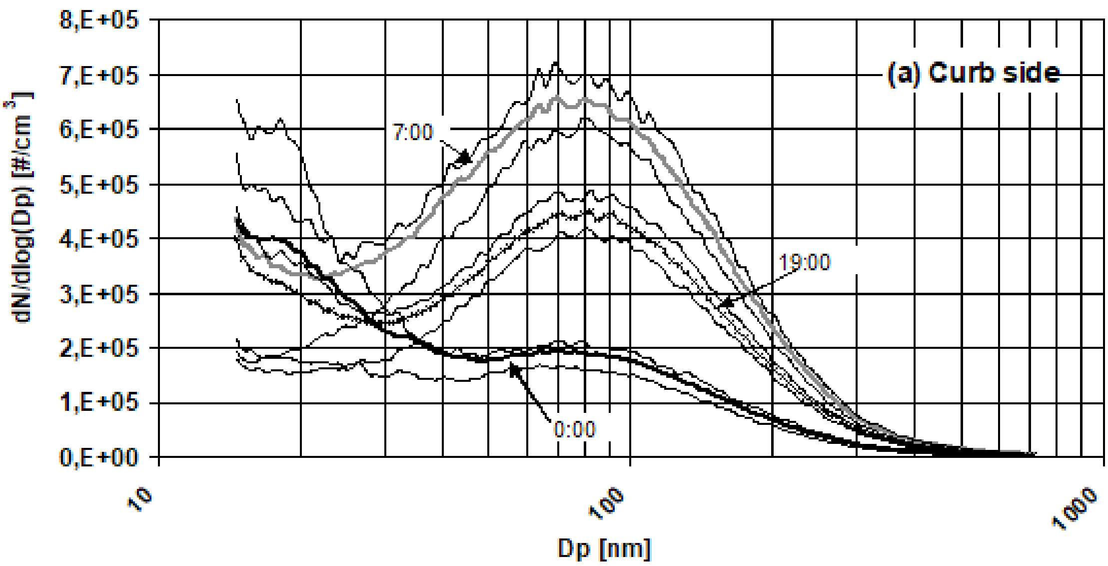

Figure 1: Size distribution of particles < 700 nm (0.7 µm) in tunnel air, as a function of time of the day, i.e. traffic volume[8]

5 Roads and Maritime Services (2018). TP03 – Health Effects of Traffic-Related Air Pollution; NSW Government, Advisory Committee on Tunnel Air Quality.
6 Roads and Maritime Services (2018). TP07 – Criteria for In-tunnel Air Quality; NSW Government, Advisory Committee on Tunnel Air Quality.
7 Vidal et al (2017) Biofiltration of road tunnel discharge - An experimental study, BHR Paper 2017.
8 Sturm et al (2003) Roadside measurements of Particle Matter (PM) size distribution; Atmospheric Environment 2003, pp 5273-5281.

Due to the different emission sources, PM in tunnel air varies strongly in terms of size distribution and chemical composition (soot and hydrocarbons from exhaust and mainly road surface material and resuspended road dirt).

2.1.2 Technologies for filtration of particulate matter

2.1.2.1 Application fields

There are two different application fields for particle removal from tunnel air. Filtration technology may be installed on either inside the tunnel, or at the location of portals or stacks.

Many early systems were installed inside tunnels to keep visibility at an acceptable level without the need for an exchange with ambient air. This reduces tunnel construction costs on projects where the erection of stacks would be very costly. Such applications were mainly in use in previous years in Japanese road tunnels with a high number of heavy goods vehicles (HGV).

PM filtration of tunnel air at portal regions, or of any air discharge into the surroundings, is now more closely associated with tunnels in urban areas experiencing high traffic volumes.

2.1.2.2 Filtration technology

PM filtration of tunnel air is well established. Techniques such as wet scrubbers and bag filters have been found unsuitable for tunnel application (PIARC 2008) and the use of electrostatic precipitators (ESP) is now considered state of the art.

An ESP consists of an ionisation stage, where the particles are charged, and a collecting stage (see Figure 2). Systems provided by different manufacturers tend to vary only in the method of cleaning at the collector stage. Some systems require wet cleaning while others manage a cleaning process without water[9].

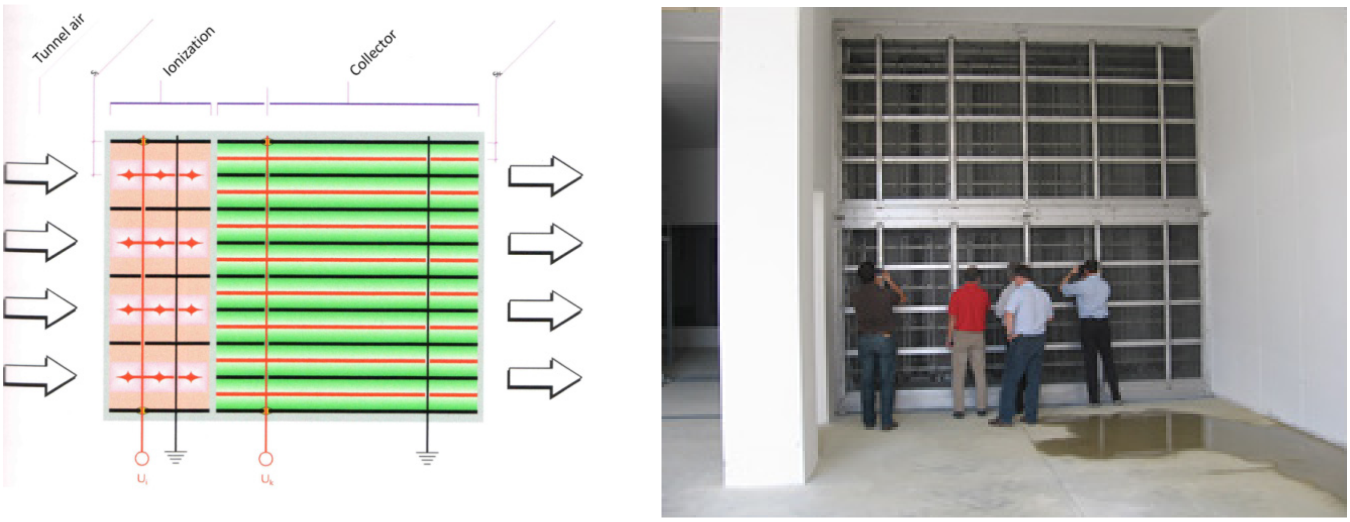

Figure 2: Left: Scheme of an electrostatic filter. Right: View of the ionisation stage of an ESP

9 A detailed description of the function of an ESP can be found in PIARC 2008.

2.1.2.3 Installation of particle filtration systems

As noted above, PM filtration is either performed to improve in-tunnel air quality or to reduce the release of particle emissions from the tunnel. To improve in-tunnel air quality, the system is usually installed in a cavern inside the tunnel and operated in bypass mode (see Figure 3).

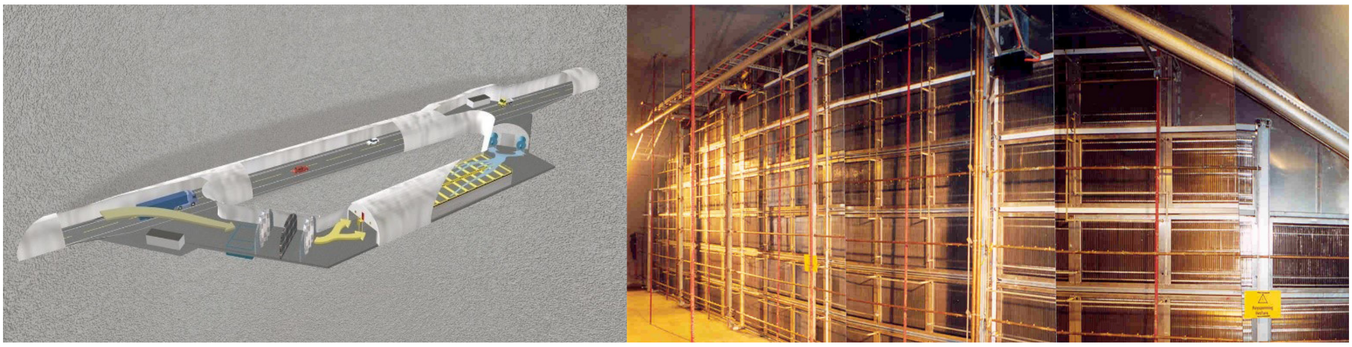

Figure 3: PM filtration system installed inside the tunnel in bypass mode; left: sketch; right: ESP[10]

When using PM filtration to reduce emissions from the tunnel, the polluted air must be extracted from the tunnel and transported to the filters before being released into the environment. In the case of a longitudinally ventilated tunnel, this requires extraction of the tunnel air, which demands considerable investment in terms of construction, ventilation equipment and operating costs. Figure 4 depicts the arrangement for air extraction and housing the ventilation and air treatment systems in the Cesena tunnel in Italy.

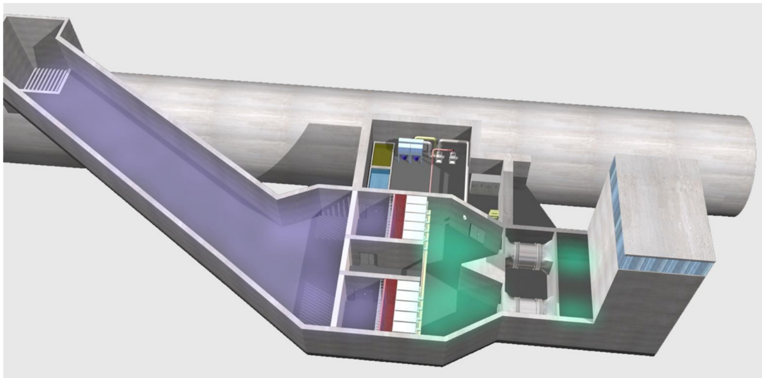

Figure 4: Tunnel with air extraction and PM filtration[11]

2.1.2.4 Electrostatic precipitator filtration systems in use today

In 2009, Brandt et al[12] listed 66 tunnels equipped with ESP for PM10 filtration, mainly in Japan, but also in Italy, Spain and South Korea. Roughly one third of them – mainly the more recent applications – were installed to reduce emissions from the tunnel, while earlier installations were generally intended to improve in-tunnel visibility. No information was available on the operational status of these installations. These findings were confirmed and updated by the more recent investigation performed at CETU[13].

The volume flow rates for most filtration units are in the region of 200 m³/s. Pressure losses are around 200 to 250 Pa per unit, excluding losses for air extraction and in the ventilation ducts. The number of units required depends on traffic volumes and tunnel length. The ventilation power required is strongly influenced by the arrangement options for associated structures such as ducts and ventilation buildings, and by parameters such as distance to stacks. Typical power requirements are in the range of 200 to 500 kW for treatment of a volume flow of some 300 – 400 m³/s.

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10 Haug R.G. (2005) Particle cleaning in Norwegian urban tunnels. Presented at PIARC meeting technical committee, Sydney, May 2005

11 Aigner Tunnel Technology (2017): http://www.aignertunnel.com/index.cfm?seite=filme-staubfilter-fuer-strassentunnel&sprache=EN (accessed 11 November 2017)

12 Brandt R., Riess I.(2009): Possibilities and limitations of tunnel-air filtration and portal-flow extractions, ISAVVT 13 2009

13 CETU (2016). The treatment of Air in Road Tunnels; State-of-the-art studies and works, document updated in December 2016; www.cetu.developpement-durable.gov.fr

More recently, only a few new tunnels have been equipped with PM filtration plants. Among these are the Sorrentina tunnel in Naples, Italy (5,171 m), which has a longitudinal ventilation system with a volume flow of 120 m³/s to be extracted at each portal, and the portal ventilation station of the Mt Blanc tunnel (French side of the tunnel) in Chamonix (360 m³/s).

2.2 Gaseous pollutants

2.2.1 *Nitrogen oxides*

NO_x exhaust emissions consist mainly of NO; however, NO_2 is the more critical component for human health. The share of NO_2 in the NO_x emissions depends on the proportion of diesel fuelled passenger cars in the road fleet, and on the total NO_x concentration in the tunnel. Diesel fuelled passenger cars with exhaust gas after-treatment systems tend to have an increased share of primary emitted NO_2. Figure 5 shows the NO_2/NO_x ratios in the air of three different tunnels with different traffic compositions. The variations depend on the number of diesel fuelled passenger cars (PCs) and light duty commercial vehicles (LCVs) within the vehicle fleet. The percent of diesel fuelled PCs and LCVs ranges from 57 per cent in the Plabutschtunnel (Austria), to 32 per cent in the Norra Länken tunnel (Sweden) and 11 per cent for the Clem 7 tunnel (Brisbane, Australia). Note that the lines given in Figure 5 represent the best fit from data sets with significant scatter. In addition, the high NO_2/NO_x ratios at low NO_x concentration levels were mainly recorded during times with little HGV traffic.

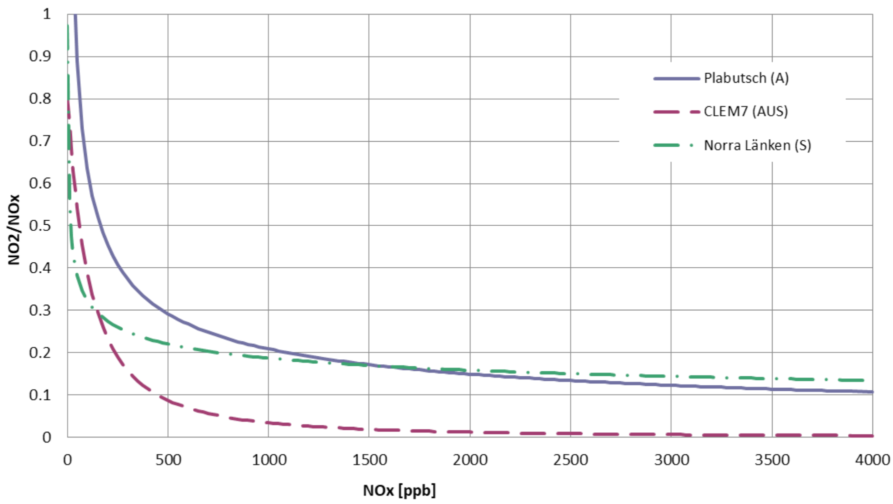

Figure 5: NO_2/NO_x ratio as a function of NO_x concentrations in tunnels with different fleet composition[14]

2.2.2 *Treatment of nitrogen dioxide*

Several technologies have been tested to treat gaseous pollutants such as NO_x (and NO_2). Each has benefits and drawbacks, as outlined below.

2.2.2.1 Catalytic conversion

Standard catalytic converters (e.g. used in cars or industrial applications) require a high effluent temperature. For road tunnels, this would mean that polluted air flow volumes of some hundreds of m³/s would need to be heated to temperatures above 200°C. Various tests in the 1990s[15,16] showed that while catalytic treatment of gaseous pollutants would be possible in principle, the necessity of achieving high effluent temperatures meant that it was not feasibly practical. There have been no further noticeable achievements in the field of catalytic treatment of gaseous pollutants.

14 Sturm, P. (2017) NOx data analysis from various road tunnels; Graz University of Technology, Austria.

15 Leistentritt R (1998) Biologische Straßenabluftreinigung im Vergleich mit Konkurenzverfahren und deren Realisierbarkeit in der Praxis. PhD Thesis Graz University of Technology, Austria.

16 Pischinger R., Pucher K., Herzog G., Söllmann G (1994): Abluftreinigung mit Katalysatoren in Straßentunneln. Bundesministerium für wirtschaftliche Angelegenheiten, Straßenforschung Heft 423, Wien, 1994.

2.2.2.2 Biological treatment

Biofilters are commonly used in industrial applications to treat odour-laden effluents by reducing organic content. Biological treatment of tunnel air has a relatively long history, with tunnel air applications starting in the 1990s. They showed satisfactory results for carbon monoxide (CO), hydrocarbon and NO_2 reduction, but a relatively low reduction rate for NO. The main problem was found to be the large volume needed for the bioreactor in order to minimise pressure loss and maintain operation costs at an acceptable level. There were also problems reported concerning temperature and humidity in regions where ambient conditions were below freezing.

In recent years, a test installation was set up in the region of Paris (Vidal et al, 2017). A relatively small volume flow (of roughly 1 to 2 m^3/s of polluted tunnel air) was sent through a bio-filtration plant. NO_2 reduction rates of between 58 per cent and 86 per cent were recorded. In addition, the soil and water of the biofilter acted as a PM trap. Although the reduction rate was found to be reasonable, the authors concluded that significant ventilation and energy consumption would be needed for an effective treatment of tunnel air at full volume. This test confirmed the results achieved in the late 1990s.

2.2.2.3 Adsorption technique

The activated carbon adsorption technique is currently the only technology being used to treat tunnel air quality in full size applications in road tunnels (e.g. Calle 30, Madrid, Spain). This technology uses activated carbon to adsorb a range of contaminant gases, including hydrocarbons and NO_2. A more detailed description of this technology can be found in the 2008 PIARC report.

2.2.2.4 Other possibilities

Other techniques, such as the use of photocatalytic processes, are still at an experimental stage. This technology requires a surface containing chemical substances enhancing catalytic reactions (e.g. titanium dioxide) and the provision of UV light. At present, there is one short tunnel in Rome (Umberto I tunnel) and a second, the Leopold II tunnel in Brussels Belgium utilising this technique.

'Before' and 'after' measurements show a positive effect[17]; however, long-term findings on the efficiency of this technology and the maintenance and cleaning efforts required for its application are not available.

2.2.2.5 Tunnel installations for treatment of gases, mainly nitrogen dioxide

Full-scale treatment installations of gaseous pollutants in tunnel air are rare, with the Madrid 'Calle 30' tunnels in Spain currently the only example of a permanent full-scale installation. A similar system has been installed in the Laerdal tunnel in Norway; however, very little information is available about the operation of this system.

While the Madrid system was installed for environmental purposes in stacks, the Norwegian system is in the centre of the tunnel and serves to improve in-tunnel air quality.

17 Guerrini G. L.; Peccati E (2008).; Tunnel 'Umberto I' in Rome – Monitoring program results; Report n. 24; CTG Italcementi Group; Bergamo; 22 April 2008.

3. Benefits and Limitations of Air Treatment Systems

The benefits and limitations of air treatment systems need to be considered on a project by project basis and account for local air quality and population conditions. While an air treatment system for particulates or NO_2 may be technically feasible, it will not lower concentrations of other pollutants and the energy usage is high. Alternatives such as portal air extraction and stack dispersion may achieve the same outcomes at a reduced cost.

Due to the volume of traffic in urban areas, roads in general and tunnel portals in particular, vehicle emissions constitute a significant source of NO_x and PM emissions. While it is recognised that the most critical component in emissions management is the ongoing regulation and reduction of emissions from motor vehicles, in long and/or heavily trafficked tunnels in urban areas, tunnel air has to be managed in order to avoid unacceptable air pollution levels. In such cases, portal air management via stacks is the most common practice, and the usage of air treatment systems is also often subject to discussion.

Any statement concerning the benefits of air treatment systems can only be made at the project level. In terms of potential application, technical feasibility alone cannot be an exclusive driving factor. Other factors, such as the benefits for the local population, energy usage rates and related air pollution levels also need to be considered. Technical alternatives, such as simple portal air extraction, or dispersion via stacks, might serve the same purpose.

Cost/benefit analysis of the air treatment trial on the M5 East tunnel in Sydney revealed that the operating costs of the system were at least one order of magnitude higher than the value of the health benefits gained, and that the total costs (operating plus investment costs) were higher still (RMS 2014). Brandt and Reiss (2009) and others[18] have concluded that the costs for tunnel air management varied between USD$400 and 950 per kilogram of PM_{10} for portal air extraction and stack dispersion, while the costs for PM10 filtration were around USD$1900 per kilogram, on a 2008 cost basis. No information was provided for $DeNO_x$ applications; however, as $DeNO_x$ plants require ESP upfront and have a noticeably higher rate of pressure loss, it can be assumed that the running costs are also noticeably higher than for the ESP alone.

In cases where unmanaged portal air contributions are considered to be too high, abatement measures such as dispersion via stacks or filtration systems must be installed to achieve the project's acceptance criteria for air quality. This means that for urban areas, tunnel air concentrations must be at very low levels to be acceptable.

The efficiency of such systems can be investigated by measuring the concentrations of effluents upstream and downstream of the filter. As such, the net effect of a filtration system on environment and subsequently on human health could theoretically be estimated. It is difficult to evaluate such a benefit as in most cases the absolute value of pollution reduction is quite small, i.e. in cases of dispersing the emissions via a proper designed stack, the benefit of an additionally installed filtration system will be marginal. However, having a filtration system installed, it might not be necessary to disperse pollutants via stacks.

To date, there have been no upgrades of existing systems where the upgrading process has included the erection of stacks or the installation of filtration systems. As such, no 'before' and 'after' investigations exist that would demonstrate the benefits of tunnel air management on the environment or on human health.

Based on the review described in this paper, it can be concluded that the use of stacks for dispersing pollutants is a viable option when portal air management is necessary. In general internationally, the operating time of such systems is only a few hours per day, depending on traffic or ambient air quality conditions. This is in contrast to the Australian and in particular, the NSW context, where approval conditions for new tunnel projects greater than one kilometre in length prohibit portal emissions and all tunnel air is released via stacks.

In the international context, there have been very few cases where portal air emissions have been totally prohibited. PM and NO_2 filtration of tunnel air is currently applied only in cases where the erection of stacks was not considered appropriate.

18 TBA Zürich (2008): Cleaning of exhaust air from road tunnels, state of the art; pp 142, 2008 (in German), 2008, accessed April 2018.

4. Conclusion

For long and/or heavily trafficked road tunnels in urban areas, tunnel air is generally managed before it is released into the environment. Based on a review of international practice:

- Tunnel air dispersion via stacks is the most commonly used alternative in cases where portal air release is prohibited.
- Filtration systems for managing PM (ESP technology) and NO_2 (activated carbon adsorption technology) are rare in the international context. They are currently installed at locations where stack dispersion is not favourable and generally operate for only a few hours a day.
- Capital, operation and maintenance costs are high due to the challenge of capturing and treating high volumes of tunnel air with very low pollutant concentration levels (compared to industrial applications).
- Any decision making process concerning tunnel air management (portal air management as well as air treatment systems) needs to prioritise health based air quality standards when considering engineering and economic practicabilities, and can only be made at the project level.
- Technical alternatives to air treatment systems, such as simple portal air extraction, or dispersion via stacks, might serve the same purpose.

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RMS 2018d: TP05 – Road Tunnel Stack Emissions, Review, NSW, Advisory Committee on Tunnel Air Quality

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8. Appendix 1: Case Studies

This section covers large tunnels and tunnel networks, where tunnel air treatment systems are in operation or the installation of such systems is part of the project.

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 ventilation systems and tunnel stack systems can be found in the associated technical papers in this series.

8.1 The Madrid Calle 30 tunnel projects

The multi-lane inner city circle road of Madrid, called Calle 30, is a route network with three intersections, 22 entrances, 24 exits and with multiple tunnels (Figure 6). Roughly 50 km of this ring road are constructed as tunnels[19], 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 By-pass 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 HGV >7.5 t and dangerous goods vehicles[20, 21].

To comply with EU and Spanish national ambient air quality standards, exhaust air in the tunnel network required PM and in certain cases also NO_2 treatment. The air filtration system comprises 26 filtration plants consisting of ESPs for particle removal, and an additional four activated carbon filters for gas cleaning.

Under normal conditions, the fans in the filtration plants operate at between 20 and 30 per cent of maximum power. Maximum power is used only in the case of fire. Anecdotal evidence has revealed that each plant is in use for about two hours a day (those with peak traffic), with operation triggered by traffic volume.

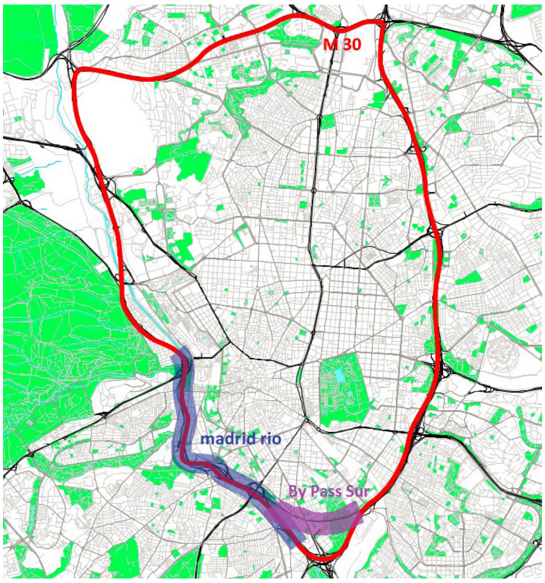


Figure 6: Map of the Madrid Calle 30 project, with $DeNO_x$ installation in the 'Rio' and 'By-pass Sur' sections (picture modified from reference)[22]

19 PIARC WG 5 (2017) 'Complex Underground Road Networks'– Part A ' Case Studies 'appendices, Appendix2.16 - SPAIN – Madrid – Rio-Tunnel, https://tunnels.piarc.org/en/system/files/media/file/appendix_2.16_-_spain_-_madrid_-_m30_rio_tunnel.pdf; accessed 18 November 2017.

20 PIARC WG 5 (2017) 'Complex Underground Road Networks'– Part A ' Case Studies ' – appendices, Appendix 2.16 - SPAIN – Madrid – By-pass-Tunnel, https://tunnels.piarc.org/en/system/files/media/file/appendix_2.16_-_spain_-_madrid_-_m30_bypass_tunnel.pdf; accessed 18 November 2017

21 Presa J (2008). Madrid Calle 30: An urban transformation project; Proceedings of the 4th international conference 'Tunnel Safety and Ventilation' 2008, Graz, pp 40-46; ISBN 987-3-85125-008-4.

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

The By-pass Sur tunnel is approximately 3.6 km long and is equipped with a transverse ventilation system[23] and four stacks for air exchange. In 2012, the traffic volume amounted to 67,750 vehicles/day. Figure 7 provides a cross section sketch of a ventilation station in this tunnel.

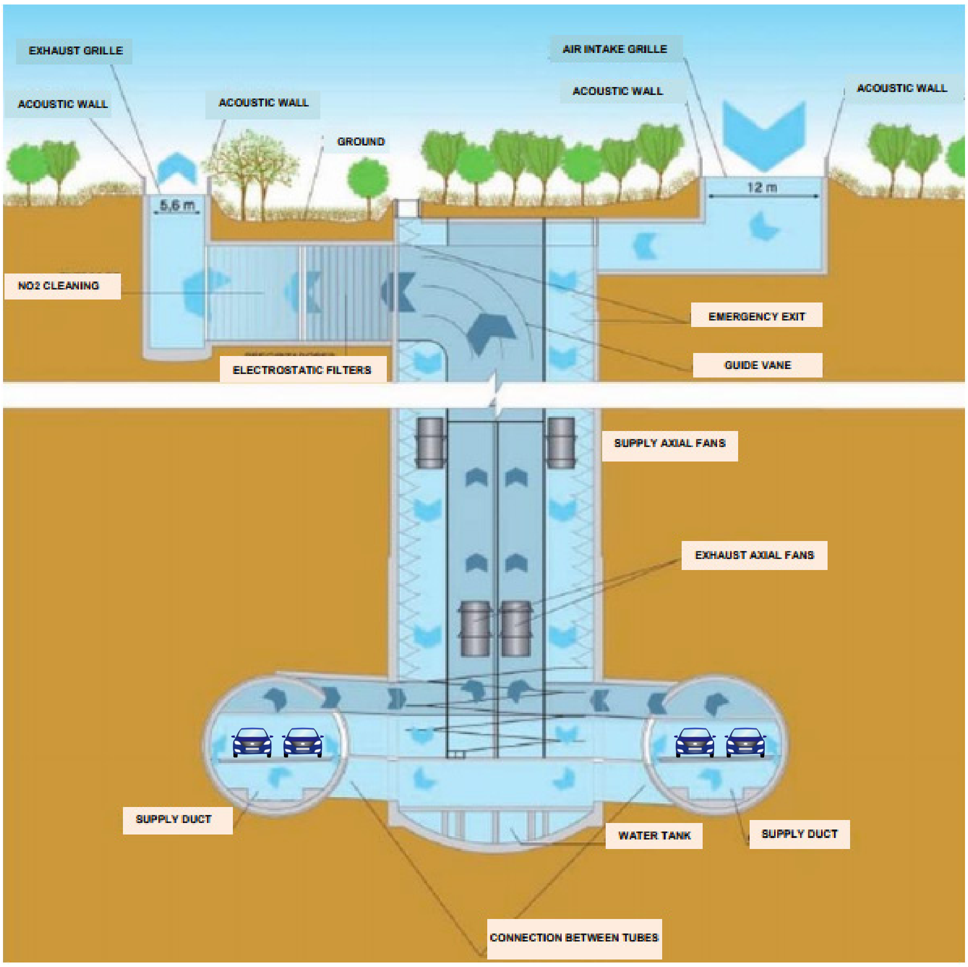


Figure 7: Sketch of a ventilation station in the By-pass Sur tunnel of the Calle 30 (picture modified from reference)[24]

Figures 8 to 10 show the installation of ventilation stations in the By-pass Sur section of the Calle 30 project.

Figure 8: Left: Ventilation station PV4, ESP at the front, DeNOx plant at back. Right: Ventilation station PV3, ESP front view[25]

23 System description see RMS 2018b.
24 Aigner Tunnel Technology GmbH (2008): Filtration efficiency for $DeNO_x$ in the PV3 station, measurements performed for the SAT process, February 2008 (tunnel 'By-pass', Calle 30 project Madrid).
25 Aigner Tunnel Technology GmbH, Austria.


Figure 9: Left: surface installation. Right: subsurface cavern installation (Aigner Tunnel Technology 2018)


Figure 10: $DeNO_x$ plant (Aigner Tunnel Technology 2018)

Volume flow rates are between 400 m³/s and 700 m³/s. The pressure loss in the air stream is strongly dependent on the space available for placing the active carbon. According to personal communication, pressure losses are between 350 Pa and 500 Pa[26] for the $DeNO_x$. This results in power consumption of around 200 kW and 500 kW per station. As a $DeNO_x$ requires an upstream PM filtration system, the power consumption for the activation of a full air treatment system (ESP + $DeNO_x$) approaches 350 to 700 kW per station. This is without taking account of the airway losses from the extraction point in the tunnel to the release of the treated air into the environment.

Table 1 and Figure 11 depict the efficiency values of $DeNO_x$ plants recorded during commissioning on the Madrid Calle 30 project. These values show that while the treatment systems work well for NO_2, they have a poor level of efficiency for NO.

Table 1: Efficiency of the $DeNO_x$ installation in the By-pass Sur section of the Calle 30 project for NO_x, NO_2 and NO[27]

Pollutant	Upstream $DeNO_x$ [ppm]	Downstream $DeNO_x$ [ppm]	Efficiency [%]	Pollutant/NO_x [%]
NO_x	0.478	0.315	34	100
NO_2	0.147	0.012	92	31
NO	0.331	0.315	8	69

26 Aigner H (2017); Personal communication per email 15 November 2017.

27 Aigner Tunnel Technology GmbH (2008): Filtration efficiency for DeNOx in the PV3 station, measurements performed for the SAT process, February 2008 (tunnel 'By-pass', Calle 30 project Madrid)

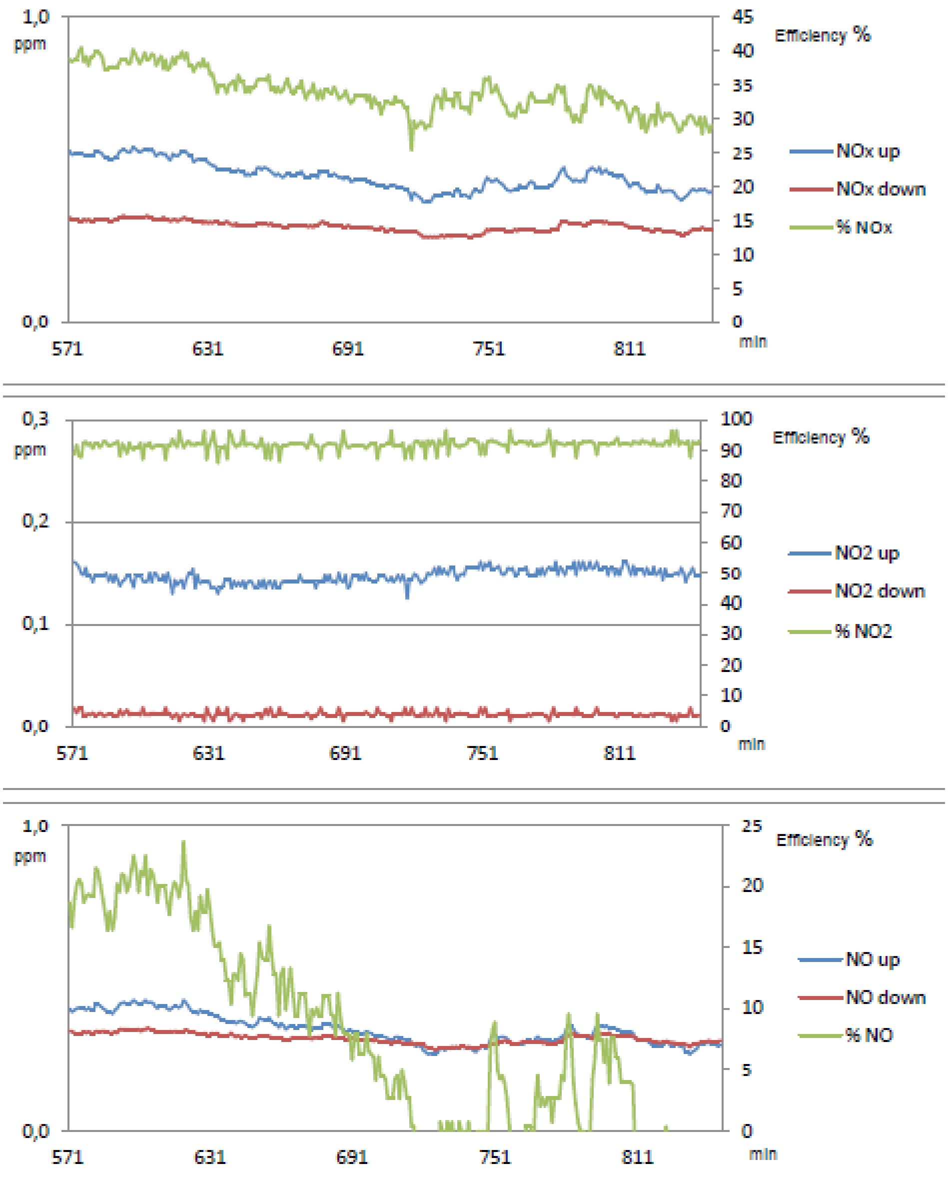


Figure 11: Cleaning efficiency of the DeNO$_x$ plant in the By-pass Sur section of the Calle 30 project for NO_x, NO_2 and NO; up = upstream filter, down = downstream filter (Aigner Tunnel Technology 2008)

The efficiency of individual PM filtration plants was measured in 2012 at the direction of the tunnel operator. The results are shown in Table 2.

Table 2: Efficiency of ESP PM filtration plants installation in the Calle 30 project (Aigner 2017)

Efficiency [%]	PM_1	$PM_{2.5}$	PM_{10}
Panasonic	80%	80%	80%
Aigner Tunnel Technology	95%	90%	90%
CTA/WATMA	85%	90%	90%
Filtrontec	75%	77%	75%
Average	84%	84%	84%

8.2 The Hong Kong Central – Wan Chai Bypass and Island Eastern Corridor Link (CWB) 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 is designed to improve traffic conditions by taking traffic off the Gloucester Road–Harcourt Road–Connaught Road Central corridor. A 3.7 km tunnel extends from the Central Rumsey Street flyover to City Garden at North Point, with slip roads for access to/from the Wan Chai area (see Figure 12). Peak traffic volumes are more than 100,000 vehicles/day.

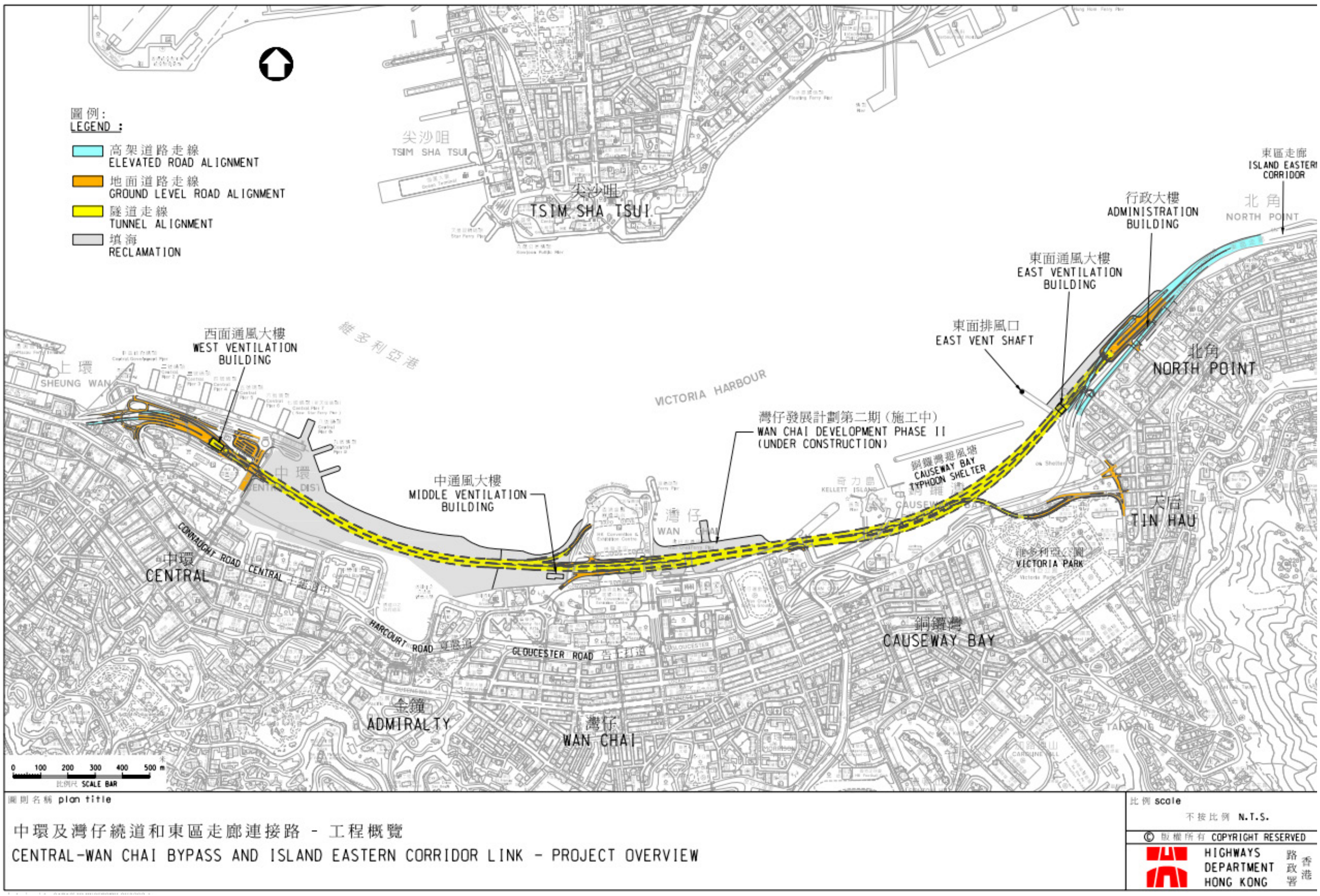


Figure 12: Map of the CWB link[28]

In-tunnel air criteria are 100 ppm for CO and 1 ppm for NO_2 (both measured at 298 K and 101.325 kPa) as a five-minute average[29].

Three ventilation buildings (see Figure 13 and Figure 14) serve as sites for ventilation and release of pollutants. At the western portal and in the centre of the tunnel, the stack is integrated into the ventilation building. At the eastern portal, a dedicated ventilation stack is located 150 m inside the breakwater of Victoria Harbour.

Air treatment system are planned to minimise the impact on the environment and to avoid the erection of a stack in the region of the ventilation building ‘east’. While a 2001 environmental impact assessment report only mentions the use of PM filtration at the eastern portal[30, 31], information made available in 2017 refers to PM and NO_2 filtration in all three stations[32]. The design volume flow rates are around 250 m³/s at the western vent station and 625 m³/s at both the central and eastern stations.

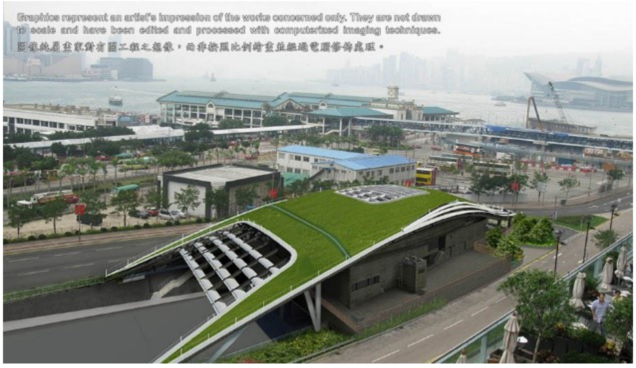
28 HYD: Highway Department, The Government of the Hong Kong Special Administrative Region, https://www.hyd.gov.hk/en/road_and_railway/road_projects/6579TH/HMW6579TH-SK0282.pdf; accessed 18 November 2017

29 EDP: Environmental assessment study CWB project, http://www.epd.gov.hk/eia/register/report/eiareport/eia_0572001/report/html/Sec3-RevA.htm, accessed 18 November 2017

30 HYD: Agreement No. CE5/95, Central-Wan Chai Bypass and Island Eastern Corridor Link, Project Review Study, Environmental Impact Assessment Report, 2001

31 HYD: Wai Chai Development Phase II, Planning and Engineering Review; Environmental Assessment Report for Wan Chai Bypass, Volume 1 – WDII Project, accessed 18 December 2007 (http://www.cwb-hyd.hk/en/library_erd.php

32 IOM: Technical visit to air purification system and tunnel ventilation system in central Wan Chai bypass tunnel (http://www.iom3.org/hong-kong-branch/news/2017/jul/22/iom3hk-technical-visit-air-purification-system-and-tunnel), accessed 21 November 2017



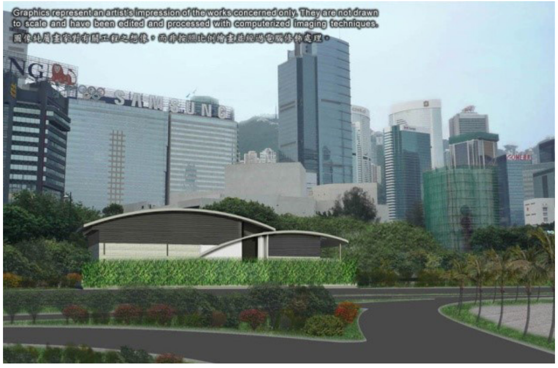


Figure 13: Image of the ventilation buildings at the western portal (left) and central (right)[33]

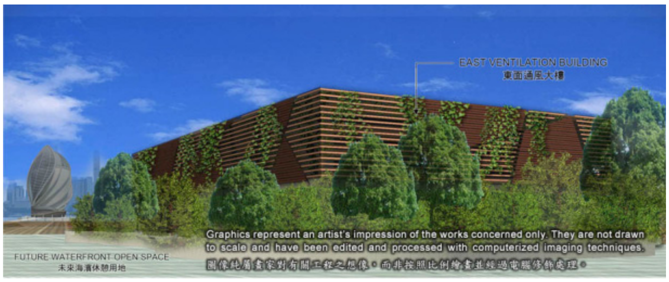


Figure 14: Image of the ventilation building (left) and ventilation stack (right) at the eastern portal (HYD 2017)
Figures 12, 13 and 14 contain images and information used with the permission of the Highways Department of the Government of the Hong Kong Special Administrative Region. All rights reserved.

No information was found in the literature concerning portal air management, the reason for using tunnel air treatment systems, or the operation of the air treatment systems.

8.3 Japan

8.3.1 Existing tunnels

Japan has the longest history of PM filtration systems for road tunnels and tunnel portal air management in the world. In 2014 Yamada et al[34] listed 1,135 tunnels in Japan, of which 41 were equipped with a longitudinal ventilation system including an ESP. Most of these systems were designed to improve visibility conditions inside the tunnel without the need for full air exchange via stacks.

Generally, urban tunnels in Japan 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, sometimes the stacks need to be quite tall. Some of the ventilation stations in the stacks are equipped with ESP.

One big project is the Yamate tunnel, which carries the Central Circular Route of the Shuto Expressway in Tokyo. The overall tunnel length is 18.2 km. This consists of a 10 km long tube section which opened at the end of 2007, a central stretch which opened in 2010, and the 8 km Shinagawa line which opened in 2015. The tunnel carries some 90,000 vehicles a day and is vented by a transversal ventilation system. Multiple stacks with ESP provide for air exchange and pollutant dispersion (see Figure 15). Public information about operation strategy and operation times is not currently available.

33 HYD: Highway Department, The Government of the Hong Kong Special Administrative Region; http://www.cwb-hyd.hk/en/about_projectfeatures_2.php#WestVentilationBuilding, access 18 November 2017

34 Yamada M., Kawabata N., Kikumoto T.: Transition of Japanese Road Tunnels Ventilation and Smoke Exhaust in Tunnel Fires; in: Proceedings of the 7th international conference 'Tunnel Safety and Ventilation' 2014, Graz, pp 257-264; ISBN 978-3-85125-320-7

Figure 15: Yamate tunnel air exchange stacks (45 m high) at Yamate Street, Tokyo

8.3.2 New tunnel – Tokyo Outer Ring Road project

The Tokyo Outer Ring Road is one of the three ring roads around the city's metropolitan centre. The section between Nerima-ku and Setagaya-ku 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 vehicles a day in 2030. The tunnel location is shown in Figures 16 and 17.

The ventilation system is based on a combination of longitudinal ventilation in the mainline tunnel, supported by air exchange at the ramps. Figure 18 shows the longitudinal profile of the tunnel. The ventilation buildings provide for air exchange, portal air management and PM filtration as shown in Figure 19.

Figure 16: Map of tunnel location in Tokyo

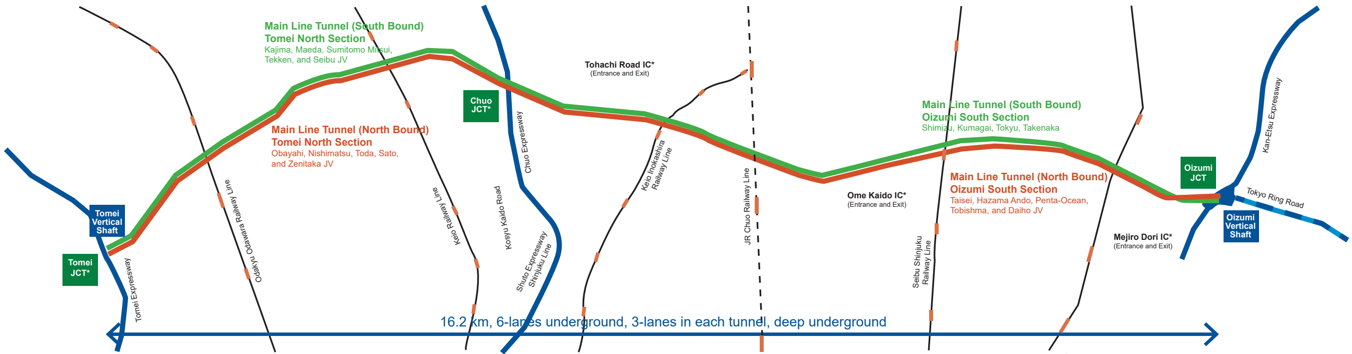


Figure 17: Map of the tunnel between Nerima-ku and Setagaya-ku (picture modified from reference)[35]

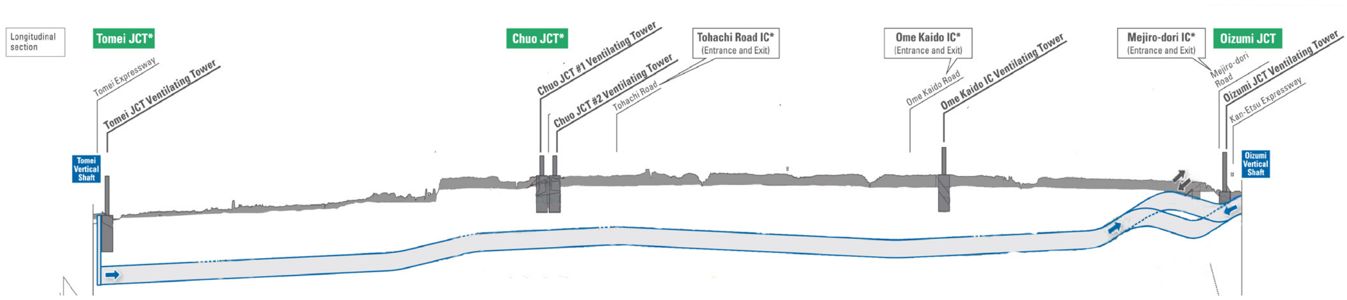


Figure 18: Longitudinal profile of the tunnel (picture modified from reference)[36]

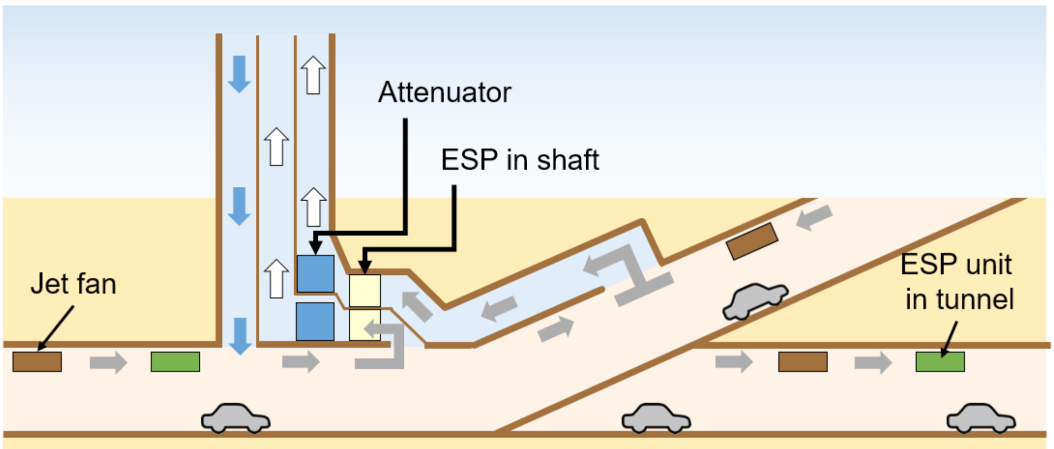


Figure 19: Sketch of the ventilation stations for air exchange and portal-air management (picture modified from reference)[36]

35 http://tokyo-gaikan-project.com/library/pdf/pamphlet02_e.pdf
36 http://www.ktr.mlit.go.jp/gaikan/gaiyo/hozentaisaku03.html; accessed 24 November 2017

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