Information document

THE TREATMENT OF AIR IN ROAD TUNNELS

State-of-the-art of studies and works

Document updated in December 2016

Tunnels Study Centre (CETU)

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Ministère de l'Environnement, de l'Énergie et de la Mer

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The treatment of air in road tunnels

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INTRODUCTION

Road tunnels, often designed to circumvent obstacles, also provide an opportunity to shield residential areas from the nuisance caused by road traffic or to bypass nature areas sensitive to pollution. Road traffic channelled through tunnels is still a source of atmospheric pollution that has to be incorporated into tunnel operation. Atmospheric pollution has to be managed both inside tunnels to protect users' safety and wellbeing, and outside tunnels at the discharge outlets in order to limit environmental impacts. These two aspects are governed by regulations that stipulate the pollution levels to be complied with inside tunnels, which are quite different to those specified for the external environment.

Ventilation techniques are the most common approach to dealing with this two-fold issue. Ventilation is also used in smoke extraction processes in the event of fire. This generally involves optimising a system that provides "sanitary" ventilation in standard use, and smoke extraction in the event of fire.

Generally speaking, the role of sanitary ventilation is to promote the dilution of pollutants inside tunnels through the intake of fresh air, which also dilutes the concentration of pollutants at tunnel portals. Mechanical air extraction systems can also be used to evacuate vitiated air from tunnels at several outlets along the length of the tunnel via one or more ventilation shafts, thus ensuring that pollutant discharges are not concentrated at the portals. These diverse ventilation mechanisms make it possible to comply with the regulations governing internal tunnel air quality. Externally, they are used to significantly reduce the impact of road pollution in areas (urban areas in particular) that may already be affected by a number of pollution sources.

Air treatment systems are designed to go beyond the simple principle of ventilation. These systems were developed in Japan from the 1980s onwards and were first used in Norway in the 1990s due to the specific features of certain tunnels there, i.e. very long tunnels with significant coverage that makes it difficult to use conventional ventilation techniques; another example is the use of studded tyres that greatly increases particulate pollution and hinders visibility within tunnels.

In recent years, rising environmental concerns have led to these systems being used for other purposes upstream of discharge to the atmosphere, the aim this time being to limit the impact on the external environment. This makes it possible to supplement the treatment of particulates with that of gases. This shifts the focus onto meeting local pollution-related concerns. Owners, through large-scale land development projects, have focused on these technologies with a view to the preservation of fresh air within a specific localised context, i.e. the tunnels on the M30 in Spain, the Madrid orbital road. The GEIE-TMB (European Economic Interest Grouping of the Mont-Blanc Tunnel) has also decided to install an extraction-based particle filter above the French platform of the Mont-Blanc tunnel, in order to contribute to the various local initiatives aimed at improving air quality in the Chamonix Valley.

The CETU published a preliminary summary paper [1] on the treatment of air in a tunnel environment in 1999. This paper was mainly based on the findings of two countries, Norway and Japan. A more detailed information paper was then published in 2010 [2], to outline the treatment techniques developed and the new installations built since 1999.

This document is a revised version of the 2010 paper, containing updates on the development of new treatment technologies and new installations built worldwide. The focus is on air treatment technologies, whether particulate filtration or the treatment of gases.

The paper is organised into three sections:

- regulations governing atmospheric pollution and road tunnels,
- filtration of particulate matter in tunnels,
- denitrification of gases in tunnels,
- alternative and innovative techniques.

1

POLLUTANTS AND RELATED FRENCH REGULATIONS GOVERNING INTERNAL AND EXTERNAL TUNNEL ENVIRONMENTS

1.1 PERMISSIBLE LEVELS INSIDE ROAD TUNNELS

The French *law on air and the rational use of energy* [3], incorporated into the Environmental Code, contains no requirements relating to permissible concentrations of pollutants in tunnels, nor even relating to the concentrations to be complied with in closed or partially closed underground structures. The main reference for underground structures is *circular 99.329 of 8 June 1999* issued by the Ministry of Health [4]. This covers two pollutants:

- **carbon monoxide** (CO),
- **nitrogen dioxide** (NO_2).

However, the monitoring of air quality in tunnels is also based on the monitoring of smoke, via measurements of **opacity**, for which the CETU has recommended thresholds (les dossiers pilotes du CETU, *Ventilation* [5]).

Lastly, the *technical instruction annexed to the circular of 25 August 2000* [6] stipulates maximum CO and opacity levels not to be exceeded in the event of an accident in a tunnel.

As exposure times for users of underground structures are generally fairly short, thresholds are calculated based on fairly short times (15 to 30 minutes at most), or even just expressed as an instantaneous threshold *(see Table 1)*.

In France, conventional ventilation systems are sized so as to ensure that these thresholds can be complied with during the structure's lifetime, with no need to use additional treatment systems.

Pollutant	Parameter	Observation time	Regulatory or recommended level		Reference
Carbon monoxide	During accidents, at any point in the tunnel	Instantaneous value	**150 ppm**	*[171 mg/m³]*	Technical instruction of 25/08/00
	Average content throughout the whole length of the tunnel	15 minutes	**90 ppm**	*[103 mg/m³]*	Circular of 08/06/99
		30 minutes	**50 ppm**	*[57 mg/m³]*	
Nitrogen dioxide	Average content throughout the whole length of the tunnel	15 minutes	**0.4 ppm**	*[752 µg/m³]*	Circular of 08/06/99
Particles opacity	During accidents, at any point in the tunnel	Instantaneous value	$9 \cdot 10^{-3}\ m^{-1}$	*[≈ 900 µg/m³] (PM_{10})*	Technical instruction of 25/08/00
	In normal situations, at any point in the tunnel	Instantaneous value	$5 \cdot 10^{-3}\ m^{-1}$	*[≈ 500 µg/m³] (PM_{10})*	CETU recommandation

Table 1: permissible level inside tunnels

1.2 PERMISSIBLE LEVELS IN THE OPEN AIR

1.2.1 National criteria

National air quality criteria are mainly based on:

- *French decree, No. 2002-213, of 15 February 2002 relating to the monitoring of air quality and its effects on health and the environment, air quality objectives, alert thresholds and limit values* [7];
- *French decree, No. 2003-1085, of 12 November 2003 [8] transposing directive 2002/3/CE of the European Parliament and of the Council of 12 February 2002*;
- *French decree, No. 2007-1479, of 12 October 2007 [9] relating to air quality and modifying the environmental code (regulatory part). This decree partial implements the "ozone" (2002/3/CE) and "heavy metals/PAH" (2004/107/CE) directives*;
- *French decree, No. 2008-1152, of 7 November 2008 [10] that completes the transposition of the directive "heavy metals/ PAH" (2004/107/CE)*;
- *French decree, No. 2010-1250, of 21 October 2010 transposing directive 2008/50/EC of the European Parliament and of the Council of 21 May 2008 on ambient air quality and cleaner air for Europe* [11];
- *French circular of 12 October 2007 relating to the dissemination of information to the public on particulates in suspension in ambient air* [12].

These texts form the basis of a regulation focusing on five types of threshold relating to some or all of the seven pollutants listed below:

- **nitrogen dioxide** (NO_2),
- **sulphur dioxide** (SO_2),
- **lead**,
- **particulate matter with diameter less than 10 µm** (PM_{10}),
- **carbon monoxide** (CO),
- **benzene**,
- **ozone** (O_3).

These five types of threshold are defined as follows:

- **Quality objective:** a level of atmospheric pollutant concentration to be attained in the long term and maintained, except where it is impossible to achieve this end using proportionate means, in order to ensure effective protection of human health and the environment as a whole.
- **Target value:** a level of atmospheric pollutant concentration set in order to avoid, prevent or limit harmful effects on human health or on the environment as a whole, ideally, to be reached within a given time.
- **Limit value:** a level of atmospheric pollutant concentration based on scientific knowledge, not to be exceeded within a given time, in order to prevent or limit harmful effects on human health or on the environment as a whole.
- **Information and recommendation threshold:** a level of atmospheric pollutant concentration beyond which short-term exposure presents a risk to the health of particularly at-risk population groups, requiring immediate and sufficient information for these groups and recommendations to reduce certain emissions.
- **Alert threshold:** a level of atmospheric pollutant concentration beyond which short-term exposure presents a risk to the health of the general population or of damage to the environment, justifying the deployment of emergency measures.

Table 2 on the following page sets out the main values defined thus.

There are also limits for fine particulate matter ($PM_{2.5}$) :

- *French decree, No. 2010-1250, of 21 October 2010 on air quality sets an annual average target value of 20 µg/m*^{3};
- *French law, No. 2009-967, of 3 August 2009 on programming for the implementation of the Grenelle de l'environnment adopted a Particulate Matter Plan together with the objective for a 30% reduction in atmospheric levels of fine particulates by 2015*.

The corresponding Particulates Plan was adopted in July 2010. It comments that *"although there are no linear relationships between ground-level emissions and atmospheric particulate concentrations, the goal will be to achieve a 30% reduction in emissions of primary particles* $PM_{2.5}$ *by 2015, i.e. a reduction of 100 kt (kilotonnes) of* $PM_{2.5}$ *by 2015"*. These various elements conform to the second National Health-Environment Plan 2009 – 2013 that provides for a 30% reduction in concentrations of fine particulate matter in ambient air by 2015.

This was a highly ambitious target. In reality, $PM_{2.5}$ emissions only fell by 15% between 2010 and 2014 [see Assessment of Air Quality in France 2014, CGDD] [13].

	Quality objectives	Target values	Limit values	Recommendation and information thresholds and alert thresholds
NO_2	**Annual average:** 40 µg/m³		**Annual average:** 40 µg/m³ **Hourly average:** not to be exceeded more than 18 hours per year: 200 µg/m³	<u>**Recommendation and information threshold**</u> **Hourly average:** 200 µg/m³ <u>**Alert threshold**</u> **Hourly average:** • 400 µg/m³, exceeded for 3 consecutive hours, • 200 µg/m³, whenever this threshold is exceeded the day before and risks being exceeded again the following day.
SO_2	**Annual average:** 50 µg/m³		**Daily average:** 125 µg/m³ not to be exceeded more than 3 days per year **Hourly average:** 350 µg/m³ not to be exceeded more than 24 hours per year	<u>**Recommendation and information threshold**</u> **Hourly average:** 300 µg/m³ <u>**Alert threshold**</u> **Hourly average over 3 consecutive hours:** 500 µg/m³
Lead	**Annual average:** 0,25 µg/m³		**Annual average:** 0,5 µg/m³	
PM_{10}	**Annual average:** 30 µg/m³		**Annual average:** 40 µg/m³ **Daily average:** 50 µg/m³ not to be exceeded more than 35 days per year	<u>**Recommendation and information threshold**</u> **Averaged over 24 hours:** 50 µg/m³. <u>**Alert threshold**</u> **Hourly average over 24 hours:** 80 µg/m³
CO			**Averaged over 8 hours:** 10,000 µg/m³	
Benzene	**Annual average:** 2 µg/m³		**Annual average:** 5 µg/m³	
O_3	**Protection of health:** 120 µg/m³ on average over 8 hours **Protection vegetation:** 6,000 µg/m³ per hour in AOT40 from May to July. *The "AOT40" is equal to the sum of the differences between hourly concentrations greater than 80 µg/m³ and 80 µg/m³ using only values for a one-hour period measured daily between 8h and 20h, during a given period.*	**Protection of health:** 120 µg/m³ maximum daily dose for the average over an 8 hour period not to be exceeded on more than 25 days per average civil year calculated over 3 years. **Protection vegetation:** 18,000 µg/m³ per hour in AOT40 averaged from May to July and calculated over 5 years.		<u>**Recommendation and information threshold**</u> **Hourly average:** 180 µg/m³ <u>**Alert threshold**</u> **For protection of the health** of the general population: Hourly average: 240 µg/m³ **For the progressive implementation of emergency measures:** • 1st threshold: 240 µg/m³, as an hourly average, exceeded for a period of 3 consecutive hours; • 2nd threshold: 300 µg/m³, as an hourly average, exceeded for a period of 3 consecutive hours; • 3rd threshold: 360 µg/m³, as an hourly average.
Arsenic		6 ng/m³ as an annual average of the total content of the PM_{10} fraction		
Cadmium		5 ng/m³ as an annual average of the total content of the PM_{10} fraction		
Nickel		20 ng/m³ as an annual average of the total content of the PM_{10} fraction		
Benzo(a)pyrene		1 ng/m³ as an annual average of the total content of the PM_{10} fraction		

Table 2: National air quality criteria (fresh air)

1.2.2 European standards

European standards on atmospheric pollution are incorporated into French law. Directive 2008/50/CE of the European Parliament and of the Council, of 21 May 2008 should be cited. This directive introduces an annual target value (less restrictive than a limit value) for particles with diameter of less than 2.5 µm, of 25 µg/m^3, to be implemented as of 2010. This value will become a restrictive limit value in 2015. Lastly, in 2020, this limit value will be lowered from 25 to 20 µg/m^3.

1.2.3 Pollutants to be considered in impact studies

Beyond those covered by current regulations, other pollutants are also being monitored due to their impact on health. This health impact raises questions on the related regulations, in cases where these pollutants are not already regulated. The health impact is also a component of road infrastructure impact studies.

As such, *the methodological note on the evaluation of the effects on health of air pollution in road impact studies* [14] specifies the type of pollutant to be factored into these studies. This note is annexed to an interministerial circular dated 25 February 2005 [15]. The list of pollutants to be taken account of depends on the challenges faced by the project in question (i.e. expected traffic density and land use). Where high stakes are involved, there are 16 pollutants that must be factored into the studies:

- 5 volatile organic compounds (VOC): benzene, formaldehyde, acetaldehyde, acrolein and 1,3-butadiene;
- 7 metals: chromium, nickel, cadmium, arsenic, lead, mercury and barium;
- nitrogen dioxide;
- sulphur dioxide;
- particulates;
- benzo(a)pyrene.

The pollutants were chosen based on a comparative analysis of the quantities emitted by road traffic and the related health risks *(selection of hazardous agents to be taken account of in assessments of health risks linked to road and rail infrastructures [16])*.

1.2.4 To sum up

While the regulations governing the inside of tunnels focus on two or three pollutants in particular, the regulations governing the outside of tunnels is far more wide ranging. This apparent plethora of pollutants actually covers four main families in addition to a few, specific pollutants:

- Volatile Organic Compounds including benzene, the best known representative;
- Polycyclic Aromatic Hydrocarbons, including benzo(a) pyrene which is used as a marker;
- Metals;
- Particulates, closely related to the metals and PAH families, as will be seen further on;
- Nitrogen dioxide;
- Sulphur dioxide;
- Carbon monoxide;
- Ozone, a secondary pollutant, concentrations of which can only be reduced by cutting emissions of the originating primary pollutants.

Some of these pollutants, although still being monitored, no longer represent a significant environmental challenge. This is the case, for example, with both sulphur dioxide and carbon monoxide where emissions and concentrations in ambient air and in tunnels have decreased substantially.

Of all these pollutants, it is **particulate matter** that raises the most questions in terms of health risks and which generally have the most serious effects. Particulate pollution also includes contamination by heavy metals and PAH where the particulate phases are the most common (i.e., the vapour phase of benzo(a)pyrene rarely exceeds 10% [17]).

In its annual pollution assessment of the Paris region, Airparif [18] revealed that, in 2014, 400,000 people living in the Ile-de-France region were at risk of potential exposure to PM_{10} at levels that exceed the legal limit. However, the number of inhabitants of the region exposed to these excess levels has been falling for several years.

Changes in the concentrations of **nitrogen dioxide** and **volatile organic compounds** must also be closely monitored, particularly due to their role in the ozone formation process and also regarding compliance with regulatory values of **benzene** and **nitrogen dioxide**. Airparif [18] also found that, in 2014, 2.3 million people living in the Ile-de-France region (including more than 90% of people in the city of Paris) were at risk of potential exposure to nitrogen dioxide at levels that exceed the legal limit.

The external environment is therefore marked by the presence of various types of pollution, including substantial road pollution along the edges of main roads. Tunnels partially channel this pollution and modify its distribution.

The installation of an air treatment system would provide a means of eliminating some of this channelled pollution, thereby providing a localised solution to a specific pollution issue, subject to cost and energy consumption requirements. Accordingly, the treatment targets the problem pollutants mentioned earlier:

- particulate pollution;
- gaseous effluents, in particular pollutants such as NO_2 and Volatile Organic Compounds (VOC).

2

ELECTROSTATIC FILTRATION OF PARTICLES

Very few tunnels in the world are equipped with air treatment systems. There are about sixty such tunnels in existence, three quarters of which are in Japan and eight in Norway. In almost all cases, electrostatic particle filtration systems are used. The Japanese were the first to implement such systems; their first installation dates back to 1979.

The particulate filtration represents both a system in itself and also a system of pre-treatment if any action is planned on gaseous effluents. However, in nearly 95% of cases, particulate filtration systems are used alone and not in conjunction with the treatment of gaseous effluents.

This figure is explained by the fact that particulate filtration is often used in Norway or Japan to improve visibility in tunnels, where visibility is affected by particulate pollution, or to minimize the need for fresh air renewal in very long tunnels. These systems are rarely used solely for environmental purposes. However, greater environmental and health-related concerns are driving interest in the use of such systems as indicated by recent European projects.

2.1 PRINCIPLE OF AIR FILTRATION IN TUNNELS

All particulate filtration systems in tunnels are based on the principle of "electrostatic precipitation". Particles in suspension in the airflow to be treated are first ionised i.e. given an electric charge. Technically speaking, the charge can be selected to be either negative or positive. The charged particulates are then collected using electrodes that carry a charge opposite to that of the ionised particles.

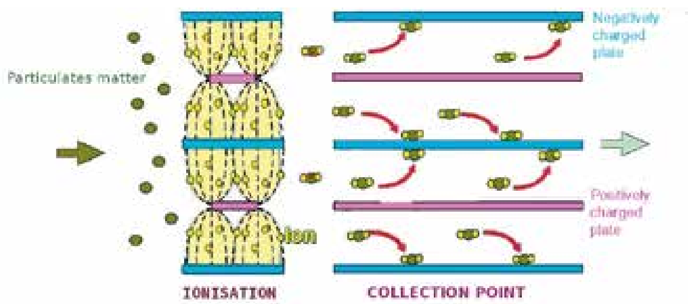

Illustration 1: block diagram showing the principle of electrostatic filtration (Source: "Managing air outside of tunnels" [19])

In the block diagram in *illustration 1*, particles shown in green are ionised by ions shown in yellow. The charged particles, in this example, positively, are recollected by streaming them through charged plates, some negative (blue plates) and some positive (violet plates). The violet plates repel the particles while the blue plates attract and collect them.

Ideally, the objective is to have small filters so as to limit the footprint of the filtration systems, and therefore their cost. Such an approach leads to an increase of airflow speed inside the filters. According to the company Kawasaki Heavy Industries [19], increasing the speed of the airflow in precipitators from 9 m/s to 13 m/s makes it possible to reduce their volume by 30% and thereby save space. Nonetheless, if the airflow is too fast this can result in collected particulates being re-expelled into the atmosphere, thereby reducing the system's performance.

System performance is also affected by clogging of the filters.

Lastly, the ionisation phase prior to the filtration of dust particles produces nitrogen dioxide (NO_2). Specifically, the ionisation produces ozone which reacts with nitrogen monoxide (NO) to form NO_2.

The various tunnelling contractors who have equipped tunnels to date all base their work on the fundamental principle outlined above, adapting it to increase performance levels, reduce the footprint and facilitate maintenance and servicing.

2.2 IMPLEMENTATION ACCORDING TO TECHNICAL REQUIREMENTS OR TARGETED OBJECTIVES

Particulate filtration systems can be implemented according to one of two principles, depending on the primary objective:

- Bypass-type installation: the objective mainly focuses on improving visibility;
- Extraction-type installation: the objective mainly focuses on reducing the impact of discharges to the environment.

2.2.1 Bypass-type installation

Bypass-type installations are generally used to provide longitudinal ventilation in very long tunnels.

The air is extracted, then filtered and re-injected into the tunnel. Several bypass passages may be installed in a given tunnel. The standard example is the 11 km long Kan'etsu tunnel in Japan, opened in 1985, which has five lateral bypass passages.

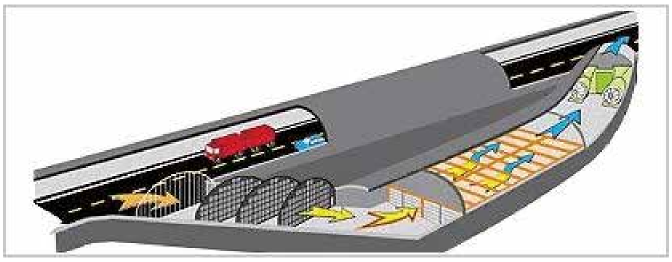

Illustration 2: block diagram of a lateral bypass passage (Source: http://www.cta.no/bypass .html)

The dimensions of lateral bypass passages vary according to the treated airflows but are approximately 150 m in length with a cross-section of 50 m^2 for a treated airflow of 200 to 250 m^3/s.

Around thirty Japanese tunnels are equipped with particulate filters fitted in bypass passages, as are five tunnels in Korea and one in Vietnam (see section 2.7). This type of installation can also be seen in six tunnels in Norway.

Bypass passages may be lateral or ceiling-based in order to adapt to civil engineering requirements. In practice, however, there are far fewer ceiling installations than lateral bypass installations. These are found in Norway in the tunnels at Hell, Nygards and Stromsas as well as in Japan in the Tokyo Bay tunnel, Aqua Line. However, the installations in Norway are no longer in use (see section 2.7).

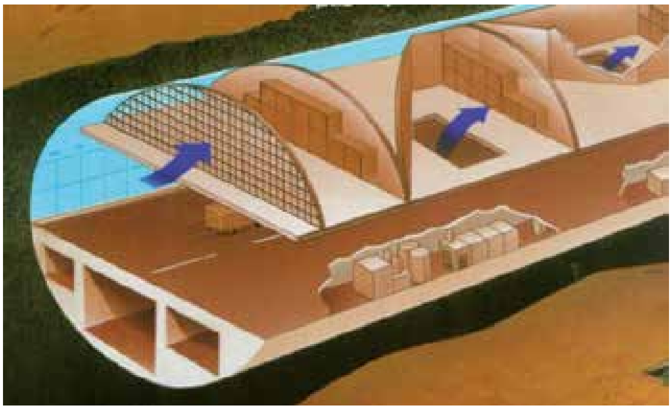

Illustration 3: block diagram of a ceiling-based installation (Source: "Managing air outside of tunnels" [19])

2.2.2 Extraction-type installation

Where major environmental requirements are involved, electrostatic precipitators can be installed at the level of the vitiated air outlets.

This type of installation is used less than bypass installations. It is found in around ten Japanese tunnels, in the Festing and Bragernes tunnels in Norway, and also in the latest European tunnels, i.e. the M30 in Madrid and the Cesene tunnel in Italy (see section 2.7).

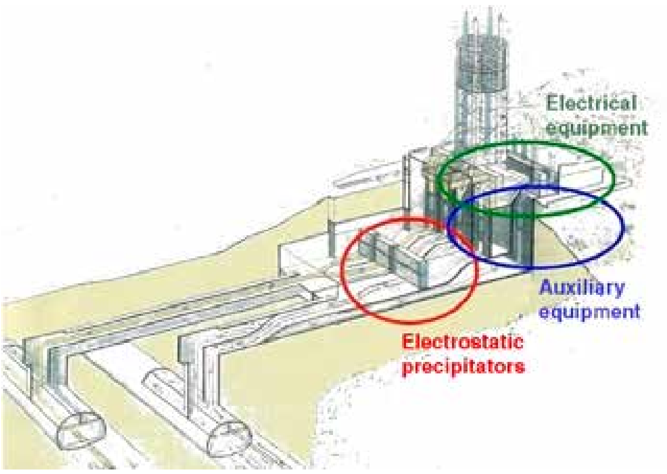

Illustration 4: block diagram of an extraction-based installation at the Hasumiya tunnel (Source: "Managing air outside of tunnels" [19])

2.2.3 Performance and operation

Whichever implementation principle is selected, it is not possible for a single, given system to simultaneously demonstrate the same level of performance in terms of both improving air quality inside tunnels and limiting the environmental impact outside tunnels. For example, the installation of an extraction-based air treatment system near to a tunnel portal makes it possible to limit the impact of discharges to the outside environment but is of no use in terms of air quality inside tunnels. Conversely, while a bypass-type installation located in the middle of the tunnel improves the quality of air inside the tunnel, it is of less benefit to the outside environment than an extraction-based installation.

Beyond the two above-mentioned implementation principles, there can also be many different ways of exploiting filtration technologies. The most widespread approach is to fit the system to the needs. These needs can be determined either using pollution level measurements or according to particular times of day, in relation to traffic peaks.

2.3 FILTER REGENERATION

Filter maintenance and regeneration, are decisive factors as they underpin the devices' long-term efficacy. This requires the use of auxiliary equipment. This equipment varies depending on whether filter regeneration is based on a wet or dry system.

The figure below illustrates the principle of wet regeneration such as proposed by Mitsubishi. The filters are rinsed with water; the treatment water is then collected and filtered in order to extract any particulate matter.

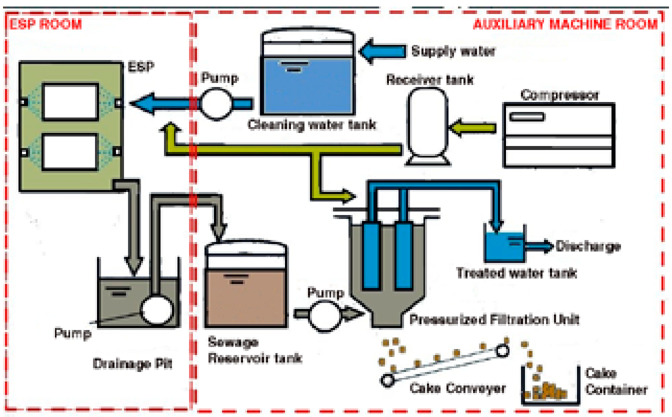

Illustration 5: block diagram showing filter regeneration via rinsing with water, Mitsubishi (Source: "Managing air outside of tunnels" [19])

Dry regeneration of filters involves dry cleaning using high- pressure air jets. The figure below illustrates the principle proposed by the company Aigner using a cross-section and a perspective view. The bottom of the filter is cleaned by a high- pressure air jet. During cleaning cycles, the filter is rotated in order to ensure full and effective cleaning.

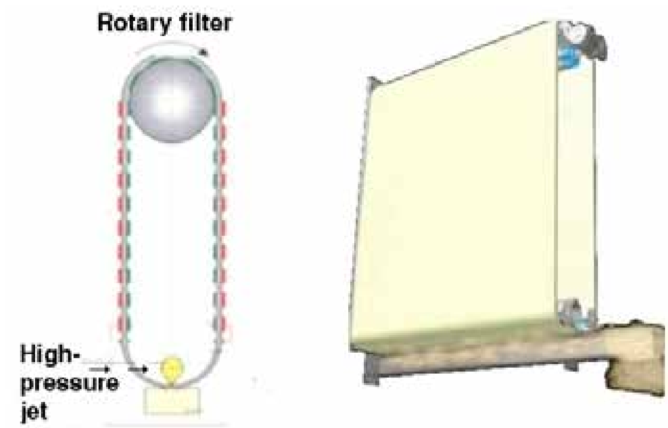

Illustration 6: block diagram showing dry regeneration of a filter by dry cleaning (Source: http://www.aigner.at/)

Technological progress has made it possible to optimise filter cleaning operations. These operations, which used to be carried out by hand, are now automated and programmed according to appropriate criteria (period between two filter cleaning cycles, loss of pressure in the system, etc.).

Mitsubishi Heavy Industries gives a one-hour cleaning cycle time for electrostatic filters followed by a 30-minute drying time. Cleaning cycle frequencies vary according to the number of parameters (airflow, particulate concentrations, etc.) but are generally around one cleaning cycle every 1 to 5 days.

Lastly, system maintenance also requires the cleaning of ionising equipment, which may also be automated.

Generally speaking, cleaning operations for these systems remain an operational requirement, even if they are largely automated these days. This cleaning is vital to ensure the systems remain in proper working order.

2.4 THEORETICAL PERFORMANCE OF SYSTEM

Eleclectrostatic filters do not stop all particulate matter. Their efficacy varies according to parameters such as airflow speed, and the composition, size and concentration of particulate matter.

The efficacy of such systems is often around 80 to 90%, which is low compared with the efficacy achieved in industrial installations where efficacy rates can reach 99.9%. An efficacy of 99.9% means that only 0.1% of the total mass of particulates has not been treated against 10% for an efficacy of 90%, i.e. a factor of 100 between the two cases.

Air treatment systems actually demonstrate higher performance where higher concentrations are concerned. In comparison to industrial discharges, tunnel pollutant concentrations are very low due to the intake of fresh air. Air treatment systems become less efficient with smaller particle sizes. In terms of health risks though, it is this small-size particulate matter, found in vehicle exhaust gases, which it is most important to treat. Particulate distribution in first generation direct injection diesel engines follows a standard log-normal distribution centred at 100 nm (0.1 µm) [20].

In general, performance figures should be examined with caution as they usually designate the mass percentage of treated particulates against all particulate matter, all sizes included.

Aigner nevertheless proposes a performance analysis of these systems based on particulate size using in situ measurements taken in the Plabutsch tunnel in Austria. The results are shown in the Table below. The second column gives the mass percentage of particulates in the given size range, while the third column shows performance.

Size	Content (by weight)	Efficiency ECCO®
< 2.5 µm	30%	54 – 91%
2.5 – 10 µm	60%	94 – 99%
> 10 µm	10%	> 99%

Table 3: Electrostatic filter performance according to particulate size (Source: http://www.aigner.at)

This same company also specified the efficacy of its system for very fine particulate matter i.e. with a diameter of less than 0.5 µm (500 nm), this time in relation to the number of particles and not their mass. Efficacy does not exceed 60% *(see illustration 7)*.

In comparison, as part of a pollutant emissions assessment carried out on vehicles fitted with a particulate filter (FAP) and used as a taxi during 120,000 km, Ademe reported that *"the FAP cuts the number of particles emitted in exhaust gases by nearly 95%, irrespective of their size"* [21].

Lastly, in regard to the theoretical performance of electrostatic precipitators (ESP), the actual and overall in situ performance may be far lower due to both the practical limits of the treatment, which only concerns a proportion of the volume of air flowing through a structure, and to the location of the filtration systems. In practice, it is an established fact that air treatment systems improve visibility within tunnels. Regarding use aimed at limiting the impact of discharges to the environment, despite recent in-tunnel applications, to our knowledge, there is only one comprehensive, independent study that assesses the efficacy of electrostatic filtration (the M5 East tunnel in Australia, *see section 2.7*).

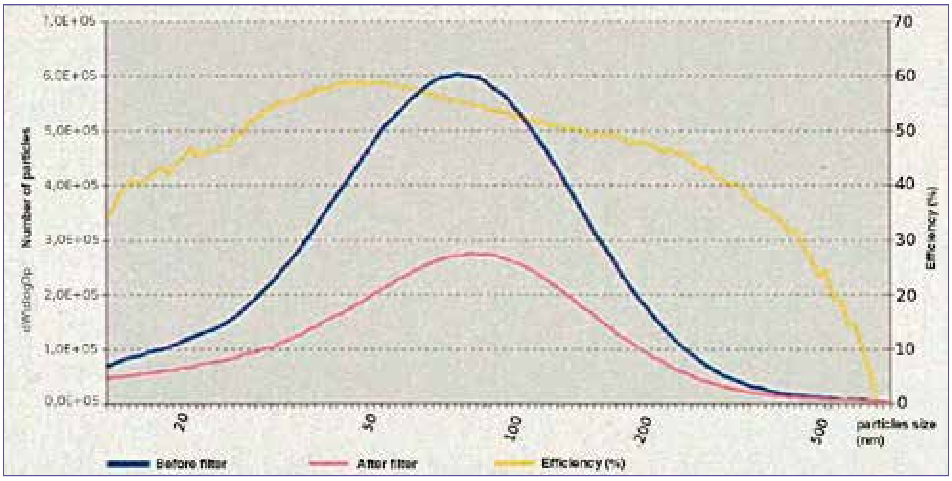

Illustration 7: particulate filter performance in relation to small-sized particulates (Source: information leaflet published by Aigner, http://www.aigner.at/)

2.5 DIMENSIONS

Electrostatic precipitators are generally small units which, when combined in series, make it possible to cover a complete airflow section.

Illustration 8: example of basic filtration modules alone (left) and in series (right) (Source: http://www.aigner.at/)

To treat a given airflow, it is therefore necessary to align a sufficient number of units, according to the treatment capacity of each basic device. Illustrations 8 and 9 present a basic module (on the left of each illustration) and an example of the treatment of an airflow section based on an alignment of several modules (on the right of each illustration).

Illustration 9: basic filtration modules alone (left) and in series (right) (Source: "Managing air outside of tunnels" [19])

Unit dimensions vary. A few examples are given below:

- Kawasaki proposes basic units that treat an airflow of 7.2 m^3/s with an associated airflow of 13 m/s for the following dimensions: 1.04 m × 0.94 m × 1.7 m with a pressure loss of 250 Pa;
- CTA proposes units that treat a volume of 3.7 to 6.25 m^3/s with an associated airflow of 7 to 12 m/s for the following dimensions: 0.854 m × 0.58 m × 0.610 m; the associated pressure loss is not specified.

Specifically, figure 10 represents the footprint of electrostatic filters when an airflow of 750 m^3/s is to be treated using precipitators proposed by Mitsubishi with respective dimensions 2.16 m × 1.7 m × 2.46 m (treated airflow of 36.6 m^3/s) and 2.16 m × 1.7 m × 3.23 m (treated airflow of 48.8 m^3/s).

N°	Treated flow	Dimensions (L × l × h) in m
1	48.8 m^3/s	2.16 × 1.7 × 3.23
2	36.6 m^3/s	2.16 × 1.7 × 2.46

Table 4: dimension of the basic electrostatic filters proposed by Mitsubishi (Source: "Managing air outside of tunnels" [19])

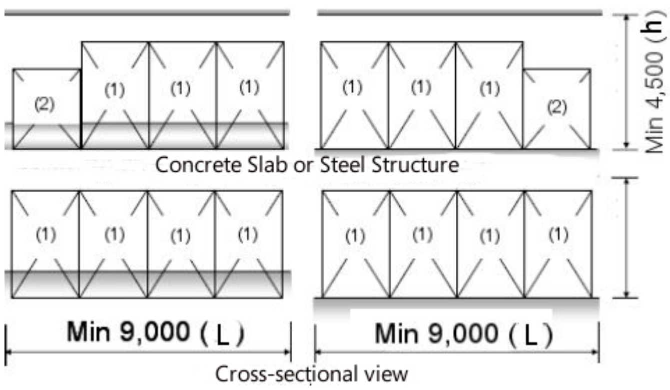

Illustration 10: footprint of electrostatic filters used to treat an airflow of 750 m^3/s (Source: "Managing air outside of tunnels" [19])

Lastly, to complete the data on dimensions, note that a system is not limited solely to its filters. When considering installations, it is also necessary to factor in the maintenance systems *(see section 2.3)* together with the appropriate electrical equipment. Based again on the specific case illustrated above, Mitsubishi Heavy Industries reports that, in addition to the electrostatic filters, the planning must also include two rooms with a ground surface area of 20 m × 11 m and 10 m × 11 m, respectively.

French studies carried out to assess treatment systems always focus on reducing the impact of discharges with a treated airflow of between 200 to 500 m^3/s.

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2.6 COST OF FILTRATION SYSTEMS

There is fairly little data on the investment cost for filtration systems and even less on their operating cost. The data given below should therefore be examined with caution. Note also that particulate matter collected by filtration systems represents waste that must be dealt with appropriately, thus generating a surplus cost.

In his report: *"Managing air outside of tunnels"* [19], Arnold Dix provides data on the installation costs for the Cesene tunnel in Italy. This tunnel, opened in 2008, has been fitted with two filtration systems, each designed to treat an airflow of 200 m^3/s. The cost is approximately 2.5 million Euros per installation. This figure includes auxiliary equipment such as those relating to system maintenance (cleaning in particular) or to its electric power supply, but does not cover civil engineering and additional ventilation requirements of the installation.

Moreover, the paper *"Approval Application of East- link, Tunnel Ventilation System Works"* [22], which concerns an impact study on the proposed construction of a tunnel on the Eastlink in Australia, gives cost estimates in terms of the electrical consumption of the filtration systems. The tunnel in question is a 1.6-km long twin-tube tunnel with 3 driving lanes in each direction. It has a cross-section of 100 m^2 and an airflow of 450 m^3/s to be treated. The study in question indicates that setting up a filtration system would involve increasing the tunnel's maximum electric power supply requirement by 30% in order to reach 1,680 kW, over half of which would be needed to cover surplus ventilation requirements. This would raise annual electricity consumption by 33%. This comparison addresses the issue of whether a precipitator should be fitted at the level of a stack. The results might have been different if the comparison had plotted a scenario involving a stack with no filter against a scenario involving a filter in a bypass passage (and therefore with no stack). The system manufacturers, however, indicate that the use of precipitators can cut costs. They point out that filtration systems reduce the amount of tunnel clogging and, therefore, result in lower cleaning requirements.

Still in Australia, estimates put the annual operating cost of the M5 East tunnel's air treatment system at 835,000 Australian dollars (M5 East Tunnel Filtration Trial Evaluation Program – Review of Operational Performance, Independent Review Role M5 East Air Filtration Project, Roads and Maritime Services NSW, February 2012 [23]), i.e. approximately 525,000 euros (1 euro = 1.59 $AUS in 2015), at a treated airflow rate of 200 m^3/s. This cost includes water and energy requirements.

Following discussions with Japanese contacts, the following costs were identified for the filtration of a flow of 700 m^3/s for a period of nearly 24 hours per day in a Japanese tunnel: an installation cost of 500 million yen (approx. 3.85 million Euros at the 2009 exchange rate) with maintenance costs of 6 million yen per year, approx. 46,000 Euros, excluding water and electricity bills (Source: discussions with Hideto MASHIMO of Public Works Research Institute, Incorporated Administrative Agency, Japan).

It is difficult to gather data on the various figures mentioned above as costs vary widely between installations depending on the operating conditions, the treated volumes, tunnel configuration, etc.

Nonetheless, a large part of the costs relating to these systems is linked to their energy consumption due to surplus ventilation requirements.

It would be useful to have a comprehensive and consistent analysis of this consumption based on a multicriteria approach setting this surplus energy cost against expected gains in terms of atmospheric pollution. This kind of analysis could be combined with a Life Cycle Analysis approach, thus making it possible to consider every environmental factor. To our knowledge, no such studies have been published to date.

2.7 OVERVIEW OF TUNNELS EQUIPPED WITH ELECTROSTATIC FILTRATION SYSTEMS

2.7.1 Norway case study

Norway counts between 900 and 1,000 road tunnels, around 115 of which are over 2,000 metres long ([24]). The country presents specific features in terms of tunnel visibility, which is deteriorated significantly due to the widespread use of studded tyres that increase abrasion phenomena and, consequently, the suspension of particulate matter and a significant effect on visibility impairment. As a result, Norway is a pioneer in the field of particle filtration.

8 tunnels are equipped with filtration systems including two, in Festning and Bragernes, designed principally to reduce the impact of discharges to the environment.

Of these 8 tunnels, the Laerdal has the greatest number of specific features *(see section 3.2)*. This tunnel has an internal air quality problem due to its length (over 20 km) and its coverage height that imposes major constraints in terms of ventilation and access to fresh air. This tunnel comprises a gas treatment system in addition to the particulate filtration system.

Feedback from the installations in Norway's eight tunnels paints a disappointing picture. In 2008, only the precipitators located upstream of the extraction systems in the Festning and Bragernes tunnels were still operational. There have been growing doubts over the benefits of putting the precipitators in bypass tunnels back into service given that they have proved less effective than predicted (*Road tunnels: a guide to optimising the air quality impact upon the environment*, PIARC [25]). These precipitators are no longer used for a variety of reasons, in particular due to the need to replace their electric cables.

As things currently stand, all of the particle filtration systems in Norway's eight tunnels (bypass-type and extraction-type installations) have been shut down because of uncertain performance, and high operating costs stemming from energy consumption.

Tunnel	Region	L in km	Year	Trafic (veh./day)	Installation type and tunnelling contractor
Festning	Oslo	1.8	1990	60,000	Extraction (CTA)
Granfoss	Oslo	1	1992	15,000	Lateral bypass passage (CTA)
Ekeberg	Oslo	1.5	1994	45,000	Lateral bypass passage (CTA)
Hell	Trondheim	4	1995	10,000	Bypass passage in ceiling (CTA)
Nygard	Bergen	0.95	1999	28,000	Bypass passage in ceiling (CTA)
Laerdal	Laerdal	24.5	2000	1,000	Lateral bypass passage (CTA)
Stromsas	Drammen	3.5	2001	12,500	Bypass passage in ceiling (CTA)
Bragernes	Drammen	3.2	2002	20,000	Extraction (Xtor)

Table 5: Norwegian tunnels equipped with a particulate filtration system (Source: Approval Application of Eastlink, Tunnel Ventilation System Works, annexe 8, Tunnel ventilation system technology review and best practice [22])

2.7.2 Beyond the Norwegian case study, the rest of Europe

In **Germany**, a pilot site was installed in the tunnel under the Elbe in Hamburg in 1994. This tunnel has a length of 3,900 metres. This pilot site was installed by the company Filtrontec, enabling it to carry out small-scale trials of its systems.

In **Austria**, the company Aigner uses the tunnels of Plabutsch in Gratz (9,755 metres) and Katschberg (5,439 metres) to trial and develop its systems; this only involves small-scale installations though.

In **Italy**, an electrostatic filtration system was set up in the "Le Vigne" tunnel, also referred to as the Ecotunnel, located on the "Secante de Cesena" in Cesene, in Emilie Romagne. This tunnel lies in a heavily populated area that is particularly sensitive to atmospheric discharges from tunnel portals. The problem was dealt with by installing an electrostatic filtration system. Aigner was selected to fit out this tunnel that has been operational since 2008. Each tube is 1,580 metres in length. The fresh air flow for each tube is approximately 200 m^3/s. The installation is based on pre-discharge particulate filtration at the level of each portal *(Source: Ventilia, November 2006, No. 61 [26])*.

In **Spain**, filtration systems have been installed in the M30 in Madrid. The M30 project is a full redevelopment of the Madrid circular and is broken down into four main work sections: M30 East, M30 South, M30 West and M30 North.

One of the largest work sections is the M30 South, which comprises in particular:

- to the west, one cut-and-cover tunnel with a length of approx. 1,600 metres;
- two separate cut-and-cover tunnels (one in each direction of circulation) on either side of the Manzanares river: each one has a length of 4,500 metres; one cut-and-cover tunnel nevertheless contains a 600-metre section in open air;
- one section referred to as the By-Pass Sur: this corresponds to two tubes – North and South – each with length 4,200 metres, the main part of which was excavated using a tunnel boring machine (approx. 3,600 metres);
- to the east, connections in a cut-and-cover tunnel with length approx. 1,200 metres between the north tube of the By-Pass Sur and the A3 motorway, which links up with Valence.

This underground series of structures is supplemented by a number of cut-and-cover access roads (around forty) that represent a cumulated length of around ten kilometres.

22 particulate filtration systems have been set up in this vast underground network, 4 of which include a gas treatment system (see section 3.2). The owner has called in the key filtration system manufacturers:

- the Austrian company Aigner: 9 installations;
- the Norwegian company CTA: 2 installations;
- the German company Filtrontec: 3 installations;
- the Japanese company Panasonic: 8 installations.

The CETU visited these installations in May 2009 in the presence of the manufacturers. The installations initially operated for 20 hours out of 24 at full power. Today, they actually operate only a few hours a week. Photographs of the systems taken during the inspection can be seen in annex.

In **France**, the GEIE-TMB (Groupement Europeen d'Interêt Economique du Tunnel du Mont Blanc) decided to install an extraction-based particulate filter above the French platform of the Mont Blanc tunnel, in order to contribute to the various local initiatives aimed at improving air quality in the Chamonix Valley. This filter, scheduled to be installed in 2010, will be located upstream of a discharge outlet in an existing extraction gallery with a capacity of 450 m^3/s. The current configuration of the ventilation system means this installation can go ahead with no need for any major civil engineering works.

2.7.3 Japan case study

To provide background context, it should be noted that Japan is a densely populated country where pollution reaches alarming levels that have driven the authorities to speed up the process of equipping of vehicles with particulate filters.

The country counts 9,000 road tunnels representing a linear length of 3,000 km, forty of which are equipped with particulate filtration systems. This figure varies slightly depending on the source (47 according to the *"Approval Application of Eastlink, Tunnel Ventilation System Works"* [22]).

The systems are generally installed to improve visibility or in response to strong ventilation requirements. They are therefore placed in bypass passages inside the tunnels. The following chart lists the main Japanese tunnels equipped with an electrostatic filtration system.

Name	Tunnel length in km	Objective	Max. flow per plant (in m^3/s)	Architecture
Aioi-cho		exhaust air	80	exhaust station
Asukayama	0.6	exhaust air	375/360	exhaust station
Enasan	8.5	visibility	300/240/255/200	bypass
Fukuchiyama	3.6	visibility	285/270/285	bypass
Gorigamine	4.45	visibility	105/105/195	bypass
Hakamagashi	5.95	visibility	190	bypass
Han-Na	5.6	visibility	270/285	bypass
Hanazonobashi	2.6	exhaust air		exhaust station
Happusan	4	visibilité	225/210/170/190	bypass
Hasumiya		exhaust air		exhaust station
Higashiyama	2.6	exhaust air		
Higo	6.3	visibility	113/90/135/260	bypass
Hihonzaka	2.05	exhaust air		
Hiroshimaseifu	1.25		85	bypass
Ichifuri	3.35	visibility	180/165	bypass
Kakuto	6.25	visibility	170	bypass
Kann-etsu	11.05	visibility	945/810	bypass
Kann-Mon	3.5	visibility and exhaust air	365	exhaust station
Karasuyama		visibility and exhaust air	175	bypass
Kasaijama	3.2	visibility	270/240/225/210/201/210	bypass
Kongosan		visibility	195/285	bypass
Koshirazu	4.55	visibility	300/180	bypass
Maiko	3.4	visibility and exhaust air	180/180	bypass (in ceiling)
Midoribashi	3.4	exhaust air	573	exhaust station
Nihonzaka	2.2	visibility and exhaust air	240/240/680/440	exhaust station + bypass
Nou			165	bypass
Ryugatake	3.65	visibility	270	bypass
Ryu-ohzan	2	visibility and exhaust air	225/210	bypass
Sekido	3.2	visibility	240/240/240	bypass
Shintoshon-nishi			318	exhaust station
Shintoshon			154	exhaust station
Sirubachiyama	4.1	visibility	195	bypass
Suginami-ku		exhaust air	60	exhaust station
Tachitoge	2.15	visibility	225	bypass
Takanomine	3.1	visibility	195	bypass
Taroyama	4.3	visibility	180	bypass
Tennozan	2	exhaust air	1643	exhaust station
Tokyo Bay	9.6	visibility AND exhaust air		bypass (in ceiling)
Tsuruga	2.1	visibility	240	bypass
Uji	4.3	visibility	285/255/210	bypass
Chuo-Kanjo-Shinjuku		exhaust air		
Honmachi		exhaust air		
Nishishinjuku		exhaust air		
Yoyogi		exhaust air		
Kanayamacho		exhaust air		
Oohashi		exhaust air		

Table 6: main Japanese tunnels equipped with particle filtration systems Source: "Possibilities and limitations of tunnel-air filtration and portal-flow extractions" [27] and https://panasonic.co.jp/es/peseng/

The Japanese were the first to use particulate filtration with an installation in the Tsuruga tunnel (2.1 km) in 1979. These systems were often used to provide longitudinal ventilation in tunnels with long straight sections such as the Kanet'su tunnel (11 km) in 1985. The environmental impact nevertheless led to the installation of electrostatic precipitators in around ten tunnels. For example, electrostatic precipitators were installed at the base of the extraction stacks in the Tennozan (2 km), Kanmon (3.5 km), Asukayama (0.6 km), Midoribashi (3.4 km) and also the Hanazonobashi tunnels (2.6 km). The Tokyo Bay tunnel (9.6 km) is mainly equipped with ceiling-based precipitators.

Filtration systems operate based on actual pollution measurements which, in the case of the Kan'etsu tunnel, results in an average operating time of 143 hours per month (20% of the time) at the north portal and 40 hours per month (3% of the time) at the south portal. The Tokyo Bay "Aqualine" tunnel only records 12 to 13 hours of operation per year (i.e. approx. 0.15% of the time). These operating periods are those given in the report *"Managing air outside of tunnels"* [19].

Discussions with Japanese contacts indicate that operating rates are highly variable. *(Source: discussions with Hideto MASHIMO of Public Works Research Institute, Incorporated Administrative Agency, Japan)*. They can range between 5 hours per month up to nearly 24 hours out of 24 where urban tunnels are concerned.

Lastly, note that Japan is experimenting with gas treatment systems in the Chuo-Kanjo-Shinjuku tunnel (See section 3. 3).

2.7.4 South Korea, Vietnam and China

In South Korea, 5 tunnels have been equipped with electrostatic precipitators, which are all located in lateral bypass passages.

In Vietnam, the Hai Van Pass tunnel, 6.5 km long and opened in 2006, is equipped with electrostatic filters in lateral bypass passages, i.e. 3 installations each with a capacity of 260 m^3/s.

In China, the building work on the Central Wan Chai Bypass tunnel (Hong Kong) has been ongoing since 2009. The tunnel, measuring 3.7 km in length, will be equipped with Filtrontec electrostatic filters with an airflow treatment capacity of around 1,500 m^3/s. The tunnel is scheduled to open in late 2017.

As far as we know, these are the only tunnels referenced as being equipped with filtration systems in these two countries. The paper "Approval Application of Eastlink, Tunnel Ventilation System Works" [22], indicates that in these two countries, electrostatic filters are mainly used to provide adequate visibility in tunnels where there are major constraints on the intake of fresh air.

Name	Objective	Max. flow per station (m^3/s)	Architecture
Chinbu	Visibility and exhaust air	285	bypass
Saritjae	Visibility	285	bypass
Safe-San	Visibility	350/350/130	bypass
Su-Jung-San	Visibility	600	bypass
Woo-Myun-San	Visibility	210	bypass

Table 7: Main Korean tunnels equipped with a particulate filtration system (Source: "Possibilities and limitations of tunnel-air filtration and portal-flow extractions" [27])

Illustration 11: Hai Van tunnel (Source: http://www.hazama.co.jp/japanese/hazamag/genbarepo/0504/genbarepo01_eng.htm)

2.7.5 Australia

In Australia, the issue of the installation of air treatment systems comes up time and again during the development of new projects. This issue is generally pursued by local residents or environmental protection associations. Among the projects in question, we can cite the Lane Cove Tunnel (Sydney), the North- South bypass in Brisbane and the Eastlink in the Melbourne region. All these projects are gravitating towards a decision not to install a filtration system, in particular, based on a digital model that indicates that such systems provide fairly low value added.

However, faced with rising concerns in the country, a tunnel was equipped in 2010, mainly to test the efficacy of actual efficacy of these systems. This installation was carried out on an existing tunnel on the M5 East in the Sydney region.

The data on this project, shown below, can be viewed in detail in the following reports:

- *"M5 East Tunnel Filtration Trial Evaluation Program – Review of Operational Performance, Independant Review Role M5 East Air Filtration Project, Roads and Maritime Services NSW",* February 2012 [23];
- *"Air filtration plant of the M5, Determination of particle removal efficiencies, Roads and Maritime Services NSW",* Brendan Haliburton & Merched Azzi, November 2011 [28]

The tunnel in question, 4 kilometres in length, is a twin-tube tunnel with two lanes per tube. It has been in operation since December 2001 and mainly encounters difficulties due to the greater density of traffic that was predicted by upstream studies with, in particular, significant HGV traffic.

An air quality improvement plan was also implemented so as to improve tunnel visibility without harming external air quality. In its former configuration, prior to installation of the treatment system, 90% of the vitiated air in the tunnel was discharged via an extraction stack, the remaining 10% being discharged at the portals.

Although measurement campaigns have indicated that these discharges do not present any significant impact on external air quality, a decision dated 18 July 2007 provided for the installation of a filtration system at the tunnel's west portal.

A structure measuring 60 × 40 × 8 metres was built to host a particulate filtration system, a denitrification system, offices and an information centre. A ventilation duct with length approx. 300 metres has also been built. Rather than being discharged by the structure, air is re-injected into the tunnel and then eventually discharged by the existing stack or the portals.

According to the specifications, the electrostatic filter had a maximum airflow treatment capacity of 200 m^3/s at tunnel airflow in the region of 320 m^3/s. The air, extracted 500 metres from the exit portal (western portal) of the southern tube, reached the treatment system after passing along a 280-metre duct. The air was then treated and immediately injected back into the tunnel, downstream of the extraction point, 500 metres from the western portal, after passing along a 280-metre duct (see illustration 12).

During the evaluation, the treatment systems were switched on for 6 hours a day, between 12 noon and 6 pm, Monday to Friday only. A range of measuring techniques was used to assess the results. The measurements consistently found a reduction in $PM_{2.5}$ and PM_{10} particles of around 65% at the particle filter inlet and outlet, compared with just 60% for total suspended particles (TSP). These results fell well short of the manufacturers' claims.

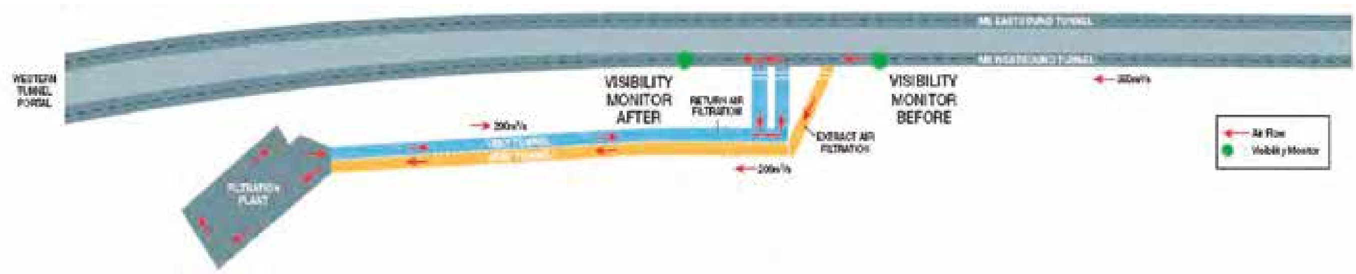

Illustration 12: overview of the air treatment installation in the M5 East tunnel (source: "M5 East Tunnel Filtration Trial Evaluation Program - Review of Operational Performance, Independent Review Role M5 East Air Filtration Project" [24])

The system's efficacy was limited in this tunnel because the treated airflow rate (200 m^3/s) was less than the actual airflow through the structure (320 m^3/s). Ultimately, the treated air re-injected 500 metres from the western portal of the southern tube accrued pollutants once again as it made its way to the end of the tunnel – a phenomenon exacerbated by the upward gradient of around 8% in the structure. Measurements were taken at the western end of the southern tube. Here, there was only a limited difference between concentration levels when the filtration system was operating and when it was switched off. The measurements showed an average reduction of 11%, varying according to traffic levels.

As well as doubts around the efficacy of the system when in operation, there were also concerns about its reliability. The plan was to switch on the system between 12 noon and 6 pm on weekdays, during a 50-plus-week testing period. During the experiment, the system was judged to be working correctly when the various generators (pre-ionizer, ionizer and filter) and the fans that moved the air around the system were operating simultaneously. The system only worked correctly for a full 6 hours on 2 out of 3 days. When expressed in actual operating hours, the system had an estimated reliability score of 84% (compared with a target of 99.5% as stated in the specifications). Over the 56-week testing period, there was not a single week when the system worked correctly for the full 30 hours (5 days at 6 hours per day).

In the end, the local authority decided to terminate the experiment on the grounds that the costs outweighed the pollution benefits. The authority still has an air quality improvement plan, but the emphasis is now on stopping the most heavily polluting vehicles from entering the tunnel.

2.8 CONCLUSIONS ON ELECTROSTATIC FILTERS

To date, particulate filtration in tunnels is based solely on the use of electrostatic filters. Current research aims to optimise this technique rather than to develop new techniques. For example, the company KGD proposes small filtration units that can be fixed directly onto existing jet-fans. Moreover, other companies are conducting research into electrostatic filtration in moist environments that would encourage the filtration of small-size particulates, i.e. with diameter less than 1 μm ([29]).

The use of electrostatic precipitators is not, however, universally accepted. Some people contend that this technology rarely has any proven scientific effect on population exposure as the positive effect is often masked by the significant base concentration that marginalises the gains. Others emphasize the potential benefits of first optimising the various pollution dispersion factors linked to tunnels, such as the position of the portals or the location of stacks enabling the displacement and dispersion of pollutants away from residential areas. Still others point to the highly uncertain nature of the overall assessment due to costly use of pre-treatment vitiated air extraction means.

It has to be said that several tunnels that have been equipped with electrostatic filters have subsequently used them very little, as revealed by some operating rates illustrated in this paper.

It remains difficult to assess the actual performance of filtration systems so long as they present such variable conditions of use. Faced with the issue of the environmental impact of tunnel discharges, in particular in areas where air quality is a major issue, there is no clear answer on exactly which provisions should be implemented. Accordingly, we can only cite as an example the approach that, when the issue was raised, led Australian authorities to model the various alternatives, whether based on the installation of a treatment system or on efforts to optimise ventilation performance.

3

DENITRIFICATION USING THE ABSORPTION METHOD

The treatment of gases in tunnels was only recently introduced into an operational phase. The Norwegians were the first to install a gas treatment system in the Laerdal tunnel in 2000. In contrast to particulate filtration, current systems are based on a diverse range of technologies, some of which are still at the experimental stage. These installations still have one point in common though; they all focus on the treatment of nitrogen dioxide (NO_2). This part is devoted to the most common denitrification process, absorption.

3.1 PRINCIPLE

Absorption-based denitrification is based on the phenomenon of sorption, i.e. on the activity of gas molecules (in this case NO_2) when placed in contact with a solid material, and which adheres to its surface. During absorption, NO_2 molecules undergo chemical change in contrast to adsorption where the molecules are not degraded but fixed to adsorbent agents.

Effective performance of gas treatment systems requires that the air has already been treated to remove particulates, i.e. by electrostatic precipitation *(see previous section)*. Manufacturers report a 90% removal rate for NO_2 *(Source: "Managing air outside of tunnels", by Arnold Dix – Counsel at Law, Adj. Professor of Engineering [19])*.

3.2 IMPLEMENTATION IN SPAIN, AUSTRALIA AND NORWAY VIA USE OF AN ACTIVATED CARBON FILTER

The absorption principle can be implemented using an activated carbon filter as seen in four treatment plants in the ByPass Sur tunnel on the M30 in Madrid (see section 2.7). There are two installations in the North tube (built by Aigner) and two others in the South tube (built by CTA). These 4 plants treat particulates upstream via electrostatic filtration.

The activated carbon filters come in the form of a metal structure with a W-shaped cross-section.

The panels making up this W (see illustration 14) are approximately fifty centimetres thick. These panels are filled with activated carbon through which vitiated air is circulated. The system requires airflow sections equivalent to those used for particulate filtration while several metres of length is necessary to ensure sufficient surface contact.

In the North tube of the By-Pass Sur tunnel, the two plants have a respective treatment capacity of 520 m^3/s (the PV3 plant) and 450 m^3/s (the PV4 plant). Pressure losses due to the denitrification system are estimated at 200 to 300 Pa. Airflow speed is approx. 0.3 m/s at the level of the activated carbon thickness for a residence time of around one second.

The manufacturer reports a performance rate of 80 to 90% on nitrogen dioxide, no effect on nitrogen monoxide (NO) and no guaranteed result on any other compounds. As the system is installed downstream of an electrostatic filter, part of the NO in the air has already been oxided to NO_2.

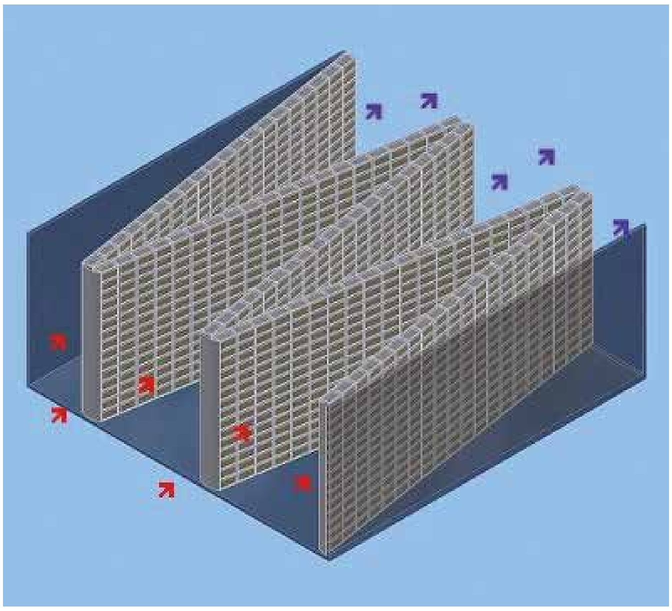

Illustration 13: 3D model of a denitrification process using activated carbon (Source: www.filtrontec.de)

According to the manufacturer, the absorbent reaches saturation after approximately 25,000 hours of operation, i.e. after about 3 years.

Even if the system is not in operation, the activated carbon reacts with ambient air and gradually degrades.

Activated carbon filters require no maintenance other than replacing them at the end of their lifetime. In Madrid, this represents a total weight of about 700 tonnes for PV3. The carbon is not reused and has to undergo a specific treatment.

In terms of performance, Filtrontec, another manufacturer of gas treatment systems using activated carbon filters, reports even better results in cases where the denitrification process is preceded by use of an electrostatic filter. This manufacturer, commissioned to equip the M5 East tunnel in Australia, says that it has developed a process for converting the greater part of the NO contained in foul air into NO_2 in the ioniser of the electrostatic precipitator. Using this patented technique, the manufacturer claims to be able to remove up to 80% of NO_2 contained in vitiated air.

Retention rate for	Harmful substances	Effectiveness of retention
Particles	PM_1	80%
	$PM_{2,5}$	85%
	PM_{10}	90%
Gaseous pollutants	Nitrogen dioxide NO_2	80%
	Nitrogen oxides NO_X ($NO + NO_2$)	60%
	Unburnt hydrocarbons	90%
	Ozone O_3	90%

Table 8: performance of activated carbon filters manufactured by FiltronTec (Source: www.filtrontec.de)

The local authority, New South Wales (NSW) state, via its Roads and Traffic Authority (RTA), asked the federal government's Commonwealth Scientific and Industrial Research Organisation (CSIRO) to assess the efficacy of the carbon bed treatment system in the M5 East tunnel. The results revealed a 56% reduction in NO_2 concentrations – capture performance well below the system manufacturers' claims, in all likelihood due to the age of the installation. However, this reasoning does not fully explain the performance gap. In the CSIRO's view, the installation is less effective than expected because active carbon is missing in some key areas where airflow is at its highest.

The organisation concluded that the NO_2 treatment system needed updating and called for further research to understand how this technology works *(Source: "Air filtration plant of M5 Tunnel, determination of nitric oxide and nitrogen dioxide removal efficiencies" [30])*.

In Spain, the use rate for denitrification systems is the same as that given for particulate filtration *(see section 2.7)*. The installations were initially operated 20 hours out of 24 at full power, and were then stabilised at their current operating level of a few hours per week.

Activated carbon filtration has also been implemented in the Laerdal tunnel in Norway. This 24-km long tunnel separates Aurland and Laerdal. A vitiated air extraction stack is located at a distance of 18 km from the portal, on the Aurland side. These 18 kilometres represent too great a distance for maintaining satisfactory air quality inside the tunnel. The tunnel has a bypass passage treatment plant at a distance of 10 kilometres from the portal, on the Aurland side.

The treatment plant comprises an electrostatic precipitation system for particulates, already described in the previous section, and a NO_2 treatment system. This plant has an airflow treatment capacity of 180 m^3/s and is able to bring NO_2 concentrations down from 1.5 ppm to 0.3 ppm. Electrostatic precipitation itself is intended to be limited to treating particulate pollution and protecting the NO_2 treatment system from premature clogging. The NO_2 treatment installation has never been used due to the low traffic density and corresponding low rate of pollution.

3.3 IMPLEMENTATION IN JAPAN USING POTASSIUM HYDROXIDE

In 2004, two types of NO_2 treatment system were developed in Japan thanks to national research programmes. One system based on adsorption (see Section 4.2.1) and the other on absorption.

Here again, system performance depended on the air being first cleaned via electrostatic precipitation in order to remove particulate matter.

Given the doubts over their long-term use, the systems underwent full-scale trials in the ventilation stacks of the Chuo-Kanjo-Shinjuku tunnel in the region of Tokyo. This 10-km long tunnel comprises 9 stacks and is located in a heavily populated area where the air quality is significantly degraded. The aim is therefore to limit the impact of tunnel discharges. Absorption-based systems have been installed at the base of 4 stacks.

The NO_2 is converted into nitrite and potassium nitrate (KNO_2 and KNO_3) by potassium hydroxide (KOH) which is modified on contact with an absorbent structure with a honeycomb structure and then introduced into a metal cube. The system's performance level drops by about 10% over a period of 8 to 10 months of operation. On the other hand it is easily regenerated by simply removing the absorbent structures from the tunnel and then subjecting them to a 4-step cleaning process:

- water washing,
- first drying,
- dunking in a solution of KOH,
- second drying.

NO_2 removal rate (daily average value)	Over 90%
Gas velocity	1.04 m/s
Regeneration interval	Regeneration of the ½ quantity of absorbent every 8 to 10 months
Pressure drop	Less than 460 Pa
Durability	Over 20 years

Table 9: characteristics of the absorption-based NO2 treatment system in the Chuo-Kanjo-Shinjuku road tunnel (Source: "Road tunnels: a guide to optimising the air quality impact upon the environment", PIARC [25])

3.4 CONCLUSION ON GAS TREATMENT SYSTEMS

Even more than electrostatic filtration, the treatment of gases in tunnels remains a little used system that is only implemented in four tunnels worldwide. Moreover, to our knowledge, only two of these systems are currently in use: the Chuo-Kanjo-Shinjuku tunnel in Japan and the tunnel on the M30 in Madrid.

It is hard to judge the operational performance of these systems to a high degree of confidence because feedback is limited to a handful of specific cases. Other than the detailed assessment of the M5 East tunnel near Sydney, there is only patchy data on the efficacy of such systems, either because they are located in tunnels with low traffic density and a correspondingly low level of pollution (Laerdal tunnel in Norway), or because they are too recent (tunnel on the M30 in Madrid).

4

ALTERNATIVE AND INNOVATIVE TECHNIQUES

4.1 BAG FILTERS

This tried and trusted industrial technique has been tested in the Tenozan tunnel in Japan ([19]).
It proved to be of limited use in tunnels, or rather, less effective than electrostatic filters due to the low particulate concentration in tunnels and the grain size distribution, which contains, in particular, a large proportion of very fine particulates.

4.2 TREATMENT OF GASES

4.2.1 Denitrification using the adsorption method

Full-scale trials of denitrification via adsorption (where NO_2 molecules are attached to adsorbent agents rather than being degraded) were performed at 5 of the 9 ventilation stacks in the Chuo-Kanjo-Shinjuku tunnel, in the region of Tokyo.

Adsorbent pellets are packaged in a tank made of FRP (fibre-glass-reinforced plastic). The NO_2 is physically adsorbed into the pores of pellets. In contrast to the absorption process, the system rapidly loses its performance capacity, as early as the 12th day of operation. The adsorbent pellets therefore require frequent regeneration. The system is regenerated using a sodium sulphate solution (Na_2SO_4) that can be stored in a dedicated regeneration equipment room. The regeneration solution is sent to the plastic tank containing the adsorbent pellets, used to regenerate the pellets and then sent back to its storage room. In other words, regeneration is carried out in situ.

NO_2 removal rate (daily average value)	Over 90%
Gas velocity	0.9 m/s
Regeneration interval	Approx. every 12 days
Pressure drop	Less than 600 Pa
Durability	Over 20 years

Table 10: characteristics of the adsorption-based NO_2 treatment system in the Chuo-Kanjo-Shinjuku tunnel (Source: " Road tunnels: a guide to optimising the air quality impact upon the environment", PIARC [25])

4.2.2 Photocatalytic denitrification

4.2.2.1 Principle

Photocatalytic denitrification uses the properties of titanium oxide (TiO_2). Under ultraviolet light, the latter activates atmospheric oxygen (O_2), producing a hydroxyl ion (OH^-) that then reacts with the nitrogen oxides (NO_X) to form acid solutions (HNO_3). This photocatalytic reaction based on the use of titanium oxide can be used to break up nitrogen oxides (NO_X) in ambient air. This principle has found favour with several civil engineering contractors, in particular, Eurovia and Calcia, who have developed its application in a diverse range of processes, i.e. acoustic screens, treatment of building facades or the treatment of road surfaces.

4.2.2.2 Deployment inside a tunnel

Because tunnels are deprived of natural light, photocatalytic denitrification relies on the artificial lighting installed in the tunnel. Yet fluorescent bulbs emit significantly lower levels of UV light than natural light, and sodium lamps emit no UV at all. The photocatalytic denitrification process will only be effective if a special UV lighting system is installed – something that requires further investment and operating costs and, through additional energy consumption, limits the system's environmental benefits.

Moreover, because there is no rainwater inside a tunnel environment, photocatalytic activity drops sharply after a few weeks because the particle deposits that build up on the treated surfaces are not leached. These particles can block active sites and prevent reactions with nitrogen oxides. The system's efficacy is only partially or fully restored once the surfaces holding titanium dioxide are washed with water.

As such, demand for UV light and fouling are major barriers to application of this system in a tunnel environment.

Polluted discharges post-leaching would not be a major issue because the nitrates formed would remain trapped inside the cement matrix in the form of salts

4.2.2.3 Deployment around a tunnel perimeter

The process can be used upstream or downstream of a tunnel, in the immediate vicinity of the portals, where nitrogen dioxide concentrations are likely to be at their highest. Eurovia's NOxer®, a TiO_2-based "depolluting coating for roadways", is used at the toll booths on the A86 duplex tunnel in the Paris region. More generally, titanium dioxide could be used in a variety of civil engineering structures around tunnel portals, such as supporting wall facings, canopies, anti-recycling walls, noise screens, etc.

This document does not explore the use of this process in open-air environments away from the immediate vicinity of tunnels.

4.2.2.4 Case study: two tunnels in Italy and Belgium

Titanium dioxide coatings are used at two tunnels in Europe: the Umberto I tunnel in Rome, and the Leopold II tunnel in Brussels.

Measurements have been taken at both tunnels to measure the efficacy of the photocatalysis system.

In Italy, the 350-metre-long Umberto I tunnel currently carries around 1,000 vehicles per hour, along two one-way lanes and one bus and taxi lane travelling in the opposite direction. There is also a footway for pedestrians, and this is the reason why a decision was made to install the photocatalysis system during renovation work on the tunnel.

A special artificial lighting circuit was installed to provide the UV light required for the photocatalysis process. Italcementi carried out a series of measurement campaigns in 2007 to assess the system's efficacy, finding that average NO_2 concentrations had fallen by 19% since completion of the renovation work. According to digital models produced for Calcia by Aria Technologies, average NO_2 concentrations in the Umberto I tunnel in Rome had fallen by 30% at an airflow rate of 1.5 m/s, and by 15% at 3 m/s.

From the analysis above, we can deduce that:

- generally speaking, photocatalysis is highly effective at mitigating pollution peaks;
- it is harder to calculate average pollution reduction performance because pollution levels in the city differed markedly between the two measurement campaigns (before and after completion of the renovation work);
- it is difficult to assess the long-term performance of the product.

The Leopold II tunnel in Brussels is the longest in Belgium, measuring 2,534 m in length. Around 65,000 vehicles pass through the tunnel each day. A photocatalytic cement plaster was applied to the tunnel's walls and ceiling to assess the efficacy of photocatalysis. The plaster was initially applied to a 70-metre section for the first measurement campaign (September 2011), and then to a 160-metre section for the second campaign (January 2013).

The results of both measurement campaigns were inconclusive. Nitrogen oxide concentrations fell by less than 2%, at a UV light intensity of 1.6 $W \cdot m^{-2}$, an airflow rate of 3 m/s, and humidity above 70% [31]. These disappointing results were attributed to a lack of UV lighting power and unfavourable conditions during the experiment (airflow rate, humidity and pollutant concentrations) [32]. Digital simulations were carried out under ideal experimental conditions (light power of 10 $W \cdot m^{-2}$, airflow rate of 1 m/s, humidity of 50%). These simulations produced more promising results, pointing to a potential 20% reduction in nitrogen oxide concentration in the 160-metre experimental section [31].

The two examples above show that laboratory results do not necessarily translate to actual in-tunnel performance. The efficacy of photocatalysis is dependent on several variables (lighting power, wind speed, humidity, pollutant concentration, etc.). Where the optimal conditions for photocatalysis are not met, this can significantly reduce system performance.

4.2.2.5 Nanoparticle risk

The prospect of adding TiO_2 to materials in the form of nanoparticles has become a topic of debate.

The French Agency for Health and Safety of the Environment and Work (AFSSET) issued an opinion on 17 March 2010 [33] suggesting that some TiO_2-based products could pose a risk to health and the environment. In terms of nanoparticle dispersion risk, issue 28 of magazine Béton[s] (May/June 2010) [34] states that "in most cases, these problems are now addressed by the way in which the products are used (aggregated or integrated into the final material, thereby reducing the risk of nanoparticle dispersion in the air). Yet toxicology and particle concentration studies are ongoing in an effort to address final user health and protection concerns."

4.2.3 Non-photocatalytic depolluting concretes

LafargeHolcim has recently developed a range of concretes and renders that remove pollution from the air.

The process works through the adsorption of NO_2 molecules, which then undergo a chemical reaction with alkaline hydrates in the cement pastes. Calcium hydroxide ($Ca(OH)_2$) and calcium silicate hydrate (C-S-H) react strongly with NO_2 molecules to form ionic compounds such as nitrates and nitrites in the cement medium. As such, this depollution technique capitalises on the intrinsic properties of concrete, to which special depolluting agents are added to boost adsorption capacity [35].

Following promising tests in the laboratory and on a car garage-size prototype, the technique was applied full-scale at the Croix-Rousse road tunnel in Lyon, France. The material was applied on the walls of one of the tunnel's ventilation stations to reduce nitrogen dioxide emissions via this shaft during extraction for health reasons. The results of the test have not yet been published.

Unlike photocatalytic denitrification, this technique appears well suited to tunnels because it does not require either natural or artificial light. However, one drawback is that the concrete surface tends to become fouled (at different rates), thereby limiting the system's efficacy. As such, the coated surfaces would need to be washed (as a minimum) to keep the system working correctly over time.

4.2.4 Cold plasma

The scientific community has high hopes for cold plasma technology, which has potential long-term applications that extend beyond tunnels.

Plasma, a partially ionized gas, is considered a "fourth state of matter". Cold plasma occurs when the temperature of the plasma is close to the ambient temperature. For many years now, scientists have been studying the potential use of cold plasma to remove pollutants from gaseous effluents, harnessing plasma's reactive properties to convert toxic compounds into harmless gases. Eventually, this process could be easy to deploy, with potential applications in tunnel environments and in treating particle pollution.

4.3 BIOFILTRATION

4.3.1 Context

The early 20th century saw the development of biofiltration, harnessing the capacity of certain micro-organisms to treat waste water and some types of solid waste. The first applications of biofiltration in air treatment emerged in the 1950s, in an effort to eliminate odours from water purification plants[1]. This technique rapidly spread to several other domains (sanitation, manufacturing, food processing, livestock farming, etc.) in the 1990s, as a way to treat volatile organic compounds (VOCs) and foul-smelling compounds[2].

4.3.2 How biofiltration works

Biofiltration involves forcing air through a filter medium that captures pollutants, encourages bacteria to grow in the rhizosphere[3], and promotes plant growth on the surface (see illustration 14). Gases and exhaust fumes are soluble in the aqueous phase. A wide range of physical and chemical processes are observed, including absorption, adsorption, nitrification and breakdown by micro-organisms in the biomass. The particles, meanwhile, are trapped through mechanical filtration (mainly sedimentation).

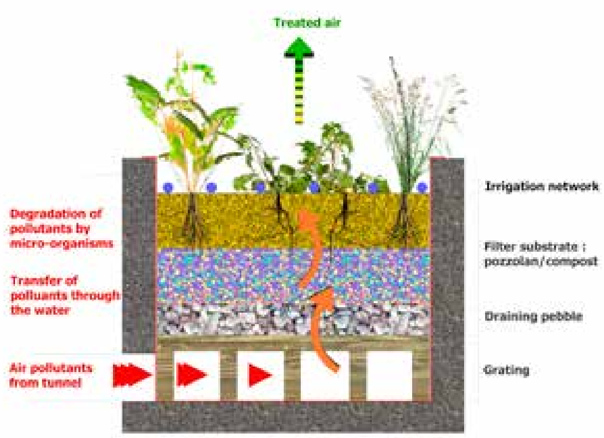

Illustration 14: how biofiltration works

1. J.S. Devigny & al. (1999) Biofiltration for air pollution control.
2. ADEME (2014) Traitement biologique.
3. The narrow region of soil that is directly influenced by root secretions and associated soil microorganisms.

4.3.3 Experimental application of biofiltration to treat vitiated air in a road tunnel

4.3.3.1 System deployed in the Guy Môquet tunnel (Thiais, Val de Marne, France)

Biofiltration has proven highly effective in several industrial applications, raising the possibility of using the technique to treat road vehicle emissions. An experiment was conducted to assess how effective the process was a treating vitiated air from a tunnel.

Because biofiltration has never been used in a tunnel environment before, a small-scale system was deployed for the initial experiment. The biofilter was designed to treat air in a small section of the tunnel (a few cubic metres), and all other parts of the system were scaled accordingly, thereby substantially reducing the installation's size.

The aims of the experiment were, first and foremost, to assess the feasibility of tunnel deployment, as well as to measure depolluting performance in this configuration, to observe changes to the system over a sufficiently long period of time, and to assess the associated maintenance and operation constraints (including water and energy consumption).

The experiment was carried out as part of a research project part-funded by ADEME [4], in partnership with the Ile-de-France Regional Directorate of the Centre for Research and Expertise on Risks, the Environment, Mobility and Planning (CEREMA) (the main contributor to the programme), the CETU, Phytorestore, the Laboratory of Microbial Evolution (EML) (joint Université Claude Bernard Lyon 1 and CNRS laboratory), and ENGIE Axima.

The biofilter was installed in the Guy Môquet tunnel, on the A86 motorway in Thiais (Val-de-Marne) – a 650-metre-long, bi-tube "cut and cover" tunnel with three traffic lanes in each direction, carrying 134,000 vehicles per day.

The system comprised two 16 m² biofilters, consisting of plant substrates 50 cm (BF50) and 100 cm (BF100) thick, installed on the open cut. A stream of vitiated air, extracted from inside the tunnel just before the exit portal of one of the two tubes, passed through the bed of the filter at a rate of 1-3 m³/s.

The experiment ran from November 2012 to April 2014, to give sufficient time to encompass all of the seasons. There were four short measurement campaigns, of 4-6 weeks each, to assess the efficacy of the biofilters and to monitor changes to their physical, chemical and biological properties throughout the life of the experiment.

Illustration 15 provides an overview of the experimental system.

Illustration 15: the site overview shows: (1) the premises housing the extractor fan; (2) the duct conveying the vitiated air; (3) the two biofilters; (4) a control biofilter without vitiated air; and (5) the bungalows accommodating the measuring equipment. The air samples at the biofilter outlets are captured by two "bell chambers" (6). The water for irrigating the biofilters is stored in (7) in tanks. The percolation water is collected under the filters and then filtered for reuse.

4.3.3.2 Particle filtration results

The measurements found particle reductions of between 30% and 90%, according to particle size and biofilter thickness.

Particle diameter	[0 – 1 µm[	[1 – 2,5 µm[	[2,5 – 10 µm[	> 10 µm
BF_{50} reduction	29%	77%	84%	36%
BF_{100} reduction	61%	93%	91%	66%

Table 12: average reductions observed across the four measurement campaigns

4. Full report available on the ADEME website: www.ademe.fr/evaluation-biofiltration-traitement-emissionsatmospheriques-tunnels-routier

4.3.3.3 NO_2 filtration results

Average reductions across the project duration were 58% for the BF50 biofilter and 80% for the BF100.

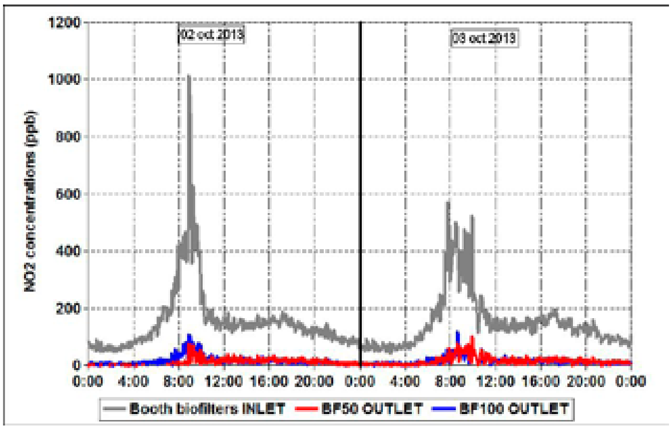

Illustration 16 : example of daily NO2 content measurements during the third campaign

Illustration 16 gives an indication of the observed reductions by comparing the NO_2 concentrations measured upstream and downstream of the biofilters.

4.3.3.4 Conclusions of the experiment

The experiment showed how biofilters can effectively treat the main road traffic pollutants, with no loss of efficacy after 18 months of operation, provided that a continuous water supply is available and several plants are replaced.

The life cycle analysis (LCA) conducted in parallel, however, revealed the major impact of the operation phase, pointing in particular to the amount of electricity needed to power the air extractor fan. Indeed, this item has more severe environmental impacts than any other category.

Doubts remain over the general environmental benefits of this technology, given the need to weigh energy consumption against the positive depolluting impacts of the biofilter.

The experiment showed a clear need, at this stage, to improve biofilter characteristics such as airflow, thickness, surface area and substrate composition. This, in turn, would help maintain pollution reduction efficacy while at the same time considerably limiting energy consumption during the operation phase, thereby improving overall environmental impact.

4.4 CONCLUSION

Denitrification is the only gas treatment method that has been effectively deployed in a tunnel environment. The other technologies mentioned here (depolluting concrete, biofiltration and cold plasma) are still in the research and experimentation phase.

While various laboratory studies have shown that photocatalysis is effective at reducing nitrogen oxide concentrations, the two in-field experiments conducted to date produced debatable and disappointing results respectively, revealing that this method appears only to work within a narrow range of conditions. As for LafargeHolcim concrete, it is still too early to determine how effective this technology is in practice and over time. While these two technologies are designed primarily to reduce nitrogen oxide concentrations, they could also have an effect on other gases.

Biofiltration seems to be the most promising technology, since it tackles both gaseous pollutants and particles. However, further development work is needed, in particular to reduce energy consumption during the operation phase and to adapt the system to the scale of existing tunnels.

GENERAL CONCLUSION

The design and development of air treatment systems in tunnels initially focused on the filtration of particulate matter and smoke that forms the visible part of the pollution. Since then, the principle has been the same in every tunnel equipped with a particulate filtration system, and is based on electrostatic filtration. It is now an established fact that, technologically speaking, electrostatic precipitators furnish excellent results in terms of filtration performance. Nonetheless, while progress has been made in the development of these systems, concerning the simplification of cleaning operations in particular, there have not been any major, groundbreaking technological advances and the devices are still bulky and less cost-effective than conventional ventilation systems, both in terms of investment and operation. Generally-speaking, these systems are also energy-intensive given the surplus ventilation requirements. While most of the older installations were designed to decontaminate air inside tunnels, the most recent installations place a greater focus on treating discharges to at-risk environments.

Regarding the treatment of gaseous effluents, major technological breakthroughs have made it possible to step up from laboratory trials to operational deployment in tunnels. However, the relatively few cases of tunnels being equipped with gas treatment systems means there is a lack of adequate data on the operational performance of such systems, specifically because they are so very recent. Current installations are mainly based on absorption-based denitrification techniques downstream of electrostatic particulate filtration. They are mainly designed to reduce the impact of discharges to the environment.

In recent years, new tunnel air treatment technologies such as depolluting concrete and biofiltration have emerged to address shortcomings in existing tunnel-based treatment systems. However, these technologies are still in the experimental phase and more work is required to determine the conditions under which they can be effectively deployed inside tunnels. As such, it is hard to say how these technologies will develop.

Air quality has become a major health and environmental concern. Despite the fact that full multi-criteria analysis has not yet provided any hard evidence to support the use of air treatment systems in preference to more conventional methods, recent tunnel projects often propose the use of air treatment systems in response to concerns expressed by local populations, who have reason to be worried about changes in their environment. Before turning to systems that may effectively provide an answer to a local pollution concern, conventional ventilation techniques (using fresh airflows to dilute pollutants) should still be considered by making use of the appropriate means, i.e. playing on the airflows and concentrations of the discarded vitiated air, as well as on the location and configuration of discharges and any other method likely to improve the dispersion of pollution and so protect the most at-risk areas.

Moreover, a consistent and comprehensive system analysis should be based on a life cycle analysis (LCA), in particular to gain an insight into energy consumption and to consider the additional infrastructure required when installing air treatment systems.

Lastly, it is useful to look at the issue of air treatment in tunnels against the background of road-related atmospheric pollution. Tunnels do not themselves create pollution; it is the traffic going through them that is the polluting factor. It is true that tunnels channel this pollution and make it possible to treat it, but only along a very short linear length in contrast to the number of vehicles circulating in ambient air. Tunnels are still atypical structures. As such, tunnel-related atmospheric pollution is limited to very localised issues.

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ANNEXE

Photographic compendium following the may 2009 visit of the M30 in Madrid

Illustration 17: Extraction fans used for both smoke extraction and air treatment, in horizontal position (cut-and-covered tunnel) – unit characteristics 203 m^3/s, 630 kW

Illustration 18: Extraction fans used for both smoke extraction and air treatment, in vertical position (By-Pass Sur tunnel) – unit characteristics: 116 m^3/s, 560 kW

Illustration 19: air treatment circuit intake (air circulates from left to right) – on the left – opening/closing dampers for the treatment circuit, on the right, the ionising devices

Illustration 20: air treatment circuit intake – close-up of the dampers and pre-filtration meshes (Aigner)

Illustration 21: ionisation device – the difference in potential is established between the points seen in the photo, air is electrically charged on passing between the blades

Illustration 23: on the left, cabinets containing the electrostatic filters and, on the right, deNO$_x$ system (air circulates from left to right)

Illustration 22: components of the ionisation system

Illustration 24: electrostatic filters mounted on rollers to simplify cleaning under high-pressure air jets (Aigner)

Illustration 25: rinsing nozzles on an ionisation device (CTA)

Illustration 27: electrostatic filters and their rinsing nozzles(CTA)

Illustration 26: ionisation device being washed under high-pressure water jets (CTA)

Illustration 28: filters being washed under high-pressure water jets (Filtrontec)

Illustration 31: DeNOx system – close-up of the panels housing the activated carbon pellets

Illustration 29: DeNOx system – air circulates between the panels seen in the photo, from the back to front – the curved shape increases the panels' surface area (W-shaped profile when seen from above) and therefore, those of the contact surfaces between air and the activated carbon, thus enhancing system performance

Illustration 30: DeNOx system – air circulates between the panels seen in the photo, a length of several metres is required to ensure a large enough contact surface area

Illustration 32: end of the treatment system (air flows in on the right, fills the plenum then flows out through the opening in the ceiling) – on the right – the acoustic panels demonstrate the size of the aeraulics section required to limit flow speeds through the system – at top right, in shadow, the opening that forms the end of the sheathing parallel to the treatment circuit making it possible to short-circuit the treatment system in the event of fire

Illustration 33: high-voltage transformer for the ionization current (Aigner)

Illustration 34: cabinets containing the basic conversion units for the ionisation current (CTA)

Illustration 35: installation of the system for treating water used to wash filters (CTA)

Illustration 36: installation of the system for treating water used to wash filters (Filtrontec)

Illustration 37: collection of treatment residues at the end of the system for rinsing filters (Aigner)

Illustration 38: collection point for treatment residues at the end of the system for treating water used to wash filters (Filtrontec)

Illustration 39: collection point for treatment residues at the end of the system for treating water used to wash filters (CTA)

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Cover: Experimental biofilter at the Guy-Môquet tunnel in Thiais (94). Photo credit: CETU - Editing and coordination: CETU - Implementation: Communiquez - Printing: VASSEL GRAPHIQUE

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