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Possibilities and limitations of tunnel-air filtration and portal-flow extractions

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ABSTRACT

Endeavouring to improve the ambient air quality, stringent criteria are often imposed onto the impact of the vitiated tunnel air at tunnel portals. Moreover particularly in urban areas, the regulatory requirements to the ambient air-quality often cannot be met. The thresholds values for NO_2 and particulates are exceeded. Therefore, firstly conventional ventilation methods for minimising the impact of tunnel air to the environment are reviewed. This includes an analysis of key technical requirements such as ventilation control and stack-flow velocities. Technical limitations of each technology are elaborated. Moreover, capital and operation costs are evaluated. It is shown that choosing an optimal technical solution, the energy consumption can be more than halved compared to using conventional solutions. Furthermore when adequately designed, the impact of the stack flow to the ambient air-quality near the stack is shown to be negligible.

The second focus is on the state of art of air-filtration systems for tunnel applications. The world-wide available technical methods are described and assessed. A cost-benefit analysis is carried out based on case studies which also incorporates non-ventilation related methods for the improvement of the air-quality at tunnel portals.

Finally based on practical examples, the impact of tunnel air onto the ambient air quality is scrutinized on a global level discussing the overall influence of vitiated tunnel air onto the ambient air.

1 AMBIENT AIR-QUALITY ISSUES REGARDING TUNNEL PROJECTS

1.1 Ambient air-quality limits

International and national requirements to ambient air quality are so stringent that they often cannot be met in urban areas. The EU-directive 1999/30/EC specifies following threshold values of the ambient air quality e.g. for the maximum annual average concentrations of particulate matter (PM_{10}) and nitrogen dioxide (NO_2)

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Table 1: Critical air quality limits with respect to traffic (3)

pollutant	statistical value	by 1 January 2010
PM_{10}	annual mean daily mean	20 µg/m^3 50 µg/m^3 (≤ 35 times exceeded)
NO_2	annual mean hourly mean	40 µg/m^3 200 µg/m^3 (≤ 18 times exceeded)

Today, air-quality limits for other pollutants, such as carbon monoxide CO, sulphur dioxide SO_2 etc. are generally met – or pollution originates from other sources than traffic.

1.2 Current ambient air-quality situation

A general characterisation of the current situation is given in the following table. It is recognised that there are significant differences in the air-quality situation in the European countries.

Table 2: Typical air-quality situation

pollutant	urban area	residential area	rural area
PM_{10} annual mean	exceeded at most locations exposed to traffic	exceeded at some locations	air quality limit generally met
PM_{10} daily mean			exceeded at some locations
NO_2 annual mean	exceeded at most locations exposed to traffic	exceeded at some locations	air quality limit generally met
NO_2 hourly mean	air quality limit generally met	air quality limit generally met	

In urban areas or areas that are exposed to traffic, the air-quality limits for particulates and nitrogen dioxide are generally exceeded.

The level of any pollutant depends on the regional and urban background level and on the emissions originating from local sources. The partition of background vs. local sources varies for different pollutants. While high NO_2-concentrations may be attributed to local sources, such as main roads or tunnel portals, the level of PM_{10} is generally dominated by the contribution of the regional and urban background.

1.3 Vehicle emissions

As part of the design and approval process, the future air quality in the vicinity of a tunnel has to be assessed. The design is based on predicted vehicles emissions. These emissions are based on assumptions of the traffic volume and composition travelling through the tunnel. The prediction is done for the most critical year in terms of total emissions. Due to the implementation of more stringent regulations for the emission of individual vehicles, a general reduction with time is expected.

The emission data shown in Figure 1 do not include the latest emission regulations EURO5 and 6 to be introduced in 2009 and 2014. Therefore, a further reduction is expected.

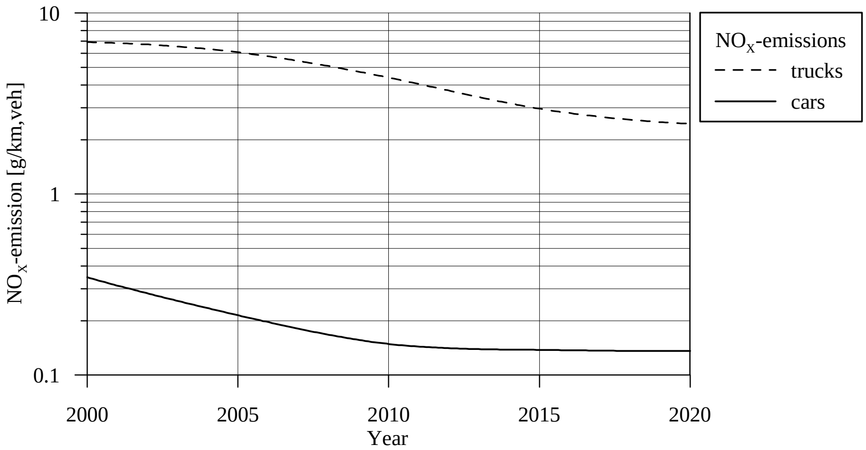

Figure 1: Predicted NO_X emissions (Germany, rural road, (4))

1.4 Case study Zurich, Switzerland

In an urban environment that is part of the City of Zurich, the noise levels caused by a national road exceed the limit in the adjacent residential area. The noise calculation demonstrates that the limits cannot be met by installation of noise barriers along the highway. Therefore, it is envisaged to build a tunnel structure as an enclosure of the existing road. The 1200 m long tunnel would give significant improvements to the residential area with regards to noise and pollution.

While solving the noise problem, a tunnel leads to a redistribution of pollutants. The traffic-induced pollution is removed from the area along the tunnel, but it is discharged at the tunnel portals – or extracted from the tunnel at the exit portal. In the portal areas, the pollution levels of NO_2 and PM_{10} are already at or above the air-quality goals defined in the environmental standards. Further emissions in the vicinity of the tunnel portals would lead to a further increase of pollution concentration. As there are many residents living in the vicinity of the tunnel portal, it appears appropriate to invest a significant part of the project budget into measures to reduce portal air discharge.

For the portal air extraction, different systems have been considered:

- conventional air extraction (fan station with two parallel axial fans, vertical stack, dilution of exhaust air in the atmosphere)
- conventional air extraction with electrostatic precipitator ESP and stack discharge
- conventional air extraction with ESP and NO_2-removal
- air extraction with large cooling-tower type fan (GRP-fan) without filtration

For the purpose of a comparison of the different technologies, it has been decided to base the design on maximum efficiency in terms of pollution removal. So, the design is not based on maximum air flow in the tunnel, but for maximum pollution at minimum investment of capital cost and power requirement. For this approach, it is beneficial that the design can be based on today's traffic data and not on predicted traffic. Apparently, a portal air extraction is very efficient especially at congested peak-hour traffic, when the traffic moves at reduced speed and the tunnel air is polluted up to the in-tunnel air-quality limit. This led to a recommended extraction flow rate of 300 m^3/s. The expected maximum flow rate in the tunnel is expected to be 420 m^3/s.

However, it has to be noted that the optimum capacity of the air extraction would be higher for the cooling-tower type arrangement, as an increased extraction rate could be achieved at much lower additional capital cost and power requirement.

2 PORTAL-AIR EXTRACTIONS

In this section, the exhaust systems for environmental protection will be described in general.

2.1 Functionality and requirements

The intent of a portal-air extraction is the reduction of pollution in the vicinity of the tunnel portal. In order to achieve this reduction, the discharge of polluted air from the tunnel has to be reduced if not completely inhibited. The design of the extraction system has to be based on the air flow in the tunnel and not on the pollution. A typical air-flow rate in a road tunnel is between 400 and 500 m^3/s during free flowing traffic. The flow rate mainly depends on traffic volume, speed and tunnel cross section. The extraction requires powerful exhaust fans.

In some countries, a typical design requirement is to ensure a “net positive in-flow of air at all portals whilst the tunnel is open to traffic”. In Switzerland, however, the design has to take into account an optimisation of air quality, power consumption and civil construction.

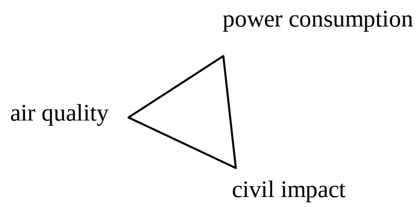

Figure 2: Design criteria for portal-air extraction

Design goals regarding air quality may be given by the environmental impact study, such as “reduction of PM_{10} portal discharge by 70%”. The operation of the extraction is then part of the optimisation process.

2.2 Conventional methods

The conventional portal-air extraction station extracts the tunnel air via an opening on top or on the side of the tunnel. The maximum air velocity at the traffic envelope should be no more than 5 m/s (extraction from the side) or 10 m/s (overhead extraction). The exhaust air passes through a set of attenuators in order to limit fan noise in the traffic space. In the fan station, a set of axial exhaust fans is operated. The fan station design has to take into account minimum pressure losses as well as optimised air flow approaching the fans. Each fan unit consists of inlet bell-mouth, active unit, transition piece (diffuser and transition from circular to square) and fan isolation damper. On the pressure side, the air flow passes another set of attenuators selected according to ambient noise criteria. A typical lay-out is shown in Figure 3.

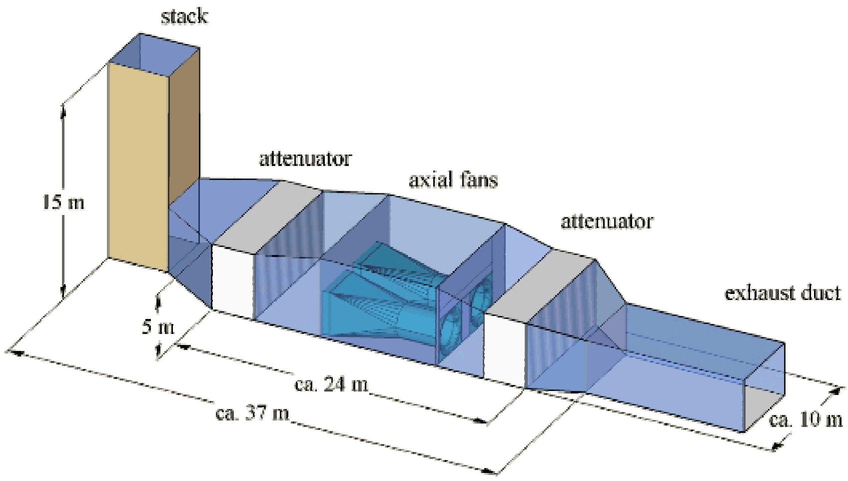

Figure 3: Conventional portal air extraction (designed for 300 m^3/s capacity)

The conventional air-extraction system could be extended to incorporate electrostatic precipitators ESP or NO_2-removal systems. The equipment would be situated between the exhaust fans and the attenuator on the suction side of the fan station. However, the space requirement and pressure drop of the filtration units have to be taken into account during exhaust station design and fan selection.

2.3 Stack fans (GRP)

The installation of cooling-tower fans in road-tunnel applications has been first described in the year 2000; (5), (6). In the past decade, the GRP-fan option has been discussed for a number of projects, although it has not been installed in other tunnels in Switzerland, yet.

In principle, the extraction is operated similar to the conventional system. In fluid traffic, the air-flow through the tunnel is driven by the piston effect of the vehicles. During congested traffic, the normal tunnel ventilation supports the air flow. The exhaust fan is controlled in order to extract the air flow from the tunnel. It passes the fans and is expelled vertically through the exhaust stack. The main difference to the conventional system is the low pressure drop of the GRP fan arrangement, as attenuators are not required due to low noise levels of the large fan. Some sound attenuation may be provided with a sound absorbing lining of the exhaust stack. The air flow through the system is at low air flow velocity, thereby minimising the pressure losses in the fan station.

Due to the lower power requirement, it appears appropriate to design the exhaust system for higher exhaust flow rates in comparison with a conventional system. The control of the exhaust system is also easier, as the penalty in power consumption for over-ventilating the system is very low. It may be sufficient, to operate the fan at constant speed during the major part of the day.

A schematic sketch of the GRP fan arrangement is given in Figure 4. The design is derived from the fan arrangement in the tunnel Spier. More details on the Spier tunnel may be found in the paper (6).

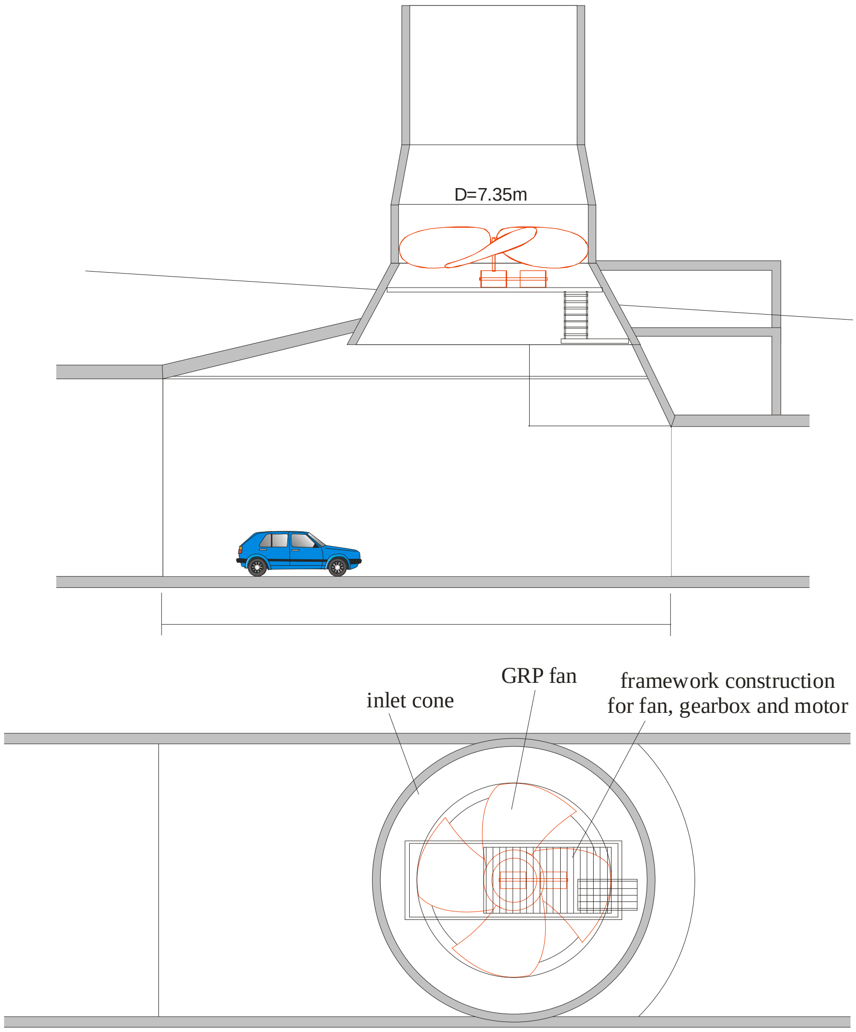

Figure 4: Schematic sketch of GRP fan arrangement

2.4 Comparison of conventional and GRP exhaust system

The comparison of the conventional and the GRP fan solution is given in

Table 3. Please note that the optimisation process during exhaust system design led to different capacities for the two solutions.

With the GRP fan, the increased capacity is available at considerably lower capital and running costs.

In order to fully realise the benefits from the GRP fan concept, the system has to be engineered at a very early stage of the project. Especially, once the stack location is fixed, a move towards the GRP fan option could require an extended period of project approval. Especially in an urban environment, the political aspects of the tunnel project render substantial changes of an already approved project very difficult.

Table 3: Comparison of conventional and GRP exhaust system

Item	Conventional system	GRP fan
Number of fans	2	1
exhaust flow rate	300 m^3/s	400 m^3/s
Total pressure	1000 Pa	330 Pa
consumed power	450 kW	220 kW
rel. civil cost (estimate)	200%	100%
rel. hardware cost (est.)	240%	100%
rel. running cost (est.)	200%	100%
maximum reduction of portal emission	60%	75%
(operation 16 hours / day) energy consumption	2600 MWh/yr	1300 MWh/yr

If the technical requirements for the tunnel equipment require redundancy in case of fan failure, resent studies have shown that an installation of a second GRP fan in series may be feasible.

While the fans are not operational, rain and snow may enter the tunnel through the open stack. The exhaust fans are not equipped with fan isolation dampers (due to the increased pressure drop). This could be considered an increased risk for tunnel users at these unexpected conditions for the drivers. In the Spier tunnel, heating elements are installed in the road surface in order to avoid ice formation. However, it was not necessary to operate these elements since commissioning, as the temperature inside the tunnel was always well above freezing.

A drawback of the GRP fan arrangement is that a combination of this exhaust system with any exhaust gas cleaning (ESP or NO_2-removal) is not possible due to the pressure drop of the filtration units. This is especially the case, if the performance specifications for the tunnel equipment require the optional installation of filtration equipment without substantial modification to the ventilation station.

2.5 Ventilation control

The control system of the portal exhaust ventilation consists of several operational modi. Each modus is given a defined priority. In principle, the exhaust-system operation is independent of the operation of the tunnel ventilation. The two systems are coupled in normal automatic mode, as some combinations should be avoided.

- manual – hardware: The extraction system is operated from the switchboard
- manual – software: The extraction system is operated manually from the human-machine interface HMI
- automatic – emergency: The extraction system is switched OFF
- automatic – time control: The extraction system is operated automatically depending on the current day of the week and time
- automatic – normal operation: The extraction system is controlled automatically based on tunnel monitor data, such as traffic volume, air-flow velocity, pollution concentration etc. and time. With the parameter “time”, the system could be operated at reduced capacity during the night.

Table 4: Operation modes for portal air extraction vs. tunnel ventilation

		portal air extraction				
		manual-hardware	manual-software	auto-emergency	auto-time control	auto-normal
tunnel ventilation	manual-hardware	yes	yes	no	no	no
	manual-software	yes	yes	no	no	no
	auto-emergency	yes def.: OFF	yes def: OFF	**OFF**	no	no
	auto-maintenance	yes	yes	no	no	no
	auto-normal	yes	yes	no	yes	yes
		priority ←				

Example: The tunnel ventilation is in mode "auto-normal" and the extraction system in mode "auto-time control". When the tunnel ventilation is switched to "auto-emergency", there is no equivalent mode for the extraction system. Therefore, the extraction system is switched to the next mode at higher priority, i.e. the extraction system is switched off.

3 AIR-FILTRATION TECHNIQUES

As an addition to a conventional extraction system, as described in section 2.2, the exhaust air may pass through a filtration system that is installed in order to extract certain pollutants. Due to the pressure drop of the filtration unit, the combination of filtration and GRP fans is not possible with the selection of GRP fans available today.

3.1 Technologies used for air-filtration

3.1.1 Methods applied for removal of particulates

In mechanical filtration, the exhaust air flow passes a filter medium. Particles remain in the filter. Usually, this technique is not recommended for road tunnel applications, as it requires an enormous cross-section for typical exhaust-air flow-rates. Otherwise, the pressure drop of the filter increases significantly with the accumulation of particles. At regular intervals, the filter medium has to be replaced or cleaned.

According to information given by a filter manufacturer, this filtration technique is currently applied to a number of Japanese road tunnels. Also, in new tunnels, this technique is installed upon request by the tunnel operator due to relatively low costs (both installation and operation).

These seemingly contradictory statements refer to different applications of mechanical filters: On one hand, they may have a high efficiency if they include filtration in several stages (increased installation and operating cost). On the other hand, mechanical filters represent a low-cost option if the low efficiency of a single stage filter is acceptable.

The typical filtration technique for road tunnel application is electrostatic precipitation (ESP). The ESP aims at the removal of particulates in the size range of 0.01 to 40 µm. Electrostatic precipitation involves three steps:

- application of an electric charge to the particles (high voltage pre-charger)
- collection of charged particles on the surface of oppositely charged collector plates
- removing particles from the collector plates through a 'wet' or 'dry' cleaning process

Some manufacturers use a combination of electrostatic and mechanical filtration. Here, an electric charge is applied to the particles. In the filtration stage, the particles are removed when the exhaust air passes a grounded mechanical filter (single stage). This system is expected to have a higher efficiency for small particles.

The power requirement for both systems, electrostatic or mechanical filters, is mainly determined by the aerodynamic resistance or pressure drop that has to be overcome by the main exhaust fans. The power requirement for the operation of the ESP itself (including cleaning process) is relatively small in comparison.

3.1.2 NO_2 removal techniques

Absorption is a physical or chemical process in which the pollutant gases NO and/or NO_2 enter the bulk phase - liquid or solid material. This is a different process from adsorption, since the molecules are taken up by the volume, not by surface.

The absorption process requires the removal of particulates from the exhaust air as an initial gas cleaning stage. The absorption filter may consist of honeycomb structures made from gypsum, activated carbon and alkaline potassium hydroxide. When the exhaust gas passes through the elements, NO_2 is absorbed. It reacts with the alkali to form the salts KNO_2 and KNO_3.

$$2\,NO_2 + 2\,KOH \rightarrow KNO_2 + KNO_3 + H_2O$$
$$NO_2 + NO + 2\,KOH \rightarrow 2\,KNO_2 + H_2O$$

During operation, the filtration elements lose their capacity for NO_2 removal. They have to be re-generated. This re-generation process includes the four stages: water washing, drying, KOH soaking and drying. The absorption elements may be regenerated up to 15 times, which gives an expected life cycle of two years following the replacement of the element.

Adsorption is a process that occurs when a gas or liquid solute accumulates on the surface of a solid or a liquid (adsorbent) forming a film of molecules. In experimental plants, the adsorbent was activated carbon of palladium coated ceramics. As for absorption filters, adsorption requires the removal of particulates from the exhaust air as an initial gas cleaning stage.

In a number of articles in conference proceedings and in the technical documentation of filter suppliers, gas cleaning through adsorption has been labelled as 'catalytic process'. However, the documentation does not explain the catalytic process at room temperature. By definition, a catalyst is not consumed by the reaction itself. With activated carbon, the filtration process is related to adsorption – and it requires the regeneration or an exchange of the activated carbon at regular intervals.

Other techniques, such as biological filters, exhaust-air treatment in gas turbines, photo-catalytic coated tunnel-lining etc. are at an early experimental stage. No large-scale plants have been installed in a road tunnel.

Figure 5 gives a schematic sketch of a conventional air extraction system with ESP and NO_2-filter. The space requirement indicated in the sketch is based on data provided by filter manufacturers. The schematic arrangement does not take into account any constraints due to the limited space that available in the vicinity of an urban road tunnel.

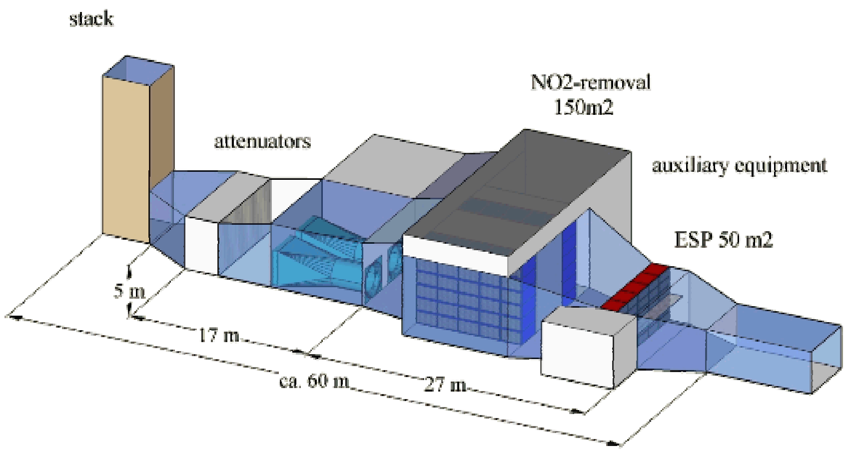

Figure 5: Portal air extraction with ESP and NO_2 Absorption (300 m^3/s capacity)

3.2 Review of installations of air-filtration plants

The following table gives an overview of filtration equipment installed in road tunnels in various countries.

Table 5: Installations of filtration equipment in road tunnels

Tunnel	filtration technology	design intent	maximum air flow rate	type of installation
Japan				
Aioi-cho	ESP + NO_2	exhaust air	80 m^3/s	exhaust station
Aqua (Tokio)	ESP + mechanical	visibility + exhaust air		
Asukayama	ESP	exhaust air	375 m^3/s 360 m^3/s	exhaust station
Enasan	ESP	visibility	300 m^3/s 240 m^3/s 255 m^3/s 200 m^3/s	bypass
Fukuchiyama	ESP	visibility	285 m^3/s 270 m^3/s 285 m^3/s	bypass bypass bypass
Gorigamine	ESP	visibility	105 m^3/s 105 m^3/s 195 m^3/s	bypass
Hakamagashi	ESP	visibility	190 m^3/s	bypass
Han-Na	ESP	visibility	270 m^3/s 285 m^3/s	bypass bypass

Tunnel	filtration technology	design intent	maximum air flow rate	type of installation
Hanazonobashi	ESP	exhaust air		
Happusan	ESP	visibility	225 m^3/s 210 m^3/s 170 m^3/s 190 m^3/s	bypass (since 2004 in Taroyama u. Gorigamine tunnels)
Hasumiya	ESP	exhaust air		
Higashiyama	ESP + mechanical	exhaust air		
Higo	ESP	visibility	113 m^3/s 90 m^3/s 135 m^3/s 260 m^3/s	bypass
Hihonzaka	ESP	exhaust air		
Hiroshimaseifu	ESP		85 m^3/s	bypass
Ichifuri	ESP	visibility	180 m^3/s 165 m^3/s	bypass bypass
Kakuto	ESP	visibility	170 m^3/s	bypass
Kann-etsu	ESP	visibility	945 m^3/s 810 m^3/s	bypass
Kann-Mon	ESP	visibility and exhaust air	365 m^3/s	exhaust station
Karasuyama	ESP	visibility and exhaust air	175 m^3/s	bypass
Kasaijama	ESP	visibility	270 m^3/s 240 m^3/s 225 m^3/s 210 m^3/s 210 m^3/s 210 m^3/s	bypass bypass bypass bypass bypass bypass
Kawasakikoro	mech. Filter	exhaust air		
Kongosan	ESP	visibility	195 m^3/s 285 m^3/s	bypass bypass
Koshirazu	ESP	visibility	300 m^3/s 180 m^3/s	bypass
Kuko-kita	mech. Filter	exhaust air		
Maiko	ESP + mech. Filter	visibility and exhaust air	180 m^3/s 180 m^3/s	bypass in tunnel crown
Midoribashi	ESP	exhaust air	573 m^3/s	exhaust station
Nihonzaka	ESP	visibility and exhaust air	240 m^3/s 240 m^3/s 680 m^3/s 440 m^3/s	bypass bypass exhaust station exhaust station
Nou	ESP		165 m^3/s	bypass
Ryousan	ESP	visibility		
Ryugatake	ESP	visibility	270 m^3/s	bypass
Ryu-ohzan	ESP	visibility and exhaust air	225 m^3/s 210 m^3/s	bypass
Sakuragicho	mech. Filter	exhaust air		

Tunnel	**filtration technology**	**design intent**	**maximum air flow rate**	**type of installation**
Sekido	ESP	visibility	240 m^3/s 240 m^3/s 240 m^3/s	bypass
Shintoshon-nishi	ESP		318 m^3/s	exhaust station
Shintoshon	ESP		154 m^3/s	exhaust station
Sirubachiyama	ESP	visibility	195 m^3/s	bypass
Suginami-ku	ESP	exhaust air	60 m^3/s	exhaust station
Tachitoge	ESP	visibility	225 m^3/s	bypass
Takanomine	ESP	visibility	195 m^3/s	bypass
Tamagawa	mech. Filter	exhaust air		
Taroyama	ESP	visibility	180 m^3/s	bypass
Tennozan	ESP	exhaust air	1643 m^3/s	exhaust station
Tokyo Bay	ESP	visibility		
Tsuruga	ESP	visibility	240 m^3/s	bypass
Uji	ESP	visibility	285 m^3/s 255 m^3/s 210 m^3/s	bypass
Honmachi	ESP + NO_2	exhaust air	309 m^3/s	*currently in design or construction stage*
Nishishinjuku	ESP + NO_2	exhaust air	240 m^3/s	
Yoyogi	ESP + NO_2	exhaust air	208 m^3/s	
Kanayamacho	ESP + NO_2	exhaust air	312 m^3/s	
Oohashi	ESP + NO_2	exhaust air	768 m^3/s	
Shinjyuku	ESP + NO_2	exhaust air	1672 m^3/s	
Italy				
Cesena	ESP	exhaust air	200 m^3/s 200 m^3/s	exhaust station
Norway				
Bragernes	ESP	exhaust air		exhaust station
Ekeberg I + II	ESP	visibility	250 m^3/s 250 m^3/s	bypass
Festning	ESP	exhaust air	600 m^3/s	exhaust station
Granfoss	ESP	exhaust air		exhaust station
Hell I, II + III	ESP	visibility		bypass in tunnel crown
Lærdal	ESP + NO_2	in-tunnel air quality	180 m^3/s	bypass
Nygårdtunnel	ESP	visibility		bypass in tunnel crown
Strømsås	ESP	visibility		bypass in tunnel crown
Spain				
Túnel Sur M30	ESP + NO_2	exhaust air	400 m^3/s 694 m^3/s	exhaust station

Tunnel	filtration technology	design intent	maximum air flow rate	type of installation
South Korea				
Chinbu	ESP	visibility and exhaust air	285 m^3/s	bypass
Saritjae	ESP	visibility	285 m^3/s	bypass
Safe-San	ESP	visibility	350 m^3/s 350 m^3/s 130 m^3/s	bypass
Su-Jung-San	ESP	visibility	600 m^3/s	bypass
Woo-Myun-San	ESP	visibility	210 m^3/s	bypass
Vietnam				
Hai Van Pass	ESP	visibility	260 m^3/s 260 m^3/s 260 m^3/s	bypass

It can be concluded that there is considerable experience for particle-removal systems (both ESP and mechanical), especially in Japan and Norway. The installation of gas-cleaning techniques, however, has been done in full scale only in very few tunnels. During our study, it was not possible to obtain reliable information on actual operation or efficiency of these installations.

4 COST-BENEFIT CONSIDERATIONS

For the road enclosure in Zurich, the cost per mass particulate matter has been estimated based on budget estimates provided by ESP suppliers. The estimated life cycle of the ESP and exhaust equipment is 20 years. An increase in traffic volume has been taken into account as well as the expected reduction of vehicle emissions. The estimate includes the non-engine emissions from tire wear and road dust.

- portal air extraction (GRP-fan) without filtration[1] 400 US$ / kg PM_{10}
- portal air extraction (conventional) without filtration[1] 950 US$ / kg PM_{10}
- portal air extraction with ESP 1900 US$ / kg PM_{10}

[1] *The particles are discharged through the stack. They are not removed from the atmosphere, but diluted to immeasurable concentrations at ground level*

The estimates are applicable only to this particular tunnel project. The effectiveness of a portal air extraction is increased with increased tunnel length, partition of trucks in the traffic mix etc.

From the analysis of costs versus PM_{10} emission, it appears more appropriate to reduce the emission at the source:

- Truck with particle filter (retro-fit) 270 US$ / kg PM_{10}
- New passenger car with particle filter 130 US$ / kg PM_{10}
- New truck with particle filter 45 US$ / kg PM_{10}

For comparison with other measures to reduce PM_{10} in the urban environment, estimates provided by the Zurich environmental agency AWEL shall be quoted:

- Tax discount on low emission vehicles 430 US$ / kg PM_{10}
- Integrated management of parking space in the city 170 US$ / kg PM_{10}
- Road surface cleaning 170 US$ / kg PM_{10}

5 CONCLUSION

From the study of pollution management by portal air extraction with conventional and GRP-fans as well as with or without filtration, following conclusions can be drawn.

- The installation and operation of portal-air extraction systems may be justified in an urban environment. The decision should be based on the current air-quality situation, on the additional impact of the emissions from the tunnel portal and on the number of people that are exposed to the pollution.
- The effectiveness of ESP or mechanical filtration to remove particulates has been proven in a number of tunnels.
- Gas-cleaning technology, especially for NO_2 or NO_X, is available on the market as well. However, full-scale installations have been finalised only very recently and data on the actual operation of this equipment is not yet available. There is no experience on long term operation of gas-cleaning equipment either in small or large scale installations.
- The installation of particle filtration is not sufficient to render an exhaust stack redundant. Typically, if the air-quality goals for PM_{10} are not met in the vicinity of a tunnel portal, the limits for NO_2 are exceeded, as well.
- Without taking aspects such as urban design into consideration, the most effective way to treat portal emissions appears to be the GRP-fan installation without filtration. At minimum cost and minimum energy consumption, the pollutants are removed from the portal area and diluted to immeasurable concentrations at ground level.

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