EXHAUST-TREATMENT TECHNOLOGIES FOR THE TUNNEL LUGANO – AN INVESTIGATION ON THE STATE-OF-THE-ART

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SYNOPSIS: Air-pollution management is a major issue in all new road tunnel projects, particularly in urban areas. Pollutant dispersion in the atmosphere by means of exhaust stacks is the most common solution. A viable alternative, or complement, is based on proper treatment of the exhaust gases.

The present paper is devoted to the state-of-the-art of exhaust-treatment technologies. The available technologies were evaluated from a technical, economical and environmental point of view. The main findings and conclusion from our investigation were as follows:

- Filtration by means of electrostatic precipitators allow for an effective extraction of particles from the tunnel exhaust. This technology is mature and sufficiently well proven for road tunnel applications.
- The treatment of gaseous pollutants constitutes a much less proven technology. Tunnel experience is not sufficiently extensive and some important issues, related to exploitation costs, durability and efficiency are not yet entirely solved.

For the particular case of the tunnel Lugano the evaluation of costs and benefits led to the conclusion that filtration is not required, since pollutant dispersion through the ventilation stack is very effective under all circumstances.

1 INTRODUCTION AND OBJECTIVES

An increasing sensitivity towards environmental concerns, mostly related to air quality, is consistently observed in recent tunnel projects, particularly in urban areas. The pollutants emitted in the tunnel are expelled in a concentrated manner at the tunnel portals or through ventilation stacks. In many cases a dilution strategy, realized using ventilation stacks with sufficient height and exhaust velocity, is perfectly adequate. In other situations this strategy needs to be combined with exhaust treatment.

The present paper describes the investigations carried out for the new 2.6 km long tunnel in Lugano, in southern Switzerland. Based on a comprehensive theoretical and experimental investigation campaign it was decided that pollutant dispersion through a stack is very effective and entirely adequate for achieving the air-pollution goals stated in the national legislation.

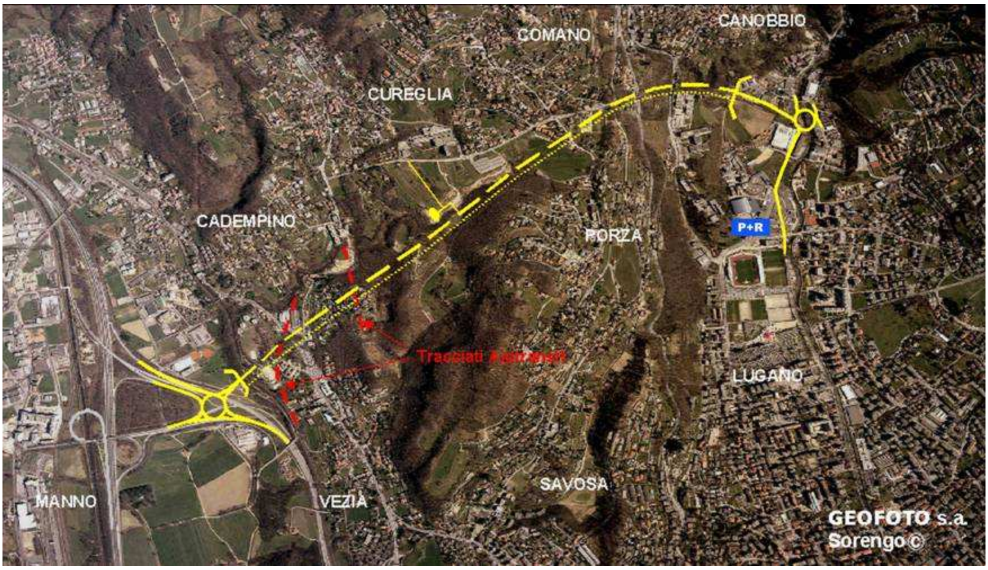


Fig. 1.1: The tunnel Lugano.

During tunnel construction an investigation was carried out in order to assess the practical applicability, the costs and the benefits of the application of new exhaust-treatment technologies. The available technologies were reviewed based on:

- Practical experience in road tunnels [10][11][12].
- Results and experiences from pilot testing in road tunnels.
- Previous independent evaluations [3][4][5][6][7][9].
- Direct information from equipment suppliers.

The investigation was focused on the tunnel Lugano, but the methodology and most conclusions are generally applicable.

The assessment of the potential costs and benefits of exhaust-treatment technologies will be treated in a companion paper by the same authors: “Air-Pollution Management for the Tunnel Lugano” [1].

2 THE TUNNEL LUGANO

The tunnel Vedeggio-Cassarate will connect the city of Lugano (with 100’000 inhabitants locally an important economic and cultural pole) with its agglomeration and with the north-south highway A2. The key tunnel data are as follows:

- Single tunnel with bidirectional traffic on totally two lanes.
- About 26’000-27’000 transits daily with approximately 4% HGVs.
- Safety and technical duct parallel to the tunnel, with 8 cross connections.

The ventilation system has two main operation modes:

– Exhaust extraction from the central part of the tunnel in normal operating conditions, Fig. 2.1. Air quality in the tunnel is therefore ensured by the air inflow through the portals.
– In case of fire it is possible to extract the smoke through dampers in a false ceiling and expel it through a stack.

In both cases the longitudinal air velocity is mastered by means of 8 jet fans installed in the portal areas. Exhaust air as well as smoke in case of fire are extracted by means of two large axial fans (230 m^3/s and 550 kW each) installed in an underground cavern in the central part of the tunnel. The gases are convected through a vertical shaft (95 m) and expelled through a stack (20 m).

Design and optimization of this ventilation system resulted from an optimization based on safety-related, functional, environmental and economic considerations. The environmental aspects are treated in a companion paper by the same authors [1] and will be summarized herein as far as they are relevant for the present purposes. The exhaust-management strategy chosen for the tunnel Lugano is based on:

– Prevention of uncontrolled propagation of the pollutants through the tunnel portals. Under such conditions dispersion would clearly be inadequate and result in excessive concentrations of the major pollutants in the portal neighborhood.
– Well-controlled exhaust air and smoke ejection in the intermediate part of the tunnel. Stack location and height (20 m) and exhaust velocity were optimized in order to allow for an optimum dispersion of the pollutants.

Several simulations allowed proving that this dispersion-based strategy is very effective. The augmentation of the major pollutant's concentrations arising from the stack's operation can be estimates for the year 2010 as follows [1]:

– NO_2 0.15 - 0.75 $\mu g/m^3$ (0.6 - 3.0% of the base load)
– PM10 0.0046 - 0.1 $\mu g/m^3$ (0.02 - 0.4% of the base load).

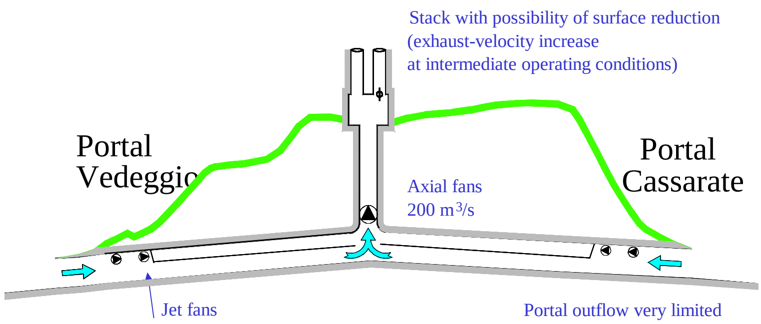


Fig. 2.1: Ventilation in normal operating conditions.

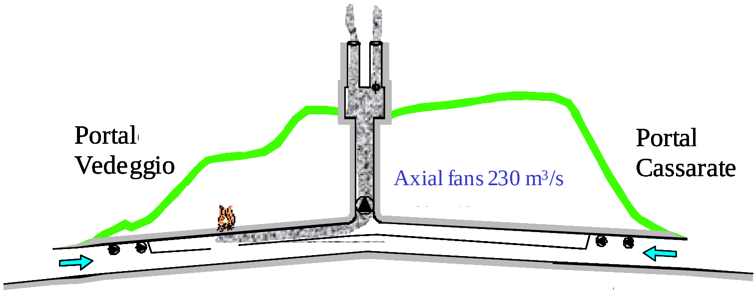


Fig. 2.2: Ventilation operating principle in case of fire.

3 EXHAUST TREATMENT TECHNOLOGIES

3.1 Overview

Several very effective exhaust-treatment technologies are currently used in industrial applications, such as chemical plants, thermal power plants or waste-incineration facilities. The issues in road tunnels are quite different because of:

– High exhaust flow rates, in the order of a few 100 m^3/s.

– Very small pollutant concentrations.

– Low temperatures.

Pollutant-dispersion strategies in road tunnels are very effective form the point of view of immission limitation. Therefore the use of exhaust-treatment technologies in road tunnels is still very limited.

While assessing the state-of-the-art it is important to distinguish between three main groups of pollutants:

– Particles (particularly small particles, PM10 etc.)

– Primary gaseous pollutants (CO, NO, NO_2, VOC, Benzene, SO_2 etc.)

– Secondary gaseous pollutants (Ozone etc.).

Filtration technologies represent a quite mature technology also in road-tunnel applications. The treatment of gaseous pollutants will be treated separately, because of the radically different technologies, which are much less advanced. Secondary gaseous pollutants are generated in the atmosphere as a result of the interaction between the primary pollutants and sunlight. These reactions occur on regional scale are only indirectly influenced by ventilation-related measures. They are therefore not treated herein.

3.2 Filtration

It is useful to distinguish three categories of suspended particles[7]:

- Combustion-generated particles, consisting of solid particles and aerosols, with diameters smaller than 1 µm. This component is rapidly diminishing owing to technical measures on motor vehicles.
- Particles generated because of consumption of the pavement and vehicles components, particularly tires and brakes.
- Resuspended particles and particle not related to motor vehicles.

Particle sizes in road tunnel range typically from 0.02 to 0.2 µm. These particles are particularly relevant form the point of view of human health because of their ability to penetrate into the lungs.

Several filtration principles are used for industrial applications, depending mainly on particle size and characteristics. Electrostatic precipitators (ESP) are by far the preferred solution in road tunnels. Cyclone separators are not sufficiently effective for the particle size predominant in tunnel exhaust and cloth filters are being abandoned for tunnel application.

A number of installations in road tunnels are in operation, particularly in Japan and Norway. Typical efficiency levels for tunnel applications are in the order of 80 to 95%. Significantly higher values are measured based ASRAE Standard 52.2 – 1999 o EN 779 because of the use of synthetic dust, which is not entirely representative for tunnel applications. Higher efficiency levels can be achieved but significantly increase energy consumption. There are no significant economic or technological risks connected with the use of ESP for particle filtration in road tunnels.

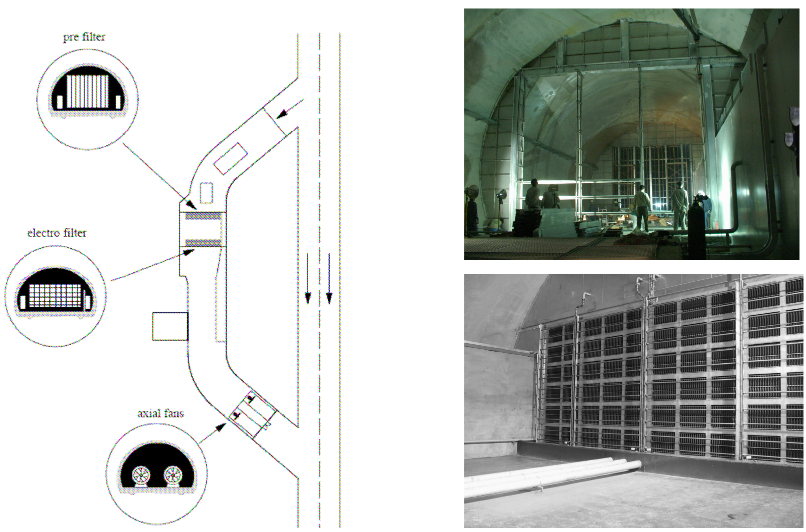


Fig. 3.1: Filters for bypass applications in unidirectional tunnels (KGD Ltd.).

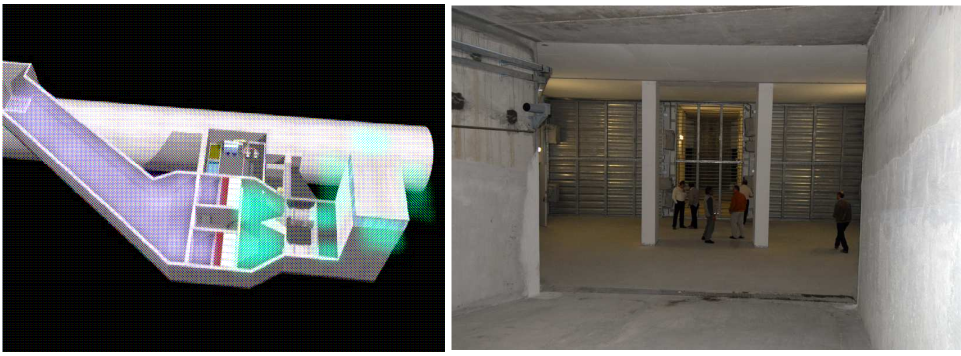


Fig. 3.2: Exhaust extraction from a unidirectional tunnel (Aigner Tunnel Technology GmbH). The whole plant is shown on the left picture, with the road tunnel in the background, the extraction duct on the left, exhaust treatment and fans in the central part and the stack on the right. The right picture shows the filtration equipment on both sides and the bypass in the middle. The filtration equipments are not used in case of fire.

3.3 Treatment of gaseous components

3.3.1 Technology

Four main technologies have been tested in the past for treatment of the gaseous components contained in tunnel exhaust:

- denitrification
- adsorbsion
- (bio)filtration
- photo catalysis.

Denitrification consists on the reduction of NO_2 to N_2 (gaseous nitrogen), NO and CO_2. The process is favored by appropriate catalytic materials, such as platinum, and is typically dependent on high temperature, because of the activation energy of the chemical reaction. This technology is well developed but its use in road tunnels is very limited. It should be noted that technologies based on the treatment of NO_2 but not NO are of limited utility because only about 10% of the NOx in the tunnel exhaust appears in form of NO_2. If not treated the NO could react with ozone outside the tunnel to generate NO_2.

Adsopbsion is a physical-chemical process by which a (generally organic) pollutant is bound to the surface of the adsorbing material by chemical or physical (Van Der Waals) forces. The most important material in this context is active carbon, which is widely used is several applications. This treatment can remove a wide spectrum of chemical components but suffers from a relatively rapid exhaustion, after which the material needs to be regenerated and, after some time, replaced.

In the process of biofiltration the exhaust air flux to be treated is conveyed through a matrix, on which a colony of suitably chosen microorganisms are grown. This is practically a biologic oxidation, where the microorganisms on the matrix can decompose the pollutants and use them as nourishment. Several alternatives are possible for the matrix: peat, earth, wood splinters, plastic materials etc.

A further technique is based on the use of wet ESP where, during the continuous wash process for collecting dust, NOx can also be removed. Efficiency of the process seems to be low [3].

A new and potentially very useful principle is based on the use of photo catalytic paints for the tunnel walls or photo catalytic concrete for the pavement. The active substance is TiO_2 or ZnO, which, in the presence of ultraviolet radiation, promote the reaction of NOx, SOx, CO, C_6H_6 etc. into harmless components. A reduction of the concentration of suspended particles and better optical characteristics of the tunnel walls are claimed too. This technology does not require specific equipments but it requires the installation of ultraviolet lamps. This principle is particularly interesting because of its simplicity and claimed effectiveness. Additional investigations are required in order to assess its effectiveness and durability.

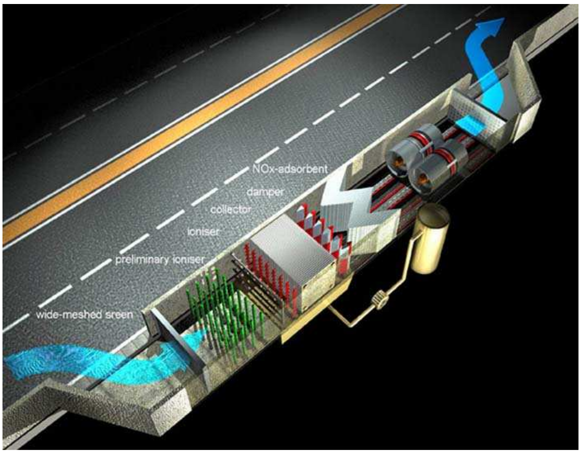
3.3.2 Applications

In spite of a wide spectrum of technologies and suppliers the use of exhaust-treatment technologies in road tunnel is not well established and most technologies exist only at the stage of pilot plant.

A reasonably well-established and diffused technology was developed by ABB jointly with the Norwegian road authority. It is based on the catalytic reduction of NO_2 to NO and CO_2 and adsorbsion of NO_2 by means of active carbon. This system was installed e.g. in the Lauerdal tunnel and in Madrid's M-30.

The catalytic reactions are very effective with fresh or freshly regenerated active carbons. They are most effective on NO_2 (efficiency over 80%) but affects also NO (roughly 30 to 60%) and other components such as VOC (60 to 80%). The catalytic effect of active carbon under road-tunnel conditions seems to decay quite rapidly and after some time only NO_2-adsorption is left. As stated above, this limitation is particularly severe for road-tunnel application because NO (which represents roughly 90% of NOx in road tunnels) can rapidly react (particularly during the ho season) with Ozone to generate high NO_2 concentrations. The indications available on durability of active carbon are not conclusive. This is, considering the high cost of active carbon (roughly 6'500 €/m^3) and regeneration costs, a relevant cost factor. The results from the new plants in Madrid will help clarifying this issue.

The practical effectiveness of the system is not well established. An indication is provided by the installations in Madrid, where only an efficiency of 80% for NO_2 was prescribed.



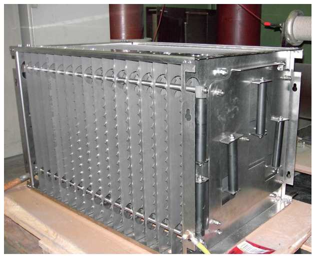


Fig. 3.3: Filter system for bypass installation (FILTRONtec GmBH). The main components, in the direction of the airflow, are: wide-meshed filter for large particles, ESP (with pre-ionizer, ionizer, collector and, on the side, water treatment), DENOx (with active carbon) and fans. The picture on the right shows an ESP module.

4 PRACTICAL EXPERIENCES

4.1 Overview

Air-treatment technologies in road tunnels can be applied with two main objectives:

- Improve the air quality within the tunnel.
- Treat the tunnel exhaust in order to reduce the environmental impact.

The first objective was dominant in the past [7]. Air-treatment stations can be under some circumstances (particularly long tunnels with high overburden, underwater tunnels or tunnels in urban areas) much cheaper than ventilation plants with very high shafts and stacks. Examples are the Kan'etsu (Japan, 11 km, 5 air-treatment stations and 2 ventilation stacks) and Lauerdal (Norway, 24.5 km, with one air-treatment station and one ventilation stack) tunnels. An important limitation of this approach is dictated by safety requirements: in many cases, as e.g. for the tunnel Lugano, a complex ventilation system is necessary for ensuring the user's safety.

Depending on the installation's objectives and on the tunnel configuration, several setups for air-treatment plants are used:

- Bypass installations (Fig. 3.1 and Fig. 3.3).
- Roof installations.
- Exhaust treatment applied to the air extracted from the tunnel and rejected into the environment (Fig. 3.2).

Bypass and roof installations are mainly useful for improving air quality within the tunnel. Only exhaust treatment can be considered for the tunnel Lugano, because of the existing ventilation station. An exhaust-treatment station could be installed at the bottom of the ventilation shaft, just behind the underground ventilation station, or on the surface.

Several exhaust-treatment plants in road tunnels are operated worldwide, particularly in Japan (roughly 40-50 plants) and Norway (about 10 plants). Extensive investigations were carried out in Australia (particularly M5 East in Sydney and CityLink in Melbourne) but none was realized yet. Other countries have only sporadically adopted filtration technologies, e.g. Vietnam and Korea. No exhaust-treatment plant for road tunnel is in operation or is currently planned in Switzerland.

The number of installation worldwide is still very limited. Even in Japan only 40-50 tunnels out of a total of 8'000, are equipped with air-treatment facilities. The worldwide diffusion of exhaust-treatment technologies in road tunnels was recently estimated by A. Dix [13] as follows: "Of the many thousands of tunnels in the world only a small proportion (estimated at <1%) have vertical air dispersion (stacks) and only <0.01% (as estimated) have contaminant removal technologies to extract pollution from the ventilated tunnel air."

A very significant new achievement is related to Madrid's M-30 ("Calle 30"). With daily traffic volumes of the order of 100'000 to 250'000 vehicles, this artery leads through very densely inhabited areas and is particularly important and delicate for an agglomeration with about 5 million citizens. Over 20 exhaust treatment stations from of at least three different makers are being installed and put into operation. All of the plants have particle filtration and several of them include an additional DeNOx stage. Particularly interesting is also the quite wide spectrum of plant sizes represented, ranging from 60 m^3/s (about the smallest flow rate of practical interest in road tunnels) up to 570 m^3/s (an high flow rate, expected to be sufficient for most tunnels worldwide). First results are scattered and do not yet allow for a conclusive assessment on the different technologies.

4.2 Japan

Japan was the pioneer in the application of exhaust-treatment technologies. Among others one shall mention Tsaruga (2.1 km, 1979), the first tunnel worldwide equipped with filters, and Kan'etsu (11 km), equipped with a complex ventilation system based on the use of ventilation stacks and bypass filtrations stations. About 40-50 road tunnels (out of roughly 8'000, with a global length of 2'500 km) are equipped with exhaust-treatment systems. An overview is provided in [12].

The main issues addressed by Japanese plants are related to visibility within the tunnels, because of the combination of a high fraction of Diesel-powered cars and a very high HGV percentage. Most plants are based on wet or dry ESP installed in bypasses. In 14 cases cloth filter have been used, but they are now being abandoned because of inadequate performance (filtration efficiency of the order of only 20%) [7][12].

In 2004 only 7 plants were equipped with facilities for treating the exhaust before injection into the atmosphere [12]. No measurement campaign for monitoring the environmental effectiveness of such installations is known [12]. It is interesting to note that the use of the exhaust-treatment equipments, based on momentary needs, is very limited for several tunnels [13][12]. DeNOx plants are much less widespread: only 2 plants in Tokyo are known, the Central Loop Shinjuku Line and the Itabashi-Aioi Overpass.

4.3 Norway

In 2001 160 of the roughly 700 tunnels in Norway (total length about 650 km) were equipped with a mechanical ventilation system, 8 of them had ESP for particle filtration and only one had facilities for treating gaseous pollutants [10][11]. As in Japan, the main reason for such plants is mostly air quality within the tunnel. A Norwegian peculiarity is the high dust concentration related to the use of spiked tires and of large amounts of sand and salt in wintertime.

The use of the exhaust-treatment facilities is very limited [7][10]. The Laerdal plant was practically never used after commissioning because of low traffic volumes. Several problems have been reported in the past, among them lower efficiency than expected and high exploitation costs [7].

5 STATE-OF-THE-ART IN EXHAUST TREATMENT IN ROAD TUNNELS

From a technological point of view the main findings and conclusion from our investigation are as follows:

- Filtration by means of electrostatic precipitators allows for an effective extraction of particle from the tunnel exhaust. This technology is mature and sufficiently well proven for road tunnel applications. Several serious and reliable suppliers with adequate references operate on the market. Technological and economic risks related to this technology are very limited.
- The treatment of gaseous pollutants based on the use of active carbons constitutes a much less proven technology for road-tunnel applications. There are as now not many full-scale applications in road tunnels and the available operating experience is totally inadequate. The main uncertainties are related to durability and exploitation costs. Technological and economic risks are therefore still considerable.
- Other technologies for the treatment of gaseous pollutants, based among others on biofilter, are not sufficiently proven. These technologies were mostly tested in laboratory or in pilot plants, among others in Hamburg's Elbe tunnel. The results are not conclusive enough for justifying full-scale applications in road tunnels.
- Promising work on the field of catalytic coatings is in progress. No reliable results are available yet.

Several exhaust-treatment plants have been installed in the past, particularly in Japan and in Norway. Important new returns of experience are expected from Madrid's M-30. The present investigation led to the following conclusions:

- The dominant approach to environmental problems in road tunnels is dilution: exhaust is extracted from the tunnel by means of ventilation stations and ejected into the environment through 10-20 m high exhaust stacks.
- Exhaust treatment in road tunnels is in the whole very rare. The overall number of plants installed worldwide is probably of the order of 100. Most of them are

bypass installation pursuing the main goal of improving visibility conditions in the tunnel.

- Only a limited number of plants pursue the goal of reducing immission levels from tunnels are known. The experience shows that several plants are used only in a very limited manner, because of a combination of several causes, including scarce need, energy costs and technical problems.

6 COSTS AND BENEFITS OF EXHAUST TREATMENT FOR THE TUNNEL LUGANO

6.1 Limitations

The evaluation of costs and benefits is clearly based on the particular situation of the tunnel Lugano. Several conclusions are nevertheless equally applicable to similar tunnels, where the tunnel exhaust in normal operating conditions is expelled through a stack. For longitudinally ventilated tunnels the costs reported will significantly increase because of the need of an additional ventilation station.

6.2 Benefits

Pollutant dispersion through the stack is very effective. The pollution-dispersion simulations carried out within this project showed that the expected additional immissions arising from the stack (yearly average) are of the order of 0.15 $\mu g/m^3$ for NO_2 and 0.005 $\mu g/m^3$ for PM10. The corresponding legal limits in Switzerland are 30 $\mu g/m^3$ for NO_2 and 20 $\mu g/m^3$ for PM10. The preexisting load is in the range of 25 $\mu g/m^3$ for NO_2 and 28 $\mu g/m^3$ for PM10. The influence of the stack is therefore expected to be in the range of the experimental accuracy and to be entirely irrelevant from a practical point of view. This aspect is treated in [1].

It can be estimated that the amount of PM10 expelled through the stack, about 200 kg/year, could be reduced by about 180 kg/year. This corresponds to only 0.1% of the whole amount of PM10 produced in the Lugano agglomeration. It should also be noted that roughly 70% of the PM10 are not homemade but are "imported" through atmospheric motions [1][2]. The potential benefits are therefore very limited even for the well-proven filtration technologies.

The expected environmental benefits are further reduced if the emissions related to realization and operation of the plants are accounted for.

6.3 Costs

The equipment's cost is estimated based on the experience resulting from recently installed plants abroad, particularly Cesena (Italy) and Madrid (M-30, Spain), as well as supplier's data. Other costs are evaluated based on specific data for ground acquisition, engineering, adaptation of existing equipments and uncertainty.

Total investment costs range roughly from 6.1 (particles filtration only) to 9.3 Million CHF (particle filtration and DeNOx). They correspond to about 20-30% of the cost of all tunnel's equipment and 2-4% of the whole tunnel's cost.

It can be estimated, based on these figures, that PM10 removal costs about 4’700 CHF/kg. The costs of individual measures on the motor vehicles (on board particle filters) are of the order of 78 CHF/kg, less than 2% of the previous figure.

	Particles	DeNOx
Specific equipment	3.6	5.3
Civil works	1.2	1.9
Other costs	1.3	2.1
Total (before taxes)	**6.1 MCHF**	**9.3 MCHF**

Tab. 6.1: Estimates of investment costs for particle filtration and NOx treatment. All values in Million Swiss Francs (1 CHF ≈ 0.6 € ≈ 0.9 US$).

6.4 Discussion

The analysis showed that the technology for particle removal with ESP is readily available and mature for tunnel applications. Its costs are not very high in comparison to the overall tunnel costs. On the other side the benefits are, in the particular case of the tunnel Lugano, very limited. Individual measures on the motor vehicles are much less expensive and far more effective.

7 CONCLUSIONS

Technological and design-related issues of exhaust-treatment technologies were investigated in order to assess the state-of-the-art and the applicability for the tunnel Lugano. Most of the conclusions can be applied to other new tunnel projects.

The main findings and conclusion from our analysis were as follows:

- Filtration by means of electrostatic precipitators allows for an effective extraction of particle from the tunnel exhaust with an efficiency of the order of 80-90% (based on total mass of suspended particles). This technology is mature and sufficiently well proven for road tunnel applications. Technical and economic risks are very limited.
- The treatment of gaseous pollutants is based on much less proven technologies. Particularly the issues related to the practical applicability in tunnel environments, exploitation costs and durability are not yet entirely solved.

The investigation carried out for the tunnel Lugano led to the conclusion that exhaust treatment technologies for particles, based on electrostatic precipitators, are practically feasible. All available technologies for the treatment of the gaseous components are not sufficiently mature. Technical and economic risks are still considerable.

For the particular case of the tunnel Lugano the evaluation of costs and benefits led to the conclusion that filtration is not required, since pollutant dispersion through the stack is very effective under all circumstances. It was therefore decided to monitor carefully the environmental situation before and after tunnel operation. Depending on the results from the first years of operation it will be decided if an upgrade of the ventilation system with a state-of-the-art exhaust-treatment system is necessary. Ventilation design is being adapted in order to leave this path open.

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