Ventilation and Exhaust Purification of Motor Vehicle Tunnels in Japan

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ABSTRACT:

Japan is a mountainous country with an extensive road network. Japan was the first country in the world to use tunnel electrostatic precipitators ('ESPs') to remove suspended particle matter ('SPM') from tunnel air to maintain tunnel visibility.

Over the last 30 years the use of ESPs in Japanese road tunnels has become more common. Over the last decade there has been increased use of ESPs in urban tunnels to remove SPM for external air quality purposes. The use of ESPs in tunnels for external environmental purposes has allowed ESPs to be installed in tunnel ventilation buildings. Over the last few years efficiencies in SPM removal have also allowed the development of technology to remove nitrogen dioxide (NO_2) by a range of NO_2 removal technologies.

This paper explores the history of the ventilation and exhaust treatments for road tunnels in Japan and explores why ESPs and/or denitrification systems are introduced into tunnels in Japan. Relevant standards and specifications are also referred to.

Keywords: Tunnel exhaust, SPM, NOx, NO_2, Purification

1. INTRODUCTION

Following the destruction of Japan's road network during the 2nd World War, expressway companies were established to construct and maintain roads independently at the Ministry of Land, Infrastructure, Transport and Tourism ("MLIT").

The main priorities for these companies included constructing two long expressways as main arteries for the national road network by Nippon Expressway Company ("NEXCO"). The first expressway was the Meishin Expressway between Nagoya and Kobe and the second was the Tomei Expressway between Tokyo and Nagoya as detailed below:

a) The Meishin Expressway; Partial opening in 1963 and full opening in 1965.
b) The Tomei Expresssway; Partial opening in 1968 and full opening in 1969.

After completion of the two basic expressways, NEXCO began to extend their road expressway network throughout Japan, creating expressways such as the Hokuriku Expressway, the Sanyo Expressway and the Kyushu Expressway.

In 1959 the MEC (Metropolitan Expressway Company) was established for the Tokyo region. In 1962 the HEC (Hanshin Expressway Company) was established in Osaka to develop the expressway network. The purpose of both the MEC and HEC was to relieve traffic jams and to increase transportation capacity on the road network.

2. NEXCO's EXPRESSWAY TUNNELS

Japan is very mountainous. All NEXCO Expressways necessarily required the construction of long mountain tunnels.

In the 1960's NEXCO's expressway tunnels were constructed with limited budgets through difficult geological conditions.

In most instances either simple longitudinal ventilation or simple longitudinal ventilation with intermediate fresh air and exhaust shafts were used. These designs were chosen because they required the minimum cross section area of tunnels and were able to meet NEXCO's in-tunnel air specifications.[1)]

Fig. 1 Typical expressway with mountain tunnels.

During the 1960's in Japan there was rapid and unexpected economic growth. This resulted in greater traffic volumes than had been expected. By the late 1960's residents near the Ten-nozan tunnel in the Meishin Expressway and the Nihonsaka Tunnel in the Tomei Expressway were sensitive to air quality.

a) Community concern in the late 1960's focused on the impact of human health at the Ten-nozan Tunnel while the concern at the Nihonsaka Tunel focused on crop damages caused by black soot. (Especially oranges and/or green tea trees)

b) In 1994 Panasonic installed the world's first ESP for purifying tunnel air in the Ten-nozan Tunnel.[2)]
c) In 2000 Fuji Electric Company installed EPSs for removing soot at the Nihonsaka Tunnel.

3. JAPANESE TUNNEL VENTILATION EXPRESSWAY STANDARDS

In 1964 NEXCO produced *'The Manual for Designing Car Road Tunnel Ventilation'*. This document might be the first standard for tunnel ventilation in Japan.

Although this document was large (around 400 pages) it is apparent that the main issue was sufficient volume of ventilation air, VI (visibility index) and CO (carbon monoxide) concentrations in the tunnels.

In 1975 the Japan Road Association (an extra governmental organisation of MLIT) published '*The Road Tunnel Manual'* which included the tunnel ventilation standards for all roads including non-expressways. This was the first official publication on tunnel ventilation in Japan.

The 1975 manual focused upon the following aspects of tunnel design:

a) Geometry
b) Design
c) Construction
d) Ventilation
e) Lighting
f) Emergency Facilities
g) Maintenance and repair

The following parameters were considered with the 1975 standard:

a) CO concentration; (100ppm or less)
b) Visibility Index 50% or more for the first and second class roads. 40% or more for the third and fourth class roads.
c) How to calculate ventilation air volume
d) How to model the dispersion on tunnel exhaust including calculation of effective heights of stacks, exit velocities, stack optimisation and ground level calculation.

It is not surprising that in 1975 there was no mention of ESPs in the manual as the technology had not yet been proven.

4. TRIALS OF ESPs – 1975

In 1975 NEXCO and its associated companies began field testing and development of ESPs at the Tsuburano Tunnel.[3)]

Early ESP trials focused upon improving VI (visibility) values. In long tunnels this meant the construction of short bypass tunnels in which ESPs could be installed.

The use of ESPs in bypass tunnels allowed visibility to be improved within tunnels without the need for an external ventilation point part way through the tunnel. The first ESP plant was installed at Tsuruga Tunnel in 1980. In 1980 there was no Japanese standard for ESPs. Designs were determined on the basis of the specific needs of a project. Approval was based upon the successful liaison between the client and the ESP manufacturers.

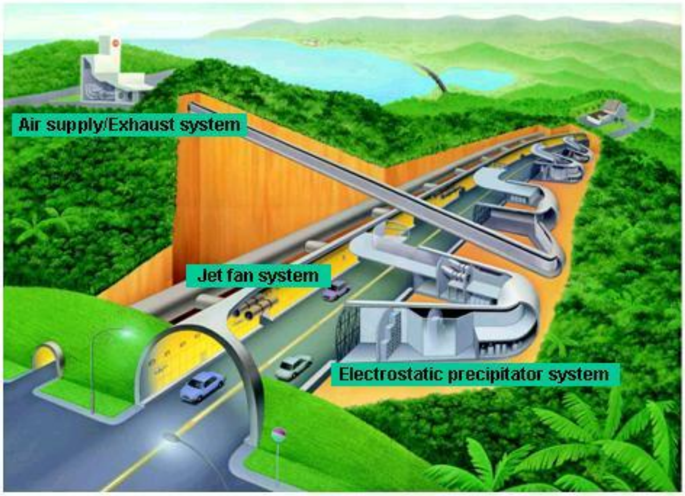

Fig2. Longitudinal ventilation with 3 ESP stations and a shaft

In 1987 a tunnel ESP standard was specified in Japan by NEXCO. This 'standard specification for tunnel ESP system' formed part of the official documents of the 'Common Specifications of Mechanical, Electrical and Communication', Version 1987 by NEXCO.

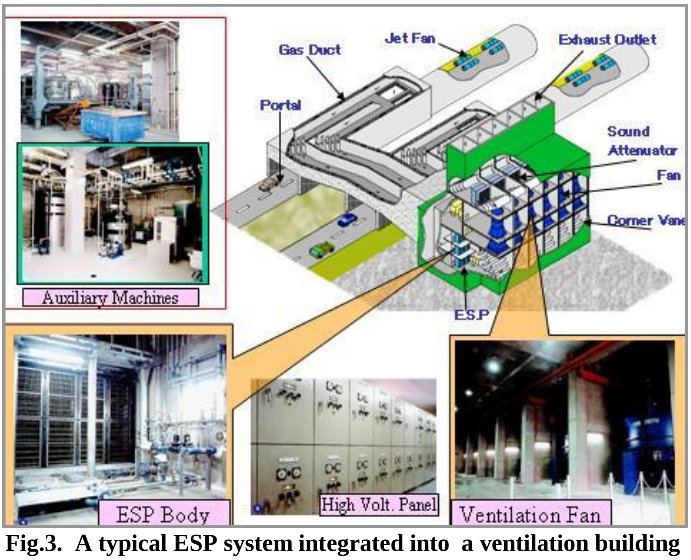

Fig.3. A typical ESP system integrated into a ventilation building

Under the NEXCO standard, the required performance of ESP systems was specified as 80% soot collection at 7 m/sec.

The 1987 NEXCO specification was designed to ensure sight improvement distances (VI) within tunnels but not for purifying tunnel air to the atmosphere to achieve environmental outcomes.

In 1994 the world's first ESP system for purifying tunnel air exhausts was installed in the Ten-nozan Tunnel. There was no specification for the environmental performance of ESPs in the Ten-nozan tunnel and accordingly the same specifications for achieving visibility improvement were used.

The 1987 NEXCO standard was revised in 1996 and 2006. A summary of these revisions appears in Table 1.

Table 1: Specification revisions of tunnel ESP systems

Specification	**First edition (1987)**	**Revision 1 (1996)**	**Revision 2 (2006)**
Processing velocity [m/s]	7	9	9
Polarity	Positive	Negative	Positive or Negative
Discharge pole	Wire	Wire	Spike
Soot Collection [%]	80	80	90
Power consumption per unit flow [W/(m3/s)]	Approx. 35	55	110
Method of cleaning ESP	Air blow	Water spray	Water spray

Following the introduction of ESPs for environmental improvement in the Ten-nozan tunnel in 1994 there were a series projects in Japan where ESPs were installed in the exhaust section of the tunnel ventilation system[5)]. Examples include:

a) 1997: Shimoneseki ventilation station in Kanman tunnel.
b) 1998: Ten-nozan west ventilation station
c) 1999: Moji ventilation station in Kanmon tunnel
d) 2000: Nihonsaka ventilation station

Installation of the ESPs for SPM removal for the above tunnels was in accordance with the NEXCO specifications. In no instance was the effect on ground level concentrations used as the basis of the specifications of the ESPs. The bassis for using the technologies is that the SPM removal occurred, not that SPM removal resulted in a change to ground level concentrations.

5. CONSTRUCTION OF METROPOLITAN EXPRESSWAYS

The first metropolitan expressway was partially opened in Tokyo in 1962. There was, and remains, an emphasis on creating radial ring roads. Even today road networks in the MEC area are still under construction with the objective of creating further outer ring roads.

In Osaka the first opening of a partial expressway was in 1964. The Osaka road system is on a growing radial network.

Fig 4. A traffic jam in around 1960

Fig 5. Highway construction in early stage in Tokyo

The use of expressway tunnels became more common in the 1990s. Typically major urban road tunnels used transverse or semi transverse ventilation systems. Generally such systems do not require air to be purified because of the continual fresh air being supplied by a transverse or semi transverse ventilation system. However in areas outside the tunnel ventilation stacks, community concerns about the effects of exhausted air were being raised.

These concerns were also applied to both longitudinally ventilated tunnels and those with ventilation stations.

In 2002 the MEC constructed its first urban tunnel with ESP systems for purifying tunnel exhaust to the atmosphere. The following projects used ESPs for external air quality management[5)]:

a) 2002; Asukayama Ventilation Station (MEC)
b) 2003; Midoribashi Ventilation Station (Nagoya Expressway)
c) 2006; Kitamachi Ventilation Station (Tokyo Metropolis)
d) 2008; Jujo&Yamashina Ventilation Station (HEC)
e) 2009; Yumeshima Ventilation Station (MLIT)

Fig 6. Ventilation station in metropolitan area

Fig 7. ESPs in a ventilation station

The performance of each of these installations was assessed on a project by project basis. The impact of installation and use of the ESP technology on ground level concentrations was not calculated. It is not expected that this will occur in the future.

It is expected that increased concerns about the effects of NO_2 by the community will promote the further development and use of NO_2 removal technologies this century.

6. DENITRIFICATION SYSTEMS

In recent years there has been increased concern about the health effects of NO_2 from tunnel exhaust.

6.1 1970s to 1980s

In the 1970s and 1980s Japan experienced significant issues with photochemical smog. Concern was widespread and there were significant issues with acid rain. There existed a demand that NOx (nitrogen oxides) should be removed from tunnel exhausts as part of a broader campaign to better manage photochemical smog and acid rain in urban areas.

6.2 1990 – Denitrification Committee

In 1990 MLIT convened a committee, "The Committee for Surveying NOx Decrease in Metropolitan Area", to develop denitrification systems capable of removing 80% or more of NOx from tunnel air.

6.3 1991 to 1992

The MLIT entered into arrangements with six private companies to develop NOx removal technologies. These companies tested their equipment at the Ohi ventilation sites in MEC. The six Japanese companies were:

a) Panasonic

b) Kawasaki Heavy Industries (KHI)
c) Mitsubishi Heavy Industries (MHI)
d) Ebara Corporation
e) Hitachi Zosen Corporation
f) KOBELCO

Each company used a different technique to remove the NOx. Each company achieved 80% efficiency or better NOx removal.

Figure 8. Field test facilities of Panasonic

6.4 1995

In 1995 MLIT announced a tender for a low concentration denitrification test plant that attained an 80% of NOx removal at 44 m^3/s of gas flow.[4)] The successful bidder was Kobelco.

6.5 NOx Removal - 1997 to 1999

Following the successful operatons of the Kobelco test plant with 80% NOx removal efficiency, MLIT announced that the field trial was a success.

6.6 NOx Removal 1997

In 1997 the committee investigating how to decrease the NOx levels in the metropolitan area confronted a series of issues.

a) The committee concluded that it was technically possible to construct full scale plants for NOx removal.
b) The cost for constructing these full scale plants in both initial capital cost and ongoing expenses was grossly disproportional to the environmental benefit achieved.
c) The environmental standards of Japan did not (and do not) specify NOx limits. NO_2 limits are set in a zone between 0.04ppm and 0.06ppm. The committee decided that NO_2 is more harmful to the human body than NO as the ACGIH regulation value in the USA for NO was 25ppm or less.

d) It was considered that if the committee concentrated only on the NO_2 removal the cost might be more realistic, however it was unclear what the removal specification should be.

Technically this issue is complex because of factors including oxidation rates of NO within the tunnel, the effect of ozone on oxidation rates produced by the EPs and the external oxidation of NO.

The committee undertook a technical comparison removal NO_2 compared with NOx removal. The analysis included:

a) Modelling of diffusion from a hypothetical exhaust stack at a hypothetical tunnel ventilation station.
b) Modelling of the impact on inhabitants in an area around hypothetical ventilation station in order to evaluate the effect of NOx concentrations with the use of such technologies.
c) The ratio of NO to NO_2 used at the inlet of the air purification system was 90% NO and 10% NO_2.
d) For NOx removal the purification ratios were 80% of NOx and 80% of NO_2. The impact of these purification ratios was modeled for both NOx and NO_2 concentrations at ground level.
e) For NO_2 removal, a range of removal values were applied as part of a simulation for likely ground level concentrations.
f) As a result of the simulations it was established that the performance of a 90% removal of NO_2 was comparable with an 80% removal of NOx (NO and NO_2).[4)] The results of the simulation case study concluded that less emphasis should be placed on NO removal.
g) It was determined that the most efficient method of ensuring the protection of health was to focus on NO_2 removal. NO_2 removal required approximately half the size plant to a NOx removal plant, the energy consumption was approximately 1/5 and the cost was approximately ½. Importantly, the ongoing operational cost with a focus on NO_2 removal were found to be 1/5 the cost of the projected NOx removal alternative.

As a result of these investigations MLIT concluded that:

a) NOx denitrification for tunnels in Japan should be abandoned.
b) The purpose of tunnel denitrification is limited to the impact upon the area proximate to the tunnel ventilation stacks and should not be calculated in terms of its effect on the total urban area.
c) The most prudent form of denitrification was NO_2 denitrification for tunnels.

6.7 2000

In 2000 MLIT announced two tenders for the tunnel denitrification test plants. The new specifications were 90% removal of NO_2 at 22 m^3/s of gas flow. This project was known as Tokyo Pilot Plants 'P2'.

6.8 2001

In 2001 two successful bidders were announced being Panasonic with NO_2 absorption technology and KHI with NO_2 adsorption technology[4)]. The two types of NO_2 denitrification were then evaluated.

Figure 9. Tokyo pilot plant P2 of Panasonic

6.9 2002 to 2003

Testing of both the NO_2 absorption and NO_2 adsorption plants was undertaken.

6.10 March 2004

MLIT announced that the 'Tokyo Pilot Plants have been successfully finished with preferable results'.

6.11 2004

MEC announced two tenders for the NO_2 denitrification plants of the Shinjuku Line tunnel in the Central Circular Route. The first tender was with a gas flow of 1672 m^3/s and the second with 1837 m^3/s.[2) 4)] The NO_2 removal ratio of 90% was the same on both tenders. The successful bidders were Panasonic in the first work section and Nishimatsu with adsorption in the second work section.

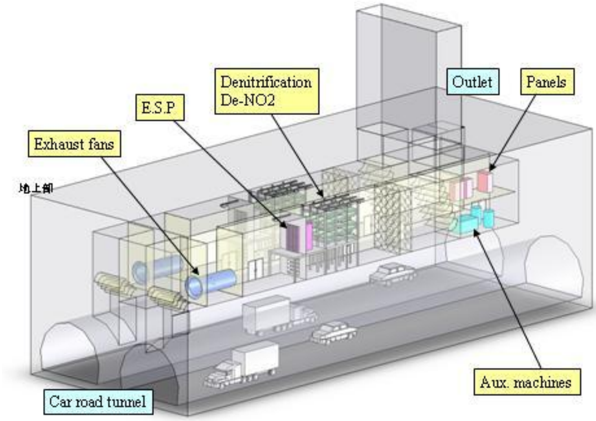

Figure 10. Underground ventilation station with denitrification

6.12 December 2007

The first work section with four ventilation stations were constructed by Panasonic and opened and put into daily operation of between 3 and 17 hours per day depending upon the operational hours of the ventilation ducts. The remaining five ventilation stations by Nishimatsu were opened in March 2010.

6.13 2009

In 2009 NEXCO announced a tender for a NO_2 denitrification plant in the Shintomei expressway. The specifications to be achieved are 180 m^3/s gas flow with 90% NO_2 removal.

In July 2009 Panasonic was successful in that bid. This project will be completed in 2011.

Figure 11. Exhaust stacks of the Central Circular Route

7. CONCLUSIONS

Originally electrostatic precipitators were used to ensure in-tunnel visibility. Subsequently they have been used in conjunction with NO_2 denitrification equipment in urban road tunnels where local NO_2 levels are an issue, to remove particles to assist with meeting external air quality objectives. The electrostatic precipitators also protect the NO_2 removal process from particles.

As at the time of authorship of this article the position in Japan is as follows:

a) The performance of ESPs and NO_2 removal equipment is described by the efficiency of the removal of suspended particles and NO_2 for a given volume of air.
b) There has been no project in Japan where the effect on ground level concentrations of either NO_2 removal or soot removal has been used to develop the specifications of the air cleaning technology.
c) The availability of denitrification technology in Japan does not of itself mean that denitrification is used on every project. For example the Jujo and

Yamashina ventilation stations of 2008 in HEC do not require denitrification despite the fact that they postdate the NO_2 denitrification plants in the Central Circular Route 2007 in MEC.

d) The use of ESPs and/or denitrification equipment is not mandated for Japanese tunnels and decisions to use ESPs or ESPs with denitrification appear to be made on the basis of local factors.

e) Where air purification is specified under new tunnel construction plans such technology is usually adopted.

f) Typically a decision about air purification and the type of technology which is used is determined by the politics of a tunnel and the dialogue between local citizens, politicians, and tunnel owners.

g) There is no official standard on emissions from tunnel exhaust stacks.

h) It is not anticipated that there will be a policy on exhaust emissions from ventilation stacks.

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