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# TUNNEL VENTILATION IN ROAD TUNNELS

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**Abstract:** Road tunnel ventilation systems serve to limit the concentration of air pollutants during normal tunnel operation and to transport smoke gases out of the tunnel during self- and assisted rescue in case of fire. Depending on the tunnel length, the traffic load and type, as well as the likelihood of traffic jams, different ventilation systems, such as longitudinal, semi- or fully transverse ventilation systems, are used. A combination of these systems is sometimes required. Ventilation is the defining issue for many tunnels and the safety and comfort of the people who use them, especially during extreme events such as fire. Wrongly conceived, it can lead to excessive demands on tunnel size and cost, and even undermine the feasibility of a project. One should always, specialize in simple, practical and sustainable solutions to tunnel ventilation and wherever possible, to harness natural ventilation. A tunnel's length and function obviously affect the viability of this, but by minimizing mechanical plant, we save both excavation and operating costs, creating less energy-intensive, more sustainable alternatives.

**Keywords:** Tunnel Ventilation, air pollutants, smoke, gases, longitudinal & transverse ventilation system

## I. INTRODUCTION

Tunnel is an artificially constructed underground passage to bye-pass obstacles safely without disturbing the over burden. Tunnels are created by the process of excavation. Tunneling is desirable when rapid transport facilities are required which need to avoid acquisition of land for roads. Tunnels are also erected when shortest route connection is needed in cities. Tunnels permit easy gradient & encourage high speed on strategic routes. India has some of the most difficult mountain terrains in the world therefore India chose to construct tunnels and by economizing the cost of construction of tunnel with minimum construction period without compromising safety is need of the hour. Without compromising with safety, we need to reduce the capital cost of construction of tunnels by using successful practices, which are already available in the world.

## II. TUNNEL VENTILATION

**Concepts:** Ventilation in tunnels has two functions:

i. In normal operation, it ensures sufficient air quality in the tunnel, generally by diluting pollutants;
ii. In a fire situation, it should make the environment as safe as possible for the tunnel users and rescue services by controlling the flow of smoke in an appropriate way.

The first reason for installing ventilation systems in tunnels was the reduction of pollution levels. The primary sources of pollutants are the emission from the vehicular engine exhaust and non-emission pollutants generated from vehicles moving inside the tunnels.

Although the emissions of pollutants by road vehicles have decreased dramatically over the last decades, this function is still important and must be paid close attention at the design stage. In some cases, natural ventilation due to the piston effect of moving vehicles may be sufficient to fulfill the air quality requirements in normal operation.

The need for a mechanical ventilation system is assessed considering, among other factors, the length of the tunnel, traffic type (bidirectional or unidirectional) and conditions (possibility of congestion) and type of vehicles.

  

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The same factors determine the requirements for ventilation in emergency situations, especially fire. The presence of other equipment or facilities (emergency exits for example), should also be taken into account. Natural ventilation might be sufficient in some cases, but mechanical ventilation is often required for tunnels over a few hundred meters in length. In addition to these major aspects, environmental issues linked to ventilation, issues relating to energy consumption and the related carbon footprint need to be considered. Those are linked to the localized, concentrated discharge of polluted air from the portals and stacks. Reducing their impact on the tunnel surroundings is part of good environmental design.

### A. Requirement of Ventilation and Fire Fighting Systems in Tunnels

A ventilation system is designed based on requirements during the following three ventilation scenarios: -

i) Consideration of ventilation during tunnel construction to provide the external air required to dilute the pollutants produced by the machines used during the different stages of the construction to allow a safe environment for the tunnel construction crew.
ii) Ventilation during normal operation of the tunnel.
iii) Consideration of a fire case inside the tunnel. While the fire case is often the dominating factor for highway and non-urban tunnels, in tunnels with a high traffic load and frequent congested traffic, the fresh air requirement for normal operation can be dominant. Ventilation systems should aim to provide minimum air requirement that is required to ensure adequate in-tunnel air quality and visibility thresholds.

### B. Ventilation Principles:

An understanding of how smoke behaves during a tunnel fire is essential for every aspect of tunnel design and operation. This understanding will influence the type and sizing of ventilation system to be installed, its operation in an emergency and the response procedures that will be developed to allow operators and emergency services to safely manage the incident. This section presents details of the general behavior of smoke and the major influences that affect its propagation in a tunnel.

In the absence of any other influences, smoke will be dominated by its buoyant properties and will rise to the tunnel roof or ceiling, and then propagate along the tunnel away from the fire in a stratified layer (see Figure 1.1). The velocity of propagation will be influenced to some extent by the fire size, but in a serious fire will be of the order of 2 m/s. As the smoke propagates along the tunnel roof, it transfers heat to the ceiling, walls and surrounding air. As this occurs, the cooler smoke layer becomes deeper. This idealized behavior is unlikely to occur in an actual tunnel since traffic movement, ventilation and/or meteorological effects create longitudinal air velocities.

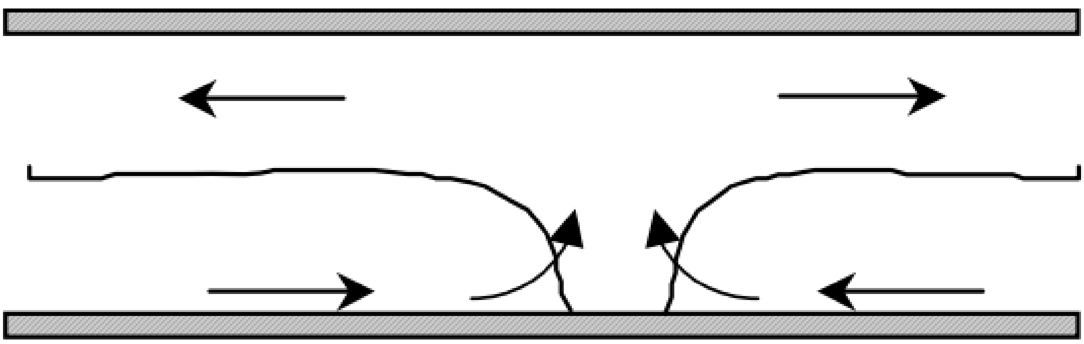

**Figure 1.1 - Smoke progress in a flat tunnel with no air velocity in the fire zone**

Influence of Longitudinal Air Velocity It is generally accepted that backlayering upstream of the fire appears when the longitudinal velocity is less than a value called the 'critical velocity' [4; 5]. On the other hand, the conditions needed to maintain the stratification of a smoke layer downstream of a fire are poorly understood.

If the longitudinal air velocity in the tunnel is low (say)

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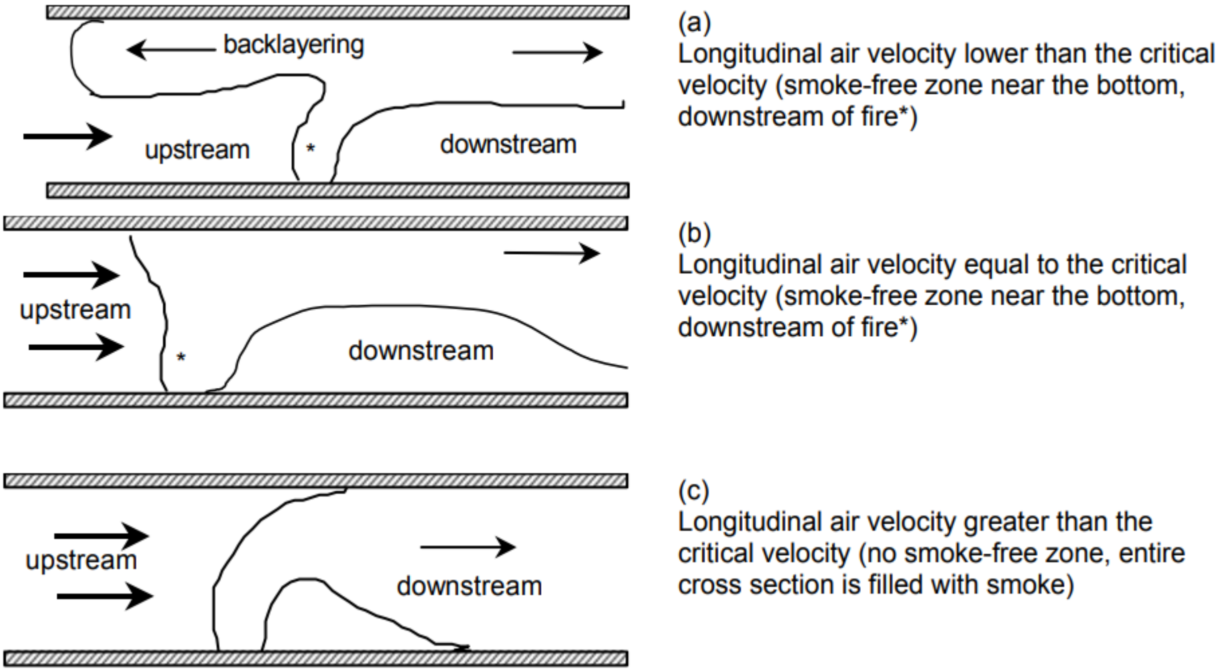


**Figure 1.2 - Influence of longitudinal air velocity on smoke progress in the fire zone**

If the longitudinal air velocity in the tunnel is low (say <1m/s) before the fire starts, then the smoke will propagate in a manner similar to that shown in Figure 1.2a. This has two important advantages:

• There is a smoke-free zone under the stratified smoke layer, allowing the tunnel user to escape;
• Smoke propagation is slow, so tunnel users have more time to escape.

Similar to the idealized behavior shown in Figure 1.1, the smoke progresses in a nearly symmetrical way on either side of the fire. It remains stratified until it cools down due to the combined effects of the convective heat exchange with the walls and the mixing between the smoke and the fresh air layers.

If the longitudinal air velocity is lower than the critical velocity, the smoke progresses upstream of the fire. In this case, and under the restriction that no aerodynamic perturbation occurs (for instance, that caused by the start-up of a jet fan within the smoke zone), the smoke layer upstream of the fire remains stratified.

For air velocities lower than or equal to the critical velocity, the smoke can, depending on the fire heat release rate, remain stratified downstream of the fire (see Figures 1.2b and 1.2c). If the longitudinal air velocity is greater than the critical velocity, the risk of de-stratification downstream of the fire is increased (see Figure 1.2c). The "de-stratification velocity" above which the smoke downstream of a fire will de-stratify is difficult to define. In contrast to the back layering upstream of the fire, the stratification downstream of the fire is more complex due to the more turbulent nature of the flow, and thus the enhanced mixing between the smoke layer and the fresh air layer. Research work is still required to better understand the conditions that will maintain smoke stratification for various velocities and to gain knowledge of the relationships between fire size, air velocity, air temperature and smoke stratification.

### C. Types of Ventilation Systems

Many different types of ventilation systems can be identified in road tunnels including, among others, the following:
- Natural ventilation; which can be induced by the air temperature and meteorological conditions and/or by traffic;
- Mechanical ventilation, which can be
  - longitudinal,
  - fully transverse,
  - semi-transverse (and reversible semi-transverse),

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(Combinations of the above systems are possible and, in some cases, unavoidable):

- Air cleaning combined with mechanical ventilation.
- Criteria and methodologies for the design and dimensioning of tunnel ventilation, which are based on the main basic ventilation principles, applicable to normal operation and fire scenarios.

**Natural ventilation**:

When ventilation can be induced by the air temperature and meteorological conditions or induced by traffic. "Naturally ventilated" tunnels are not equipped with fans for the mechanical control of the airflow in the traffic zone. Some kind of natural ventilation exists in any tunnels and conditions wherein air turnover is always induced by a mix of factors such as atmospheric conditions and traffic. A tunnel may be sufficiently ventilated by wind, by a difference in air pressure between portals, and possibly by some convective or chimney effect.
Factors influencing natural ventilation:

**a)** Difference of Pressure between two portals
**b)** Strong wind outside the tunnel
**c)** Gradient in the tunnel

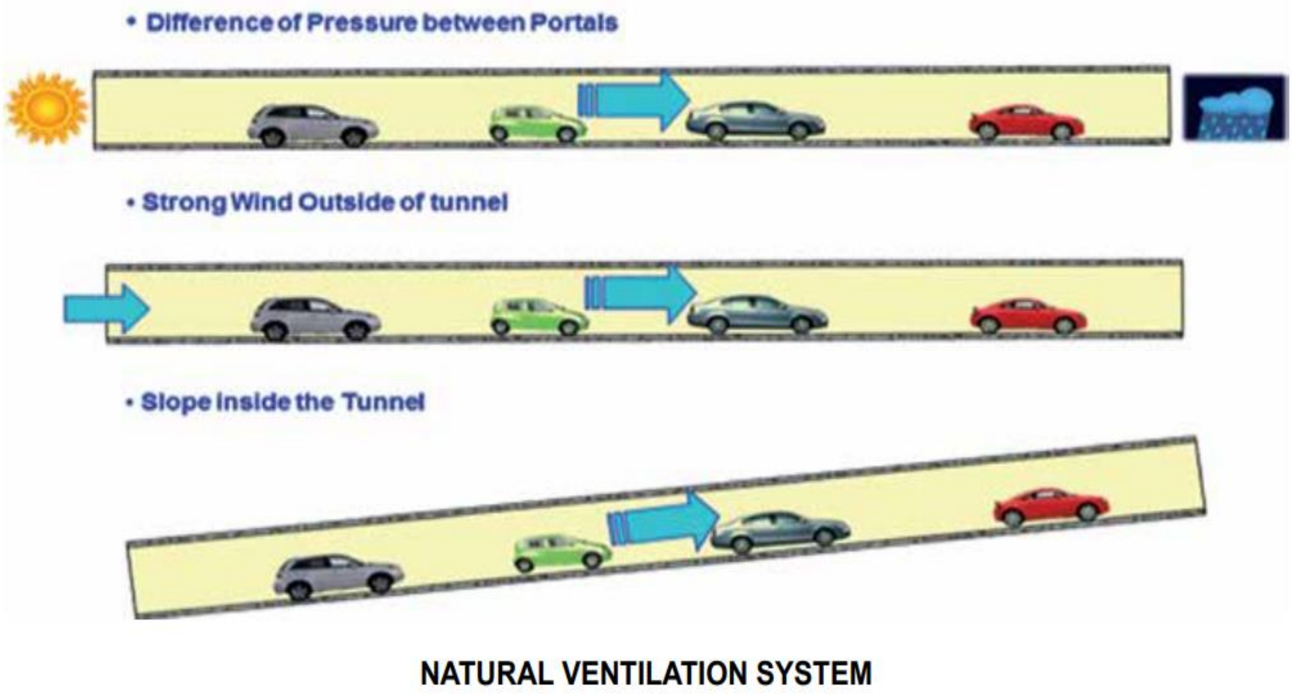


Figure 1.3

## III. MECHANICAL FORCED VENTILATION SYSTEM

**Mechanical ventilation systems use using external dedicated devices**:

fans and other mechanical control devices to ensure suitable air flow inside tunnels. These systems can be: - Longitudinal Ventilation System; Fully transverse Ventilation System; Semi-transverse Ventilation System, which are illustrated as under;

**Longitudinal Ventilation System:**
Longitudinal ventilation system is an easy and cheap way to ventilate road tunnels generally above 500 m to 4000 m in length and light traffic density. A longitudinal ventilation system creates a uniform longitudinal flow of air all along the tunnel. Air enters the tunnel from the portal, practically clean, and gets gradually polluted with substances emitted by vehicles, thus reaching the tunnel exit with a higher percentage of pollution. This system is relatively cheap and easy to install and is particularly suitable for tunnels carrying one-way traffic, where the "piston effect" assists the airflow.

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In tunnels with longitudinal ventilation, the concentration of noxious substances increases in the direction of the airflow and decreases with the fresh air rate. The maximum concentration increases according to the tunnel length. The longitudinal airflow velocity has a practical upper limit; consequently, for a given traffic and slope of the roadway, the tunnel length for which longitudinal ventilation is possible has a maximum limit too. As a first estimate, this upper limit could be evaluated knowing the cross-sectional area of the tunnel and the maximum air velocity (today considered to be about 8 to 10 m/s) which is cost effective and does not disturb vehicles and the staff operating within the tunnel. Moreover, the mechanical power of the ventilation system increases with the third power of the tunnel length in tunnels used bi-directionally. For tunnels that require an overall airflow over the aforementioned threshold, the longitudinal ventilation is still possible, but it has to be supplemented with shafts for massive exchange of exhaust with fresh air. The longitudinal (Jet) fans need to comply with fire rating (250°C - 2 hrs/400 °C – 2 hrs) in accordance with design of the tunnel.

Longitudinal ventilation systems utilize the tunnel tube as the “duct” for smoke extraction. Such systems are seen as providing reliable safety in case of a fire accident for unidirectional tunnel tubes. Although there is a slight possibility that road users can be affected by the smoke being pushed by the fans (for example, if they cannot leave the tunnel downstream of the fire due to a traffic jam), most road users can be expected to be located in the upstream (smoke free) area of the tunnel. In a bi-directional tunnel, on the other hand, a large number of road users may be affected by smoke if only a longitudinal system is used. In such cases, the combination of longitudinal ventilation and smoke extraction via ceiling dampers can be satisfactory under certain conditions. In any case, longitudinal ventilation should be used in bi-directional tunnels only if a risk analysis shows it is acceptable. Considerations in jet fan design include the influence of fire on the jet fan system, the meteorological effects at tunnel portals (mainly wind), the optimal placement of the fans, the efficiency of the fans, and the sound levels created by the fan system.

**Sound Impact of Jet Fans in a Tunnel :**

Jet fans operating in a tunnel can generate high noise levels, and can have adverse effects on speech transmission between people in the tunnel. This may become a safety issue when the noise level prevents the tunnel users from understanding what they are asked to do or when it makes it difficult for the firemen to communicate with each other. Therefore, some care must be taken in the assessment of sound emission by the jet-fans. Among the mechanized ventilation systems, this system is the easiest and cheapest ventilation systems. Longitudinal ventilation is accomplished by using jet fans by accelerating a small pocket of the air present in the tunnel, through an exchange of momentum, are able to induce, on the overall air inside the tunnel, a movement in the desired direction.

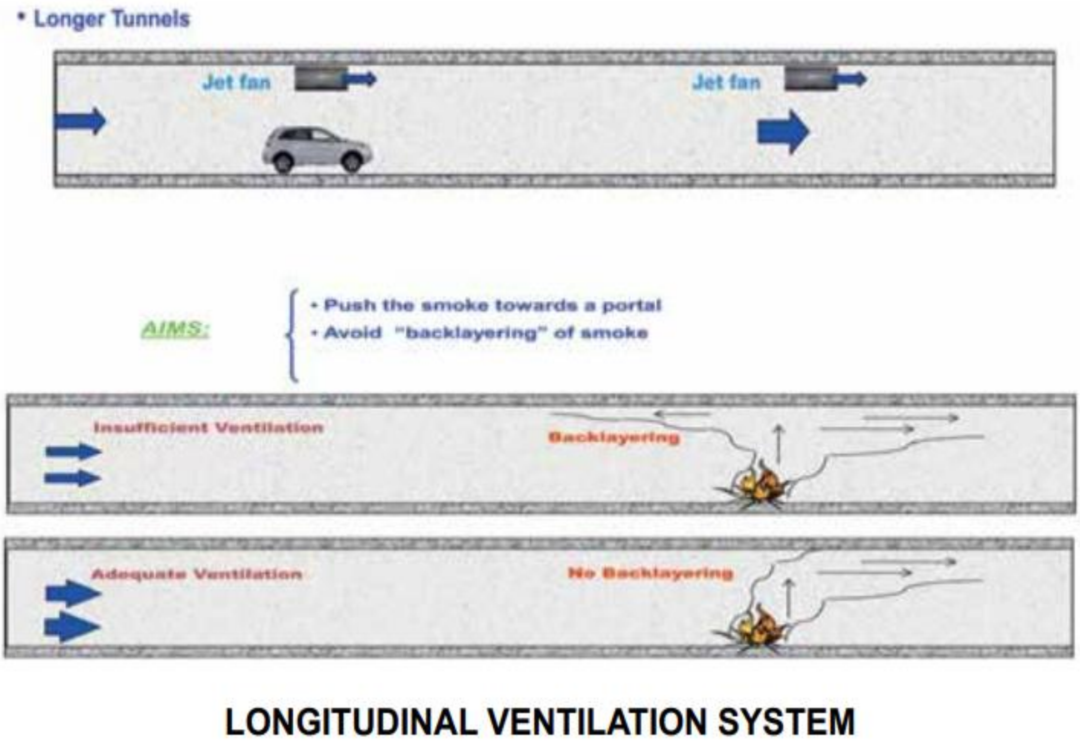


Figure 1.4

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As per RVS 09.02.31, the longitudinal velocity of air inside the tunnel arising due to meteorological conditions and traffic flow should not exceed 10 m/s. Also, to raise the operational safety under the fire effects and minimize turbulence, the fans and ventilators shall be deployed over the length of the tunnel.

**b) Fully transverse ventilation system**

With fully-transverse ventilation system, supply air is introduced, distributed all over the length of the tunnel, and exhaust air is extracted. The air streams (injected fresh air and extracted exhaust air) create a flow in the main tube, in transverse direction to the longitudinal axis of the tunnel. Longitudinal air flow in the tunnel is difficult to control. Hence, the independent ventilation sections are created in which fresh air injection and exhaust air extraction can be operated separately. A butterfly flap is installed between two ventilation sections to separate them.

The aim of transverse ventilation is to protect the tunnel users by keeping the smoke stratified in a hot layer underneath the ceiling of the tunnel and extracting it at the ceiling. Smoke stratification is not a very robust effect; it can easily be disturbed by the longitudinal airflow induced by moving vehicles, pressure differences between portals, ventilation, etc. As a consequence, it is highly advisable to control the longitudinal airflow by means of the tunnel ventilation.
In the following text, the wording “transverse ventilation system” includes both full transverse and semi- (partial) transverse systems. The specific name of the system employed is a function of the presence of fresh air and extraction air ducts and/or the operational imbalance of injected and extracted airflow rates.
Generally, transverse ventilation uses ducts that run parallel to the tunnel. Two kinds of ducts are utilized:

- Fresh air ducts are used to inject fresh air into the tunnel in order to dilute the polluted gases produced by the vehicles;
- Extraction or exhaust ducts are used to extract air from the tunnel volume. The main purpose of extraction is to remove the smoke and hot gases produced by a fire. In some cases, the extraction capacity may be used in order to limit the longitudinal velocity in the tunnel under normal operation.

Extraction capacity is usually concentrated to a zone smaller than the length of the duct by the addition of motorized, remotely controlled dampers, also known as “point extraction”. The fans serving the ducts are often located in ventilation plants close to the tunnel portals or shafts; however, many variations can exist.

Dimensioning Rules Fresh Air requirements
The dimensioning rules for the fresh air fan capacities and ducts are directly linked to the pollution dilution requirements. The pollutants that must usually be controlled are carbon monoxide (CO), and particulate matter that negatively affects visibility. Some countries also control nitrogen oxides (NOx). The fresh air requirement calculations utilize the following parameters:

- The unit emissions of the vehicles (provided by PIARC or national recommendations);
- The traffic density and speed;
- The threshold limits for each pollutant.

Generally, the ventilation sizing is directly related to the calculated airflow requirement. This approach does not take into account the traffic piston effect. In some cases, such as with fast moving traffic, the piston effect can self-ventilate the tunnel.

Smoke control in tunnels with transverse ventilation

To size a transverse ventilation system, two aspects must be considered

- The smoke flow rate
- The requirements to control the longitudinal air flow.

The PIARC report [2] provides a table and the relevant relationship between heat release and smoke flow rates. The control of the longitudinal airflow is as important design criteria as the extraction flow rates and must be carefully studied.

Extraction Duct Equipment

The extraction fans must be sized to ensure the required extraction airflow rates for all fire locations in the tunnel. In the past, extraction ducts were typically connected to the tunnel with a number of small, evenly spaced open vents. The spacing between these vents was typically 10 to 20 m and the airflow rate on the order of 80 m3 /s/km. This concept has since evolved by replacing the small, open vents with larger vents equipped with remotely controlled motorized dampers and spaced further apart.

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The use of thermal fuses and panels has been assessed and found to have adverse effects: the effectiveness of the smoke control system using such thermal devices was found to be compromised by the untimely opening of some dampers and/or the opening of dampers in non-optimal locations.

Requirements for smoke stratification

Most recommendations related to transverse ventilation system operation point out the necessity to preserve the stratification conditions as well as to remove the smoke from the tunnel. Centralized monitoring and control of equipment is required to optimize the ventilation response. The precise location of the fire must be known in order to concentrate the extraction capacity in the fire area by opening the appropriate damper(s) and control the longitudinal airflow in this area in order to keep smoke stratification. The stratification characterization is still under development and subject to research work. The main condition for stratification development appears to be the limitation of longitudinal velocity. Longitudinal velocity tends to:

- Increase the turbulence and mixing effects between smoke layers,
- Increase the thermal exchange between the individual smoke layers and between the smoke and the walls.

Other main causes of stratification destruction are:

- The drag effect induced by vehicles moving beneath a stratified layer;
- The injection of fresh air into the tunnel, which can induce a swirl along the tunnel and/or, in the case of vents located at the ceiling, cause smoke convection to the tunnel floor;
- The turbulence caused by jet fans activated in the vicinity of the stratified layer.

With transverse ventilation systems, the problem of longitudinal velocity control is difficult to solve since the velocity varies according to the location along the tunnel. Ventilation system operation is therefore dependent on fire location.

The most common recommendation for controlling longitudinal velocity with a transverse system is to act on the injection and extraction flow rates. There are several problems associated with this solution:

- It is recognized that fresh air injection can present a risk to smoke stratification, especially if the jet passes through the smoke layer. Therefore, fresh air vents should not be located along the top of the walls. Furthermore, some studies performed for the Mont Blanc Tunnel renovation have shown that even if the injection is performed at the bottom of the walls, the risk of smoke de-stratification may remain. To minimize this risk, fresh air injection velocities should be kept as low as possible;
- Severe changes in longitudinal velocity can occur if the natural ventilation flow varies during the fire;
- Operation is complex because the relationship between the ventilation system operation and the resulting longitudinal velocity is not direct. Moreover, natural ventilation introduces an additional complexity.

This technique of acting on injection and extraction flow rates is limited to relatively low ranges of atmospheric pressure differences. It may be necessary to install jet fans to ensure longitudinal velocity controlfor transversely ventilated tunnels with high atmospheric influences (e.g. long tunnels crossing high mountains).

**Equipment Specifications:**

Extraction Fans

Studies and full-scale tests show that significant dilution by fresh air can take place inside the duct. The fresh air/smoke mixture is also subject to thermal exchange with the duct walls before reaching the fans. There can also be residual thermal expansion of the gases passing through the fans. These phenomena must be taken into account when establishing the thermal resistance criteria and capacities of the extraction fans.

The thermal resistance of the fans must ensure that the extraction of the hot smoke is possible with any configuration. The PIARC report [2] refers to the Memorial Tunnel and the Zwenberg Tunnel fire tests in which semi-transverse ventilation systems were used. The temperature rise at the fans hardly reached 200°C with uniformly spaced extraction ports. However, when the fire location is relatively close to the extraction point, the exhaust temperature may be significantly higher than 200ºC. This was the reason for increasing the thermal resistance of exhaust fans in Austria and Germany to 400ºC for 90 minutes, and in France 200 or 400ºC for 120 minutes depending on the location of the fans relative to the traffic room.

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**Smoke Dampers:**

To fulfill their function, dampers must be able to withstand normal tunnel environmental conditions and operate under emergency conditions. The main considerations include the following:

- Dampers may be subjected to large pressure differentials when in the closed position (i.e., 2000 Pa to 6000 Pa depending on the length of the extraction duct), and must be able to open under these conditions
- Dampers must be able to operate properly under high temperature conditions and must be constructed in such a way to prevent individual parts from separating and falling into the tunnel during fire conditions.
- Dampers should be reasonably airtight to avoid short-circuiting that would reduce the efficiency of the smoke extraction.

In the emergency mode, the smoke extraction dampers in the fire area are opened and the remaining dampers are closed and smoke is evacuated through the ceiling which is the reason that this ventilation system is suitable in very long tunnels. The schematic diagram of fully transverse ventilation system during normal and emergency operation is shown in Figure

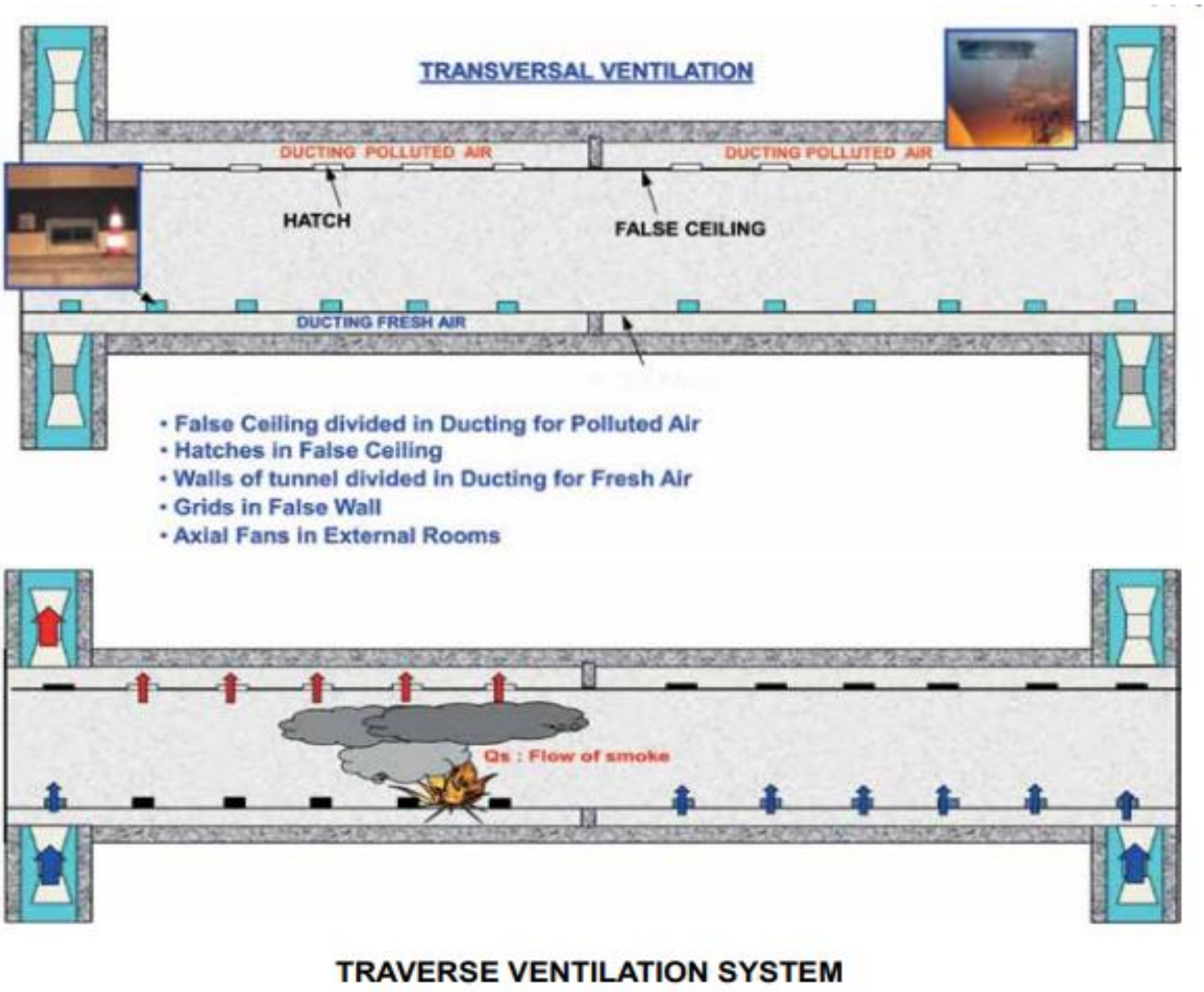


Figure 1.5

**c) Semi-Transverse ventilation system**

In this system, the air supply is introduced via the tunnel portals while the exhaust air is extracted over the length through equally spaced smoke extraction dampers throughout the tunnel. The extracted air flows via overhead duct outside the tunnel. In the reversible semi-transverse ventilation system, fresh air is introduced via ducts and the exhaust air flows longitudinally to the two portals.

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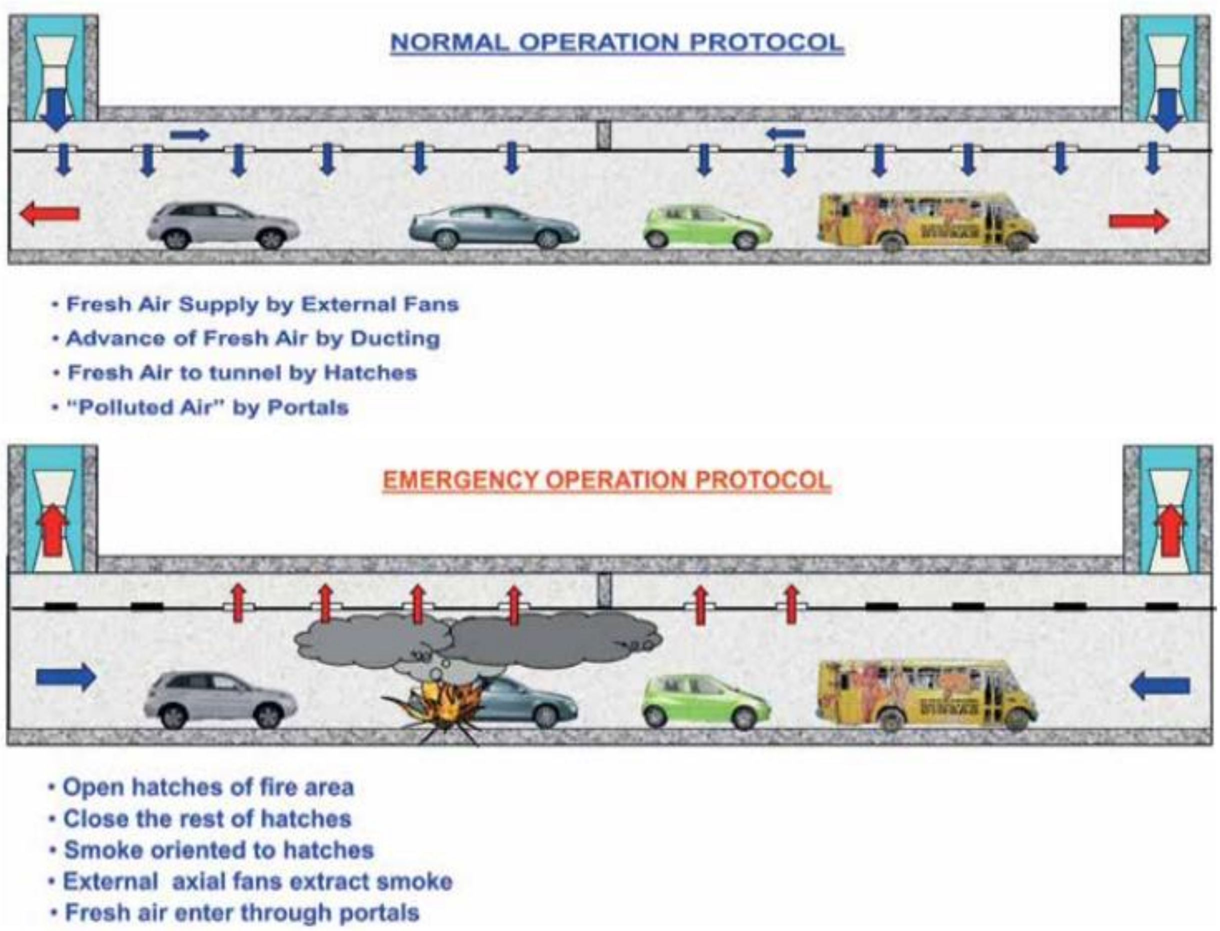


SEMI TRAVERSE VENTILATION SYSTEM

This system uses a combination of jet fans and axial flow fans. The maximum longitudinal velocity of air flow should be 10m/s as per RVS 09.02.31. The smoke-extraction dampers shall be opened fully in the area of the scene of fire and other dampers shall be closed. The schematic diagram showing semi-transverse ventilation system is shown in Figure 3.

**D. Factors to be considered for Ventilation Design**

I. Heat release rate of fire (in MW) – defendant on the type of goods passing through the tunnel and potential flammability, this is generally 50 MW minimum.

Influence of the Fire Heat Release Rate

The smoke flow produced by the fire is roughly proportional to its heat release rate. The fire plume entrains fresh air from the lower part of the tunnel. As the fire develops, the fire plume becomes an additional resistance to the longitudinal airflow.

II. Geometric Data:

a) Unidirectional or Bidirectional tunnel; Length of tunnel;
b) Cross section of tunnel;
c) Perimeter of tunnel.
d) Altitude (m.a.s.l) of the Tunnel at entry and Exit point.
e) Gradient for various spans of the tunnel.

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Influence of the Tunnel Slope (Roadway Grade)

The tunnel slope causes an acceleration of the smoke propagation in the ascending direction (due to buoyancy). This chimney effect is a function of smoke temperature and roadway grade; a fully developed fire on a steep grade can result in high longitudinal velocities and little or no smoke on the descending side of the fire. Combined with certain geometric tunnel properties, this could lead to the whole tunnel cross section becoming filled with smoke.

f) Tunnel Lining: Concrete roughness coefficient; Guniting roughness coefficient;

III. Intermediate adit *or Shaft: location and dimensions.*
IV. Meteorological and Geographic Data:
V. Latitude,
VI. Air Density;
VII. Relative Humidity;
VIII. Wind velocity and any dominating influence
IX. Traffic Data: Direction of traffic: Number of Lanes.

Traffic Volume: Daily Traffic (DMI): Rush Hour traffic (HMI); Number of Diesel/Petrol vehicles; and percentage (Light/Medium/Heavy).

Influence of the Traffic During the minutes following the start of the fire, the traffic patterns in the tunnel is modified. First, the fire creates an obstacle to the traffic, and cars that are driving toward the fire have to stop. These stopped vehicles create an additional resistance to longitudinal airflow. Secondly, barriers or portal lights will be utilized to stop additional traffic from entering the tunnel. Cars that are past the fire incident can normally exit the tunnel without difficulty, increasing the piston effect in the downstream section of tunnel. These traffic changes, in combination, will affect the overall resistance to airflow in the incident tunnel.

Emissions of Vehicles:

Carbon Monoxide emissions and Fume emissions ($m^3$/hour) Admissible Contamination levels for Carbon Monoxide (CO), Nitrogen Oxide (NOX) and Fumes for speeds up to 20 km/h and beyond.
Taking into account the volume of air required for the dilution of pollutants visibility and fire safety considerations, an assessment can be performed and the ventilation system can be chosen for a particular tunnel. Other factors, such as tunnel length, location, type of traffic, environmental laws, and any special conditions should be considered.

Admissible Concentration of Toxic Gases The concentration of CO inside the tunnel should not exceed 70 ppm for normal flowing traffic. This concentration may be permitted up to 100 ppm during traffic congestion. If the CO concentration reaches 200 ppm, tunnel operations should be immediately suspended. Threshold values for $NO_2$ concentration are imposed due to two reasons. One is to protect the environment close to the portals or at stack outlets. The second is to protect tunnel users. In the first case, ambient air quality analysis is usually performed to assess the impact of emissions emanating from the ventilation exhaust points (tunnel portals or at stack outlets) to locally sensitive receptors. Where sensitive receptors are near the ventilation exhaust points, increasing the ventilation airflow rate can enhance emission dilution. It is recommended to permit a maximum average in-tunnel concentration of 1.0 ppm $NO_2$ along the length of the tunnel at any one time. For a short-time working exposure a limit of 5 ppm is recommended.

### E. Visibility

The presence of particulates leads to reduced visibility inside the tunnel. The consideration of visibility criteria in the design of the tunnel ventilation system is required due to the need for visibility levels that exceed the minimum vehicles topping distance at the design speed. There are two primary sources of PM in a tunnel, exhaust emissions and non-exhaust emissions. Exhaust emissions consist of PM emanating from the tailpipe as a result of fuel combustion. Non-exhaust PM consists of tyre and brake wear, road surface abrasion and re-suspended dust. Visibility is reduced by the scattering and absorption of light by PM suspended in the air. The amount of light scattering or absorption is highly dependent upon the material, diameter of the particle and particle density. The principle for measuring visibility in a tunnel is based on the fact that a light beam decays in intensity as it passes through air. The level of decay can be used to determine the opacity of air. Opacity meters for tunnels typically use these effects to measure visibility within the tunnel. This process is described by the formula: -
$E = E0 .e{-}KL$

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Where “E0” is the light source (or emitter) intensity,

“E” is the light receptor intensity and
“L” is the distance between the emitter and receptor expressed in meter.
“K” is the extinction coefficient and is expressed in 1/m.

In tunnel ventilation, visibility is expressed the extinction coefficient K.

Extinction is defined as the loss of intensity E - E0 after travelling the distance L through the tunnel air relative to the source strength E0.

According to the extinction coefficient is expressed as: - K = − 1/L. In (E/E0)

The extinction coefficients used for the design of the ventilation system are given below:-

• K = 0.003 m1 means clear tunnel air (visibility of several hundred meters)
• K = 0.007 m-1 approximates a haziness of the tunnel air and
• K = 0.009 m1 approximates a foggy atmosphere.
• K = 0.012 m-1, threshold value which should not be exceeded during operation and which results in a very uncomfortable tunnel atmosphere.

However, there is normally enough visibility for a vehicle to stop safely at an obstacle. Strong fluctuations visibility can occur e.g. when several diesel-trucks move as a group, when some unusually smoky vehicles are in the tunnel, or when the ventilation control reacts too slowly to emission peaks.

Traffic control and Ventilation system should be able to handle such situations to prevent any untoward incident inside the tunnel.

### F. Ambient Air Concentration

Ambient air supplied to the tunnel as fresh air contains background levels of CO, NO2 and PM. These background levels are normally relatively low, but they should be checked, particularly in the case of urban tunnels. Typical values of CO range between 1 to 5 ppm. Likewise, concentrations of NO2 up to 200 µg/m³ are typical peak values, but can be exceeded in dense urban areas. The situation is aggravated further when air from the portal of one bore re-circulates and enters the portal of the adjacent bore as “fresh air”. Simple structural design features such as barrier walls between portals could be applied to minimize or avoid recirculation of tunnel air. Thus the safety level of the tunnel can be enhanced.

Minimum Air Exchange in tunnels with mechanical ventilation, the minimum air exchange rate are determined using design values. Where traffic volumes are low, the minimum fresh air requirement might be quite small. However, the ventilation system should be able to accommodate sudden demands such as for high emitting Heavy Goods Vehicles.

For such cases, an air-exchange rate of at least 4 times per hour should be considered. Where longitudinal ventilation systems are provided, a minimum longitudinal air velocity of 1.0 to 1.5 m/s is recommended (to be used as a design criterion).

### G. Objectives of Ventilation for Fire and Smoke Control

From the point of view of safety in case of fire, the following criteria have to be applied in the ventilation design: -

a) The purpose of controlling the spread of smoke is to keep people as long as possible in a smoke-free part of the traffic room. This means that either the smoke stratification must be kept intact, leaving more or less clear and breathable air underneath the smoke layer (this is applicable to bi-directional or congested unidirectional tunnels) or/and to completely push the smoke to one side of the fire (this should preferably be applied to non-congested unidirectional tunnels where there are normally no people downstream of the fire).

b) People must, in any cases, be able to reach a safe place in a reasonably short time and covering a reasonably short distance (see Section I). Therefore, facilities such as emergency exits or fireproof shelters should be provided whenever necessary c) The ventilation system must be able to keep clear of smoke the air in unharmed structures (escape routes, twin traffic tube, etc.) d) The ventilation system must be able to produce good conditions for firefighting.

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## H. Tunnel Fires, Fire Detection and Fixed Fire Fighting Systems

Tunnel Fire Characteristics In order to design the tunnel ventilation system and suppression systems for fighting fires in a tunnel, the designer should carry out a risk and probability estimation of design fire incident for the particular Tunnel. Subsequently the design fire load should be based on density of traffic in the tunnel, types of vehicles being allowed in the tunnel especially those carrying inflammable and other dangerous products, traffic management in the Tunnel and fixed fire fighting systems being provided. Factors like Type of cargo including bulk transport of fuel, Fire detection systems in place, Ventilation profile, Tunnel geometry (tunnel width, height, cross section, length), tunnel volume (available oxygen), shape of tunnel, grade inside tunnel, location of exits, and tunnel drainage etc need to be taken into account he designer must suggest a Tunnel fire curve which is likely to simulate the probable scenario inside the tunnel in case of a fire incident. Some such tunnel fire curves are described at Annexure F. Tunnel Fires may be characterized by the following aspects: -

Table 1.0

| Ser No | Time Dependant Design Fire Variables | Values Range |
|---|---|---|
| 1 | Fire Size - Maximum Fire Heat Release Rate | 1.5 – 300 MW (5 – 1020 MBtu/hr) |
| 2 | Fire Growth Rate (slow, medium, fast, ultra fast) | 0.002 – 0.178 kW/sec² as high as 0.331 kW/sec² measured at one test. 20 MW/min linear fire growth rate has been used for several tunnel projects where Flammable and Combustible Liquid Cargo were allowed to pass through the tunnel |
| 3 | Fire Decay Rate | 0.042 – 0.06 ($min^{-1}$) |
| 4 | Perimeter of Fire | Car – truck perimeter or pool of liquid fuel spill |
| 5 | Maximum Gas Temperature at Ceiling | 110°C – 1350°C (Maybe higher with new Carriers) |
| 6 | Fire Duration | 10 min – 6+ days |
| 7 | Smoke and Toxic Species Production Rate | 20 – 300 $m^3$/sec |
| 8 | Radiation | From 0.25 to 0.40 of total heat flux up to 5125 $W/m^2$ |
| 9 | Flame Length | Up to full tunnel height |

## I. Automatic Tunnel Fire Detection and Warning Systems

The key objective of the automatic tunnel fire detection and warning systems is to provide prompt, accurate, and reliable fire detection while preventing nuisance alarms. Prompt and accurate fire detection will result in timely activation of tunnel ventilation system in the predetermined mode of operation to maintain tenable environment for evacuees. The successful management of tunnel fires requires that fires are detected quickly and accurately while they are still at a controllable size (in the order of 1 – 5 MW [3 – 17 MBtu/hr]). Accurate fire detection is critical in preventing fire spread and fire growth. If a fire is detected early, the fire protection system could suppress a small fire or take a larger fire under control, not allowing it to grow further or spread to other vehicles.

## J. Smoke Management:

The other critical aspect in case of a fire incident is of smoke management. There are two commonly used concepts for smoke management in road tunnels to achieve a smoke-free environment for egress: -

- Longitudinal ventilation concept: Directing smoke along the tunnel in the opposite direction of egress. The longitudinal ventilation concept is achieved by producing air velocity that meets or exceeds the critical velocity along the tunnel which prevents smoke back-layering. The critical velocity depends on the fire size.

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• Extraction ventilation concept: Extracting smoke at the fire location and relying on smoke stratification to allow for egress under the smoke layer. The extraction concept is achieved by maximizing the exhaust rate in the ventilation zone that contains the fire and by avoiding disruption of the smoke layer by longitudinal air velocities. This concept depends on the smoke production rate which is a function of the fire size. Smoke stratification may not occur for fires with relatively small heat production rates (low buoyancy) and especially when the flame is not visible (for example, rubber tire fires). Also, stratification can be destroyed by airflow passing by the fire site or by fixed firefighting systems. Extraction ventilation systems designed for large size fires should be designed and analyzed for both stratified smoke and non-stratified smoke.

### K. Fixed Fire Fighting Systems

The designer may provide fixed firefighting systems inside a tunnel to control or mitigate fires. Fixed water-based firefighting systems are categorized based on their performance objectives as:-

• Fire Suppression Systems with the goal to reduce the fire HRR by sufficient application of water, e.g. Deluge system with adequate water storage inside/ outside tunnel.

• Fire Control Systems with the goal to stop or significantly slow the fire growth rate, e.g. Deluge system with adequate water storage inside/outside tunnel.

• Volume Cooling Systems with the goal to provide substantial cooling of the products of combustion but not intended to reduce fire HRR, e.g. Water Mist System

• Surface Cooling Systems with the goal of protecting the main tunnel structural elements but not intended to reduce fire HRR, e.g. Water Mist System or Deluge System

### L. Fire Rating for Fittings

All fittings provisioned inside the tunnel need to have proper fire ratings so as to ensure serviceability in the temperature environment expected during a tunnel fire. All electrical fittings and alarm systems need to be designed in such a way that their serviceability is not affected during an expected tunnel fire incident.

Passive fire protection systems
Tunnel lining and interiors may be coated with fire proof coatings to keep the strength of structural elements and concrete lining within safe temperature ranges. These systems should be chosen based on test results from accredited labs.

It is appropriate to mention here the objectives of the ventilation system during a fire, without getting into too much detail on how they are achieved. During the self-evacuation phase (also called the self-rescue phase, during which tunnels users would, of their own volition, attempt to evacuate from the tunnel), the ventilation system aims to create and maintain a tenable environment for the evacuation of tunnel users. Specifically, this environment consists of acceptable visibility and air quality levels. Role of the Ventilation System during the Fire-Fighting Phase During the fire-fighting phase, the ventilation system operation has to be decided by the head of emergency operations, which should choose the best solution taking into account the possibilities of the ventilation system and the operational needs of the firemen.

### M. Tests

Three kinds of tests may be performed in order to check the equipment and the safety objectives of the ventilation system:
• Reception (factory) tests are aimed at checking that the equipment actual performance matches the specified requirements. The test guidelines generally point out the procedures for these test operations.

• On-site unit tests are aimed at checking that equipment operation is in accordance with the project specifications.

• Integration tests are aimed at checking that the safety objectives match, especially with regard to smoke control. The first set of integration tests may be performed without a fire in order to quantify the ventilation capacity, and a second set of tests may involve a calibrated fire in order to account for the buoyancy effects and to visualize the smoke development.

It is generally impossible to perform integration tests with fires as large as the design fires. Most commonly, the main purpose of these tests is to train tunnel operators and members of the fire brigade.

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## IV. CONCLUSION

Advantages and disadvantages of smoke control/ventilation system. For the ventilation system, usually it divided into two types, which is mechanical ventilation and natural ventilation. Mechanical ventilation As for mechanical system, if it well designed, installed and maintained, there are a number of advantages to a mechanical system.

• These systems are considered to be reliable in delivering the designed flow rate, regardless the impacts of variable wind and ambient temperature. As mechanical ventilation it can be integrated easily into air-conditioning, the indoor air temperature and humidity can also be controlled

• Filtration systems can be installed in, so that harmful microorganisms, particulates, gases, odours and vapours can be removed.

• The airflow path in mechanical ventilation systems can be controlled, for instance allowing the air to flow from areas where there is a source (e.g. patient with an airborne infection), towards the areas free of susceptible individuals.

• Mechanical ventilation can work everywhere and anytime when electricity is available. However, mechanical ventilation systems also have problems.

• Mechanical ventilation systems often do not work as expected, and normal operation may be interrupted for numerous reasons, including equipment failure, utility service interruption, poor design, poor maintenance or incorrect management (Dragan, 2000). If the system services a critical facility, and there is a need for continuous operation, all the equipment may have to be backed up—which can be expensive and unsustainable.

• Installation and particularly maintenance costs for the operation of a mechanical ventilation system may be very expensive. If a mechanical system cannot be properly installed or maintained due to shortage of funds, its performance will be compromised. Because of these problems, mechanical ventilation systems may result in the spread of infectious diseases through health-care facilities, instead of being an important tool for human. There are several methods to limit this migration, and some are designed to provide a tenable environment for occupants to egress the building. A smoke control system can include physical barriers that limit smoke from migrating outside the zone, a combination of physical barriers and mechanical systems, or only mechanical systems to control the spread of smoke. However, each type of system has their advantages and disadvantages.

Natural ventilation As well as for natural ventilation, if it is well installed and maintained, there are also several advantages of a natural ventilation system, compared with mechanical ventilation systems.

• Natural ventilation can generally provide a high ventilation rate more economically, due to the use of natural forces and large openings. Natural ventilation can be more energy efficient.

• Well-designed natural ventilation could be used to access higher levels of daylight. From a technology point of view, natural ventilation may be classified into simple natural ventilation systems and high-tech natural ventilation systems. The latter are computer- controlled, and may be assisted by mechanical ventilation systems. High-tech natural ventilation may have the same limitations as mechanical ventilation systems. However, it also has the benefits of both mechanical and natural ventilation systems. If properly designed, natural ventilation can be reliable, particularly when combined with a mechanical system using the hybrid (mixed-mode) ventilation principle, although some of these modern natural ventilation systems can be more expensive to construct and design. In general, the advantage of natural ventilation is its ability to provide a very high air-change rate at low cost, with a very simple system. Although the air-change rate can vary significantly, buildings with modern natural ventilation systems (that are designed and operated properly) can achieve very high air-change rates by natural forces, which can greatly exceed minimum ventilation requirements. There are a number of drawbacks to a natural ventilation system.

• Natural ventilation is difficult to control, with airflow being uncomfortably high in some locations and stagnant in others. There is a possibility of having a low air- change rate during certain unfavourable climate conditions.

• There can be difficulty in controlling the airflow direction due to the absence of a well-sustained negative pressure; contamination of corridors and adjacent rooms is therefore a risk.

 

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• Natural ventilation precludes the use of particulate filters. Climate, security and cultural criteria may dictate that windows and vents remain closed; in these circumstances, ventilation rates may be much lower.

• Natural ventilation only works when natural forces are available; when a high ventilation rate is required, the requirement for the availability of natural forces is also correspondingly high.

• Natural ventilation systems often do not work as expected, and normal operation may be interrupted for numerous reasons, including windows or doors not open, equipment failure (if it is a high-tech system), utility service interruption (if it is a high-tech system), poor design, poor maintenance or incorrect management.

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