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Operational Strategies for Emergency Smoke Ventilation in Tunnels

Abstract: This *White Paper* establishes guidelines for emergency ventilation of tunnels in the event of a fire.

Keywords: smoke control, response management, ventilation

Summary: Ventilation in tunnels is required for normal and emergency operation. During normal operation, its purpose is to provide a clean air environment and to maintain reasonable temperatures during congested conditions. During emergency operation, ventilation is needed to influence the flow of smoke and combustion products so as to create a safer environment for tunnel users to escape and for emergency services to intervene. This document presents a guide to tunnel ventilation systems and their operation during emergency conditions. The emergency ventilation system design requires the identification of the potential fire and smoke threat in terms of visibility, temperature and toxicity effects. Therefore, given the layout of the tunnel, the designer has to consider the characteristics of the traffic (expected flow, type of vehicles and combustible load); the means to safeguard tunnel users by keeping a smoke-free area and providing sufficient exit facilities for egress and rescue, and to support the responding emergency services; the minimum ventilation and/or extraction capacity to cope with the design fire scenario; other safety facilities such as egress routes, doors, passageways, and various equipment (video cameras, phone facilities, fixed fire suppression systems, fire extinguishers and communication circuits); meteorological conditions between the portals that may create, through pressure difference, very important natural air flow velocities inside the tunnel.

Scope and purpose: To amplify these topics, this *White Paper* provides an overview of ventilation system types and the objectives for some control, strategies for smoke management, and how these are impacted by the design of the tunnel and its ventilation system. Finally, operational strategies for rail and road tunnels are described. This document is intended for use by system operators, emergency responders.

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The American Public Transportation Association greatly appreciates the contributions of the Security Emergency Management Working Group, in drafting this *White Paper*.

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1. Ventilation systems and the objectives for smoke control

Tunnel ventilation can be achieved by either natural or mechanical means. Natural systems rely on the piston effect of moving vehicles, external wind, and temperature and pressure differentials between the portals to produce airflow through the tunnel. Mechanical ventilation systems use fans to produce airflows and may use ducts and dampers to distribute this airflow. Regardless of mechanical ventilation equipment, naturally induced airflows are present in all tunnels to a varying extent.

Tunnel ventilation is based on the application of either dilution or removal of smoke. Dilution is usually an efficient method for normal operation, in which case the objective is to maintain air quality and visibility. It can increase tenability by reducing concentrations of toxic gases. During emergency operation, smoke management is ideally achieved by removal of air, for example by the extraction of air and smoke. Hence, vitiated air is replaced by clean or smoke-free air, which is either supplied mechanically or drawn in through the portals.

The general classification of a ventilation system is based on the direction of airflow. Longitudinal ventilation is in the direction of the tunnel axis; air may be introduced or removed from the tunnel at a limited number of points, such as portals or ventilation shafts, or ceiling-mounted jet fans may be used to produce the required airflow through the tunnel. In transverse and semi-transverse ventilation systems, which are generally more common in road tunnels, air movement is perpendicular to the tunnel axis in the plane of a cross-section.

Longitudinal ventilation for smoke control is ideal in a non-congested road tunnel with unidirectional operation. The ventilation flow would be in the direction of traffic, and so traffic ahead of an incident will exit the tunnel, and traffic behind the incident will be in fresh air. In a rail tunnel, the objective would be to move smoke in a direction that would facilitate evacuation of the train. The challenges occur in a road tunnel that is congested, and so the simple philosophy described would not be achievable. In a rail tunnel, the location of the fire is critical – if the fire is in the central car of a multiple car-train, then one half of the passengers would be in smoke.

Semi-transverse ventilation systems have the characteristic of either extracting or injecting air in a distributed fashion over the length of the tunnel. Typically, the extraction or injection flow rate is constant along the length of the tunnel. Semi-transverse systems operating in exhaust are not efficient for smoke control, and recent developments in semi-transverse systems apply remotely controlled dampers enabling point extraction of smoke. In this case, only the dampers nearest to the fire are opened, and the remaining ones are closed. The efficiency of the smoke extraction is greatly increased if the longitudinal velocity in the tunnel can also be controlled from the beginning of the fire, for example by jet fans, thus avoiding extensive smoke spread. The aim would be to provide longitudinal flow on either side of the extraction zone – effectively pushing smoke topwards it. Smoke can then be extracted over a short distance near to the fire. This overcomes the shortcoming of traditional semi-transverse systems, where extraction is performed over longer sections of tunnel.

Transverse systems use both a supply and an exhaust air duct to uniformly distribute air to and remove air from a tunnel. Typically, air is supplied at a low level near the roadway and extracted along the tunnel ceiling. Here again, systems that incorporate remotely controlled dampers enabling point smoke extraction are more efficient for smoke control. During a fire, the fresh air supply is sometimes reduced along the tunnel length, for example to preserve stratification and to create a longitudinal velocity toward the fire. Where the capability exists, the supply may be further restricted in the fire section.

Optimal strategies for the operation of tunnel ventilation need to consider the real fire situation and its development with time, noting that the normal operating condition is the starting point for the initiation of the emergency response. The ultimate goal of smoke control would be the achievement of a system that is capable of taking the correct on-line decisions and of instructing all rescue services as a function of the actual situation. However, due to the complexity and diversity of fire hazards, optimal control is perhaps beyond the reach of the actual state of knowledge and technology. Hence, strategies based on predefined intervention plans and procedures using the available knowledge and equipment must be developed.

1.1 Strategies for smoke management

The strategy to be adopted for smoke management depends on a number of factors that need to be considered during the development of a response plan:

- **The sequence of events** that that might be thought to occur during a fire. Noting that they will overlap each other, they include the following:
  - ignition
  - communication to tunnel control center
  - evacuation, either promoted by tunnel users directly, or assisted by emergency services
  - operation of ventilation strategy
  - firefighting
- **The objectives for smoke control** for these events, which may include the following:
  - preservation of stratification during the early stages of evacuation
  - activation of longitudinal ventilation to push smoke in one direction
- **The design features** of the tunnel and ventilation system

The optimal strategy for smoke management can depend on the situation in the tunnel prior to the incident and depends on whether tunnel users may be present on either side of the fire. Two examples serve to illustrate this:

- **In a tunnel with unidirectional travel,** and where there is no congestion, it could be assumed that vehicles downstream of an incident would be able to exit the tunnel unhindered and so the immediate operation of longitudinal ventilation to propel smoke downstream would provide a simple and reliable solution.
- **Where there is congestion, or bidirectional traffic,** or in the special case of a train fire occurring in the middle of a train, then users may be on either side of the fire, and a longitudinal system would have limitations. In this case it may be appropriate to allow the smoke to stratify, i.e. to rise to the roof of the tunnel under the influence of buoyancy, allowing tunnel users to escape underneath the smoke layer. A potential risk with this option is that some passengers upwind may not be aided that would otherwise have been had the ventilation system been activated. This too carries its own risk that those evacuating downwind may be subject to higher smoke levels compared to those during non-activation of the fans. The tunnel operator should assess what provides the most benefit to the most number of people, realizing that any ventilation system has limitations.

Hence, the dynamics of smoke movement need to be considered, particularly as they relate to the evacuation phase of the incident response. In systems that employ longitudinal smoke management, the following general parameters may be a useful starting point:

- **At near-zero velocity** (a longitudinal velocity less than about 0.5 m/s), smoke will stratify and spread in both directions, and concentrations of toxic gases will increase, leading to untenable conditions, as the gases are not diluted. This strategy may be less favorable than providing a low-velocity airflow, as at zero velocity the concentration of toxic gases as well as the temperature might be very high in the region of the fire.
- **At low velocity** (a longitudinal velocity in the tunnel of 1.2 ± 0.2 m/s), the low turbulence and strong buoyant forces promote smoke stratification, enabling people to escape underneath the smoke

layer. Moreover, the concentrations of the toxic gases are likely to be reduced. In this case, the smoke is likely to spread on both sides of the fire.

- **At critical velocity** (typically about 2.5 to 3 m/s), the benefit is that no backlayering of smoke is present, and the smoke is blown entirely to one side of the fire. However, smoke stratification is very unlikely.
- **Above the critical velocity,** the smoke is kept on the downstream side of the fire, allowing passengers to evacuate upwind of the fire location High flow rates may have the advantage of reducing temperature and decreasing toxicity; on the other hand, they may lead to higher heat release rates and will completely destroy stratification.

In some cases, a longitudinal flow velocity of between 1 and 2 m/s is thought optimal. In other situations, the simple philosophy of engaging all available equipment, for example all jet fans, to blow the smoke out of the exit portal or vent shaft is used. Intermediate strategies ensure a longitudinal velocity that corresponds to the critical velocity at the location of the fire. In any event, large flow fluctuations and in particular flow reversals should be avoided.

In the case of smoke extraction using a transverse or a semi-transverse ventilation system, including remotely controlled dampers, the smoke should be extracted as close to the fire as possible, the objective being to contain the smoke within the extraction zone. The extraction zone should be as short as practicable while still covering the fire area, to maximize airflow to the affected location. It is recommended that the smoke be extracted at full capacity at the incident location, avoiding the spread of smoke by implementing smoke control management from the beginning of the fire.

In the case of transverse ventilation, the transverse flow injection should be reduced to avoid destratification or to unduly influence the longitudinal airflow. On the other hand, fresh air injection may be useful for other considerations, for example fresh air supply to the egress routes or for those trapped in the tunnel.

The requirements of emergency services should be taken into account when designing the ventilation response procedures for the assisted rescue and firefighting phases. Generally, when the emergency services appear on site, they take over the command. In many situations, the same ventilation strategies apply as during the self-rescuing phase for the succeeding phases. However, the longitudinal flow velocity control might be changed for the needs of the emergency services.

In some cases dedicated firefighting ventilation programs are made available. They may involve longitudinal ventilation at other velocities than are required for the evacuation phase.

1.2 Response of ventilation control systems to fire

The control system should allow for a response of the ventilation system to a reported incident. This response is based on information retrieved from various sources inside the tunnel. The information is received and validated, and the ventilation response is activated automatically, semi-automatically or manually:

- **In automatic control,** there is generally no intervention by the tunnel operator. The tunnel operator can, however, intervene in the automatic process. This type of response is more appropriate for road tunnels than for rail tunnels.
- **In a semi-automatic system,** the tunnel operator chooses the procedure of the smoke control system and starts it. The semi-automatic control system, when started, controls the components of the smoke control system according to a previously programmed procedure associated to the input objectives defined by the tunnel operator.

- **In manual systems,** the operator analyzes the available data and activates each equipment component or groups of components of the smoke control system following a procedure that should be predefined for the fire.

Consideration needs to be given to the complexity of the ventilation system and the organization of operating personnel, as well as the evacuation response. Experience shows that a complex ventilation system is much more efficiently managed by an automatic system than by an operator performing under high-stress conditions. However, where evacuation direction is a factor, such as in rail transit tunnels, an automatic mode may not be appropriate.

1.2.1 Overview of the control process

During normal operation, the main objective of the control of ventilation is to maintain the air quality within pre-established values under consideration of operational costs. In contrast, fire is a rare event that is usually preceded by incidents such as breakdowns, accidents or acts of terrorism. The transformation of these incidents to fire situations is faster than the processes related to normal operation. Therefore, the response of the operator and/or the automatic system must be rapid.

Consequently, the response time for the entire chain of events — i.e., detection, identification, alarm validation and intervention — must be reduced to optimize the conditions during the evacuation phase. Furthermore, depending on the installed level of equipment (linear heat detector, CCTV, smoke detectors, etc.) in the tunnel and the level of surveillance, different strategies can be established.

It is important to realize that the best strategy to be adopted depends on the quality and reliability of the information available. One of the goals of the ventilation control system in the case of fire is to extract reliable information. Then the first challenge is the “change” from normal operational control to the appropriate fire mode.

In general, this process is dynamic and implies different steps depending on the different quality and quantity of information gained. Once a fire alarm is detected, automatic or manual validation of the alarm is required. The actions taken depend on the available information.

Once the fire alarm is confirmed and the ventilation strategy is defined, the control system must be able to achieve the predefined condition (for example a particular longitudinal velocity). It may be appropriate to place the system in alert and starting condition, even before confirmation of the fire and its position.

The following are some of the important tasks of the control systems in order to help during the evacuation phase:

- Validate whether there is a fire or smoke condition.
- Determine the fire or smoke location and if possible the type of fire (trash, vehicle, etc.).
- Determine evacuation direction.
- Decide whether to initiate ventilation and direction.
- Initiate ventilation if chosen as the response.
- Ensure that if there are no plausible measurements or observations, such as might occur with multiple alarms due to a moving vehicle on fire, then a compromise ventilation mode that is deemed to minimize risk should be implemented as a precaution.

1.3 Input data defining fire and ventilation scenario

1.3.1 Fire detection

Fire detection systems will enable the initial identification of a fire event. They have different characteristics depending of their form, but may be generally classified as follows:

- **Automatic detecting sensors:** Developed specifically for fire and smoke detection, these sensors put out an alarm signal as soon as an incident is triggered (e.g., heat detection, CCTV information, smoke detection).
- **Human triggering:** Manual triggering of the alarm by the operator due to appropriate information from sources like CCTV (e.g., incident or smoke detection), emergency phone calls, signals from inside the tunnel (emergency buttons, fire extinguisher removal, doors opened, etc.) or from information from automatic detection systems if an operator response for validation is required.
- **Indirect (automatic) detection:** This kind of detection would be the result of a logical interpretation and correlation process of signals coming from different sources (carbon monoxide and/or particles concentration, air velocity, traffic speed, etc.).

Detection is conducted based on exceeding threshold values for a prescribed duration. It is useful to include the rates of change of the measurements in the evaluation.

The detection of a fire is of paramount importance, since missing an event could mean the loss of time. This in turn implies that a certain number of false alarms have to be accepted. Nevertheless, generating too many false alarms could tire the operator with a similar result (canceling them out without paying much attention). The reliability of the fire detection system is therefore very important.

In this context it is important that different sections of the tunnel are identified unambiguously, so that users who report fires can accurately convey their location to the operator. Particularly when using smoke extraction, the location of the fire needs to be detected in order to incorporate the correct response with respect to ventilation control.

Normally, smoke detection is less accurate in determining the location of the fire than is a high-temperature alarm using a linear heat detector. Moreover, the reaction due to several independent fire detectors by one or more systems has to be considered. This concerns the detection of moving fire sources (moving trains on fire) as the location of the initial detection of the fire might not be the same as the location where the vehicle comes to a standstill (in particular information retrieved from CCTV and smoke detection).

Normally, the response has to be organized in a hierarchy such that particular signals have higher priorities in defining the fire scenario. For example, in a tunnel equipped with smoke detectors, linear heat detectors, CCTV, opacity meters, etc., a decision process should be formulated that gives the most reliable guidance with regard to fire location. This is particularly important in the case where smoke extraction is through the use of remotely controlled dampers.

2. Operational strategies

2.1 Rail tunnels

Operational strategies are designed to complement other safety strategies, and in particular the approach to ventilation. Each transit agency should consider its own unique issues that may require different or other additional procedures.

The following general guidelines are common in subway systems:

- If a fire is detected on a train, and the train is operational, then it should be sent to the next station if possible. Evacuation from the train is much easier at a station than in a tunnel. This also helps first responders in assisting with the evacuation and fighting the fire.
- Other trains in the immediate area should be stopped. The piston effect of trains in a tunnel dominates the effect of ventilation systems, and so it would be challenging to manage ventilation unless other nearby trains are stopped.
- The communication and command structure must be clear. If the train operator contacts a control center with details of an emergency, then operating procedures should be in place with regard to the strategy for smoke management, who operates fans, when to activate fans, and how to operate the fans (such as push-pull, station all exhaust, station push-pull, point extract system, etc.).
- The train operator should contact Control with relevant information about the emergency and action being taken with passengers.
- First responders such as fire and police departments should be called out for a response and notified of ongoing transit response.
- Following trains should not enter the same ventilation block as the incident train. This may seriously impair the ability of the ventilation system to control smoke in the desired manner. It also potentially exposes the passengers on those follow-on trains to the smoke from the fire. The prohibition of a second train in the same ventilation zone may be achieved with the design of the train control system.
- Adjacent tunnels should be kept available for a rescue train or a fire department access train in the event that the train is stranded in the tunnel. The rescue train can expedite evacuation of passengers and transport of first responders to the scene.
- The train operator, if able, should lead passengers to a safe refuge.
- Traction power should be de-energized on the involved track so that evacuees and first responders are not at risk.

2.2 Road tunnels

In road tunnels, generally similar concepts are employed. A major difference is that involving the concept of self-rescue. Road tunnel users are freer entities than those in a rail tunnel, and there is no immediate, local commander to give direction. It is particularly important, therefore, that the initial smoke strategy prolongs the time available for self-rescue, so that users can appraise the unfamiliar situation and surroundings and take appropriate action prior to the arrival of the emergency services.

Typical operational strategies for road tunnels include the following:

- Notify rescue resources according to operational procedures.
- Give support to emergency services comprising information of the course of events, creation of access passages, and possible change of operational mode of technical systems in order to create the best conditions for the rescue operation.
- Handle the external information to media and the public according to a common information and media plan.

Other tunnel operator interventions depend on the specific tunnels and their technical systems. Interventions could include the following:

- Activate necessary traffic control restrictions and cooperation with emergency services on site if other activities concerning traffic restrictions are required.

- Activate fire ventilation scenario in order to ensure safe self-rescue and a safe environment for the rescue services approaching the fire. Cooperate with the fire brigade in operating the ventilation system if changes are wanted.
- Give information and orders to users by using the public address system or the radio system on how to act in the tunnel.

Abbreviations and acronyms

CCTV	closed-circuit television
m/s	meter per second